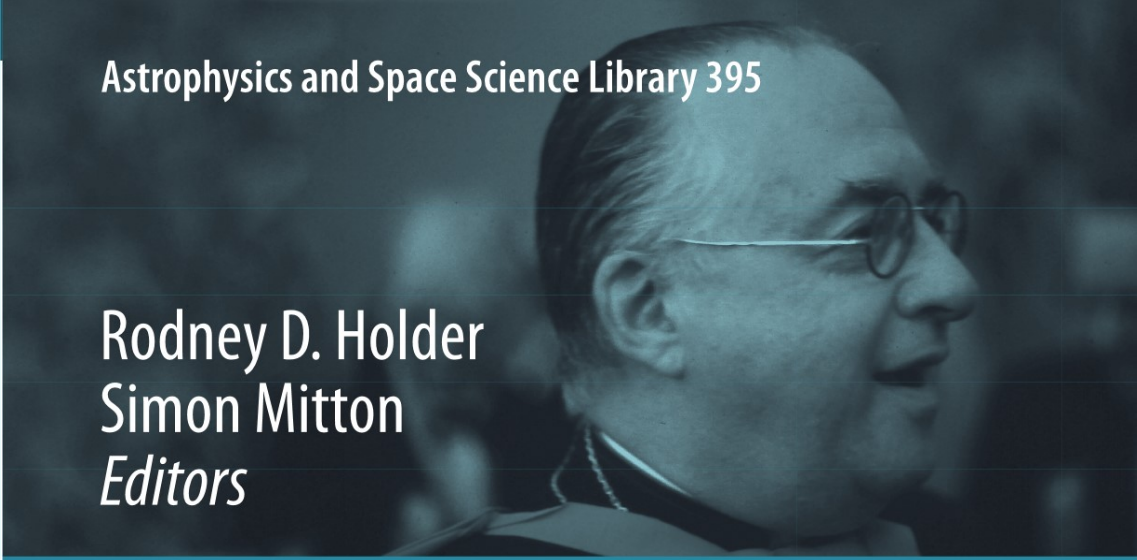

Astrophysics and Space Science Library 395

Rodney D. Holder
Simon Mitton
Editors

Georges Lemaître: Life, Science and Legacy

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Foreword

I’ll begin this Foreword with a text from Georges Lemaître:

> The evolution of the universe can be likened to a display of fireworks that has just ended – some few wisps, ashes and smoke. Standing on a well-chilled cinder, we see the fading of the suns, and try to recall the vanished brilliance of the origin of the worlds.

Lemaître lived just long enough to learn about the evidence for that ‘vanished brilliance’ – the cosmic background radiation, sometimes called the afterglow of creation, and also to learn a great scientific as well as poetic truth that links us to the stars – that each of us contains carbon, oxygen and iron atoms forged in thousands of different stars from all over the Milky Way that lived and died before the solar system formed. We are the ‘nuclear waste’ from the fusion power that makes stars shine.

But Lemaître would have been even more elated had he been alive today to have learnt about current discoveries and debates, especially as they impinge on issues that would have engaged him as a Catholic philosopher as well as a scientist. The crescendo of discovery is owed primarily to advancing instrumentation – more powerful telescopes in all wavebands, better sensors for faint radiation, and space technology. Equally important have been powerful computers. Armchair theorists deserve little credit. We can now specify conditions one second after the Big Bang with more confidence than a geologist has when talking about the early history of our Earth. However, this progress brings into focus some questions that Lemaître couldn’t even have posed – about what happened still earlier – and how, from amorphous beginnings in what he called the primeval atom, the cosmos evolved to its present complexities.

There were a set of key steps in the evolution of the cosmos: the first particles, protons and neutrons; the first stars and galaxies; the synthesis of the chemical elements in stars; the formation of planets around later-generation stars; and then of course, on at least one planet, the formation of a biosphere, which led to the emergence of brains capable of pondering their origins.

This chain of events is sensitive to some cosmic numbers – key parameters. Had they been different, the universe would have been sterile or stillborn. These numbers were all imprinted in the first tiny fraction of a second, when energies and densities were so extreme that our experiments offer no direct guide to the relevant physics.

The cover of *Discover* magazine one month had a nice image: it showed a circle, beneath the caption 'the universe when it was a trillionth of a trillionth of a trillionth of a second old – actual size'. According to a popular theory, the entire volume we can see with our telescopes 'inflated' from a hyper-dense blob no bigger than that.

And in our time we've an enlarged perspective on another question:

> How big is the universe? We can only see a vast but finite volume, a finite number of galaxies. That's essentially because there's a horizon, a shell around us, delineating the distance light can have travelled since the Big Bang. But that shell has no more physical significance than the circle that delineates your horizon if you're in the middle of the ocean. We'd expect far more galaxies (or ocean) beyond the horizon.

There's no perceptible gradient across the visible universe, which suggests it stretches thousands of times further. But that's just a minimum. If it stretched far enough, then all combinatorial possibilities would be repeated. There would, far beyond the horizon, be replicas of you, and indeed replicas of our entire Hubble volume. The volume of space-time within range of our telescopes, what astronomers have traditionally called 'the universe', could be only a tiny fraction of the aftermath of our Big Bang. But that's not all. "Our" Big Bang may not be the only one: one option is brane worlds in which many universes are embedded in a higher-dimensional space. Other space-times alongside ours – 1 mm away. Another scenario is 'eternal inflation', which is a grander version of old steady-state cosmology, with big bangs that are continually popping off within an expanding substratum.

What we've traditionally called 'the universe' could be just one patch of space-time in a vast cosmic archipelago.

A challenge for twenty-first century physics is to decide whether there have been many big bangs rather than just one, and (if there are many) whether they are governed by different physics, so that what we call the laws and constants of physics are just parochial bylaws in our cosmic patch. Many theorists suspect this. If these theorists are correct, the big bangs might ring the changes, and then it would occasion no surprise that there was one big bang fine-tuned enough to allow the chain of events that led to the emergence of a biosphere.

We don't know – but one day we may. It's speculative science, not metaphysics.

Four hundred years ago, Kepler thought that the Earth was unique, and its orbit was related to the other planets by beautiful mathematical ratios. We now realise that there are zillions of stars, each with planetary systems. Earth's orbit is special only insofar as it's in the range of radii and eccentricities compatible with life. Maybe we're due for an analogous conceptual shift, on a far grander scale. Our Big Bang may not be unique, any more than planetary systems are. Its parameters may be 'environmental accidents', like the details of the Earth's orbit.

Will there be such a theory? We're still groping for the truth – in the fashion of ancient cartographers, we must still inscribe 'here be dragons'. And there are questions that we can't yet formulate: Donald Rumsfeld's famous 'unknown unknowns'.

Einstein averred that "The most incomprehensible thing about the universe is that it is comprehensible". He was right to be astonished. Our minds, which evolved to cope with life on the African savannah, can also comprehend the microworld of atoms, and the vastness of the cosmos. Humans are more than just another primate species. We are special: our self-awareness and language were a qualitative leap, allowing cultural evolution, and the cumulative diversified expertise that led to science and technology. But some aspects of reality – a unified theory of physics, or of consciousness – might elude us simply because they're beyond human brains, just as surely as Einstein's ideas would baffle a chimpanzee.

This raises another question. Is there life out there? Is there perhaps advanced life to whom the problems of string theory are a doddle? We don't know, but we've now learnt something that's relevant to this question, and which makes the night sky far more interesting than it was to our forbears. Many stars – perhaps even most – are orbited by retinues of planets, just like the Sun is.

Most planets are not detected directly but inferred. The first technique was to look for any wobble in the star's motion. The evidence up till now pertains mainly to giant planets – objects the size of Saturn or Jupiter. But we'll be especially interested in possible twins of our Earth: planets the same size as ours, orbiting other Sun-like stars, on orbits with temperatures such that water neither boils nor stays frozen. Detecting Earth-like planets via their gravitational pull on their parent stars is a real challenge. Being hundreds of times less massive than Jupiter, they induce motions of merely centimetres per second. But there's another technique that can do this: we can look for their shadow. A star will dim slightly when a planet is in transit in front of it. And these dimmings would repeat at regular intervals. The Kepler spacecraft is finding dozens of planets no bigger than the Earth by this technique

But we'd really like to see these planets directly – not just their shadows. And that's hard. To realise just how hard, suppose an alien astronomer with a powerful telescope was viewing the Earth from (say) 30 light years away, the distance of a nearby star. Our planet would seem like, in Carl Sagan's memorable phrase, 'a pale blue dot', very close to a star (our Sun) that outshines it by many billions of times: a firefly next to a searchlight. The shade of blue would be slightly different, depending on whether the Pacific Ocean or the Eurasian land mass was facing them. The alien astronomers could infer the length of the day, the seasons, whether there are oceans, whether the water on those oceans is rough or smooth, the gross topography, and the climate. By analysing the faint light, they could infer that it had a biosphere. In 20 years, we'll have telescopes that can do this.

Will there be life on any of these planets? We still know too little to say whether alien life is likely or unlikely – indeed the origin of life on Earth is another big unsolved problem. And we shouldn't restrict attention to Earth-like planets. Science fiction writers have other ideas – balloon-like creatures floating in the dense atmospheres of Jupiter-like planets, swarms of intelligent insects, nanoscale robots, and so on. (And, it's better to read first-rate science fiction like than second-rate science.)

Even if simple life is common, it is of course a separate question whether it's likely to evolve into anything we might recognize as intelligent or complex. There are SETI searches for artificial signals. Perhaps one day they will succeed. We'd then be one in a huge number of intelligent beings, which would not have surprised people in the eighteenth century. Thomas Wright of Durham was an early believer in a plurality of worlds: "In the great Celestial Creation, the catastrophy of a world, such as ours, or even the total dissolution of a system of worlds, may be no more to the great author of nature than the most common accident of life with us. And in all probability such final and general Doomsdays may be as frequent there as even birthdays or mortality with us upon the Earth."

On the other hand, perhaps ET doesn't exist. Earth's intricate biosphere may be unique. That may be disappointing. But it would have its upside: it would entitle us to be less cosmically modest. Our tiny planet could then be the most important place in the Galaxy. It could perhaps even be a seed from which life could spread through the entire Galaxy.

Finally, let's focus back closer to the here and now. I'm often asked: Is there a special perspective that astronomers can offer to philosophy and our general view of our place in nature? Thomas Wright thought so: "I can never look upon the stars without wondering why the whole world does not become astronomers, and reconcile them to all those little difficulties incident to human nature without the least anxiety." This doesn't reflect my impression of my colleagues, nor indeed myself. We're not specially serene and relaxed. Astronomers worry just as much as anyone about what happens next year, next week, or tomorrow.

But I think our subject does give us a special perspective. We view our home planet in a vast cosmic context. And in coming decades we'll know whether there's life out there. But, more significantly, we're mindful of the immense future that lies ahead. The stupendous time spans of the evolutionary past are now part of common culture (but maybe not in Kansas). Our present biosphere is the outcome of more than four billion years of evolution. But most people still somehow think we humans are necessarily the culmination of the evolutionary tree. That hardly seems credible to an astronomer.

Our Sun formed 4.5 billion years ago, but it's got six billion more before the fuel runs out. It then flares up, engulfing the inner planets. And the expanding universe will continue, perhaps forever, and is destined to become ever colder, ever emptier. To quote Woody Allen, "Eternity is very long, especially towards the end". Any creatures witnessing the Sun's demise six billion years hence won't be human – they'll be as different from us as we are from a bug.

Posthuman evolution, here on Earth and far beyond, could be as prolonged as the Darwinian evolution that's led to us, and even more wonderful. Darwin himself realised that no species would preserve its unaltered likeness into distant futurity. And of course this evolution is even faster now. Machines may take over.

Even in this concertinaed timeline – extending billions of years into the future, as well as into the past – this century may be a defining moment. It's the first in our planet's history where one species (ours) has Earth's future in its hands, and could jeopardise life's immense potential.

This pale blue dot in the cosmos is a special place. It may be a unique place. And we're its stewards at a specially crucial era. That's a message for us all, whether we're interested in astronomy or not.

Cambridge, United Kingdom Martin J. Rees

Contents

Georges Lemaître: A Brief Introduction to His Science, His Theology, and His Impact

Rodney D. Holder and Simon Mitton

Abstract For several decades historians of astronomy have overlooked the achievements in cosmology of the Belgian priest and professor of physics, Georges Lemaître (1894–1966). In 1927 he became the first to propose a theory of the expansion of the universe to explain the redshifts of galaxies, an advance that is often attributed to Edwin Hubble. Lemaître published the original version of the Hubble Law, and he produced the first estimate of the Hubble constant. He proposed a "Fireworks Universe" that became better known as the Big Bang theory for the origin of the universe, for which he is now popularly regarded as the "father of the Big Bang." This Introduction gives an overview to the 13 chapters in this book, which is devoted to the science and theology of a remarkable scholar, cosmologist, and theologian.

For several decades historians of astronomy overlooked the towering achievements of the Belgian priest and professor of physics, Georges Lemaître (1894–1966). In 1927 he became the first to propose a theory of the expansion of the universe as a means of explaining the recession of the nebulae, an advance that is mistakenly attributed to Edwin Hubble. It was Lemaître who published the original version of what became the Hubble Law, and he produced the first estimate of the Hubble constant. He proposed what later became known as the Big Bang theory for the origin of the universe, for which he is now widely acclaimed as the "father of the Big Bang." This Introduction gives an overview to the 13 chapters in this book, which is devoted to the science and theology of this remarkable scholar, cosmologist, and theologian.

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Georges Lemaître, Rome 1962 (Thomas Gold/ copyright Carvel Gold)

In chapter 2 "Georges Lemaître: The Priest Who Invented the Big Bang", the biographer Dominique Lambert sets the scene with a concise scientific biography of Lemaître, written from his personal knowledge of the extensive archives at the Université Catholique de Louvain. Lambert charts the remarkable intellectual journey that Lemaître undertook after the First World War. After gaining a master's degree in mathematics and physics, he studied Aristotle and Aquinas. From 1920 to 1923 he fulfilled 3 years of ecclesiastical studies for the Roman Catholic priesthood (a crash course!), while maintaining his intense interest in the new physics. During this period the future cosmologist mastered Einstein's paper of 1915 on general relativity, and was stimulated by the papers on relativity by Théophile de Donder, professor at the Université Libre de Bruxelles, and an associate of Einstein. When ordained on 22 September 1923 Lemaître was already an accomplished specialist in general relativity. Two weeks later he left Belgium for the University of Cambridge where he worked with Arthur Eddington. Lambert demonstrates the influence of Eddington in directing Lemaître towards inhomogeneous models of the universe. Lambert documents the steps that led to Lemaître's landmark paper of 1927 on the expanding universe, and then 4 years later to the concept of the primeval atom, the disintegration of which gave birth to the "fireworks universe."

The third chapter, by the noted historian of cosmology Helge Kragh, reminds cosmologists that it is important not to read history backwards in order to credit Lemaître's hypothesis that the universe came into existence via the stupendous explosion of a primeval atom as some kind of immense advance. That's not how others saw it in the 1930s.

Kragh shows us that a proper (that is to say scholarly) appreciation of Lemaître's contributions requires us to work conceptually within the framework of the decade 1925–1935. It is only by distancing ourselves from the excitement of cosmology in recent times that we can understand why Lemaître's "abominable" hypothesis had so little impact in his own time. Kragh does credit Lemaître with the discovery of the expansion of the universe on the grounds that he gave theoretical and observational reasons for such a model, and Eddington publicized this "very substantial advance" in *Nature* in 1930. And Kragh reminds us that "Nowhere in his paper of

1929 did Hubble conclude that the galaxies recede from us or otherwise suggest that the universe is expanding .... Throughout his life Hubble maintained an agnostic attitude with respect to the reality of the expansion of the universe." Expansion was the concept that drew Lemaître to "the strange and unwelcome" idea that the universe had a finite age. He was in part led to this conclusion by noting that some radiaoactive elements had chronological timescales of the order of the Hubble time.

Lemaître was fascinated by the ancient idea that light might be the primordial medium of the world, a concept that has theological as well as scientific overtones. He went on to connect the hypothesis with Robert Millikan's views on cosmic rays. Millikan felt that these were high-energy photons whereas Lemaître preferred a corpuscular explanation. Kragh rates Lemaître's 457 word letter to *Nature* (published 9 May 1931) as "one of the most remarkable communications in the history of modern science. It was not an ordinary scientific paper, but rather a spirited scenario of a possible cosmic beginning, a visionary piece of cosmo-poetry that was meant to open the eyes of the readers rather than convince them." This paper proposed the primeval-atom hypothesis. The hypothesis that cosmic-rays played a part in the expansion never really took off, although Lemaître promoted this "favourite hypothesis" to his life's end.

Helge Kragh concludes his chapter with a historical survey of the impact of Lemaître's cosmological proposals. When the primeval-atom theory became known, together with Lemaître's championing of an explosive origin for the universe, the response he generally met was one of skepticism and neglect. According to Kragh: "one may find it strange, almost embarrassing, that physicists and astronomers received Lemaître's pioneering contribution with such indifference." This is attributed to the fact that Lemaître was not an accomplished promoter of his own ideas. Kragh's conclusion is that: "Our present hot big-bang standard theory has its *conceptual roots* in Lemaître's old primeval-atom speculation, but otherwise it is a very different theory and one which in its actual development owes little to the work of the father of the big bang."

In chapter 4 "Georges Lemaître and Fred Hoyle: Contrasting Characters in Science and Religion", one of us (RDH) examines the fascinating professional relationship between Georges Lemaître, Catholic priest and champion of what Hoyle termed the "Big Bang", and Fred Hoyle, a non-believer who never lost faith in the steady-state cosmology that he developed in 1948 with Hermann Bondi and Thomas Gold. On the face of it theirs was an implausible friendship. Lemaître entered professional astronomy only after completing a rigorous clerical training in Belgium, followed by ordination. In his professional life he behaved modestly, and was inclusive. In later life he moved through the inner circles of the Vatican, and became President of the Pontifical Academy of Sciences. Hoyle, by contrast, came from a gritty middle-class background that led him always to challenge authority and privilege. Within the academy he courted controversy. His achievements earned him Fellowship of the Royal Society, and a Knighthood. It is easy to give too much attention to Hoyle's combative nature in the heat of the moment: he was a most generous and kind man who transformed the standards of theoretical astrophysics and cosmology in Britain.

Holder's chapter examines the influence of ideology on the science of these two giants of cosmology in the mid-twentieth century. Hoyle was in high-school when Lemaître announced the primeval atom, which implied an evolving universe of finite age. The steady state theory was promoted from 1948, almost 20 years after the Primeval Atom. Holder shows how Hoyle, along with Bondi and Gold, arrived at a steady-state model that allowed the universe to be infinitely old, and unchanging in its bulk appearance. A common feature of ideology in the two competing cosmological models was the test of "simplicity." Skeptics on both sides were suspicious of too many arbitrary fixes (such as: hypotheses, the cosmological constant, absence of good quality data). Holder examines the evolution of Hoyle's attitude to religion, which can be traced through comments in several of his popular books. Holder argues that "Hoyle's view of religion is naïve in a number of ways." The chapter draws attention to the fact that "fine tuning" is significant in the area in which cosmology and theology interact, and Hoyle made a major contribution to this. In concluding, this chapter tells us that "Lemaître's ideas are still very much with us, notably in the discovery a decade ago that the cosmological constant takes a small positive value," but that Hoyle too anticipated significant aspects of modern cosmological debate.

In chapter 5 "Lemaître, the Big Bang and the Quantum Universe", George V. Coyne SJ of the Vatican Observatory, continues with the science and religion theme. He shows how Catholic thought has evolved over three centuries, from a position of conflict to one of open dialogue. The historical periods covered are: the rise of modern atheism (seventeenth to eighteenth centuries); anticlericalism in Europe (nineteenth century); the awakening to modern science (early twentieth century); and the present. Lemaître's participation in the revival of interest in science is examined in this chapter. Coyne also discusses Lemaître's horrified reaction to Pope Pius XII's over-eager appropriation of the Big Bang in validation of the theological doctrine of creation. He sees the current, more open-ended attitude of the Church to dialogue with science as an inheritance from Lemaître.

William Carroll's chapter concerns the philosophical and cosmological discourse on "creation" and "origins." In line with Coyne's account noted above, Carroll says: "confusion between cosmological research and creation would have been abhorrent to Georges Lemaître," who always shrank from making the identity between the *commencement naturel* of the universe, and creation. By the 1950s he clearly understood the separation between theological and cosmological methods of discourse. At this late stage in his career he notes that expansion from a primeval atom may be "a beginning" but it is not "a creation." With these preliminaries, Carroll juxtaposes the philosophy of Thomas Aquinas with twenty-first century cosmological theories. In order to answer the question "What can cosmologists tell us about the 'mystery of the creation of the universe'?" Carroll constellates string theory, the inflationary universe, Big Bang cosmology, the multiverse scenarios, and so forth, and then examines Creation through the lens of Thomas Aquinas.

Lemaître and Aquinas agree that that Creation is a philosophical construct that cannot be settled by considerations arising from modern physics and cosmology.

David Block (chapter 8 "Georges Lemaître and Stigler's Law of Eponymy") has sketched an intriguing detective story that explores the differences between Lemaître's seminal paper of 1927 published by the *Annales de la Société Scientifique de Bruxelles*, and the translated version published by the Royal Astronomical Society in 1931. This is a saga in which "censorship" and "conspiracy theory" are entwined. In a light-hearted manner Block comments on the irony (Stigler's Law of Eponymy) that "No scientific discovery is named after its original discoverer."

With chapter 9 "Building on the Legacy of Georges Lemaître in Contemporary Cosmology", by William R. Stoeger SJ of the Vatican Observatory, we return to theoretical cosmology. Lemaître's concept of a primeval atom, later dubbed the Big Bang, set cosmology on a path toward the Friedmann-Lemaître-Robertson-Walker (FLRW) models of our universe that are mainstream in contemporary cosmology. After reviewing FLRW cosmology, Stoeger turns his attention to Lemaître's general spherically symmetric cosmological solutions with pressure and a cosmological constant. Stoeger points out that work on these generalizations of the FLRW models has been important in confirming the standard model: "there has been an explosion of important work expanding on his contributions to the study of inhomogeneous models – both for elucidating and confirming the large-scale structure of our universe, and for modeling more carefully the formation of galaxies and clusters of galaxies." Stoeger's chapter issues an urgent call for further research on Lemaître-Tolman-Bondi (LTB) models as well Lemaître models, in order to gain a complete description of dark energy and the cosmological constant.

The next two chapters, by Don Page and by George Ellis, explore the multiverse concept. Page argues in favour of the multiverse as a solution to the fine-tuning problem, while Ellis takes the opposite point of view. Page gives a number of reasons for accepting a multiverse, including for example that it may be a natural consequence of inflation and of string/M-theory, and he sees the multiverse concept as consistent with theism – indeed as portraying a grander view of creation than a single universe. Ellis is concerned that multiverse claims involve vast extrapolation from the domain of the universe we can observe, and that they are essentially untestable, even relying on physical theories which are untested and probably untestable. He concludes by noting "that multiverse proposals are good empirically-based philosophical proposals for the nature of what exists, but are not strictly within the domain of science because they are not testable."

In chapter 12 "Lemaître's Prescience: The Beginning and End of the Cosmos", Bernard Carr conducts a broad and deep review of philosophical issues in modern cosmology. This enormous survey of modern topics commences with the idea that Lemaître's concept of the primeval atom links microphysics and macrophysics. Fancifully we can regard Lemaître as the first quantum cosmologist. Particle physics is now an intrinsic component of our enquiries about the nature of the Big Bang. Carr next considers the issue of fine-tuning and the cosmological constant, which he identifies as the most important fine-tuning question. Carr's review then visits the idea of the multiverse as an explanation of fine-tuning. He points out that: “Lemaître’s family of solutions with differing cosmological constant provides a particularly interesting version of the multiverse.” This then takes us to Carr’s reflections on the border between cosmology and metaphysics: he argues that what we mean by “the nature of science” is subject to evolution.

Robin Collins offers a philosophical insight into the problem of fine-tuning, and the responses that have been offered by way of explanation. He identifies three categories of response: the multiverse explanation; theism; and the brute fact approach that things are as they are, and no explanation is required. He examines these in turn.

Because the multiverse hypothesis permits the existence of a very large number of regions of space-time with different values for the fundamental parameters, it should be no surprise that there is a universe that has observers – or so it is claimed. Collins notes that, at best, the multiverse hypothesis merely shifts the problem up a level – to why there is a mechanism which generates the multiverse with the right set of laws to produce observers. He then develops a stronger argument.

Collins argues that a tautology – the observer-selection principle – lies at the heart of the multiverse explanation. In the multiverse case, he says, we should regard ourselves as generic observers. However, “fluctuation observers” or “Boltzmann brains” would be vastly more prevalent in a multiverse than the kind of observers we actually are. Importantly, the universe is fine-tuned, not for observers per se, but for embodied conscious agents (ECAs) like ourselves who “can significantly interact with each other” and “can develop scientific technology and discover the universe”.

In contrast to the multiverse, theism renders it unsurprising that a universe fine-tuned for ECAs exists and that we find ourselves in such a universe. God, says Collins, would structure the universe so as to realize aesthetic and moral value, and axiarchism more generally claims that the universe is non-accidentally structured in this way. He further argues that, if one objects that theism or axiarchism involves a huge faith commitment, then naturalism of either the single universe or multiverse variety suffers from at least as great a leap of faith. Surprising for some will be Collins’ conclusion that the theistic/axiarchic stance is more conducive to the pursuit of science than the alternatives. He argues that, because such a stance gives confidence that the universe is discoverable, it can significantly impact one’s scientific practice, for example in motivating the search for deeper theories in keeping with the aesthetic and moral value of the universe.

The concluding chapter by John Polkinghorne offers a scientist-theologian’s reflections on Lemaître and his legacy. Polkinghorne notes how Lemaître was able to hold his devout faith and scientific creativity in “consonant harmony”. He concurs with Lemaître’s belief, explored elsewhere in this volume, that the doctrine of creation is not primarily concerned with how things began but with the question “Why is there something rather than nothing?” This chapter reminds us that Georges Lemaître was instrumental in persuading Pope Pius XII not to appeal to the Big Bang as a prop supporting Christian belief. However, Polkinghorne thinks that, while the influence of science on theology is not so direct and “coercive” as the Pope had it, Lemaître nevertheless runs the risk of taking the separation between the two realms too far – as did Stephen Jay Gould with his concept of “non-overlapping magisteria”. Polkinghorne thus proposes a middle way in which God’s handiwork is hinted at, rather than either hidden or demonstrated, in the astonishing order and intelligibility of the universe, and the fruitfulness of its processes, which science is engaged in exploring. For Polkinghorne, this is all a sign of the Mind of the Creator behind the universe, as also is the “fine-tuning”, whereby carbon-based life can only arise if the laws of nature take “very specific, precisely-defined, forms”. Polkinghorne also notes that a multiverse would surely need some constraint in order to be life-bearing, and that a multiverse is speculative and as metaphysical a hypothesis as that of God. He sees the greater challenge to theology as coming from what cosmology says about the end of the universe rather than its beginning. At that point theology will appeal to the faithfulness of God whose new creation has already begun with the resurrection of Jesus Christ, which, as Polkinghorne acknowledges, takes us into territory more appropriately explored elsewhere.

Georges Lemaître: The Priest Who Invented the Big Bang

Dominique Lambert

Abstract This contribution gives a concise survey of Georges Lemaître works and life, shedding some light on less-known aspects. Lemaître is a Belgian catholic priest who gave for the first time in 1927 the explanation of the Hubble law and who proposed in 1931 the "Primeval Atom Hypothesis", considered as the first step towards the Big Bang cosmology. But the scientific work of Lemaître goes far beyond Physical Cosmology. Indeed, he contributed also to the theory of Cosmis Rays, to the Spinor theory, to Analytical mechanics (regularization of 3- Bodies problem), to Numerical Analysis (Fast Fourier Transform), to Computer Science (he introduced and programmed the first computer of Louvain),... Lemaître took part to the "Science and Faith" debate. He defended a position that has some analogy with the NOMA principle, making a sharp distinction between what he called the "two paths to Truth" (a scientific one and a theological one). In particular, he never made a confusion between the theological concept of "creation" and the scientific notion of "natural beginning" (initial singularity). Lemaître was deeply rooted in his faith and sacerdotal vocation. Remaining a secular priest, he belonged to a community of priests called "The Friends of Jesus", characterized by a deep spirituality and special vows (for example the vow of poverty). He had also an apostolic activity amongst Chinese students.

Georges Lemaître was born in the Belgian industrial town of Charleroi in 1894. After secondary school he attended the Catholic University of Louvain to be trained as a mine engineer (Lambert 2002, 2011). But after 3 years, the First World War put an end to this project. During the war Lemaître served as a volunteer in both infantry and artillery. He never became an officer because he had dared to correct the ballistic computations of his instructor. After the war he changed subject and

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completed, in only 1 year, a Master in Mathematics and Physics with a thesis under the direction of the famous mathematician Charles de la Vallée Poussin. During this year, in 1919, he also studied philosophy, mainly that of Aristotle and St Thomas Aquinas, in the Institute founded by Cardinal Mercier. After that he entered the Seminary of Malines in order to become a Roman Catholic priest. During this period, 1920–1923, Cardinal Mercier gave him permission to continue to study physics. He read Einstein's paper on general relativity and the first publications of Théophile de Donder of the University of Brussels, who was at this time one of the best specialists in Einstein's theory of gravitation. The influence of de Donder was important. The first scientific paper of Lemaître was in fact dedicated to the variational calculus invented by de Donder (Lemaître 1923) and which is still today a subject of active studies.

At the end of his ecclesiastical studies Lemaître became himself a specialist in general relativity and he produced a manuscript entitled "La physique d'Einstein" (Lemaître 1922) which enabled him to obtain a grant to travel, after being ordained in 1923, to Cambridge, UK to study astronomy with Sir Arthur Eddington. In 1924 he went to the Massachusetts Institute of Technology and Harvard College Observatory in order to complete a Ph.D. thesis. At Eddington's suggestion his Ph.D. thesis was dedicated to describing, in the framework of general relativity, the gravitational field inside a sphere filled with an isotropic but inhomogeneous fluid. He discovered two particular solutions corresponding, on the one hand, to the Einstein static universe of constant density of energy-matter, and on the other hand, to the empty de Sitter universe, both discovered in 1917. This discovery becomes important for his first major work in cosmology, as we shall see shortly. This Ph.D. thesis is important historically because Lemaître happens to be one of the pioneers of the study of inhomogeneous models (Krasinski 1997). He returned to this field during his contact with Richard Tolman during the 30s.

When Lemaître returned to Belgium in 1925 after visiting many important observatories and collecting a great quantity of data concerning the distance and the speed of the nebulae he was appointed as a professor in Louvain. From 1925 to 1964 he gave lectures on classical mechanics for the engineers and on relativity for mathematicians and physicists. His main scientific works, as we shall discuss shortly, led him to international recognition and, supported by Einstein himself, he received the famous Francqui Prize in 1934 and many other prestigious awards.

Lemaître's first important scientific contribution was dedicated to an explanation of the Hubble law. Hubble observed that, with respect to the Earth, the speed v of distant galaxies (called at this time nebulae because they were considered simply to be gas clouds residing in our Milky Way) is proportional to their distances, with constant of proportionality the so-called Hubble constant H. The fact that the distant galaxies recede from us according to the Hubble law is puzzling because it apparently gives the Earth a strange central position that had been abandoned since the time of Copernicus!

In 1927 the young Lemaître published a solution of Einstein's equations of general relativity corresponding to an expanding homogeneous and isotropic universe and which gives a natural explanation of the Hubble law (Lemaître 1927). In fact, that solution had been found independently by Alexander Friedmann in 1922–1924, but the latter was not aware of its astronomical relevance and furthermore, unfortunately, his paper had been blocked by Einstein who could not admit, partly for philosophical reasons, the idea of a non-static universe.

Lemaître's explanation of Hubble's law is as follows. In the particular solution of Einstein's equations, which he found, the universe is a three-dimensional sphere filled with a constant density of galaxies. The distance between two distant points in this universe is growing in time according to an exponential law. And the computations show that the speed of the galaxies has to be proportional to their distance, exactly in line with Hubble's observations. In this model each point on the sphere can be considered as a center that sees all the galaxies moving away from it, solving the puzzling geocentric situation. Furthermore this expanding universe without beginning or end tends, in the past, to the static Einstein universe and in the future (the volume is growing and thus the density is decreasing) to the zero density universe of de Sitter. Thus both cosmologies are also limiting cases of the solution discovered by Lemaître in his MIT Ph.D. thesis! Therefore we could well call the Hubble law the Hubble-Lemaître law because nobody besides Lemaître gave the relativistic explanation of the astronomical data discovered by Hubble.

In the 1927 paper Lemaître did not consider the problem of the origin of universe. His model had no beginning. But it is worth noting that this problem had already been present in his mind at least since the First World War, during which he read the books of Henri Poincaré, trying to discover what could be considered as the fundamental reality of which the physical universe could be made. He hesitated first between electricity and light before finally deciding that it is light that is this fundamental reality. We have witnesses among his friends in the trenches (and especially notebooks published recently by Daniel Vanacker) showing that Lemaître, between two battles, thought of building a cosmology based on the fundamental concept of radiation (Lambert 2008).

His intuitive and qualitative ideas received their first rigorous treatment around 1930 in the context of some hypothetical ideas of Millikan and his collaborator G.Harvey Cameron (Kragh 2004; Kragh and Lambert 2008). The problem addressed by Millikan was to explain the origin and nature of the cosmic rays detected by balloons or mountain observatories. He assumed that these rays were in fact electromagnetic radiation. The Millikan-Cameron hypothesis is the following: one starts from electromagnetic waves. These can give rise to matter (protons and electrons; the neutron was not yet discovered!) by a hypothetical process of materialization. Then, protons and electrons formed atoms and the mass defect energy is lost as electromagnetic radiation that is nothing, according to Millikan, but the high energetic cosmic rays. The latter can then again give rise to protons and electrons and so on. Lemaître adapted this hypothesis in the context of an expanding universe where the wavelength of electromagnetic waves is stretched by the cosmological expansion. He adopted the idea of a materialization process of the radiation, but he did not consider the fact that cosmic rays can serve again as a source of elementary particles.

He arrived at the following conclusion: “One could admit that *the light* was the original state of the matter and that all the matter condensed in stars was formed by the process proposed by Millikan” (Lemaître 1930, p. 180, my italics). This was nothing but his First World War idea. This strange and hypothetical idea is what led him progressively on the path to the prehistory of big bang theory, namely the primeval atom Hypothesis.

What catalyses drastically the presentation of such a hypothesis is the publication by Eddington of a paper in *Nature* in 1931. The British astronomer extrapolated the expanding universe backwards into the past. The universe seems to collapse and tends to what could be considered as a beginning of the present order of the universe. But according to Eddington this is “philosophically repugnant” because it is a mere confusion between physics and the theology of creation (Eddington 1931).

His former student Lemaître answered immediately, saying that it is not at all repugnant. In a short paper in *Nature* he said, and we know why because of the Millikan-Cameron context, that the beginning of space-time can be considered as the disintegration of a single quantum: the Primeval Atom. This “quantum”, that is, the initial state of the expanding universe, is nothing but a quantum mechanical rewriting of his version of the Millikan thesis. Now the beginning of the world is, as he said poetically, “a little before the beginning of space and time” and it cannot be described strictly by our present physics. Then it could not at all be “repugnant” and, on the contrary, now the notion of the beginning of space-time can receive a pure physical description as the pulverization of a quantum (Lemaître 1931a).

These ideas will be described at length, in 1946, in Lemaître’s great book *The Primeval Atom Hypothesis* with a preface by the famous Swiss philosopher and mathematician Ferdinand Gonseth of the ETH (Lemaître 1946). This book was in fact preceded by a work, written shortly before the Second World War, and which was not published during Lemaître’s life (Heller and Godart 1985), the subject of which was a synthesis of the cosmology of the expanding universe beginning with the disintegration of the Primeval Quantum. By this time Lemaître’s cosmology is strongly fixed and it will not change until his death.

As early as 1933, Lemaître had given a wonderful survey of his cosmology in a technical paper (Lemaître 1933) called “L’Univers en expansion” (“The Expanding Universe”). This paper is also very interesting because it involves some subjects treated by Lemaître in his Ph.D. thesis and an original approach to the problem of singularities. In particular Lemaître constructed coordinates which enabled him to show that Schwarzschild radius is not a real physical singularity. His coordinates cover half of the now well-known Penrose diagram for the Schwarzschild geometry. He thus initiated the study of what we now call “horizons”. It is worth noting that already in 1925 Lemaître had taken an interest in singularities, showing that we can eliminate a fictitious horizon in de Sitter universe, by an appropriate coordinate change (Lemaître 1925).

Following a suggestion of Einstein himself, who believed that the initial singularity was a metaphysical concept and not a physical one, Lemaître proved that such a singularity is inescapable even if space-time becomes anisotropic, as in a “Bianchi

Type I" universe. In doing this he had started on the path towards the famous singularity theorem proved by Hawking and Penrose (Hawking and Ellis 1973).

According to Lemaître, the complete history of the universe is not pre-written in the Primeval Atom. This history shows some real innovations due to the Heisenberg indeterminacy relations. As he said: "Clearly the initial quantum could not conceal in itself the whole course of evolution; but, according to the principle of indeterminacy, that is not necessary. Our world is now understood to be a world where something really happens; the whole story of the world need not have been written down in the first quantum like a song on the disk of a phonograph. The whole matter of the world must have been present at the beginning, but the story it has to tell may be written step by step" (Lemaître 1931a). It is worth noting that in 1931 Lemaître published a paper dedicated to an application of the Heisenberg relations to the components of the electric field (Lemaître 1931b; Lambert 2003). He studied quantum physics during his stay at MIT but during his career he did not really go deeper in the study of quantum mechanics and quantum field theory. Indeed he failed to appreciate that quantum physics was not unified with general relativity. This prevented him from appreciating the tremendous progress made by a young generation of physicists after the Second World War, working on quantum electrodynamics and elementary particle physics, which he ironically characterized as a kind of "entomology".

Lemaître coupled his cosmological intuitions with a solution of Einstein's equations that involved an initial singularity. This cosmological model is a three-dimensional sphere growing according to a three-phase scenario. During the first phase, after the initial impulse the radius of the universe undergoes a deceleration. Following Lemaître, the Primeval Atom is disintegrated progressively giving rise to a cloud of atoms of various atomic weights. Then the radius tends to a quasi-static state, the second phase, during which the matter cloud can collapse giving rise to large-scale structures, galaxies and clusters. Finally during a third phase, the radius of the universe is reaccelerating under the influence of the so-called cosmological constant, which acts like a repulsive gravity. Lemaître emphasized, contrary to Einstein, the importance of the initial singularity and of the cosmological constant, saying that the latter hides the quantum contributions to the gravitation. This cosmological constant can serve also to make the quasi-static period longer or shorter and thus can be used to fit the age of the universe arising from astronomical data. Lemaître estimated that the age of the universe must be of the order of billions of years.

We can now compare our recent vision of the universe and this Primeval Atom hypothesis. We know now that our universe is expanding, having started from a very dense state (which may not be an initial singularity, a Big Bang, because the limit of our physics now is the Planck time, i.e. 10^{-43} s). The Hubble constant is around 65 km s^{-1} Mpc^{-1}, which leads to an estimate of the age of the universe of between 13 and 15 billion years. The current consensus in cosmology is that our universe is probably not spherical but infinite and flat (Euclidean), but it is reaccelerating now under the effect of a cosmological constant (which can certainly not be zero). The density of the matter (normal, i.e. baryonic matter, and dark matter) is in fact not at all sufficient to counter the repulsive effect of the cosmological constant and to lead to a collapse (as in the Phoenix universe, a universe which is periodically reborn from its own ashes). We can now study the early universe using the famous maps of the cosmic microwave background (CMB), where one can see the origin of structure in the universe as energy fluctuations of order of 10^{-5}, dating from the time when matter and radiation decoupled 380,000 years after the Big Bang.

Today we can say that nearly all the cosmological intuitions of Lemaître were correct: the three-phase expansion curve with the cosmological constant effect, the dense initial state, and even the idea of the existence of a fossil radiation. Lemaître believed that high-energy disintegration products of the Primeval Atom remain today that could be used to study the physics of the early universe. He believed that this fossil radiation was in fact the cosmic rays, but we know now that these rays are not to be confused with the CMB. Lemaître also took a wrong turn concerning nucleosynthesis: his hypothesis that the chemical elements were produced in a cold Big Bang, from the disintegration of a big quantum is incorrect. We know now that the nucleosynthesis of the light elements occurs in the three first minutes by fusion of elementary particles and the nucleosynthesis of heavier elements (carbon and beyond) begins only when the first stars appear, namely shortly before 1 billion years.

If Lemaître had still been alive in 2006 we can speculate that he would have received a share in the 2006 Nobel Prize for Physics. In the event it was awarded to John C. Mather and George F. Smoot for "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation." In effect they rigorously verified the properties of the standard cosmological model, the Big Bang cosmology that had been introduced by Lemaître. We can develop this re-writing of history further: he would have already deserved the 1978 Nobel Prize for Physics, because Arno A. Penzias and Robert W. Wilson received the latter "for discovery of the cosmic microwave background."

I have said that Lemaître was convinced that the fossil radiation was in fact the cosmic rays. In 1965 when he was ill in a hospital in Louvain he learned from his assistant Odon Godart of the discovery of the CMB by Penzias and Wilson. He was happy because the fossil radiation had been proved to exist, but he was very sad that its nature was not cosmic rays. Today, one can say that Lemaître's intuition concerning the fossil radiation could be partly true. Physicists are not yet able to explain the origin of some ultra-high energy cosmic rays (UHECR), that is, cosmic rays whose energy is greater than 10^{20} eV. Theoretical physicists assume that the UHECR could be disintegration products of topological defaults or "SUSY particles" (supersymmetric partners of usual particles) produced at the very beginning of the universe.

In fact an error made by a great scientist is sometimes very fruitful. Convinced by the cosmological importance of the cosmic rays, Lemaître studied the properties of those rays from 1935 until his death. In particular he studied and classified the orbits of charged particles in the magnetic field of the Earth. This is the so-called Störmer problem. In order to draw such orbits he used the Bush machine at MIT, a differential analyzer, an analogue computer built on the same principle as the computer of Blaise Pascal called the "Pascaline".

The motion of charged cosmic rays in the geomagnetic field can be described by a rotating plane and by a movement in this plane of a point in a potential landscape with a central valley. The differential equations describing this movement are non-linear and their solutions cannot be derived analytically. Therefore these "Störmer non-linear equations" were integrated numerically by Lemaître, and this led to many interesting results. Lemaître and his Mexican friend Sandoval Vallarta contributed to the Störmer problem with many papers, characterizing for example the form of the allowed cones in which the cosmic rays are received and the curves describing the intensity of the cosmic rays versus latitude (see Lambert 2011).

This work generated a real school in Louvain, and it is interesting to note that the latter involved mainly Chinese students, in particular Tchang Yon Li who became an important physicist. Lemaître had learned Chinese, and for several years in the 1930s he was the director of a house for Chinese students in Louvain. He contributed together with Father Vincent Lebbe (a priest who worked hard to convince Pope Benedict XIV to ordain the first Chinese bishops; these ordinations were performed in 1926 by Pius XI) to welcome many Chinese students to Belgium (Lambert 2008).

The Störmer work required computers and Lemaître was really fascinated by computers. He introduced the first electronic computer at Louvain in 1958, a Burroughs E101 desk computer, and he was one of the first European programmers of this machine. At the end of his life he invented, with his nephew, Gilbert Lemaître, a new language, the so-called Velocode, which was a precursor of Basic. In the 1930s, Lemaître had already used and programmed an electro-mechanical machine in order to compute, under the leadership of the Nobel Prize winner, and doctor *honoris causa* of Louvain, Hugh Taylor, the energy levels of monodeutero-ethylene. This was his first and only work in chemical physics.

In order to carry out numerical integrations, Lemaître invented many new mathematical techniques. For example, before Cooley and Tuckey, he introduced in the 1950s a version of what is now called, the Fast Fourier Transform (FFT). Lemaître's students, for example René de Vogelaere, at the end of the 1950s, used this Lemaître version of the FFT in his lectures in the United States. Unfortunately, Lemaître did not publish these impressive mathematical discoveries.

Lemaître's fascination for computing processes gave rise to a strange program of reforming the basic pedagogy of arithmetic. Lemaître was convinced that we have to change the way we are doing elementary arithmetical operations and the way of representing numbers to respect more tightly our brain functioning. He thus invented new symbols based on stenography and on musical notation (Lemaître 1954); and we know that Lemaître was also a very good pianist. The basic principle is that numbers have to show what they are representing, like the number 3 in Roman or Chinese notation, which is three bars. He thus tried to find some nice pictures to represent the figures, and to build some visual methods to combine the latter in order to deal with arithmetic computations. But such new pedagogical techniques did not attain the level of success for which Lemaître had hoped! Nevertheless his works can now be connected with some very recent papers in the neuro-psychology of computing processes, e.g. that of Stanislas Dehaene of the Collège de France.

One of the questions more frequently asked concerning Lemaître's life is the way he reconciled science and faith as a priest (Lambert 1997a, b). Lemaître was a priest deeply rooted in his faith and sacerdotal vocation. From 1920 to his death in 1966 he belonged to a community of priests called the "Friends of Jesus" ("Amis de Jésus") characterized by a deep spirituality (Lambert 1996). For example, he translated mystics like Jan Van Ruusbroec and regularly made silent retreats of ten days in a house called "Regina Pacis" in Schilde, near Antwerp. In this sacerdotal fraternity belonging to the Malines diocese the secular priests made religious vows. Lemaître took a vow of poverty and a special vow by which he offered his life to Christ; this special vow he pronounced was called *votum immolationis*.

Owing to his clerical status, scientists such as Einstein were convinced that Lemaître had invented the Primeval Atom hypothesis in order to defend his faith or to give it a scientific basis. In fact this was not true. For him the initial singularity is only a *natural* beginning, namely an initial state described by natural science and by mathematics (Lemaître 1958, p. 7):

> It is an inaccessible ground of space-time. Such a picture finds a natural geometrical support in the point-singularity which arises in Friedmann's theory. The radius of space can start from zero. Such a singular event which arises when space has a zero-volume is a bottom of space-time which terminates every line of space-time. I do not pretend that such a singularity is inescapable in Friedman's theory, but I simply point out it fits with the quantum outlook as a *natural beginning* of multiplicity and of space-time.

This notion is for him completely independent of theology. In fact science and faith are for him "two paths to truths"! Two ways to approach reality but which cannot be confused. This has some analogy with the position of the American paleontologist Stephen J. Gould and his NOMA, "non overlapping magisteria", principle. His view on the relation between science and faith are expressed clearly in a communication during a Solvay conference in 1958 (Lemaître 1958, p. 7):

> This is the philosophical background of the Primeval Atom hypothesis. As far as I can see, such a theory remains entirely outside any metaphysical or religious question. It leaves the materialist free to deny any transcendental Being. He may keep, for the bottom of space-time, the same attitude of mind he has been able to adopt for events occurring in non-singular places in space-time. For a believer, it removes any attempt to familiarity with God, as were Laplace's chiquenaude or Jeans' finger. It is consonant with the wording of Isaiah speaking of the Hidden God, hidden even in the beginning of the universe. It does not mean that cosmology has no meaning for philosophy . . .

At the end of the manuscript of his famous 1931 paper, which is considered as the starting point of the Big Bang theory, he intended to write the following conclusion to mark sharply the border between the science of the natural beginning and the theology of creation:

> I think that everyone who believes in a Supreme Being supporting every being and every acting believes also that God is essentially hidden and may be glad to see how present physics provides a veil hiding the creation.

In fact this way of presenting his thought is exactly the same as that of Blaise Pascal with whom he shared many scientific and philosophical traits. This conception also explains why he made an intervention in Rome in 1952 in order to ask the Pope not to use his Primeval Atom hypothesis as an argument in favor of a Christian way of reading the cosmos. The problem for Lemaître was not only the risk of confusion between science and theology, but also the fact that his cosmology at the beginning of the 1950s did not yet have a firm observational basis. Pope Pius XII, who very much liked astronomy and greatly appreciated Lemaître's works, took his intervention into account and avoided any explicit allusion to the Primeval Atom until his death in 1958 (Lambert 2008). Therefore, we see that Lemaître did not deserve the jokes made on the BBC by his friend Fred Hoyle, who called him "the Big Bang man". This is indeed the origin of this term first used by Hoyle in 1949, although Lemaître never used it, speaking instead of the cosmological fireworks (Lambert and Reisse 2008).

There are many further domains in which Lemaître worked and made interesting contributions. I refer here rapidly by way of example to his work, dating back to 1931, concerning a generalization of the Dirac-Eddington equation (Lemaître 1931c), in which he introduced, before Ettore Majorana, an example of what we called now the Majorana spinors, introduced in 1937 (Lambert 2005). He discovered the invariance group properties of this Dirac like equation that is connected to some nice symmetry properties of a quartic surface called the Kummer surface. Lemaître's equation is in fact invariant under the group Spin(3,3) which is isomorphic to SL(4,**R**). This isomorphism allows us to connect his work to real projective geometry in 4 dimensions. But Spin(3,3) is locally isomorphic to SO(3,3) which is nothing but the conformal group of the pseudo-Euclidean space endowed with a metric of signature (2,2). Lemaître's work thus has connections with conformal geometry. Finally, there is a nice relation between Lemaître's work and the *hyperbolic quaternions* (or *Gödel quaternions* (Gödel 1949) because the famous logician used them in his wonderful paper about a universe with closed time-like lines). These quaternions generate a pseudo-normed algebra (not a division one!) **G** associated with the pseudo-Euclidean space of signature (2,2), in a similar way to that whereby Hamilton quaternions generate a normed and division algebra **H** associated with a Euclidean space of 4 dimensions. Now the group SL(2,**G**) happens to be the invariance group of Lemaître's equation, i.e. SO(3,3). This is completely analogue to the well-known fact that SL(2,**H**) is in fact SO(1,5). This kind of isomorphism is important in theoretical physics. And John Baez has recently emphasized the link between the group SL(2,**O**), where **O** denotes the algebra of Cayley-Graves octonions, and SO(1,9) acting on ten dimensional space-time, which plays a central role in superstrings theory (Harvey 1990; Gürsey and Tze 1996; Baez and Huerta 2011) (Fig. 1).

Lemaître was in fact a specialist in spinor theory and he exchanged many letters on this subject with Elie Cartan. At the beginning of the sixties he also had contacts with Jacques Tits, the famous Belgian mathematician who discovered the so-called building theory explaining many features of exceptional Lie groups and algebras. As we have said above, his algebraic work is connected, with the quaternions. Lemaître corrected the proofs of Eddington's book *Relativity Theory of Protons and Electrons* (Eddington 1936) where the Cambridge astronomer used Hamilton quaternions and a particular Clifford algebra in a project which would culminate with his *Fundamental Theory*. The fascination of Lemaître with these numbers is

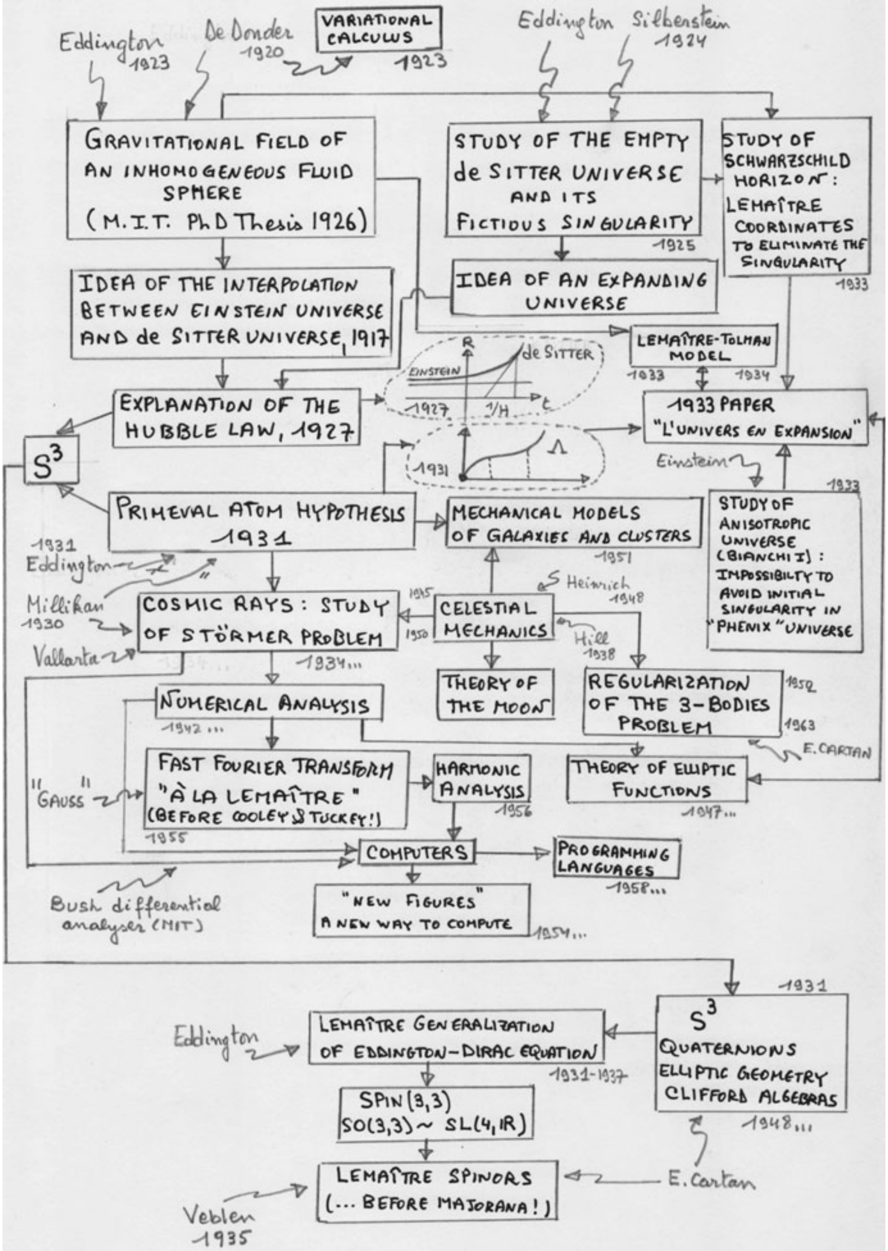

Fig. 1 Lemaître scientific works network. This suggests the deep unity of his contributions and the central role played by his Primeval Atom cosmological model (1931) based on the sphere S^3

understandable: the Hamilton quaternions of unit norm define a sphere that is nothing but the three-dimensional sphere, the spherical universe used by Lemaître in all his cosmological works. And the geodesics of this sphere are nothing but the paths followed by light rays. Geometrically these geodesics are also the famous Villarceau circles (which generate tori foliating the 3-sphere!) which are the fibers of the Hopf fibration ($S^3/S^1 = S^2$) discovered in 1931, the same year as the Primeval Atom cosmology based on an S^3 universe and the same year as the discovery of Dirac monopole theory based on … the Hopf fibration! In fact Lemaître used this spherical model, this finite universe but without a border, for mathematical reasons but also mainly because he considered that the universe had to be commensurable to human reason, which, according to him, would not be the case with an infinite universe …. This could open a deep debate on the potential or actual nature of infinity. But Lemaître was philosophically an Aristotelian and a disciple of St Thomas Aquinas who did not admit an empirical actual infinity.

