Looking at the Sky: From Pythagoras to Einstein Through Galileo and Newton

No Admission Without Knowledge of Geometry

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> *The material world—the reality—is not something given, but is born with us. For the "given" to become reality, it must be resurrected in the literal sense of the word. This is the role of Science, this is the role of Art.*
>
> [a]Ossip Mandelstam, Letter to Marietta Shaginyan, April 5, 1933.

1 Prelude

E quando miro in cielo arder le stelle;
Dico fra me pensando:
A che tante facelle?
Che fa l'aria infinita, e quel profondo
Infinito Seren? che vuol dir questa
Solitudine immensa? ed io che sono?
…
E dell'innumerabile famiglia;
Poi di tanto adoprar, di tanti moti
D'ogni celeste, ogni terrena cosa,
Girando senza posa,
Per tornar sempre là donde son mosse;

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M. Streit-Bianchi et al. (eds.), *Advances in Cosmology*,
https://doi.org/10.1007/978-3-031-05625-3_1

Uso alcuno, alcun frutto
Indovinar non so.[1]

Giacomo Leopardi's wandering shepherd looks up into the sky, searching for the meaning of all things (*A che tante facelle?*) and of its very life (*ed io che sono?*). The attempt to find in the skies the point and the purpose of all the nowhere-going movements and struggles of everything and every human being (*di tanto adoprar, di tanti moti*) is doomed to failure (*Uso alcuno, alcun frutto / Indovinar non so*).

The questions raised by the shepherd have been asked by men and women of all epochs, though rarely expressed with such intense words. The gesture of looking at the starry sky seems to be specific to the genus homo as much as the *nosce te ipsum* [1] to such an extent that it could be also taken as a definition of what being human is all about.

The terrestrial landscape has changed a great deal, but, to the naked eye, the sky has not changed at all, because the couple of million years elapsed after the appearance of the first *homines* on Earth are, on a cosmic scale, *like a day that has just gone by, or like a watch in the night*.[2]

All men and all women have seen the same sky. Yet, their cosmogonic narrations and their cosmological representations are very different from each other and above all are radically different from that which is supposed to be the modern scientific vision of the world, our vision. The story of the ideas that led to this vision is extraordinarily fascinating, dramatic and sometimes tragic and has been narrated a thousand times in books that have rightly become classical. We will go over some of its highlights again [2].

2 A Name, an Idea

The idea of universe is not a primitive idea [3]. If, as customary, we let history begin with the invention of writing around the year 3000 BC, we see that humanity was able to do without the idea of universe, or, better to say, its explicit thematization, during half of its history, not to mention the immensity of prehistory: a word to designate the totality in a unified way appeared in Greece only around the year 500 BC.

Previously, a more or less exhaustive enumeration of the things contained in the totality or else a binary opposition were used—the biblical and Homeric formula *Heaven and Earth* being the best known. It is only when this distinction between the things on which we can—in principle—have an influence and those which are

[1] *…And when I gaze upon the stars at night – In thought I ask myself – "Why all these torches bright? – What mean these depths of air, – This vast, this silent sky, – This nightly solitude? And what am I?" – …– "And all this mighty motion, and this stir – Of things above, and things below, – No rest that ever know, – But as they still revolve, must still return – Unto the place from which they came, – Of this, alas, I find nor end nor aim!"*
Giacomo Leopardi, Canto notturno di un pastore errante dell'Asia (excerpt) 1830.

[2] Psalms 90, 4.

completely beyond us is put aside, that the "world" can appear. Wittgenstein expresses this state of affairs with the formula "The subject does not belong to the world, but it is a frontier of the world".

Legend has it, that was Pythagoras to choose the proper noun: "cosmos", which, as everyone knows, opposes itself to chaos and designates order and beauty, or to say it better, the beauty that derives from the order. "Pythagoras was the first, who named the encompass of the whole a Cosmos, because of the order which is in it" [4].

The Latin name "mundus" has exactly the same meaning as cosmos.[3] Pliny the Elder tells us in his *Naturalis Historia* that "The Greeks gave to all things the name 'cosmos' and we called it 'mundus' by virtue of its perfect and absolute elegance." The name "universe" (*Unvorsum*), a poetic contraction of *unus* and *versus*, appears for the first time in the fourth book of Lucretius' *De Rerum Natura*. Lucretius gives this word the meaning of a set of particles that rotate all together.

The thirtieth fragment of Heraclitus gives us a glimpse of the eternal cosmic order, that of a self-sufficient totality which does not require external instances: "This world, which is the same for all, no one of gods or men has made; but it was ever, is now, and ever shall be an ever-living fire, with measures of it kindling, and measures going out."

On the contrary, according to Plato, order does not pre-exist the primordial chaos of the chora but it results from the creative action of a demiurge. Timaeus recounts the mythical birth of the universe: "The world …has become a visible living creature containing the visible—the sensible God who is the image of the intellectual, the greatest, best, fairest, most perfect—the one only begotten heaven."

The order of the universe is not only the visible manifestation of the intelligible God; it is also the model to be imitated to return to the original state of excellence, which was lost by the incarnation of the soul. Cosmology will keep this ethical dimension for two millennia, until the birth of the scientific vision of the world. Thus, the word cosmos–order is already a "cosmology". It gives a description of the totality that is not neutral but implies a judgment of value. Perhaps, it is interesting to compare this stance with the modern point of view, exemplified here again by Wittgenstein's words: "The sense of the world must lie outside the world. In the world everything is as it is and happens as it does happen. In it here is no value—and if there were, it would be of no value." As for the means to describe and try to understand the order of the cosmos, the Greeks also explain to us the relative roles of "physics" and "mathematics": "The task of the contemplation of nature (*theoria phusikè*[4]) is to examine the substance of the sky and the stars, the power and the quality of generation and corruption, and, by Zeus!, it is capable of leading demonstrations on the subject of the size the form and the order of things. As for astronomy (*astrologia*) it does

[3] The original sense of "woman's ornament" is metaphorically turned into order and beauty, the beauty resulting from order (cosmetics). The usage was for a long time perceived as a metaphor. The "cosmic" unique usage took centuries to emerge. Mundus is the etymological source of the Italian word "monile".

