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The Age of Enlightenment

8.1 The Triumph of Reason

Hard on the heels of the Renaissance came the Enlightenment, a triumph of reason and empirical methods. There were three characteristic philosophies: deism, which accepts the existence of a creator, but one that no longer interferes with the Universe; liberalism, which believes in human rights and freedom; and republicanism, which holds that a nation should be governed as a republic with an emphasis on liberty. These were the ideals of the time, and they show through every aspect of eighteenth-century culture.

Isaac Newton could be thought of as the greatest scientist that had ever lived until then. He was born in England in 1642 and died there in 1726. Newton was a mathematician, physicist, astronomer, and theologian, and he was considered by his contemporaries as a natural philosopher. He formulated the laws of motion and the universal law of gravitation, which remained the most important scientific theories for more than two centuries, until Einstein formulated his special and general theories of relativity. Newton's publication "Philosophiae Naturalis Principia Mathematica," known as "Principia" for short, was a turning point in the scientific revolution. The story of the apple falling from the tree may actually be true or just a famous anecdote, but the idea suggested to him how he could formulate the effects of gravity. The realization was that the same force that pulled the apple to the ground also held the Moon on its orbit around the Earth, and the planets in their orbits around the Sun.

It was the greatest theory ever formulated, but Newton needed astronomical telescopes and precise measurements of the planetary motions to prove

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the correctness of his theory. The necessary observations were provided by a German musician and astronomer William Herschel who had emigrated to England and was soon considered the best astronomer and telescope builder of his time. He constructed a larger and more powerful telescope than any other ever built in the eighteenth century. Thanks to Herschel's expertise, Newton could successfully put his theory of gravity to the test. Using his telescopes, Herschel himself discovered many new nebulae, clusters of stars, and a new planet, the first discovered since the Ancient Greeks hundreds of years before. The planet he discovered was Uranus. Herschel, who soon became Sir William Herschel, realized that there were plenty of new discoveries to be made in the Solar System and beyond. And he was absolutely right!

Edmond Halley was an English astronomer, who was born in 1650 and died in 1742. He discovered the proper motion of closer stars relative to more distant ones. He also used Newton's theory to deduce the periodicity of certain comets, and in particular the one which bears his name. Indeed, Halley's Comet had been seen and catalogued by Chinese astronomers many centuries before. It was also seen by the painter Giotto in the thirteenth century. Giotto must have witnessed it crossing the sky in 1301, because he painted it in his representation of the nativity in the Scrovegni chapel in Padua, Italy. I myself had the good fortune to see Halley's Comet in the night sky of the Sonoran Desert in Arizona. It was beautiful, exciting, and so bright in the sky. Thank you, Sir Edmond! It turns out that the comet has been witnessed many times through centuries. Edmond Halley was quite right about the periodicity of comets. During his many observations of the sky, he catalogued 350 southern hemisphere stars, and by observing the transit of Mercury, he realized that he could use a future transit of Venus to determine the distances between the Earth, Venus, and the Sun.

Giovanni Cassini was an Italian mathematician, astronomer, and engineer, who was born in Italy in 1625 and died in France in 1712. At only 25 years old, he became professor of astronomy at the University of Bologna, the oldest university in the world, and later became the director of the prestigious Paris Observatory. He discovered four natural satellites of Saturn: Iapetus, Rhea, Tethys, and Dione. He also noted the division of Saturn's rings and he was the first to observe the differential rotation of Jupiter's atmosphere.

In 1997, the Cassini Space Probe was launched to study the planet Saturn and its system. It was the fourth probe to visit Saturn and the first to orbit around the planet. The Cassini Space Probe no longer exists, having crashed into the planet's atmosphere after twenty years of honorable service.

8.2 Science from the Nineteenth Century to Contemporary Astrophysics

By the nineteenth century, astronomers were going beyond merely cataloguing stars and planets. New and more efficient telescopes were built, opening up the possibility of discovering new planets and other celestial bodies. There was more and more research in other fields of science relevant to the development of astronomy, such as mathematics, physics, chemistry, and geology. The increasing interest in studying the formation of stars, planets, and comets rather than just cataloguing them led to a general improvement in scientific methods.