Finally the last scientific work of Lemaître was devoted to a very original contribution to the three-body problem in classical mechanics (Lemaître 1963). Lemaître found a wonderful coordinate change that regularizes the three-body problem. This avoids singularities that appear when the bodies approach each other, making the gravitational forces tend to infinity. Celestial mechanics fascinated him. He transferred its methods many times to other fields such as Störmer theory.

We see that Lemaître's scientific legacy is not confined within the limits of physical cosmology. It is to be hoped that more and more mathematicians, physicists and historians will carefully study these other aspects of Lemaître's work and will perhaps discover some new impetuses and intuitions for their own researches. We are convinced that these less well-known works of the priest who "invented" what became termed the Big Bang can be still relevant for present-day major researches in mathematics and physics.

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‘The Wildest Speculation of All’: Lemaître and the Primeval-Atom Universe

Helge Kragh

Abstract Although there is no logical connection between the expanding universe and the idea of a big bang, from a historical perspective the two concepts were intimately connected. Four years after his pioneering work on the expanding universe, Lemaître suggested that the entire universe had originated in a kind of explosive act from what he called a primeval atom and which he likened to a huge atomic nucleus. His theory of 1931 was the first realistic finite-age model based upon relativistic cosmology, but it presupposed a material proto-universe and thus avoided an initial singularity. What were the sources of Lemaître’s daring proposal? Well aware that his new cosmological model needed to have testable consequences, he argued that the cosmic rays were fossils of the original radioactive explosion. However, this hypothesis turned out to be untenable. The first big-bang model ever was received with a mixture of indifference and hostility. Why? The answer is not that contemporary cosmologists failed to recognize Lemaître’s genius, but rather that his model was scientifically unconvincing. Although Lemaître was indeed the father of big-bang cosmology, his brilliant idea was only turned into a viable cosmological theory by later physicists.

About 80 years ago, in a little known letter to *Nature*, Georges Lemaître introduced the audacious hypothesis that the entire universe had come into being a finite time ago in a cataclysmic explosion of what he picturesquely called a ‘primeval atom.’ Today his idea is widely recognized as the conceptual beginning of what much later became known as the big-bang theory of the universe. Although Lemaître’s version of the explosive universe differed in important respects from the modern one, there are enough similarities to justify the claim that the conceptual foundation of relativistic big-bang cosmology goes back to the spring of 1931. Yet, to appreciate the true nature of his seminal contributions to physical cosmology it is important

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not to read history backwards and judge them by the standards of modern theory. One needs to understand them within the context of Lemaître's own time, which primarily means the decade 1925–1935. For example, it is only by adopting a contemporaneous perspective that one can understand why his theory, today hailed as a revolution in cosmological thought, only had a very limited impact on the further development of the science of the universe. This lack of appreciation was basically justified, simply because Lemaître's theory was not scientifically convincing in its original formulation.

While there are good historical reasons to celebrate Lemaître as the founding father of what eventually became the big-bang standard cosmology, this does not imply that our present conception of the universe can be traced back to his work in some direct way. Far from, for there is little continuity in the historical development of cosmology between the emergence of the primeval atom in 1931 and the reborn big-bang theory of the 1960s. If Lemaître's cosmological hypothesis merits historical attention it is not because it was the seed from which our modern view of the universe grew, but because it was a remarkable and interesting theory in own right and at its own time.

The Expanding Universe

'I found M. Lemaître a very brilliant student, wonderfully quick and clear-sighted, and of great mathematical ability' (Douglas 1956, p. 111). Thus wrote Arthur Eddington in a letter of 24 December 1924 to Théophile de Donder, a Belgian physicist and specialist in the general theory of relativity. The following year, while staying as a Ph.D. student at the Massachusetts Institute of Technology, Lemaître made his debut in theoretical cosmology with an examination of Willem de Sitter's empty world model proposed in 1917. By introducing a division of space and time coordinates other than the one used by de Sitter, he derived a de Sitter-like world model in which' the radius of space is constant at any place, but is variable in time.' However, although he found the non-static model promising because it suggested an interpretation of the nebular redshifts in terms of the Doppler effect, he dismissed it on the ground that the constant space curvature had to be zero. His reason was philosophically and probably also theologically rooted, namely 'the impossibility of filling up an infinite space with matter which cannot but be finite' (Lemaître 1925, p. 192). Lemaître did not suggest an expanding universe in 1925, but his paper anticipated his masterpiece two years later and prepared him mentally for the idea of a closed universe growing in time.

It is unknown precisely how Lemaître arrived at his theory of the expanding universe announced in his classical paper in the *Annales de Société Scientifique de Bruxelles*, except that his earlier paper of 1925 undoubtedly served as an inspiration. One might speculate that he knew of Alexander Friedmann's ill-fated work of 1922, in which the expanding universe was discussed as one mathematical possibility among others, but this is a speculation that lacks foundation. He only became aware of Friedmann's paper in the fall of 1927, when he had the opportunity to discuss his theory with Einstein, who was attending the fifth Solvay congress in Brussels. At any rate, from an examination of the relationship between the rival models of Einstein and de Sitter, both of them conceived as static at the time, Lemaître was led to 'consider an Einstein universe where the radius of space (or of the universe) varies in an arbitrary way' (Lemaître 1927, p. 51; Nussbaumer and Bieri 2009). Yet he was not interested in arbitrary variations of the world radius, but in just the variation that agreed with astronomical data for the one and only real universe. Guided by Vesto Slipher's data of extragalactic redshifts he focused on the solution of the Friedmann-Lemaître equations that corresponded to a closed universe expanding from an Einstein state of radius $R_0 = 1/\Lambda^{½} \cong 270$ Mpc $\cong 9 \times 10^8$ light years, where Λ is the cosmological constant.

As indicated by the title of the paper – 'A Homogeneous Universe of Constant Mass and Increasing Radius Accounting for the Radial Velocity of Extragalactic Nebulae' – Lemaître realized that the observed redshifts are a cosmical effect of the expansion of the universe and not caused by galaxies moving through a fixed space. On this basis he derived a linear relationship between recession velocity and distance, $v = kr$, and even estimated a value for the expansion constant, namely $k \cong 625$ km s^{-1} Mpc^{-1}. In other words, he found what later became known as the Hubble relation and the Hubble constant, and he did so two years before Edwin Hubble famously obtained a linear relation between the recessional velocities of spiral nebulae and their distances. On the other hand, Lemaître's derivation was theoretical and not supported by convincing empirical evidence – no such evidence existed at the time. He never claimed that priority to Hubble's relation or law belonged to him. In a later book review (Lemaître 1950) he referred to how his work of 1927 related to those of Friedmann and Hubble:

> If my mathematical bibliography was seriously incomplete because I did not know the works of Friedmann, it is completely up to date from an astronomical point of view; I calculate the expansion coefficient (575 km sec^{-1} per megaparsec, 625 with a doubtful statistical correction). Naturally, before the discovery and study of galactic clusters, there could be no question of establishing Hubble's law, but only to determine its coefficient. The title of my note left no one in doubt of my intentions.

If one insists that the expansion of the universe was discovered by a particular scientist, then Lemaître is undoubtedly a better choice than either Friedmann or Hubble (Kragh and Smith 2003). Yet, although Lemaître explicitly predicted the expansion, he could not justify the prediction with observational data that convincingly supported the linear law he suspected. In so far as Lemaître did not establish observationally that the universe is in fact expanding, he did not make a discovery; but in so far as he gave theoretical as well as observational reasons for it, he did discover the expansion of the universe. As to Hubble, he established the empirical redshift-distance relation, but he did not clearly interpret the redshifts as caused by the recession of the galaxies. Nowhere in his paper of 1929 did Hubble conclude that the galaxies recede from us or otherwise suggest that the universe is expanding. In fact, words such as 'recession' and 'expansion' do not occur in his paper. Throughout his life Hubble maintained an agnostic attitude with respect to the reality of the expansion of the universe.

From a sociological point of view it makes sense to date the discovery of the expanding universe to 1930 rather than 1927. The reason is that Lemaître's paper, published in a somewhat obscure journal, was thoroughly ignored until Eddington belatedly drew attention to this 'very substantial advance' in a book review in *Nature* of 7 June 1930 (Eddington 1930). Only then was it 'rediscovered' and quickly recognized as a pioneering contribution to theoretical cosmology. In the wake of the rediscovery followed the recognition of Friedmann's important papers of 1922 and 1924. While there were a few citations to Friedmann's papers in the scientific literature in the 1920s, there may only have been a single one, a self-citation, to Lemaître's. In a survey article of early 1929 he briefly referred to his work two years earlier, and also used the occasion to refer to Friedmann's theory, but this article did not attract any attention either (Lemaître 1929; Hetherington 1973).

Towards a Universe of Finite Age

In his work of 1927 Lemaître assumed an expanding universe with the properties $R \to R_0$ for $t \to -\infty$ and $R \to \infty$ for $t \to \infty$. There was no proper beginning of the universe, which consequently could not be ascribed a definite age. On the other hand, he conceived the static Einstein universe of radius R_0 as a kind of pre-universe out of which the expansion had grown as the result of some instability. As a physical cause for the expansion he noted that the pressure of radiation does work during the expansion, which 'seems to suggest that the expansion has been set up by the radiation itself.' He suggested the following picture: 'In a static universe light emitted by matter travels round space, comes back to its starting point, and accumulates indefinitely. It seems that this may be the origin of the velocity of expansion [which] … in our interpretation is observed as the radial velocity of extragalactic nebulae' (Lemaître 1927, p. 56). The role of light as a possible mechanism for the initial instability of the Einstein world would reappear a few years later in a different context, namely when Lemaître took the crucial step of extrapolating this kind of pre-universe to a primeval 'atom' from which the entire universe originated in an explosive act.

The general idea of a finite-age universe was considered strange and unwelcome by almost all astronomers and physicists, but of course Lemaître was not the first to suggest the possibility by means of scientific (rather than philosophical or theological) arguments. In his paper of 1922 Friedmann had considered the idea within the framework of relativistic cosmology and written about 'the time since the creation of the world' as the time that had passed from the initial singularity to the present. In the case of a cyclical universe with $\Lambda = 0$ he even calculated 'a world period of about ten billion years.' However, to the Russian physicist this was merely a mathematical curiosity, not a possible physical reality. Lemaître undoubtedly received some inspiration from Friedmann, but there were other and probably more important sources, of which I shall call attention to two. One of them was radioactivity, such as Lemaître (1949a, p. 452) explicitly mentioned in a work of 1949:

> The idea of this [primeval-atom] hypothesis arose when it was noticed that natural radioactivity is a physical process which disappears gradually and which can, therefore, be expected to have been more important in earlier times. If it were not for a few elements of average lifetimes comparable to T_H [the Hubble time], natural radioactivity would be completely extinct now. … The hypothesis that all the actually existing elements have resulted from the disintegration of heavier elements now extinct finds some support, therefore, in nuclear physics.

This line of reasoning can be found much earlier, probably first in 1911 when the Austrian physicist Arthur Haas argued that the existence of radioactive elements is incompatible with an eternal universe. The argument was taken up by the Belgian neo-scholastic philosopher Desiré Nys, who advocated it in a book of 1913, and it also appeared in some of Eddington's writings (Kragh 2007). According to Lemaître, it was no coincidence that the age of the universe was comparable to the lifetimes of uranium and thorium, for had the universe been much older the two elements would no longer exist. He inferred that our present world is the nearly burned-out result of a previous highly radioactive universe, such as he first suggested in the fall of 1931 (Lemaître 1931a). The argument from radioactivity is closely connected to the so-called entropic creation argument (Kragh 2008), which is an argument for the finite-age universe based on another irreversible process, namely the continual increase of entropy in the universe. Lemaître was familiar with this argument, which appeared prominently in the neo-scholastic literature as a possible proof of God's existence. He later said that in formulating the primeval-atom hypothesis he was 'guided by thermodynamic considerations while attempting to interpret the law of the degradation of energy within the framework of quantum theory' (Lemaître 1946, p. 147).

The idea that light plays a crucial cosmological role, and may even be thought of as the primordial medium of the world, is old and can be found in both theological and scientific versions (Kragh 2006). *Fiat lux*. It was an idea that fascinated Lemaître, who in early 1931 – before his note on the primordial atom – imagined the possibility of a static proto-universe in which 'all the energy was in the form of electromagnetic radiation and suddenly condensed into matter' (Lemaître 1931b, p. 501). This picture of a primordial radiation universe, which at some moment underwent a gigantic phase transition or materialization, had a certain similarity to contemporary ideas proposed by James Jeans and Robert Millikan, among others. In a little known paper of 1930, in which he discussed Millikan's view of cosmic rays within the framework of the expanding universe, Lemaître speculated that 'One could concede that the light had been the original state of matter, and that all the matter condensed in the stars was formed by the process proposed by Millikan,' namely a kind of photon-to-matter pair creation (Lemaître 1930). However, while Millikan argued that the enigmatic cosmic rays consisted of high-energy photons, Lemaître thought they were corpuscular, mainly consisting of protons, electrons and alpha particles. Although there is no solid documentation for it, it seems reasonable to assume that Lemaître initially thought of the original state of the universe in terms of light or photons, and that he only switched the imagery from light to atoms in the early months of 1931 (Kragh and Lambert 2007).

The Primeval-Atom Hypothesis

Lemaître's note of 9 May 1931 to the letter section of *Nature*, comprising a mere 457 words, is one of the most remarkable communications in the history of modern science. It was not an ordinary scientific paper, but rather a spirited scenario of a possible cosmic beginning, a visionary piece of cosmo-poetry that was meant to open the eyes of the readers rather than convince them. The unusual form of the communication is underlined by the fact that Lemaître chose to write as a private person and not in his capacity as professor of the University of Louvain: he signed it with his name and private address – 'G. Lemaître, 40 rue Namur, Louvain.' The very title of the note indicated the essence of his daring hypothesis, an argument for the beginning of the world in part based on quantum theory and also, if only indirectly, on thermodynamics. The fundamental indeterminacy of quantum mechanics helped him explain how the present world in all its colourful diversity could be the result of a single, undifferentiated atomic entity, for 'the whole story of the world need not have been written down in the first quantum like the song on the disc of a phonograph' (Lemaître 1931c). About a month later he gave an oral presentation of his idea to the Belgian Astronomical Society.

Whereas the letter to *Nature* did not qualify as a scientifically based hypothesis, and was not intended to do so, later the same year Lemaître presented a better argued and more elaborate version. At the London meeting of the British Association for the Advancement of Science in October 1931, the astrophysicist Herbert Dingle had organized a session on 'The Question of the Relation of the Physical Universe to Life and Mind' with the participation of Eddington, de Sitter, Jeans and Millikan, among others. Lemaître, who was invited to give a talk at the session, argued that the cosmic rays were the remnants of the disintegration of the primeval superatom from which the stars were once formed. 'At the origin, all the mass of the universe would exist in the form of a unique atom,' he said. 'The whole universe would be produced by the disintegration of this primeval atom.' At about the same time he further developed his ideas into a definite model of the universe, which he presented in the pages of *Revue des Questions Scientifiques*:

> The first stages of the expansion consisted of a rapid expansion determined by the mass of the initial atom, almost equal to the present mass of the universe. . . . The initial expansion was able to permit the radius [of space] to exceed the value of the equilibrium radius. The expansion thus took place in three phases: a first period of rapid expansion in which the atom-universe was broken down into atomic stars, a period of slowing-down, followed by a third period of accelerated expansion (Lemaître 1931a, p. 422).

Although Lemaître's universe of 1931 counts as a big-bang model (*avant le mot*), it was not a universe originating from a singularity, that is, from the physically impossible state of infinite space curvature and mass density. He always resisted the idea of an initial singularity in the strict meaning of the term. According to him, at

$t = 0$ the universe already ‘existed’ in the shape of the material primeval atom that contained within it the entire mass of the universe and the radius of which he estimated to be about one astronomical unit. The matter density would correspond to that of an atomic nucleus, of the order 10^{15} g cm^{-3}. At least in principle, such a hypothetical superatom was comprehensible and would, immediately after its disintegration, be subject to the laws of physics. On the other hand, Lemaître insisted that it was physically meaningless to speak of time (and hence existence?) in the primeval atom before the initial explosion. Apparently adopting an operationalist methodology, he found it impossible to define a physical state for a system when there was no conceivable method of time measurement.

Nearly 30 years later, in a presentation given to the eleventh Solvay congress in 1958, Lemaître elaborated on his view of a ‘natural beginning’ of the universe. With this phrase he wanted to emphasize that it was not a supernatural event, and also that the primeval atom could not have evolved from some even simpler state. Because of the random character of the explosion, being a quantum event, ‘from the same beginning, widely different universes could have evolved.’ This was a view agreeing with the one held by Leibniz, while it disagreed with the so-called indifference principle on which Descartes had based his cosmogonical theory. ‘The splitting of the Atom,’ said Lemaître, ‘can have occurred in many ways and there would be little interest to know their relative probabilities. The one which really occurred might have been very improbable’ (Lemaître 1958, p. 6 and p. 8). Not only was the beginning of the universe natural, it was also inaccessible in the sense that it can never be reached but only approached in some asymptotic manner – because, ‘in absolute simplicity no physical questions can be raised.’

Whereas Lemaître considered the superdense primeval atom to be real, he denied that the cosmic singularity formally turning up in big-bang cosmology at $t = 0$ could be ascribed physical reality. When running the movie of the cosmic development backwards in time, at some stage physical conditions would prevent the unwelcome singularity scenario. However, as a specialist in general relativity theory he also realized that the hypothetical ‘annihilation of space’ was not easily got rid of. When in 1933, at the request of Einstein, he made calculations of anisotropic models to see if the singularity would then disappear, the result was disappointing (Lemaître 1933). Yet neither he nor Einstein considered the calculations as proof that the initial singularity was therefore physically inevitable. As he declared, ‘Matter has to find a way to avoid the annihilation of its volume.’ Another point worth emphasizing is that Lemaître was always careful in describing his universe as one that had originated in the past, had exploded, or had begun expanding, while he never spoke of the beginning as a *creation*. The initial explosion of the primeval atom was not a creation of the universe out of nothing, not a physical representation of what is described in Genesis. In this area as in others, he was careful in keeping science and theology apart.

Two more features of Lemaître’s 1931 model need to be emphasized. Like the earlier Lemaître-Eddington model it was a closed universe with a positive space curvature, meaning that it was finite in space and material content. Ever since his first encounter with cosmological theory in 1925, he was convinced that the one and

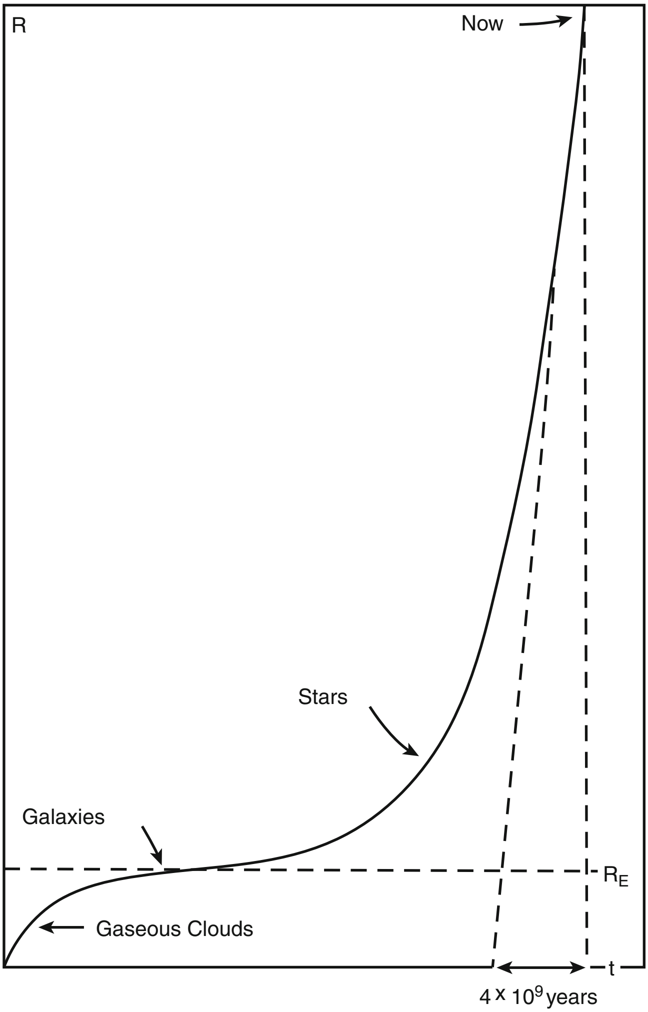

Fig. 1 Lemaître's world model of 1931, here in a version he presented in 1958. The radius of the closed world is plotted against the time since the beginning of the world

only real universe has to be finite. This was not so much for scientific reasons, but rather for reasons of epistemology. There was in Catholic philosophy a long tradition of rejecting 'infinitism' as epistemically meaningless and theologically heretical, and Lemaître saw no reason to depart from this tradition. He strongly believed that the universe was comprehensible to the human mind, a belief he could not reconcile with an infinite space populated with an infinity of objects. In a conversation with Richard Tolman he said that a closed model was preferable because 'an infinite universe could not be regarded in its totality as an object susceptible to scientific treatment' (Tolman 1934, p. 484).

Another feature common to the two models of 1927 and 1931 was the crucial role played by the cosmological constant Λ. Whereas after 1930 most cosmologists followed Einstein in abandoning the constant as superfluous, Lemaître remained convinced that a non-zero Λ was essential for cosmology. In his exploding model of 1931 the constant determined the length of the so-called stagnation phase and thereby provided the model with an age long enough to avoid problems with the age of the stars (Fig. 1). Moreover, he found it methodologically convenient to operate with a cosmological constant because it gave relativistic cosmology greater flexibility and an increased empirical content. In his address to the 1958 Solvay congress he said, almost prophetically: ‘If some extension of relativity towards a broader field, such as quantum theory, has to be achieved the superfluous [Λ] term shall be very much welcomed’ (Lemaître 1958, p. 15). Although Lemaître recognized the objections against Λ, which he discussed in his correspondence with Einstein, he found that the advantage of keeping a non-zero cosmological constant greatly outweighed the disadvantages (Kragh 1996, pp. 53–54). This view, unorthodox at the time, he kept until his death in 1968.

Cosmic Rays as Fossils of the Past

Lemaître realized that his scenario of an exploding atom constituting the beginning of the cosmic expansion was hypothetical and might even appear bizarre to many of his colleagues in physics and astronomy. In order to convince them that it was more than an airy hypothesis he needed some physical evidence from the original explosion. If the universe had really once been in a highly compact and hot state, would it not have left some traces that could still be subjected to analysis? Lemaître thought that there were indeed such traces or fossils from the ultimate past, and that these were to be found in the cosmic rays that had been discovered in about 1912 but were still badly understood. In his address to the British Association he argued that the rays had their origin in the disintegration of the primeval superatom, that they were ‘ashes and smoke of bright but very rapid fireworks.’ He imagined that the primeval atom would first disintegrate into ‘atomic stars’ of mass comparable to those of the presently observed stars, and that the further disintegration of these atomic stars would produce the cosmic rays and, eventually, the ordinary matter now observed. Thus, the cosmic rays were not direct products of the original explosion but had their origin in the early formation of stars, which he dated some ten billion years back in time:

> Cosmogony is atomic physics on a large scale – large scale of space and time – why not large scale of atomic weight? Radioactive disintegration is a physical fact, cosmic rays are like the rays from radium. Have they not escaped from a big scale super-radioactive disintegration, the disintegration of an atomic star, the disintegration of an atom of weight comparable to the weight of a star. … Cosmic rays would be glimpses of the primeval fireworks of the formation of a star from an atom, coming to us after their long journey through free space (Lemaître 1931d, p. 705).

The hypothesis of cosmic rays as the descendants of the primeval atom had the advantage that it had testable consequences. As a possible test of his cosmological theory Lemaître proposed that ‘cosmic rays cannot be formed uniquely of photons, but must contain, like the radioactive rays, fast beta rays and alpha particles, and even new rays of greater masses and charges.’ In his article in *Revue des Questions Scientifiques* from about the same time he dealt with the cosmic rays in largely the same way as he had done at the meeting of the British Association. The rays, he wrote poetically, were ‘one of the most curious of the hieroglyphs of our astronomical library.’

Lemaître’s interest in the cosmological implications of the cosmic rays predated his primeval-atom hypothesis. He first considered the cosmic rays in the context of the expanding universe in a paper of 1930, arguing that the radiation energy of cosmic photons would originally have been much greater than that presently observed. He estimated that the original frequency was at least 20 times greater than the observed, a result of the redshift caused by the expansion of space. While in 1930 he seems to have considered cosmic rays as primarily made up of photons, with the primeval-atom hypothesis he changed to the view that a substantial component of them consisted of charged atomic particles. At the time there were two rival conceptions of the cosmic rays, one principally advocated by Millikan and the other by Arthur Compton. While Millikan held the rays to consist of high-energy photons, Compton and his collaborators argued that they were charged particles of extragalactic origin. Understandably, Lemaître preferred the latter hypothesis.

In collaboration with the Mexican physicist Manuel Vallarta he engaged in complicated calculations of the energies and trajectories of charged particles in the Earth’s magnetic field, concluding in favour of Compton’s hypothesis. Moreover, the two physicists concluded optimistically that Compton’s data and their own calculations gave ‘some experimental support to the theory of super-radioactive origin of the cosmic radiation’ (Lemaître and Vallarta 1933, p. 91). The Lemaître-Vallarta theory was well known in the 1930s when it attracted scientific as well as public attention. It was the most cited of Lemaître’s papers in the period. According to *The New York Herald Tribune* of 3 September 1933, ‘Abbé Lemaître, he of the expanding universe, . . . links up the cosmic rays with the birth of the universe and the beginning of time.’

Although Lemaître was correct in his belief that cosmic rays consist mainly of charged particles, he failed in convincing the majority of physicists and astronomers that the radiation stemmed from the original explosion of the universe. One of the few physicists who seriously considered the hypothesis was Paul Epstein, a theoretical physicist at the California Institute of Technology and a colleague of Millikan. In an early survey of cosmological models, Epstein (1934, p. 77) included Lemaître’s explosion theory and his idea that the corpuscular cosmic rays ‘are the messengers of some super-radioactive materials which existed once but have long since disappeared in the solar system.’ Although he found the idea interesting, he did not endorse it.

As the knowledge of the content of the cosmic radiation gradually improved, it became more and more clear that it could not be explained as the result of a singular explosive act in the distant past. Most of the rays turned out to have a more local origin, either solar or galactic. Yet Lemaître kept to his idea, which he defended on various occasions in the 1940s and 1950s. For example, at a conference of the Astronomical Society of Anvers in January 1949 he gave an address on 'Cosmic Rays and Cosmology' (Lemaître 1949c). In a paper published on the occasion of Einstein's seventieth birthday, he repeated his favourite hypothesis, now connecting it to the formation of the original gaseous clouds out of which the stars were assumedly formed. These clouds would absorb the cosmic rays and thereby increase their size and mass until they gravitationally condensed into stellar bodies. According to Lemaître, some of the mass increase would be caused by the transformation into hydrogen atoms of the kinetic energy of the original cosmic rays particles, whose energy he estimated to have been about 10,000 times that of the observed cosmic rays (Lemaître 1958). He did not specify the mechanism of the process. Since he found the energy-mass density of the cosmic rays to be of the order 10^{-34} g cm^{-3}, and the mass density of the universe was known to be about 10^{-30} g cm^{-3}, he concluded that the cosmic rays were indeed the primordial form of matter (Lemaître 1949c).

In the view of Lemaître, there was no fundamental difference between stars and cosmic rays. 'All kind of matter,' he said in 1949, 'must be present in the cosmic rays and matter is nothing else than condensed cosmic rays' (Lemaître 1949b, p. 366). Moreover, he thought that what he called 'super alpha-rays' – nuclei of atomic number up to about 40 recently found in the cosmic radiation – supported his idea that the rays do not consist of light particles only but that 'all atomic elements exist in the rays.' These speculations about cosmic rays and matter were unfruitful and left no mark on the further development of either astrophysics or cosmology. In spite of Lemaître's clear recognition that there might still today exist fossils of the cosmic past, he failed to understand that the abundance distribution of the chemical elements, and particularly the abundance of helium, makes up such a fossil.

Early Responses

Whereas Lemaître's theory of the expanding universe was received very favourably after it became generally known in 1930, responses to the primeval atom hypothesis were quite different. As to the expanding universe, not only was the concept accepted at an early time by leading scientists such as Eddington, Einstein, de Sitter, Robertson and Tolman, it was also disseminated to the public through a number of popular books, including Jeans' *The Mysterious Universe* (1930), de Sitter's *Kosmos* (1932), and Eddington's *The Expanding Universe* (1933). By the late 1930s the expansion of the universe had secured a nearly paradigmatic status among astronomers and cosmologists. Alternative explanations of the redshifts, for example in terms of tired-light cosmologies, did not disappear, but they were no longer taken seriously by mainstream astronomers.

When it comes to the reception of the finite-age universe in Lemaître's physical version, one needs to distinguish between popular and scientific responses. Newspapers and popular science magazines found the primeval-atom hypothesis fascinating and in some cases described it in detail and at an early date. Thus, Lemaître's note to *Nature* of 9 May 1931 found its way to *The New York Times* only 10 days later, where it was quoted nearly *in extenso*. In July 1932 the theory featured in the widely read American magazine *Popular Mechanics*, and later the same year *Popular Science* included an article by the Harvard astronomer Donald Menzel dramatically entitled 'Blast of Giant Atom Created Our Universe.' Menzel could inform readers of the magazine that Lemaître's theory did away with the old query of what happened before the beginning, for 'nothing can happen where there is no room for it to happen.' As to the future of the cosmos, Menzel mentioned the possibility of a later contraction, as in Einstein's cosmological model of 1931, but 'Dr. Lemaître prefers to believe that the whole universe was born in the flash of a cosmic sky-rocket and that it will keep expanding until the showering sparks which form the stars have burned to cinders and ashes' (Menzel 1932, p. 105).

The positive attention that Lemaître's explosion theory received in the popular press contrasted strongly with the cool and sometimes hostile response from the scientific community. It took some time until his theory was noticed at all, probably a result of Lemaître's unfortunate decision to publish it in French in *Revue des Questions Scientifiques*, a journal most physicists and astronomers outside Belgium and France would not even be aware of. On the other hand, many would know the theory from lectures and conferences. During the years 1931–1934, Lemaître lectured widely on the expanding universe and the primeval-atom hypothesis, about which he spoke at meetings in London, Paris, Chicago, Princeton, Montréal, Pasadena and elsewhere. For example, on 25 April 1933 he lectured on 'The Primaeval Atom Hypothesis' before the Kapitza Club, Cambridge University, in front of Paul Dirac and other Cambridge physicists.

At any rate, when the theory did become known, the general response was either dismissal or neglect. Consider Richard Tolman, who in his authoritative textbook of 1934, *Relativity, Thermodynamics and Cosmology*, found it necessary to warn against 'the evils of autistic and wishful thinking' in cosmology, in which he counted the belief that the universe was created in the past. There can be little doubt that he thought of Lemaître, when he wrote: 'The discovery of models, which start expansion from a singular state of zero volume, must not be confused with a proof that the actual universe was created at a finite time in the past.' As far as he was concerned, 'no definiteness could now be attached to any idea as to *the* beginning of the physical universe' (Tolman 1934, pp. 486–488; Tolman 1932) (Fig. 2).

The beginning of the world was a radical concept, which was difficult to accept, and to which scientists had to accustom themselves. Eddington belonged to those who never became accustomed with it, indeed never wanted to. Like most other scientists he felt uneasy about a created universe, a notion he found to be 'repugnant.' While Eddington's opposition was philosophically (and possibly also religiously) based, the reluctance of Hubble was rooted in his cautious empiricist attitude to science. Although he did not refer to Lemaître in his classical study of 1936, *The Realm of the Nebulae*, he did consider the explosive universe in the Rhodes Memorial Lectures he delivered in Oxford the same year. Hubble showed that with a particular value of the cosmological constant, about 6×10^{-18} (light years)$^{-2}$, Lemaître's model might be brought in agreement with observational data,

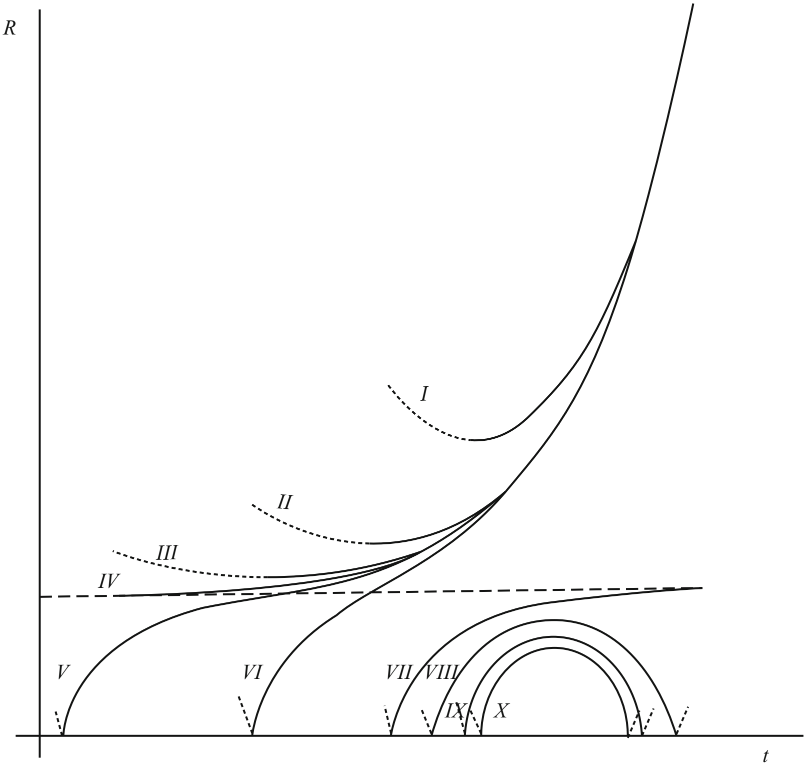

Fig. 2 Graphical representations of physically realistic world models, as of 1934. The Lemaître-Eddington model is shown by the curve IV, whereas curves V and VI correspond to Lemaître’s primeval-atom universe (Source: Tolman 1934, p. 411)

but then the density would have to be suspiciously high (~ 10^{-26} g cm^{-3}) and the size of the universe suspiciously small (4.7×10^8 light years). The model he considered was ‘the type that will always be associated with the name of Lemaître,’ and for this model he concluded that although it could not be ruled out, it was unattractive and ‘rather dubious’ (Hubble 1937, p. 62; Hubble 1936).

The eminent Princeton cosmologist Howard Robertson basically agreed with the scepticism expressed by Tolman and Hubble. In an address of 1932, he mentioned the theoretical possibility of an initial singularity; but he found it unattractive and preferred ‘emotionally more satisfactory’ solutions such as the non−singular Lemaître-Eddington model. At this occasion he mentioned Lemaître only in connection with the appealing Lemaître-Eddington model, whereas he associated the finite-age possibility with Friedmann’s solution. The following year, in an influential survey in *Reviews of Modern Physics*, he specifically excluded from what he considered plausible universe models those which have ‘arisen in finite time from the singular state $R = 0$’ (Robertson 1933, p. 80). In his extensive bibliography he included a reference to Lemaître (1931a), but in the text he ignored the primeval-atom model. Also the German astronomer Otto Heckmann found the Lemaître-Eddington model to be attractive 'because it allows the possibility of a world without catastrophic behaviour either in the past or in the future' (Heckmann 1932, p. 106). In his survey of cosmological models, he did not mention Lemaître's exploding universe.

In a few cases the responses to the primeval-atom hypothesis bordered on ridicule. John Plaskett, a Canadian astronomer who shared Hubble's empiricism, credited Lemaître, in an address of 1933, as the effective pioneer of the expanding universe, adding that 'Unfortunately this important paper was buried in a little read publication and entirely escaped attention.' While Plaskett was willing to take the expanding universe seriously, when it came to its beginning in an explosive event he had no more patience. Lemaître's hypothesis, he said, was 'the wildest speculation of all, even 'an example of speculation run mad without a shred of evidence to support it' (Plaskett 1933, p. 252). The verdict of Ernest Barnes, the mathematically trained Bishop of Birmingham, was not much different. In a book of 1933 he opined, probably correctly: 'I do not think that many cosmogonists have yet been persuaded by this theory of Lemaître. It is usually regarded as a brilliantly clever *jeu d'esprit* rather than a sober reconstruction of the beginning of the world' (Barnes 1933, p. 408). He was unwilling to 'bring in God ... to let off the cosmic fire-work of Lemaître's imagination' – but then, so was Lemaître, apparently unknown to Barnes.

Generally speaking, during most of the 1930s big-bang solutions of the Friedmann equations – which, in addition to Lemaître's, also included Einstein's cyclical model of 1931 and the Einstein-de Sitter model of 1932 – were part of the cosmological literature, but they were rarely taken seriously or assigned physical reality. In the few cases where researchers entertained ideas somewhat similar to Lemaître's, such as did Paul Dirac in England (1938), Hans Ertel (1935) and Carl Friedrich von Weizsäcker (1938) in Germany, and George Gamow and Edward Teller in the United States (1939), they did not refer to Lemaître's primeval-atom hypothesis. The German pioneer of quantum mechanics, Pascual Jordan, was perhaps the only scientist who subscribed to a version of Lemaître's big-bang universe before World War II and actually referred to it. In a book of 1936 he summarized: 'Ten billion years ago – Lemaître especially deserves credit because of the closer execution of this representation – the initially small universe arose from an original explosion' (Jordan 1936, p. 152). The following year he gave a brief but sympathetic account of the *Urexplosion* suggested by Lemaître (Jordan 1937). The model favoured by Jordan was clearly inspired by Lemaître's fireworks model, and like his Belgian source it was finite in space as well as in time. However, contrary to Lemaître, Jordan preferred to put the cosmological constant equal to zero.

Conclusion: The Fate of Lemaître's Model

Given the later success of big-bang cosmology one may find it strange, almost embarrassing, that physicists and astronomers received Lemaître's pioneering contribution with such indifference. But there were good reasons for the cool reception and the marginal role that the primeval-atom hypothesis played in the period. For one thing, the hypothesis was simply not well known, since Lemaître did not communicate it in a clear and quantitatively developed form in one of the major scientific journals. More importantly, from the perspective of the 1930s it could not help appearing speculative and unconvincing. The only testable consequence of Lemaître's primeval atom was the composition of the cosmic rays, which he claimed to be fossils of the original explosion, and this alone was far from enough to make it acceptable. Contrary to other models of the big-bang type, such as the Einstein-de Sitter model, Lemaître's explosive model had the advantage that it avoided the so-called time-scale difficulty of a universe being younger than its constituent parts. This was a conceptual advantage, but one that relied solely on adopting a positive cosmological constant and not on the postulated primeval explosion. From the perspective of the period there were no good reasons to prefer the explosion scenario over, say, the smoothly expanding Lemaître-Eddington model.

This situation only changed after World War II, first with Gamow's independent development of a big-bang theory based on the nuclear reactions in the early universe and later with the prediction and discovery of the cosmic microwave background. However, rather than considering Gamow's nuclear-physical approach to cosmology as a realisation of his own ideas, Lemaître chose to ignore it, claiming that 'It is not very profitable to insist on [the detailed nature] of the extreme physical conditions which arose at the very beginning' (Lemaître 1949a, p. 453). As it turned out, in this evaluation Lemaître was plain wrong: it was precisely investigations of the detailed nature of the very early universe that transformed big-bang cosmology from a somewhat speculative *jeu d' esprit* to an advanced and empirically convincing theory of the origin and development of the universe. This transformation, principally due to Robert Dicke, James Peebles and Yakov Zel'dovich, occurred about 1965 and was largely independent of the earlier works of Lemaître or Gamow. Our present hot big-bang standard theory has its *conceptual roots* in Lemaître's old primeval-atom speculation, but otherwise it is a very different theory and one which in its actual development owes little to the work of the 'father of the big bang.'

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Georges Lemaître and Fred Hoyle: Contrasting Characters in Science and Religion

Rodney D. Holder

Abstract Georges Lemaître was a jocular Roman Catholic priest and Fred Hoyle a bluff Yorkshireman who despised organized religion. Both were giants of twentieth century cosmology but espoused diametrically opposed cosmological models. This paper explores the extent to which ideology, and particularly religion, played a part in the controversies over the big bang and steady-state theories. A particular problem for many cosmologists, including Hoyle, was posed by the idea that the universe had a temporal beginning: an eternal, unchanging universe seemed metaphysically preferable. And Hoyle was highly polemical about religion in his popular writings. In contrast, Lemaître saw no theological import from the big bang, and never entered a debate about its theological implications until, perhaps unexpectedly, he took issue with an address given by the Pope. Hoyle's seminal work on stellar nucleosynthesis led him to speak of a 'superintellect monkeying with physics' though this was never identified with the God of classical theism. The work of both Lemaître and Hoyle resonates with more recent debates concerning cosmology.

Introduction

In Georges Lemaître and Fred Hoyle we have two characters who are so utterly different in many ways, yet shared one very significant attribute: they were giants in twentieth century cosmology and astrophysics.

In short, here we have a Belgian Roman Catholic priest who can rightly be described as the Father of the big bang, and in Hoyle an atheist Yorkshireman who pioneered the alternative of a steady-state universe with neither beginning nor end. What I particularly want to explore is the extent to which ideology influenced the

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science in these two great figures, though personal characteristics will also be important in the study.

Georges Lemaître

Lemaître's 'primeval atom', unlike the model in his 1927 paper, provided the first ostensibly physical big bang model, comprising as it did the two components of expansion *and* a beginning in time. Adumbrated in a brief but remarkable letter to *Nature* (Lemaître 1931a), it was described in an address he gave to the British Association (Lemaître 1931b), and developed in one of the more substantial papers of the *annus mirabilis* of 1931 (Lemaître 1931c).

There was a great deal of ideological suspicion of the idea that the universe had a beginning, from the time such theories were first mooted until the big bang was finally established beyond reasonable doubt by observation of the predicted background radiation in 1965. Lurking in cosmologists' minds was no doubt the suspicion that, if the universe had a beginning, did it not therefore require a creator? It seems to me that atheists have often perceived that difficulty as a problem, whereas theologians can happily see God creating a universe with either a finite or an infinite past.

Among those who disliked the idea that the universe had a beginning were Einstein, who had assigned a particular value to the cosmological constant so as to yield a static universe, and Eddington, who wrote in 1931 that 'philosophically, the notion of a beginning of the present order of Nature is repugnant to me' (Eddington 1931, quoted in Kragh 1996, p. 46). Interestingly enough these two were quite different with regard to religious faith, and that is reflected in the many others who took sides in the steady-state versus big bang controversy. Einstein believed in Spinoza's pantheistic God whereas Eddington was a Quaker. Helge Kragh writes that astronomers in general preferred to speak of the 'cosmic time scale' rather than to date the present epoch from an absolute beginning of time (Kragh 1996, p. 76). Indeed, says Kragh, 'most astronomers preferred to neglect what may seem to be a natural consequence of the evolutionary, relativistic worldview' (Kragh 1996, p. 142).

Another who did so was of course Fred Hoyle. Indeed it was Hoyle who coined the term 'big bang', applied as term of abuse because he hated the idea. Nevertheless the terminology stuck and Lemaître's term 'primeval atom' faded. Hoyle first used the term 'big bang' in a radio broadcast he gave in 1949. He repeated it in another broadcast in 1950, following which it appeared in print when Hoyle's talk was published in full in the BBC's magazine *The Listener* (Mitton, pp. 127–129).

Clearly Lemaître did not share these concerns, but interestingly enough he also did not want to identify the beginning of the universe in time with the theological doctrine of creation. We shall examine this, and Lemaître's view of science and theology as two different realms, in this chapter, in comparison with the views of Hoyle.

Fred Hoyle

Hoyle was a bluff Yorkshireman, from the beginning something of an outsider to the Cambridge world he came to inhabit from his time as an undergraduate. And though he became part of the Establishment—elected FRS, Professor at Cambridge, knighted—he continued to advance controversial theories and engage in hot polemical disputes throughout his career.

One of Hoyle's aphorisms was 'it is better to be interesting and wrong than boring and right' (Foreword by Paul Davies in Mitton 2011, p. x). And this is something the great man lived up to.

Hoyle was a controversialist from the earliest point of his scientific career. He did important work on accretion by stars with Raymond Lyttleton, and later Hermann Bondi. However, Hoyle and Lyttleton failed to get their work published by the Royal Astronomical Society because they refused to accept criticism and modify their paper accordingly, eventually publishing it in *Proceedings of the Cambridge Philosophical Society* (the story is told in Mitton 2011, pp. 62–80). There were in fact severe problems with these papers in the context for which they were conceived, though they became important many years later when accretion was seen to be operative in binary star systems. In these systems one member of the pair, a compact object such as a neutron star, accretes material from the other. The papers by Hoyle and Lyttleton, and Bondi, are even cited in the doctoral thesis of the present author, who in his youth studied accretion in the very different context of intergalactic gas by the galaxy.

Accretion was an idea ahead of its time and rightful context but the controversy characterised Hoyle's relationships with many in the scientific establishment. By way of example, among Hoyle's more outlandishly controversial ideas was that of panspermia, particularly because Hoyle was here stepping outside the area of his own expertise. Panspermia is the idea that life on earth was seeded from space (publicised in Hoyle and Wickramasinghe 1978). Along with this came the idea that disease-causing viruses were introduced from space. Hoyle and his colleague Chandra Wickramasinghe thought that Darwinian evolution alone was inadequate to account for the explosion of speciation over the last 600 million years unless further genetic information were seeded from space (Hoyle and Wickramasinghe 1978, p. 32). Mitton's rather blunter statement that they simply did not accept Darwinian evolution (Mitton 2011, p. 309) is borne out in Hoyle's 1983 book *The Intelligent Universe*. Here we get the statement that 'the Darwinian theory is wrong because random variations tend to worsen performance' (Hoyle 1983, p. 48). Inevitably this view did not endear Hoyle and Wickramasinghe to the biologists who were the experts in such matters.

Hoyle and Wickramasinghe even claimed in 1985 that the intermediate fossil archaeopteryx was a fraud, only publishing this outlandish idea in *The British Journal of Photography*, and this was another claim that got them into deep water with the experts.

Despite these aberrations, it remains true that Hoyle was a very great scientist and his greatest and enduring contribution to astrophysics was his work on stellar nucleosynthesis in collaboration with Geoffrey and Margaret Burbidge and William Fowler. The magisterial paper produced by these four, invariably shortened to B^2FH, showed how virtually the whole periodic table of the chemical elements could be built up through nuclear reactions in stars (Burbidge et al. 1957). This earned Fowler a share of the Nobel Prize in 1983, though Fowler forever after regretted that his friend Hoyle was undeservedly excluded from the award.

Interestingly, helium could not be produced in sufficient quantity this way and in the 1960s Hoyle and colleagues Roger Tayler and Bob Wagoner showed how the very lightest elements could be created in the conditions of a hot big bang (Hoyle and Tayler 1964; Wagoner et al. 1967). Performing calculations more accurate than those of George Gamow's team in the 1940s, Hoyle and his colleagues thus helped provide evidence favouring the theory he despised!

Clearly, however, it was the steady state theory which both made Hoyle well-known, not least among the general public, and which also was the source of his most serious disputes within the astrophysical community.

The Steady State Theory

By the 1940s, the evidence of the redshifts, interpreted as due to the expansion of the universe, had seemed to indicate that some version of the big bang theory was correct. The Einstein static, eternal universe did not seem to reflect reality. However, a major challenge was that the estimated age of the universe, a couple of billion years or even less as deduced from the Hubble law, was smaller than the estimated age of stars and galaxies, and indeed of the earth itself! More accurate observations came much later, in the late 1940s and early 1950s. Today the age is believed to be about 13.7 billion years, comfortably older than the objects within it, and the three significant figures indicating how far cosmology has advanced as a science of measurement.

In 1948, however, the view that there was any kind of evolution at all was challenged by a new theory which ran clean contrary to the big bang idea. As formulated by Hermann Bondi and Thomas Gold in that year, it was based on a metaphysical principle called the 'perfect cosmological principle' (Bondi 1961, p. 12). This principle amounted to the assumption that not only does the universe on the largest scale present a uniform aspect at every place within it, as assumed by the big bang theory too and indeed necessary to obtain the Friedmann-Lemaître solutions, but also at every time in its history. Put simply, the universe looks the same at any place and any time, always excluding local irregularities. It should be stressed that this is indeed a metaphysical principle, not an empirical scientific principle derived from observation or experiment.

In order to account for the observed expansion it was necessary in the steady-state theory that new matter be created in the space created between the receding galaxies, and at just the right rate. In fact, other steady-state continuous creation models had arisen in the pre-war period, quite often associated with a metaphysical preference for God to be continuously creating rather than, as it were, winding up the universe at the beginning and letting it run down. Physicists such as Robert Millikan and many others put forward such highly speculative steady-state type theories, and in 1933 such ideas were endorsed from the theological perspective by W.R. Inge, the well-known Dean of St Paul's Cathedral (Kragh 1996, p. 150). However, there seems to have been an atheist agenda attached to the steady-state theory proper put forward by Bondi, Gold and, significantly, Hoyle who simultaneously came up with a rather different version of the theory. Nevertheless the steady-state still attracted Christian support, notably from the cosmologist W.H. McCrea. Moreover, the Anglican theologian E.L. Mascall noted how it was entirely in keeping with Aquinas' notion of God both bringing things into existence and preserving them in existence so that 'if he withdrew his action from them, all things would be reduced to nothing' (Mascall 1956, pp. 158–159, quoting *Summa Theologiae*, Ia.9.2).

Kragh notes that it was particularly Hoyle who objected to a singular creation event that was beyond the realm of scientific understanding (Kragh 1996, p. 174). In his 1948 paper Hoyle wrote: 'For it is against the spirit of scientific enquiry to regard observable effects as arising from "causes unknown to science", and this is in principle what creation-in-the-past implies.' (quoted in Kragh 1996, p. 179). As noted above, and as explained in more detail in William Carroll's chapter in this present book, the Christian doctrine of creation can in fact happily account for either type of universe. But another reason the trio rejected standard cosmology was the time-scale problem. This could be solved in the Eddington-Lemaître, Lemaître models but at the seemingly unacceptable cost of fine-tuning the cosmological constant. This was deemed a fudge that ought to be unnecessary in a true theory.

Interestingly enough, Hoyle initially objected to matter creation, as suggested by Gold, and this delayed progress on the steady-state theory (Kragh 1996, p. 177). After all, matter creation would constitute a violation of the law of conservation of energy. In the event this would mean that two versions of the steady-state theory would emerge, both in 1948, the one authored by Hoyle and the other by Bondi and Gold. Another very significant difference within the trio is that, unlike Hoyle, Bondi and Gold regarded general relativity as suspect when extrapolated so as to apply to the universe as a whole.

In his version of the theory, Hoyle modified Einstein's equations of general relativity by replacing the cosmological term with a 'creation tensor' that did, after all, violate energy conservation! The rate of matter creation governed by the creation tensor just matches the rate at which matter disappears across the horizon of the visible universe. But Hoyle preferred his approach rather than that of Bondi and Gold who started instead from the abstract 'perfect cosmological principle'. For Hoyle that principle was a consequence of his theory rather than an axiom. In contrast Bondi and Gold judged it necessary to ensure that the laws of physics did not change over time, and they claimed that without such a principle cosmology could not be counted a science (Kragh 1996, p. 182).

At this stage I could suggest that perhaps a theological principle would have done what Bondi and Gold wanted! They are right that some metaphysical principle is required to undergird the constancy of physical laws. Theologians would say that this principle is the faithfulness of God. The constancy of physical laws is a sign of God's reliability in maintaining those laws, and the God of the Christian religion is not capricious but faithful. It is this kind of view which informed the natural philosophers of the scientific revolution, those such as Johannes Kepler who saw himself 'thinking God's thoughts after him' when uncovering the laws of planetary motion. No science at all is possible without some sort of presupposition about there being order and law-like behaviour out there to be discovered. Why that should be the case is not explained by science, but is explained by theology. But it is not an explanation that would have appealed to the proponents of the steady-state theory.

The perfect cosmological principle implies that the Hubble expansion rate we observe today is the same as that at all times, past, present and future. This enabled Bondi and Gold to calculate, very straightforwardly and without any appeal to general relativity, the rate of creation of matter required to balance the expansion. In Bondi's book, which utilises an up-to-date figure for the Hubble constant, he gives a rate of something like the equivalent of one hydrogen atom per litre coming into existence every 500 billion years (Bondi 1961, p. 143). Hoyle put his comparable figure more graphically in his 1950 radio broadcasts as one atom per year in a volume equal to that encompassed by St Paul's Cathedral. Clearly that is many orders of magnitude below any detectable threshold. (Hoyle 1950, p. 106).