[4] To perceive the *logoi* in beings is the act known as *theoria phusikè*, the second of the three stages of the spiritual life distinguished by Evagrius and the tradition that followed him [5].

not undertake to speak of anything like that, but it demonstrates the order (*taxis*) of celestial things, having declared that the sky (*ouranos*) is truly a cosmos; it speaks of forms, sizes, distances from the Earth to the Sun and the Moon, eclipses, conjunctions of stars, on the quality and quantity that are shown in their revolutions." (Posidonios, 135-51 avant J.-C.). The *theoria phusikè* has therefore the task of examining the substance of the sky and the stars. On the other hand, mathematics must be limited to saving the appearances. This warning will return dramatically seventeen centuries later.

3 Aristotle and the Ptolemaic World

Physics enters in cosmology with Aristotle: the physical foundations of the standard cosmological model of the ancient world are rooted in the Aristotelian conceptions of movement and gravity. The Stagirite distinguishes between three types of movements. Two of them occur in the sublunary world: the natural movements of falling heavy bodies (made in prevalence of earth and water) and of rising light bodies (made in prevalence of air and fire) are caused by their tendency to proceed to their "natural place"; on the contrary, violent movements require an external force as a cause.

The very existence of a natural place explains the central position and the spherical shape of the Earth. It also explains what gravity is. An apple falls because it aims to go where heavy bodies naturally go. That place is necessarily at the center of the universe, where the Earth is located (otherwise it would also end up falling there). Moreover, the Earth cannot spin around its axis nor can it revolve around the Sun because the perfect circular movement cannot exist in the changeable and corruptible sublunary world. Terrestrial creatures move on straight and irregular trajectories, because they are limited and imperfect and must seek food and help outside of themselves.

The motionless center of the cosmos is therefore not a place of delight, but rather a garbage dump where all the heaviness of the sublunary world falls. And yet it is the unique and privileged center around which the spheres of the superlunary world revolve, bringing the stars with them in their race without beginning or end.

The heavens are concentric crystalline spheres made of the fifth element: the aether or quintessence. The aether has no weight or lightness and therefore cannot go towards the center or away from it: its movement is by nature circular and uniform. Eudoxus of Cnidus, a disciple of Plato, had invented them as a calculation device but Aristotle considers the spheres of the heavens as physically existing. There are fifty-five of them and the last one is fixed and borders the finite universe; indeed, if the universe has a center, it can only be finite.

Can we bend outside this last frontier? The question makes no sense because there is no outside. There is nothing. Not even the void…"It is evident not only that there is not, but also that there could never come to be, any bodily mass whatever outside the heavens. …There is also no place or void or time outside the heaven. For in every place body can be present; and void is said to be that in which the presence of body, though not actual, is possible; and time is the number of movement. But in the absence of natural body there is no movement, and outside the heaven, as we have shown, body neither exists nor can come to exist.” [6].

The world has to wait for Giordano Bruno to meet the one “who has pierced the air, penetrated the sky, toured the realm of stars, traversed the boundaries of the world, dissipated the fictitious walls of the first, eighth, ninth, tenth spheres, and whatever else might have been attached to these by the devices of vain mathematicians and by the blind vision of popular philosophers.” [7].

Perfected by Ptolemy in the Almagest and in the Hypotheses planetarum, the system of the spheres (and epicycles) has been the foundation of the standard vision of the world for centuries. It accounts for the celestial movements of the stars with good precision. It also gives a cosmological basis to anthropology and ethics, extending the “scientific” representation into an answer to the question about being-in-the-world. That world would collapse under the deadly blows of the *De Revolutionibus Orbium Coelestium* by Nicolaus Copernicus.

4 The Copernican Revolution

In fact, canon Copernicus was not a revolutionary. His inspiration and his cosmological principles were strongly linked to the traits of Aristotelianism described above: they are the perfection of circular movements but also the finiteness and the spherical shape of the universe and the solidity of the crystalline spheres. And more than observing the sky, Copernicus, as a good humanist, sought his sources in the classics: “…I began to be annoyed that the movements of the world machine, created for our sake by the best and most systematic Artisan of all, were not understood with greater certainty by the philosophers, who otherwise examined so precisely the most insignificant trifles of this world. For this reason I undertook the task of rereading the works of all the philosophers which I could obtain to learn whether anyone had ever proposed other motions of the universe’s spheres than those expounded by the teachers of astronomy in the schools. And in fact, first I found in Cicero that Hicetas supposed the earth to move. Later I also discovered in Plutarch that certain others were of this opinion.” [8]. In fact, the Copernican revolution which “places the Earth as mobile and the Sun, on the other hand, as immobile at the center of the universe, is based on exactly the same astronomical data of the *Almagestus*.[5] There was nothing new under the Sun (nor above). Except that once the Earth is removed from the center of the universe, a question that we thought was decided comes back strongly: what is gravity?

[5] And also on the astronomical data transmitted by the Arabs. Albategnius and some other Arab astronomers are quoted by Copernicus.

