Chapter 1

Cooking the elements

> Far out in the uncharted backwaters of the unfashionable end of the western spiral arm of the galaxy lies a small unregarded yellow Sun.[1]

The origin of the energy from the Sun and stars was a long-standing mystery. Hundreds of lifetimes were devoted to discovering the secret of the stars and, in modern times, countless hours of computing time have been committed to understanding the details of stars' lives. Now we know the answer.

Awakening

On a sunny summer day you probably enjoy spending an afternoon at the beach, lying or sitting on pristine white sand, gazing at the unending blue ocean in front of you. Although our Sun is far away, you can feel its heat on your skin and will use a lotion to protect yourself from its damaging ultraviolet radiation, and wear dark glasses to relieve your eyes from its blinding light. It is this energy that drives life on Earth. The light from the Sun is good indeed, and you might wonder how it is produced.

If you go for a walk along the shore, you will find places where a great variety of living things can be found: small fishes, crabs, algae, plants and insects in "most beautiful and most wonderful forms." You will also find a great assortment of the remnants of life, seashells, "some prettier than ordinary," which you may like to collect. Where did all this come from? At the end of the beach there are rocks and some have very sharp hard edges. This is evidently the product of erosion over a long time by the action of the waves as they hit the shore. How long a time was needed? It was not until the twentieth century that scientists were able to provide answers to the above questions. You will learn about them as you read on.

By earthly standards the Sun is unimaginably far away, its typical distance from Earth being 150 million kilometers (93 million miles). Can you

[1] Douglas Adams, *The Hitchhiker's Guide to the Galaxy*, Six Stories, p. 5.

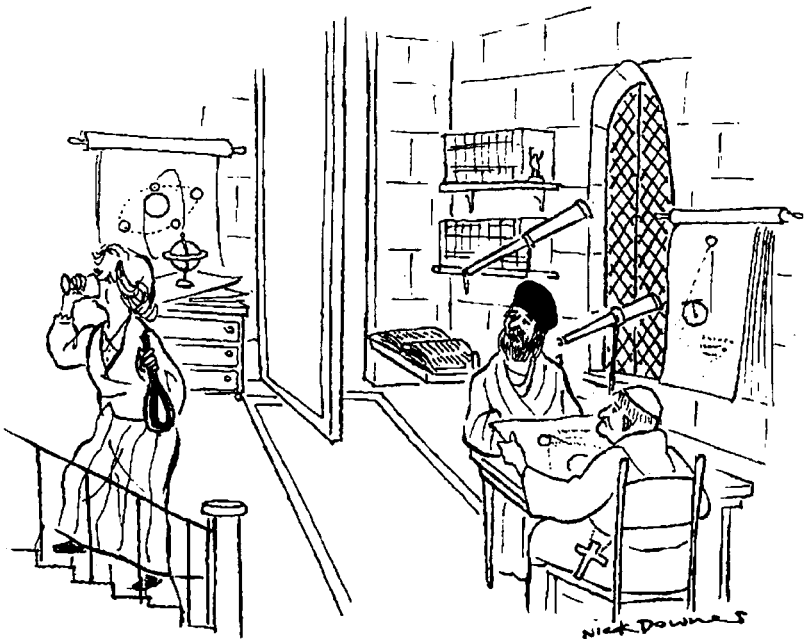
Above the photosphere of the Sun, the region from which sunlight is emitted, an atmosphere of very hot ionized gas extends for millions of miles: the chromosphere. This stunning ultraviolet image, obtained by the NASA Transition Region and Coronal Explorer (TRACE) spacecraft, shows fountains of million degree ionized gas flowing along solar magnetic fields forming giant arches, some over 300 000 miles high. (Standford–Lockheed Institute for Space Research)

imagine this? At 60 miles per hour it would take you about 175 years to reach the Sun, but light traveling at the enormous speed of 300 000 km (186 000 miles) every second takes only 8 minutes to traverse this large distance.

A fundamental law of physics states that nothing in nature can travel faster than light. It takes only about 0.1 second for light to circle the Earth, and light reaches the Moon in 1.25 seconds. The high speed of light, which is the speed of any electromagnetic wave, is the reason you can talk on the phone halfway around the Earth and get what seems to be an instant reply.