One of the most bitter disputes in all cosmology was occasioned by Hoyle's defence of the steady-state theory. It involved the future Nobel prize winning Cambridge radio astronomer Martin Ryle and was mainly concerned with counts of radio sources, once these were established to be extragalactic (which Ryle originally denied but Hoyle rightly asserted), relative to their brightness. If the steady state theory is correct then sources of a given brightness should be uniformly distributed throughout space. There is then a simple and easily derivable formula for the number N of sources of brightness greater than S, i.e. $N \propto S^{-3/2}$. A plot of $\log N$ against $\log S$ should then yield a straight line of slope $-3/2$.

From about 1954 onwards Ryle sought to catalogue radio sources and to disprove the steady state theory. Indeed he apparently achieved results that did so, getting a slope different from $-3/2$. The trouble was that the survey results Ryle presented in 1954 (the 2 C, second Cambridge survey) were unreliable. Observers in Australia contradicted them, and the survey results of 1958 (3 C, third Cambridge survey) were still disputed. However, by 1961 further results were much more accurate, were confirmed by other observers, and did indeed seem to refute the steady state theory. These latter results were further confirmed by the complete Cambridge 4 C survey carried out between 1958 and 1964, though the steady state advocates stuck to their guns despite the mounting evidence. It was of course the observation of the microwave background in 1965 which provided the clinching evidence in favour of the big bang.

The Rôle of Ideology

Hoyle

We have begun to see already that ideological factors were at work when both the big bang theory and steady-state theories were being developed, and we need to look at this a little more closely.

One feature that is common to many of the scientists on all sides of the big bang versus steady-state divide is the search for simplicity. Lemaître, influenced by Einstein, wrote in 1922 that 'Scientific progress is the discovery of a more and more comprehensive simplicity.' (Kragh 1996, p. 28). Einstein himself in 1931 rejected his earlier espousal of a positive cosmological constant because of its ugliness and lack of simplicity. Bondi and Gold appealed to the principle of simplicity to justify giving priority to the perfect cosmological principle over the principle of conservation of matter/energy which, given the non-detectability of new matter, could be regarded as only approximate.

The idea that the simplest of competing hypotheses is most likely to be true has been a useful guiding principle in science. However, one could regard the Bondi-Gold theory as too little driven by empirical data, indeed as rather Platonic and rational in being deductive rather than inductive, and that conservation of energy and the validity of physical laws across space and time are as simple assumptions to make as is compatible with observation and experiment. It is surely preferable to seek solutions in terms of current well-established physical theories before amending those theories or abandoning them altogether and applying over-arching metaphysical principles. Eddington would be a scientist who, in his search for a 'fundamental theory', which occupied most of his life from the 1930s, was also adopting a more rational and Platonic approach.

Hoyle, on the other hand, would I think be in the majority among scientists in downplaying grand metaphysical principles and hardly discussed the philosophy of science. However, he did not simply embrace the alternative empiricist approach either, but (rightly I think) noted that no empirical facts were bare or uninterpreted facts. Thus for Hoyle, theory and observation go hand in hand (Kragh 1996, p. 195). While Bondi shared this view, as Kragh notes, he was more emphatic and provocative in claiming that errors in observation are likely to be more frequent than errors in theory (Kragh 1996, p. 238). While observation was of course still deemed important, these views gave the steady state cosmologists grounds for resisting apparently falsifying data, as well as for having postulated a completely undetectable rate of creation of new matter.

It is in the area of religion where there is the greatest divide. There are two major questions where modern cosmology and theology potentially interact. The first relates to whether the universe had a temporal origin or not. As noted above this is not really a problem for theology, if the doctrine of creation is properly understood (as explained in detail by William Carroll in this volume); nevertheless it is the case that a temporal origin is perceived to be a problem by atheists, up to and including Stephen Hawking in the present day. If we can get rid of the temporal origin it is claimed, falsely of course, that we then get rid of God. The second question relates to the special way in which the big bang and the laws of physics need to be set up in order for the universe to give rise to life—the so-called fine-tuning—and we return to this shortly.

We have seen that Hoyle disliked the notion of an initial cause beyond the realms of science, which is what seems to be implied by the big bang, and he certainly associated the steady-state theory with atheism (Kragh 1996, p. 253). Indeed he freely expressed an emotional preference for the steady state even though he saw that this in itself was irrelevant to its acceptance (Hoyle 1955/1970, pp. 353–355).

In the last chapter of his book *The Nature of the Universe*—'Man's Place in the Expanding Universe'—he explains why he believes the steady-state theory to be superior to the big bang. There are reasons of physics such as the time-scale problem and difficulties to do with galaxy formation, and with either theory one is face with the problem of creation. However, Hoyle is clear about his preference: 'In the older theories all the material in the Universe is supposed to have appeared at one instant of time, the whole creation process taking the form of one big bang. For myself I find this idea very much queerer than continuous creation.' (Hoyle 1950, p. 105). Incidentally this book transcribes Hoyle's further radio broadcasts of 1950 and we have in it the reoccurrence of the pejorative term 'big bang'.

At the end of this chapter Hoyle adds a personal reflection, in which he writes this about religion:

> it seems to me that religion is but a blind attempt to find an escape from the truly dreadful situation in which we find ourselves. Here we are in this wholly fantastic Universe with scarcely a clue as to whether our existence has any real significance. No wonder then that many people feel the need for some belief that gives them a sense of security, and no wonder that they become very angry with people like me who say that this security is illusory (Hoyle 1950, pp. 115–116).

It is no surprise that Hoyle's broadcasts gave rise to considerable controversy, and indeed the long-running dispute with Ryle began at about the same time (Mitton 2011, p. 172). There were a number of scientists who criticised Hoyle for his too unqualified presentation of his own speculative theory. In July 1950 the philosopher of science Herbert Dingle was allowed to say as much in a responding broadcast. The novelist Dorothy L. Sayers was also allowed to do something similar with respect to Hoyle's views on religion, which had occasioned the ire of Geoffrey Fisher, Archbishop of Canterbury, among others (Mitton 2011, pp. 135–137).

Further association of the steady-state theory with atheism occurs in Hoyle's book *Frontiers of Astronomy*. The theory contrasts with the big bang which requires the acceptance of starting conditions 'which we are obliged to accept as conditions arbitrarily imposed for no reasons that we understand'. He writes:

> This procedure is quite characteristic of the outlook of primitive peoples, who in attempting to explain the local behaviour of the physical world are obliged in their ignorance of the laws of physics to have recourse to arbitrary starting conditions. These are given credence by postulating the existence of gods, gods of the sea . . ., gods of the mountains, gods of the forests, . . ., and so forth (Hoyle (1955/1970), p. 351).

It seems to me, in contrast to Hoyle, that physics normally proceeds precisely by applying the laws to a set of starting conditions to see how a system evolves. It is in cosmology now, as in Hoyle's day, where the avoidance of starting conditions is uniquely being sought.

Elsewhere Hoyle expresses what he sees as the gulf between the way science and religion work. In a lecture given in 1957 at Great St Mary's, the University Church, in Cambridge he said this:

> Religious thought is not controlled by the requirement that it must make correct predictions concerning the events that take place in the external world. It is controlled by doctrines usually laid down many centuries ago in canonical forms, in the Bible for the Christian, in the Koran for the Muslim. The existence of these written doctrines would seem to make any rooted change of outlook difficult to achieve (Hoyle 1959, pp. 57–58).

In similar vein Catholicism, like Communism, argues by dogma:

> An argument is judged "right" by these people because they judge it to be based on "right" premises, not because it leads to results that accord with the facts. Indeed if the facts of the case should disagree with the dogma then so much worse for the facts (Hoyle 1957, p. 139).

Hoyle shares with the religious person a sense of awe before the universe and the sense that there must be some 'deep laid purpose' there. It is the particularities of religion that he rejects, such as miracles, which he sees as God constantly correcting his own poor handiwork when things go wrong, (Hoyle 1957, p. 157) and, in the case of Christianity, such specific doctrines as the divinity of Christ and the Virgin Birth. Indeed Hoyle is utterly scathing about such beliefs, which amount to a 'denial of rational thought' and 'contradict the very fabric of the world' (Hoyle 1957, p. 152), thus negating the faculty which separates man from the beasts. He states: 'Religion, if it is not to be pernicious nonsense, must be based on rational thinking.' (Hoyle 1957, p. 152). If religion *were* to change its dogmas, in the way science does, such changes would have to be on the scale of seeing Jesus as just an exceptional man rather than God incarnate (Hoyle 1959, p. 58).

I would argue that Hoyle's view of religion is naïve in a number of ways. Religion may not be predictive—and there are other areas of human enquiry which are not predictive, such as ethics and history—but it *is* explanatory. Scientific laws codify the regularities normally observed in nature. They have nothing to say about singular instances, which miracles are. And Christian doctrines can be regarded as rationally formulated responses to historical evidence and the experience of the Church.

As an example of the explanatory role of religion, the doctrine of the *imago dei* explains why the inherent logic of the human brain parallels the structure of the universe as a whole. Hoyle recognises and alludes to this fact but circumvents it by identifying God with the universe (Hoyle 1959, p. 56; Hoyle 1957, p. 157). How the universe manages to create a pattern of itself inside our heads, as Hoyle believes it does, remains unclear, but for him 'The Universe constitutes everything that there is.' (Hoyle 1957, p 158).

The first chapter of *The Ten Faces of the Universe* (Hoyle 1977) is called 'God's Universe' and in it Hoyle launches another tirade against Christian belief.

He remarks that ‘the attributes of God so frequently and confidently announced from the pulpit were quite indefensible’ and lists some of them: ‘God the father—i.e. the family man; God the maker of all things—i.e. a craftsman or artisan; God almighty—a war leader; God in heaven, wherever that may be’. (Hoyle 1977, p. 4). Rather than engaging with what theologians say about these matters, Hoyle contents himself with remarking that they are ‘plainly man-made’ and ‘without meaning’. (Hoyle 1977, pp. 4, 6–7). Again, only equating God with the universe makes any sense to him. His solution to the Northern Ireland problem would have been to ‘arrest every priest and clergyman in Ireland and to commit every man jack of them to long jail sentences on the charge of causing civil war’. (Hoyle 1977, p. 7). After all, the violence is simply due to priests and clergymen instilling ‘nonsense words and concepts’ into children, and different nonsense words at that into Roman Catholic and Protestant children.

Despite this negativity towards religion Hoyle does, however, recognise as significant the second area in which cosmology and religion interact, namely that concerning the ‘fine-tuning’. Thus he notes that there are very surprising connections between the origin of life, the building up of chemical elements in stars, and the laws of nuclear physics. These connections are either ‘random quirks’ (Hoyle 1959, p. 64) or signs of a superintellect behind the universe (Hoyle 1981, p. 12).

Hoyle famously predicted a resonance, an enhanced effect, in the carbon atom at just the right level to ensure that carbon could be manufactured efficiently by nucleosynthesis in stellar interiors despite the intermediate product, beryllium, being unstable. At the same time it turned out that there was an energy level in oxygen just below that which would make the production of oxygen resonant and thereby turn *all* the carbon into oxygen. Indeed it is worth quoting Hoyle more extensively on this point. In the Great St Mary’s lecture he said this:

> If this were a purely scientific question and not one that touched on the religious problem, I do not believe that any scientist who examined the evidence would fail to draw the inference that the laws of nuclear physics have been deliberately designed with regard to the consequences they produce inside the stars. If this is so, then my apparently random quirks have become part of a deep laid scheme. If not, then we are back again to a monstrous sequence of accidents (Hoyle 1959, p. 64).

In an article of 1981 he wrote:

> From 1953 onward, Fowler and I have been intrigued by the remarkable relation of the 7.65 MeV energy level in the nucleus of ^{12} C to the 7.12 MeV level in ^{16}O. If you wanted to produce carbon and oxygen in roughly equal quantities by stellar nucleosynthesis, these are just the two levels you would have to fix, and your fixing would have to be just about where these levels are actually found to be. Is that another put-up, artificial job? Following the above argument, I am inclined to think so. A commonsense interpretation of the facts suggests that a superintellect has monkeyed with physics, as well as with chemistry and biology, and that there are no blind forces worth speaking about in nature. The numbers one calculates from the facts seem to me so overwhelming as to put this conclusion almost beyond question (Hoyle 1981, p. 12).

To me it seems difficult to reconcile these remarks with the minimalist religious view expressed by Hoyle earlier whereby God is identified with the universe. Persons are intelligent, not the universe per se, and the Christian God at any rate is conceived as personal. Hoyle's alternative to this, in *The Intelligent Universe*, is a considerable degree of speculation to do with backwards and forwards causation in time:

1. Information comes from the future to control quantum events in a manner similar to that which John Wheeler has argued for ('observer created reality');
2. Life-bearing information is transferred into new forms from past to future along lines popularized by Frank Tipler and resulting in 'collective immortality'; and
3. These two time flows of information are interrelated thus: 'We are the intelligence that preceded us in its new material representation—or rather, we are the re-emergence of that intelligence, the latest embodiment of its struggle for survival'. (Hoyle 1983, p. 239).

This paradoxical-sounding scheme appears to resemble the closed quantum causal loops invoked by Wheeler and more recently Paul Davies. Hoyle recognises the similarity of the quantum controller in (1) both to the Christian God outside the Universe and to Greek deities who manage an existing cosmos. The advantage of his scheme is that God's existence is also dependent on the Universe.

Hoyle also blames attacks on the steady state theory in the 1950s as arising 'because we were touching on issues that threatened the theological culture on which western civilization was founded' whereas the 'big bang theory requires a recent origin of the Universe that openly invites the concept of creation'. (Hoyle 1983, p. 237).

Lemaître

Clearly Lemaître was in the opposite camp to Bondi, Gold and Hoyle in the matter of religion. But how did it affect his approach to cosmology? Incidentally, Bondi later became President of the British Humanist Association and of the Rationalist Press Association—a really serious atheist!

Odon Godart and Michal Heller discovered an unpublished manuscript from about 1922 in which Lemaître states that the universe began with light just as Genesis had suggested. However, Godart further notes that 'Lemaître was too careful a scientist to build his theory on what was no more than an intuitive opinion; a scientific basis was necessary'. (Godart 1984, p. 395).

According to Kragh, Lemaître's theology may have influenced his preference for a spatially finite universe (positive curvature) over an infinite universe. The finitude of the universe was asserted by Aquinas and goes back to Aristotle, though at times an infinite universe had also been postulated, for example by Cardinal Nicholas of Cusa in the fifteenth century. This is interesting, since it is again a matter which is in dispute in recent philosophical discussion of cosmology. Indeed some, including George Ellis and the philosopher William Lane Craig, have questioned whether an infinitude of physical things, as opposed to infinities treated in pure mathematics, can actually exist. In any case an infinity can always be added to and is never 'complete'. Again according to Kragh, Lemaître could not take the steady-state theory seriously, mainly because it differed so radically from his own view, but possibly also because he thought it incompatible with his theology. (Kragh 1996, p. 198). However, none of this implies that he had advanced his own theory from theological motives, and indeed the weight of evidence is that he did not consider his theory to have any intrinsic theological significance. In this regard the following quotation (Kragh 1996, p. 60) is particularly apposite:

> As far as I can see, such a theory [of the primeval atom] remains entirely outside any metaphysical or religious question. It leaves the materialist free to deny any transcendental Being. He may keep, for the bottom of space-time, the same attitude of mind he has been able to adopt for events occurring in non-singular places in space-time.

As explained in this volume in Dominique Lambert's chapter and expounded in more detail in George Coyne's chapter, in 1952 there arose a notable disagreement between Lemaître and Pope Pius XII when the latter ventured to suggest that the big bang theory supported the doctrine of creation. The pope had addressed the Pontifical Academy of Sciences on 22 November 1951 in the following terms:

> Clearly and critically, as when it [the enlightened mind] examines facts and passes judgment on them, it perceives the work of creative omnipotence and recognizes that its power, set in motion by the mighty *Fiat* of the Creating Spirit billions of years ago, called into existence with a gesture of generous love and spread over the universe matter bursting with energy. Indeed, it would seem that present-day science, with one sweep back across the centuries, has succeeded in bearing witness to the august instant of the primordial *Fiat Lux*, when, along with matter, there burst forth from nothing a sea of light and radiation, and the elements split and churned and formed into millions of galaxies. . . .
>
> What, then, is the importance of modern science in the argument for the existence of God based on change in the universe? By means of exact and detailed research into the large-scale and small-scale worlds it has considerably broadened and deepened the empirical foundation on which the argument rests, and from which it concludes to the existence of an *Ens a se*, immutable by His very nature.. . . Thus, with that concreteness which is characteristic of physical proofs, it has confirmed the contingency of the universe and also the well-founded deduction as to the epoch when the world came forth from the hands of the Creator. Hence, creation took place. We say: therefore, there is a Creator. Therefore, God exists! (Kragh 1996, p. 257).

Lemaître, usually irrepressibly cheerful, was deeply unhappy about this. Scientifically it portrayed science as unequivocal about the big bang, which was certainly not the case. The big bang was still a hypothesis and had a strong rival in the steady-state theory. Ernan McMullin recalls Lemaître saying that the universe could easily have gone through a previous phase of contraction. (McMullin 1981, p. 53, quoted in Kragh 1996, p. 431, n. 186). Indeed George Gamow, who did so much important work on the big bang in the late 1940s thought the same, as related in his book *The Creation of the Universe*. (Gamow 1952, p. 29, cited in Mascall 1956, pp. 153–154). In addition, Lemaître thought it confirmed the suspicions of Hoyle and others of a theological agenda behind the big bang. Lemaître had himself steered clear of such arguments. Thus he neither commented on Hoyle's atheistic assertions in his BBC broadcasts, which resulted in *The Nature of the Universe*, nor on the opposite argument from the big bang to God advanced in the 1940s by the great mathematician E. T. Whittaker, whom, incidentally, the Pope quoted in his controversial address. (Deprit 1984, p. 387).

Theologically the Pope's statement confused creation, which is inaccessible to science, with origination in the sense that science could investigate—essentially the same mistake as Hoyle! Lemaître intervened with the Pope's science adviser and succeeded in dissuading the Pope from further ventures into scientific territory, which he deemed unhelpful.

To Lemaître theology and science were two different realms, two different paths to truth—indeed as he once said, two paths both of which he had decided to follow. He was, naturally, very far from being a fundamentalist. To believe that the Bible teaches science is like 'assuming that there must be authentic religious dogma in the binomial theorem'. If the Bible is right about immortality and salvation, it is simply fallacious to believe it is right about everything else—that is completely to miss the point of why we were given the Bible in the first place. (Kragh 1996, p. 59).

When Dirac said to Lemaître that he thought cosmology was the branch of science closest to religion, Lemaître disagreed, saying he thought psychology was the closest. (Farrell 2005, p. 191).

Anticipations of Modern Debates

Lemaître's ideas are still very much with us, notably in the discovery a decade ago that the cosmological constant takes a small positive value. Perhaps as a thinker very much 'outside the box' it is no surprise that Hoyle too in a sense anticipated much that is going on in the present day both in the popular media, and in cosmology and the philosophy thereof. Let me give three rather different examples, one a salutary lesson, the second highlighting a consequence of the steady state theory shared with more modern theories, and the third a fascinating reflection on cosmology at the time of his 60th birthday.

We have seen how Hoyle's forays into the popular media, both broadcast and written, provoked hostility from many of his colleagues and that is a present danger too. One example in Hoyle's case comes from a review of his book *Frontiers of Astronomy* in the *Manchester Guardian*:

> Mr Hoyle has done it again. . . . Here is the universe from A to Z, all cleverly parcelled up. It is indeed clever, too clever. . . . Perhaps the most serious deficiency of this book is that it conveys no impression of the great many uncertainties that exercise astronomers just now and which give their subject such high interest. And, because the book might have been a valuable one, it is a pity that Mr Hoyle has been so dogmatic. For in spite of his lucid prose and his fine illustrations, much of the dogma is unacceptable (*Manchester Guardian* 15 July 1955, p. 6, quoted in Mitton 2011, p. 182).

Cosmology is clearly a subject that captures the popular attention, but it seems to me that these criticisms could apply a fortiori to much of today's popular cosmology writing.

In a radio broadcast in 1949 Hoyle postulated that, in an infinite universe, as in his continuous creation model, anything that can happen does happen somewhere sometime. Thus there would be multiple copies of Hoyle doing a similar broadcast elsewhere in the infinite universe. (Mitton 2011, p. 131). Although Hoyle did not see this, it seems to me that this is a good reason to be sceptical of the theory and modern multiverse theories which say the same thing. It is at least paradoxical and raises questions of human identity and free will, since I or some copy of me makes all the choices I could possible make infinitely many times, and a theory which avoids such paradoxes is surely simpler and metaphysically preferable, provided of course it accounts for the observations.

More positively, and yet more humbly, in a BBC interview with John Maddox, editor of *Nature*, to celebrate his 60th birthday, Hoyle made these prescient remarks:

> Many of the past generation believed they were very close to the ultimate structure for the universe, and that it was only a question of time before extra work would fix the final details. I don't believe this at all myself. I think what we see is a tiny fragment of a much bigger structure. The big advances in astronomy come when there are big advances in physics. We shall find it difficult to arrive at a unique answer for the universe because we see only a part of it (Mitton 2011, pp. 306–307).

Postscript: How Did Hoyle and Lemaître Relate at a Personal Level?

All the evidence would indicate that Hoyle and Lemaître got on very well at the personal level despite the fundamental disagreements over cosmology, and indeed over religion—and we have noted Hoyle's view of priests! I will end with a nice anecdote given by John Farrell concerning a 2-week drive Hoyle, his wife Barbara, and Lemaître did together through Italy and the Alps in 1957. They were dining one night, which happened to be a Friday. Hoyle ordered a steak and Lemaître fish. When the food came, Hoyle's steak was of moderate size, whereas Lemaître's fish was enormous. Hoyle commented, 'Now at last, Georges, I see why you are a Catholic!', at which Lemaître became 'red-faced and peevish'. Hoyle was puzzled, thinking he had committed some terrible 'religio-diplomatic indiscretion' as he put it. That was until he remembered that Lemaître hated fish! (Farrell 2005, pp. 156–157).

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Lemaître, the Big Bang and the Quantum Universe

Michael Heller

Abstract Lemaître's work on the geometric nature of singularities and his speculations concerning the applications of quantum physics to cosmology are confronted with later achievements in these fields. His works on the global structure of the de Sitter solution and the appearance of "non-regular" points in the Schwarzschild solution led to the conclusion that the "vanishing of the radius of the universe" is a generic property of cosmological models. This conclusion was strengthened when Lemaître proved that, against Einstein's intuition, space anisotropy (in Bianchi I models) does not remove the singularity. This is why Lemaître regarded the initial singularity as a "geometric support" of his Primeval Atom hypothesis. This hypothesis was not yet a quantum gravity idea (in the present sense of this expression), but it was certainly an application of quantum physics to the early stages of cosmic evolution. The beginning itself is aspatial and atemporal, and both space and time emerge only when the simplicity of the Primeval Atom gives place to physical multiplicity. How do the problems with which Lemaître struggled appear in the light of the present state of cosmological research?

Introduction

Eighty years ago, in 1931, Georges Lemaître published eight papers, among them two that occupy a special place in the history of cosmology. The first of them is the translation into English (Lemaître 1931a) of his paper originally published in French (Lemaître 1927) in which he, for the first time, compared red shift measurements of "distant nebulae" with theoretical predictions following from a relativistic world model. The second paper, a short essay in fact, is the work published in *Nature* (Lemaître 1931b), the anniversary of which is the reason for

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our present Conference. Both these papers are important in what follows. My topic is the Big Bang and the Quantum Universe. The name “Big Bang”, never used by Lemaître (although coined by Fred Hoyle with an eye on Lemaître’s views), suggests that my account will not be purely historical. Indeed, my intention is to make a link between our present theoretical conundrums and Lemaître’s intuitive insights into the same type of questions asked with even less empirical support than we have to-day.

Lemaître is often associated with the image of the exploding universe from a “primordial seed” resembling a shapeless atom. However, we should not forget that he was an excellent mathematician and his cosmological speculations had a strong mathematical basis. This is why, in the present essay, I focus on the mathematical structures of both Lemaître’s work and our present investigations.

I start with a brief account of the early work on singularities and Lemaître’s part in it (section “Early Work on Singularities”), and then I show how his cosmological works led him from the idea of a smooth beginning to the Primeval Atom hypothesis and the initial singularity as its “geometric support” (section “From Logarithmic Infinity to the Primeval Atom”). Is the singularity unavoidable in the classical (non-quantum) evolution of the universe? Modern singularity theorems give the answer to this question (section “Singularity Theorems”). Lemaître was one of the first cosmologists to notice that in the very early phases of the cosmic evolution quantum effects were essential, and proposed daring speculations about what the quantum beginning could look like (section “Lemaître’s Quantum Cosmology”). To-day, we are facing very similar difficulties but we treat them with a much higher degree of sophistication, which does not necessarily mean with a deeper insight (section “The Singularity Issue To-Day”). An insight into some of Lemaitre’s philosophy (section Theoretical Zero) closes the paper.

Early Work on Singularities

The popular view of the Big Bang as a point out of which the universe exploded into existence, although appealing to our imagination, is highly misleading. In fact, the problem of the beginning appeared in modern cosmology not as a great idea, but rather as a technical nuisance.

On 18 November 1915, a week before he presented to the Berlin Academy of Science the correct form of his gravitational field equations, Einstein derived the perihelion motion of Mercury from an approximate solution of the equations that turned out later to be a special case of the correct equations (Einstein 1915). The exact solution was found by Karl Schwarzschild in 1916 (Schwarzschild 1916a), but already in Einstein’s approximate solution two “non-regular points”, at $r = 0$ and at $r = 2\,M$, appeared. Einstein was too busy with investigating the motion of Mercury to pay any attention to these points. It was David Hilbert (Hilbert 1917) who noticed the problem: in his view, neither of these points is regular.

Already at this stage, singularities were revealing their difficult character. Even Hilbert did not grasp the difference between a genuine singularity and one arising from an inappropriate choice of the coordinate system.[1]

Einstein was unhappy with the Schwarzschild solution because it presented a well-defined metric structure of space-time due to a single body, and in his view, this contradicted Mach's Principle which was for him a leading motive in creating general relativity.[2] His dissatisfaction grew even more when Willem de Sitter published a new solution to his equations (de Sitter 1917) that represented an empty universe (with vanishing matter density and positive cosmological constant). This "anti-Machian" situation was not acceptable to Einstein. He argued that the model does not correspond to physical reality because of its singular character. Indeed, in coordinates used by de Sitter, it exhibits two non-regular points, at $r = 0$ (and $\psi = 0$) and at $r = \pi R/2$. Einstein claimed that the first of these singularities can be removed by the change of coordinates,[3] but the second is truly disastrous for the de Sitter solution.[4] Later on Eddington (Eddington 1923) rewrote de Sitter's metric in other coordinates, and claimed that de Sitter's world is in fact not empty: the second singularity represents "a 'mass horizon' or a ring of peripheral matter necessary in order to distend the empty region within" (p. 165). For a long discussion that took place see Earman (1995), Earman and Eisenstaedt (1999), and Kragh (1996). And here Lemaître enters the stage.

Lemaître's first published work in the field of relativistic physics concerned de Sitter's solution (Lemaître 1925). Even in this short note one can see the mathematical mastery of its author. In both coordinate systems, that used originally by de Sitter and that used later on by Eddington, the universe is static and its space is spherical (with positive constant curvature). Lemaître introduces new coordinates in which the universe is non-static (it expands) and space is Euclidean. These new coordinates clearly display the homogeneous and isotropic structure of de Sitter's world. All its points are on equal footing and the spurious central singularity disappears. There is also no "mass horizon". At the end of his note, Lemaître comments on two main results of his calculations, namely on the non-static character of the de Sitter world and the zero curvature of its space. As far as the

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[1] Hilbert proposed the following criterion: "By [non-regular point] I mean that a line element or a gravitational field $g_{\mu\nu}$ is regular at a point if it is possible to introduce by a reversible, one-one transformation a coordinate system, such that in this coordinate system the corresponding functions $g'_{\mu\nu}$ are regular at that point, i.e., they are continuous and arbitrarily differentiable at the point and in a neighbourhood of the point, and the determinant g' is different from 0" (quoted from (Earman 1995, p. 6)). This seemingly correct criterion does not distinguish between genuine singularities and coordinate singularities; more on this topic can be found in Earman (1995).

[2] In Einstein's interpretation of Mach's Principle the metric structure of space-time should be determined by the mass distribution in the universe.

[3] In Einstein's words, this singularity is only an "apparent violation of continuity, as can readily be shown by a suitable change of coordinates"; see Earman and Eisenstaedt (1999).

[4] "Thus, he concluded, with the cautionary proviso of 'until proof to the contrary', that de Sitter's solution must be regarded as having a genuine singularity and thus this 'solution does not accord with the field equations for any choice of coordinates'" (Earman and Eisenstaedt 1999, p. 193).

non-static character of the de Sitter solution is concerned, Lemaître quotes Eddington (1923, p. 161) who says: “It is sometimes urged against de Sitter’s world that it becomes non-statical as soon as any matter is inserted in it. But this property is perhaps rather in favor of de Sitter’s theory than against it”. And then Lemaître remarks: “Our treatment evidences this non-statical character of de Sitter’s world which gives a possible interpretation of the mean receding motion of spiral nebulae” (Lemaître 1925, p. 41). Strangely enough, Lemaître does not comment on the fact that de Sitter’s world is empty. Even stranger (at least from our present point of view) is that, according Lemaître, the compromising property of the de Sitter universe is that its space is Euclidean, i.e., flat and extending to infinity. Lemaître calls this property “completely inadmissible”. With it, “we are led back to the Euclidean space and to the impossibility of filling up an infinite space with matter which cannot but be finite”. He concludes: “De Sitter’s solution has to be abandoned, not because it is non-static, but because it does not give a finite space without introducing an impossible boundary”.

The idea of the “closed universe” belonged to Lemaître’s deeply rooted philosophical prejudices. It was suggested, not only to him (the idea was quite popular among early relativistic cosmologists), by Einstein’s work on his static universe in which he had to assume a “closed space” to avoid problems with the boundary conditions at infinity. In his seminary years Lemaître wrote an essay entitled *La physique d’Einstein* (never published[5]) to present as one of the conditions to obtain a scholarship abroad. In it he expressed the view that the space had to be finite since otherwise it would not be accessible to the human mind and, as it were, proportional to its possibilities (Lambert 2000, p. 61). One can see in this view some traces of the neothomist doctrine, to which young Lemaître was exposed at the University of Louvain. According to this doctrine, an actual infinity is self-contradictory. Since matter could not be actually infinite, in an infinite space it would have to have “an impossible boundary”. Lemaître cherished this view to the end of his life. For the title of his conference at the Catholic Institute in Paris in 1950 he chose *L’Univers, problème accessible à la science humaine*, published posthumously in Lemaître (1978). And in one of his later essays he emphatically wrote: “Man fits in Nature. If he wanted to comprehend the whole, he perhaps would be presumptuous, but this presumption and his daring would not be infinite, would not be blameworthy or absurd. This pursuit is the normal ambition of humanity” (Lemaître 1960).

Lemaître also played an important role in solving the enigma of the Schwarzschild singularity. The problem was seminally present in his doctoral thesis presented to the Massachusetts Institute of Technology (never published, see Lambert (2000, pp. 81–87)). Some of its results were further developed and incorporated into Lemaître’s important paper (Lemaître 1933). The idea was

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[5] The typescript is preserved in the Lemaître archive in Louvain-la-Neuve.

suggested to Lemaître by Eddington. The problem of finding the solution to Einstein's equations for a homogeneous spherically symmetric perfect fluid was solved by Schwarzschild (the so-called interior Schwarzschild solution (Schwarzschild 1916b). Eddington suggested that the problem could be badly posed since density is not a coordinate independent quantity (see Eddington 1923). Lemaître defined an invariant quantity composed of density and pressure,[6] and found a solution that, for small densities, approximated the Schwarzschild solution. He then considered the case when the fluid is inhomogeneous (but of constant invariant density), and produced the solution known today as the Tolman-Bondi solution.[7] As special cases of this solution he obtained Einstein's static universe and de Sitter's empty universe. Later on, this suggested to him an idea that there must exist intermediate solutions (expanding but non-empty) between these two models. In the course of the work on these problems Lemaître found a coordinate system for the Schwarzschild solution in which the singularity at $r = 2\,M$ disappears (for more see Lambert (2000, pp. 81–87) and Earman and Eisenstaedt (1999)). There remains the central singularity at $r = 0$ as the only "real singularity" in this solution.

At the end of his paper (Lemaître 1933) there is a section in which Lemaître deals directly with the singularity problem. The genesis of the problem is the following. In 1931 Einstein finally fully acknowledged the correctness of Friedmann's contribution to cosmology and rederived the oscillating solution (Einstein 1931). Lemaître called it the "phoenix world". Einstein was extremely unhappy with the existence of the singularity at every transition from the contraction to the expansion phase, and had an idea that the appearance of singularities is due to the assumption of spatial isotropy made in the construction of the model. He discussed this problem with Lemaître and suggested to him a simple anisotropic metric form (today known as the Bianchi I metric) with the advice to compute the corresponding world model to see the singularity to disappear. Later on Lemaître confessed that he "had no difficulty to compute" the model (Lemaître 1958a). It turned out that the singularity continues to exist. Lemaître comments on this result: "The above is not a formal proof of the impossibility to avoid zero volume by anisotropy because the form (12.5) [of the considered metric] is not the most general imaginable, but this indicates—after all in a quite general case—that anisotropy acts in the opposite direction" [than that foreseen by Einstein] (Lemaître 1933). In his calculations Lemaître had used some elements similar to those that later on were used in the proofs of singularity theorems (Godart and Heller 1985, pp. 95–97).

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[6] It was defined as $T = \rho - 3p$ in units in which $c = 1$; Lemaître called T invariant density.

[7] Lemaître qualifies this solution as "probablement nouvelle" (Lemaître 1933); in fact, it was obtained, in 1922, by Marcel Brillouin with the help of a different method (see Lambert 2000, p. 83).

From Logarithmic Infinity to the Primeval Atom

Lemaître was a good mathematician and loved calculations, but when doing cosmology he was not looking for mathematical elegance, his ambition being to understand the physical universe. This is clearly visible in his masterpiece work of 1927. When he learned, from Hubble himself (Lambert 2000, pp. 87–91) that the spectra of "spiral nebulae" are red shifted, he decided to connect this fact with cosmological models. Inspired by the idea coming from his doctoral thesis, he computed all spatially isotropic and homogeneous solutions to Einstein's equations (with cosmological constant) for positive space curvature, but he chose to publish only one of them.[8] The model favoured by Lemaître is expanding, but when time goes to minus infinity the model asymptotically approaches the static Einstein world (one could say that its beginning is at "logarithmic minus infinity"); today it is called Eddington-Lemaître world model. Lemaître's main result was the conclusion that the predictions following from this model do not contradict actual red shift measurements. Of course the same could be demonstrated for many other expanding solutions, but Lemaître had to face yet another empirical constraint. At that time there was a discrepancy, if not a contradiction, between the age of the universe as estimated from the expansion of the universe and the age of the oldest stars and the oldest rocks on the Earth. The former led to the figure $T = 2 \times 10^9$ years, whereas the latter up to two times as high. The choice of the model with "logarithmic minus infinity" has evidently settled this problem. An additional argument for the reality of the model for Lemaître was the absence of the compromising singularity in it.

However, soon after the publication of the paper, the situation changed. Lemaître paid attention to another of his solutions, the one in which after the initial rapid expansion, there is an almost static stage (very slow expansion) again followed by an accelerated expansion. Moreover, by manipulating the value of the cosmological constant, the almost static stage can be made as long as one wishes (now the model is called Lemaître's model). The model had the initial singularity, but Lemaître already knew that the singularity cannot be simply removed from cosmology, and perhaps it would be better, instead of trying in vain to avoid it, to incorporate it into the cosmic scenario. In this way, the initial singularity in his world model provided "a natural geometric support" to the idea of the Primeval Atom.

The idea itself was born in 1931 (Lemaître 1931b) from the polemics with Eddington, and its physical motivation came from quantum physics. The beauty of the Primeval Atom hypothesis consists in its extreme simplicity. The essence of the idea could be enclosed in a few lines: "I would rather be inclined to think"—wrote Lemaître—"that the present state of quantum theory suggests a beginning of

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[8] At Lemaître's archive in Louvain-la-Neuve his calculations of all solutions are preserved (for details see Godart and Heller (1985, p. 57)). At that time Lemaître did not know that these solutions were already published by Alexander Friedmann.

the world very different from the present order of Nature. Thermodynamical principles from the point of view of quantum theory may be stated as follows: (1) Energy of constant total amount is distributed in discrete quanta. (2) The number of distinct quanta is ever increasing. If we go back in the course of time we must find fewer and fewer quanta, until we find all the energy of the universe packed in a few or even in a unique quantum" (Lemaître 1931b). And this is exactly the Primeval Atom. The name is somewhat misleading since Lemaître did not have in mind an atom in the modern physical sense, but rather "the word 'Atom' should be understood in the primitive Greek sense of the word. It is intended to mean absolute simplicity, excluding any multiplicity" (Lemaître 1958b).

Singularity Theorems

With Lemaître's Primeval Atom hypothesis a step has been made at establishing what is to-day called the Big Bang theory of the universe. In classical (non-quantum) cosmology the initial singularity, marking the beginning of the universe, is a geometric counterpart of the Big Bang. Let us pause for a while to consider the (classical) singularity issue from our present perspective.

As long as the attention of researchers was focused on single solutions the singularity problem remained in darkness. The geometric nature of singularities was additionally obscured by the strong dependence of the picture obtained on coordinates; to disentangle the situation still constituted a real difficulty. For instance, the central singularity in the Schwarzschild solution (which is in fact a strong curvature singularity) was considered to be a minor nuisance, whereas the coordinate singularity at $r = 2\,m$ was widely discussed. The darkness started slowly to dissipate when people began to use test particles for probing space-time completeness. Space-time is considered to be singularity-free if all timelike and null geodesics (that can be histories of freely falling test particles or photons) in it are complete and inextendible. If at least one such geodesic is incomplete, this means that a given history of a test particle or photon ceases to happen, that is it hits a singularity.

This strategy led to the formulation of singularity theorems. The first theorem of this kind was proved by Roger Penrose in 1965 (Penrose 1965); it referred to gravitationally collapsing objects. Soon after, Stephen Hawking applied Penrose's method to open cosmological models (Hawking 1965). Then a series of theorems followed proving the existence of singularities in various space-time configurations; this is set out in the fundamental monograph of Hawking and Ellis (1973) and an extensive review in Tipler et al. (1980). With these theorems the physical (and partly philosophical) issue of the "beginning" or "end" was transformed into an almost purely geometric problem.

In proving singularity theorems one has to formulate a set of assumptions and to show that they are in conflict with the postulate of (timelike or null) geodesic completeness of space-time. Various theorems employ various combinations of these assumptions but, generally speaking, they could be grouped into the following three classes:

- Positive curvature conditions that imply caustics and focusing of families of geodesics.[9]
- Conditions imposed on space-time that connect global properties of space-time with the geometry of geodesics. Examples of global properties are: the existence of a (global) Cauchy surface[10] or non-compactness of time slices of space-time.[11] In many situations these global conditions force caustics to become obstructions for geodesics to be complete.
- Some configurations in space-time that interact with the above two classes of conditions, such as the existence of a trapped surface,[12] or everywhere contracting or expanding instantaneous spaces. They play the role of "initial conditions" that enforce some desirable properties on families of geodesics.

Let us note that nowhere in the above conditions is general relativistic dynamics, as expressed in Einstein's field equations, engaged. This can interfere only through the so-called positive energy conditions that are related to the matter content of the universe (components of the energy-momentum tensor). It follows that the source of singularities lies in the space-time geometry rather than in specific properties of matter (or in general relativistic kinematics rather than in its dynamics).

Various theorems use various combinations of the above assumptions. The idea is to use the weakest assumptions under which a singularity is still present. However, the less that is assumed, the less can be said about the singularity. The weakest assumptions imply that there exists at least one incomplete timelike or null geodesic. Information gained from singularity theorems should be combined with that provided by the existence of singularities in known solutions to Einstein's equations. It turns out that there exist non-singular solutions in which even the strongest of the above conditions are satisfied, but some others are not. On the other hand, the most general conditions which would guarantee non-singular behaviour are not known.

The lessons that can be drawn from all this are the following. First, that the singularity issue in general relativity is a serious one, in the sense that choosing a singularity-free solution and basing upon it the entire cosmological scenario is a

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[9] Caustics are regions in which families of geodesics do not form smooth space-time submanifolds; they are singularities of families of geodesics rather than singularities of space-time.

[10] A Cauchy surface is a spacelike hypersurface that no inextendible history of a particle or photon (i.e., no timelike or null curve) in a given space-time intersects more than once. A Cauchy surface is a global Cauchy surface if every such history in a given space-time intersects it exactly once.

[11] World models with non-compact time slices are called open world models.

[12] Technically, a trapped surface is a compact two-dimensional submanifold of space-time such that the expansion of both outgoing and ingoing future directed null geodesics, that are orthogonal to this submanifold, is everywhere negative. Physically, this means that a trapped surface is formed provided there is enough matter accumulated in a small region of space-time. Such situations are expected to occur in gravitational collapse.

fudge rather than the real answer to the problem. Second, since the input from general relativity to singularity theorems is rather small, if we want to get rid of singularities, we should manipulate geometry rather than the dynamical side of gravity.

Lemaître's Quantum Cosmology

Although the singularity theorems are mathematical theorems and as such they are definitive, they do not settle the problem of singularities in cosmology. According to the view prevalent at present, quantum gravity effects, when properly taken into account in the history of the very early universe, should remove the singularities from the model. To do so they must either violate at least one of the conditions of the singularity theorems, or somehow circumvent the theorems themselves. Quantum cosmology is expected to do this.

Lemaître was one of the first cosmologists, if not the first one, who seriously included quantum physics in a cosmological model. To be sure, it was not a quantum gravity theory, but rather elementary laws of quantum mechanics that were laid at the foundations of the Primeval Atom hypothesis; nevertheless the Primeval Atom itself is certainly a quantum object and the early history of the universe, as seen by Lemaître, is a quantum history. In what follows I shall, almost literally, use Lemaître's wording (taken from Lemaître 1958b, pp. 105–109) in describing the quantum history of the world.

In the classical view, the same deterministic laws that are able to predict the future could also be employed to compute more remote conditions in the past from which the "initial conditions" of the present universe might have evolved. Therefore, it is difficult to understand how the initial conditions could really have been a beginning. This is, essentially, one of Kant's antinomies. However, the advent of quantum physics has changed the situation. According to the basic postulates of quantum mechanics, any physical system, and therefore the universe as well, is described as an assembly of potential states which can be, or not be, occupied. The most probable distribution is that of equal occupation of all possible states. Since the entropy is a measure of the total number of individual energy packets, we may say that the final state is the one with maximal entropy. And conversely, a state of minimum entropy would be a state in which energy is condensed into as few packets as is possible. This state is called the Primeval Atom and can be regarded as a physical beginning of the universe.

The subsequent evolution is not encoded in this initial state. Classical determinism does not stand any more. Initial conditions need not have the same degrees of freedom as does the universe that has evolved from them. Events progress with energy being split into more and more distinct packets. From the same beginning, widely different universes can evolve. When the number of individual packets becomes very large, the essential indeterminacy ceases to be effective and is gradually replaced by the determinism characteristic of macroscopic phenomena.

Standard quantum mechanics does not address the question of quantizing space-time, but at this point Lemaître goes beyond standard quantum mechanics. He assumes that space and time are intrinsically statistical concepts and, consequently, that one cannot ascribe any physical meaning to them before one has a sufficiently large number of physical individuals. In Lemaître's view, space and time emerge from the simple initial state as the process of "energy pulverization" progresses. He writes: "Beginning of multiplicity really means beginning of the very meaning of any notion which involves a great number of individuals. Space and time are such notions. It stands just before the beginning of space and time which progressively acquire a meaning as multiplicity is sufficiently increased. As space and time are the indispensable tools of any physical notion, it stands just before Physics. It is an inaccessible ground of space-time" (Lemaître 1958b, pp. 6–7).

In Lemaître's day this "ground" was indeed inaccessible. Today various models of quantum gravity offer a wide field of speculations concerning the "birth of space and time", at least qualitatively along lines sketched by Lemaître. In the modern view, however, the quantum gravity regime should remove the initial singularity from the picture of the universe. For Lemaître, on the other hand, the initial singularity in Friedmann's cosmological models gives a "natural geometric support" to his Primeval Atom hypothesis. He comments: "The radius of space can start from zero. Such a singular event which arises when space has a zero-volume is a bottom of space-time which terminates every line of space-time. I do not pretend that such a singularity is inescapable in Friedmann's theory, but I simply point out how it fits with the quantum outlook as a natural beginning of multiplicity and of space-time" (Lemaître 1958b, p. 7).

The Singularity Issue To-Day

The present common wisdom asserts that we cannot reach the "bottom of space-time which terminates every line of space-time" since the structure of the space-time manifold itself breaks down at the Planck threshold. We could reach this threshold by going backwards in time till the density of cosmic 'stuff' is 10^{93} g cm^{-3} or, equivalently, by going to smaller and smaller distances until the typical length scale is of order of 10^{-33} cm. Beyond Planck's threshold quantum gravity effects take over, and it is up to various quantum gravity scenarios to reconstruct what happens in this pre-geometric phase. This does not mean that we could simply ignore the singularity theorems. We should rather adapt them to the new situation. Of course, everything depends on the correct theory of quantum gravity, when it finally is formulated. There is, however, but a little doubt that it will have a quantum theoretic character. Therefore, it seems reasonable in testing the existence of singularities to use potentially fundamental fields rather than non-spacelike geodesics (i.e. histories of particles or photons). We would also prefer to have general conditions under which singular solutions do not appear rather than to have particular singularity-free scenarios.

The idea of using test fields rather than test particles goes back to C.S.J. Clarke (1998). In classical general relativity, space-time is regarded as well behaved if it is globally hyperbolic.[13] Clarke, based on many examples, claims that it is not global hyperbolicity that guarantees a space-time to be well behaved but rather a well-posedness of the initial value problem for test fields. The idea was transferred from classical gravity to quantum gravity by Martin Bojowald (2007). He formulated the principle of quantum hyperbolicity which says that "if a state can uniquely be extended across or around all submanifolds of classically singular configurations they do not pose obstructions to quantum evolution in any case". Verification as to whether this principle is satisfied in concrete cases requires two things: first, to locate a potential (classical) singularity and, second, to see if states can uniquely be extended across or around this location. This should be valid for all types of singularities, strong curvature singularities included.

To test the quantum hyperbolicity proposal one could consider the Wheeler-DeWitt wave functions defined on the space of metrics (DeWitt 1967), trying to extend the metric variables across the singularity. The difficulty is that the classification of singularities in terms of the metric behaviour is not known; therefore in practice one limits oneself to mini- or midi-superspaces.

Conceptually, the situation is much better in loop quantum cosmology which offers a background independent and non-perturbative treatment of quantum gravity. In this approach, basic fields, space discreteness and quantum dynamics are well defined (Rovelli 2004). However, the problem with the quantum hyperbolicity principle consists in the fact that in loop quantum gravity it is hard to find even a trace of a classical singularity and one does not know where to look for "resolved singularities".

Superstring theories, in their present most common formulations, describe gravitational excitations on a fixed metric background. This, in principle, eliminates the standard treatment of singularities. However, in many cases singularities can be resolved by additional degrees of freedom available in this approach (see, for instance Craps 2006). The existence of singularities should no longer be tested with the help of curves (histories of test particles) but rather in terms of space-time sheets or higher dimensional volumes (histories of strings or branes), and this can radically change the situation. It would be desirable to have some general theorems analogous to those proved for causal curves. However, this approach is difficult to apply to curvature singularities.

This is only a sample of problems that should be carefully analysed before the problem of the beginning is satisfactorily solved or at least correctly posed. Perhaps we should follow Lemaître's example not to be afraid of bold hypotheses, but only when everything that could be done with the help of responsible mathematics has been done.

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[13] Space-time is globally hyperbolic if it has a global Cauchy surface.

Theoretical Zero

When thinking about the "beginning of the universe" metaphysical questions come to mind almost automatically. To take such thoughts seriously seems fully justified as long as one is conscious of where one's science ends and metaphysics begins, even if the borderline between them is somewhat fuzzy. I conclude this essay by letting Lemaître lay before us some of his ideas concerning these "limiting questions" of cosmology and leaving the reader with the liberty of drawing parallels between Lemaître's proposals and the present state of affairs in cosmology.

After presenting his reconstruction of physical processes in the very early universe Lemaître asks: "What happened before that?" (Lemaître 1996, p. 47).[14] Before that we have to face the "theoretical zero" of the radius of space. Lemaître thinks that it is only a theoretical approximation of what physically was "a very trifling quantity, let us say a few hours of light". And he continues: "We may speak of this event as of a beginning. I do not say a creation. Physically it is a beginning in that sense that if something has happened before, it has no observable influence on the behaviour of our universe, as any feature of matter before this beginning has been completely lost by the extreme contraction at the theoretical zero". Lemaître envisages two possibilities: either the "theoretical zero" was the consequence of the previous contracting phase of the universe, or the universe began its existence in that way. Both these possibilities are outside of the reach of science. "All preexistence of the universe has a metaphysical character. Physically everything happens as if the theoretical zero was really a beginning. The question if it was really a beginning or rather creation: something starting from nothing, is a philosophical question which cannot be settled by physical or astronomical considerations". Science is able to speak only about the "natural beginning" (in the above sense). And it is a happy circumstance that the theory of relativity provides such a natural beginning, since "otherwise we would not know when to stop our investigation" in our backward reconstruction of the history of the universe.

The problem of the natural beginning is intrinsically connected with the problem of time. It seems that it is impossible to have a present that would be followed by a future but would not be preceded by a past. However, the theory of relativity teaches us that time cannot exist without space, and "space-time may have a bottom because space has a finite magnitude, a radius, and zero is a possible value of this radius". It is exactly this circumstance that enables us to speak about the natural beginning: "There can therefore be an instant of time such that past and future of this instant are distinguished by the fact, that in the future there is space, and in the past there is no space. Such an instant is a natural beginning…".

On this essentially classical picture we should superimpose quantum properties of the Primeval Atom (see section "Lemaître's Quantum Cosmology") owing to which space and time are entirely lost in quantum indeterminacies of the initial state.

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[14] The rest of the present section is based on this reference, and all quotations are taken from it.

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Georges Lemaître: Science and Religion

George V. Coyne

Introduction

In order to appreciate the contribution which Georges Lemaître made to the relationship between religion and science it is necessary to understand how the Catholic Church, of which he was a priest, passed in the course of three centuries, from a position of conflict with the sciences to one of compatible openness and dialogue. In doing this I hope to show that the natural sciences have played a significant role in helping to establish the kind of dialogue that is absolutely necessary for the enrichment of the multifaceted aspects of human culture. I will speak of the following four periods of history: (l) the rise of modern atheism in the seventeenth and eighteenth centuries; (2) anticlericalism in Europe in the nineteenth century; (3) the awakening within the Catholic Church to modern science in the first six decades of the twentieth century; (4) the Church's view today.

Rationalism and the Rise of Modern Atheism

In his detailed study of the origins of modern atheism Michael Buckley (Buckley 1987) concludes that it was paradoxically precisely the attempt in the seventeenth and eighteenth centuries to establish a rational basis for religious belief through arguments derived from philosophy and the natural sciences that led to the corruption of religious belief. Religion yielded to the temptation to root its own existence in the rational certitudes characteristic of the natural sciences. According to Buckley such philosophers as Leonard Lessius and Marin Mersenne decided that the existence of God must be so well established from philosophical arguments that

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evidence derived from religious experience itself became secondary or even forgotten. This rationalist tendency found its apex in the enlistment of the new science, characterized by such figures as Isaac Newton and René Descartes, to provide the foundation for religious belief. Although the Galileo case, as it is called, is thought to provide the classical example of confrontation between science and religion—actually in the trial of 1633 science was not at the table—it is really in the misappropriation of modern science by such as Isaac Newton to mistakenly establish the foundations for religious belief that we find the roots of a much more deep seated confrontation. From these roots, in fact, sprang the divorce between science and religion in the form of modern atheism.

Thus science served to corrupt religious belief. The certainties born of the scientific method gave birth to the desire for like certainties as a foundation for religious belief. That desire was radically misplaced and led to a lengthy period of misunderstanding between religion and science.

Anticlericalism

As to the second movement in the dissonant symphony between religious belief and science initiated by the rationalism of the seventeenth and eighteenth centuries we turn to nineteenth century anticlericalism. Some episodes that reveal aspects of this anticlericalism and its influence on the development of the relationship between science and religion are described by Sabino Maffeo in his history of the Vatican Observatory on the occasion of its 100th anniversary (Maffeo 1991). In fact, the founding of the Observatory in 1891 by Pope Leo XIII is set very clearly in that climate of anticlericalism and one of the principal motives that Leo XIII cites for the foundation is to combat such anticlericalism. His words show very clearly the prevailing mistrust of many scientists for the Church:

> So that they might display their disdain and hatred for the mystical Spouse of Christ, who is the true light, those borne of darkness are accustomed to calumniate her to unlearned people and they call her the friend of obscurantism, one who nurtures ignorance, an enemy of science and progress . . . (Maffeo 1991, p. 205).

He then terminates this *Motu Proprio* in which he established the Observatory by stating:

> . . . in taking up this work we have become involved not only in helping to promote a very noble science, which more than any other human discipline raises the spirit of mortals to the contemplation of heavenly events, but we have in the first place put before ourselves the plan . . . that everyone might see that the Church and its Pastors are not opposed to true and solid science, whether human or divine, but that they embrace it, encourage it, and promote it with the fullest possible dedication (Maffeo 1991, p. 205).