Until recently it was believed that the *De revolutionibus* was already completed in 1530. Today it is known that the sixth book was written only after 1539. Four hundred copies were printed only in 1543, shortly before the author's death. The initial print run was not sold out. The text is preceded by a preface written anonymously by Andreas Osiander who had been commissioned by Georg Rheticus, the author of the *Narratio prima* [9], to oversee the publication of the book. Osiander was a former Catholic priest turned Lutheran theologian, very active and vaguely heretical. By professional deformation, he saw rather well the risks inherent in the theses of Copernicus, theses that undermined the scientific bases of the cosmic order that philosophy and theology conceived as anthropocentric. To counter these risks, Osiander, in his anonymous preface *To the Reader Concerning the Hypothesis of This Work*, repeats in even more drastic terms Posidonius' arguments:

"Since the novelty of the hypothesis of this work has already been widely reported, I have no doubt that some learned men have taken serious offence because the book declares that the earth moves, and that the sun is at rest in the center of the universe; these men undoubtedly believe that the liberal arts, established long ago upon a correct basis, should not be thrown into confusion. But if they are willing to examine the matter closely, they will find that the author of this work has done nothing blameworthy. For it is the duty of an astronomer to compose the history of the celestial motions through careful and expert study. Then he must conceive and devise the causes of these motions or hypotheses about them. Since he cannot in any way attain the true causes, he will adopt whatever suppositions enable the motions to be computed correctly from the principles of geometry for the future as well as the past. The present author has performed both these duties excellently. For these hypotheses need not to be true nor even probable. On the contrary, if they provide a calculus consistent with the observations that is enough." [10].

A computational hypothesis, which concerns only mathematicians, that's all. Revolution is something different!

Yet, the revolution was secretly underway. On the evening of November 11, 1572, leaving his uncle's underground alchemical laboratory and looking towards the zenith, Tycho Brahe, the greatest ever observer of the sky with the naked eye, saw a "nova et nullius ævi memoria prius visa Stella," a new star, brighter than Venus, in the constellation of Cassiopeia. It was unheard of! He doubted his vision and asked the peasants who were passing by if they saw the same star as him in the sky. This event would change the life of Tycho who became the first of the modern astronomers. The Stella nova was there to destroy the idea of immutability of the heavens, because there were changes in the superlunary world. Stars could be born and perhaps die …

After that, it was the turn of the crystalline spheres to break apart under the blows of the great comet of 1577. Tycho observed it for several months; the parallax of the comet allowed him to decide a thousand-year-old question: the comets were indeed celestial bodies. "All the comets which I have observed move in the ethereal region of the world and never in the sublunary region as Aristotle and his followers wanted us to believe for many centuries!" And as its trajectory, which was not at all circular, went through the orbs of the planets "the reality of crystalline spheres must be excluded from the heavens." The spheres do not really exist, the sky is free, open in all directions and there is no obstacle to the race of the planets. But, once destroyed the crystalline spheres *a quo moventur planetae*? What is the cause of the motion of planets and other celestial bodies?

Finally, the last to dissolve was the circular motion of the planets, already undermined by the superlunary comets. It is all the more ironic that the main motivation of Copernicus' work was to reestablish the perfection of the circular and spherical geometry. However, the astronomical data that Tycho had entrusted to Johannes Kepler and that Kepler had been studying hard for six years, said something else: the orbit of the planet Mars was not circular, nor reducible to a composition of circles, but it was an ellipse with the Sun at one of its focuses. Kepler wrote the *Astronomia Nova,* αιτιολοητος *seu physica coelestis, tradita commentariis de motibus stellae Martis ex observationibus G.V. Tychonis Brahe*, a book that since 1609 marks forever the history of astronomy. Yet the planetary ellipses were to remain a dead letter for a long time. It is only after Newton's law of universal gravitation that everybody accepted the Keplerian orbits of the planets. Today they still remain elliptic (roughly!)

5 The Galileo Affair

The *Astronomia Nova* was unlucky to appear shortly before the publication of Galileo's *Sidereus Nuncius* (1610). The Galilean heavenly messenger announces the revolution in broad daylight. He reveals that the Copernican point of view is not just a technical question for mathematicians but concerns everyone. Since then, the Galileo affair has been one of the most significant events in the history of western culture [11, 12]. Countless literary, philosophical and scientific books have supported virtually every possible stance regarding Galileo's condemnation, the relationship between science and religion, the birth of modern science and the scientific method. We are going to mention here only the few aspects that are relevant for our cosmological tale.

Galileo propagated the revolution by means of a canon-shaped telescope—the *cannocchiale*. This Dutch-made instrument was originally an object for the amusement of the wealthy. Galileo perfected it obtaining a much better magnification and sold it to the Senate of Venice as a military instrument.

Then, on the evening of August 25, 1609, he pointed his perfected telescope towards the sky and discovered a world that no one had ever seen. He observed the lunar landscape with mountains and valleys and myriads of stars of the Milky Way. On January 7, 1610, he observed three stars near Jupiter and then, on January 13, a fourth one. Their positions had changed: they were circling around Jupiter as everyone could see. Freed from verbose debates ("e noi liberati da verbose discussioni") the millenary conception of an unchanging and perfect sky that revolves around the Earth was over. Six and a half years later, on March 5, 1616, Copernicus' *De Revolutionibus orbium coelestium* was added to the Index, sixty-three years after its publication.

All of this is well known. But there is something here that must not escape our post-modern eyes. Today, Galileo's gesture of observing the sky with his *cannoc-*

chiale may seem obvious and even obsolete, but it was not at all so in his epoch and for many reasons. First there was nothing to see in the sky. Everything had to go as it had always been. Worse, the instrument used to observe the sky was unworthy, made by mechanicians and engineers, and therefore not very commendable for honest gentlemen and for academics (who often stubbornly refused even to touch the telescope).