The field of spectroscopy was developed in physics and chemistry, and became a crucial tool to identify the chemical components of the stars and to understand the formation of the Solar System. The discovery of spectroscopy by the chemist Robert Wilhelm Bunsen and the physicist Gustav Robert Kirchhoff was used to compare the spectrum produced by passing sunlight through a prism with spectra produced chemically in the laboratory. This idea could be applied to demonstrate which chemicals were present in the Sun, and indeed, spectroscopy was soon being used to study the solar corona during total eclipses, which are the only times when the corona is visible.

During the nineteenth century, expeditions to observe solar eclipses became very popular, and for the first time, it was not only professionals that showed an interest, but also amateur astronomers. It was around this time that international collaborations sprang up between different observatories, and it was in 1865 that the term "astrophysics" was coined by Johann Karl Friedrich Zolner to describe the relevant mix of physics, chemistry, and astronomy. Astrophysics is thus the study of astronomical objects and phenomena, such as the Sun, the stars, galaxies, extrasolar planets, and the famous cosmic microwave background. Astrophysicists use methods from many and varied disciplines of physics, including classical mechanics, electromagnetism, statistical mechanics, thermodynamics, quantum mechanics, and nuclear and molecular physics. In short, it is a branch of theoretical and observational physics.

The Sun is treated by astrophysicists as a special celestial body, not because it is a powerful god, as it was considered in Antiquity, but because it is the nearest star to Earth. All the other stars are tremendously far away, so cannot be observed in anything like the same detail as the Sun. But by studying the Sun and comparing it with the others, astrophysicists have been able to understand a great deal about the other stars. On 14 December 2021, NASA's

Parker Solar Probe was launched to observe the Sun at close range. It is the first time in human history that a spacecraft has been able to get so close to the Sun, in fact, coming close enough to reach the Sun's upper atmosphere, the corona, and observe the magnetic fields there.

Since prehistoric times, man has looked up at the skies and invented gods, visualizing the Sun god as crossing the sky on a golden chariot, or, as in ancient Egypt, sailing over the Blue Nile on a boat. A beautiful humanized divine Sun was created in Ancient Greece and Rome, a generous life-giver for humanity, but at the same time the ancient peoples of Mesoamerica portrayed their most important divinity as cruel and bloodthirsty. Think, for example, of the religious cult of the Aztec kings, who believed in the importance of honoring the Sun by drinking the blood of sacrificed victims. Throughout human history, the Sun was represented as a god through myths, legends, and cults, and depicted by the visual arts to help people get a better understanding. There were myths like the flight of Icarus whose wax wings melted when he dared to get too close to the Sun, whereupon he fell into the sea and died. And there were many more myths, legends, and superstitions in the different cultures of the ancient civilizations.

But right from the beginning, there were some insightful minds who, observing the sky, imagined that the world might actually be more complicated than it was made out to be in the myths and legends. In Ancient China, Ancient Greece, and even during the European "Dark Ages," hesitant and timid ideas appeared in the minds of some humans who dared to imagine the possibility of a different Universe (Fig. 8.1).

During the later years of the cultural rebirth in the Renaissance, the vision of the world began to change. The Sun was no longer seen as a god, while its important role in human life was maintained. Heliocentrism began to take over, with our star placed at the center of the Solar System and all the other planets, including the Earth, orbiting around it. So, we might say that the status of the Sun as a sacred divinity was kept, but in a different way. It maintained its great importance in the known Universe, and especially its role as life-giver to all living beings on Earth. On the other hand, our planet lost its central position and therefore its importance in the cosmos. And as we now know, even this grand view of the Sun would not last long, in the sense that there have been more and more discoveries which prove our Sun to be just another star, no different from many, many millions of others in the Universe. At any rate, for us, inhabitants of planet Earth, the Sun is still our life-giver, as powerful and important as only a god could be.

Fig. 8.1 The universe. This is my vision of how our universe might be, with strange objects immersed in a dark blue space. Blown glass

8.3 Discoveries in the Nineteenth and Twentieth Centuries

Since the Enlightenment in the eighteenth century and during the nineteenth century, science steadily took on a more modern approach. One truly revolutionary discovery which was absolutely fundamental for science was the theory of electromagnetism. The first to understand how the phenomena of electricity and magnetism could be unified into a theory of electromagnetism was the mathematician and physicist James Clerk Maxwell, who was born in 1831 in Edinburgh, Scotland, and died in 1879 in Cambridge, England. This discovery is widely considered one of the greatest scientific achievements of the nineteenth century. Maxwell discovered that electric and magnetic fields could propagate together as waves at the speed of light, and concluded that light is actually an electromagnetic phenomenon. Needless to say, this discovery is essential to many modern technological applications. Indeed, any system exploiting electricity or magnetism owes much to Maxwell's ingenious set of equations.