Although the historical circumstances did not provide a healthy climate for a dialogue between religion and science, the founding of the Vatican Observatory, even if couched in triumphalistic terms, proved to be a quite positive contribution to the dialogue, both at the time of its foundation and in its subsequent 100 year history (Maffeo 1991, pp. 189–202).

Awakening to Science: The Role of Georges Lemaître

We now pass to the period of enlightenment. For the purposes of this chapter and for the sake of brevity, when I speak of the awakening of the Church to science during the first six decades of the twentieth century, I am really speaking of the personage of Pope Pius XII. He was a man of rich culture and even in his youth he had become acquainted with astronomy through his association with Giuseppe Lais, Oratorian, who was an astronomer at the Vatican Observatory from 1890 to 1921 and the one most responsible for the completion of the International Sky Mapping Program of the Vatican Observatory (Maffeo 1991, p. 35). The Pope had an excellent college level knowledge of astronomy and he frequently discussed astronomical research with Daniel O'Connell, the then Director of the Vatican Observatory (Maffeo 1991, pp. 174, 184, 185). Pius XII's discourses on astronomical and cosmological themes are summarized by McLaughlin (McLaughlin 1957, pp. 183–206). However, the Pope was not immune from the rationalist tendency discussed above and his understanding of the then most recent scientific discussions concerning the origins of the universe led him to a somewhat concordant approach to seeing in these scientific results a rational support for the Scriptural, and derived doctrinal, interpretation of creation. This tendency was first revealed in the address, *Un'Ora*, delivered to the Pontifical Academy of Sciences on 22 November 1951 (Discourses 1986, pp. 73–84) in which he attempted to examine the scientific results from which arguments for the existence of God the Creator might proceed. Even at that time the Papal discourse created a great deal of negative comment (Gamow 1952; Mascall 1956). But this was only the beginning of what was to be a very difficult period. It was only, in fact, through the most delicate but firm interventions of Georges Lemaître and Daniel O'Connell that the Pope was dissuaded from following a course which would have surely ended in troubling times for the relationship between the Church and scientists (Turek 1989).

The specific problem arose from the tendency of the Pope to identify the beginning state of the Big Bang cosmologies, known principally to the Pope from Lemaître's book, *The Primeval Atom*, with God's act of creation. He had stated, for instance, that:

> ... contemporary science with one sweep back across the centuries has succeeded in bearing witness to the August instant of the primordial *Fiat Lux*, when along with matter there burst forth from nothing a sea of light and radiation ... Thus, with that concreteness which is characteristic of physical proofs, modern science has confirmed the contingency of the Universe and also the well founded deduction as to the epoch when the world came forth from the hands of the Creator (Pius 1952, pp. 41–42).

Lemaître had considerable difficulty with this view of the Pope. Although he was a respected cosmologist, he was also a Catholic priest and, since solid scientific evidence for his theory was lacking at that time, he was subject to the accusation that his theory was really born of a spirit of concordism with the religious concept of creation. Lemaître insisted that the Primeval Atom and Big Bang hypotheses should be judged solely as physical theories and that theological considerations should be kept completely separate (Lemaître 1958, p. 7).

The contrasting views reached a climax when the time came for the preparation of an address which the Pope was to give to the Eighth General Assembly of the International Astronomical Union to be held in Rome in September 1952. On his way to a scientific congress in Cape Town, South Africa, Lemaître stopped in Rome to consult with Daniel O'Connell and the Cardinal Secretary of State of the Vatican concerning the address. The mission was apparently a success, since in his discourse delivered on 7 September 1952 (Pius 1952, p. 732), although he cited many specific instances of progress made in the astrophysical sciences during the last half century, he made no specific reference to scientific results from cosmology or the Big Bang. Never again did Pius XII attribute any philosophical, metaphysical, or religious implications to the theory of the Big Bang.

A Summary

To summarize, from what has been said of the three selected historical periods, I believe we can conclude the following. First, as an inheritance from the origins of modern atheism in the seventeenth and eighteenth centuries, there has been within the Church a tendency to associate scientific research with atheism. Up until the 1970s, for instance, all of the organization of formal dialogue between the Church and the world of science was handled by the Vatican Secretariat for Non-believers (currently called the Pontifical Council for Dialogue with Non-believers). Most recently this dialogue has been organized by the Pontifical Council for Culture, founded in 1982. Secondly, a type of "siege" mentality in response to currents of anticlericalism characterized the thinking of the Church at the time of the foundation of the Vatican Observatory. Thirdly, when enlightened to the magnificent progress in scientific research in the first six decades of this century, the Church in the person of Pius XII wished too hastily to appropriate the results of science to its own ends. Recently there has been a view from Rome that contrasts in a significant way with each of these previous historical periods. Since the intervention of Lemaître, which I have just described, set the stage for future developments in the science-religion dialogue on the part of the papacy, I would like to briefly discuss those developments as an inheritance of Lemaître.

Partnership in Dialogue

Although there are many others, the principal source for deriving the most recent view from Rome concerning the relationship of science and faith is to be found in the message of John Paul II written on the occasion of the tercentennial of Newton's *Principia Mathematica* and published as an introduction to the proceedings of the meeting sponsored by the Vatican Observatory to commemorate that same tercentennial (John Paul 1988). The newness in what John Paul II has said about the relationship consists in his having taken a position compellingly different from previous official positions of the Church. I would like now to briefly analyze that message in light of what I have just claimed.

John Paul II clearly states that science cannot be used in a simplistic way as a rational basis for religious belief, nor can it be judged to be by its nature atheistic, opposed to belief in God.

> . . . Christianity possesses the source of its justification within itself and does not expect science to constitute its primary apologetic. Science must bear witness to its own worth. While each can and should support the other as distinct dimensions of a common human culture, neither ought to assume that it forms a necessary premise for the other. The unprecedented opportunity we have today is for a common interactive relationship in which each discipline retains its integrity and yet is radically open to the discoveries and insights of the other (John Paul 1988, p. M9).

He furthermore states:

> . . .science develops best when its concepts and conclusions are integrated into the broader human culture and its concerns for ultimate meaning and value . . . Scientists . . . can come to appreciate for themselves that these discoveries cannot be a substitute for knowledge of the truly ultimate. Science can purify religion from error and superstition; religion can purify science from idolatry and false absolutes. Each can draw one another into a wider world, a world in which each can flourish (John Paul 1988, p. M 13).

Nothing could be further from the attitude of Leo XIII, born of the anticlericalism of the seventeenth and eighteenth centuries, than the following words of John Paul II:

> By encouraging openness between the Church and the scientific communities, we are not envisioning a disciplinary unity between theology and science like that which exists within a given scientific field or within theology proper. As dialogue and common searching continue, there will be growth towards mutual understanding and gradual uncovering of common concerns which will provide the basis for further research and discussion (John Paul 1988, p. M7).

I would judge that the newest element in the new view from Rome is the expressed uncertainty as to where the dialogue between science and faith will lead. Whereas the awakening of the Church to modern science during the papacy of Pius XII resulted in a too facile appropriation of scientific results to bolster religious beliefs, Pope John II expresses the extreme caution of the Church in defining its partnership in the dialogue:

> . . .Exactly what form that (the dialogue) will take must be left to the future (John Paul 1988, p. M7).

I consider this to be the newest and most important posture that the modern Church has taken in its approach to science. It is radically new and in complete contrast with previous history. It is diametrically opposed to accusations of atheism, to a posture of antagonism; it is awakened but expectant.

I would like to end by addressing a question that John Paul II raises: “Can science also benefit from this interchange?” (John Paul 1988, p. M7). To my mind it takes a great deal of courage and openness to ask that question. I do not believe that it has a very clear answer. In fact, it is very difficult to see what the benefits to science as such, that is as a specific way of knowing, might be. In the Papal message it is intimated that the dialogue will help scientists to appreciate that scientific discoveries cannot be a substitute for knowledge of the truly ultimate (John Paul 1988, p. M7). In what way, however, do scientific discoveries participate, together with philosophy and theology, in the quest for that ultimate? This is a serious and open question. Obviously, the new view from Rome does not have all the answers, but it is an invitation to a common quest, a quest which owes a great deal to the spirit of Georges Lemaître.

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Aquinas and Contemporary Cosmology: Creation and Beginnings

William E. Carroll

Abstract Discussions in the Middle Ages about creation and the temporal beginning of the world involved sophisticated analyses in theology, metaphysics, and natural philosophy. Mediaeval insights on this subject, especially Thomas Aquinas' defense of the intelligibility of an eternal, created universe, can help to clarify reflections about the philosophical and theological implications of contemporary cosmological theories: from the "singularity" of the Big Bang, to "quantum tunneling from nothing," to multiverse scenarios. Thomas' insights help us to see the value of Georges Lemaître's insistence that his cosmological reflections must be kept separate from an analysis of creation. This essay will look at different senses of "beginning" and examine the claim that creation, in its fundamental meaning, tells us nothing about whether there is a temporal beginning to the universe. Multiverse models, like that recently proposed by Stephen Hawking and Leonard Mlodinow, may challenge certain views of a Grand Designer, but not of a Creator.

Discussions concerning the origin of the universe have now routinely included topics from particle physics as well as cosmology. Often, however, there is considerable confusion as to what is meant when one speaks of the "origin" of the universe, and this confusion is only increased when philosophical and theological discourse about creation is added to the discussion. Such confusion was apparent near the end of March 2010 in commentary that accompanied the initial functioning of CERN's Large Hadron Collider. Two beams of protons, each with an energy equivalent of 3.5 trillion electric volts, smashed into one another in a tunnel seventeen miles in circumference. Physicists have great hopes that this huge particle accelerator, built 300 ft underground on the Swiss-French border, will provide new and fascinating insights into what the universe was like shortly after

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the Big Bang. One goal is to discover the elusive Higgs boson, a particle reputedly responsible for the conversion of the energy of the Big Bang into the mass of the nascent universe. Some in the media were quick to cite the observation of physicist Michio Kaku of City College of New York who remarked that the new experiments at CERN would be "a huge step toward unraveling Genesis Chapter 1, Verse 1—what happened in the beginning. This is a Genesis machine. It'll help to recreate the most glorious event in the history of the universe"(Higgins and Borenstein 2010). It has been easy for some to reach the conclusion that experiments conducted using this machine will, as one author in *Le Monde* put it, permit us "d'éclaircir le mystère de la création de l'Univers" (Hir 2010). Almost a decade earlier, a science journalist for *The New York Times* predicted that high-speed particle accelerators would help scientists to work out "a mechanistic, gears-and-levers theory of the Genesis moment itself—the hows, if not the whys of creation *ex nihilo*" (Glanz 2001).

Such confusion between cosmological research and creation would have been abhorrent to Georges Lemaître. Even though his initial interest in a "primeval atom" from which the universe is expanding had a religious context, as Dominique Lambert has argued,[1] Lemaître always resisted drawing the conclusion that the *commencement naturel* of the universe ought to be identified with the universe's creation. This was especially evident in his strong reaction to Pope Pius XII's claim in 1951 that the new cosmology of an expanding universe was providing support for what the opening of Genesis revealed.[2] By the 1950s, Lemaître had developed a clear understanding of the methodological separation between theological and cosmological levels of discourse,[3] a clarity which was not always present in his early years. In an essay written after World War II (but left by Lemaître in manuscript[4]), he notes that the initial expansion of the universe from a primeval atom may be referred to as "a beginning." He continues:

> I do not say a creation. Physically it is a beginning in that sense that if something has happened before, it has no observable influence on the behaviour of our universe, as any

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[1] Lambert has documented this early interest in letters (1916–17) between Lemaître and his friend, Joris Van Severen. "Pendant environ un an (from 1917), Lemaître va déployer pour lui-même cette intuition fondamentale qui debouche sur un exégèse particuliére des premiers versets de la Genèse et qui constitue l'une des sources lointaines, cachées mais authentiques, de son hypothèse cosmogonique." Dominique Lambert, *L'itinéraire spirituel de Georges Lemaître* (Bruxelles: Éditions Lessius, 2007), p. 27.

[2] "[I]t would seem that present-day science, with one sweeping step back across millions of centuries, has succeeded in bearing witness to that primordial 'Fiat lux' uttered at the moment when, along with matter, there burst forth from nothing a sea of light and radiation . . .. Thus, with that concreteness which is characteristic of physical proofs, it has confirmed the contingency of the universe and the well-founded deductions as to the epoch when the cosmos came forth from the hands of the Creator. Hence creation took place in time. Therefore, there is a Creator. Therefore, God exists!" Pope Pius XII, Address to the Pontifical Academy of Sciences, 22 November 1951.

[3] *ibid*., p. 57.

[4] It was to be published in the *Japanese Catholic Encyclopedia,* but never appeared in print. The full manuscript appeared as "The Expanding Universe" in Michael Heller's *Lemaître, Big Bang, and Quantum Universe* (Tucson, AZ: Pachart Publishing House, 1996).

> feature of matter before this beginning has been completely lost by the extreme contraction at the theoretical zero. A pre-existence of the universe has a metaphysical character. Physically everything happens as if the theoretical zero was really a beginning. The question if it was really a beginning or rather a creation: something starting from nothing, is a philosophical question which cannot be settled by physical or astronomical considerations (Lambert 2000a).

I do not propose here to probe in any detail the development and mature expression of Lemaître's thought on this subject, since this has been done in the contributions of Dominique Lambert and Helge Kragh to this volume. Rather, I would like to look at a distant source of Lemaître's general distinction between creation and cosmology, a source with which he probably became familiar during his philosophical studies at Louvain, especially just after World War I when he completed courses giving him access to a baccalaureate in Thomistic philosophy at the Institut Supérieur de Philosophie (Lambert 2000b).

Even with Lemaître's familiarity with the philosophy of St. Thomas Aquinas (1224–1274)—not unexpected for one preparing for the priesthood in post World War I Europe—it may seem strange to juxtapose Thomas Aquinas and the cosmological theories of the twenty-first century, even stranger, perhaps, to argue that what Thomas has to say about beginnings and creation can speak directly to debates in our own day about the philosophical and theological implications of current cosmological speculations. Despite dangers of falling into anachronistic commentary or of failing to recognize profound differences in the ways in which terms such as science, creation, and time have come to be used in the centuries that separate us from Thomas Aquinas, I want to enter into discourse where even angels may fear to tread to examine the enduring relevance of the thought of the Angelic Doctor, especially in natural philosophy, metaphysics, and theology. Astronomers often note that to look out at the heavens is to look back in time. Perhaps to look back in time to mediaeval discussions of creation and science will help us to look out more clearly and to avoid confusions about both what we are seeing and what the philosophical and theological implications of contemporary science are.

Developments in cosmology and particle physics have long encouraged flights of fancy about what the natural sciences can discover about the world. It seems easy to draw connections between developments in cosmology concerning the beginning of the universe and theological reflections about creation. Nevertheless, we ought to be alert to what it is that cosmology explains, or seeks to explain, and what creation means. What can cosmologists tell us about the "mystery of the creation of the universe"? An answer to this question requires us to be clear about the explanatory domains of the natural sciences, philosophy, and theology. As early as 1988, in the foreword to Stephen Hawking's *A Brief History of Time*, Carl Sagan reached the conclusion that Hawking's cosmological model, which denied a beginning to the universe, "left nothing for a Creator to do" (Hawking 1988). Theories concerning what happened "before the Big Bang" as well as those which speak of an endless series of big bangs are often attractive because they too deny a fundamental beginning to the universe and thus appear to make a Creator irrelevant. In *The Grand Design* (Hawking and Mlodinow 2010a), published in September 2010, Hawking and his co-author, Leonard Mlodinow, make the same point. Just as the universe has no edge, so there is no boundary, no beginning to time. Therefore to ask what happened before the beginning—or even at the beginning—would be meaningless.

> In the early universe – when the universe was small enough to be governed by both general relativity and quantum theory – there were effectively four dimensions of space and none of time. That means that when we speak of the beginning of the universe, we are skirting the subtle issue that as we look backward toward the very early universe, time as we know it does not exist! We must accept that our usual ideas of space and time do not apply to the very early universe. That is beyond our experience, but not beyond our imagination (Hawking and Mlodinow 2010b).

Ultimately, they claim: "Spontaneous creation is the reason there is something rather than nothing, why the universe exists, why we exist. It is not necessary to invoke God . . . to set the universe going" (Hawking and Mlodinow 2010c).

Citing a version of contemporary string theory, known as M-theory, they tell us that the creation of a great many universes out of nothing "does not require the intervention of some supernatural being or god." Rather, these multiple universes "arise naturally from physical law" (Hawking and Mlodinow 2010d). Foundational questions about the nature of existence that have intrigued philosophers for millennia are, so they claim, now the province of science, and "philosophy is dead" (Hawking and Mlodinow 2010e). Theology, if mentioned at all, is simply dismissed as irrelevant.[5] The new book has fewer than 200 pages, divided into eight chapters, each with a suggestive title such as: The Mystery of Being; What Is Reality?; Choosing Our Universe; The Apparent Miracle; and culminating in The Grand Design. The principal argument they offer is that once we recognize that our universe is but one of an almost infinite number of universes then we do not need a special explanation—a Grand Designer—for the very precise initial conditions that account for life and our existence. As they say, "just as Darwin . . . explained how the apparently miraculous design of living forms could appear without intervention by a supreme being, the multiverse concept can explain the fine-tuning of physical law without the need for a benevolent creator who made the universe for our benefit."[6] But, the Grand Designer rejected by Hawking is not the Creator, at least not the Creator which traditional philosophy and theology affirms.

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[5] This was Hawking's answer to a query about theology in a television interview in the United States [The Larry King Show on CNN], 10 September 2010.

[6] Hawking and Mlodinow, 165. "Bodies such as stars or black holes cannot just appear out of nothing. But a whole universe can. Because gravity shapes space and time, it allows space-time to be locally stable but globally unstable. On the scale of the entire universe, the positive energy of matter *can* be balanced by the negative gravitational energy, and so there is no restriction on the creation of whole universes. Because there is a law like gravity, the universe can and will create itself from nothing." Hawking and Mlodinow, p. 180. "The ultimate theory must be consistent and must predict finite results for quantities that we can measure. We've seen that there must be a law like gravity, and for a theory of gravity to predict finite quantities, the theory must have what is called supersymmetry between the forces of nature and the matter on which they act. M-theory is the most general supersymmetric theory of gravity. For these reasons M-theory is the only complete theory of the Universe. If it is finite – and this has yet to be proved – it will be a model of a universe that creates itself." pp. 180–181.

Hawking's work is part of a larger context of speculations which have intrigued cosmologists. Christopher Isham wrote in 1993 that, with respect to the quantum origination of the universe, the central theoretical question is "whether this coming into being of the universe can be explained, or at least described, using the methods of theoretical physics" (Isham 1993). Since current theories of the quantum origination of the universe take seriously that there is some real sense in which the universe "began" around 14 billion years ago, the challenge is to ascribe scientific meaning to such an event and, in particular, to the associated concept of the beginning of time. According to traditional Big Bang cosmology the answer to Isham's query is "no;" but some recent research programmes have sought to discover such explanations. As we shall see, we ought to keep distinct different senses both of "beginning" and of what it means "to come to be."

Alexander Vilenkin developed a variation of an inflationary model of the expanding universe which accounts for the birth of the universe "by quantum tunneling from nothing." "Nothing," for Vilenkin, is a "state with no classical space-time … the realm of unrestrained quantum gravity; it is a rather bizarre state in which all our basic notions of space, time, energy, entropy, etc. lose their meaning" (Vilenkin 1983). Describing these speculations in his book, *The Inflationary Universe*, Alan Guth appropriates traditional theological terminology in a chapter called: "A Universe *ex nihilo*." His analysis involves complex speculations about "gravitational potential energy" stored in "gravitational fields." But what I wish to point out is the striking conclusion he draws: "The universe could have evolved from absolutely nothing in a manner consistent with all known conservation [of mass/energy] laws. While no detailed scientific theory of creation is known, the possibility of developing such a theory now appears open" (Guth 1997).

Andrei Linde, speculating on what he admits is a bizarre question—what happened before the Big Bang—has developed a theory of "eternal inflation," according to which what we know as the Big Bang is only one of many in a chain of big bangs by which "the universe endlessly reproduces and reinvents itself." According to Linde, "our universe" began as a bubble that ballooned out of the space-time of a pre-existing universe. He thinks that it makes little sense to search for some "original bubble."[7] Lee Smolin has spoken of a whole chain of universes which develop according to a theory of "cosmological natural selection," so that "our universe forms part of an endless chain of self-reproducing universes whose physical laws evolve as they are passed along." For Smolin, "the laws of physics in this universe (or universes) are less like commandments from God and more like the zoning regulations promulgated by some fractious city council, ever susceptible to amendment and compromise." Smolin thinks that the universe is like a city, "an endless negotiation, an endless construction of the new out of the old. . . ..

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[7] Quoted in Dennis Overbye, "Before the Big Bang, There Was … What?" *The New York Times*, 22 May 2001. Overbye offers an excellent *tour d'horizon* of the then current cosmological speculations: from quantum tunneling from nothing, to eternal inflation, to string theory and multiple universes, to Neil Turok's "ekpyrotic" universe [from "ekpyrosis," which denotes the fiery death and rebirth of the world in Stoic philosophy], to Linde's modification, called the "pyrotechnic universe."

No one made the city. There is no city-maker, as there is no clockmaker. If a city can make itself without a maker, why cannot the same be true of the universe?" Each black hole, just like the black hole in which the Big Bang occurred, begets a new universe which expands, evolves, and eventually creates new black holes which spawn new universes: "... over many cycles a kind of Darwinian pressure would encourage the formation of universes whose physics favored black holes, since universes that did not make black holes would have no progeny."[8]

The desire in some cosmological circles to get rid of the troubling singularity of the Big Bang itself can be seen in the work of Neil Turok. Using a development of superstring theory, Turok offers a model in which the birth of the present universe is the result of a collision of enormous four-dimensional membranes. Turok's universe, like the one described by Linde, is an endless cycle of universes in collision with other universes. Turok notes that his model is, as he says, "philosophically very appealing.... Time is infinite, space is infinite, and they have always been here.... It is exactly what the steady-state-universe people wanted. Our model realizes their goal."[9] As Turok points out, many cosmologists in the 1950s and early 1960s were reluctant to accept the Big Bang theory because if the universe were thought to have such a beginning then the initial conditions would have to be in some sense accidental, that is, not included within the explanatory framework of the natural sciences. The initial conditions, thus, would have to have a source beyond the explanatory domain of the natural sciences: such conditions might seem to offer evidence for the existence of God. Turok is critical of the linear, inflationary model of the development of the universe and argues that the cyclical model he sets forth fits as well with all the evidence. Turok presented his cosmological speculations in a book written with Paul Steinhardt of Princeton University, the title of which is suggestive: *The Endless Universe: Beyond the Big Bang* (2007). As we have seen, for them, "the big bang [now in lower-case letters] is not the beginning of space and time, but, rather, an event that is, in principle, fully describable using physical laws. Nor does the big bang happen only once. Instead the universe undergoes cycles of evolution."[10]

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[8] Quoted in an interview in Dennis Overbye, "The Cosmos According to Darwin," *The New York Times Magazine*, 13 July 1997, 26 and 27.

[9] *Science* (26 April 2002).

[10] *The Endless Universe* (New York: Doubleday, 2007), p. 8. "Although the cyclical model does not require a beginning of time, it is compatible with having one. One could imagine the sudden creation from nothing of two infinitesimal spherical branes arranged like two concentric soap bubbles, both of which undergo continuous expansion as well as regular collisions with each other under the influence of an interbrane force. Both brane bubbles would grow enormously with every new cosmic cycle. After several cycles of expansion, the pair of branes would appear very flat and very parallel to any observer like us, with access to only a limited region of space. For such an observer, there would be little difference between this universe with a beginning, and a universe in which two flat, parallel branes had been colliding forever into the past." pp. 165–166. Note that Turok and Steinhardt identify "creation from nothing" with a beginning of time – and they admit this as theoretically possible, even though they prefer their model. Thus, they would have to admit that cosmology itself could not determine whether or not there was a beginning of time. As with so many others, on all sides of the debate, they treat creation and having a temporal beginning as necessarily linked.

But others have embraced traditional Big Bang cosmology, which seems to affirm an absolute beginning to the universe, as providing scientific support for, if not actual confirmation of, the Genesis account of creation. I have already mentioned Pope Pius XII's remark in 1951 that this cosmology offered support for what the opening of Genesis revealed. The argument is that an initial singularity, outside the categories of space and time, points to a supernatural cause of the beginning of the universe. The relationship between the temporal finitude of the universe and the conclusion that it is created can be found in the work of Robert J. Spitzer. In his recent book, *New Proofs for the Existence of God: Contributions of Contemporary Physics and Philosophy*, Spitzer claims that modern physics reinforces the mediaeval Kalam cosmological argument and shows us that the past time of the universe is finite.[11] William Lane Craig had already advanced some of these arguments.

In a way, the debate is about whether or not cosmology discloses a beginning of the universe: Hawking denies the intelligibility of such a notion and others argue for variations of an eternal universe. William Lane Craig and Robert Spitzer claim that cosmology does indeed point to a beginning. The debate, framed in such terms about a beginning, leads the exponents either to reject or to embrace the idea of creation. Despite fundamental differences as to what contemporary cosmology tells us, all these views tend to identify what it means for the universe to be created with its having a temporal beginning. As we shall see, this emphasis on beginnings leads to confusion about creation.

News of the experiments to be conducted at CERN and the publication of books such as that of Hawking and Mlodinow (and more recently Brian Greene's *The Hidden Reality: Parallel Universes and the Deep Laws of the Cosmos* (Greene 2011), which describes several (9) models of different multiverse scenarios and Roger Penrose's *Cycles of Time* (Penrose 2011)), all provide renewed interest in questions concerning the relationship between cosmology and creation, but, unfortunately, much of the discussion contains old errors concerning what cosmology, philosophy, and theology tell us about the world and its origin. This is true even when more careful commentators remind us that the Large Hadron Collider can offer at best only insights about the very early history of the universe, shortly after the Big Bang.

The distance between minute fractions of a second after the Big Bang and creation is, in a sense, infinite. We do not get closer to creation by getting closer

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[11] Robert J. Spitzer, *New Proofs for the Existence of God: Contributions of Contemporary Physics and Philosophy* (Grand Rapids, Michigan: Eerdmans, 2010), especially chapter 5 (pp. 177–215). Spitzer argues that developments in relativity theory and quantum mechanics have led to an ontological understanding of time quite different from that found in Aristotle and Thomas Aquinas (for whom time is viewed as the measure of motion). Combining what he terms this new conception of time with arguments about infinity informed by the German mathematician David Hilbert (1862–1943), Spitzer thinks that he can show the impossibility of the "past infinity of time," thus proving that time must have a beginning, and hence must have a Creator. With respect to this topic, Spitzer notes the importance of William Lane Craig's *The Kalam Cosmological Argument* (New York: Barnes and Noble, 1979).

to the Big Bang. Since, as we shall see, creation is not really an event at all, it is not within the explanatory domain of cosmology; it is a subject for metaphysics and theology. Similarly, the "nothing" in some cosmological models that speak of the Big Bang in terms of "quantum tunnelling from nothing," is not the nothing referred to in the traditional sense of creation out of nothing. The "nothing" in cosmological reflections may very well be nothing like our present universe, but it is not the absolute nothing central to what it means to create; it is only that about which the theories say nothing.

One part of the confusion between creation and the natural sciences has its source in a broad commitment to a kind of "totalizing naturalism." This is the view that the universe and the processes within it need no explanation beyond the categories of the natural sciences. The claim is that contemporary science is fully sufficient, at least in principle, to account for all that needs to be accounted for in the universe. Whether we speak of explanations of the Big Bang itself (such as quantum tunneling from nothing) or of some version of a multiverse hypothesis, or of self-organizing principles in biological change, the conclusion which seems inescapable to many is that there is no need to appeal to a creator, that is, to any cause which is outside the natural order. Here is how one cosmologist, Lee Smolin, has put it:

> We humans are the species that makes things. So when we find something that appears to be beautifully and intricately structured, our almost instinctive response is to ask, 'Who made that?' The most important lesson to be learned if we are to prepare ourselves to approach the universe scientifically is that this is not the right question to ask. It is true that the universe is as beautiful as it is intrinsically structured. But it cannot have been made by anything that exists outside of it, for by definition the universe is all there is, and there can be nothing outside it. And, by definition, neither can there have been anything before the universe that caused it, for if anything existed it must have been part of the universe. So the first principle of cosmology must be 'There is nothing outside the universe.' . . .. The first principle means that we take the universe to be, by definition, a closed system. It means that the explanation for anything in the universe can involve only other things that also exist in the universe (Smolin 2001).

Thus, whatever kind of "creation" science can disclose, or be used to deny, through particle accelerators or elaborate mathematical models, it would be a scientific account of origins employing, as Smolin would say, principles drawn from within the universe. But such a conception of "creation" is not what philosophers and theologians mean when they speak of creation.

Confusions concerning creation and cosmology, as I have suggested, run the gamut from denials of creation because the universe is conceived as having no beginning, to explanations of a beginning in exclusively scientific terms which avoid any appeal to a Creator, to opposing claims that the Big Bang itself offers a kind of scientific warrant for belief in God's creation of the universe. Contrary to all these claims, we need to recognize that creation is a metaphysical and theological affirmation that all that is, in whatever way or ways it is, depends upon God as cause. The natural sciences have as their subject the world of changing things: from subatomic particles to acorns to galaxies. Whenever there is a change there must be something that changes. Whether these changes are biological or cosmological, without beginning or end, or temporally finite, they remain processes. Creation, on the other hand, is the radical causing of the whole existence of whatever exists. Creation is not a change. To cause completely something to exist is not to produce a change in something, is not to work on or with some existing material. When God's creative act is said to be "out of nothing," what is meant is that God does not use anything in creating all that is: it does not mean that there is a change from "nothing" to "something." Cosmology and all the other natural sciences offer accounts of change; they do not address the metaphysical and theological questions of creation; they do not speak to why there is something rather than nothing. It is a mistake to use arguments in the natural sciences to deny creation. It is also a mistake to appeal to cosmology as a confirmation of creation. Reason (as well as faith) can lead to knowledge of the Creator, but the path is in metaphysics not in the natural sciences. Discussions of creation are different from arguments from order and design to a source of order and design. Similarly, discussions about the fine-tuning of the initial conditions of the universe do not directly concern the topic of creation; thus whether or not multiverse theories do away with the need to explain such fine-tuning (as, for example, Hawking claims) they do not offer a commentary on creation. Creation, as we have seen, provides an explanation of why things exist at all.

To avoid further confusion, we need also to recognize different senses of how we use the term "to create." We often speak of human creations, especially with respect to the production of works of art, music, and literature. What it means for God to create is radically different from any kind of human making. When human beings make things they work with already existing material to produce something new. The human act of creating is not the complete cause of what is produced; but God's creative act is the complete cause of what is produced; this sense of being the complete cause is captured in the expression "out of nothing." To be such a complete cause of all that is requires an infinite power, and no creature, no human being, possesses such infinite power. God wills things to be and thus they are. We should remember that to say that God is the complete cause of all that is does not negate the role of other causes that are part of the created natural order. Creatures, both animate and inanimate, are real causes of the wide array of changes that occur in the world, but God alone is the universal cause of being as such. God's causality is so different from the causality of creatures that there is no competition between the two, that is, we do not need to limit, as it were, God's causality to make room for the causality of creatures. God causes creatures to be causes.

Already in the thirteenth century the groundwork was set for the fundamental understanding of creation and its relationship to the natural sciences. Working within the context of Aristotelian science and aided by the insights of Muslim and Jewish thinkers, as well as his Christian predecessors, Thomas Aquinas provided an analysis of creation and science which remains true. As Thomas wrote: "Over and above the mode of becoming by which something comes to be through change or motion, there must be a mode of becoming or origin of things without any mutation or motion, through the influx of being."[12] Thomas drew heavily upon the analysis of Avicenna, who carefully distinguished between the ways in which metaphysicians and natural philosophers discuss agent (or efficient) cause. As Avicenna said: "... the metaphysicians do not intend by the agent the

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[12] Thomas Aquinas, *On Separated Substances*, c.9.

principle of movement only, as do the natural philosophers, but also the principle of existence and that which bestows existence, such as the creator of the world."[13] Avicenna distinguished between two kinds of agent causes: an agent that acts through motion, and a divine agent which is "a giver of being."[14] Such an agent needs only the power to create and nothing else. On the basis of the ontological distinction between essence and existence, Avicenna argued that all beings other than God (in whom this distinction disappears) require a cause in order to exist.[15] Since existence is not part of the essence of things, it needs to be explained by a cause extrinsic to the thing that exists; and, ultimately, there must be an Uncaused Cause.[16] David Burrell has emphasized the importance of Thomas' reading of

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[13] *al-Shifa': al-Ilahiyyat*, translated in Georges Anawati, *La Métaphysique du Shifa'* (Paris: J. Vrin, 1978), VI.1.

[14] Avicenna argues in his *Liber de philosophia prima* that the world is an ensemble of possible beings, which of themselves have no existence, but do in fact exist. They exist only because they are the emanated effect of the efficient causality of one necessary being, which is perfect and lacks nothing. Possible beings in this emanated universe are arranged hierarchically, ordered in a causal chain under the one necessary being, first cause of all. From necessary being in its eternal productive act only one effect can come forth, the first immaterial being or intelligence. The rest of the chain of being continues with each intelligence eternally causing the being and nature of each succeeding intelligence, up to the tenth intelligence, the Giver-of-Forms, from which issues immediately the material universe, matter and form. For Avicenna, emanation proceeds through intermediaries.

[15] Avicenna recognized the need to affirm both the contingency of the created order and, yet, a necessity in it so that there can be a science of things. As L. Goodman puts it: Avicenna "fused the Aristotelian metaphysics of self-sufficiency with the monotheistic metaphysics of contingency.... The key to [his] synthesis of contingency with the metaphysics of necessity lies in the single phrase: *considered in itself*. Considered in itself, each effect is radically contingent. It does not contain the conditions of its own existence: and considered in itself, it need not exist.... But considered in relation to its causes, not as something that in the abstract might never have existed, but as something concretely given before us ... considered in relation to its causes, this object must exist in the very Aristotelian sense that it does exist, and must have the nature that it has in that its causes gave it that nature." L. Goodman, *Avicenna* (London: Routledge, 1994). 63, pp. 66–67.

[16] Charles Kahn emphasizes the importance of Islamic philosophy, and especially Avicenna, in the development of a really new notion of radical contingency: "My general view of the historical development is that existence in the modern sense becomes a central concept in philosophy only in the period when Greek ontology is radically revised in light of the metaphysics of creation: that is to say, under the influence of biblical religion. As far as I can see, this development did not take place with Augustine or with the Greek Church Fathers, who remained under the sway of classical ontology. The new metaphysics seems to have taken place in Islamic philosophy, in the form of a *radical* distinction between necessary and contingent existence: between the existence of God, on the one hand, and that of the created world, on the other. The old Platonic contrast between Being and Becoming, between the eternal and the perishable (or, in Aristotelian terms, between the necessary and the contingent), now gets reformulated in such a way that for the contingent being of the created world (which was originally present only as a 'possibility' in the divine mind) the property of 'real existence' emerges as a new attribute or "accident,' a kind of added benefit bestowed by God upon possible beings in the act of creation. What is new here is the notion of radical contingency, not simply the old Aristotelian idea that many things might be other than they in fact are—that many events might turn out otherwise—but that the whole world of nature might not have been created at all: that it might not have *existed*." Charles Kahn, "Why Existence Does not Emerge as a Distinct Concept in Greek Philosophy," in Parviz Morewedge (ed.), *Philosophies of Existence, Ancient and Medieval* (New York: Fordham University Press, 1982), pp. 7–17, at pp. 7–8.

the *Liber de causis* in the development of his understanding of the Creator as cause-of-being (Burrell 2003). Although Thomas will come to differentiate his own position on essence and existence from that of Avicenna,[17] he too thought that the science of metaphysics is able to demonstrate that all things depend upon God as the cause of their existence. Unlike many of his contemporaries, Thomas did not restrict his analysis of creation to theology, although he recognized that a full understanding of creation does include what faith discloses. His philosophical account of creation enabled him to distinguish the act of creating from any kind of change, but in such a way as to make creation—understood as the complete dependence of all that is on God—accessible to reason alone.

Creation is not essentially some distant event; rather, it is the on-going complete causing of the existence of all that is. At this very moment, were God not causing all that is to exist, there would be nothing at all. Creation concerns first of all the origin of the universe, not its temporal beginning. Indeed, it is important to recognize this distinction between origin and beginning. The former affirms the complete, continuing dependence of all that is on God as cause. Whatever is created has its origin in God. But we ought not to think that to be created must mean that whatever is created has a temporal beginning. It may very well be that the universe had a temporal beginning, as the traditional interpretation of the opening of Genesis acknowledges, but there is no contradiction in the notion of an eternal, created universe: for were the universe to be without a beginning it still would have an origin, it still would be created. This was precisely the position of Thomas Aquinas, who accepted as a matter of faith that the universe had a temporal beginning but also defended the intelligibility of a universe, created and eternal. It is the failure to recognize that to be created does not necessarily entail a temporal beginning that causes considerable confusion in contemporary debates about the implications of cosmology for arguments about whether or not the universe is created.

Thomas also thought that neither science nor philosophy could know whether the universe had a beginning.[18] He did think that metaphysics could show us that

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[17] Aquinas develops the notion of radical dependency in such a way that creaturely existence is understood not as something which happens to essence (as it does for Avicenna) but as a fundamental *relation* to the Creator as origin. “In one fell swoop, Aquinas has succeeded in restoring the primacy Aristotle intended for individual existing things, by linking them directly to their creator and by granting Avicenna’s ‘distinction’ an unequivocal ontological status. Yet as should be clear, this is more than a development of Avicenna; it is a fresh start requiring a conception of *existing* that could no longer be confused with an *accident*, and which has the capacity to link each creature to the gratuitous activity of a free creator. Only in such a way can the radical *newness* of the created universe find coherent expression, for the *existing* ‘received from God’ will be the source of all perfections and need not presume anything at all—be it matter or ‘possibles.’” David Burrell, “Aquinas and Islamic and Jewish Thinkers,” in *The Cambridge Companion to Aquinas*, edited by Norman Kretzmann and Eleonore Stump. (Cambridge University Press, 1993), pp. 60–84, at pp. 69–70.

[18] “That the world had a beginning . . . is an object of faith, but not of demonstration or science. And we do well to keep this in mind; otherwise, if we presumptuously undertake to demonstrate what is of faith, we may introduce arguments that are not strictly conclusive; and this would

the universe is created,[19] but he would have warned against those today who use Big Bang cosmology, for example, to conclude that the universe has a beginning and therefore must be created.[20] He was always alert to reject the use of bad arguments in support of what is believed. The singularity in traditional Big Bang cosmology may represent the beginning of the universe we observe, but we cannot conclude that it is the absolute beginning, the kind of beginning which would indicate creation. As some contemporary cosmologists recognize, there could very well be something before the Big Bang. Indeed, Gabriele Veneziano, a theoretical physicist at CERN and one of the fathers of string theory in the late 1960s, observes that "the pre-bang universe has become the latest frontier of cosmology."[21]

When it came to how to read the opening of Genesis, Thomas Aquinas observed that what is essential is the "fact of creation," not the "manner or mode" of the formation of the world.[22] Questions concerning order, design, and chance in nature refer to the "manner or mode" of formation of the world. Attempts in the natural sciences to explain these facets of nature do not challenge the "fact of creation." A world with a temporal beginning concerns the kind of world God has created. It may very well be easier to accept that a world which has an absolute temporal beginning is a created world, and such a world may be especially appropriate for understanding sacred history, important as it is for believers. But an eternal world, one without a beginning to time, would be no less a created world.

When Lemaître says that the question of whether the beginning of the universe to which his theory points is creation is "a philosophical question which cannot be settled by physical or astronomical considerations," he echoes, in part, Thomas' judgment that whether or not the universe has an absolute beginning cannot be determined by science. But Thomas adds that philosophy cannot make such a determination either. For Thomas, the temporal finitude of the world is exclusively

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furnish infidels with an occasion for scoffing, as they would think that we assent to truths of faith on such grounds." *Summa theologiae* I, q. 46, a. 2. [Unde mundum incoepisse est credibile, non autem demonstrabile vel scibile. Et hoc utile est ut consideretur, ne forte aliquis, quod fidei est demonstrare praesumens, rationes non necessarias inducat, quae praebeant materiam irridendi infidelibus, existimantibus nos propter huiusmodi rationes credere quae fidei sunt.] Resp: Dicendum quod mundum non semper fuisse, sola fide tenetur, et desmonstrative probari non potest. . ..

[19] The argument involves a recognition that the difference between what things are (their essences) and that they are (their existence) must ultimately be resolved in a reality (God) in whom essence and existence are identical. Thus, what it means to be God is to be, and God is the uncaused cause of all beings. One need not accept the validity of Thomas' claim to demonstrate that the universe is created in order to understand his distinction between creation and science and that "to create" is not to produce a change.

[20] "quod creationem esse non tantum fides tenet, sed etiam ratio demonstrat." *In II Sent.*, dist. 1, q. 1., a. 2. An English translation and commentary of this discussion of creation can be found in Steven E. Baldner and William E. Carroll, *Aquinas on Creation* (Toronto: Pontifical Institute of Mediaeval Studies Press, 1997).

[21] See his essay: "The Myth of the Beginning of Time," *Scientific American*, April 2004.

[22] *In II Sent.,* dist. 12, q. 1, a. 2.

a matter of revelation. It may be that Lemaître links creation and temporal beginning too closely so that he does not distinguish as clearly as Thomas does between creation understood philosophically and creation understood theologically.

Cosmological theories are easily used, or rather misused, to support or to deny creation. Each time, however, as I have suggested, "to create" has been joined inextricably to temporal finitude such that to be created necessarily means to begin to be; thus, to deny a beginning is to deny creation. It was the genius of Thomas Aquinas to distinguish between creation understood philosophically, with no reference to temporality, and creation understood theologically, which included the recognition that the universe does have an absolute temporal beginning (Baldner and Carroll 1997). Thomas' analysis of creation, and its relationship to what the natural sciences and philosophy tell us, is a good example of the importance of science and philosophy for theological reflection—indeed, of the appropriate autonomy of these disciplines in any theological view of the world. Creation understood theologically includes far more than the universe's having a temporal beginning. Trinitarian theology involves a recognition that creation is "through the Son" and is intimately connected to the drama of Fall and Redemption. For the purposes of this essay, I have limited my analysis to Thomas' philosophical account of creation since it is this account which is crucial for distinguishing creation from the explanatory categories of cosmology and the other natural sciences.

There is a wider confusion at work here as well—wider than the confusion of creation with beginnings: that is, the failure to distinguish between creation and change, and hence to recognize that the natural sciences, including cosmology, have nothing to tell us about the ultimate cause of existence of things. God's creative power is exercised throughout the entire course of cosmic history, in whatever ways that history has unfolded. No explanation of cosmological or biological change, no matter how radically random or contingent such an explanation claims to be, challenges the metaphysical account of creation, that is, of the dependence of the existence of all things upon God as cause.[23] When some thinkers deny creation on the basis of theories in the natural sciences, or use cosmology to confirm creation, or reject the conclusions of science in defense of creation, they misunderstand creation or the natural sciences, or both. The experiments that have begun at CERN may very well offer new and spectacular insights into the nature of the very early universe, but they will tell us nothing about the creation of the universe. Speculations about our universe's being but one among a vast multiverse system may appeal to the imaginations of mathematical cosmologists like Stephen Hawking, but such speculations do not call into question the fact that whatever is, in whatever way or ways it is, is caused to be by God.

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[23] See my essay, "At the Mercy of Chance? Evolution and the Catholic Tradition," *Revue des Questions Scientifiques* 177:2 (2006), pp. 179–204.

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Georges Lemaître and Stigler's Law of Eponymy

David L. Block

Abstract One of the greatest discoveries of modern times is that of the expanding Universe, almost invariably attributed to Hubble (Proceedings of the National Academy of Sciences of the United States of America 15:168, 1929). What is not widely known is that the original treatise by Lemaître (Annales de la Société Scientifique de Bruxelles, Sèrie A 47:49, 1927) contained a rich fusion of both theory and of observation. The French paper was meticulously censored when published in English: all discussions of radial velocities and distances, and the very first empirical determination of H_0, were suppressed. Stigler's law of eponymy is yet again affirmed: no scientific discovery is named after its original discoverer (Merton, American Sociological Review 22(6):635, 1957). An appeal is made for a Lemaître Telescope naming opportunity, to honour the discoverer of the expanding universe.

Lemaître (1927): A Theoretical Paper?

The title of the original 1927 paper indicates to the reader that the content will be a fusion of both theory *and of observation*: "Un univers homogène de masse constante et de rayon croissant, rendant compte de la vitesse radiale des nébuleuses extra-galactiques." Which translates into English thus: "A homogeneous universe of constant mass and increasing radius accounting for the radial velocity of extra-galactic nebulae".

Lemaître spent the years 1924–1925 at the Harvard College Observatory. He had an excellent foundation in observational astronomy, writing about terms such as the effective temperatures of stars, trigonometric parallaxes, moving-cluster parallaxes, absolute bolometric magnitudes, dwarf branch stars, giant branch stars, and the like.

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Astrophysics and Space Science Library 395,
DOI 10.1007/978-3-642-32254-9_8,

To speak of Lemaître (1927) as a most remarkable and absolutely brilliant theoretical paper only, is a grave injustice to the very title. Not only does Lemaître derive a linear relationship between the radial velocities of galaxies and their distances in the above paper, but he is eager to determine the rate at which the universe expands. Lemaître (1927) carefully uses the radial velocities of 42 extra-galactic nebulae tabulated by Strömberg (1925), and he converts apparent magnitudes m into distance [$\log r = 0.2\ m + 4.04$] following Hubble (1926). The actual value which Lemaître obtains in 1927 for the rate of expansion of the Universe is 625 km s^{-1} Mpc^{-1}; 575 km s^{-1} Mpc^{-1} with different weighting factors (Fig. 1).

Jaki (1974) elaborates: "Lemaître's treatment of the problem could hardly be more impressive with respect to specific results . . . a formula and a table of values for the redshift of receding galaxies in fine agreement with the actually observed data . . ."

When the Royal Astronomical Society decided to publish an English translation in 1931 from the journal Annales de la Société Scientifique de Bruxelles, a most dramatic censorship of the first empirical determination of H_0 occurred (Fig. 2). A meticulously researched book (with a foreword by the late Allan Sandage) has been published on this precise theme. It is entitled *Discovering the Expanding Universe* (Nussbaumer and Bieri 2009). Professor Nussbaumer graciously sent me a copy of the original French paper in 2009, and the sectors censored out in the English translation appear in Fig. 2. Equation (24) holds the key. In an independent study, Sidney van den Bergh (2011) affirms that the suppressions in Eq. (24) were intentional.

It would be historically accurate to say that the *testing* of a linear velocity-distance relation is due to the meticulous observations by Hubble and Humason in subsequent years, but not the *formulation* of this relation, as seen in the complete original equation (24).

Priorities in Scientific Discovery

And now, I give some insight into the mindset of Edwin Hubble. He was fiercely territorial, as we see in a letter from Hubble to de Sitter, dated 21 August 1930, wherein Hubble writes: "I consider the velocity-distance relation, its *formulation*, testing and confirmation, as a Mount Wilson contribution and I am deeply concerned in its recognition as such" (emphasis added).

Nussbaumer and Bieri (2009) respond as follows:

> . . . the *formulation* and its central place in cosmology was first given by Lemaître . . . there is no justification to glorify Hubble's publication of 1929 [as the] original discovery of the linear velocity- distance relationship . . . (emphasis, mine).

Lemaître was eclipsed. Multitudes of textbooks proclaim Hubble as the discoverer of the expanding universe. But herein lies a repeated pattern. In 1927,

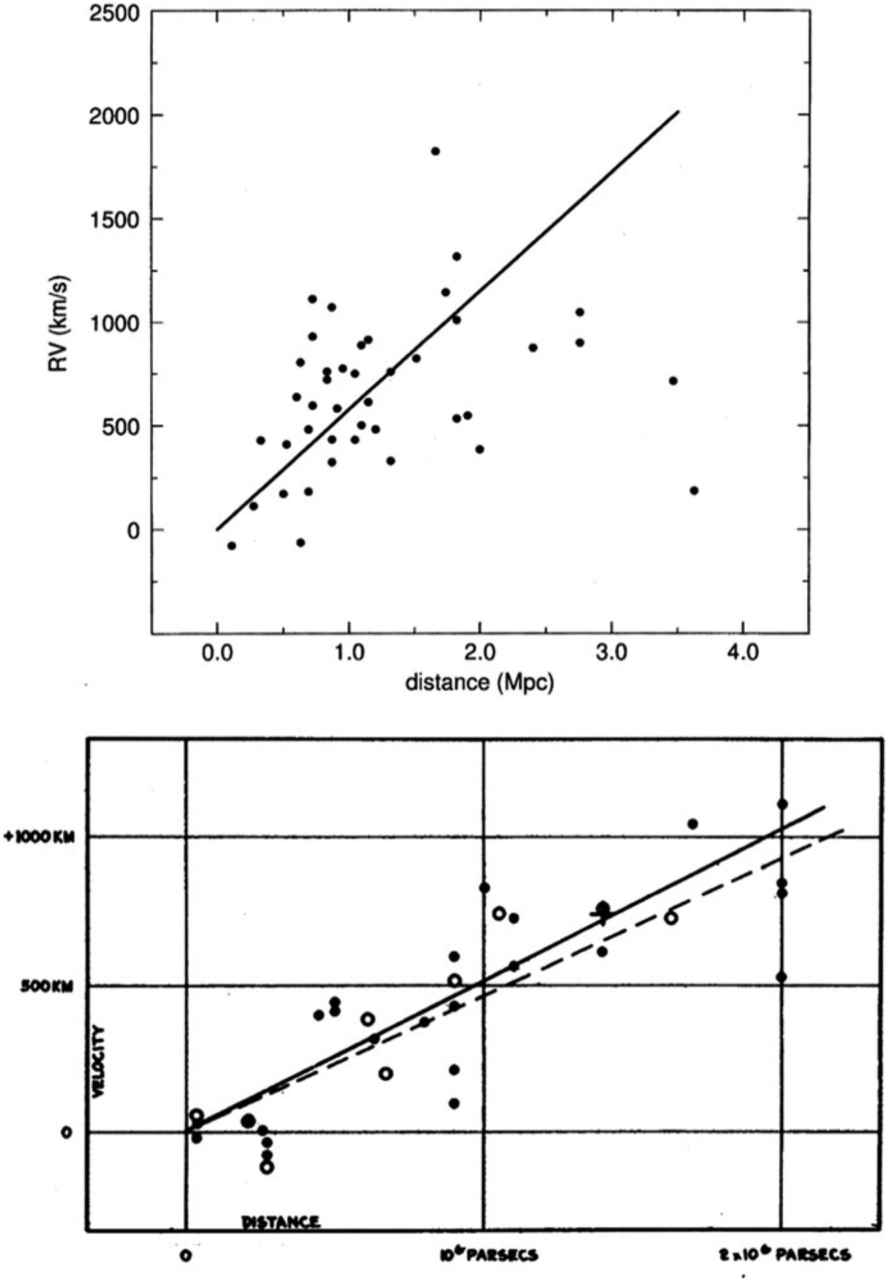
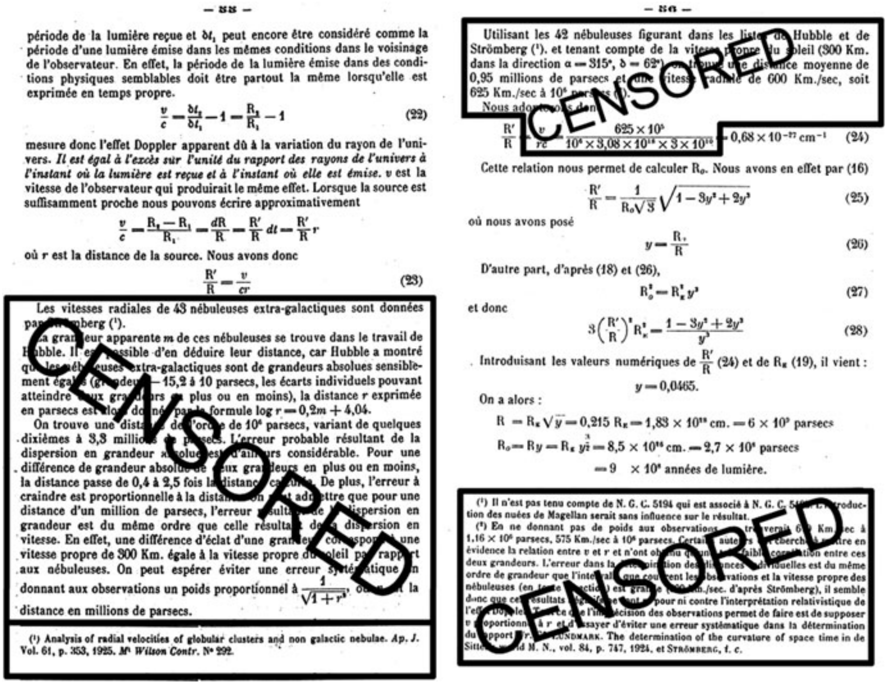


FIGURE 1

Fig. 1 *Upper panel*: The data used by Lemaître (1927) to yield the first empirical value of the rate of expansion of the Universe in which v/r is predicted to be constant (see Eq. 24 in Fig. 2). Lemaître derived values of 625 km s^{-1} Mpc^{-1} and 575 km s^{-1} Mpc^{-1}. The *solid line in the top panel* has a slope of 575 km s^{-1} Mpc^{-1} and is reconstructed by H. Duerbeck. *Lower panel*: the radial velocity–distance diagram published by Hubble, 2 years later, in 1929, with best slope of 530 km s^{-1} Mpc^{-1} (*Top panel*: Courtesy H. Duerbeck)



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période de la lumière reçue et δt_1 peut encore être considéré comme la période d'une lumière émise dans les mêmes conditions dans le voisinage de l'observateur. En effet, la période de la lumière émise dans des conditions physiques semblables doit être partout la même lorsqu'elle est exprimée en temps propre.

$$\frac{v}{c} = \frac{\delta t_2}{\delta t_1} - 1 = \frac{R_2}{R_1} - 1 \qquad (22)$$

mesure donc l'effet Doppler apparent dû à la variation du rayon de l'univers. *Il est égal à l'excès sur l'unité du rapport des rayons de l'univers à l'instant où la lumière est reçue et à l'instant où elle est émise.* v est la vitesse de l'observateur qui produirait le même effet. Lorsque la source est suffisamment proche nous pouvons écrire approximativement

$$\frac{v}{c} = \frac{R_2 - R_1}{R_1} = \frac{dR}{R} = \frac{R'}{R}\,dt = \frac{R'}{R}\,r$$

où r est la distance de la source. Nous avons donc

$$\frac{R'}{R} = \frac{v}{cr} \qquad (23)$$

Les vitesses radiales de 43 nébuleuses extra-galactiques sont données pa[illegible]berg (1).