It is by disregarding this official science that, with his solitary gesture, Galileo abandons the conception of the human natural senses as an absolute criterion of knowledge, and, trusting in what he sees through his instrument, lays the foundations of the scientific revolution that has forever changed the history of humanity.

Copernicanism is also the pillar of the project to establish a new science. The Copernican overturn of the cosmic order leads to the revolutionary idea that there is only one physics that governs the movements on Earth as in Heaven and opens the way for geometry to come down in our sublunary world to explain celestial and terrestrial phenomena on the same basis. Heaven, so to speak, descends to Earth (Fig. 1).

The most recent Galilean studies indeed point out how erroneous it would be to separate Galileo's researches on the movement and the fall of massive bodies—made in Pisa from the 1580s and in Padua thereafter—from his subsequent astronomical studies. These studies had already led him to reject scholastic physics. Aristotle taught, for example, that a body weighing ten pounds falls from a certain height in ten times less time than a body weighing one pound. Legend has it, that the young Galileo climbed the tower of Pisa and, at the passage of the academic procession, dropped the two weights that arrived on the ground almost at the same time. Experimental evidence had never been sought for before. It was an absolute novelty of the new Galilean scientific method.

In the bitterness of his old age, the prisoner Galileo had nevertheless the courage to go back to the study of free fall and the movement of the projectiles, in the third and fourth parts of his last book, *Discorsi e dimostrazioni matematiche intorno a due nuove scienze* (1638). "La filosofia è scritta in questo grandissimo libro che continuamente ci sta aperto innanzi a gli occhi (io dico l'universo), ma non si può intendere se prima non s'impara a intender la lingua, e conoscer i caratteri, ne' quali è scritto. Egli è scritto in lingua matematica, e i caratteri son triangoli, cerchi, ed altre figure geometriche, senza i quali mezi è impossible a intenderne umanamente parola; senza questi è un aggirarsi vanamente per un oscuro laberinto."[6] [13].

[6] Philosophy is written in this grand book, which stands continually open before our eyes (I say the 'Universe'), but can not be understood without first learning to comprehend the language and know the characters as it is written. It is written in mathematical language, and its characters are triangles, circles and other geometric figures, without which it is impossible to humanly understand a word; without these one is wandering in a dark labyrinth.

Fig. 1 Albrecht Dürer: *Melancholia I* (1514). Geometry comes down to Earth from the Skies. The wings of the angels are now useless…[14]

To better appreciate the greatness of this last work, we must remember that in the seventeenth century geometry had nothing to do with physics in the sublunary world (Fig. 1). Even the eminently practical problem of calculating the trajectory of a projectile posed by the new techniques of artillery, was approached by compulsorily studying the Physics of Aristotle to find the correct way to compose violent movements with natural movements (Fig. 2). In this context, it is possible to understand the novelty and importance of the experimental works of the young Galileo and of the Discorsi of his maturity where he shows that the trajectory of a projectile is a parabola resulting from the composition of two movements that do not interfere with each other: a straight horizontal motion in accordance with the principle of inertia and a uniformly accelerated vertical motion whose acceleration does not depend on the mass of the body.

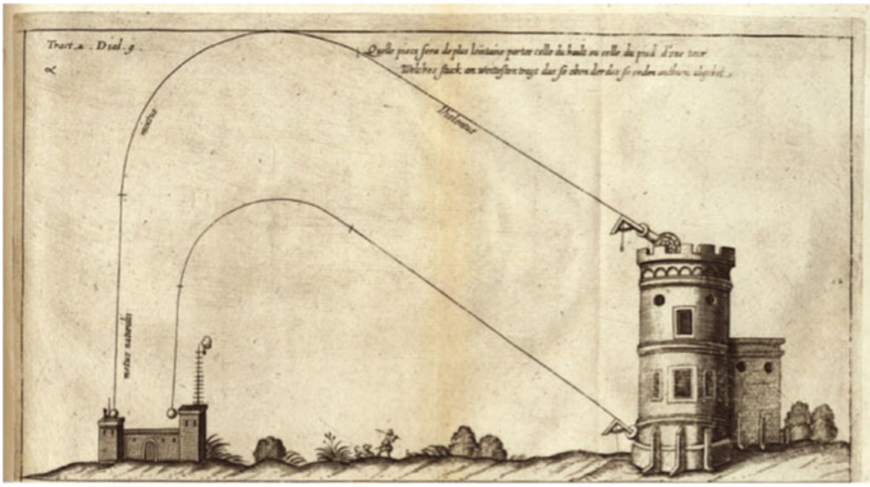

Fig. 2 Diego Ufano: *Artillerie (1628)*

The principle of equivalence of Galileo stating that all bodies fall (in void) with the same acceleration is, perhaps, the most important result of Galileo's new experimental science. It contains the germ of an answer to the questions about the nature of gravity and its universality (it is universal because it acts in the same way on all things and because it founds every science of the universe—including Aristotle's cosmology!) But this (provisionally) definitive answer will not come until three centuries later. Meanwhile Galilean science will find its climax and its accomplishment in the work of the greatest man of science ever: Isaac Newton (Fig. 3).