When it reached the twentieth century, astrophysics would go through a number of scientific revolutions. Right through the nineteenth century, the composition of the Sun had remained completely unknown, and even in the 1920s, the brilliant astronomer Sir Arthur Eddington thought that the Sun had much the same composition as the Earth. It was eventually thanks to the work of the astrophysicist Cecilia Payne that this situation was rectified. She discovered that the composition of the Sun is very different from that of our planet. In fact, it is made up of 74% hydrogen, 24% helium, and 2% metals. This discovery was another great breakthrough in the history of science.

To give another example, in the early twentieth century, it was thought that there was only one planetary system, our own, and that the Milky Way was all there was in the Universe. Later in the century, the astronomer Peter van de Kamp suggested that there should be other planetary systems besides our own, and by the end of the twentieth century, many such exoplanets had been discovered. So, our Solar System is not the only one in our galaxy, as had been thought for thousands of years. We may say that the twentieth century has been the era of astronomical ages, for we have been able to determine, at least approximately, the ages of planets, stars, galaxies, and even the Universe itself, although we still don't know the origin of everything on Earth and in the Universe.

Here is a comment on twentieth century physics by theoretical physicist Hans-Thomas Elze:

> The twentieth century, and in particular its first half, was a period with such a large number of discoveries in science that it cannot be compared with any earlier epoch that we know of. This holds especially in physics, with revolutionary new concepts entering the way we describe and try to understand the physical world around us. Especially, the developments of special and general relativity and of quantum mechanics have changed forever our understanding of matter, space, time, and the cosmos as a whole. Earlier ideas were mostly derived from experiences gained via our senses, more or less in our daily human lives, and considering phenomena that we are able to perceive first-hand "with our own eyes". The change came when technical instruments became more and more sophisticated and allowed us to study (and manipulate) reality beyond the range of our senses: the very small, the very large, the very fast, and so on and so forth, with no natural or intrinsic end to further exploration in sight.
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> Let me mention some of the outstanding physicists who played a decisive role in interpreting the new experimental findings in the early 1900s and reformulating this new knowledge into powerful theories that allow us to predict new and even stranger phenomena. We must keep in mind that

this has not just been the academic playground of a few “mad scientists”, but that their studies and “practical” applications of their results have transformed all our lives ever more rapidly and profoundly, for better or for worse – think of nuclear forces and the resulting bombs, of radio, television, digital computers, the internet, and smartphones. Think also of the upcoming possibilities of quantum computers and, perhaps most questionably these days, artificial intelligence.

One of the first steps was taken by Max Planck, a German theoretical physicist (1858–1947), who studied problems raised earlier in the description of radiation emitted by hot bodies. In a bold intellectual step he took in 1900, this allowed him to introduce a “quantum of action”, implying that no physical action (which has a precise meaning in terms of measurable quantities) can take place in smaller bits and pieces than this quantum! This was then interpreted in due time as a first indication from experimental science that the physical world may have fundamentally discrete aspects – but recall Plato’s outrageous idea of atoms composing matter, more than two thousand years earlier.

Then, in 1905, Albert Einstein, who was born in Germany in 1879 and died in the USA in 1955, interpreted the so-called photoelectric effect in terms of photons, massless particles that can be thought of as composing electromagnetic radiation. Up to this point, this radiation was generally regarded as being made up of waves, following Maxwell’s theory, not as pointlike clumps of energy – but recall the debate between Goethe and Newton about the nature of light. These photons have a quasi-mechanical effect when they impinge on a metal surface, where they kick out small, massive, and electrically charged particles called electrons. Einstein understood this and gained a Nobel Prize for his work – all in that same year when he also formulated the special theory of relativity, considering bodies moving at very high velocities with respect to each other and deducing the relationship between mass and energy, encoded in the famous equation $E = mc^2$ – which manifests itself, for example, in nuclear energy and, thus, the energy-producing processes that make the Sun shine – besides formulating a statistical theory of Brownian motion.