[illegible]a gran[illegible]eur apparente m de ces nébuleuses se trouve dans le travail de H[illegible]bble. Il e[illegible]ssible d'en déduire leur distance, car Hubble a montré qu[illegible] les [illegible]éb[illegible]euses extra-galactiques sont de grandeurs absolues sensiblement éga[illegible]s (gr[illegible]ndeu[illegible] — 15,2 à 10 parsecs, les écarts individuels pouvant atteindre [illegible]ux gra[illegible]rs [illegible] plus ou en moins), la distance r exprimée en parsecs est [illegible] do[illegible]né[illegible] pa[illegible] formule $\log r = 0{,}2m + 4{,}04$.

On trouve une dista[illegible] de[illegible]'or[illegible]e de 10^6 parsecs, variant de quelques dixièmes à 3,3 millio[illegible] [illegible]se[illegible]s. L'erreur probable résultant de la dispersion en grandeur [illegible]olue[illegible] est d'ai[illegible]urs considérable. Pour une différence de grandeur absolu[illegible] [illegible]ux gra[illegible]deurs en plus ou en moins, la distance passe de 0,4 à 2,5 fois la distance ca[illegible]. De plus, l'erreur à craindre est proportionnelle à la dista[illegible]on [illegible] admettre que pour une distance d'un million de parsecs, l'erreur [illegible]sult[illegible]e [illegible]dispersion en grandeur est du même ordre que celle résulta[illegible] de [illegible] dispersion en vitesse. En effet, une différence d'éclat d'une grande[illegible] co[illegible]spo[illegible] une vitesse propre de 300 Km. égale à la vitesse propre d[illegible]oleil pa[illegible] rapp[illegible]t aux nébuleuses. On peut espérer éviter une erreur s[illegible]té[illegible]atique [illegible]n donnant aux observations un poids proportionnel à $\frac{1}{\sqrt{1+r^2}}$, o[illegible] la distance en millions de parsecs.

(1) Analysis of radial velocities of globular clusters and non galactic nebulae. *Ap. J.* Vol. 61, p. 353, 1925. *Mt Wilson Contr.* N° 292.

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Utilisant les 42 nébuleuses figurant dans les liste[illegible] d[illegible] Hubble et de Strömberg (1). et tenant compte de la vite[illegible] p[illegible] [illegible]u [illegible]oleil (300 Km. dans la direction $\alpha = 315°$, $\delta = 62°$) [illegible] u[illegible]e dis[illegible]nce moyenne de 0,95 millions de parsecs et [illegible] vitess[illegible] radi[illegible]e de 600 Km./sec, soit 625 Km./sec à 10^6 [illegible] (2).

Nous ado[illegible] don[illegible]

$$\frac{R'}{R} = \frac{v}{rc} = \frac{625\times10^5}{10^6\times3{,}08\times10^{18}\times3\times10^{10}} = 0{,}68\times10^{-27}\ \text{cm}^{-1} \qquad (24)$$

Cette relation nous permet de calculer R_0. Nous avons en effet par (16)

$$\frac{R'}{R} = \frac{1}{R_0\sqrt{3}}\sqrt{1-3y^2+2y^3} \qquad (25)$$

où nous avons posé

$$y = \frac{R_0}{R} \qquad (26)$$

D'autre part, d'après (18) et (26),

$$R_0^2 = R_E^2\,y^3 \qquad (27)$$

et donc

$$3\left(\frac{R'}{R}\right)^2 R_E^2 = \frac{1-3y^2+2y^3}{y^3} \qquad (28)$$

Introduisant les valeurs numériques de $\frac{R'}{R}$ (24) et de R_E (19), il vient :

$$y = 0{,}0465.$$

On a alors :

$$R = R_E\sqrt{y} = 0{,}215\,R_E = 1{,}83\times10^{28}\ \text{cm.} = 6\times10^9\ \text{parsecs}$$
$$R_0 = Ry = R_E\,y^{\frac{3}{2}} = 8{,}5\times10^{26}\ \text{cm.} = 2{,}7\times10^8\ \text{parsecs}$$
$$= 9 \times10^8\ \text{années de lumière.}$$

(1) Il n'est pas tenu compte de N. G. C. 5194 qui est associé à N. G. C. 5[illegible] [illegible]roduction des nuées de Magellan serait sans influence sur le résultat.

(2) En ne donnant pas de poids aux observations [illegible] tr[illegible]verait 6[illegible] Km[illegible]ec à $1{,}16\times10^6$ parsecs, 575 Km./sec à 10^6 parsecs. Certai[illegible] aute[illegible]s [illegible]cherch[illegible] [illegible]re en évidence la relation entre v et r et n'ont ob[illegible]nu q[illegible]un[illegible] faibl[illegible] corr[illegible]tion entre ces deux grandeurs. L'erreur dans la [illegible]in[illegible]tion de[illegible] di[illegible]nces [illegible]dividuelles est du même ordre de grandeur que l'inte[illegible]valle que couvrent les [illegible]bs[illegible]vations et la vitesse propre des nébuleuses (en [illegible] [illegible]ctio[illegible]) est gra[illegible]e ([illegible]m./sec. d'après Strömberg), il semble donc que ce[illegible] résultats [illegible] pour ni contre l'interprétation relativistique de l'ef[illegible] Dop[illegible]le[illegible] [illegible]ce q[illegible]e l'im[illegible]écision des observations permet de faire est de supposer v [illegible]oportionn[illegible] à r et d'[illegible]ssayer d'éviter une erreur systématique dans la détermination du [illegible]pport [illegible]. [illegible]UNDMARK. The determination of the curvature of space time in de Sitte[illegible] [illegible]d M. N., vol. 84, p. 747, 1924, et STRÖMBERG, *l. c.*

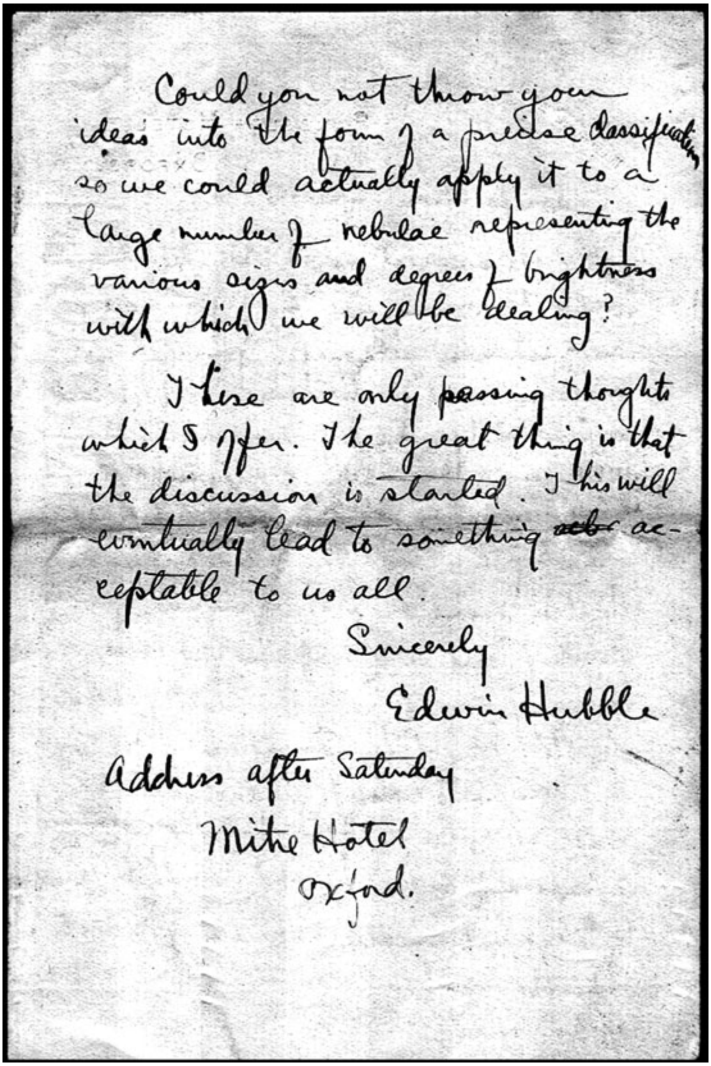
Fig. 2 Sections in *black boxes*, pertaining to the discussion and use of radial velocities of galaxies and their distances by Lemaître (1927) to provide the first empirical determination of H_0 were meticulously and ingeniously suppressed or censored in the English translation. Equation (24) is absolutely crucial

Knut Lundmark penned these words, cited by Sandage (2004): "As to Hubble's way of acknowledging his predecessors I have no reason to enter upon this question here."

Is it not strange that Vesto Slipher is not referenced *at all* in Hubble's landmark paper of 1929? The vast majority of radial velocities in that paper are from Slipher. Perhaps an even more glaring example is Fig. 3, written to J. H. Reynolds on a visit to England.

As elucidated by Block and Freeman (2008), Reynolds rises to the Hubble request. He publishes his results in Reynolds (1920). Hubble very carefully studied this paper and actually pencilled in some handwritten comments, shown to me by the late Allan Sandage. (For example, next to each of the Reynolds class II, III and IV are the Sa, Sb and Sc notations penciled in by Hubble. Dr. Sandage furthermore affirmed to me that the correspondence between Reynolds types and Hubble types is "one-to-one"). Hubble (1926) appeared in print 6 years after Reynolds – with no reference to Reynolds (1920). Was Lundmark correct?

In the English speaking world, a total eclipse fell on the remarkable astronomical insight of Lemaître (Kragh and Smith 2003). The translator has been demonstrated to be Lemaître himself (see below my Note Added in Proof). What an intriguing



Could you not throw your ideas into the form of a precise classification so we could actually apply it to a large number of nebulae representing the various sizes and degrees of brightness with which we will be dealing?

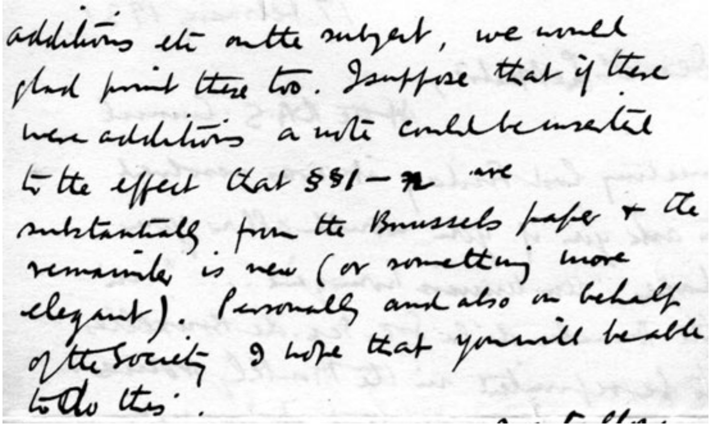
These are only passing thoughts which I offer. The great thing is that the discussion is started. This will eventually lead to something ~~[illegible]~~ acceptable to us all.

Sincerely
Edwin Hubble

Address after Saturday
Mitre Hotel
Oxford.

Fig. 3 Hubble requests the following from J. H. Reynolds: "Could you not throw your ideas into the form of a precise classification so we could actually apply it to a large number of nebulae representing the various sizes and degrees of brightness with which we will be dealing?" The letter is believed to have been written in 1919, a year in which Hubble is recorded to have dined in England. This letter was first reproduced in Block and Freeman (2008). The original is in the archives of the Royal Astronomical Society of London

proof of Stigler's Law of Eponymy; Lemaître was, through his own actions, robbed of being attributed with one of the greatest discoveries in astronomy of all time. There are myriads of speculations as to why Lemaître decided to omit his empirical computation of the rate of expansion of the universe from the English



additions etc on the subject, we would
glad print these too. I suppose that if there
were additions a note could be inserted
to the effect that §§1–72 are
substantially from the Brussels paper + the
remainder is new (or something more
elegant). Personally and also on behalf
of the Society I hope that you will be able
to do this.

Fig. 4 The alarming "presence of a censor" is seen in this February 1931 letter from WM Smart to G. Lemaître. In extremely polite terms, Lemaître is told by Smart that Hubble's observational result of 1929 is "something more elegant". The reason we know that Smart is specifically alluding to Hubble (1929) is as follows: Lemaître is given full freedom to translate his 1927 French paper, from paragraph 1 to paragraph 72 (which at first glance, appears as a symbol "n", but which is actually the number "72" as affirmed by D. Lambert – private communication). Here follows the punch-line: paragraph 73 is Lemaître's equation 24. Paragraph 73 would have been the empirical determination by Lemaître of his expansion coefficient, published in 1927 (Courtesy: Lemaître Archives, Louvain-la-Neuve)

translation of his monumental 1927 paper (Fig. 4), although historians of astronomy must never forget his *original* intentions, as recalled by Lemaître himself several years later (in 1950, see below). The history is not irrelevant.

CODA: A Lemaître ELT?

One of Galileo's masterful works was entitled *Sidereus Nuncius* – the starry messenger. The moral of the censorship (Fig. 2) is – as Martin Gaskell (private communication) poignantly reminded me – Mark chapter 4, verse 22. I allow Nussbaumer and Bieri (2009) to have the final word here regarding the legendary Georges Lemaître: "Even in his influential *The Realm of the Nebulae* published in 1936, he [Hubble] avoided any reference to Lemaître. Was he afraid that a gem might fall from his crown if people became aware of Lemaître's pioneering *fusion of observation and theory* 2 years before Hubble delivered the *confirmation*?" (italics, mine).

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Note Added in Proof – "The History of This Science Competition Is Not Irrelevant" – Reflections by Lemaître Himself, in 1950

The world has before its eyes one of the most brilliant examples of *Stigler's law of eponymy* –which in its simplest form, asserts that: no scientific discovery is named after its original discoverer. "Priorities in Scientific Discovery: A Chapter in the Sociology of Science" (Merton 1957) is of crucial importance in this context.

In a Comment published in *Nature* Mario Livio (*Nature*, 479, 171, 2011) has unearthed a letter from Lemaître to W. M. Smart (dated 9 March 1931). From that document, it is clear that Lemaître himself translated his 1927 paper into English and who also omitted his determination of the coefficient of expansion of the Universe (H_0) from values of radial velocities available as of 1927. However, in his Comment Livio omits a vital reference, namely thoughts penned by Lemaître himself in 1950 (*L'expansion de l'Univers, Bibliographie: Annales d'Astrophysique*, 13, 344):

> About my contribution of 1927, I do not want to discuss if I was a professional astronomer. I was, in any event, an IAU member (Cambridge, 1925), and I had studied astronomy for two years, a year with Eddington and another year in the U.S. observatories. I visited Slipher and Hubble and heard him in Washington, in 1925, making his memorable communication about the distance [to] the Andromeda nebula. While my Mathematics bibliography was seriously in default since I did not know the work of Friedmann, it is perfectly up to date from the astronomical point of view; I calculate [in my contribution] the coefficient of expansion (575 km per sec per megaparsecs, 625 with a questionable statistical correction). Of course, before the discovery and study of clusters of nebulae, there was no point to establish the Hubble law, but only to calculate its coefficient. *The title of my note leaves no doubt on my intentions:* A Universe with a constant mass and increasing radius as an explanation of the radial velocity of extra-galactic nebulae. *I apologize that all of this is too personal*. But, as noted by the author (p. 161) "the history of this science competition is not irrevelant" and it is useful to highlight the details to enable an exact understanding of the scope of the argument that can be drawn from this. (Emphasis added)

In 1950, Lemaître clearly did not want the rich fusion of theory and observations contained in his 1927 paper to be buried in the sands of time.

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Building on the Legacy of Georges Lemaître in Contemporary Cosmology

William R. Stoeger

Abstract For many years now theoretical cosmologists have been building on the rich legacy of Georges Lemaître's ideas and accomplishments in mathematically modelling the structure and dynamics of the universe. His recognition and careful demonstration of the viability and attractiveness of expanding models of the universe, along with his seminal idea of the "primeval atom," which would later be referred to as the Big Bang, are very well known. This has led directly, through other important contributions by Friedmann, Robertson and Walker, to the standard perfectly isotropic and spatially homogeneous (smooth) Friedmann-Lemaître-Robertson-Walker (FLRW) models of our universe. These are certainly a key part of Lemaître's legacy. After reviewing those models, we discuss another very important, but less well-known, contribution to fundamental cosmology, his general spherically symmetric cosmological solutions with pressure and a cosmological constant (vacuum energy, which is a leading candidate for dark energy). These models are generalizations of the FLRW models and, in general, are inhomogeneous. In recent years they have stimulated a great deal of research in the quest for further confirming the standard model, understanding the limitations of its perturbed versions, or possibly replacing it with something more adequate. Their importance for advancing our understanding and modelling of the universe, and the ways in which they are presently being studied and deployed, is described and discussed.

Lemaître's Legacy to Contemporary Cosmology

From the other contributions in this volume, we already know and appreciate very well Georges Lemaître's outstanding contributions to the foundations of contemporary physical cosmology. This recognition and appreciation has grown

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Astrophysics and Space Science Library 395,
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remarkably over the past 25 years. The standard perfectly isotropic and spatially homogeneous models of the universe have been often referred to as Friedmann-Robertson-Walker (FRW) models, after three of the key people who contributed to their development. Now, more commonly—especially among theoretical and mathematical cosmologists—they are called Friedmann-Lemaître-Robertson-Walker (FLRW) models, in recognition of the key role Lemaître played in their conceptualization and formulation.

Certainly, his key insight that the universe is expanding and cooling provided the essential foundations for our contemporary understanding and modelling of the universe. One very important and closely connected contribution is Lemaître's argument that it originated and expanded from an initial extremely dense quantum of mass-energy, a "primeval atom" or "cosmic egg," which predated the emergence of space and time. This, of course, is Lemaître's early version of the Big Bang (Lemaître 1931a, 1950). What strongly recommended his suggestions to Eddington, Einstein and others was his detailed demonstration that the Einstein field equations easily accommodate such expanding cosmological solutions. (Lemaître 1931b) This has led directly to the standard FLRW models, which have been so successful, and have provided the basic theoretical description of the universe. A particular FLRW model, one which is very close to spatially flat with the mass-energy density consisting of about 27 % matter (including nearly 23 % dark matter) and 73 % dark energy (with a very small amount of residual radiation energy density), has fit with great precision all the cosmologically relevant data we have so far been able to obtain—including those from the cosmic microwave background (CBR) probes, primordial-element-abundance (helium, deuterium, tritium, lithium) determinations, and redshift-distance and mass-density results. (Spergel 2003) In the next section, we shall briefly review these FLRW models and the observational results that they fit so well.

The influence of Lemaître's contributions does not stop here, however. He also solved the Einstein field equations (EFE) for much more complicated cosmologies, inhomogeneous generalizations of the FLRW models. In particular, in a remarkable paper (Lemaître 1933) he gives a detailed solution to the EFE for a spherically symmetric expanding inhomogeneous universe with both matter and vacuum energy (a cosmological constant Λ) and with pressure. This paper has been considered so important that it was reprinted in 1997 in a more accessible journal. It contains a number of cutting-edge results that anticipated much later findings.[1] The pressure-free models of this class of cosmologies are now referred to as Lemaître-Tolman-Bondi (LTB) models, and have been the subject a great deal of recent research. The full class of these general spherically symmetric models (including

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[1] Among these are: the first recognition and arguments that the Schwarzschild singularity at $r = 2\,M$ (the location of the event horizon of a Schwarzschild black hole) is not an essential singularity, hut rather a coordinate singularity; a clear definition of mass for perfect fluids in general relativity; the first instance of a proven singularity theorem in cosmology, anticipating the more detailed later formulations of Penrose and Hawking; and a discussion of the gravitational processes by which "nebulae" might be formed. (Krasiński 1997a).

those with perfect-fluid matter and radiation with pressure and pressure gradients) are often referred to as Lemaître models. In section "Beyond the Standard FLRW Model: Lemaître and LTB Models and Their Importance" we shall briefly discuss LTB models and their critical importance for making progress in cosmology. Essentially, they provide us with the simplest inhomogeneous cosmologies. Carefully studying them and their relationships with observations will enable us to either confirm the present standard model or to modify it.

In section "Recent Research on LTB and Lemaître Cosmological Models", we shall elaborate further on LTB models, both those with and those without a cosmological constant, briefly discuss some of the outstanding recent work on them, mention their generalizations (i.e., those with nonzero pressure) and some of the applications of those generalizations, and briefly discuss perturbations of LTB models. We shall also briefly describe the types of observations that will be important for testing them. Again, it is important to emphasize that, since FLRW models are a special class within the more general class of LTB models, this work may result in confirming the standard model. One of the central aims of this effort is to determine whether or not there is significant dark energy (or a nonzero). As we have already seen, present observations require dark energy for the standard concordance FLRW model, but they do not require it for some LTB models which also fit all the present data extremely well. (Clarkson and Regis 2011; Regis and Clarkson 2012) However, there are further independent data (Hellaby 2006; Araújo and Stoeger 2009a, b; Araújo and Stoeger 2010) which may eventually be able to tell us whether the best-fit LTB model needs a cosmological constant (dark energy) or not. Favorable consideration of Λ is also part of Lemaître's legacy. In a paper in P. A. Schilpp's well-known volume, *Albert Einstein: Philosopher-Scientist,* Lemaître explains its significance, and argues compellingly for its natural suitability, both from mathematical and physical points of view. (Lemaître 1949) In section "Conclusions", we offer our concluding remarks.

The Standard FLRW Models and the Observations Supporting Them

The standard FLRW models, which have been the theoretical foundation of contemporary cosmology, are special cases of the LTB models.[2] They are as LTB models, therefore, spherically symmetric, or isotropic. But they fall into the very special class of perfectly smooth spatially homogeneous LTB models. Their mass-energy density at any given time is constant, i. e., independent of spatial position.

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[2] There are some FLRW models, those for instance which describe the early radiation-dominated era of the universe, which are not—strictly speaking—special cases of LTB models, because they have non-zero pressure. Instead they are special cases of the more general Lemaître models, which allow for nonzero pressure.

Because they are spatially homogeneous, they are therefore isotropic about every point in the universe. (Kolb and Turner 1990) An FLRW universe will look exactly the same to every observer in it, no matter where he or she is located and no matter in which direction he or she looks.

Everyone knows that the actual universe is not this way. It is lumpy on all small and intermediate scales - there are stars and planets, clusters of stars, galaxies, and clusters of galaxies. FLRW obviously does not describe the universe on these scales! However, there is a great deal of evidence which suggests that on the very largest scales (averaging over large volumes greater than, say, 800 million light years in radius) the universe is almost smooth, almost-FLRW. And some of these almost- or perturbed FLRW models, like the particular one we mentioned above, fit these large- scale characteristics of the universe extremely well, and fit them on all scales at very early times (before significant structure formed). Certainly, the near smoothness of the CBR seems to be the strongest indicator of this. (Clarkson and Maartens 2010) And so this almost-FLRW universe ("almost," because it is perturbed, to account for the small deviations, on average, from constant mass-energy density on large scales due to galaxies and clusters of galaxies) has maintained its status as the standard model. How can we describe FLRW models in a little more detail? An FLRW universe is really a 3-dimensional perfectly smooth sphere of mass-energy expanding and cooling with the passage of time (it can also be contracting and heating up! See below.). The sphere of mass-energy is *not* expanding within a static, larger space. Rather 3-D space itself is expanding and dragging the mass-energy with it. The geometry of this space is very simple: it is described by a single function of time, $R(t)$, which is often referred to as the scale factor. As time elapses $R(t)$ increases or decreases - space expands or contracts. Since space contains mass-energy usually modelled as a perfect fluid, which responds adiabatically to the expansion or the contraction, the mass-energy in the universe cools as it expands, and heats up as it contracts.

What determines how the FLRW universe expands or contracts? The simple answer is gravity, as described by Einstein's general relativistic field equations (EFE), along with the initial conditions for the rate of expansion or contraction at one given time, the density of mass-energy at that time, and the equation of state of that mass-energy (the dependence of the pressure on the density). The mass-energy generates the gravitational field which dictates how rapidly the expansion decelerates, or accelerates, and that in turn effects a change in density, pressure and temperature. Thus, an FLRW model is uniquely determined by just two parameters, which must be determined by observations: the expansion rate at a given time, that is the Hubble parameter H, which is essentially the time-derivative of R(t), at some $t = t_0$, and the density of mass-energy at that time, together with an equation of state. Usually in late universe cosmology the equation of state is set to $p = 0$ (dust). In a much earlier radiation-dominated epoch it is just $p = (1/3)\rho$, where ρ is the mass-energy density—in this case the radiation- energy density. It turns out, as is intuitively clear, that the information given by the mass-energy density at t_0 is equivalent to that given by the deceleration parameter q_0, which is essentially the second time-derivative of $R(t)$. If the cosmological constant Λ is not zero, or there is some other form of dark clergy, then it and its effective equation of state are additional independent parameters which must be determined by observational data.

We cannot determine these cosmic parameters directly. But we can obtain the redshifts of distant galaxies, their luminosity distances, galaxy number counts, and—with some difficulty—the amount of luminous and dark matter in these galaxies and clusters of galaxies. We can also study the cosmic microwave background radiation, and its small anisotropies on different angular scales. These measurements within certain errors give us the rate of expansion now (Hubble parameter), some indication of the mass-density of the universe now, and some indirect measure of the value of the dark energy (for simplicity represented here by Λ), presuming that the universe is almost-FLRW. We can also add the data on primordial abundances of the lightest elements (hydrogen, helium, lithium) to this, to strengthen and improve the fitting, particularly with regard to the density of baryons in the universe. Although there are pieces which don't quite fit, and we don't really understand the resulting magnitude of Λ, which according to these indirect determinations amounts to 73 % of the present total mass-energy density of the universe, the overall fit of the standard FLRW model to a variety of different categories of precise cosmological data is truly remarkable. Georges Lemaître would be deeply pleased.

There are three general categories of FLRW models. Closed FLRW models expand for awhile, but eventually stop expanding and then contract under the influence of the gravitational field generated by the mass-energy it contains. For this to happen the model universe has to have enough mass-energy. Then there are the open FLRW models. These do not contain enough mass- energy to reverse the expansion into contraction, and they expand forever. If $\Lambda = 0$, the expansion constantly slows down (decelerates) but never reverses. Λ generates a *repulsive* gravitational force (because of very high negative pressure), and, unless balanced or dominated by the attractive gravitational force of normal mass-energy, will push the universe to expand more and more rapidly forever. Finally, there are flat FLRW models, which are just right in between the closed and open models. These models also expand forever, but if $\Lambda = 0$ an infinitesimal increase in mass-clergy density will lead them to collapse eventually.

And so into which category does our concordance FLRW model fall? From all indications, assuming an FLRW background model, our universe is very, very close to flat and it is very difficult to say for sure which side of flat it is (open or closed). But, if it is correct that the influence of Λ (dark energy) dominates its expansion, then either way it will certainly continue to expand forever at an accelerating rate.

Before concluding this brief discussion on FLRW models, we should expand on two other features. The first is that all of them contain a Big Bang, or initial singularity, at a finite time in their past (in the standard or concordance model it is 13.7 billion years ago). This is, in a manner of speaking, at the temporal "beginning" of the model, when the density, temperature and curvature go infinite. This, of course, is exactly what Lemaître expected, and predicted. It is important to note, however, that this singularity—the fact that these physical parameters go infinite—almost certainly *does not* represent the reality of that very early stage of the universe. Instead, it indicates a breakdown in the model at extremely high temperatures. We now have strong evidence that, as we go back into the past, there comes a point where we must graft onto the standard model one which is based on quantum gravity. We have not yet been able to do that adequately. When we do, then that addition will in some sense describe and explain the Planck era, the early quantum-configuration-dominated phase from which our universe began to expand and cool.

The second feature of the standard almost-FLRW model we need to explain more fully is precisely its "almost" character. This means that it possesses perturbations, or small fluctuations, to the exact concordance FLRW model the cosmologically relevant observational data support. As we have already emphasized, an exact FLRW model is perfectly homogeneous, and does not allow for any lumpiness at all, on any scale. If our universe were exactly FLRW we would not be here! Though the observations provide evidence that it is very close to the standard exact FLRW model on the largest scales, it also contains a great deal of structure on intermediate and small scales. So, using the concordance FLRW solution as the "background" model, we then add small deviations or perturbations to it, which describe the early development of lumpiness in our universe. These obey linear growth equations—as long as they are small compared with the background FLRW parameters such as matter-density. These perturbed models turn out to work very well for the very early phases of our universe, and for representing the early growth of large-scale structure of our universe. However, they cannot adequately model what happens when the density contrast of condensing structures gets to be comparable to or larger than the background density. At that point we deal with the local—not global or cosmological—evolution of those individual structures. To do so we use other methods, which are nonlinear.

In studying the early growth of the structure perturbations within the concordance FLRW background, we find that, in order to account for the kinds and patterns of structure we observe now, 13.7 billion years after the Big Bang, we need more nonbaryonic (or dark) matter than the baryonic matter we and everything we see is made of. Analyses of the CBR anisotropy data and the primordial elemental abundance data help us to set the present percentages at: 4 % of the total mass-energy density is baryonic matter, and 23 % of the total mass-energy density is non-baryonic matter. This dark matter, as the name implies, only interacts with baryonic matter and with itself very rarely, except through its gravitational influence. That's how we know it's there. Thus, we cannot see it, or observe its direct interactions with matter. We do not know yet what particles constitute this non-baryonic dark matter—only that it must be relatively cold and very weakly interacting.

We now move on to discuss Lemaître and LTB models, the broader classes of cosmologies which Lemaître pioneered. These are, as we have already mentioned, assuming much more importance and receiving much more attention in current cosmological research.

Beyond the Standard FLRW Model: Lemaître and LTB Models and Their Importance

If we keep the restriction of spherical symmetry but remove the demand for spatial homogeneity from the FLRW models, we end up with the Lemaître cosmological models, which he introduced and studied so thoroughly in his outstanding 1933 paper (Lemaître 1933). In his treatment he included both the cosmological constant, of which he was so fond, and perfect fluid matter and radiation, with pressure. A year later Tolman (1934), referring to Lemaître's paper, (Krasiński 1997a), authored his own study on the special, somewhat simpler dust ($p = 0$) cases of these Lemaître models. Much later Bondi (1947) revived interest in them with his own detailed analysis. These Lemaître models with $p = 0$ are therefore now known, as we have already mentioned above, as Lemaître-Tolman-Bondi (LTB) models.

As we have also briefly indicated, removing spatial homogeneity radically changes the model. Since LTB models are spherically symmetric, they are isotropic, but spherical symmetric and isotropic relative only to one location. There is now only a single spatial center of symmetry, which is almost always taken to be that of our position as observers. In these models the universe is *not* spherically symmetric relative to any other spatial location! This means that our position in this universe is privileged—that it is unlike any other location in our observable universe. Thus, in LTB models the cosmological, or Copernican, principle no longer holds. Confronting these models with observations, which is already being done, (Clarkson and Maartens 2010) will enable us to demonstrate whether and to what extent it does hold—that is, whether the universe is almost spatially homogeneous on the largest scales. And further, if the observable universe is close to an LTB model, how far from its center of symmetry or simply from the center of a very large under-dense region (a "void") within it could we be and still record the observational results we now have? Thus, at present the LTB models provide an apt and relatively simple foil for the standard FLRW model. At the same time they provide a spring-board for studying non-spherically symmetric perturbations to LTB and using relevant observations (e. g. of the CMB) to confront them.

In LTB models the inhomogeneities on each 3-D spatial slice through space-time are radial variations in matter-energy density and in other parameters and variables, e. g. the spatial curvature. As one moves outward from our central spatial location on a surface of constant time, we find that the density varies with radial coordinate distance r from our position. But there is no dependence of the density on either of the two angular coordinates, θ and φ. This is very much like the spherically symmetric concentric waves at any one moment after a rock is dropped into a pond. The key variable in the LTB models is a radial distance $R(t, r)$, often called the "areal distance," or an "area distance." It is really no longer a "scale factor," as it is in FLRW models, because it varies with the radial coordinate r on 3-D constant-time slices. The parameters which determine the model are $M(r)$, which is the gravitational mass contained within a comoving sphere of radius r (this can be related to the density), *E(r),* which is the curvature ("closed," "open," or flat—or elliptic, hyperbolic or parabolic) on 3-D spatial slices, and $t_B(r)$, which is the "bang time," the time at which expansion starts in the model. This can be different at different values of r! (Krasiński 1997b; Pelbański and Krasiński 2006)

As we already discussed in the section "The Standard FLRW Models and the Observations Supporting Them", there is a great deal of observational support for the standard concordance FLRW model of the universe. However, there remain a number of its key features which must be studied within a broader context, and other crucial issues which must be resolved, before it is definitively confirmed as the most adequate model of our universe. It is precisely through confronting LTB models, both those with a cosmological constant and those without, with old and new observational data and through completing the related theoretical work, that many of these uncertainties and issues can be resolved. That is because the LTB models are the simplest non-perturbative inhomogeneous models that we have. Understanding the large-scale inhomogeneities they admit and their effect on cosmological observations will go a long way towards improving our confidence in our description of the universe.

The importance of LTB models can be best appreciated by summarizing some of our uncertainties and reservations about the concordance almost-FLRW model. First of all, as we have already emphasized, it must have a positive cosmological constant Λ, which represents vacuum energy, or dark energy. We really do not understand very much about vacuum energy, and even less about non-vacuum dark energy, particularly its magnitude (very small, but still apparently dominant) and its origin. We do not observe the cosmological constant or dark energy, but rather deduce it from the anomalously faint apparent luminosities of Type Ia supernovae, assuming an almost-FLRW universe. Studying these inhomogeneous LTB models and confronting them with more precise, deeper and soon-to-be-available independent data will help us determine whether or not our universe really possesses a significant dark clergy, that is a non-zero Λ, or whether, instead, the apparent gentle acceleration of the cosmic expansion is due to the influence of large-scale inhomogeneities (for instance, we may be near the center of very large underdense region, or void)(Clarkson and Maartens 2010).

Secondly, very closely related to, but broader than, this dark-energy question, is the issue of uniqueness. The concordance FLRW model is *not* the only model which provides a best-fit to the presently available data. It has been shown by a number of people that an inhomogeneous LTB model without a cosmological constant can fit all presently available data, (Mustapha et al. 1997) including CBR measurements (Clarkson and Regis 2011; Regis and Clarkson 2012). Thus, we must do further theoretical and observational work to determine which of these very different models really best describes the space-time structure and the dynamics of our universe. Obviously, to do this we need more—and new categories of—data which will distinguish among these competing models.

Thirdly, the application of almost-FLRW models is generally assumed from the outset without complete justification. There is fairly good evidence that the universe is isotropic, and *some but much less* observational evidence that the universe *may be* spatially homogeneous on the largest scales. We cannot directly observe spatial homogeneity, as we have no direct observational access to the cosmological extent of any one constant time slice. This partial evidence for almost spatial homogeneity has given us the "green light" to assume it, and use FLRW models as the basis for our description of the universe. The fact that they fit the data encourages us to continue using them. However, as we have just seen, we do not yet have adequate justification for doing so! What we really need to do—to confirm our use of FLRW models - is assume that the universe is represented by a less-special, more general model, like an LTB model, with or without a Λ, and then demonstrate from enough mutually independent types of data that our universe is almost-FLRW on the largest scales. We cannot accomplish this simply by considering perturbations to FLRW. This is why use of LTB and Lemaître models is so important, and has generated so much recent interest and investigation. As is now obvious, the main issue here is the cosmological principle. Is the universe almost spatially homogeneous on the largest scales, or not?

Fourthly, it is clear that the universe is *not* almost-FLRW on intermediate and small scales. And we really do not know, even now, what the smallest scale is on which the universe can be fit by the concordance (standard) almost-FLRW model. Using the more general LTB models will help us do that. And fifthly, any careful study of the growth of structure in our universe really needs to be supplemented and checked by studying non-perturbative deviations from FLRW. These would all be important questions for Lemaître, were he still working with us today.

Now we briefly turn to consider a sampling of the outstanding work that is being done on LTB and Lemaître models and on their perturbations.

Recent Research on LTB and Lemaître Cosmological Models

The amount of significant research centering on or employing LTB and Lemaître models has accelerated very noticeably over the past 25 years. This is certainly due to the need to explore descriptions and models of our universe and its structures that take us beyond considerations of FLRW and perturbed or almost-FLRW models. A critical part of that research has been directed towards linking the free parameters of those models to observations, so that it becomes clearer what types of independent observational data is needed to constrain them, and what data would indicate that an LTB model is an almost-FLRW model. At the end of the last section, we summarized the principal reasons for this need to pursue our cosmological research beyond almost-FLRW models. It is impossible in this chapter to summarize adequately all the important work that has and is being done in this area. Here I shall simply provide some examples of, and reference to, some of the more notable contributions.

For discussion we can conveniently divide results and contributions on these models into several categories: First, careful expositions and treatments of LTB and Lemaître models and their characteristics and properties; second, their connection with cosmologically relevant observables; thirdly, their direct confrontation with various types of cosmologically relevant observational data and comparison with FLRW models, including more focused contributions exploring their use in validating whether and to what extent the cosmological principle holds; fourthly, explorations of perturbations to LTB models; and finally application of the Lemaître models to the formation of structures within the universe. We shall briefly discuss and reference work in each of these areas.

Apart from the foundational papers of Lemaître (1933) and Bondi (1947) the best recent treatments of LTB and the more general Lemaître models (those perfect fluid models with isotropic or even anisotropic pressure and pressure gradients—Lemaître's paper considers both) are found in Krasiński's *Inhomogeneous Cosmological Models*, chapters "Georges Lemaître: The Priest Who Invented the Big Bang and 'The Wildest Speculation of All': Lemaître and the Primeval-Atom Universe" (Krasiński 1997b), and especially in Plebański and Krasiński's *An Introduction to General Relativity and Cosmology,* Chapter. "18" (Pelbański and Krasiński 2006) and in Bolejko et al.'s *Structures in the Universe by Exact Methods* (Bolejko et al. 2010). These treatments particularly the latter two, discuss all the principal characteristics of these models, including their free parameters, horizons, big-bang structure, shell-crossings, etc., and provide relatively up-to-date references to important results. A very helpful paper by Wainwright and Andrews (2009) gives a brilliant treatment of the dynamics of LTB models, including their asymptotic behavior and of the spherically symmetric perturbations (both growing and decaying modes) to FLRW and their relationship to LTB parameters.

One of the largest bodies of work on LTB models is that of exploring how LTB models, and their anisotropic perturbations, can be determined by observational data, taking their inspiration from the key paper by Kristian and Sachs in 1966 (Kristian and Sachs 1966). Some of this work has been pursued employing the usual orthogonal $3 + 1$ coordinate formulation (O(3+1)), in which space-time is foliated into space-like hypersurfaces along the normal time-coordinate [this is better than "O-3 + 1"]. But significant other theoretical work has used "observational coordinates" (OC), through which space-time is foliated into past light-cones (PLC) along the observer's world line, such that each instant of time labels a PLC. The motivation for this formulation is the ease with which key observations, e.g. redshifts and angular-diameter (observer-area) distances can be related to the metric variables on our PLC, and the functional relation between red-shift and the null radial coordinate obtained [eliminate space between "red-" and "shift"]. All the data coming to us via electromagnetic radiation is arrayed on our PLC.

In both formalisms, the work that has been done demonstrates in detail how to solve the LTB EFE field equations uniquely given idealized data, consisting of galaxy redshifts, angular-diameter distances (to which luminosity distances can be easily converted), and galaxy number counts (which in principle, but with difficulty, will give the mass-energy density as a function of redshift). Some later papers using one or the other framework add the maximum of the angular-diameter distance and time-drift of galaxy redshifts as eventually feasible measurements which can in principle provide independent information to constrain the value of the cosmological constant (Hellaby 2006; Araújo and Stoeger 2009b) and the cosmic mass-energy density, (Araújo and Stoeger 2010) respectively.

Two key papers which have carried out this work in O(3+1) and give the flavor of the approach are those of Mustapha, Hellaby and Ellis (Mustapha et al. 1997) and Hellaby (2001). Hellaby in his important 2006 paper (Hellaby 2006) and later in his 2010 paper with Alfedeel (Alfedeel and Hellaby 2010) shows how in general LTB and Lemaître models the cosmic mass is defined, even when the pressure is non-zero, what the apparent horizon is and why it is important, and derives the simple algebraic relationship connecting the value of the cosmological constant Λ with the maximum of the angular-diameter distance and the gravitational mass a sphere of that radius contains. It is this relationship which, in principle, enables Λ to be determined from observational data. It is worth noting, in this context, that the definition of mass in these models was one of the important results Lemaître presented in his 1933 paper. (Lemaître 1933) In two other papers Lu and Hellaby (2007) and, a year later, McClure and Hellaby (2008) demonstrate how to obtain a LTB metric with $\Lambda = 0$ from simulated data by numerical integration, and study the stability of some of the key equations.

The foundational paper for the OC approach is the 1985 paper by Ellis et al. (1985). There the motivation and relationships between the metric variables and the observables are laid out carefully, and theorems proving the uniqueness of solutions to the general EFE given an idealized data set consisting of galaxy redshifts, angular-diameter (observer-area) distances, galaxy number counts, cosmological proper motions, and integrated null-shear measurements are explained. The latter two, of course, are zero in an exactly isotropic space-time. A non-zero Λ is not included, nor the discussion of the supplementary independent observations needed to determine its value. The present status of this approach and detailed accounts of the results so far for LTB cosmologies are given in the two recent papers by Araújo and Stoeger already cited (Araújo and Stoeger 2009b, 2010). Two other recent papers, by Hellaby and Alfedeel (2009) and by Araújo and Stoeger (2011) compare and contrast teh O(3+1) and the OC approaches to determining the LTB metric of the universe from observations.

There has been a great deal of research directed towards confirming the cosmological principle to determine whether our universe is almost spatially homogeneous on cosmic scales. Typically, such work attempts to fit a universe with a large local under-dense region (or void) to the cosmological data, including various kinds of measurements of the CBR. In most cases, a full LBT and/or Lemaître model analysis is not used, but instead either a low-density FLRW or LBT dust model (a "void") surrounding the observer matched to a higher density FLRW model at high redshifts. All of this work has been referenced and critically reviewed in great detail in Clarkson and Regis's paper (Clarkson and Regis 2011). They have also provided a Lemaître model framework and analysis for further investigation of this important problem, along with guidelines for meeting some of the important challenges in resolving it. Some of the other papers which have considered real observational data within a LTB and Lemaître framework to see if such models fit the observations are those of Tomita and Inoue (2009) Tomita (2010) Dunsby et al.

(2010), and Clarkson and Maartens (2010). Despite the many technical difficulties in carrying out this work and the controversy surrounding it, the preliminary results, as we have already mentioned above, clearly show that there are inhomogeneous models that can fit the presently available cosmological data, without a non-zero Λ (Regis and Clarkson 2012; Clarkson and Regis 2011). Once other independent types of cosmologically relevant data are available, e. g. the maximum of the angular-diameter distance and its redshift, and better measurements of the cosmic mass-energy density (possibly through redshift time-drift data), we will be able to determine whether we do need a non-zero Λ and whether the concordance FLRW model or some inhomogeneous model end up winning this competition. It is worth mentioning in this context that Uzan et al. (2008) have used an LTB background to suggest how the time-drift of galaxy redshifts can be used to test whether there is almost spatial homogeneity on the largest scales.

Another important area of research on focuses on the behavior of LTB and Lemaître perturbations. This work is crucial for understanding and modelling formation and development of galaxies and clusters of galaxies in inhomogeneous cosmologies. It turns out that this subject is extremely difficult. However, a good start has been made by Zibin (2008) Clarkson, Clifton and February, (Clarkson et al. 2009) Clarkson and Maartens (2010) and others. An excellent overview of this subject, its progress and challenges is given in the Clarkson and Maartens paper.

Finally, a number of people, notably Krasiński, Hellaby and Bolejko, have pioneered the exact use of LTB and Lemaître models to study the local formation of structure voids, clusters of galaxies, etc. without resorting to linear perturbation treatments. Though such applications suffer from certain obvious limitations (e.g. their inability to deal with rotation), they also enjoy many advantages. A very recent and important reference for this research is the book by Bolejko et al. (2010). It is also worth noting that Bolejko and Stoeger (2010) have recently shown that certain LTB and Lemaître models - those with spatial curvature very much less than the Ricci curvature induced by the mass-energy density—can undergo spontaneous temporary homogenization. This process may be important in achieving the necessary homogeneity conditions for initiating inflation in the very early universe.

Conclusions

In our discussion we have reviewed the central ground-breaking contributions of Georges Lemaître to cosmology, emphasizing his outstanding but perhaps less well-known theoretical work in solving and interpreting the solutions to the general spherically symmetric Einstein field equations. These results have provided the foundations for the study of inhomogeneous cosmological models—the more restricted Lemaître-Tolman-Bondi (LTB) models, where the pressure is assumed to be zero, the Lemaître models for more general perfect fluids, and non-spherically symmetric perturbations to these exact solutions. It is apparent, from what we have seen here, that, beyond the well-appreciated and fundamental developments of Lemaître's work in Big Bang cosmology and particularly in the standard spatially homogeneous FLRW models, there has been an explosion of important work expanding on his contributions to the study of inhomogeneous models—both for elucidating and confirming the large-scale structure of our universe, and for modeling more carefully the formation of galaxies and clusters of galaxies.

In particular, we have discussed and summarized the recent and ongoing research connecting cosmologically relevant observations to LTB models, in order to increase and confirm our understanding of the principal features of our universe. Since FLRW models are special cases of the more general LTB and Lemaître models, this makes perfect sense. Such research is even more urgent, given our ignorance and uncertainty about dark energy and the cosmological constant, which seems to be absolutely necessary for an adequate almost-FLRW description of space-time, our inability to directly confirm large-scale spatial inhomogeneity, our need for further, more precise and deeper observational data, and the strong indications we have that the standard concordance FLRW model is not a unique best-fit to the data. As Clarkson and Maartens comment at the end of their outstanding paper (Clarkson and Maartens 2010), "Only by developing a family of inhomogeneous spacetimes to the same level of sophistication as the standard concordance model, and directly comparing them side by side, will we really be able to understand whether Λ is real, or actually a consequence of our homogeneity assumption." This basic open approach motivates all the work in this area—to confirm, increase, and, if need be, modify our understanding and our description of the universe, and to learn what their limitations are, in particular the length scales below which they are inapplicable. Lemaître would be in thorough accord with this philosophy. That, too, is part of his legacy to contemporary cosmology.

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Multiple Reasons for a Multiverse

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Abstract The apparent fine tuning of many of the constants of physics has been used as a design argument for the creation of the universe by an intelligent God. However, an alternative explanation is that there is a huge multiverse with very many different sets of constants of physics, and we are in one in which the constants have values that permit its being observed. Here I shall give several reasons for taking this possibility seriously. Even though multiverse hypotheses undercut one particular argument for design, I shall argue that they are consistent with theism and might be God's preference for creation.

Introduction

Before Darwin, some Christians took the marvels of humanity as evidence of separate and individual design. Now, some Christians take the marvels of the constants of physics as evidence of separate and individual design. It could be that this is equally mistaken.

It does seem to be true that we could not exist if many of the constants of physics were significantly different. For example, if the mass and charge of the proton and electron were much different from what they are, suitable stars to produce elements and to sustain planets could not exist. If the cosmological constant (which makes empty space have a repulsive gravitational effect, pushing particles apart) were not nearly so incredibly tiny, structures such as galaxies, stars, and planets would not have formed at all. The fact that the constants we observe are apparently in a very narrow range to permit structures allowing life is called *fine tuning*.

There are several different explanations given for the observed fine tuning. Some say it was done separately by God to allow life (Ross 1983, 1988, 1989, 2001;

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Swinburne 1990, 1991; Manson 2003; Holder 2004; Mann 2005; Collins 2006). Others say it is an accidental fluke. Yet others say it arises from a huge multiverse of very many different possible constants of physics (Rees 2001; Susskind 2006; Carr 2007; Davies 2007; Vilenkin 2006; Greene 2011). Here I shall give multiple reasons that one might have for preferring a multiverse explanation at a scientific level (Page 2010), while not necessarily denying that God is the author and creator of this type of universe.

Parallels Between Evolution and Multiverse Ideas

When Darwin proposed evolution, many conservative Christians accepted it as not necessarily contrary to Christianity. One famous example was Benjamin B. Warfield (1851–1921), the conservative Christian theologian and principal of Princeton Theological Seminary from 1887 to 1921. Warfield wrote the chapter on "The Deity of Christ" in *The Fundamentals,* from which the term Fundamentalism arose. Thus one of the most famous original Fundamentalists accepted the possibility of Darwinian evolution, writing (Warfield 2000, p. 130), "I am free to say, for myself, that I do not think that there is any general statement in the Bible or any part of the account of creation, either as given in Genesis 1 and 2 or elsewhere alluded to, that need be opposed to evolution."

However, many Christians later came to oppose evolution, perhaps most famously some other Fundamentalists. Although there were many reasons for this, which I cannot get into here, one possible reason is that evolution did remove one particular design argument for the existence of God, that all of the marvelously many different species of living things on Earth had been separately designed and created by God. Nevertheless, evolution did not disprove the existence of God or of some overall design. Indeed, there are many leading theologians and scientists today that accept both evolution and creation by God, such as Francis Collins (2006, passim), the director of the Human Genome Project (1990–2003).

It seems to me that there may be a parallel development occurring today. Before Darwin, some Christians took the marvels of humanity as evidence of separate and individual design. Now, some Christians take the marvels of the fine-tuning of the constants of physics as evidence of theism and often of separate and individual design of these constants by God. Here I wish to argue that this could be equally mistaken.

I have found that my views are rather similar to those of a minority of theists, e.g. (Leslie 1989, pp. 64–65; Leslie 2001, pp. 211–214; Collins 2002, passim; Barr 2003, passim; Collins in Carr 2007, pp. 459–480; Swinburne 2012, passim), who recognize that a multiverse could reveal an even more grand design of the universe, since the physical process that generates the multiverse would have to have suitable basic laws and initial conditions to produce any life at all. The laws and initial conditions would apparently have to be even more special to produce not just life, but life like ours observing the order we actually do see around us. Stephen Barr, Gerald Cleaver, Robin Collins, Klaas Kraay, John Leslie, Richard Swinburne, and others claim that since God is infinitely creative, it makes sense to say that He might create a physical reality much larger than the single visible part of the universe or multiverse that we can observe directly (see, e.g., Leslie 1989, p. 180; Leslie 2001, pp. 18–19, 215–216; Barr 2003, pp. 151–153; Robin Collins in Carr 2007, pp. 460–462; Kraay 2010, pp. 361–366).

Fine Tuning in Our Universe

Now it does seem to be true that we could not be here if many of the constants of physics were significantly different, so that in our part of the universe, the constants of physics do in fact seem to be fine tuned for our kind of life. This is generally agreed upon both by those who attempt to use this fine tuning to support theism, as in (Swinburne 2012, passim), and by many scientists who are usually neutral or opposed to such an attempt (Carter 1974, pp. 291–298; Carr and Rees 1979, pp. 605–612; Davies 1982, passim; Barrow and Tipler 1986, passim; Rees 2000, passim; Barrow 2002, passim; Bostrom 2002, passim; Susskind 2006, passim; Carr 2007, passim). Of course no one knows what other forms of life might be possible if the constants of physics were significantly different, but the general consensus seems to be that if would be very difficult to imagine the possibility of any complex life existing at all if certain combinations of the constants of physics were greatly different.

For example, one of the most remarkable fine tunings is the value of the cosmological constant or energy density of the dark energy responsible for the current acceleration of distant galaxies away from each other. Measurements show that the cosmological constant is more than 120 orders of magnitude smaller than unity in certain natural units (called Planck units, obtained by setting to unity the speed of light, Planck's quantum constant of action, and Newton's gravitational constant). With the other constants kept fixed, it would be difficult to have a universe with gravitationally formed structures lasting long enough for life if the cosmological constant were even just a few orders of magnitude (powers of 10) larger than its observed value. But even if one tuned the other constants to allow the possibility of such structures when the cosmological constant has a value many orders of magnitude larger than its observed value, one still seems to need it to be many orders smaller than unity. So one does not see how to avoid at least some significant amount of fine tuning of this parameter. (Basically, if the cosmological constant were of the order of unity in the natural Planck units, the spacetime of the universe would always have large quantum mechanical fluctuations, and no one knows any plausible way to have persisting complex structures that one could call life in such a case.)

Another constant that is many orders of magnitude away from unity, in this case about 36 orders of magnitude larger than unity, is the ratio of the electrostatic repulsion to the gravitational attraction between two protons (the nuclei at the centers of hydrogen atoms). With other constants kept fixed, it seems that one could not have the types of stars that appear to be necessary for life if this constant differed by much more than even one order of magnitude (factor of 10) from its actual value. Again one could try to imagine a universe hospitable to some other form of life when this constant is significantly different by also tuning other constants to an appropriate range, but it seems that complex life of any form relying mainly on the electromagnetic and gravitational forces would be impossible if this constant were close to unity. (Then it seems that one could not have stars, planets, and living organisms with large numbers of atoms, since the number of atoms in such structures generally scales as a positive power of this constant and would approach some small number near unity if this constant were itself near unity.)