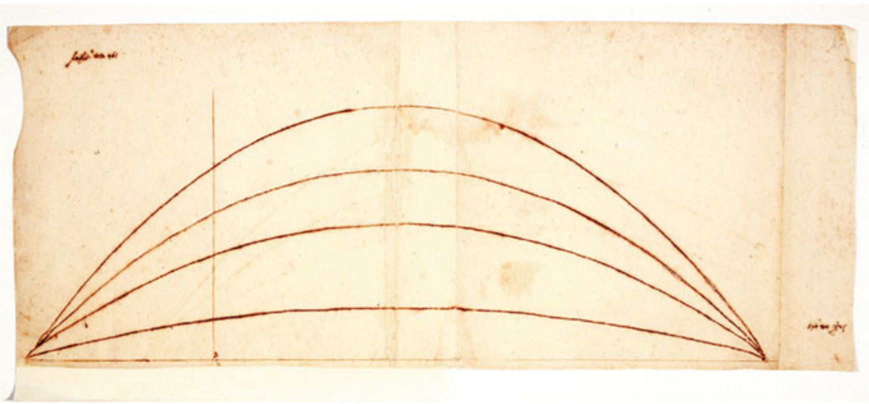

Fig. 3 Galileo Galilei. Codex 72. Folio 42 r. Galileo's new geometric theory of movement applied to ballistics

6 Never at Rest: Newton

It is with Newton that the discussion on the nature of space and time bursts into the *Philosophia Naturalis*, that is to say in the physical science. The first book of his immortal work, the *Philosophiae naturalis principia mathematica*, starts with the *Scholium* focusing on the notions of the three elements that make up the universe, space, matter and movement: "I do not define time, space, place, and motion, as being well known to all. Only I must observe, that the common people conceive those quantities under no other notions but from the relation they bear to sensible objects. And thence arise certain prejudices, for the removing of which it will be convenient to distinguish them into absolute and relative, true and apparent, mathematical and common. [...] Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration. Relative, apparent, and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year. Absolute space, in its own nature, without relation to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute spaces; which our senses determine by its position to bodies; and which is commonly taken for immovable space." [15].

The almost insurmountable problem is that there is no hold on absolute space. One can even doubt its existence, as will do, among others, Huygens, Leibniz and Mach. Newton responds to this objection with the famous example of a vase that contains water and they rotate together: the concavity of the free surface of water is the proof of the movement of water "relatively" to absolute space. It is once again the circular movement that plays a distinguished role; here it offers us the possibility of discerning absolute movements from relative movements. But doubts remain, and it is precisely by resuming this ideal dialogue with Newton on absolute space and the relativity of inertia that Einstein, in 1917, will lay the foundation of the modern scientific cosmology.

Newton speaks about inertia and the universality of gravity in the third book of the *Principia*. The crucial focus is given in the third *Regula Philosophandi* at the beginning of the book: "All bodies are moveable, and endowed with certain powers (which we call the *vires inertiae*) of persevering in their motion, or in their rest we only infer from the like properties observed in the bodies which we have seen. [...] Lastly, if it universally appears, by experiments and astronomical observations, that all bodies about the earth gravitate towards the earth, and that in proportion to the quantity of matter which they severally contain, that the moon likewise, according to the quantity of its matter, gravitates towards the earth; that, on the other hand, our sea gravitates towards the moon; and all the planets mutually one towards another; and the comets in like manner towards the sun; we must, in consequence of this rule, universally allow that all bodies whatsoever are endowed with a principle of mutual gravitation. For the argument from the appearances concludes with more force for the universal gravitation of all bodies than that for their impenetrability; of which, among those in the celestial regions, we have no experiments, nor any manner of observation. Not that I affirm gravity to be essential to bodies: by their vis insita I mean nothing but their *vis inertiae*. This is immutable. Their gravity is diminished as they recede from the earth."

Newton then sets out the law of Universal Gravitation: two bodies attract each other with a force proportional to the product of their masses and inversely proportional to the square of their distance. This law applies to the apple that falls on the Earth (and the Earth that falls on the apple) as to the Moon that falls around the Earth and to the planets that turn around the Sun. Newton accomplished Galileo's project of unification and abolished the principle of a substantial difference between Heaven and Earth. Better still: a single law accounts for a wide variety of phenomena. Newton's law is now part of the culture of teenagers from all over the world (those who have the chance to go to school).

And yet—as everyone knows—Newton declares himself ignorant as to the physical reality of gravitational attraction: "Hitherto we have explained the phenomena of the heavens and of our sea, by the power of Gravity, but have not yet assigned the cause of this power. [...] I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses. For whatever is not deduced from the phenomena, is to be called an hypothesis; and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy."

Newton had tried to find an explanation for gravity as a contact force caused by invisible particles, but he realized that this explanation could not work. In a letter to Richard Bentley he wrote: "You sometimes speak of gravity as essential and inherent to matter. Pray do not ascribe that notion to me, for the cause of gravity is what I do not pretend to know and therefore would take more time to consider of it. It is inconceivable that inanimate brute matter should, without mediation of something else which is not material, operate upon and affect other matter without mutual contact, as it must be if gravitation, in the sense of Epicurus, be essential and inherent in it. And this is one reason why I desired you would not ascribe innate gravity to me. That gravity should be innate, inherent, and essential to matter, so that one body may act upon another at a distance through a vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it."

After such a long journey, the question *what is gravity* remains unanswered.

The *Principia* do not contain cosmological assertions *per se*. The cosmological question is briefly mentioned in the correspondence with Richard Bentley. One of Bentley's questions is still relevant to those seeking to understand the formation of cosmic structures, and can be summarized as follows: a uniform distribution of matter in space may give birth to the Universe as we see it by purely natural causes? Newton replied that an infinite universe was needed: "As to your first query, it seems to me that if the matter of our sun and planets and all the matter in the universe were evenly scattered throughout all the heavens, and every particle had an innate gravity toward all the rest, and the whole space throughout which this matter was scattered was but finite, the matter on the outside of the space would, by its gravity, tend toward all the matter on the inside, and by consequence, fall down into the middle of the whole space and there compose one great spherical mass. But if the matter was evenly disposed throughout an infinite space, it could never convene into one mass; but some of it would convene into one mass and some into another, so as to make an infinite number of great masses, scattered at great distances from one to another throughout all that infinite space."