The diameter of the Earth is about 13 000 km (8000 miles), so the Sun is 11 500 Earth diameters from us. If the Earth were the size of a penny, the Sun would be a ball 7 feet across placed about 700 feet away. At this scale, the Moon, actually at a distance of 384 000 km (238 000 miles) from the Earth, would be almost 2 feet away and only $\frac{3}{16}$ inch in size.

The Earth completes an orbit around the Sun once per year, indeed this is the definition of a year. Today we accept this fact without batting an eyelid, but it was the cause of great turmoil in the sixteenth century, and caused much personal suffering to a few. An Earth that moved, and was not at the



"THERE WAS A TIME WHEN I THOUGHT THE EARTH REVOLVED AROUND HER."

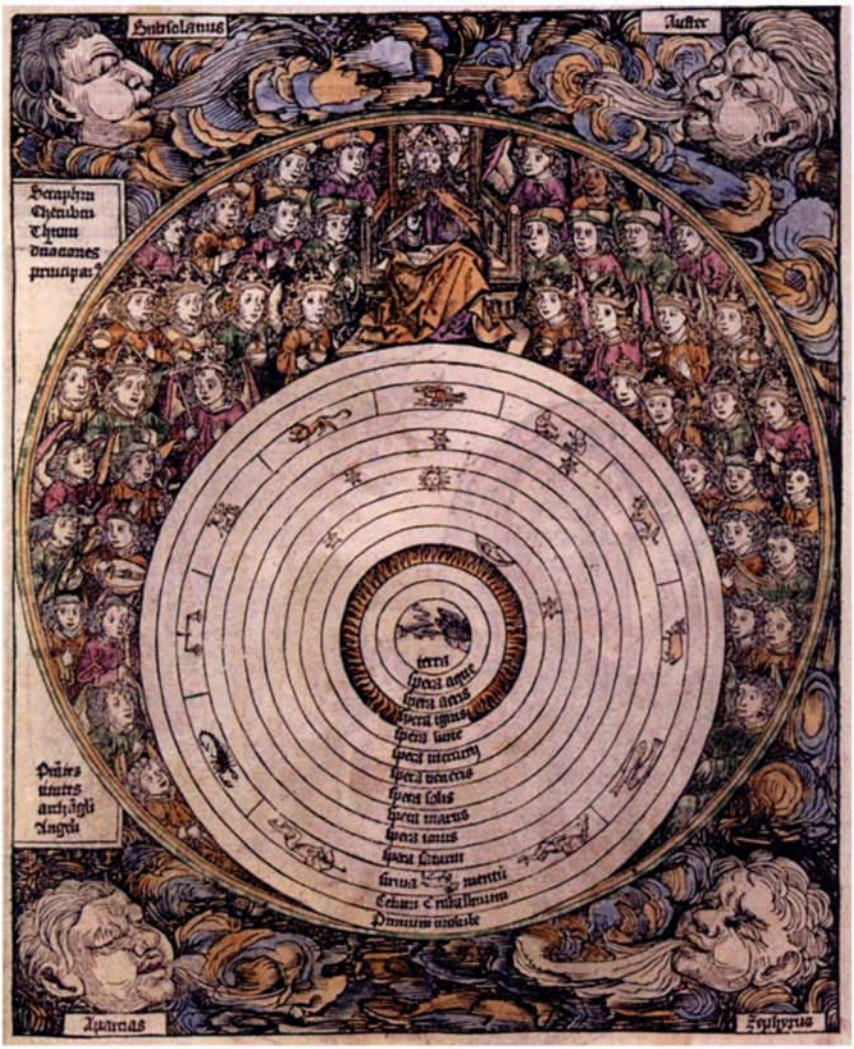
center of the Universe created by God, was not in accord with Christian doctrine of that time, and to rock the boat was to risk severe punishment. For more than 1500 years the Christian doctrine had been in harmony with the views of nature proposed by Plato, Aristotle, and Ptolemy. In this view, all cosmic objects were attached to impenetrable transparent crystalline spheres and orbited the Earth in perfect circles at constant speed. They were composed of a special "perfect" fifth element – quintessence – that gave them perfection of form and let them obey laws of motion different from those of Earth. Nearest was the Moon (which does orbit the Earth, although not in a perfect circle and certainly not on a crystal sphere), followed by Mercury, Venus, the Sun, Mars, Jupiter and Saturn, with an eighth sphere occupied by the eternal, unchanging, stars. The outer planets, Uranus, Neptune, and Pluto had not yet been discovered.