Martin Rees (2000, passim) discusses in much more detail these two constants and four others in our universe that are crucial for its properties. Life as we know it would apparently be impossible if any one of them were greatly different (with the others held fixed). So although it might not be necessary for all of them to have their observed values, there are some combinations of them that apparently could not be very much different and yet give a universe with life, at least life at all similar to present life on earth.

Explanations for Fine Tuning

So there is a general consensus that there is at least some fine tuning of the constants of physics in our part of the universe, though not that all of the constants had to have values close to what we observe. But what is the explanation for this phenomenon? There are three general types of explanations that are often put forward.

Some suggest that the fine tuning was done by a separate act of God to allow life. Others say that it is presumably an accidental fluke. And yet others propose that it arises from a huge multiverse of very many different possible constants of physics. It is also noted in several sources, such as (Leslie 1989, p. 22; Leslie 2001, p. 211; Bostrom 2002, p. 11; Barr 2003, pp. 153–154; Carr 2007, pp. 16–17, 27, 411–412, 459–480), that the three explanations are not mutually exclusive, so that virtually any combination of them is logically possible. However, it is the multiverse explanation that is now rapidly growing in favor, though not without a lot of opposition from both theists and non-theists.

One must quickly point out that each of these three explanations really stands for a class of explanations, so that one should actually compare specific proposals taken from these classes rather than the classes themselves. Theists of different theological convictions might propose different ideas of how God would choose the constants. Those saying that the fine tuning is a fluke might say that the constants are determined by any number of different mathematical structures that just happened to give biophilic values, or they might propose that there is truly some random process determining the constants in some way not derivable from any simple mathematical structure. And of course there are a huge number of possible multiverse theories.

Some multiverse theories seem to me to be too general to be plausible, such as the idea of David Lewis (1990, passim) that all logical possibilities actually exist, or the original idea of Max Tegmark (1998, pp. 1–51) that all mathematical structures have physical reality. These would seem to leave it unexplained why what we see has the order that it does, whereas a random possibility from all logical possibilities or from all mathematical structures would surely be far more chaotic (Leslie 1989, pp, 97–98; Leslie 2001, pp. 23–30; Barr 2003, p. 156; Vilenkin 2006, p. 203). However, there might be other multiverse theories that are more explanatory of the order that we do observe, perhaps arising naturally out of elegant but specific laws of nature.

One natural way to get a multiverse is to have a universe so large that highly varied conditions occur somewhere. Another is from Everett many-worlds (DeWitt and Graham 1973, passim), that all the quantum possibilities are actually realized. However, those possibilities do not necessarily give varying constants of physics.

One scenario that seems more hopeful is to get multiverses from inflation (Linde 1990, pp. 292–3 17; Guth 1997, pp. 245–252; Vilenkin 2006, pp. 203–205), which is a very rapid exponential expansion of the early universe that may make the universe enormously larger than what we can observe of it. If the inflationary scenario can include phase transitions, and if the constants of physics can differ across phase transitions, inflation tends to produce all such possibilities.

Recently it has been realized that string theory and M-theory apparently leads to a huge multiverse of 10^{500} or so different vacua or sets of constants. This would apparently be enough for the constants we see to occur somewhere (maybe once per 10^{200} vacua or so). Then perhaps 10^{300} or so vacua would fit what we see.

If only one universe in 10^{M} could fit our observations, but if 10^{N} different universes exist in the multiverse, then it might not be surprising that what we observe exists if $N > M$. For example, in the previous paragraph, I was saying that perhaps N is around 500 and M is around 200, so then indeed $N > M$. However, the actual numbers are known very poorly. We really don't yet know whether $N > M$ in string/M theory, but that seems plausible. Then what we see could be explained without its having to be individually selected. One might still ask whether the multiverse explanation always works, assuming that it has enough universes (e.g., $N > M$). Is it sufficient to explain what we see by a multiverse theory in which there are enough different conditions that ours necessarily occurs somewhere? I would say no, but rather that there is the further requirement that the conditions we observe should not be too rare out of all the conditions that are observed over the entire multiverse. A theory making our observations too rare should not be considered a good theory.

Good theories should be both intrinsically plausible and fit observations. Intrinsic plausibility is quantified by what is called the a priori probability of the theory, the probability that one might assign to it from purely theoretical background knowledge, without considering any observations. The fit to observations is quantified by the conditional probability of the observation given the theory, what is called the *likelihood*. Then the probability of the theory after taking into consideration the observation, what is called the a posteriori probability of the theory, is given by Bayes' theorem as being proportional to the product of the a priori probability and the likelihood.

I take the a priori probabilities of theories (intrinsic plausibilities before considering the observations) to be subjective but to be generally assigned higher values for simpler theories, by the principle that is called Occam's razor. One problem with this is that David Deutsch (in a private communication) notes that simplicity depends on one's background knowledge that itself depends on the laws of physics.

The *likelihood* of a theory is itself neither the a priori nor the a posteriori probability of the theory, but rather the conditional probability, not of the theory, but of the observation given the theory. A theory that uniquely gives one's observation would have unit likelihood but might have very low a priori probability.

For example, consider an extreme solipsistic theory that only one's actual momentary observation exists, not anyone else's or even any of one's own in either the past or the future, and perhaps not even that an external world exists at all. This theory would predict that observation with certainty if it were correct. (If the theory were true, certainly the observation would be that single one predicted by the theory.) Therefore, for that observation the likelihood is unity. However, such an extreme solipsistic theory, giving all the details of one's observation or conscious perception without an external world giving other observations, would surely be highly complex and so would be viewed as extremely implausible, much more implausible than an alternate theory in which the observation resulted from the existence of an external world that also gives other observations. Therefore, this extreme solipsistic theory would be assigned very low a priori probability.

At the other extreme, consider the simple theory that predicts all possible observations equally, arguably a consequence of something like the modal realism of David Lewis (1990, passim). Since this theory is so simple, it might be assigned a high a priori probability, but then because of the enormous number of observations it predicts with equal probability (presumably infinitely many), it would give very low likelihood (presumably zero).

The Growth of Our Knowledge of the Universe

Our whole growth of knowledge of the universe has been an expansion of its scope. As one develops as an infant, one rapidly grows beyond the view that one's present observation is all that is real, as one forms memories about the past and anticipations of the future. One then goes beyond solipsism and gains an understanding that other persons or observers exist as well. In the early stage of human development, there was the focus on one's family, which was then gradually extended to one's tribe, one's nation, one's race, and, one might hope, to all humans. But then, when one further considers what other conscious observations may be going on, one might well believe that consciousness extends to other creatures, such as other animals.

Of course, one's direct observation never extends beyond one's own immediate conscious perception, so one can never prove that there are past or future perceptions as well. I know philosophers who do not believe the future exists. Similarly, one can never directly experience even the present conscious perceptions of another, which engenders the problem of other minds in philosophy. Nevertheless, most of us believe that we have fairly good indirect evidence for the existence of other conscious experiences, at least for other humans on Earth with whom we can communicate, though it is logically possible that neither they nor any external world actually exists. (For me, I believe that it is much simpler to explain the details of my present observation or conscious perception or experience by assuming that an external world and other conscious experiences also exist, than by assuming that just my own momentary conscious perception exists.)

We may now extend the reasoning to suppose that if the universe is large enough, it will also include conscious extraterrestrials, even though we do not have even indirect evidence for them that is so nearly direct as our (inevitably still indirect) evidence for other conscious beings on earth. We can further theorize that if the universe is so large that there never will be any contact between its distant parts and our part, there still might be other conscious beings not in causal contact with us, so that we never could communicate with them to get, even in principle, the indirect evidence of the same qualitative nature that we have for other humans here on earth with us.

A next step might be to postulate conscious beings and experiences in other universes totally disconnected from ours, so that even if one could imagine traveling faster than the speed of light, there would simply be no way to get there from here; the two parts would be in totally disconnected spacetimes. A similar situation would occur for putative conscious experiences in other branches of an Everett many-worlds wavefunction or quantum state. From accepting the existence of such disconnected observers, it hardly seems like an excessive additional step to imagine observers in universes or parts of the multiverse with different constants of physics. One might even imagine observers in entirely different universes, not related to ours in the way an entire multiverse might be related by having one single over-arching set of natural laws.

So in this sense, the idea of a multiverse seems to be rather a natural extension of our usual ideas of accepting a reality beyond one's immediate conscious perception, which is all the experience for which one has direct access. All the rest of one's knowledge is purely theoretical, though one's brain (assuming it exists) is apparently constructed to bring this knowledge into one's awareness without one's having to be consciously aware of the details of *why* one seems to be aware of the existence of other conscious beings.

Despite the naturalness of the progression of ideas that leads to multiverse theories, there are various objections to it. However, none of the objections seem to me to be convincing, as there are highly plausible rebuttals to the objections.

Objections to Multiverse Ideas

A scientific objection to a multiverse theory might be that the multiverse (beyond our observed part, which is within one single universe) is not observable or testable. But if one had precise theories for single universes and for multiverses that gave the distributions of different conditions, one could make statistical tests of our observations (likely or unlikely in each distribution). Unfortunately, no such realistic theory exists yet for either a single universe or a multiverse, so I would agree that at present we simply do not have any good theories of either to test.

Another objection is that a multiverse is not a clear consequence of any existing theory. Although it is beginning to appear to be a consequence of string/M theory, that is not yet certain, which is why there can be theorists like David Gross who are still holding out hope that string/M theory might turn out to be a single-universe theory after all, possibly enabling theorists (if they could perform the relevant calculations) to fulfill their wildest dreams of being able to calculate the constants of physics uniquely from some simple principles. One first needs to make string/M theory into a precise theory and calculate its consequences, whether single universe or multiverse. And if that theory gives predictions that do not give a good statistical fit to observations, one needs to find a better theory that does.

A philosophical objection to a multiverse theory is that it is extravagant to assume unfathomable numbers of unobservable universes. This is a variant upon the psychological gut reaction that surely a multiverse would be more complex than a single universe, and hence should be assigned a lower a priori probability. But this is not necessarily so. The whole can be simpler than its parts, as the set of all integers is quite simple, certainly simpler than nearly all the (arbitrarily large) individual integers that form its parts.

As a further rebuttal of the accusation of extravagance, a theist can say that since God can do anything that is logically possible and that fits with His nature and purposes, then there is apparently no difficulty for Him to create as many universes as He pleases. He might prefer elegance in the principles by which He creates a vast multiverse over paucity of universes, that is, economy of principles rather than economy of materials.

Another philosophical objection to multiverses is that they can be used to explain anything, and thereby explain nothing. I would strongly agree with this criticism of multiverse theories that are too vague or diffuse, which do not sufficiently restrict the measure on the set of observations to favor ordered ones such as what we observe. There is a genuine need for a multiverse theory not to spread out the probability measure for observations so thinly that it makes our observation too improbable. So this objection would be a valid objection to vast classes of possible multiverse theories, but I do not see that it is an objection in principle against a good multiverse theory. Certainly not just any multiverse theory is acceptable, and even if simple single-universe theories do not work for explaining our observations, it will no doubt be quite a challenge to find a good multiverse theory that does succeed.

Most of the objections I have raised and attempted to answer so far would apply both to theistic and nontheistic scientists. However, if one is a theist, one might imagine that there are additional objections to multiverse theories, just as some theists had additional objections to Darwin's theory of evolution beyond the scientific objections that were also raised when that theory had much less support. For example, a theist might feel that a multiverse theory would undercut the fine-tuning argument for the existence of God. I shall not deny that it would undercut the argument at the level of the constants of physics (though I think there would still be such a design argument from the general apparently elegant structure of the full laws of nature once they are known). However, the loss of one argument does not mean that its conclusion is necessarily false.

I personally think it might be a theological mistake to look for fine tuning as a sign of the existence of God. I am reminded of the exchange between Jesus and the religious authorities recorded in the Gospel of Matthew 12:38–41:

> Then some of the scribes and Pharisees answered, saying, Teacher, we want to see a sign from You. But He answered and said to them, An evil and adulterous generation seeks after a sign, and no sign will be given to it except the sign of the prophet Jonah. For as Jonah was three days and three nights in the belly of the great fish, so will the Son of Man be three days and three nights in the heart of the earth. The men of Nineveh will rise up in the judgment with this generation and condemn it, because they repented at the preaching of Jonah; and indeed a greater than Jonah is here.

In other words, I regard the death and resurrection of Jesus as the sign given to us that He is indeed the Son of God and Savior He claimed to be, rather than needing signs from fine tuning.

Another theistic objection might be that with a multiverse explanation of the constants of physics, there is nothing left for God to design. But God could well have designed the entire multiverse, choosing elegant laws of nature by which to create the entire thing. In any case, whatever the design is, whether a logically rigid requirement, a simple free choice God made, or a complex free choice God made, theists would ascribe to God the task of creating the entire universe or multiverse according to this design.

A third more specifically Christian objection might be that if the multiverse, or even just our single part of the universe, is large enough for other civilizations to have sinned and needed Christ to come and redeem them by something similar to His death on the Cross here on Earth for our sins, then His death may not sound as unique as the Bible says in Romans 6:10: "For the death that He died, He died to sin once for all; but the life that He lives, He lives to God." But the Bible was written for us humans here on Earth, so it seems unreasonable to require it to describe what God may or may not do with other creatures He may have created elsewhere. We could just interpret the Bible to mean that Christ's death here on earth is unique for our human civilization.

Conclusions

In conclusion, multiverses are serious ideas of present science, though certainly not yet proven. They can potentially explain fine-tuned constants of physics but are not an automatic panacea for solving all problems; only certain multiverse theories, of which we have none yet in complete form, would be successful in explaining our observations. Though multiverses should not be accepted uncritically as scientific explanations, I would argue that theists have no more reason to oppose them than they had to oppose Darwinian evolution when it was first proposed.

God might indeed love the multiverse.

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Multiverses, Science, and Ultimate Causation

George Ellis

Abstract This chapter the motivation and evidence for the various types of multiverses that have been proposed. A key problem is their lack of testability, because of the existence of cosmic horizons; nevertheless they are claimed to be a scientific hypothesis. I review the arguments in their favour, and suggest none is conclusive, although there is one case where they could be disproved (the small universe case) and one that would indeed be quite convincing circumstantial evidence (circles in the CMB sky associated with variation of fundamental constants).

Multiverse proponents are in fact proposing weakening the criteria for a scientific theory, which is a dangerous tactic. The scientific status of these proposals is particularly brought in to question by various claims of physically existing infinities, which cannot possibly be verified. Finally I comment that multiverses do not solve issues of ultimate causation, as claimed by their proponents. If one wants to investigate this issue, one must extend the kind of data one considers beyond data obtainable from physics experiments and astronomical observations, to include broader areas of human experience, that are also evidence on the nature of the universe.

The Idea

The idea of a multiverse—an ensemble of universes, or of expanding universe domains like that we see around us—has recently received increasing attention in cosmology (Carr 2009). It has been conceived of as occurring either in separate places, in the same overall encompassing universe (as in chaotic inflation), at

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different times, in the same encompassing universe (as in various forms of eternal universe), through splitting of the quantum wave function (as in the Everett many-worlds interpretation of quantum mechanics), or as a set of totally disjoint universes, with no causal connection whatever with each other.

The crucial point that makes it interesting is that physical properties may be different in the different universes envisaged, or even in different expanding domains within a single universe. In this context, definitions are important. Some workers refer to the separate expanding universe regions in chaotic inflation as 'universes', even though they have a common causal origin and are all part of the same single spacetime. In keeping with long established use, I prefer to use the word Universe to refer to the single unique connected spacetime of which our observed universe region (centred on our Galaxy and bounded by our visual horizon in the past) is a part, *when the physics is the same in each domain*. In keeping with more recent trends, I will refer to situations with many expanding domains *with different effective physics in each* as a Multiverse. This may include a collection of genuinely disconnected spacetimes—those which are not locally causally related.

The Motivation

Why are ensembles being proposed? There are basically three motivations.

Generating Mechanisms

It has been claimed that a multi-domain universe is the inevitable outcome of the physical originating processes that generated our own expanding universe region from a primordial quantum configuration; they would have generated many other such regions as well.

This was first modelled in a specific way by Vilenkin (1983) and was developed by Linde (1983, 1990) in his chaotic cosmology scenario. Since then many others, e.g. Sciama (1993), Leslie (1996), Deutsch (1997), Tegmark (1998, 2004), Smolin (1997), Lewis (2000), Weinberg (2000a), Rees (1999, 2001), and Davies (2004) have discussed ways in which an ensemble of universe domains might originate physically; the predominant one is chaotic inflation. The crucial further claim is that the landscape of string theory provides a natural mechanism whereby physics would vary from domain to domain in such a universe (Susskind 2003, 2006).

Universality

Their existence can be seen as the result of an overall philosophical stance underlying physics: the idea that "everything that can happen happens" (Sciama 1993; Tegmark 2004). This is a logical conclusion of the Feynman path integral approach to quantum theory, viewed as a basic underlying physical principle that provides a foundation for quantum physics and in some sense a fundamental approach to the nature of existence. Clearly this implies that we consider all possible alternative physics as well as all possible alternative spacetime geometries.

Fine Tuning: The Anthropic Issue

An ensemble has been proposed as an explanation for the way that our universe appears to be fine-tuned for the existence of life and for consciousness to appear. We need stars, planets, and heavy elements (specifically, carbon) in order for physically based life to exist—but in many universes, some or all will not be there. It is now clear that if any of a number of parameters which characterize the observed universe—including both fundamental constants and initial conditions—were slightly different, no complexity of any sort would come into existence and hence no life would appear (Barrow and Tipler 1986; Balashov 1991). No Darwinian evolutionary process at all would be able to take place, as biology would not exist. Thus for example Martin Rees (1999) suggests there are just six numbers expressing these relationships that must all be fine-tuned in order that life can exist, namely:

1. $N =$ electrical force/gravitational force $= 10^{36}$,
2. $E =$ strength of nuclear binding $= 0.007$,
3. $\Omega =$ normalized amount of matter in universe $= 0.3$,
4. $\Lambda =$ normalised cosmological constant $= 0.7$,
5. $Q =$ seeds for cosmic structures $= 1/100{,}000$,
6. $D =$ number of spatial dimensions $= 3$.

Consequently, the universe is fine tuning for life (Barrow and Tipler 1986), as regards the laws of physics (Tegmark 2004), and as regards the boundary conditions of the universe (Rees 1999, 2001).

A multiverse seems to be the only scientifically based way of explaining the precise adjustment of all these parameters simultaneously so that complexity and life eventually emerged. The existence of a sufficiently large collection of expanding universe domains, which taken overall include the full range of possible combinations of parameter values, ensures that in some of them things would come out right for life to exist because this set of models would explore all of parameter space. In most of these domains life will not occur because conditions will be wrong. But in a few of them it will just happen to work out all right. So although there is an incredibly small probability of a domain existing that will allow life, if there exist enough domains with all sorts of properties occurring in all combinations, it becomes essentially inevitable that somewhere the right mix of circumstances will occur, so in some of them surely life will come into being. Those observers existing in such domains will obviously find the constants there such as to support the existence of life (else they would not be there!)

Particularly, this argument is proposed to explain the small value of the cosmological constant (Weinberg 2000a; Susskind 2006)—too large a positive value for Λ results in no structure forming, and hence no life coming into existence; too large a negative value results in a universe too short lived for life to develop. Then anthropic considerations mean that the value of Λ we observe will be small [in fundamental units], thus justifying an actual value extremely different from the 'natural' one predicted by physics—namely 120 orders of magnitude different.

An important point is that in order that an ensemble with varied properties provide an explanation of fine tuning, it must be an *actually existing ensemble*, not a potential or hypothetical one.[1] This is essential for any such anthropic argument.

One may finally note that these motivations are not necessarily in conflict with each other; indeed one might for example attempt to propose a generating mechanism based on the ideas of universality that will also provide an anthropic explanation.

Varieties of Multiverse

As already mentioned, a variety of kinds of multiverses have been envisaged. In his recent book *The Hidden Reality* (Greene 2011), Brian Greene advocates nine different types of multiverse:

1. ***Existence beyond the horizon***: Invisible parts of our own universe. In the terminology introduced in section "The Idea", this is not a multiverse: it is just a hidden part of our own universe.
2. ***Chaotic inflation***, leading to different expanding domains in separate places (Vilenkin 1983; Linde 1983, 1990; Guth 2001)
3. ***Brane worlds*** of M-theory (Four-dimensional space-times embedded in higher dimensional spacetimes).
4. ***Cyclic universes***, leading to different expanding domains at different times (Smolin 1997; Steinhardt and Turok 2002; Penrose 2010)
5. ***The Landscape of string theory*** embedded in a chaotic cosmology (Susskind 2003, 2006)
6. ***The Everett quantum multi-universe***: other branches of the wavefunction (Deutsch 1997)
7. ***Holographic projections*** (currently a trendy proposal in cosmology),
8. ***Computer simulations*** (I comment on this below),
9. ***All that can exist must exist***—the "grandest of all multiverses", the separate universes being totally disjoint from each other (Sciama 1993; Lewis 2000; Tegmark 2004).

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[1] An example of a paper that apparently only considers hypothetical ensembles is Bjorken (2004). The author talks about "constructing ensembles". Regrettably, we are unable to do so.

Now one thing is clear—they can't all be true, for they conflict with each other. This abundance of possibilities does not in fact work in favour of the hypothesis, unless one can decisively decide between them: but one can't. There remains the final possibility:

10. ***Maybe none of them is true*—there is just one universe.**

Note again that we are concerned with really existing multiverses, not potential or hypothetical.

I will concentrate mainly on the chaotic inflation version, perhaps enhanced with the string theory landscape option, because this is the one that has most going for it—it is embedded in a strong cosmological model that makes serious observational predictions.

The Big Issue: Multiverses and Testability

The problem with all multiverse claims is that there is no direct way to show they are true. Various indirect ways of showing they exist have been proposed. However it is my contention that these are not proofs in the usual scientific sense.

Two central scientific virtues are testability and explanatory power. In the cosmological context, these are often in conflict with each other (Ellis 2006). The extreme case is multiverse proposals, where no direct observational tests of the hypothesis are possible, as the supposed other universes cannot be seen by any observations whatever, and the assumed underlying physics is also untested and indeed probably untestable. In this context one must re-evaluate what the core of science is: can one maintain one has a genuine scientific theory when direct and indeed indirect tests of the theory are impossible? If one claims this, one is altering what one means by science. One should be very careful before so doing. There are many other theories waiting at the door, wanting to be called science (astrology, Intelligent Design, etc.); and they will downgrade the value of science as a reliable tested theory. We do not wish cosmology to join that club. Consequently the very nature of the scientific enterprise is at stake in the multiverse debate: the multiverse proponents are proposing weakening the nature of scientific proof in order to claim that multiverses provide a scientific explanation. This is a dangerous tactic.

For a cosmologist, the basic problem with all multiverse proposals is the presence of a cosmic visual horizon (Ellis and Stoeger 1988). This horizon is the limit to how far away we can see, because signals travelling toward us at the speed of light (which is finite) have not had time to reach us from farther out since the universe became transparent to light. All the proposed parallel universes lie outside our horizon and remain beyond our capacity to see, now or ever, no matter how technology evolves. In fact, they are too far away to have had any influence on our universe domain whatsoever. That is why none of the claims made by multiverse enthusiasts can be directly substantiated.

The situation is indicated in Fig. 1: a causal diagram (a spacetime diagram with spatial distances scaled so that light rays are at ±45°) with our galaxy's world line

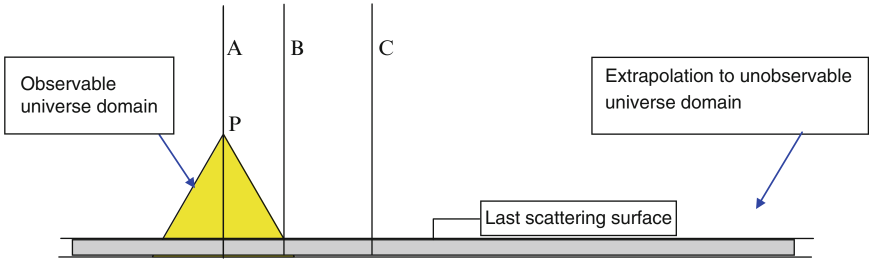

Fig. 1 Causal diagram of the observable region of the universe (horizontal distances are not to scale: they have been chosen so that world lines of matter are vertical, even as the universe expands). The start of the universe is the horizontal line at the *bottom*. *P* is here and now. The *triangular* domain is the entire visible universe, bounded by our past light cone: the paths of incoming light from the left and right. *A* is our world line. *B* is the visual horizon: the world line of the furthest out matter we can see through any electromagnetic radiation whatever, because the universe is opaque to such radiation at times earlier than the events on the last scattering surface. *C* is an example of a galaxy we have no causal contact with and about which we will never have any information (remember that the time from start of the universe to P is 14 billion years)

the vertical line at the centre; all other galaxy world lines are other vertical world lines. The horizontal line at the bottom is the start of the universe at time $t = 0$ (note that spatial distances are badly represented in this diagram, in order to represent light rays as diagonal lines). The shaded region between the two horizontal lines indicates the universe prior to decoupling of matter and radiation: this part of our spacetime history is unobservable because the universe was opaque to radiation then. It ends at the surface of last scattering, when matter and radiation separated from each other; this is when the Cosmic Microwave Background Radiation (CMB), observed inter alia by the Wilkinson Microwave Anisotropy Probe (WMAP), was emitted. The entire observable universe lies in triangular shaded region, because no signal can travel faster than light.[2]

The key observational point is that the domains considered by multiverse proponents are beyond the particle horizon and are therefore unobservable. The proponents are telling us we can state in broad terms what happens 1,000 times as far as our cosmic horizon, 10^{100} times, $10^{1000000}$ times, an infinity—all from data we obtain within the horizon. It is an extrapolation of an extraordinary kind. Maybe the universe closes up on a very large scale and there is no infinity out there. Maybe all the matter in the universe ends somewhere and there is empty space forever after. Maybe space and time come to an end at a singularity that bounds the universe. We just do not know what actually happens, for we have no information about these regions and never will.

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[2] For more detail, see the spacetime diagrams by Mark Whittle at http://sol.astro.virginia.edu/class/whittle/astr553/Topic16/t16_light_cones.html.

Despite these problems, various proposals have been made suggesting we can indeed verify the multiverse proposal. What are the arguments and evidence for existence of a multiverse?

The Slippery Slope Argument

The first, due to Martin Rees (2001, 2003), encourages us to go down the following slippery slope. First: we believe on good grounds that galaxies exist within the visual horizon but beyond the limits of detection of present day telescopes. We have not seen them yet, but will do so as detectors improve. Second: nobody seriously doubts that they exist in other similar nearby domains that intersect with ours: we share some galaxies with them, even though we cannot see all the same galaxies that observers over there can. We believe conditions there are similar to here, and have some marginal evidence that this is the case because we can see part of those domains. Third, by a further extension of this kind of argument, it is reasonable to expect they will exist even beyond in never-observable regions quite distinct from our own domain and without any present causal observational connection with it but with a joint causal past. So finally it is reasonable to assume we can take another similar step and assume galaxies exist even in completely disjoint universes without any causal connection with ours whatever. At each step we can reasonably assume that galaxies will continue to exist, as they did in the last stage, because each is a similar move and in each case the previous step is true.

The problem is that this series of steps at its latter stages assumes a continuity of structure for which there is no evidence whatever, and there is no guarantee of such continuity.[3] And the argument taken at its face value asserts what used to be assumed as the *Cosmological Principle* (Bondi 1960; Weinberg 1972): namely that the universe is *globally* a Robertson-Walker universe, that is, spatial homogeneity and isotropy continue without bound in all directions. But that argument would then disprove another multiverse contender—namely chaotic inflation, in which case there is no such global Robertson-Walker geometry. Indeed it would say, in my terms (see above), that there is no multiverse—just unseeable domains in a single universe. Actually the proposal is neither provable, nor disprovable. Uncertainty remains, because no evidence is available.

Implied by Known Physics that Leads to Chaotic Inflation

Many researchers have proposed processes at or near the Planck era which would generate an ensemble of expanding universe domains, one of which is our own observable universe. The chaotic inflationary proposal (Linde 1983, 1990, 2003) is one of the best-known scenarios of this type. The scalar field (inflaton) in these

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[3] A discussion of testability in this context is given in Ellis (1975).

scenarios drives inflation and leads to the generation of a large number of causally disconnected regions of the Universe. Our own observable universe region is then situated in a much larger universe that is inhomogeneous on the largest scales, because the different domains can have different cosmological parameters. No FLRW approximation is possible globally; rather there are many FLRW-like sub-domains (with different FLRW parameters) in a single fractal universe (Guth 2001).

Applying a stochastic approach (Vilenkin 1983; Starobinsky 1986; Linde et al. 1994), probability distributions can be derived for such models from specified inflaton potentials on using the slow-roll approximation for the inflationary era. This kind of scenario suggests how overarching physics, or a *law of laws* (represented by the inflaton field and its potential together with the Friedmann equation and Klein Gordon equation), can lead to a really existing ensemble of many very different FLRW-like regions of a larger Universe.

However even if inflation can be taken as a well-tested theory because of its prediction of the CMB anisotropy patterns, it is not a unique theory with well determined parameters, or even with well determined physics. It employs inflaton potentials which as yet have no connection to the particle physics we know at lower energies. If the version proposed is of the type suggested by Linde (based on slow rolling down a quadratic potential), the parameter values may or may not be such as to lead to eternal chaotic inflation (Linde and Noorbala 2010). If it is of the type proposed by Susskind and Yamauchi et al. (2011), the key physics (Coleman-de Lucia tunnelling) is extrapolated from known and tested physics to new contexts; the extrapolation is unverified and indeed is probably unverifiable; it may or may not be true. Furthermore, there is no clear theoretical link showing their dynamics would lead to different physics occurring in different domains in cosmology. This is not implied by any known physics. Many versions relate this to the supposed huge numbers of vacua of string theory (Susskind 2003; Davies 2004). However there is no direct link between string theory vacua and chaotic inflation The dominant proposal to link inflation to string theory is via the KKLT mechanism (Kachru et al. 2003), which is hypothetical and untested.

These proposals rely on extrapolations of presently known physics to realms far beyond where its reliability is assured. It is often implied that these proposals are implications of known physics: that *known physics* implies a multiverse. This is not the case. The true proposal is that *known physics* leads by major extrapolation to *hypothetical physics*, and by implication to the multiverse. The physics is hypothetical rather than tested! It is a great extrapolation from known physics. This extrapolation is untestable: it may or may not be correct.

Anthropic Issues: Values of Fundamental Constants

It is the only physical explanation for fine tuning of parameters that lead to our existence, in particular the value of the cosmological constant. This has been discussed above (section "The Motivation").

In brief: a remarkable fact about our universe is that physical constants have just the right values needed to allow for complex structures, including living things. Weinberg, Rees, Susskind and others contend that a multiverse provides a viable explanation for this apparent coincidence. If all possible values occur in the collection of universes, then viable ones for life will surely be found somewhere. This reasoning has been applied, in particular, to explaining the value of the cosmological constant that is speeding up the expansion of the universe today.

One of the issues here is that the proposal is far from unique, because it is not obvious what variations should be allowed in the assumed multiverse (Ellis et al. 2003). For example, most analyses of the issue assume physics is essentially the same everywhere with only the constants differing—but if one takes the multiverse seriously, this need not be the case, for example there could be life without the weak force (Gedalia et al. 2011). We can suppose whatever we like about what varies in the multiverse, and no one can prove it either correct or incorrect.

The multiverse is indeed a possible valid explanation for the value of the cosmological constant; in fact it is really the only scientifically based option right now for explaining this value. But we have no hope of testing it observationally: it is a theoretical explanation unsupported by observational verification of its basic assumptions, so its adoption is based in prioritising explanation over observational testing.

The Speciality Argument

A refinement of this argument considers the issue: Is the universe even more specially tuned than our presence requires, or is it ‘typical’ of the subset in which we could have emerged? The claim is that if our universe turns out to be even more specially tuned than our presence requires, the existence of a multiverse to explain such “over-tuning” would be refuted. Hence this shows that multiverses are indeed a scientific idea, as they can be disproved in this way. The main application of this argument so far is to the cosmological constant Λ (Weinberg 2000b; Rees 2003; Hartle 2004): in any universe that allows life to exist, we would not expect Λ to be too far below the threshold for existence of life, else it would be more fine-tuned than necessary. Present data indicates that this is indeed so; thus, our universe is not markedly more special that it needs to be as far as Λ goes, provided we take into account the prior that life does indeed exist. Consequently, explaining its fine-tuning by assuming a multiverse is acceptable.

But the statistical argument only applies if a multiverse exists; it is simply inapplicable if there is no multiverse: we cannot apply a probability argument if there is no multiverse to apply the concept of probability to. This argument thus assumes the desired outcome before it starts; it simply is not applicable if there is only one physically existing universe. In that case we only have one object we can observe; we can do many observations of that one object, but it is still only one object (one universe), and you can’t do statistical tests if there is only one existent entity. In fact there is no value of Λ that can prove a multiverse either exists or does not exist. The argument is elementary logic: let **L** be a range of values for Λ, and **M** the multiverse hypothesis.

1. If M $\rightarrow$ **L**, it does not follow that **L** $\rightarrow$ **M**
2. If M $\rightarrow$ **L** only probabilistically, it does not follow that $\{$not **L**$\}$ $\rightarrow$ $\{$not **M**$\}$

This argument is in fact a weak consistency test on multiverses, that is indicative but not conclusive. Probability is a probe of the consistency of the multiverse proposal, not a proof of existence. Consistency tests must be satisfied, but they are not confirmation unless no other explanation is possible. The additional problem is that we don't know the measure to use here; but the result depends critically on it.

An alternative form of the analysis uses detailed calculations of structure formation, and is based on a 'principle of mediocrity'—the assumption that our civilisation is typical in the ensemble of all civilisations in the universe (Vilenkin 1995; Weinberg 2000a). However the mediocrity assumption may or may not be true; its adoption is based on philosophical presuppositions rather than scientific proof. Additionally, the physical assumptions used in the specific calculation may be reasonable, but they are not proven to be true.

Overall this argument is supportive but far from conclusive.

A Multiverse Is Indicated by the Theory that "Everything that Can Happen, Happens"

In seeking to explain why nature obeys certain laws and not others, some physicists and philosophers have speculated that nature never made any such choice: all conceivable laws apply somewhere (Sciama 1993; Deutsch 1997; Lewis 2000). The idea is inspired in part by quantum mechanics, which, as Murray Gell-Mann put it, holds that everything not forbidden is compulsory.[4] A particle takes all the paths it can, and what we see is the weighted average of all those possibilities. Perhaps the same is true of the entire universe, implying a multiverse. But astronomers have not the slightest chance of observing this multiplicity of possibilities. Indeed we cannot even know what the possibilities are. We can only make sense of this proposal in the face of some unverifiable organising principle or framework that decides what is allowed and what is not—for example, all possible mathematical structures must be realised in some physical domain (as proposed by Tegmark 1998, 2004). But we have no idea what kinds of existence this principle entails, apart from the fact that it must of necessity include the world we see around us. And there is no way whatever that we can verify the existence or nature of any such organising principle.

It is in some ways an attractive proposition: but its proposed application to reality is pure speculation. And in the end it is a theoretical explanation, taken to have priority over observation.

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[4] Gellman was quoting from T.H. White, *The Once and Future King*.

Proposed Observational Tests for a Multiverse

Although the theoretical arguments fall short of being a proof, cosmologists have also suggested various observational tests as to how measurements can indeed refute or support the multiverse

Can be Disproved if We Determine there are Closed Spatial Sections

There are two variants of this proposal. The first is that only negatively curved FRW models can emerge in a chaotic inflation multiverse, because Coleman-de Lucia tunnelling only gives universes with negative spatial curvature ($k = -1$: Freivogel et al. 2006). But that claim is already disputed; there are other papers suggesting tunnelling to positive curvature spaces ($k = +1$) is possible. Furthermore, as emphasized above, it depends on a very specific speculative mechanism, which has not been verified to actually work, and indeed such verification is impossible.

The second is the comment that if the spatial sections of the universe are positively curved ($k = +1$), then the universe is finite, and the chaotic inflation version of the multiverse is therefore disproved. Now one might try to prove this by showing that the spatial curvature of the observed domain is positive. Then if this continues unchanged beyond the horizon, the universe is necessarily spatially closed. But this extrapolation might not be true: we could live in high density lump imbedded in a low density universe, so the extrapolation of the $k = +1$ model to the unseen domain may not be valid. This version is not conclusive. However, there are some specific cases where this project could indeed be carried out. These are if we live in a ‘small universe’, where we have already seen right round the universe (Ellis and Schreiber 1986; Lachieze-Ray and Luminet 1995), for then the universe closes up on itself in a single FLRW-like domain, and we can indeed see it to be so. Then no further such domains that are causally connected to us can exist in a single connected spacetime.

This small universe situation is observationally testable, and indeed it has been suggested that the Cosmic Background Radiation (CMB) power spectrum might already be giving us evidence that this is the case, because of the lack of power on largest angular scales (Luminet et al. 2003). This proposal can be tested in the future by searching for a drop in CMB power at large scales and an alignment of the CMB quadrupole and octopole axes (for which the present evidence is good, see Katz and Weeks 2004) and—more conclusively—for the existence of identical circles in the CMB sky (Cornish et al. 1998). The evidence in this regard is inconclusive: simpler cases have been ruled out, but more complex ones (with rather large identification scales) might eventually be shown to be the case. Confirmation of a small universe in this way would disprove the chaotic inflationary multi-domain scenario.

Filled Circles in the CMB Sky: Previous Era Remnants

The background radiation might contain remnants of universes that existed before the big bang in an endless cycle of universes. The specific case of the Conformal Cyclic Cosmology proposed by Penrose might be observable in principle by anomalous filled circles in CBR anisotropy observations (Penrose 2010; Tod 2011). It has indeed been suggested this might have already been seen (Gurzadyan and Penrose 2011a, b), but this claim has been received with considerable scepticism (Moss et al. 2010). Similar claims have been made as regards the ekpyrotic universe and loop quantum cosmology models (Nelson and Wilson-Ewing 2011) but have not been confirmed. In any case many of the multiverses would not lead to such evidence; so one can test only some specific classes of multiverse models in this way.

Filled Circles in the CMB Sky: Bubble Collisions

In eternal inflation driven by a scalar potential with multiple minima, the observable universe exists in one of numerous bubbles formed by transitions out of a false vacuum. There is a competition between the expansion rate of the universe at that time and the bubble nucleation rate. If they are about comparable it is possible these bubbles could collide (Kleban 2011), perhaps leading to detectable effects on the CMB radiation. It is claimed (Aguirre and Johnson 2009) that this constitutes a direct experimental test of eternal inflation and the landscape of string theory vacua. This has already been tried: Feeney et al. (2011) present observational tests of eternal inflation based on this idea, performing a search for cosmological signatures of collisions with other bubble universes in cosmic microwave background data from the WMAP satellite. They conclude that the WMAP 7-year data do not support the idea of bubble collisions, constraining the average number of detectable bubble collisions on the full sky to be less than 1.6 at 68 %.

If they were ever observed, this would be good supporting evidence for the multiverse hypothesis (it does not of course determine what happens much further out, but it does support the mechanism supposed to lead to these kinds of multiverses). However, if the expansion rate is much larger than the bubble nucleation rate, no such collisions will occur; hence the result is not definitive either way. One should also note that if we were to see such circles it would suggest the rate of nucleation is so large relative to rate of expansion that it might imply chaotic inflation would soon to come to an end (when all the available compact comoving inflationary space is used up).

Variation of Fundamental Constants

Supporting evidence for the proposed mechanism leading to variations in one or more fundamental constants would be observation of a variation in such constants which would corroborate the premise that the laws of physics are not so immutable after all (Barrow 2005; Shaw and Barrow 2007). Some astronomers claim to have found such variations (Webb et al. 2008). This is a controversial claim (see Uzan 2010 for a review of the arguments and data). Nevertheless it raises a very intriguing possibility: one can combine this with the idea of bubble collisions to suggest that if we ever did see such variation, it might be due to such collisions (Olive et al. 2011). A domain wall produced by spontaneous symmetry breaking might lead to domains on either side of the wall exhibiting slight differences in their respective values of the fine-structure constant h. If such a wall is present within our Hubble volume, absorption spectra at large redshifts may provide a variation in h relative to the terrestrial value. This would probably be the best observational support one could get for the multiverse scenario as it would support both the existence of the mechanism and its relevance to the cosmological context. It would be as close as one could get to direct observation of a multiverse.

Confirm or Undermine the Foundations

Finally, physicists might prove or disprove some of the theories that predict a multiverse. They might for example eventually find that the possibility space for supersymmetry has dwindled away so much, as experiments such as the LHC narrow down the mass range for squarks and gluinos, that it forces them to abandon string theory. That would undermine much of the motivation for supporting the multiverse idea, although it would not rule it out altogether.

Scientific Criteria

The underlying issue in determining if these arguments are sufficient to establish the existence of a multiverse or not, is which is more important in cosmology: theory (explanation) or observations (tests against reality)? Do we drop the need for testing in view of the brilliance of the theory?

Criteria for a Scientific Theory

To put the discussion on a more systematic basis we need to consider the various criteria for a good scientific theory. I suggest these can be characterised as follows (Ellis 2006):

1. ***Satisfactory structure***: (a) internal consistency, (b) simplicity (Occam's razor), (c) beauty' or 'elegance';
2. ***Intrinsic explanatory power***: (a) logical tightness, (b) scope of the theory—unifying otherwise separate phenomena;
3. ***Extrinsic explanatory power***: (a) connectedness to the rest of science, (b) extendability—a basis for further development;
4. ***Observational and experimental support***: (a) the ability to make quantitative predictions that can be tested; (b) confirmation: the extent to which the theory is supported by such tests.

The problem is that these criteria conflict with each other. You have to choose between them! Any satisfactory theory has to satisfy most of these criteria; it is the last that characterizes a *scientific* theory, in contrast to other types of theories. But that is the where multiverse theories are weakest.

Too Much Freedom

All in all, the case for the multiverse is inconclusive. The basic reason is the great freedom of the proposal, which allows almost anything to be explained—and consequently nothing specific can be predicted: any observation can be accommodated by some multiverse variant.

The key step in justifying a multiverse is extrapolation from the known to the unknown, from the testable to the untestable. You get different answers depending on what you choose to extrapolate, and experiment can't tell you which is the correct extrapolation. Most proposals involve a patchwork of different ideas that don't really fit together in a coherent whole (in particular, no cogent mechanism has been shown to actually cause physics to be different in each domain in a multiverse). In effect, multiverse proponents prioritize explanation (which drives this theory) over verification. The various "proofs" in effect propose that we should accept a theoretical explanation instead of insisting on the need for observational testing. But such testing has up to now been the central requirement of the scientific endeavour, and we abandon it at our peril. If we weaken the requirement of solid data, we have weakened the core reason for the success of science over the past centuries.

Now it is true that a satisfactory unifying explanation of some range of phenomena carries greater weight than a variety of separate arguments for the same set of phenomena, even if it assumes existence of unobservable quantities. Thus if each step in a chain of evidence is well understood and inevitable, then indirect evidence carries nearly as much weight as direct evidence. But not all the steps in this chain are inevitable. A key issue is how many unverifiable entities are needed for the explanation: are we hypothesizing more or less entities than the number of phenomena to be explained? In the case of the multiverse we are supposing existence of a huge number—perhaps even an infinity—of unobservable entities to explain just one existing universe. Of course we can explain almost anything in this way; but it hardly fits William of Occam's stricture that "entities must not be multiplied beyond necessity".

Problems with Infinity

It is often claimed that really existing ensembles involve an infinity of universes (e.g. Vilenkin 2007). However David Hilbert very strongly argued that a really existing infinite set is not possible (Hilbert 1964). The essential idea of infinity is that it is a number that can never be attained: it is always beyond reach. Hence Hilbert's basic position is that "the infinite is nowhere to be found in reality, no matter what experiences, observations, and knowledge are appealed to." Thus, it is important to recognise that infinity is not an actual number we can ever specify, determine or reach—it is simply the code-word for "it continues without end". And something that is not specifiable or determinate in quantity or extent is not physically realisable. Whenever infinities emerge in physics, we can be reasonably sure there has been a breakdown in our models. It is plausible that is true here too. I regard this as a significant argument against the usually claimed infinities in multiverses, and hence against the eternal chaotic inflation proposal as usually presented.

This is a philosophical argument. But additionally one should note that this claim is completely untestable: if we could see the members of an infinite ensemble of universes (which we can't), we could not possibly count them in a finite time, because we would (by definition) never compete the counting. Thus this claimed existence of physically existing infinities is not a scientific statement—if science involves testability by either observation or experiment. This strong claim in the multiverse context emphasizes how tenuously scientific that idea is.

Multiverses and Ultimate Causation

The need for the multiverse would fall away if we could explain the values on the basis of some fundamental physical theory that uniquely predicted these values—but then the basic puzzle would remain, namely why do these values allow life to exist? However, we are saved this predicament because that uniqueness is eluding physicists, who are rather faced with the 10^{500} possibilities of the landscape of string theory. So proponents of the multiverse make one final argument: that there are no good alternatives. As distasteful as scientists might find the proliferation of parallel worlds, if it is the best explanation, we would be driven to accept it; conversely, if we are to give up the multiverse, we need a viable alternative.

But is it the only explanation? That depends how broad your view of causation will go. This exploration of alternatives depends on what kind of explanation we are prepared to accept. This is a philosophical choice, based on the possibilities for ultimate explanation.

Ultimate Explanation

The basic options for ultimate causation of the universe are (Ellis 2006, 2011),

- Pure chance ("happenstance")
- High Probability
- Inevitability
- Design

The multiverse proposal is a way of trying to propose the second (the universe is in fact probable) in the face of its apparent improbability. But in fact it does not resolve the fundamental issues. All the same issues that arise in relation to the universe arise again in relation to the multiverse. If the multiverse exists, did it come into existence through necessity, chance, or purpose? That is a metaphysical question that no physical theory can answer for either the universe or the multiverse.

The various physical proposals made for generating mechanisms leading to the individual universes in a multiverse are either based in as yet unproven physics acting in an existent universe, or are in effect conceived of as mechanisms that precede the existence of physics, for they precede the existence of the universe. In either case the basic question above recurs, in a new form: *why that physics, that leads to this specific distribution function*? It could have been otherwise. All the same anthropic issues arise as for a single universe: Why this multiverse, and not another one? Why one which allows life?

Thus the multiverse proposal says nothing about ultimate causation. Does the idea of a multiverse preclude the monotheistic idea of a creator God?—is the idea in fact contrary to the idea of a creator? I argue that the answer is No, as already foreshadowed by Olaf Stapledon in his book *Starmaker*. The ideas can exist together: God could have chosen to operate via creation of multiverses. Indeed if one believes in a creator God, that is a much greater creator! Existence of a multiverse says nothing about ultimate theological issues.

Finally, given this uncertainty, is there a philosophically preferable version of the multiverse idea? I argue that Lee Smolin's idea of a Darwinian evolutionary process in cosmology (Smolin 1997) is the most radical and satisfactory one: it introduces the idea of Darwinian natural selection into cosmology: an extension of physics fundamentals to include biological principles. It is incomplete in several ways (Rothman and Ellis 1992) but represents a refreshing change from the view that the usual kinds of physical principles are all that occur in the cosmological domain.

What Kind of Data Is Relevant for Discussing This?

Purely physical arguments encompass only a part of the data available to us. In dealing with issues of ultimate causation, one needs to take into account data other than the physical—such issues as the existence of love and hate, of beauty and ugliness, or good and evil. For example, there is indeed meaning in the universe, no matter what eminent physicists may say. It undoubtedly exists. If it did not, you would not be reading this chapter!

Hence an evaluation of the ultimate cause of either a universe or multiverse must take into account issues such as the origin of meaning and morality as well as the physical and astronomical data. I will not pursue this here (see Murphy and Ellis 1996; Ellis 2011) except to comment on one issue: is the degree of faith required to believe in a multiverse more or less than that required to believe in a creator God? I argue that because of the lack of conclusive evidence in both cases, the degree of faith required to believe in either is the same. Both can be argued on the basis of reasonable extrapolation from known data. Neither is in fact provable. Despite scientific appearances, belief in a multiverse is an exercise in faith.

Conclusion

The multiverse idea is not provable either by observation, or as an implication of well established physics. It may be true, but cannot be shown to be true by observation or experiment. However it does have great explanatory power: it provides an empirically based rationalization for fine tuning, developing from known physical principles. Here one must distinguish between explanation and prediction. Successful scientific theories make predictions, which can then be tested. The multiverse theory can't make any unique predictions because it can explain anything at all. Any theory that is so flexible is not testable because almost any observation can be accommodated.

I conclude that multiverse proposals are good empirically-based philosophical proposals for the nature of what exists, but are not strictly within the domain of science because they are not testable. I emphasize that there is nothing wrong with empirically-based philosophical explanation, indeed it is of great value, provided it is labelled for what it is. To make progress, we need to keep to the idea that empirical testing is the core of science. We need some kind of causal contact with whatever entities we propose; otherwise there are no limits. The link can be a bit indirect. If an entity is unobservable but absolutely essential for properties of other entities that are indeed verified, it can be taken as verified. But then the onus is to prove it is absolutely essential to the web of explanation.

I suggest that cosmologists should be very careful not make methodological proposals that erode the essential nature of science in their enthusiasm to support specific theories as being scientific, for if they do so, there will very likely be unintended consequences in other areas where the boundaries of science are in dispute. It is dangerous to weaken the grounds of scientific proof in order to include multiverses under the mantle of 'tested science' for there are many other theories standing in the wings that would also like to claim that mantle. It is a retrograde step towards the claim that we can establish the nature of the universe by pure thought, and don't then have to confirm our theories by observational or experimental tests: it abandons the key principle that has led to the extraordinary success of science.

What is strange is that people who claim to be strong on the difference between science and faith also defend the multiverse strongly: for example Richard Dawkins in *The God Delusion* (Dawkins 2006). Dawkins and colleagues pontificate about the way science is evidence based, as opposed to religion which is faith based. They then embark on a faith-based defence of the multiverse, abandoning the standards they have just set for what science ought to be. The philosophy apparently is, you stoutly demand the need for evidence when it suits your purposes, and abandon it when it does not. What we rather need is an honest philosophy of cosmology that is consistent about evidence, and admits when it is not attainable.

Appendix

I am astounded that serious scientists and philosophers can propose that the universe could be a computer simulation (Bostrom 2003; Greene 2011). It is totally impracticable from a technical viewpoint, and ignores the way the human mind is bodily-embedded and not an algorithmic computer process. It raises far more questions than it answers:

- Where is this computer?
- How did it come into being?
- Why does it not crash every few seconds?
- How could this be proved to be the case—what evidence is there? How could it be disproved?

Protagonists seem to have confused science fiction with science. Late night pub discussion is not a viable theory.

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Lemaître's Prescience: The Beginning and End of the Cosmos

Bernard Carr

Abstract Lemaître anticipated what are now assumed to be the most plausible models for both the beginning and the end of cosmos. He was also prescient in forging a link between microphysics and macrophysics, a process which is only culminating today, and his solutions with a cosmological constant provide a particularly interesting version of the modern-day multiverse scenario. Although some of his ideas were at first regarded sceptically by mainstream physics, their later reception illustrates that the boundary between cosmology and meta-cosmology is always evolving. He was generally reluctant to link cosmological and theological ideas but I will argue that cosmology offers some scope for productive science-religion dialogue and suggest that mind may be a fundamental rather than incidental feature of the universe.

Introduction

Lemaître's many contributions to cosmology are well described elsewhere in this volume but perhaps his most striking achievement was to be the first person to anticipate the currently favoured models for the beginning and the end of the cosmos. In these anticipations, he showed remarkable prescience. His proposal of the Big Bang model preceded the discovery of the cosmic background radiation by 34 years, his highlighting of quantum effects in the early universe preceded the inflationary model by 50 years, and his studies of models with a cosmological constant preceded the discovery of the cosmic acceleration by 67 years.

While these achievements explain my choice of title and are described briefly here, most of this article will not focus on Lemaître's own work. Rather it will use

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his ideas as the starting point for a discussion of more modern topics. I first explain how his idea of the primeval atom was a crucial step in linking microphysics and macrophysics, a process which is only culminating today. I then discuss the (possibly anthropic) fine-tuning of the cosmological constant, the term given such prominence in Lemaître's work. This is one of many such fine-tunings but it is perhaps the most important one because of the *degree* of tuning and because it has led many prominent particle physicists to become interested in the topic. I then review the idea of a multiverse as a possible explanation of these fine-tunings, but only briefly since this is discussed in other contributions to this volume. Lemaître's family of solutions with differing cosmological constant provides a particularly interesting version of the multiverse, although the physical motivation for this only arose recently.

Some of these ideas stretch science to its limits – perhaps even beyond – so the rest of this paper trespasses into even more philosophical domains! Although cosmology is now firmly established as a branch of mainstream physics, sceptics have often regarded it as bordering on metaphysics. The discussion about 'meta-cosmology' at the meeting emphasized that this is still true today. However, I argue that the cosmology/meta-cosmology border is always evolving and that the nature of science changes as it does so. Indeed, the term 'prescience' in my title is intended as a *double entendre,* since many of Lemaître's cosmological ideas were regarded as 'pre-science' when first advocated. I then use a variety of perspectives to argue that mind is a fundamental rather than incidental feature of the Universe and infer that science should expand to accommodate it. Finally, I turn to issues on the border of cosmology and theology. Despite being a priest, Lemaître was always reluctant to link these two areas – merely regarding them as independent paths to truth – but my own view is that modern cosmology might be expected to offer at least some scope for productive science-religion dialogue.