The idea of an infinite universe was not new. Giordano Bruno had already advanced it more than a century before [7]: "The universe is infinite and therefore there is no body in it to which it would belong to be at the center or on the periphery or between these two extremes." And why would the universe be infinite according to Bruno? Because there is no reason why it shouldn't be. Bruno appeals to the principle of sufficient reason[7] a century ahead of Leibniz and affirms the primacy of intellectual knowledge over sensible knowledge [16]: "I am sure that it will never be possible to find even a half-probable reason why there should be a limit to this corporeal universe, and therefore a reason why the stars, which are contained in its space, should be finite in number."

Compared to the fiery enthusiasm of Bruno in preaching the infinity of the universe and the absence of any center (a center which, let us stress it, persists in the Copernican system), Newton's argument appears somewhat utilitarian. Anyway, finite or infinite, the Newtonian (static) universe is unstable. The difficulty could not be overcome and Newton abandoned cosmology. To solve this difficulty, or better to say, to free oneself from it, it will be necessary to wait for the beginning of the twentieth century and Einstein's two theories of relativity, the modern physical theories of space and time that have replaced the absolute space and time of Newton.

7 Albert Einstein, the New Magellan

By the end of the 19th century the aether had become topical in physics, not as the fifth element of the superlunary world, but as the medium where electromagnetic waves propagate. Ironically, ether also reintroduced a strange asymmetry in the physical world, similar to that of Ptolemaic cosmology. There were on the one hand the laws of mechanics, valid in all inertial frames, and, on the other hand, the laws of Maxwell's electromagnetism, valid only in the referential of the aether. But all attempts to detect the aether experimentally, including the experiments of Michelson and Morley, had failed.

In 1905 Albert Einstein, a young third-class employee at the *Federal Intellectual Property Office* in Bern, cut short all efforts to give an explanation to these negative results in the framework of Newtonian physics: aether does not exist, he said, and *the laws of physics are identical in all inertial reference systems.* This is the statement of

[7] But also to the infinite power of God that produces all the infinite effect that it can produce.

the (meta-)principle of relativity of Einstein. It is a law on the laws of physics. And since the speed of light appears in Maxwell's equations as a constant of physics, its invariance follows: it does not depend on the reference frame (that is, the speed) of the experimentalist who measures it.

The speed of light is therefore a conversion factor: time can be measured in metres and distances in seconds (or light-years): "Accordingly we can express the essence of this postulate very tersely in the mystical formula: 300,000 km = 1 s." Space and time, thus, are the same thing (up to a minus sign): "Henceforth, space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality" (H. Minkowski, 1908).

Without having taken this fundamental step, that is to say without having merged space and time into the Minkowski spacetime [17], the question of a scientific cosmology could not be asked. But the crucial ingredient was still missing: gravity. Indeed, Newton's law of universal gravitation does not find its place within Einstein's relativity of 1905 because it presupposes an instantaneous action at a distance—this is also very exactly what shocked Newton. What to do next?

In 1907, Einstein was still employed at the *Patent Office* in Bern (his work as "shoemaker"as he ironically calls it). In his spare time, he reflects upon the way to integrate gravitation into the new relativistic framework. Legend has[8] it, that one morning a Bernese newspaper reported the story of a worker who fell from the roof of a building under construction. Suddenly, Einstein had *den glücklichsten Gedanken*, the happiest idea of his life: "I was sitting on a chair at the Federal Office in Bern when suddenly an idea came to my mind: a person in free fall does not feel his own weight. I was amazed. This simple thought made a profound impression on me. It pushed me toward a new theory of gravitation."

A man who falls freely does not feel his weight and sees his tools floating around him as if there were no gravity: this is Galileo's Principle of Equivalence. And, on the contrary, a man in a spaceship that accelerates into empty space would feel heavy on his seat; if he dropped an object, it would fall to the ground on a parabolic trajectory. There would be no way to distinguish the effects of gravity and acceleration locally: this is Einstein's Principle of Equivalence. Einstein's principle continues and accomplishes the discourse initiated by Galileo and Newton three centuries before.

An immediate consequence of Einstein's principle of equivalence is that gravity must bend the rays of light in the same way as it curves the trajectories of material bodies that would otherwise be rectilinear. A new conception of gravity then emerges: gravity is not to be thought as a force that acts at a distance but rather as a geometric property of the spacetime; the gravitational attraction is a manifestation of the spacetime curvature. The spacetime around the sun is curved and the planets follow geodesics in a non-Euclidean geometry. The resulting orbits are ellipses, with the notable exception of Mercury, whose trajectory is not closed. This is Einstein's answer to the question *a quo moventur planetae.*

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[8] Curiously, the three great moments of the history of gravitation are all accompanied by a mythical narrative (all three presumably imaginary): Galileo who drops objects from the top of the leaning tower of Pisa, Newton and the apple falling on his head, Einstein and the worker falling off the roof.

And which is the agent curving the spacetime? The matter contained in the universe, or, more precisely, its energy-momentum content. Einstein's equations of 1915 tell exactly how this happens. They mathematically translate the following idea into a set of equations:

$$\text{Spacetime Curvature} = \text{Energy-Momentum of Matter.}$$

After writing his equations Einstein naturally turned to cosmology and tried to apply them to the entire universe. This is the founding act of a new science, the modern scientific cosmology. The new, very bold idea is that a cosmological model, a model for the universe, corresponds to a global exact solution of the equations for the geometry of spacetime. Einstein thus resumed the discussion initiated by Newton in the *Principia* on the nature of space and inertia.