This Earth-centered system, called geocentric, was outlined in one of the most influential books of antiquity, *The Almagest* ("the greatest") published

in the ninth century AD by Arab translators of the original Greek work of Claudius Ptolemy. He was the most renowned astronomer and geographer of the ancient world, living at Alexandria in Egypt in the second century AD. To fit the observed positions of the planets, which sometimes appear to reverse their direction of motion in the sky, the Ptolemaic system stated that the planets were on circles, called epicycles, whose centers moved on other circles, called deferents, which were centered on the Earth. Since in this system Venus never reached a point where it was opposite the Sun from Earth, it would never show a full phase, like the full Moon, which we see when the Moon and the Sun are on opposite sides of the Earth. The Ptolemaic system was a complex, gigantic, clockwork mechanism pushed along by divine forces, and it described the observed motions of the planets and stars adequately.

Eventually, Nicolaus Copernicus rocked the boat with the publication of his book *De Revolutionibus Orbium Coelestium* (*On the Revolutions of the Heavenly Orbs*) in 1543, fifty-one years after Columbus reached America. It is said that a copy of his book was brought to Copernicus on the last day of his life, May 24, 1543, at Frauenburg, now Frombork, in Poland, on the coast of the Baltic Sea. In academic circles there is a saying "publish or perish," expressing the need for academics to publish research if they want to advance academically. For Copernicus we could say that it was a case of publishing *and* perishing. Copernicus was born at Torun, in Poland, on February 19, 1473, and became famous throughout Europe for his studies in astronomy. He proposed a system with the Sun at the center, a heliocentric system, which is our modern view. The heliocentric system was not really new. We know that Aristarchus, a Greek philosopher of the Pythagorean school, born about 310 BC, had formulated just such a system. However, we know of this only indirectly and the influence of Aristotle and Ptolemy put the heliocentric system on ice for 1500 years. In this system, the Earth rotated on its axis once per day, and moved about the Sun in a circular orbit once per year.

Although today we refer to the "Copernican Revolution," Copernicus was not a revolutionary. He delayed the publication of his book for many years because he feared rejection of his theory. The Copernican Revolution crept in through the back door, so to speak, over a period of many years. It was only half a century after the death of Copernicus that the heliocentric system became the subject of great controversy. For many, the problem with this new system was that the status of the Earth was downgraded to merely that of another planet, no longer the center of the Universe, contradicting the holy scriptures. The Catholic Church did not object to the heliocentric system as long as it was presented as a hypothesis to "save the appearances,"



The Ptolemaic (geocentric) system is depicted here as part of an account of the last day of creation by Hartmann Schedel (1440–1514) in the Nuremberg Chronicles (Nuremberg, 1493). After the spheres of earth, air, water, and fire there were seven spheres with the wanderers – the planets – followed by the sphere of the fixed stars, and then the Primum Mobile responsible for imparting motion to the entire system. God on his throne views his creation accompanied by the nine choirs of angels (from the Seraphims to Angels) labeled in Latin on the left. The four winds are at the four corners. The reason that our week has seven days, and the names for the days of the week, are a remnant of this cosmic conception. (Courtesy of Adler Planetarium and Astronomy Museum, Chicago, Illinois)

"SURELY YOU WERE AWARE WHEN YOU ACCEPTED THE POSITION, PROFESSOR, THAT IT WAS 'PUBLISH OR PERISH.'"