Einstein arguably became the most famous scientist in history, especially when a prediction that followed from his general theory of relativity of 1915 was glamorously confirmed in 1919. It implied that the path of light from a distant star that passed very close to the Sun before reaching us on Earth would be slightly bent due to the gravitational attraction of the large mass of the Sun, which acts on the starlight photons! In order to observe the predicted small effect, the overwhelmingly intense light of the Sun had to be blocked for a short while. But how could this possibly be done? Two expeditions instigated by the renowned astrophysicist Arthur Eddington to Brazil and to Sao Tome e Principe in the Gulf of Guinea were sent to observe the total solar eclipse that took place in 1919, which blackened out the Sun in the sky and allowed us to see starlight that literally came from behind it. A glamorous conjunction of ideas indeed!

General relativity has changed our views of space and time and the role of the gravitational force in all of this.

Following these first revolutionary steps, there was a rapid succession in the progress that brought relativity and quantum mechanics into full bloom. Most notably, the dynamics of the motion and interaction of the quanta and their waves attracted theoretical and experimental physicists, since it could be studied in ever more detail in the laboratories of the time.

Max Born, a German physicist (1882–1970), naturalized British, is known for his research on the further development and foundations of quantum mechanics, solid state physics, and optics. He received the Nobel Prize in Physics for his fundamental work in quantum theory, especially for suggesting a statistical interpretation of the so-called wave functions associated with all quanta.

During the founding years of the new theory of quanta and related seemingly strange phenomena, Niels Bohr, a Danish physicist born in Copenhagen (1885–1962) played an important role in guiding the discussions among the leading physicists through his firm stand on philosophical principles, which eventually led to the "Copenhagen interpretation" of quantum mechanics. He remained in continuing controversy with Einstein, and related debates remain active up to the present day. Bohr made fundamental contributions to our understanding of the structure of atoms and undertook important steps towards a precise mathematical formulation of quantum theory, receiving the Nobel Prize in Physics in 1922.

Werner Heisenberg was a German theoretical physicist (1901–1976) and one of the pioneers of the theory of quantum mechanics. He is widely known for his principle of uncertainty. He received the Nobel Prize for his work in formulating quantum theory in unconventional, but very powerful mathematical terms that have stood the test of time. He wrote his far-reaching paper when he was only 23 years old.

Erwin Schrödinger, an Austrian theoretical physicist (1887–1961), along with Heisenberg, has been considered one of the founding fathers of quantum theory. In fact, he proved later that his own and Heisenberg's formulations, though employing very different methods, were equivalent, describing the same physics. He received the Nobel Prize in 1933, together with another outstanding physicist, Paul Dirac. In popular culture Schrödinger is known because of "Schrödinger's cat," a thought experiment invented to illustrate some particularly strange and mind-boggling consequences of quantum theory, which have since been observed!

I have made this excursion into some aspects of the history of physics in the early twentieth century to point out the intimate connectivity among all scientific knowledge, and physics in particular. There are not only bare facts out there to be measured, but scientists have been able to identify patterns within these facts, "laws of nature" that appear miraculously comprehensible to humans! From the early twentieth century onwards, the range of understandable phenomena has been increasing in manifold ways and at breathtaking speed.

Quantum theory and the theories of special and general relativity are indispensable in order to understand what we can observe in increasing detail about the Sun. Without them, the nuclear fusion reactions that power its energy production would remain mysterious. Nor could the chaotic behavior of the Sun's outer layers and their hot radiation be unraveled as plasma physics par excellence, a study which may eventually help us to build fusion energy machines on Earth. And we could have no picture of what will happen to the Sun in the far future. Back down on Earth, without these theories, we could not even dream of building the ever more precise instruments we need to learn about the world around us, the Universe. All is one.

(Professor of Theoretical Physics, Hans-Thomas Elze)

Professor Elze's comments bring out perfectly the importance of the twentieth century as a revolutionary moment in science, reminding us of all those brilliant minds who changed our vision of the world and, through their discoveries, made possible the technology we now take for granted. Specifically, he pointed out that, without the scientific discoveries of the great physicists of the past century, it would have been impossible to know how the Sun and the other stars in the Universe work. Many books have been written and many documentaries and movies have been made about Einstein, both as a physicist and regarding his private life. In popular culture he has been pictured as the typical eccentric scientist, but nothing was typical about Einstein. He was simply a genius!