Brief Summary of Lemaître's Cosmological Contribution

Although the first relativistic cosmological models were those of Einstein and de Sitter in 1917, these were static and empty, respectively, so not relevant to the real universe. Friedmann's 1922 paper provided the first dynamical solutions with matter but Lemaître's 1927 paper (which derived these solutions independently) was the first one to make a direct comparison with observations. Indeed, David Block (2011) has argued that Lemaître anticipated Hubble's law, a modern fit to his data giving a Hubble constant of 625, compared to the value of 530 given in Hubble's own 1929 paper. Lemaître has not received credit for this because the relevant part of his paper was not included when the translated version appeared in 1931. Whatever the status of this claim for priority, what is indisputable is that he was the first person to consider the implications of the Universe having started in a state of great compression. He announced his model of the 'primeval atom' at a 1931 meeting of the British Association (curiously on the topic of science and

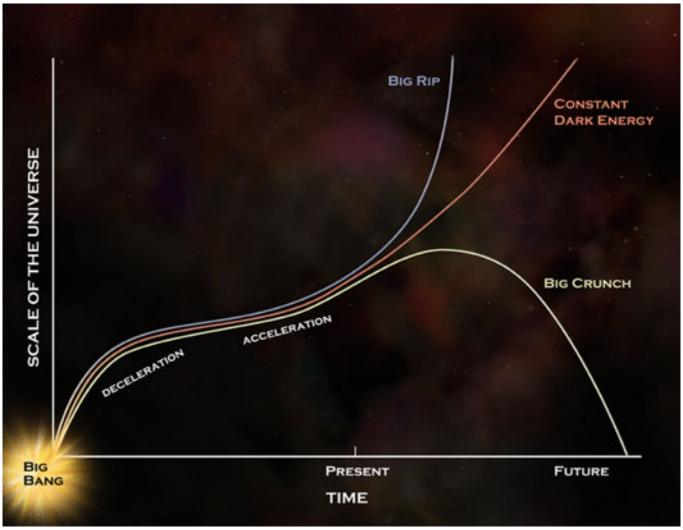


Fig. 1 The evolution of the cosmos from its beginning until its end, the middle curve being currently favoured (Credit: NASA/Chandra X-ray observatory)

religion) and it was published in *Nature* the same year. He is therefore rightly regarded as the 'father of the Big Bang', although it was 15 years before his 1946 book *L'Hypothese de l'Atome Primitif* appeared and then a further 3 years before Fred Hoyle introduced the term Big Bang.

The claim that Lemaître anticipated the *future* of the cosmos arises because of his studies of models with a cosmological constant. The Eddington-Lemaître model of 1930 starts with a Big Bang, then has a prolonged coasting phase in which it is very close to the Einstein static model, and finally enters an exponentially expanding de Sitter phase. This requires fine-tuning of the cosmological constant but it was popular in the 1950s as an explanation for why the age of the Universe seemed to be much larger than the inverse Hubble timescale then favoured. Nowadays a coasting phase is unnecessary because we know that the Hubble constant is much smaller (around 72). However, the discovery in 1997 that the Universe is accelerating revived interest in more general models with a cosmological constant. In this case, the most likely future fate of the universe is exponential expansion. Of course, we cannot be sure of this: quintessence models may offer a different fate, phantom-dominated models face the 'big rip' and the conformal cyclic model ends up with another big bang. However, Lemaître's model is at least the most plausible in the immediate future. The justification for my title is epitomized in Fig. 1, which shows the evolution of the scale factor in Lemaître's model from beginning to end.

As discussed elsewhere in this volume, Lemaître made many other crucial contributions to cosmology. His work on inhomogeneous gas clouds in 1933 led to the famous Lemaître-Tolman-Bondi models, so crucial for understanding the growth of density fluctuations into the observed large-scale structure. His realization that the cosmological constant relates to the vacuum density and that there could be quantum fluctuations in this density anticipated the attractions of the inflationary model. His development of numerical computing in the 1950s – using the most sophisticated machines available at the time and Fast Fourier Transform techniques – presaged the era of computational cosmology. He did not get everything correct: he was wrong in attributing cosmic rays to the Big Bang and his cold model of cosmological nucleosynthesis (in which the initial vacuum disintegrates into a cloud of atoms) was superseded. Nevertheless, he surely richly deserves the epithet 'prescient'.

Lemaître and the Macro–Micro Connection

The history of physics might be regarded as a process in which the development of new instruments, like the telescope and the microscope, has allowed us to extend observations *outwards* to progressively larger scales and *inwards* to successively smaller ones. The outward journey explores the *macroscopic* domain and is associated with astronomy, while the inward journey explores the *microscopic* domain and is associated with particle physics. Of course, a lot of interesting physics – including the whole domain of biophysics – is associated with complex structures in the intermediate *mesoscopic* domain and that will be the focus of the next section. This process has revealed ever larger and smaller levels of structure in the Universe: planets, stars, galaxies, clusters of galaxies and the entire observable Universe on the macroscopic side; cells, DNA, atoms, nuclei, subatomic particles and the Planck scale on the microscopic side.

The journey has also led to the discovery of the forces which determine the nature of these structures – gravity and electromagnetism on large scales, the weak and strong forces on short scales – and the associated laws of nature. These forces link the macroscopic and microscopic domains, so that the outward and inward journeys are not disconnected but constantly throw light on each other. Both journeys have also led to new conceptual ideas and changes in our worldview. The macro one has led to the shifts from geocentric to heliocentric to galactocentric to cosmocentric worldviews and to the radical change of view of space and time entailed in relativity theory. The micro one has led to atomic theory, quantum theory and a progressively unified view of the forces of nature and the fundamental constituents of matter. Any final paradigm of physics must amalgamate relativity and quantum theory in some way.

So physics has revealed a unity about the Universe which makes it clear that everything is connected in a way which would have seemed inconceivable a few decades ago. This unity is succinctly encapsulated in the image of the *Cosmic Uroborus* (the snake eating its own tail) shown in Fig. 2 and based in part on a version from Abrams and Primack (2011). This demonstrates the intimate link between the macroscopic domain (on the left) and the microscopic domain (on the

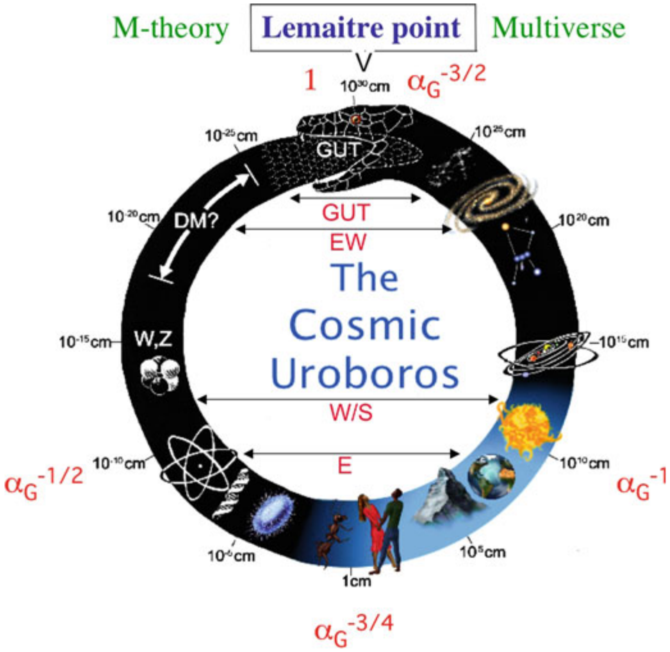


Fig. 2 The *Cosmic Uroborus* summarizes the different types of structure in the Universe. Also shown are the cross-links associated with various forces. The overall scale in Planck units is determined by the gravitational fine structure constant $\alpha_G \sim 10^{-40}$. The macro and micro scales merge at the Big Bang, associated with Lemaître, where qualitatively new physics may arise

right). The numbers at the edge indicate the scale of these structures in centimetres. As one moves anticlockwise from the tail to the head, the scale increases through 60 decades: from the smallest meaningful scale allowed by quantum gravity (10^{-33} cm) to the scale of the observable Universe (10^{27} cm). So one can regard the Uroborus as a clock in which each minute corresponds to a decade in scale.

The horizontal lines in Fig. 1 correspond to the various interactions and illustrate the subtle connection between microphysics and macrophysics. For example, the 'electric' line (E) connects an atom to a planet because the electric force binds the electron to the nucleus in an atom and also determines the structure of solid objects. The 'strong' and 'weak' lines (W/S) connect a nucleus to a star because the strong force which holds nuclei together also provides the energy released in the nuclear reactions which power a star and the weak force which causes nuclei to decay also prevents stars from burning out too soon. The 'electroweak' line (EW) connects dark matter particles to galaxies because these may provide the invisible halos revealed by galactic rotation curves. The line associated with 'grand unified theory' (GUT) connects with large-scale structure because the density fluctuations which led to this originated when the temperature of the Universe was high enough for GUT interactions to be important.

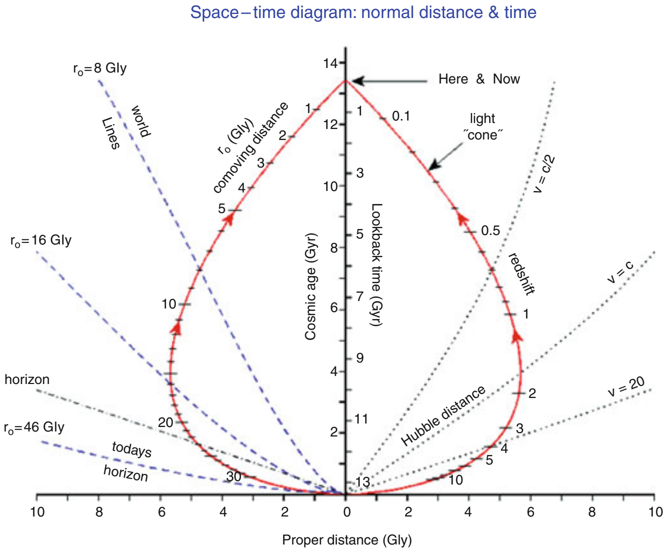


Fig. 3 The path of the past light-cone in a conformal spacetime representation of the Big Bang model in which one expands the spatial distances to see the causal structure. Light cones are always at ±45°, so there is a maximum observable distance (Credit: Mark Whittle)

The Big Bang might be regarded as the ultimate micro–macro link since it implies that the entire observable Universe was once compressed to a tiny volume. This is why the head of the snake meets the tail. Since light travels at a finite speed, we can never see further than the distance light has travelled since Big Bang; this is about 40 billion light-years, three times the age of the Universe times the speed of light because the cosmic expansion helps light travel further. More powerful telescopes probe to earlier times, rather than larger distances, as illustrated in Fig. 3. This is why early universe studies have led to an exciting collaboration between particle physicists and cosmologists. This link was anticipated in Lemaître's model of the primeval atom, so it is appropriate to label the top of the Uroborus as the 'Lemaître point'.

Cosmologists now have a fairly complete picture of the history of Universe: as one goes back in time, galaxy formation occurred at a billion years after the Big Bang, the background radiation last interacted with matter at a million years, the Universe's energy was dominated by its radiation content before about 10,000 years, light elements were generated through cosmological nucleosynthesis at around 3 min, antimatter annihilated with matter at about a microsecond (before which there was just a tiny fractional excess of matter), electroweak unification occurred at a billionth of a second (corresponding to nearly the highest energy which can be probed experimentally), grand unification and inflation occurred around 10^{-35} s, and the quantum gravity era (the smallest meaningful time) was at 10^{-43} s.

The last few decades have seen two further key developments on the outer front. First, the detection of temperature anisotropies in the cosmic background radiation

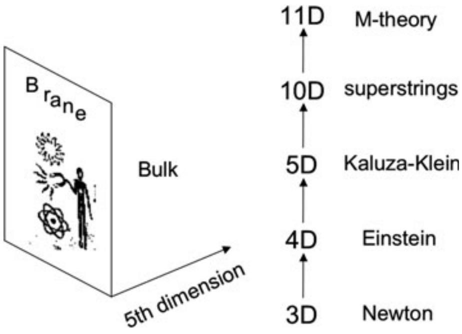


Fig. 4 The sequence of extra dimensions invoked in modern physics, the last of which is extended in brane cosmology

and ever more precise measurements of their dependence on angular scale have confirmed the quantum origin of the density fluctuations (Spergel et al. 2003). Second, although one expects the expansion of the Universe to slow down because of gravity, observations of distant supernovae suggest that it is *accelerating* (Riess et al. 1998; Perlmutter et al. 1999). We do not know for sure what is causing this but it must be some exotic form of 'dark energy', most probably related to the cosmological constant which plays such an important role in Lemaître's solutions. These discoveries have led to the concordance ΛCDM model and the popularity of the inflationary model. Another idea that has become topical is that our entire Universe may be just one member of huge ensemble of universes called the multiverse, a notion we discuss further later.

On the inner front, we have learnt that it may be possible to incorporate gravity into the unification of forces, leading some physicists to proclaim that we are on the verge of obtaining a Theory of Everything (TOE). However, in order to describe all the subatomic interactions, this requires extra wrapped-up dimensions of the kind proposed by Theodor Kaluza (1921) and Oskar Klein (1926) to explain electromagnetism. For example, superstring theory suggests there could be six additional spatial dimensions and the way they are compactified is described by the Calabi-Yau group. There were originally five different superstring theories but it was later realized that these are all parts of a single more embracing model called M-theory, which has seven extra dimensions. In one particular variant of M-theory, proposed by Lisa Randall and Raman Sundrum (1999), the eleventh dimension is extended, so that the physical world is viewed as a four-dimensional brane in a higher-dimensional bulk. The development of these ideas is summarized in Fig. 4. We do not experience these extra dimensions directly – their effects only become important on the smallest and largest scales (i.e. at the top of the Uroborus) – so it is clear that our ordinary senses reveal only a limited aspect of physical reality.

Lemaître and the Anthropic Principle

Taken together, scientific progress on both the outer and inner fronts – culminating in the Big Bang model – can be regarded as a triumph. However, this achievement has come at a price. The anthropocentric view which prevailed at the start of the journey has been demolished and the more we probe the Universe, the more irrelevant humans seem to become. We are completely insignificant not only as judged by scale but also in terms of duration. If the history of the Universe were compressed into a year, *homo sapiens* would have persisted for only the last few minutes. Indeed, Newton's mechanistic paradigm suggests that the Universe is just a machine, completely oblivious to the presence of observers.

Curiously, in recent decades cosmology has brought about a reversal in this trend and we will see that Lemaître (albeit unwittingly) played a role in this. This is because it seems that some features of the Universe have to be as observed because otherwise it could not produce life and we would not be here speculating about it. This notion – dubbed the Anthropic Principle by Brandon Carter – arises because some of the constants of physics seem to be fine-tuned for the emergence of observers (Carter 1974; Carr and Rees 1979; Barrow and Tipler 1986; Hogan 2000; Rees 2001). Although 'anthropos' is the Greek for 'man', this is a misnomer because the fine-tunings have nothing to do with *homo sapiens* in particular. As discussed later, they just seem necessary for the development of complexity.

As a simple example of an anthropic argument, consider the question: Why is the Universe as big as it is? The mechanistic answer is that, at any particular time, the size of the observable Universe is the distance travelled by light since the Big Bang. There is no compelling reason the Universe has the size it does; it just happens to be about 10^{10} year old. There is, however, another answer to this question, which Robert Dicke (1961) first gave. In order for life to exist, there must be carbon, and this is produced by cooking inside stars. The process takes about 10^{10} year, so only after this time can stars explode as supernovae, scattering the newly-baked elements throughout space, where they may eventually become part of life-evolving planets. On the other hand, the Universe cannot be much older than 10^{10} year, else all the material would have been processed into stellar remnants. Since all the forms of life we can envisage require stars, this suggests that it can only exist when the Universe is aged about 10^{10} year. So the very hugeness of the Universe, which seems at first to point to our insignificance, is actually a prerequisite of our existence. This is not to say that the Universe itself could not exist with a different size, only that we could not be aware of it then.

Dicke's argument is an example of what is called the Weak Anthropic Principle and is no more than a logical necessity. This accepts the constants of nature as given and then shows that our existence imposes a selection effect on when (and where) we observe the Universe. Much more controversial is the Strong Anthropic Principle (SAP), which claims that there are tunings between the physical constants themselves. Some of the tunings involve the dimensionless coupling constants which characterise the strengths of the four forces: $\alpha \sim 10^{-2}$ for electromagnetism, $\alpha_G \sim 10^{-40}$ for gravity, $\alpha_W \sim 10^{-10}$ for the weak force and $\alpha_S \sim 10$ for the strong force. Indeed, it is possible that all these parameters are roughly determined by anthropic arguments. The fact that α_G is tiny is of particular interest since this determines all the scales appearing in Fig. 2, simple physics showing that these can be expressed as powers of α_G (Carr and Rees 1979). This is because the main-sequence lifetime of stars is roughly $\alpha_G^{-1} t_P$, where $t_P \sim 10^{-23}$ s is the proton timescale, so Dicke's argument implies that the size of the observable Universe must be roughly $\alpha_G^{-3/2} \sim 10^{60}$ in Planck units. This explains the clocklike feature of the Uroborus (i.e. the factor of 60). If α_G were different, the form of the Uroborus would remain the same but all the scales would change.

One of the most striking SAP arguments is associated with the existence of stars with convective and radiative envelopes. Both types of star can exist only if α_G is roughly the 20th power of α (Carter 1974). This is because the critical mass which divides these types of stars is roughly $\alpha_G^{-2} \alpha^{10} m_p$, where m_p is the proton mass, whereas the *expected* masses of stars span a few decades around $\alpha_G^{-3/2}$ m_p. The relationship $\alpha_G \sim \alpha^{20}$ is clearly satisfied numerically but physics does not explain why the relationship should have this particular form. Its anthropic significance is that only radiative stars can end their lives as supernovae, whereas only convective stars may generate winds in their early phase and this may be associated with rocky planets. This is one of the most striking coincidences because of the high power of α involved. Don Page (2009) has discussed this argument in more detail and shown that it constrains the electron charge to 3%.

In order for neutrinos to eject the envelope of a star in a supernova explosion, α_G must be roughly the fourth power of α_W. If the weak force were weaker, the neutrinos would stream through the stellar surface unimpeded; if it were much stronger, they would be trapped inside the core and never reach the surface. The same coincidence explains why an interesting amount of helium (roughly 23% by mass) is generated by cosmological nucleosynthesis because the amount produced is very sensitive to the temperature at which the weak interactions freeze out. If the weak force were slightly stronger, freeze-out would occur later and the amount would be drastically reduced. If it were slightly weaker, freeze-out would be earlier and almost all the nucleons would burn into helium, preventing the formation of hydrogen-burning stars. At least the latter condition might be anthropically excluded since helium-burning stars may be too short-lived for life to arise on surrounding planets.

Perhaps the most famous SAP argument concerns the generation of carbon (a prerequisite of at least our form of life) in the helium-burning phase of red giant stars via the triple-alpha reaction: two alpha particles first combine to form beryllium and this then combines with a third alpha particle to form carbon. However, as Hoyle first pointed out (Mitton 2011), the beryllium would decay before interacting with another alpha particle were it not for the existence of a remarkably finely-tuned resonance in this interaction. This is sometimes described as an anthropic prediction because the resonance was only confirmed experimentally later, although Kragh (2010) takes a different view. More recent work by Oberhummer et al. (2000) – calculating the variations in oxygen and carbon production in red giant stars as one changes the strength of the nucleon

Table 1 Cosmological parameters constrained by anthropic arguments

N = ratio of electrical and gravitational force between protons ~ 10^{38}
E = strength of nuclear binding in proton rest mass units ~ 0.007
Ω = matter density in critical units ~ 0.3
Λ = cosmological constant in critical units ~ 0.7
Q = amplitude of density fluctuations at horizon epoch ~ 10^{-5}
S = photon-to-baryon ratio ~ 10^{9}

interactions – indicates that the strength must be tuned to within at least 0.5% of its observed value if one is to account for this.

Several constraints involving the value of α_S are associated with chemistry. For example, if α_S were increased by 2%, all the protons in the Universe would combine at Big Bang nucleosynthesis into diprotons. In this case, there could be no hydrogen-burning stars, so – as mentioned above – there might not be time for life to arise; also there would presumably be no water. If α_S were increased by 10%, the situation would be even worse because everything would go into nuclei of unlimited size and there would be no interesting chemistry. The lack of chemistry would also apply if α_S was decreased by 5% because all deuterons would then be unbound and one could only have hydrogen. There are also chemistry-related fine-tunings involving the electron mass and the neutron-proton mass difference. Of course, from the perspective of modern particle physics, α_S is no longer so fundamental and the QCD interaction strength would be regarded as more important (Hogan 2000). Nevertheless, fine-tuning is still required at some level.

Other anthropic constraints are associated with various cosmological parameters, as listed in Table 1. Some of these involve the photon-to-baryon ratio $S \sim 10^9$. In the standard Big Bang model, the formation of galaxies cannot occur until the background radiation density falls below the matter density but this occurs after the main-sequence lifetime of a star, which we have seen is roughly $\alpha_G{}^{-1}t_p$, unless $S < \alpha_G{}^{-1/4} \sim 10^{10}$. On the other hand, if one requires that the Universe be radiation-dominated at cosmological nucleosynthesis, to avoid all the hydrogen going into helium, one requires $S > (m_p/m_e)^{4/3}\alpha_W{}^{2/3}\alpha_G{}^{-1/6} \sim 10^4$. Nowadays we believe the value of S results from baryon-violating processes in the early Universe – possibly occurring at the GUT epoch around 10^{-34} s after the Big Bang. However, in most GUT models S is predicted to be of the form α^{-n} where n is an integer, so the anthropic constraint $S < \alpha_G{}^{-1/4}$ merely translates into the constraint $\alpha_G < \alpha^{4n}$. If $n = 5$, this just gives the convective star condition.

A particularly interesting anthropic constraint is associated with the cosmological constant, denoted by Λ in Table 1, and this is how Lemaître enters the story. In principle, unless there is some physical law which requires it to be *exactly* zero, the value of this constant is arbitrary, so it could lie anywhere between plus and minus the Planck density (which is 120 orders of magnitude larger than the observed value). The actual value therefore seems implausibly small. There is also the puzzling feature that the observed vacuum density is currently very similar to the mean matter density, a coincidence which would only apply at a particular cosmological epoch. However, as first pointed out by Steven Weinberg (1987) and later discussed by George Efstathiou (1995) and Alex Vilenkin (1995), the value of Λ is constrained because galaxies could not form (and hence life could not arise) if it were much larger than observed. This is because the growth of density perturbations is quenched once Λ dominates the density, so if bound systems have not formed by then, they never will. Thus if one were to contemplate an ensemble of Lemaître models with a wide spread of values of Λ, our own existence would require that we occupy one of the tiny fraction in which the value is sufficiently small. The precise form of this constraint depends on the amplitude of the primordial density fluctuations at the horizon epoch, denoted by Q in Table 1. In particular, Tegmark and Rees (1998) have derived the anthropic upper limit on Λ as a function of Q. This is not the only explanation for the smallness of Λ but there is a reluctant acceptance that it may be the most plausible one. As we will see shortly, this possibility arises explicitly in M-theory. So although Lemaître himself never speculated about the Anthropic Principle, his cosmological models are the basis for one of the most popular variants of the idea. An alternative explanation for the near equality of the vacuum and matter densities is to invoke some form of scalar field – termed 'quintessence' – rather than a cosmological constant. However, some anthropic fine-tuning may be required even in this case (Kallosh 2007).

The fine-tunings discussed above might be regarded as a prerequisite for the large variety of structures appearing in Fig. 2. This is because a 'Pyramid of Complexity' arises as the Universe expands and cools (Reeves 1991), with different levels of structure as one goes from quarks (at the bottom) to nucleons to atoms to molecules to cells and finally to living organisms (at the top). No violation of the second law of thermodynamics is involved because local pockets of order can be purchased at the expense of a global increase in entropy, the fraction of matter going into these structures decreasing as one ascends the pyramid. The structures arise because processes cannot occur fast enough in an expanding Universe to maintain equilibrium. However, disequilibrium is only possible because of the anthropic fine-tuning of the coupling constants. This suggests that the Anthropic Principle should really be interpreted as a Complexity Principle. This raises the question of what qualifies as an observer in anthropic considerations (i.e. what minimum threshold of awareness is required). It would be arrogant to assign this distinction to humans alone. However, this issue may not be crucial since – whatever threshold one selects – it is likely to be attained relatively quickly (i.e. on a timescale of several billion years) once the first signs of life arise (Kauffman 1995). The crucial point is that it is likely to entail or lead to some form of *consciousness*, as indicated at the top of Fig. 5.

Anthropic arguments used to be regarded with disdain by many physicists – and in some quarters still are – because they seem to exclude the more usual type of physical explanation for the values of the constants. Three very different views of the Anthropic Principle are illustrated by following quotes. One is from the protagonist Freeman Dyson (1979):

> I do not feel like an alien in this Universe. The more I examine the Universe and examine the details of its architecture, the more evidence I find that the Universe in some sense must have known we were coming.

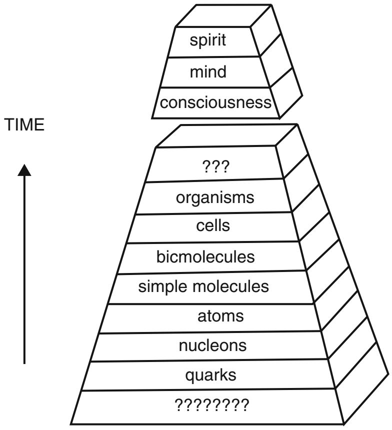


Fig. 5 Pyramid of complexity, showing build-up of increasingly complex structures with time from Big Bang, culminating in the emergence of possibly non-physical qualities

This might be contrasted with the view of the antagonist Heinz Pagels (1985):

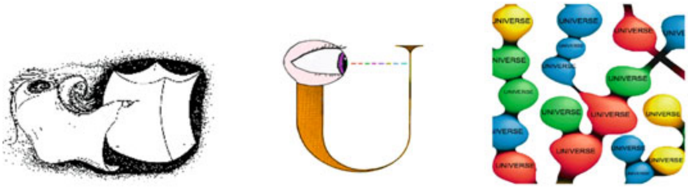
> The influence of the anthropic principle on contemporary cosmological models has been sterile. It has explained nothing and it has even had a negative influence. I would opt for rejecting the anthropic principle as needless clutter in the conceptual repertoire of science.

An intermediate stance is taken by Brandon Carter (1974):

> The anthropic principle is a middle ground between the primitive anthropocentrism of the pre-Copernican age and the equally unjustifiable antithesis that no place or time in the Universe can be privileged in any way.

As we will see, the rising popularity of the multiverse picture has recently encouraged a drift towards Carter's view. However, the A word is still taboo in some quarters.

As far as is known, the relationships discussed above are not predicted by any unified theory and, even if they were, it would be remarkable that the theory should yield exactly the coincidences required for life. Cosmologists have therefore turned to more natural interpretations of the anthropic coincidences and these are illustrated in Fig. 6. The first possibility – clearly relevant to the science-religion debate – is that they reflect the existence of a 'Creator' who tailor-made the Universe for our benefit. Such an interpretation is logically possible, but most physicists are uncomfortable with it. Another possibility, proposed by Wheeler (1977), is that the Universe does not properly *exist* until consciousness has arisen. This is based on the notion that the Universe is described by a quantum mechanical wave function and that consciousness is required to collapse this wave function. Once the Universe has evolved consciousness, one might think of it as reflecting back on its Big Bang origin, thereby forming a closed circuit which brings the world into existence. Even if consciousness really does collapse the wave function (which is far from certain), this explanation is also somewhat metaphysical. The third



God created universe

Consciousness created universe

Selection effect in multiverse

Fig. 6 Three possible interpretations of anthropic fine-tunings

possibility is that there is not just one universe but lots of them, all with different (randomly distributed) coupling constants (Carr 2007). In this multiverse proposal, we just happen to be in one of the small fraction which satisfy the anthropic constraints. This leads into the next section.

Multiverse Proposal

In the standard Big Bang theory, one can never see further than the distance light has travelled since the Big Bang and this defines the horizon of the *observable* universe. However, it would be perverse to claim that nothing *exists* beyond this distance. One would expect there to be other expanding domains which are still part of our Big Bang but unobservable. This is what Max Tegmark (2003) classifies as the Level I multiverse and it is relatively uncontroversial. If taken to extremes, it leads to some bizarre possibilities (like our having identical clones at great distance if space is infinite) but it would be hard to deny its existence at some level.

Recent developments in cosmology and particle physics have led to the more radical proposal that there could also be other Big Bangs which are completely disconnected from ours. These might be regarded as the inevitable outcome of the physical process that generated our Universe, corresponding to what Tegmark (2003) classifies as the Level II' multiverse. If one has a model for generating one Big Bang, it is not surprising that it would also produce others. Physicists have widely different views on how the different universes might arise, so the issue is not *whether* there is a Level II multiverse but how many kinds there are. Some come from cosmologists and others from particle physicists, so the multiverse might be regarded as the culmination of scientific attempts to understand the largest and smallest scales in Fig. 2.

Let us first examine the cosmological proposals. Some invoke oscillatory models in which a single universe undergoes cycles of expansion and recollapse (Tolman 1934), though without necessarily understanding what causes the bounce. In this case, the different universes are strung out in time. Others invoke the inflationary scenario, in which our observable domain is a tiny part of a single bubble which underwent an extra-fast accelerated expansion phase at some early time as a result of the effect of a scalar field (Guth 1981). Inflation not only implies that our observable domain is a tiny patch of a much larger Universe. Some versions also predict that there could be many other bubbles, corresponding to other universes spread out in space. A variant of this idea is eternal inflation, in which the universe is continually self-reproducing, so that there are an infinite number of bubbles extending in both space and time (Vilenkin 1983; Linde 1986).

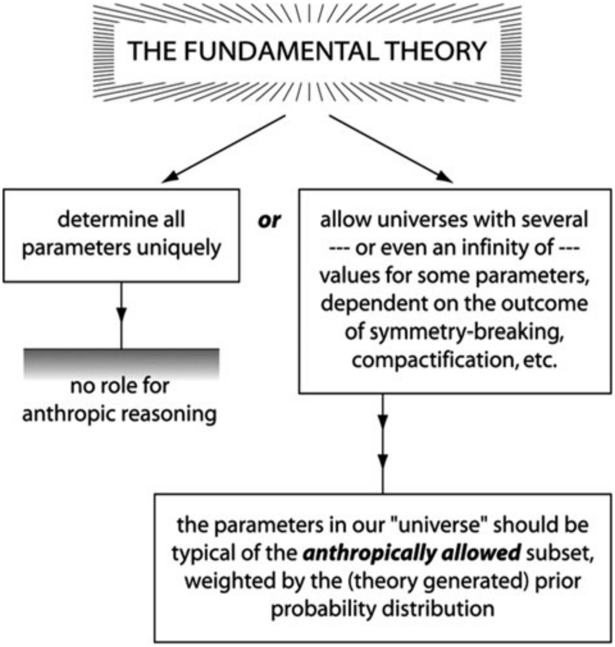
We now turn to multiverse proposals inspired by particle physics. The holy grail of particle physics is to find a TOE which unifies all the known forces. We have seen that the current front-runner is M-theory, in which the physical constants are uniquely determined for each vacuum state. It was originally hoped that M-theory would predict all the constants of nature uniquely. However, recent developments suggest that the number of vacuum states (i.e. compactifications) could be enormous (e.g. 10^{500}), each one corresponding to a different universe and a different set of constants (Bousso and Polchinksi 2000). In this string landscape scenario, the values of the constants would be contingent on which universe we happen to occupy (Susskind 2005). One cannot predict the distribution of Λ across the different universes precisely but it would be very unlikely to have a peak in the observed range. In another version of M-theory, we have seen that the eleventh dimension is extended and our Universe corresponds to a four-dimensional brane embedded in a five-dimensional bulk. In this case, there might be many other branes and collisions between the branes might even generate Big Bangs of the kind which initiated the expansion of our own Universe. This might take place repeatedly to give a form of the cyclic model (Steinhardt and Turok 2006).

The oldest form of the multiverse is the Everett many-worlds interpretation of quantum mechanics (Everett 1957), in which the Universe branches every time an observation is made. Tegmark classifies this as the Level III multiverse and it is the most natural framework in which to describe quantum cosmology, which applies when the classical spacetime description of general relativity breaks down at the Planck time (10^{-43} s). In this approach one has a superposition of different histories for the Universe and uses the ‘path integral’ approach to calculate the probability of each of these. In some scenarios this replaces the Big Bang singularity with a bounce and leads to a form of the cyclic model.

The most extreme version of the multiverse, described by Tegmark as Level IV’, postulates disconnected universes governed by completely different laws or mathematical structures. It derives from an underlying philosophical stance that everything that *can* happen in physics *does* happen, so any mathematically possible universe must exist ‘somewhere’.

Although the multiverse proposal was not originally motivated by an attempt to explain the anthropic fine-tunings, it seems clear that the two concepts are interlinked. For if there *are* many universes, the question arises as to why we inhabit this particular one and (at the very least) one would have to concede that our own existence is a relevant selection effect. A huge number of universes will

Table 2 This shows the 'decision tree' which determines whether anthropic explanations are relevant or the best one can hope for (Credit: Rees)



allow all possible combinations to occur, so somewhere – just by chance – things will be right for life. Many physicists therefore regard the multiverse as providing the most natural explanation of the anthropic fine-tunings. If one wins the lottery, it is natural to infer that one is not the only person to have bought a ticket.

In assessing this view, the key issue is whether some of the physical constants are contingent on accidental features of symmetry-breaking and the initial conditions of the Universe or whether some fundamental theory will determine all of them uniquely. The two cases essentially correspond to the multiverse and single universe options, as illustrated in Table 2. This relates to a famous question posed by Einstein: "Did God have any choice when he created the universe?" If the answer is no, there would be no room for the Anthropic Principle. Most physicists would prefer this but it now appears unlikely. What we call 'laws of nature' may just be local by-laws, in which case trying to predict the values of the constants may be as forlorn as Kepler's attempts to predict the spacing of the planets in the Solar System based on the properties of Platonic solids (Rees 2001).

One important question is whether our Universe is typical or atypical within the ensemble. Advocates of the Anthropic Principle usually assume that life-forms similar to our own will be possible in only a tiny subset of universes (Vilenkin 2006). More general life-forms may be possible in a somewhat larger subset but life will not be possible everywhere. On the other hand, by invoking a Copernican perspective, Lee Smolin (1997) has argued that *most* of the universes should have properties like our own, so that we are typical. His model proposes that the physical constants have *evolved* to their present values through a process akin to mutation and natural selection. The assumption is that whenever matter gets sufficiently compressed to undergo gravitational collapse into a black hole, it gives birth to another expanding universe in which the fundamental constants are slightly mutated. Our own universe may itself have been generated in this way (i.e. via gravitational collapse in some parent universe). Cosmological models with constants permitting the formation of black holes will therefore produce progeny (which may each produce further black holes since the inherited constants are nearly the same), whereas those with the wrong constants will be infertile. A Darwinian process can take place, leading preferentially to universes that produce many black holes; in this case, the presence of life may be incidental.

Despite the popularity of the multiverse proposal, some physicists are deeply uncomfortable with it (Ellis et al. 2004). The ideas involved are highly speculative and they are currently – and may always remain – untestable in the sense that astronomers may never be able to observe the other universes directly. This view may be too pessimistic – some authors claim that scars from collisions with other universes might be seen in the cosmic background radiation (Garriga et al. 2006) – but it could prove to be correct. For these reasons, some physicists do not regard these ideas as coming under the purview of science at all. Since our confidence in them is based on faith and aesthetic considerations (e.g. mathematical beauty) rather than experimental data, they regard them as having more in common with religion than science. This view has been expressed forcefully by commentators with widely differing metaphysical outlooks, such as David Gross, Martin Gardner and George Ellis. Indeed, Paul Davies (2006) regards the concept of a multiverse as just as metaphysical as that of a Creator who fine-tuned a single universe for our existence.

However, another view might be that an idea is scientific providing it is *implied* by a theory which is testable. So if we have a theory which *predicts* the multiverse, then verifying that theory would at least provide *indirect* evidence for the proposal. For example, it is possible that the extra dimensions of M-theory will be visible at the TeV scale and therefore detectable with the Large Hadron Collider. Admittedly, this would only apply if the extra dimensions were as large as a millimetre and it would be very fortuitous if this scale just happened to correspond to the largest currently accessible energy scale. Whether the theories which predict the multiverse (e.g. M-theory) are testable may therefore be difficult to assess.

So the issue is not whether other universes exist but whether speculations about them are part of science and that in turn depends on what is meant by science. The problem is that scientific progress has not only changed our view of the Universe, it has changed our view of science itself. This is reflected in a comment by Weinberg (2007):

> We usually mark advances in the history of science by what we learn about nature, but at certain critical moments the most important thing is what we discover about science itself. These discoveries lead to changes in how we score our work, in what we consider to be an acceptable theory.

Weinberg is referring specifically to M-theory and the multiverse but this remark is of more general application and might be used to justify even more daring speculations. Nevertheless, many physicists strongly resist the notion of the changing nature of science. For a dialogue about these issues in the context of the multiverse, see Carr and Ellis (2008).

Pre-Science and Meta-Cosmology

In a sense the current debate about the scientific status of M-theory and the multiverse is nothing new. The boundary between physics and metaphysics is inevitably blurred at the frontiers of knowledge and there has always been a debate over whether the latest ideas about the smallest and largest scales of nature are part of legitimate science. In particular, cosmology has always had to struggle to maintain its scientific respectability because speculations about processes at very early and very late times depend upon theories of physics which have not yet been tested. Because of this, more conservative physicists have often regarded cosmological speculations as going beyond the domain of legitimate science. The reception of Lemaître's own ideas provides an interesting illustration of this distinction between cosmology and what might be termed 'meta-cosmology'. However, I would argue that the boundary between meta-cosmology and cosmology is continuously shifting as new ideas evolve from being pre-scientific to scientific. Some historical examples should suffice to illustrate this point, each of which conveys a particular lesson.

To the ancient Greeks, the heavenly spheres were the unchanging domain of the divine and therefore outside science by definition. It required Tycho Brahe's observation of a supernova in 1572 and the realization that its apparent position did not change as the Earth moved around the Sun to dash that view. Because this contradicted the Aristotelian view that the heavens cannot change, the claim was at first received sceptically. Frustrated by those who had eyes but would not see, Brahe wrote: *"O crassa ingenia. O caecos coeli spectatores"*. [Oh thick wits. Oh blind watchers of the sky.] *Lesson 1: theoretical prejudice should not blind one to the evidence*. I would claim that the analogue of Tycho's supernova in the multiverse debate is the fine-tunings, even though we are literally 'blind' in the sense that we cannot see the other universes.

Long after Galileo had realized that the Milky Way is nothing more than an assembly of stars and Newton had shown that the laws of nature could be extended beyond the Solar System, there was still a prejudice that the investigation of this region was beyond the domain of science. In 1835 August Comte commented on the study of stars:

> Never, by any means, will we be able to study their chemical compositions. The field of positive philosophy lies entirely within the Solar System, the study of the Universe being inaccessible in any possible science.

Comte had not foreseen the advent of spectroscopy, which identified absorption features in stellar spectra with chemical elements. *Lesson 2: new observational developments are hard to anticipate*. Perhaps one day we will find extra dimensions at the Large Hadron Collider or create baby universes in the laboratory or visit other universes through wormholes.

Cosmology attained the status of a proper science in 1915, when the advent of general relativity gave it a secure mathematical basis. Nevertheless, for a further decade there was resistance to the idea that science could be extended beyond the Galaxy. Indeed many astronomers refused to believe that there *was* anything beyond. Although Kant had speculated as early as 1755 that some nebulae are island universes similar to the Milky Way, most astronomers continued to adopt a Galactocentric view until the 1920s. Indeed, the term 'Universe' almost became taboo in scientific circles. Ernest Rutherford once remarked "Don't let me hear anyone use the word 'Universe' in my Department!", a comment some might echo today about the multiverse. The controversy came to a head in 1920 when Heber Curtis defended the island universe theory in a famous debate with Harlow Shapley. The issue was finally resolved in 1924, when Edwin Hubble measured the distance to M31 using Cepheid variable stars. In many ways this parallels the current debate about whether anything exists beyond our cosmological horizon. *Lesson 3: more conservative cosmologists might prefer to maintain the cosmocentric view but the tide of history may be against them*. The evidence for other universes can never be as decisive as that for extragalactic nebulae but the transformation of worldview required may be just as necessary.

A few years later Hubble – using radial velocities for several dozen nearby galaxies obtained by Slipher – discovered that all galaxies are moving away from us with a speed proportional to their distance. Lemaître pointed out that the most natural interpretation of this is that space itself is expanding but Einstein rejected this model at the time because he believed the Universe (i.e. the Milky Way) was static and he even used the cosmological constant to allow this possibility. Hence his famous remark to Lemaître in 1927: "Your maths is correct but your physics is abominable". In fact, Einstein continued to uphold the static model even after the evidence was against it and he only accepted the expanding model – admitting his "biggest blunder" – several years after Hubble published his data. Eddington was equally loath to accept the implications of the cosmic expansion, as illustrated by the remark which prompted Lemaître's 1931 paper: "Philosophically, the notion of a beginning of the present order of nature is repugnant to me." In contrast to Lemaître, he regarded the Big Bang as an unfortunate fusion of physics and theology. *Lesson 4: one should not reject theoretical predictions just because they go against one's prejudices or do not yet have observational support*. Knowing how much weight to attach to theory and observation can be tricky.

Even after Hubble's discovery gave cosmology a firm empirical foundation, it was many more decades before it gained full scientific recognition. When Ralph Alpher and Robert Herman were working on cosmological nucleosynthesis in the 1940s, they recall: "Cosmology was then a sceptically regarded discipline, not worked in by sensible scientists" (Alpher and Hermann 1988). Although they were only using known physics, people were sceptical of applying this in unfamiliar contexts. Only with the detection of the microwave background radiation in 1964 was the hot Big Bang theory established as a branch of mainstream physics and subsequent studies of this radiation have established cosmology as a precision science. *Lesson 5: one must be prepared to apply known physics in new domains*. Admittedly, some cosmological speculations depend upon unknown physics but that relates to Lesson 4.

These examples show that the domain of legitimate science is always expanding, so that today's meta-cosmology becomes tomorrow's cosmology. Similar considerations apply to the smallest scales. More generally, our prevailing model of physical reality regularly undergoes paradigm shifts (Kuhn 1970) in which the sorts of questions one can address and experiments one can contemplate change. Much scientific progress is made within the context of a particular paradigm but eventually anomalies (e.g. the fine-tunings) arise which cannot be explained and this results in a crisis which ultimately leads to the adoption of a new one.

The nature of science itself changes during these paradigm shifts. For example, it used to be assumed that science depends on *experiments* but astronomers cannot experiment with stars and galaxies. They can only let nature do this for them by observing billions of these objects in different states of evolution. Cosmology is in a worse state because we can only observe our own Universe and it is usually assumed that *observability* is essential in science. However, there are many entities posited by physics which cannot be seen (e.g. quarks and the interior of black holes) – one just needs *some* aspects of a theory to be observable for it to be regarded as scientific. Others have emphasized the importance of *testability* in science, but the issue is on what timescale one should demand this. It is surely unreasonable to deny that string theory qualifies as science because it has not been tested experimentally after only 20 years. It might take a 100 years, but the definition of science should not depend upon how long a problem takes to solve.

Nevertheless, it seems likely that some questions will be forever beyond science and there is one sense in which the current situation is very special. This is because for the first time the macro and micro science/philosophy boundaries in Fig. 2 have merged, the very large and very small being unified through quantum gravity. The question then becomes: does this merging represent the *completion* of science or merely a *transformation* in its nature – of the kind to which Weinberg refers and which tends to happen with every paradigm shift. In the latter case, what would be the features of this new type of science? One might be the transcendence of space and time and the invocation of higher dimensions, as already advocated in some theories. People argue about whether these extra dimensions are physical or just mathematical artefacts (Woit 2006; Smolin 2007), but this applies to many ideas in modern physics. Indeed, the paradigm provided by physics deviated from commonsense reality long before the multiverse and M-theory proposals. Another component of the new science may be a more explicit reference to mind and this leads into the next section.

Is Mind Fundamental or Incidental to the Cosmos?

The image of the Uroborus in Fig. 2 encapsulates the triumph of physics in explaining the dazzling array of increasingly complex structures which have evolved in the 14 billion years since the Big Bang. The culmination of this complexity – at least on Earth – is the human brain, whose remarkable attributes include consciousness, mind and spirit. It is therefore curious that these attributes are almost completely neglected by science and judged to be without significance. The mainstream view is that consciousness has a purely passive role in the Universe, minds are just the froth generated by billions of neurons, and spiritual evolution is a delusion. In fact, most physicists assume that the study of such topics is beyond their remit altogether because physics is concerned with a ‘third person’ account of the world (*experiment*) rather than a ‘first person’ account (*experience*). They infer that their focus should be the objective world, with the subjective element being banished as much as possible.

However, some aspects of the Uroborus encourage a different view. For example, Fig. 2 suggests that humans do have a distinctive position in the world after all: we may not be at the centre of the Universe geographically but we at least appear to be at the centre of the scales of structure. This is because simple physics shows that the size of a human is roughly the geometric mean of the Planck length and the size of the observable Universe. (This relates to the fact that we do not break apart when we fall down under gravity.) Although this argument just involves our *physical* characteristics and applies to the whole biological realm, the Uroborus also represents our *mental* attributes, because it shows the way in which we have systematically expanded our outermost and innermost limits of awareness through scientific progress (i.e. it represents a blossoming of consciousness). This is illustrated in Fig. 7, which shows the range of scales encompassed at various points in the history of science. Thus the physical evolution of the Universe from the Big Bang (at the top of the Uroborus) through the Pyramid of Complexity to humans (at the bottom) is just the start of a phase of *intellectual* evolution, in which mind works its way up both sides to the top again. Indeed, it is striking that on the macroscopic front science has already expanded as far as possible. On the microscopic front we may never get much below the electroweak scale in our *experiments* but we can still probe to the Planck scale in our *theories*. The situation at Lemaître’s time is shown by the ‘Lemaître lines’ in Fig. 7.

The unity of the cosmos and its various interconnections has also led some scientists to see evidence of a great intelligence at work in the Universe. For example, James Jeans (1931) famously remarked: “The Universe is more like a great thought than a great machine”. This impression derives from the fact that the world is so cleverly constructed. At the very least, the coherence of the laws that regulate it seems to point to the existence of some underlying organising principle. This also relates to the question of why the Universe is comprehensible at all. It seems remarkable that after just a few millennia we are already on the verge of a TOE. As Roger Penrose (1997) has emphasized, there seems to be a closed circle:

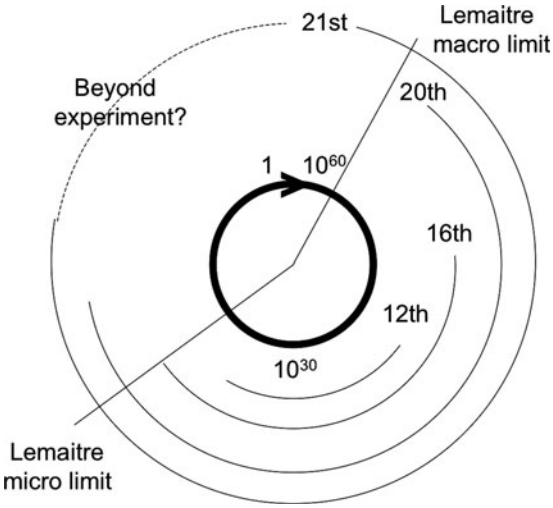


Fig. 7 Expansion of awareness through science to ever larger and smaller scales in successive centuries, the Uroborus being represented by the *central circle*, with the situation at Lemaître’s time indicated

the laws of physics lead to complexity, complexity culminates in mind, mind leads to mathematics, and mathematics allows an understanding of physics. But why should the structure of the world reflect the structure of our minds and why should our brains have the ability to generate the required mathematics? And since the fundamental view of reality provided by physics is itself a mental model, why are physicists so keen to expunge mind from the cosmos?

There is also an inherent beauty in the Universe, which is in some sense a mental attribute. The nature of this beauty is hard to define but it involves mathematical elegance, simplicity and inevitability. In particular, all the laws of nature seem to be a consequence of a simple set of symmetry principles. For example, symmetrizing electricity and magnetism gives Maxwell’s equations; symmetrizing space and time gives special relativity; and invoking gauge symmetries leads to the unification of the forces of nature. Such symmetries can only be appreciated intellectually but they are profoundly elegant and can be very moving for physicists. The importance of beauty was appreciated by Paul Dirac (1963), who claimed “it is more important to have beauty in one’s equations than to have them fit experiment” and by John Wheeler (1977) who said: “One day a door will surely open and expose the glittering central mechanism of the world in all its beauty and simplicity”.

These arguments suggest that mind may be a fundamental rather than *incidental* feature of the Universe. Despite this, most physicists are uncomfortable with attempts to incorporate consciousness into their description of the world, so the C word is almost taboo. Even some psychologists have tried to abolish to it. According to the behaviourist John Watson (1910):

> The time seems to have come when psychology must discard all reference to consciousness; when it need no longer delude itself into thinking that it is making mental states the object of observation.

Although attempts by behaviourists to extend mechanism to the mind are now unpopular with psychologists, a mechanistic outlook still persists among many physicists and this probably contributes to their discomfort with consciousness. Philosopher Daniel Dennett (1978) is even more forthright:

> Consciousness appears to be the last bastion of occult properties, epiphenomena and immeasurable subjective states – in short, the one area of mind best left to philosophers, who are welcome to it. Let them make fools of themselves trying to corral the quicksilver of phenomenology into a respectable theory.

On the other hand, some people are sceptical of claims to be close to a TOE when such a conspicuous aspect of the world is neglected. Thus the linguist Noam Chomsky (1975) declares "Physics must expand to explain mental experiences", and Roger Penrose (1994) predicts "We need a revolution in physics on the scale of quantum theory and relativity before we can understand mind". Anthropic arguments have led Andrei Linde (2004) to suggest that consciousness is as fundamental to the cosmos as space-time and mass-energy.

Certainly physics in its *classical* form cannot incorporate consciousness. This was appreciated more than a century ago by William James (1890), who stressed the incompatibility between the localised features of mechanism and the unity of conscious experience. However, classical physics has now been superseded by quantum physics. There are many different interpretations of quantum theory but at least some of them suggest that it may involve consciousness (Squires 1990). Thus studies of quantum phenomena convinced Louis de Broglie (1963) that "the structure of the material Universe has something in common with the laws that govern the workings of the human mind" and John Wheeler (1977) that "mind and Universe are complementary", while Bernard d'Espagnat (1983) claims:

> The doctrine that the world is made up of objects whose existence is independent of human consciousness turns out to be in conflict with quantum mechanics and with facts established by experiments.

Some people have proposed that consciousness is involved in the collapse of the wave-function (Stapp 1993), and it has even been suggested that mentality may have some connection with quantum gravity (Penrose 1997).

Cosmos, Creation, and the Lemaître Point

At first sight cosmological progress has entailed an ever-diminishing role for God. The 'primitive' view, in which the heavens were the domain of the divine and humans were the focus of creation, with a direct link to the God (or Gods) who sustained the world, has been shattered. Newton's discovery of universal gravity – linking astronomical phenomena to those on Earth – has removed the special status of the heavens, and the more we understand the Universe, from the vast expanses of the cosmos to the tiny world of particle physics, the more soul-less it seems to become. The extent of physical space is now so all-encompassing that there seems to be nowhere left for the soul (Wertheim 1999). As Weinberg (1977) says: "The more the Universe seems comprehensible, the more it seems pointless".

The arguments propounded in the last section for the importance of mind in the cosmos might be regarded as counteracting this view. For once one accepts that mind is fundamental, that is one step closer to granting that spirit may also be fundamental. Indeed, mind might be regarded as the start of the slippery slope to spirit, which is why the word spirit appears at the top of Fig. 5. Of course, most scientists are even more uncomfortable straying into the domain of theology (viz. God) than philosophy (viz. consiousness), so the G word is even more taboo than the C word. But perhaps there is a process of desensitization in which the A, C and G words become successively acceptable!

Of course, the remit of religion goes well beyond the materialistic issues which are the focus of cosmology. Nevertheless, in so much as religious and cosmological truths overlap, they must be compatible. This has been stressed by George Ellis (1993), who distinguishes between Cosmology (with a big C) – which takes into account "the magnificent gestures of humanity" – and cosmology (with a small c), which just focuses on physical aspects of the Universe. In his view, morality is embedded in the cosmos in some fundamental way and individuals count. On the other hand, science itself cannot deal with such issues and it seems unlikely that – even in some extended form – it will ever prove or disprove the existence of God. Some people may see in the physical world some hint of the divine but the evidence can only provide what John Polkinghorne (1994) describes as 'nudge' factors. Convictions about God's existence must surely come from 'inside' rather than 'outside' and even those eminent physicists who are mystically-inclined do not usually base their faith on scientific revelation (Wilbur 2001). It seems clear that Lemaître himself was in this category.

In concluding my chapter, I wish to focus on just one issue on the cosmological/theology interface: whether one should attribute the anthropic fine-tunings to God or the multiverse – an issue which has been addressed by many authors (Leslie 1989; Lewis 2000; Holder 2004; Collins 2007). From a theological perspective, the God-multiverse debate is just the latest incarnation of the traditional question of whether God is required to create the Universe. Even though few people now interpret religious creation myths literally, the idea that the Universe must have some first cause still has appeal. Although the Big Bang provides a very cogent picture for the creation of the Universe, this does not preclude God, since one can still ask "Who lit the fuse?" Indeed, the fact that the Universe had a finite beginning was claimed by Pope Pius XII to support Genesis, although Lemaître discouraged him from making such pronouncements. Implicit here is the notion that the physical description of creation is incomplete, since it must break down at sufficiently early times.

However, as time proceeds, cosmologists have provided an ever more complete description of the early Universe and in the last few decades they have even began to address the question of what happens at the singularity. One might envisage the following dialogue:

Q. How did the Universe originate?
A. The Universe started as a state of compressed matter.

Q. But where did the matter come from?

A. The matter arose from radiation as a result of baryon-non-conserving processes occurring when the Universe had the size of a grapefruit.