As very often, Einstein's preoccupation in writing his *Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie* is at first epistemological: at the very beginning of the paper, he declares that [18] "In a consistent theory of relativity there can be no inertia relatively to "space," but only an inertia of masses relatively to one another. …If I have a mass at a sufficient distance from all the other masses in the universe, its inertia must fall to zero." Einstein will later call this property the *Mach principle*.

The metric structure of the universe also must be entirely determined by matter; no matter, no universe and therefore no absolute space. But general relativity still keeps a remnant of absolute space by the boundary conditions that must be specified at infinity to determine the geometry of spacetime. These conditions are a clear violation of the Mach principle. Here is Einstein's "crazy idea"[9] to solve this problem: a spherical universe.

A spherical universe? Again?

Einstein's spherical space is very different from that of Aristotle and Copernicus which is a spherical three-dimensional bubble bordered by the two-dimensional spherical surface of the fixed stars. Instead, one must imagine the sphere of Einstein as a "hypersurface": a three-dimensional sphere immersed in a four-dimensional Euclidean space (for lack of imagination, we can think of the leather surface of a football sphere, but having three dimensions rather than two). It is therefore a non-Euclidean three-dimensional spherical geometry, that is to say a curved geometry of the space. This sphere obviously has no center, or rather it has its center every-

[9] *I have completely abandoned my views, rightfully contested by you, on the degeneration of the metric. I am curious to hear what you will have to say about the somewhat crazy idea I am considering now.* A. Einstein. Letter to W. De Sitter of February 2, 1917.

I have again perpetrated something relating to the theory of gravitation that might endanger me of being committed to a madhouse. A. Einstein. Letter to P. Ehrenfest, February 4, 1917.

where[10] and any point is equivalent to any other point. It has no boundary either; and therefore: no boundary, no conditions on the boundary.

Einstein contradicts Bruno's principle of sufficient reason and finds a reason (unsuspectable for Bruno, although somewhat utilitarian) for the finitude of the universe. But he agrees with Bruno about the absence of a center of the universe and also about the absence of an edge, which has now become possible even for a finite universe.

There was also a second guiding principle in Einstein's cosmological research, a principle that was very reasonable in 1917: the universe is static and therefore the geometry of the universe must not change as time goes by. Einstein then faced an unforeseen difficulty: his *General Theory of Relativity* of 1915 does not allow for static solutions with a spherical spatial geometry. At this point he got the idea that would go down in history as his *biggest blunder*—the biggest mistake of his life: to add to his equations a constant term, the cosmological constant, designated by the letter Λ of the Greek alphabet:

Spacetime Curvature + Λ = Energy-Momentum of Matter.

The cosmological constant acts as repulsive gravity and can counteract the gravitational attraction. Adding this term is nevertheless—Einstein says [18]—"an extension of the equations which is not justified by our real knowledge of gravitation." With this additional term Einstein's equations admit a perfectly Machian spherical and static solution: it is the static model of Einstein of 1917. In this model, the radius of spherical space is directly proportional to the total mass of the universe. And so, if there is no mass, there is no universe either!

It should be noted, however, that a positive curvature of space is possible even if the additional term is not present: "This term is necessary only for the purpose of making possible a quasi-static distribution of matter as required by the low speed of stars." [18]. This commentary indicates that already in his 1917 paper Einstein was aware of the fact that his original equations of 1915 implied a dynamic universe, but he had set aside this possibility.

Today Einstein is sometimes accused of lack of confidence in his original equations of 1915 which made him miss the discovery of the expansion of the universe, foreseen on theoretical grounds by Alexander Friedmann and Georges Lemaître in the 1920s and observed by Edwin Hubble in 1929. But in 1917 the visible universe still coincided with the Milky Way, the nebulae enigma had not yet been solved and the hypothesis of a static universe was perfectly reasonable.

Like the great Magellan,[11] Einstein had left for his cosmological adventure on a false trail based on wrong maps but, like Magellan, he did find the *paso*, he went

[10] *Sphaera infinita cuius centrum est ubique, circumferentia tamen nullibi* : this is the second definition of God that can be read in the *Liber XXIV philosophorum*, an anonymous medieval treatise attributed to Hermes Trismegistus. Nicolas de Cues applies this definition to the universe: The world machine has, so to speak, its center everywhere and its circumference nowhere (*De docta ignorantia*, 1440). Bruno at many different places later takes up the definition.

[11] *Magellan was deceived by his forerunners' mistake when, upon the warrant of Behaim's chart, Schoner's globe, and the unnamed pilots' story, he formed his great design of circumnavigating*

through the dangers of the *estrecho* and opened the way for navigating in an ocean never seen before by the human eyes. Today, a century after the reading the *Kosmologische Betrachtungen* at the *Prussian Academy* on February 8, 1917, our way of thinking at the universe has not changed. Alternative theories of gravitation are multiplying, cosmological models abound, quantum mechanics is added to and plays the cosmological game, but the paradigm set by Einstein a century ago remains intact.

8 The Fate of the Universe

Our tale could stop here. It is however impossible to conclude this story without alluding to the expanding universe and the destiny of the cosmological constant. Einstein had refined his cosmological ideas through a very intense exchange of letters with the Dutch astronomer Willem de Sitter. Shortly after the publication of Einstein's paper, de Sitter published a second solution of Einstein's cosmological equations: a universe without matter made only with the cosmological constant.

De Sitter's solution, which is perfectly anti-Machian, displeased Einstein a great deal, but his attempts to demonstrate that there was a fault somewhere in de Sitter's calculations and that his universe was not empty, were vain. Finally, Einstein surrendered to the fact that the de Sitter universe was indeed an empty (i.e. without matter) regular solution of his cosmological equations but, he said, it was nevertheless a model without physical interest because of its being not globally static.