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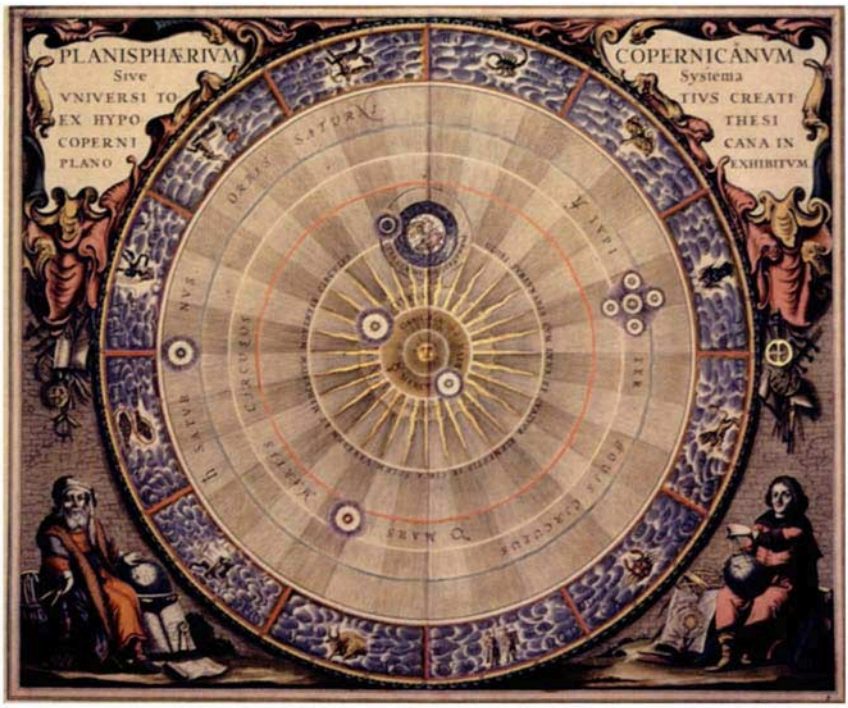
that is, to agree with astronomical observations. In the heliocentric system, the order of the planets, also in circular orbits about the Sun, became as we know it today, Mercury being closest to the Sun followed by Venus, the Earth (with the Moon in orbit about it), Mars, Jupiter and Saturn. Still, the heliocentric system, based on circular orbits and motion at constant speed, was not accurate enough when used to predict the positions of the planets, which actually move in elliptical orbits.

Galileo Galilei, probably the best-known figure in the history of science,



The Copernican (heliocentric) system as depicted in *Harmonia macrocosmica* by Andreas Cellarius (Amsterdam, 1661).The Moon goes around the Earth, and Jupiter is shown with its four moons. (Courtesy of Adler Planetarium and Astronomy Museum, Chicago, Illinois)

was born in Pisa, Italy, on February 15, 1564, three days before the death of the great Michelangelo Buonarroti (1475–1564). He is considered the father of physics, having introduced the idea that the book of nature was written in the language of geometry and mathematics, together with the notion that to understand nature it is necessary to observe and experiment. Although his telescope was thousands of times less powerful than today's large optical telescopes, he made important discoveries with it, which he promptly published in 1610 in *Sidereus Nuncius* (*Sidereal Announcement*). In the book Galileo reported mountains on the Moon, which previously had been thought of as a perfect sphere made from quintessence. He also reported on innumerable "fixed" stars in the Milky Way, and most significantly announced the discovery of the moons of Jupiter, which he found to orbit this giant planet. This immediately showed that not everything revolved about the Earth as predicated by the geocentric theory of the Universe. Soon Galileo also observed the phases of Venus, including a full phase, which

directly contradicted the geocentric model. He insisted that the Copernican system was not just a mere hypothesis to save the appearances, but the absolute truth, and the scriptures needed a new interpretation. This, and his acerbic attacks against those who differed with him, including members of the Jesuit order, led to his troubles with the ecclesiastic authorities.

Although Galileo did not realize it, he must have seen the then-undiscovered planet Neptune, since we can compute that in January of 1613 it lay close to Jupiter. As it was, Neptune was discovered much later, at the Berlin Observatory on September 23, 1846, by Johann Gottfried Galle (1812–1910) while searching a position in the sky predicted by the Englishman John Couch Adams (1819–1892) and the Frenchman Urbain Leverrier (1811–1877) to contain a new planet. These two mathematicians had independently computed this to explain observed irregularities in the orbit of Uranus, the seventh planet, discovered in England in 1787 by the German-born astronomer William Herschel (1738–1822). Adams and Leverrier correctly interpreted the irregularities of Uranus as a gravitational effect from a yet unknown eighth planet.

In Rome, in the year 1616, the chief theologian of the Roman Catholic Church, Roberto Cardinal Bellarmino (1542–1621), informed Galileo that the Sacred Congregation of the Holy Office had condemned Copernicanism as altogether opposed to holy scripture, and the book of Copernicus was placed in the *Index Librorum Prohibitorum*, the blacklist of books banned by the Inquisition. He notified Galileo that the Inquisition had prohibited defending the Copernican hypothesis or even believing it to be true.