Q. But where did the radiation come from?

A. The radiation was generated from empty space as a result of a vacuum phase transition.

Q. But where did space come from?

A. Space appeared from nowhere as a result of quantum gravity effects.

Q. But where did the laws of quantum gravity come from?

A. The laws of quantum gravity are probably no more than logical necessities.

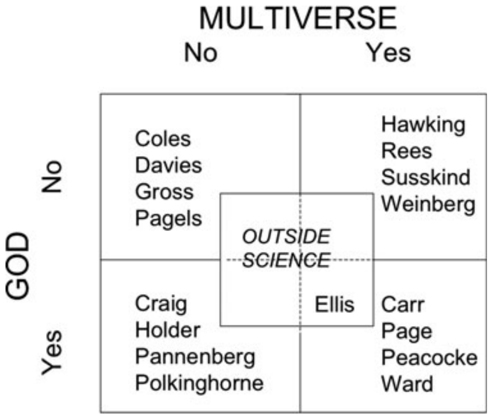
Each step in this dialogue represents many years of painstaking theoretical work but the upshot is clear. To physicists of an atheist persuasion, no first cause is needed because the Universe contains its own explanation, a view propounded by Stephen Hawking (2001). Even if God does exist, it is not clear He could have created the Universe differently. Of course, to theologians this is a very naïve perspective: the question of *how* the Universe was created is distinct from the question of *why* it was created.

The multiverse proposal adds one more step to this dialogue. There is no doubt that most physicists prefer the multiverse to a Creator. The notion may not be entirely mainstream, but it is at least predicted by speculative physics. Indeed, anthropically-inclined physicists like Susskind and Weinberg are attracted to the multiverse precisely because it seems to dispense with God as the explanation of cosmic design. Thus atheists hope that multiverse theory will have the same impact in the context of cosmic design as evolutionary theory did in the context of biological design. An evolutionary mechanism arises explicitly in Smolin's multiverse proposal.

In fact, this dichotomy between God and multiverse is clearly simplistic. It may be true that any physical mechanism for creating our Universe will create others. But if one has a sausage-making machine, one still needs to ask who made the sausage-making machine. So while the fine-tunings certainly do not provide unequivocal evidence for God, nor would the existence of a multiverse preclude Him. For if God can create one universe, He can presumably create many. Nevertheless, it is not surprising that the multiverse proposal has commended itself to atheists. Indeed, Neil Manson (2003) has described it as "the last resort for the desperate atheist". For if ours is the only universe, then one has a problem explaining the fine-tunings and might well be forced into a theological direction. If there is a multiverse, at least one is not compelled to invoke God.

On the other hand, we have seen that some physicists regard the notion of a multiverse as just as metaphysical as the notion of God. One thus has a spectrum of increasingly metaphysical views: (A) no multiverse and no God (for those who regard both God and the multiverse as equally unpalatable); (B) multiverse and no God (for those who regard the multiverse as the natural atheistic explanation of fine-tunings); (C) no multiverse and God (the standard theological view); (D) multiverse and God (an alternative theological view which combines both notions).

Table 3 Possible views of God and the multiverse and their relationship to science



GOD \ MULTIVERSE	No	Yes
No	Coles Davies Gross Pagels	Hawking Rees Susskind Weinberg
Yes	Craig Holder Pannenberg Polkinghorne	Carr Page Peacocke Ward

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These views are represented by the 2 × 2 display shown in Table 3. There are other possible views. One might believe in the multiverse or God but not regard them as having anything to do with science (Ellis 1993), corresponding to the central square in Table 3. Or one might remain agnostic about one or both of them. Paul Davies (2006) takes a third view, in which the laws of physics evolve so as to retroactively affect the past. It should be stressed that what is meant by "God" in Table 3 is deliberately vague. The term is not necessarily being used in the western monotheistic sense and it need not imply Intelligent Design.

In 2009 I organized a meeting in Cambridge entitled 'God or Multiverse?' to consider these options. Two theologians – John Polkinghorne and Keith Ward – joined two cosmologists – myself and Peter Coles – and someone who might be regarded as straddling the border – Rodney D. Holder, who did his Ph.D. in cosmology before becoming ordained – to discuss these issues. Obviously we did not expect to answer the question posed by the title definitively but between us we explored the variety of views mentioned above. For pedagogical purposes, I placed the speakers in particular boxes in Table 3 and I have now generalized this to include other prominent scientists and theologians. Of course, this is very simplistic since nobody wants to be pigeon-holed so precisely. Probably most of us are tottering on the abyss of the central square. An interesting question is where Lemaître himself would appear in Table 3.

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Modern Cosmology and Anthropic Fine-Tuning: Three approaches

Robin Collins

Abstract The anthropic fine-tuning of the cosmos refers to the claim that the laws of nature, the constants of physics, and the initial conditions of the universe must be set to an enormous degree of precision for embodied conscious agents to exist. Three major responses have been offered to this fine-tuning: the multiverse explanation; theism; and the claim that it is just a brute fact that requires no further explanation. In this chapter, I will consider each explanation in turn, and provide some novel arguments for the superiority of a theistic or related explanation. In the last section, I will show how whether or not one adopts a theistic or related explanation can significantly influence what features of the universe one considers in need of further scientific explanation, and the type of scientific explanation that one should find satisfactory. In particular, I will argue that in some cases atheism, not theism, serves as a science stopper in discouraging a search for deeper scientific explanations of phenomena.

Cosmic Fine-Tuning: Three Responses

The anthropic fine-tuning refers to the claim that the laws of nature, the constants of physics, and the initial conditions of the universe must be set to an enormous degree of precision for embodied conscious agents (ECAs) such as humans to exist. This fine-tuning has been much discussed elsewhere (e.g., Barrow and Tipler 1986; Rees 2000; Collins 2003; Collins forthcoming – a). Three major responses have been offered to this fine-tuning: the multiverse explanation; theism; and the claim that it is just a brute fact that requires no further explanation, a view which I call "single-universe naturalism." I will start with the multiverse explanation.

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Multiverse Explanation

The multiverse explanation of the fine-tuning begins with the multiverse hypothesis. This hypothesis claims that there are a very large, if not infinite, number of regions of space-time with different values of the fundamental parameters of physics, different initial conditions, and perhaps even different laws of nature. It then claims that in a sufficiently varied multiverse, it is no surprise that some universe is observer-structured – that is, structured so that observers will arise in it. Finally, it invokes the so-called *observer-selection principle*, which is the tautological claim that embodied observers can only exist in a region of space-time that allows for them to exist. This renders it unsurprising that as embodied observers we find ourselves in an observer-structured region of space-time since it is impossible for us to exist in any other type of region.

The observer-selection principle is essential to the multiverse explanation because it prevents it from undercutting the need to explain other seemingly surprising events and features of the universe. For example, normally one would think that it is too coincidental for a six-sided die to land 50 times in a row on four just by chance. Yet, in a large enough multiverse, someone will observe this to happen. Nonetheless, it is still improbable that a generic observer will see such an occurrence. Hence, purportedly, the multiverse hypothesis combined with the observer-selection principle can render it unsurprising both that we exist and that we find ourselves in an observer-structured universe while at the same time not undercutting ordinary claims of improbability.

Elsewhere (Collins 2007, 2009, pp. 262–269), I have argued that by far the most popular versions of the multiverse hypothesis – namely, those that postulate that the multiverse was generated by some physical process – push the problem of fine-tuning up one level to the laws required to generate the multiverse. For, I argued, in order to generate even one life-permitting universe, this process must be governed by precisely the right set of laws. Here, I want to briefly outline what I believe to be an even more powerful objection to the multiverse explanation, one that applies to any type of multiverse.

The objection begins by noting that the universe is *not* fine-tuned so that observers can exist; rather it is fine-tuned so that, at least within some epoch, the kind of observers who are most likely to occur are ECAs who can interact with each other for good or ill. Indeed, it appears to be additionally fine-tuned so that those observers can develop scientific technology and discover the universe. The reason that it is not fine-tuned for observers is that sufficiently large non-fine-tuned universes will still contain observers, at least for many of the fundamental parameters of physics. Specifically, for certain fundamental parameters, as one moves further and further away from the fine-tuned values that the fundamental parameters have in our universe, the resulting universe becomes first less optimal for scientific discoverability and the concurrent development of technology; then, given the universe is large enough, it becomes overwhelmingly dominated by "fluctuation observers" who are isolated and last for only a brief time. Thus, sufficiently large non-fine-tuned universes will be populated by observers, but for any finite volume in such universes, fluctuation observers will be much more likely to occur than ECAs.

What is a fluctuation observer? The idea of a fluctuation observer presupposes a view of consciousness almost universally assumed by naturalists who advocate a multiverse: namely, one in which the mind – and hence being an observer – is a result of the right structural arrangement of matter. A fluctuation observer can then be defined as a localized fluctuation in the organization of mass-energy in some region that results in the right kind of highly organized material structure to constitute an observer. In the literature, both thermal fluctuations and quantum fluctuations have been postulated to give rise to these observers. However, because the former type of fluctuation is conceptually clearer than the latter, I will focus on it. [1]

Thermal fluctuations refer to the constantly varying states of individual particle and field states in a material system as a result of thermal energy contained in the system. For instance, the molecules of a gas in a box at room temperature will have constantly changing velocities and positions as they collide with each other. Because of thermal fluctuations, there is a finite, though very, very small probability for the mass-energy in a system to move from a highly disorganized (high entropy) state to a highly organized (low entropy) state. One such highly organized state is that needed for the existence of an observer. Originally, Ludwig Boltzmann (1844–1906) – one of the major founders of the branch of physics known as statistical mechanics – attempted to use this idea to explain why we live in a low entropy universe. He proposed that if we were in a large enough universe, eventually some region would undergo a random thermal fluctuation to a sufficiently low entropy state to produce observers, thus explaining why we find ourselves in a low entropy universe.

In response, it was pointed out that it is vastly more likely for such a localized fluctuation to give rise to an isolated observer that is surrounded by a chaotic, high-entropy arrangement of mass-energy than one surrounded by an ordered, low-entropy universe such as ours. Such an isolated observer came to be called a "Boltzmann Brain." The claim that isolated local islands of order are vastly more probable than larger regions of order is illustrated by the well-worn analogy of monkeys randomly typing on a typewriter. It is enormously more likely for the monkeys to occasionally produce a meaningful word than for them to produce a meaningful paragraph, let alone a play of Shakespeare. Similarly, if one randomly shook 100 coins laid out in a row, it would be vastly more likely for a small number of coins in a row – say five coins – all to come up on heads somewhere than for the entire set of coins all to land on heads. In the case of fluctuation observers, calculations by Roger Penrose show that, using the canonical probability measure of statistical mechanics, it is around 10 raised to 10^{120} times more likely for an isolated fluctuation observer to arise in a region of space surrounded by chaos than in a large, low entropy universe such as ours (2004, pp. 762–765).

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[1] There is a significant literature on this issue. A good place to begin is Davenport and Olum (2010). For a discussion of the history of the problem, see Davies (1974, 103f).

Since the time of Boltzmann, the existence of fluctuation observers has been considered the outstanding problem with multiverse explanations of the low entropy of the universe; more recently, it has also been discussed as a problem for some types of universes that will expand forever, since purportedly these could give rise to an unlimited number of fluctuation observers via quantum fluctuations (Davenport and Olum 2010). What has not been recognized is that isolated fluctuation observers would exist in universes in which the fundamental parameters are not fine-tuned, and that this undercuts the ability of a multiverse to explain many other cases of fine-tuning.

The existence of such observers is especially clear for those fine-tuned parameters – such as the strength of gravity, the dark energy density, and the strength of the primordial density fluctuations – that can be varied without affecting the properties of atoms or molecules. If these "chemistry-irrelevant" parameters were changed, any atom in the periodic table could still come into existence as a result of thermal fluctuations; further, any organized combination of such atoms could fluctuate into existence in this way. Hence material structures identical to our brains – and that last for as much time as necessary to be counted as observers – would exist in sufficiently large universes that have non-fine-tuned values for the chemistry-irrelevant parameters. In particular, as these chemistry-irrelevant parameters are moved further and further away from their current values, the universe first becomes less conducive for scientific discoverability and technology, with eventually the predominant kind of observers being fluctuation observers.

For example, consider a universe with a dark energy density a million times the value in our universe, but otherwise having the same laws and initial conditions as ours. Even if observers could form via a standard evolutionary process, the universe would have expanded so much by the time a typical observer formed that it would find itself in the only galaxy in its visible universe. As stated by Tegmark and Rees, "When the Universe had reached its current age . . . ours would be the only galaxy in the local Hubble volume – alas, a drab and dreary place for extragalactic astronomers. . ." (Tegmark and Rees 1997, p. 6). Further increases in the dark energy density would not allow ECAs to form at all. Fluctuation observers would still exist, however. For example, during the early part of such a universe's expansion, it would contain a high density of mass-energy undergoing thermal fluctuations; since one possible, though enormously improbable, configuration of this mass-energy would consist of a structure the same as that of our brains, if the universe were large enough, many such structures would form. It would be vastly more likely for a fluctuation observer to exist in isolation, however, than in a community of interacting agents; the reason is that a community of agents requires much more organized complexity than a single observer, and thus is much less likely to arise by a chance fluctuation.

As another example, consider varying the strength of gravity as given by the dimensionless gravitational constant, $\alpha_G \equiv 2\pi G(m_p)^2/hc$, where m_p is the mass of the proton, h is Planck's constant, and c is the speed of light. As I have pointed out elsewhere (Collins forthcoming – a), the range of values for α_G is zero to the Planck scale, which is about 10^{38} times the current value of α_G. Now consider a planet of the same size and composition as Earth. As α_G is moderately increased – say by tenfold – most kinds of technology would become more difficult, e.g., building a structure for performing scientific experiments would become more difficult since it would be more difficult for ECAs to lift the building materials. As α_G is increased further, at some point terrestrial ECAs would become impossible since a life-form with a brain large enough to qualify as an ECAs would be crushed; this would only allow for ECAs to evolve under water, which clearly would not allow them to develop scientific technology since they could not forge metals. Further increases would make even this sort of life impossible. Although decreasing the size of the planet would compensate for increasing α_G, this can only partially compensate for an increase in α_G for several reasons (Collins forthcoming – a). For example, at some point one would have to decrease the size of the planet so much that it could not contain an ecosystem for ECAs to evolve; and to keep enough gravitational attraction to retain an atmosphere, the size of a planet cannot be decreased fast enough to keep the force on the surface from increasing with an increase in $\alpha_{G.}$. The result is that even taking into account the possibility of ECAs evolving on smaller planets than Earth, as α_G is moderately increased (say by a 100-fold), it becomes much more difficult for the ECAs that do evolve to develop scientific technology; then, at some point – for example, a billion-fold increase in α_G (which is only one part in 10^{29} of its possible range of values) – it becomes impossible for ECAs to evolve at all. Yet, isolated fluctuation observers would still exist.

The existence of these fluctuation observers in non-fine-tuned universes shows that the chemistry-irrelevant parameters of physics are not fine-tuned for observers, but rather for ECAs that can significantly interact with each other, and moreover, that can develop scientific technology and discover the universe. Yet, because of its reliance on the observer-selection principle, without additional postulates, the multiverse hypothesis can only take away the surprise that we exist in an observer-structured universe, not in a universe structured for ECAs (see Fig. 1).

In response, multiverse advocates could point out that non-fine-tuned universes will have a much lower density of observers than fine-tuned universes, at least during the time period for which observers are likely to evolve in a fine-tuned universe. They could then argue that if one considers oneself a generic observer and weights the probability of finding oneself in a given universe by its density of observers, then one should not be surprised to be in a fine-tuned universe. The problem with this response is that density seems irrelevant for such probabilistic weightings across universes. Rather, if anything, it is the relative number of observers per universe that should matter. Consider, for instance, two universes – A and B – with universe A having 1/10 the density of observers as universe B but being 100 times as large. If one did not have any other information about which universe one is in, if anything one should expect to find oneself in universe A, not B, since it contains ten times as many observers. Since there is no upper bound on the size of a universe in current multiverse theories, however, we have no basis for thinking that the number of observers in fine-tuned universes is greater than in non-fine-tuned universes. Thus, one could argue, since the proportion of universes that are not fine-tuned seems to be vastly larger than those that are fine-tuned, it is still

Fig. 1 The small light region at the *center* represents the region of parameter space in which the chemistry-irrelevant constants are fine-tuned for ECAs to evolve. Since observers can exist for all the other values of these constants (as represented by the *dark region*), the universe is not fine-tuned for observers. Thus, since the multiverse hypothesis relies on the observer-selection principle, it can only render unsurprising that we exist somewhere in the *entire region*, not that we find ourselves in the *light region*. It thus fails to account for the fine-tuning

highly surprising that, as generic observers, we find ourselves in an ECA-structured universe.

In fact, in the typical current inflationary multiverse models, each universe is infinite (Vilenkin 2006, pp. 96–101; Susskind 2006, pp. 312–313); hence there are infinitely many observers in both fine-tuned and non-fine-tuned universes. Although density could suddenly become relevant in the transition from finite to infinite universes, in the absence of a positive argument for this happening, our intuitions in the finite case remain the only guide we have to the infinite case. Further, even granting density as relevant, of itself the multiverse would still not be able to explain the low entropy of the universe: even when restricted to a finite region of space the size of our visible universe, a random configuration of mass-energy in that region is vastly more likely to result in an isolated observer surrounded by chaos than a group of interacting agents surrounded by low entropic conditions, as in our universe. Thus, to account for the fine-tuning of entropy, the multiverse advocate would have in addition to postulate the existence of some law or mechanism that makes the existence of low entropy universes vastly more likely than would be expected by chance.

Another response multiverse advocates might give is that the existence of infinitely many observers in both fine-tuned and non-fine-tuned universes undercuts any claim of surprise or improbability regarding the fine-tuning; for, there will be an infinite number of observers who exist in fine-tuned universes and an infinite number in non-fined-tuned universes, and hence the number in each kind will be the same. Such a response, however, threatens to undermine almost all probabilistic inferences, since for almost any improbable occurrence, O, in a sufficiently large and varied multiverse there will be an infinite number of observers who observe O. For example, there will be an infinite number of observers who toss a coin 100 times in a row and observe it coming up heads each time. Our probability judgments in these cases, therefore, are based on considerations that are independent of the number of observers who observe the outcomes in question: for example, in the above case of the coin toss, it is based on our judgment that each possible sequence of coin tosses is equally likely. Similarly, I suggest, in cases in which the multiverse contains both infinite universes that are fine-tuned and infinite universes that are not fine-tuned, our judgment of the degree to which it is surprising that we exist in a fine-tuned universe should be independent of the number of observers in each type of universe. Rather, I suggest, it should be based on our intuitive judgment of the proportion of universes of each type, which in turn should be based on the volume of parameter space that is ECA-structured relative to the volume of parameter space that allows for observers. Of course, one could reject this judgment of proportion. If one does that, however, then one might as well reject the need to explain the fine-tuning in the first place, since it is based on a similar judgment of proportion. In that case, the multiverse hypothesis becomes irrelevant.[2]

Another possibility is to build into the definition of the relevant kind of observer that it is part of a community of interacting agents. The problem here is that one can always do this for any attribute F of the universe, thus making it certain that a generic observer will observe F. This would undercut ordinary claims of improbability, such as the case of the die mentioned previously. Further, since a community of interacting agents is itself a material structure, non-fine-tuned universes will also contain such communities. However, the probability of a community of ECAs forming in any finite region drops precipitously with the size of and material organization required for the community. Hence it is still vastly more likely for a generic observer to find itself in the smallest and least structured community required for it to be an observer than in a larger, highly structured community of observers, such as that of the human race.

Finally, multiverse advocates could postulate that, contrary to the canonical measure used in statistical mechanics, there is a true probability measure that will make it likely that a generic observer will find itself in an ECA-structured universe. In this case, however, the work of explaining the fine-tuning is being done by the right choice of probability measure, not the multiverse hypothesis. Accordingly, it is difficult to see how multiverse advocates do better than single-universe advocates in explaining the fine-tuning. For example, in an attempt to explain the fine-tuning, the latter could also postulate the existence of the right probability measure, namely one that gives a significant probability to the existence of an ECA-structured universe.

The above analysis undercuts the initial motivation for the multiverse explanation by showing that its seeming ability to explain the fine-tuning was based on conflating the real fine-tuning for ECAs (and secondarily, technology and

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[2] For a defense of this intuitive judgment of proportion, see Collins 2009, pp. 226–239.

discoverability) with a non-existent fine-tuning for observers. This in turn was the result of conflating conscious observers that arise through a normal evolutionary process – which are likely to be interacting agents – with mere observers, which need not arise through such a process. Without this initial motivation, however, it is hard to see why we should take the multiverse explanation more seriously than other naturalistic contenders. Finally, it should be clear that the existence of these fluctuation observers also undercuts the so-called *weak anthropic principle objection*, which claims that, even if there is only one universe, it is illegitimate to claim that the fine-tuning is surprising or "improbable" since a universe that is not fine-tuned could not be observed.

Theistic/Axiarchic Explanation

In contrast to the naturalistic-multiverse explanation, theism does render it unsurprising both that an ECA-structured universe exists, and that – considering ourselves as generic observers – we find ourselves in such a universe. To begin, we would expect an all good God to create a reality with at least a positive, if not optimal, balance of good over evil. Thus, arguably, theism should lead us to expect a universe structured in such a way that moral and aesthetic value is positively realized. Given that we can glimpse some special value that highly vulnerable embodied conscious agents like us can realize that could plausibly be thought to outweigh the evils – such as suffering – that result from such embodiment, it follows that it is not highly surprising that God would create an ECA-structured universe. I propose that one such value is the ability to engage in particular kinds of virtuous actions – such as self-sacrificial love, courage, and the like – that the vulnerability that comes from embodiment allows. In a theodicy I have developed elsewhere (Collins forthcoming – b), I claim that these actions allow for eternal connections of appreciation, contribution, and intimacy between conscious agents. For example, if someone significantly helps me in times of suffering, it can create a connection of appreciation in me that has the potential of lasting all eternity, and hence growing in value.

It is the assumption of God's perfect goodness and our being able to glimpse some good that an ECA-structured universe might realize that allows theism to render the existence of an ECA-structured universe unsurprising. In contrast, the hypothesis of a generic intelligent agent does not render it unsurprising that an ECA-structured universe exists, since we have no reason to think such an agent would create an ECA-structured universe over any other possibility. One could, of course, build into one's hypothesis of a designer that it had a desire to create an ECA-structured universe, but unless one can offer some independent justification for the designer having such an attribute, it merely transfers the issue of fine-tuning up one level to why the designer had that desire instead of all the other possibilities. It would be like explaining why John Q won the lottery by hypothesizing that the lottery commissioner wanted him to win; without independent justification, such a hypothesis merely transfers the improbability up one level to why the lottery commissioner desired John Q to win instead of the millions of other people who bought tickets. Long before the discovery of fine-tuning, however, people have thought that goodness (and beauty) were fundamental to ultimate reality – for example, in book VI of the Republic Plato hypothesized that the Form of the Good was responsible for the existence of everything else, a view that became central to the Neo-Platonists. Neo-Confucian philosophers – who comprised the leading philosophers for around a 900 years in China starting around 1000 CE – argued for a similar idea (Fung 1948, pp. 297–298). And, of course, theists have argued that this is a non-arbitrary attribute of God. Consequently, the theistic explanation does not obviously fall prey to this aspect of the arbitrariness problem.

The above analysis of the central role of God's goodness in explaining the fine-tuning, however, shows that theism falls more broadly under what has been called an axiarchic explanation. As I define it, the axiarchic thesis is the claim that non-abstract reality is non-accidentally structured so that moral (and aesthetic) value is positively, or optimally, realized. Usually advocates of this view add the additional claim that reality is structured in this way because of some kind of metaphysical necessity (or at least consider the axiarchic thesis to explain the existence and structure of the world).[3] I define axiarchism in a more minimalist way, not making any additional metaphysical or explanatory claims except that this belief plays an epistemically normative role as an ideal of natural order (INO), a concept I explain below. (Its ability to play this normative role is all I mean by the idea of "non-accidental" in my definition of axiarchism.) Theism implies the axiarchic thesis, but one can be an axiarchist without being a theist – for example, one could deny the existence of God and yet hold that of metaphysical necessity the world is structured to optimally realize moral and aesthetic value. Because of this, in the remaining part of this chapter, I will be considering axiarchism's relation to naturalism instead of merely focusing on the relation of theism to naturalism.

Single-Universe Naturalism

As I will define it, single-universe naturalism is the claim that an ECA-structured universe is a brute, inexplicable fact with no further explanation, along with a denial of the axiarchic thesis. This version of naturalism is often presented as being based on an unwillingness to go beyond what the evidence warrants, and thus not itself a positive faith commitment.[4] Thus, it might initially seem like a better alternative than

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[3] John Leslie (1979), for instance, advocates the former view whereas Hugh Rice (2000) advocates the latter. Also see Nicholas Rescher (2000).

[4] For example, in his *Atheism: A Very Short Introduction*, Julian Baggini states that "Atheism is not a faith position because it is belief in nothing beyond which there is evidence and argument for…" (2003, p. 32).

any version of axiarchism, since axiarchism appears to involve an enormous faith commitment in the order of events in reality being non-accidentally ordered in such a way as to positively realize moral and aesthetic value. In contrast, I argue in the next section that even apart from the fine-tuning evidence, naturalism – whether of a single universe or multiverse variety – involves a faith commitment regarding the structure of reality as great as that of axiarchism. Indeed I will argue, when everything about the structure of the world is considered – both its fine-tuning and the existence of evil – axiarchism is significantly confirmed over non-axiarchic versions of naturalism. Further, I will argue in the last section of this chapter that these different faith commitments can lead to significant differences in one's scientific methodology.

Axiarchism, Naturalism, and Scientific Methodology

My argument begins by considering what has become known as the *underdetermination of theory by data problem*. This is the problem that for any set of extant observational data, there are indefinitely many logically consistent hypotheses that can account for the data but which have different predictive consequences in untested domains. Consequently, in order for scientists to choose one theory over another – even merely for its potential predictive success in unobserved domains or new applications – they must go beyond mere logical consistency and fit with data. Rather, they must rely on what are called *theoretical virtues*. The most commonly cited theoretical virtue is that of simplicity, a virtue that says that everything else being equal, we should prefer simple theories over complex ones. Using this virtue commits one to some claim in the neighborhood of the idea that the relevant aspects of the world (such as the fundamental laws of nature) are more likely to be simple than complex.

The need for invoking simplicity is nicely illustrated by the case of "curve fitting," in which scientists attempt to find the right equation that both accounts for a body of data and can serve as a trustworthy basis for future predictions or extrapolations. For example, suppose that one collects data on the relation between the magnitude of force exerted on a mass and the magnitude of the mass's acceleration. The data will consist of measurements of accelerations that result from various forces. Graphically, this could be represented by a plot of data points (with error bars), with the amount of force on the y-axis and the amount of acceleration on the x-axis. It is a mathematical fact that for any number of data points, there always exist infinitely many functions that will perfectly go through the data points, but radically disagree about the values of the force associated with unobserved values of acceleration. Consequently, to choose the appropriate function to use for predictions, scientists must consider something more than fit with data. Typically, scientists consider the simplicity, naturalness, elegance, or some other purported feature of an equation – such as how well it fits with background information (such as previous theories or similar cases). Indeed, the equation they ultimately choose might even miss one or more of the points by a greater amount than experimental error. (See Fig. 2)

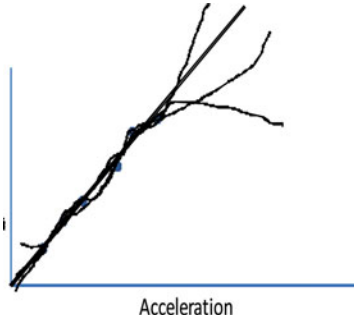

Fig. 2 In extrapolating from the data points using the solid line instead of the other possible curves, scientists are implicitly assuming the world is in some sense more likely to be simple than complex

In the terminology I will now introduce, the use of a theoretical virtue implicitly commits one to claiming that some corresponding property is what I call an *ideal of natural order* (INO). Roughly, I define some overarching property to be an INO for a person if and only if: (1), methodologically the person is explicitly or implicitly committed to treating the world as being, or is likely to be, structured in such a way that there is a positive realization of that property; and (2), that commitment guides their inductive practices and choice of theories. For example, the use of simplicity in scientific theory choice implicitly commits one to something in the neighborhood of the claim that the world is more likely to be simple than complex (at least in its basic law structure). Thus, insofar as scientists use simplicity this way, they are committed to simplicity as an INO. Finally, I define a *primitive* INO (a PINO) as an INO that is not based on a commitment to some other INO – e.g., if simplicity is an INO for one because one holds that the world is structured to optimize elegance, then simplicity would not be a PINO.

As shown by the curve-fitting example, INOs form the basis of our inductive practices – such as being able to extrapolate from observed data and to choose the best explanation of some set of phenomena. This means that one's PINOs cannot be justified in a non-circular way by their past success, since any argument from their past success to their future reliability would be an argument from observed data (namely, their past success) to unobserved data (namely, their future success), and thus would itself require assuming one's PINOs. Nonetheless, it seems possible for their past success to increase one's confidence in them, and thus in some way confirm them; and likewise for their past failure to undermine them.

In general, naturalists and axiarchists share the same INOs, with some qualifications to be discussed below. Where they differ is in their PINOs. Consider simplicity. Both axiarchists and naturalists would accept simplicity as an INO. Naturalists would likely take some appropriately qualified version of this INO as primitive – such as claiming that it is a brute fact that the universe is structured in a simple way, and it is a brute fact that simplicity should be an epistemic norm to decide between scientific theories. In contrast, axiarchists claim that reality is ordered in such a way as to positively realize moral (and aesthetic) value – that is, the axiarchic thesis itself is their PINO; or put succinctly, axiarchists see goodness as a PINO.

If the axiarchic thesis is to make sense of the use of simplicity and other theoretical virtues in scientific methodology, axiarchists must at least show that axiarchism renders the use of such virtues unsurprising. One such explanation is that simplicity contributes to elegance, at least for the classical notion of elegance as simplicity with variety, famously stated by in the eighteenth century by William Hogarth (1753). Thus, for this reason alone, axiarchism renders it unsurprising that an elegant universe has a high degree of complexity while having a highly simple underlying law structure.

Axiarchists could also argue that there are certain moral goods that can be more fully realized in a world structured for the development of scientific technology and discoverability. For instance, technology (which depends on discoverability) allows for the embodied conscious agents (ECAs) that arise in the universe to influence each other for good or for ill on a much larger scale, thereby greatly increasing the range and extent of potential virtuous responses and positive connections between these agents. In addition, one might think scientific discovery is intrinsically valuable. They could then go on to argue, as I will below, that the universe's manifesting the right kind of simplicity greatly aids in its discoverability. Thus, given that we can glimpse some good coming from a universe that gives rise to ECAs that can discover it, axiarchism renders it unsurprising that the universe will be discoverable.

Although the axiarchic thesis constitutes an enormous assumption about the structure of reality beyond what we can observe or deduce by the accepted rules of logic, any PINO of the naturalist will also. Thus, even if axiarchists can offer no further justification for their thesis (such as via an argument for theism), that would not make axiarchism worse off than naturalists who must posit their PINO without further justification.

One could also put the point as follows. If value is defined more generally as any property that comes in degrees and plays a normative role, then to engage in scientific enquiry one must be committed to some value being a PINO. Axiarchists hold that this value involves moral value; naturalists deny this, opting for some non-moral value – typically simplicity, or somewhat reluctantly, elegance.

A major problem for the naturalist is that the use of simplicity in scientific theory choice seems implicitly to assume that the universe is teleologically structured for discoverability, an assumption that is highly problematic for naturalism. The kind of simplicity that has been successful in science, and is now implicitly considered normative, is simplicity in the *humanly practical limit*, not absolute simplicity or elegance. To illustrate, consider Newton's equation of gravity, $F = Gm_1m_2/r^2$. This equation is very simple when written in the Newtonian mathematical framework (namely, one based on Euclidean geometry with its three spatial dimensions and one independent time dimension). Similarly, Einstein's equation of gravity has great simplicity when expressed in the mathematical framework of general relativity (namely, a four-dimensional semi-Riemannian manifold). Yet, if one wrote Einstein's equations of motion in the Newtonian conceptual framework, one would obtain Newton's law, $F = Gm_1m_2/r^2$, plus a large number of small correction terms. These correction terms would only become important for large gravitational fields or relativistic velocities. Yet, they exist, and hence within the Newtonian framework the experimentally correct equation of gravity is actually enormously complex – its simplicity lies in its humanly practical limit. Furthermore, the fact that it has such a simple limiting form for *practical purposes* depends on specific contingent facts about our existence – for example, that our planet is not orbiting close to a black hole; thus it need not have been that way.

Similar things could be said about the relation of quantum mechanics to classical mechanics: if the predictions of quantum mechanics (in terms of expectation values) are written out in the classical mathematical framework with real numbers denoting quantities, one obtains simple equations (corresponding to the equations of classical mechanics), with infinitely many correction terms that are very small except when quantum effects become important. This simplicity in the humanly practical limit – which I henceforth call *qualified simplicity* – has allowed us to discover the classical equations while at the same time providing the experimental basis for moving to the quantum framework.

To make sense of the success and continued use of this qualified simplicity, one cannot merely assume that the underlying law structure of the world is likely to be simple or elegant. Neither of these would give us any grounds for thinking that the equations of physics would be simple in the humanly accessible limits within ultimately unsatisfactory mathematical frameworks (such as the Newtonian framework), but not simple outside those practically useable limits. Being structured for discoverability, however, does make sense of it. Given our limited cognitive capacities, we would expect a discoverable world to be one structured so that qualified simplicity is a useful guide. Thus we would expect a universe that is optimally discoverable to be such that (1), at each conceptual framework (such as the flat space-time of Newtonian mechanics), simplicity would offer a generally good guide; but (2), it would fail at the boundaries, thereby forcing the ECAs in that universe to go to the next theoretical rung (e.g., such as to the curved space-time of Einstein) in their scientific quest.

The naturalist could respond that it is also a lucky brute fact that the universe has exhibited qualified simplicity. This response, however, misses an important point: scientists continue to be confident in this form of simplicity. If the success of qualified simplicity (or any other type of simplicity) is merely considered an accidental regularity – something that just happens by chance – there are no grounds for expecting it to continue. Yet, scientists do expect qualified simplicity to continue to work – and this is true even in the practice of predictively relying on virtually any equation of physics, since as illustrated by the curve fitting example, there are always an indefinite number of competitors that account for the data but yield radically different predictions. Qualified simplicity is what separates out the equations actually used from these competitors. (It is not absolute simplicity since most physicists think that current physics is a low energy approximation to some higher-level set of theories, most likely formulated in a mathematical framework as different from the current one as the framework of general relativity is from Newtonian mechanics.) Thus, one must not only assume that the world just happens to have been structured for the success of qualified simplicity, but that it is *non-accidentally* structured in this way, whatever further account one gives of this idea of being non-accidental. Because qualified simplicity makes essential reference to *the ECA-assessable limit*, relying on it appears to involve an implicit teleological commitment to the universe being structured for discoverability, which is at best difficult to reconcile with naturalism.[5]

Finally, consider the structure of the world. Two salient facts stand out: the basic structure of the universe is extraordinarily fine-tuned so that embodied conscious agents (ECA) can arise in it, and the world contains a lot of evil. For example, with regard to the former, the cosmological constant (or equivalently, the dark energy density of the universe) is commonly estimated to require a fine-tuning of one part in 10^{120} (that is, 1 followed by 120 zeroes) for ECA to arise.

Elsewhere (Collins, 2009) I use a variation of the *likelihood principle* of confirmation theory to argue that the fine-tuning strongly confirms theism/ axiarchism.[6] My argument was that given the extreme fine-tuning necessary for an ECA-structured universe (i.e., one structured so that ECA could arise), the existence of such a universe is very surprising (i.e., epistemically improbable) under what I called the naturalistic-single-universe hypothesis (that is, the hypothesis that naturalism is true and that there is only one universe). Further, I argued that the existence of such a universe is not surprising under theism/axiarchism. Thus by the likelihood principle the existence of an ECA-structured universe confirms theism/axiarchism over the naturalistic-single-universe hypothesis.[7]

To support the claim that the existence of such a universe is not surprising under theism/axiarchism, I argued that, despite the seemingly enormous difficulty presented by the problem of evil, we can nonetheless glimpse how the existence of ECA-structured universe could make an overall positive contribution to the moral value of reality. As mentioned previously, one such value is the ability of ECAs to engage in particular kinds of virtuous actions – such as self-sacrificial love, courage, and the like – that the vulnerability that comes from embodiment allows (Collins forthcoming - b). I also pointed out that a universe with agents who are highly vulnerable to their environment and to one another will almost inevitably contain the kind of evils we find in our universe (Collins forthcoming – b).

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[5] Philosopher Mark Steiner (1998) has developed this idea in some depth for the case of physics. By looking at many examples, he argues that the practice of scientists assumes that the world is more user-friendly than would make sense under naturalism. He does not use my example of simplicity, however.

[6] Roughly, the likelihood principle says that if a body of data E is epistemically more probable (i.e., more to be expected) under a hypothesis h_1 than a hypothesis h_2, it confirms h_1 over h_2, with the degree of confirmation proportional to the ratio of conditional epistemic probabilities. (Conditional epistemic probability measures the degree one proposition – such as that corresponding to E – should be expected under another proposition – such as that corresponding to $h_{1.}$)

[7] Here I am assuming that axiarchism is a confirmable thesis, which some might doubt given the foundational epistemological role it plays. Even if not confirmable in a Bayesian sense, for the reasons cited above, it still has the merit of comporting much better with what we know about the structure of the universe than naturalism.

Consequently, insofar as we can glimpse some overall positive moral value realized by such a universe – such as those just cited – the combination of the existence of such a universe with its consequent evils is rendered unsurprising under theism/axiarchism. Under naturalism, however, it is still very surprising that we find ourselves in such a universe and hence theism/axiarchism is strongly confirmed over universe naturalism even when the existence of evil is taken into account. Next, I will consider how whether one adopts the axiarchist's, or naturalist's, PINO can make a difference in one's scientific practice, particularly in the area of cosmology.

Implications for Scientific Practice

I will start with the implications of axiarchism. Historically, the belief that the universe is aesthetically structured at some basic level strongly influenced the practice of physics from the scientific revolution until today. As Morris Kline, one of the most prominent historians of mathematics, points out, "From the time of the Pythagoreans, practically all asserted that nature was designed mathematically." (1972, p. 153). Of course, in Christian Europe this notion of a mathematical design to nature was motivated by theism, two of the most prominent advocates of such a view being Galileo and Kepler. Both claimed that their physical speculations were guided by a belief in God as the "great geometer." Although often no longer grounded in theistic belief or more generally axiarchism, this tradition has continued into the twentieth century, with Albert Einstein being its most prominent advocate. Indeed, Paul Dirac took this to the extreme of saying "it is more important to have beauty in one's equations than to have them fit experiment" (1963, p. 47).

Further, as discussed above, axiarchism can give us confidence that the universe is structured so that we can discover it, a confidence that has been amply confirmed by the success of science. This boost in one's confidence in the universe's discoverability resulting from axiarchism can have a significant impact on one's scientific practice. To begin, consider the commonly raised objection to the fine-tuning argument that there are features of the universe that seem irrelevant to life. For example, cosmologist Sean Carroll states that

> . . .there is a better reason to be skeptical of the fine-tuning claim: the indisputable fact that there are many features of the laws of nature which don't seem delicately adjusted at all, but seem completely irrelevant to the existence of life? (p. 636)

Carroll, and Mario Livio, and Steven Weinberg (Mario Livio 2000, pp. 240–241; Weinberg 2001, pp. 253–254) all raise one specific example in common, that involving the extra generations of quarks and leptons. As Carroll explains,

> All of the ordinary matter in the universe seems to be made out of two types of quarks (up and down) and two types of leptons (electrons and electron neutrinos), as well as the various force-carrying particles. But this pattern of quarks and leptons is repeated threefold: the up and down quarks are joined by four more types, just as the electron and its neutrino are

> joined by two electron-type particles and two more neutrinos. As far as life is concerned, these particles are completely superfluous (Carroll 2005, pp. 636–637).

Although it is not clear that axiarchism requires that every element in the universe serve a purpose, nonetheless an axiarchist would be motivated to search for a way in which such features did serve a purpose. For example, in the case of these extra generations of quarks and leptons, an axiarchist would be motivated to search for a reason, such as the generations being a necessary consequence of some deeper more elegant theory, or being indirectly necessary for life, and or aiding in discoverability. In this case, axiarchism motivates a search for deeper laws or principles that manifest such purpose, with the seemingly irrelevant particles providing important clues. Indeed, in the above example, the three generations fall into a fairly neat symmetrical pattern – for example, the particles in each row are identical except for mass. This gives us reasons independent of axiarchism for thinking that there is some elegant underlying theory that explains their existence. (See Fig. 3). Further, the three additional particles have a low enough energy that we can detect them; if the *tau* particle, for instance, was much larger, we would not have discovered the symmetrical pattern. Thus, arguably, their masses are just right to motivate us to look for a deeper theory. This further reinforces considering them to be clues.

Interestingly, in this case the denial of axiarchism ends up being a "science stopper" – encouraging us to accept that there is no deeper reason for the extra generations – whereas axiarchism encourages the search for a deeper explanation. The non-axiarchist objection commits what could be called the "ungodly appeal to gaps" fallacy: as some theists in the past appealed to gaps in our scientific understanding to argue for God's intervention in natural affairs, these non-axiarchists appeal to gaps in our understanding of how these features contribute to the value-optimality of the universe to argue for the non-existence of God (and the denial of axiarchism).

As another example, consider the so-called *cosmic coincidence problem* in current cosmology – that is, the fact that at present the dark energy density is approximately that of the matter-radiation energy in the universe. Although a considerably larger dark energy would probably not allow for galaxies to form, a smaller value would not be detectable. Further, it seems that a zero value for dark energy would be more elegant. Given this, an axiarchist should be motivated to think the detectable dark energy density is likely to serve a role in discoverability – such as being a clue to a deeper theory.

My analysis above implies that non-axiarchists have different stopping points for what they consider a satisfactory final scientific explanation, stopping points corresponding to their respective PINOs. Non-axiarchists will be satisfied if they can find some *simple*, or perhaps elegant, ultimate explanation that does not commit them to any appearance of teleology. Thus they will attempt to explain away any feature that appears be teleologically ordered. One sees this, for instance, in such writers as Peter Atkins (1987), who advocates a "bare bones" view of the world,

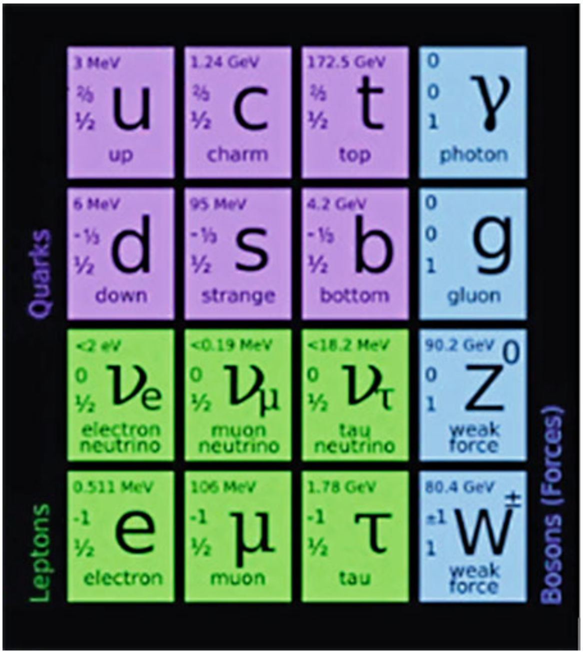

Fig. 3 Each of the first three columns forms a generation of matter, with the last column showing the force carriers. The first two rows of the first three columns are quarks (From http://www.final.gov/pub/inquiring/matter/madeof/index.html. In the public domain)

seeing this as the one demanded by the ideals of science. This also leads to a preference for severe sorts of reductionism among non-axiarchists.

In contrast, axiarchists see a teleologically ordered structure of laws and initial conditions as the final stopping point of explanation – whether that structure is one that maximizes elegance, provides an optimal environment for the formation of ECAs, or optimizes the ability of those agents to engage in science, or something else. Consequently, each has different methodological implications for what needs an explanation, when we should search for a deeper theory, and what that deeper theory might look like. Axiarchists who eschew the “God of the gaps” will seek scientific explanations for seeming causal gaps in the universe – since generally causal gaps decrease the universe’s elegance – but not for teleologically ordered structures of laws and initial conditions, unless they can glimpse a way in which a deeper theory might be more value-optimal. Further, they will search for explanations of any basic structure of the universe that appears to conflict with their PINO – such as one that appears to take away from the elegance and discoverability of the universe while at the same time seeming to serve no other purpose. Thus, for instance, axiarchists will see much less need than naturalists to offer a scientific explanation of the seemingly enormously improbable initial configuration of mass-energy at the beginning of the universe, though they still might have some motivation to find an explanation in terms of more fundamental laws since arguably this would be more elegant. On the other hand, since, as noted above, many of the particles in modern physics appear to serve no life-permitting role, they will be motivated to seek an explanation for them in terms of a deeper theory that brings out their overall contribution to the aesthetic and moral value of the universe. In contrast, as we saw above, non-axiarchists will be less motivated to seek a deeper explanation, especially those who use the existence of these particles as evidence against theism or axiarchism. So in these ways whether or not one is an axiarchist can make a difference in one's scientific practice at the forefront of physics and cosmology.

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Some Theological Reflections

John Polkinghorne

Abstract Georges Lemaître's status as a pioneer cosmologist and catholic priest make him an iconic figure expressing the complementary compatibility of science and religion. His emphasis that creation is to be understood as concerned with the whole of the universe's history and not solely with its beginning is an essential insight. The greatest challenge to theology lies in the scientific prediction of ultimate cosmic futility. These and other relevant issues are briefly discussed.

This book has been a rich and illuminating collection of chapters, reflecting on the life and influence of Georges Lemaître in many ways and from many perspectives. I was intrigued to learn that Lemaître once went on a touring holiday with Fred Hoyle and his wife—the quiet and modest Roman Catholic priest in company with the exuberant and assertive English atheist, their common interest in cosmology presumably being the bond between them.

For those of us who work in the field of science and religion, Lemaître is an iconic figure. It is inspiring to remember the devout believer who was also an outstandingly creative scientist and the pioneer of big bang cosmology, able to hold these two aspects of his life together in a consonant harmony. The full significance of Lemaître's scientific work was not realised during his lifetime, and in this he reminds me of another Christian believer whose outstanding scientific work also only received posthumous recognition, the Austrian monk, Gregor Mendel. In a different respect Lemaître reminds me of Galileo, who despite his difficulties with the Church authorities remained a committed Catholic believer to the end of his life. The point of comparison here is the fact that even the greatest scientists do not succeed in being right about everything. Galileo was mistaken in his explanation of the tides, despite believing it to be a pillar of his system, and Lemaître was mistaken in his account of cosmic rays.

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It is a theological commonplace to observe that the doctrine of creation is not primarily concerned with how things began, but why things exist at all. Its focus is on ontological origin, rather than on temporal origin. It seeks to answer the question ‘Why is there something rather than nothing?’, rather than ‘Who lit the blue touch paper of the big bang?’ God is as much the Creator today as God was 13.7 billion years ago. Lemaître certainly realised this clearly enough and hence his careful warning to Pope Pius XII against appealing to the Big Bang in support of Christian theological beliefs. This recognition of the relation between cosmology and the doctrine of creation does not mean that scientific insight has no influence on the tone of theological discourse—for example, the great age of the universe certainly suggests the thought that the Creator is not a God in a hurry—but that this influence is oblique and insightful in its character and not coercively demonstrative. I feel, however, that Lemaître’s tendency to express this fact in terms of speaking of a *deus absconditus* (a hidden God), might carry the risk of implying too sharp a separation between theological and scientific insight, of the kind which was expressed by Stephen J. Gould in his concept of non-overlapping magisteria, which regarded science and religion as parallel explorations of reality which never actually intersect each other at all. I would prefer to speak of God’s presence to creation as being veiled, rather than hidden. The universe is certainly not full of objects stamped ‘made by God’, but there are hints and rumours of the divine mind and purpose to be discerned in the wonderful order of the universe and in the great fruitfulness of cosmic process that scientific exploration has revealed to us. Hence the revival today of a modest form of natural theology, claiming that theistic belief explains more than atheism can (Polkinghorne 1998).

The deep intelligibility of the universe, which has enabled physicists to discover both the secrets of the subatomic world of quantum theory, so counterintuitive to everyday expectation, and the nature of the vast realms of cosmic space-time, is a remarkable fact that can itself become intelligible if we see it as a sign that the Mind of the Creator lies behind that remarkable cosmic order and that human beings, to use an ancient and powerful phrase, are creatures made in the image of their Creator.

We know that the universe started extremely simply, as an almost uniform expanding ball of energy. After 13.7 billion years, that universe is now a world of great complexity, the home of saints and scientists. This remarkably fertile history has come about through the unfolding of natural processes, which have explored and brought to birth the great potentiality with which the finely-tuned laws of nature actually operating in this universe are endowed. Although it was ten billion years before carbon-based life actually appeared on the cosmic scene, the universe was pregnant with that possibility from the beginning. The insights expressed in the Cosmic Anthropic Principle show us that the evolution of carbon-based life is only possible in a universe in which the given laws of nature take very specific, very precisely defined, forms, so that a life-bearing world appears to be a very exceptional cosmic possibility among the portfolio of conceivable universes - hence the notion of ‘fine-tuning’ (Barrow and Tipler 1986; Holder 2004).

The religious believer can see this unfolding history of fruitful process, not as the result of a sequence of extraordinarily happy accidents, but as an act of continuous creation, the expression of the will of the universe's Creator who, as the Ordainer and Sustainer of the laws of nature, acts as much through natural processes as in any other way. (The implicit theological mistake of the Intelligent Design movement is the failure to recognise this latter fact.) Those who wish to avoid a theistic explanation of fine-tuning are driven to the expedient of invoking the concept of the multiverse, the idea that our universe is only one of a large, possibly infinite, portfolio of worlds, each separate from the others and each possessing its own laws of nature, with ours simply by chance the world where carbon-based life is a possibility. However, it is not clear that without further constraint on its character a multiverse would have to yield a winning ticket in the cosmic lottery for life. Mere infinity will not do the trick, as if by itself it would imply the presence of any particular desirable property, such as that of permitting carbon-based life. After all there are an infinite number of even integers, but none has the property of oddness.

Because of the unobservability by us of the other worlds that it postulates, the multiverse proposal is as metaphysical in character as the hypothesis of a Creator God. The existence of highly speculative theories which might encourage such ontological prodigality, such as string theory's supposition of a 'landscape' of 10^{500} different universes, does not seem to modify this assessment of metaphysical status, since conjectures of how matter might behave in regimes 16 orders of magnitude beyond energy scales of which we have direct empirical experience hardly qualify as scientific knowledge.

Of course, it is theologically possible that God might wish to create more worlds than ours. It is not for human beings to seek to limit the divine creative generosity. Don Page made this point at the Conference. However, I do not think that the Creator would create many different worlds without there being, so to speak, a point to the existence of those other universes. In other words, those other worlds would not make up a random set, like the universes of the string landscape, but would surely have their individual creative fruitfulness, of a kind comparable to the evolution of carbon-based life in ours. The late Arthur Peacocke sometimes spoke of the of the idea that God might explore possibilities through the existence of many worlds, but surely the Creator is fully aware of possibilities and can make the choice in the divine mind, without needing to experiment in that way.

The greatest challenge for theology from cosmology is presented by what science can say about endings, rather than beginnings. This universe will eventually come to an end, either in a bang or in a whimper. That is to say either it will finally collapse again into a final fiery 'big crunch', or it will continue to expand forever, becoming yet colder and more dilute, so that eventually carbon-based life can no longer exist anywhere within it. The discovery of dark energy presently accelerating expansion makes the latter possibility the more likely expectation. Of course the time-scales involved in these prognostications are immense, amounting to many billions of years. Yet, however distant the prospect may seem now, this universe is surely condemned to eventual futility. What then for the status of the claim that it is the expression of a Creator's purpose? The distinguished physicist and staunch atheist, Steven Weinberg, notoriously once said that the more he understood the universe, the more it seemed pointless to him. This is a challenge that theology must face.

The fact is that every story that science can tell, whether of human life on a timescale of tens of years or of the cosmos on a timescale of many billions of years, ends in death and decay. The second law of thermodynamics, decreeing the increase of entropy and the consequent rising of the waters of chaos, ensures that in the end all is futility. However, science's 'horizontal' story of the unfolding of present physical process is not the only tale to tell. Theology has the 'vertical' story of the faithfulness of the divine Creator. Jesus appealed to this in his dispute with the Sadducees about whether there is a human destiny beyond death (Mark 12:18–27). He reminded them that God is the God of Abraham, Isaac and Jacob, who surely did not abandon the patriarchs when their earthly lives were ended as if they were of no further use or concern, but is 'the God not of the dead but of the living'. Christian theology sees the divine creative purpose as intrinsically two-step, first this world ('the old creation'), existing at some distance from the veiled presence of its Creator, to be transformed in the fullness of time into 'the new creation', freely open to the unveiled presence of God and in consequence endowed with such strong self-organising principles in its new laws of nature that the thermodynamic drift to death and decay no longer operates within it. This is not the place to seek to explore this fundamental Christian hope in more detail, (Polkinghorne and Welker 2000; Polkinghorne 2002) but we should note that it is part of Christian belief that the new creation has already begun to come into being with the seminal event of the resurrection of Christ. The tomb was empty because the dead body of Jesus had been transformed into his risen and glorious body as the first fruit of the new creation.

Theologians sometimes seem to have a very limited view of creation. When they speak of the world, they often mean planet Earth and not the vast universe with its 100,000 million galaxies. When they speak of the future, they often seem to mean at most the next 1,000 years. The cosmological discoveries that Georges Lemaître played so important a part in initiating can help to encourage theologians to take a grander view of the scope of divine creativity.

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