In fact, until the early 1930s almost no one had taken seriously the fundamental articles of Friedmann (1922, 1924) who made use of the original equations of general relativity of 1915 to describe expanding universes. Einstein was one of the few to have read them, and he even wanted to publish a note about an error in Friedmann's work. But there were no mistakes. In the retraction of his commentary one could have read "…Friedmann's paper while mathematically correct is of no physical significance…" but, fortunately, Einstein deleted this sentence on the proofs of his paper at the last moment before publication.

Lemaître's independent work of 1927 is based on the cosmological equations of 1917 and also describes an expanding universe. Lemaître's understanding was much more deeply physical than Friedman's; in his original paper (in French) Lemaître gives indeed the first description of the Hubble's law, a law which is now rightly called the Hubble-Lemaître's law: galaxies move away from each other with a speed proportional to their distance because of the expansion of the universe. Einstein listened to this explanation at the 1927 *Solvay Congress* in Brussels but again he was not happy. Lemaître claimed that the universe had a history and Einstein, who was a follower of Spinoza, could not believe it. Einstein's remark at Lemaître on

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the world. The enigma of Magellan is solved as soon as we recognize that he planned and acted in honest error. Let us not underrate the importance of error. Through the promptings of genius, guided by luck, the most preposterous error may lead to the most fruitful of truths. Excerpt from [19].

this occasion remained famous: “Vos calculs sont corrects, mais votre physique est abominable.”

Based on his cosmological model Lemaître also conceived the physical idea of the Big Bang, a name invented by Fred Hoyle during a *BBC* program to mock the cosmology of Lemaître’s primitive atom—the explosive beginning of space and time. In an article published by the journal Nature the English physicist Arthur Eddington commented this idea: “Philosophically, the notion of a beginning of the present order of nature is to me repugnant.”

We are witnessing here a complete reversal of the perspectives of ancient cosmology; any suspicion of an undue and indigestible mixing between physics and philosophy or, worse, theology, must be pursued with maximal force.

On a trip to Pasadena Einstein learned of Hubble’s latest observations and was persuaded of the advantages of dynamic models to describe the universe. In two articles published shortly afterwards, Einstein asserts that the original reasons for introducing the cosmological constant no longer existed. Farewell to the cosmological constant.

Einstein’s last message to Lemaître in 1947 was: “The introduction of such a constant implies a considerable renunciation of the logical simplicity of the theory... Since I introduced this term, I had always a bad conscience…I am unable to believe that such an ugly thing should be realized in nature.” And here is Lemaître’s prophetic answer of 1949: “The history of science provides many instances of discoveries which have been made for reasons which are no longer considered satisfactory. It may be that the discovery of the cosmological constant is such a case.”

In fact, Einstein himself had been prophetic in 1917 when, in a letter to de Sitter, he wrote that “In any case, one thing is clear. The theory of general relativity allows adding the term Λ in the equations. One day, our real knowledge of the composition of the sky of fixed stars, the apparent motions of the fixed stars and the position of spectral lines as a function of distance, will probably be sufficient to decide empirically whether or not Λ is equal to zero. Conviction is a good motive, but a bad judge.”

In 1997, exactly seventy years after its discovery, we indirectly observed the cosmological constant, or maybe something similar that we now call “dark energy”. Nowadays everyone believes in its existence and the de Sitter’s empty spacetime has become the paradigm of our universe and also its everyday improving approximation.

It is thought that the cosmological constant constitutes seventy percent of the energy content of the universe and that its proportion is destined to increase, if one believes in the standard cosmological ΛCDM (cold dark matter) model. In the end, only the cosmological constant will remain.

La nuit éternelle commence, et elle va être terrible. Que va-t-il arriver quand les hommes s’apercevront qu’il n’y a plus de soleil?[12]

We do not know the answer to Nerval’s anguished cry. Perhaps it is better to leave the last word to poetry, as in the beginning of our journey.

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[12] Gérard Nerval - Aurélia ou le Rêve et la Vie (1855).

Fernando Pessoa—who was an enthusiastic reader of Giacomo Leopardi—echoes Leopardi's Asian wandering shepherd in his heteronym Alberto Caeiro's *Guardador de Rebanhos* with the following words[13]:

Num dia excessivamente nítido,
Dia em que dava a vontade de ter trabalhado muito
Para nele não trabalhar nada,
Entrevi, como uma estrada por entre as árvores,
O que talvez seja o Grande Segredo,
Aquele Grande Mistério de que os poetas falsos falam.

Vi que não há Natureza,
Que Natureza não existe,
Que há montes, vales, planícies,
Que há árvores, flores, ervas,
Que há rios e pedras,
Mas que não há um todo a que isso pertença,
Que um conjunto real e verdadeiro
É uma doença das nossas ideias.

A Natureza é partes sem um todo.
Isto e talvez o tal mistério de que falam.

Foi isto o que sem pensar nem parar,
Acertei que devia ser a verdade
Que todos andam a achar e que não acham,
E que só eu, porque a não fui achar, achei.

[13] On an excessively clear day, A day when I wanted to work hard not to work on it at all, I saw like a road through the trees, It might have been be the Great Secret, That Great Mystery of which false poets speak. I saw that there is no Nature, That Nature does not exist, That there are hills, valleys, plains,That there are trees, flowers, herbs,That there are rivers and stones. But that there is no whole to which they belong, That a real and true whole Is a disease of our ideas. Nature is parts without a whole.
This maybe the mystery they are speaking of. This is what without thinking or stopping, I understood should be the truth That everyone is trying to find and does not find, And only I, because I didn't try, succeeded.

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