In 1625, in Florence, Galileo began work on his *Dialogo Sopra I due Massimi Sistemi del Mondo, Tolemaico e Copernicano* (*Dialogue Concerning the Two Chief World Systems, Ptolemaic and Copernican*). It was published in 1632, causing a storm, although it had been cleared by ecclesiastic authorities. Maffeo Cardinal Barberini (1568–1644), elected Pope Urban VIII in 1623, was an old friend and supporter of Galileo, but felt betrayed by him, because his Dialogue clearly favored the Copernican system and appeared to make fun of Urban. At the end of 1632 Galileo was summoned to Rome to stand trial, at age 70 and in poor health, on *suspicion* of heresy. His book was found to favor the Copernican system and was added to the infamous index, where it remained until 1822. Galileo was pronounced guilty and made to humiliate himself by publicly abjuring his opinions, which he did on this knees before his judges at the Dominican convent adjacent to the church of Santa Maria Sopra Minerva, on June 22 of 1633. He was placed under house arrest in Arcetri near Florence for the rest of his life, which ended on January 8, 1642. His remains are in a tomb, built only in 1737, at the church of Santa Croce,

In this view, the Sun is setting over the cloud-covered Pacific Ocean behind the European Southern Observatory's Very Large Telescope Array (VLT) at the summit of Cerro Paranal, at an altitude of 8600 feet (2635 meters) in the northern Chilean Andes mountains. The Paranal area in the Chilean Atacama desert is believed to be the best site for astronomical observations in the southern hemisphere. Four telescopes with gigantic 26 feet (8 meter) diameter mirrors can work in single or in combined mode. In the latter, the VLT provides the total light-collecting power of a 16-meter single telescope. The YEPUN (*Sirius* in the Mapuche language) telescope is in the front, with the main mirror cover in place. From left to right in the background are, Antu (*The Sun*), Kueyen (*The Moon*) and Melipal (*The Southern Cross*). In his *Sidereus Nuncius*, Galileo wrote: "other things, possibly more important, will with time be discovered by me or by others, with the aid of similar instruments . . ." The VLT is a marvel of modern science and engineering – Galileo would be proud of us. (ESO)

in Florence, near that of Michelangelo. As we shall see later, even worse things could happen in those days to those who did not toe the line.

There is no evidence that Galileo said under his breath "eppur si muove" (yet it does move) after his trial, when he formally renounced the view that the Earth moves, although I can imagine that it crossed his mind many times. During the last years of his life he wrote his most important treatise,

Discorsi e Demostrazione Matematiche Intorno a Due Nuove Scienze (*Discourses and Mathematical Demonstrations Concerning Two New Sciences*), smuggled out of Italy and published in Leyden in 1638, which laid down the foundation of the science of mechanics. It is ironic to think that, had he not been embroiled in this miserable episode and prevented from further studies in astronomy, he would perhaps have never returned to physics. Three hundred and sixty years after Galileo's conviction, the Catholic Church reviewed his trial and found that, because he had not been convicted of heresy by the Inquisition, there was no need to acquit him.

On December 25 of the year of Galileo's death, as if passing the baton, Isaac Newton (1642–1727), possibly the greatest scientist of all times, was born in Woolsthorpe, Lincolnshire, England. The publication in 1687 of his *Philosophiae Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy: Principia* for short) represents the culmination of the Copernican revolution, and stands at the foundation of physical science. It is, without doubt, the most important work ever published in the physical sciences. As he himself acknowledged, Newton published this work after being encouraged and helped by Edmund Halley (1656–1742), after whom the famous comet is named. In his book, Newton formulated the Law of Universal Gravitation expressing the way any object exerts an *attractive* force on every other object, and the laws of motion.

The gravitational force between the Earth and the Sun determines the Earth's orbit. The same is true of all the planets. The orbit of the Moon around the Earth is similarly determined by the force of attraction between them. The gravitational force is large for large masses, and becomes larger when two objects are close to each other. It varies as the inverse of the square of the distance between the two masses, so that if we move 10 times closer to a mass, the force becomes 100 times stronger. Gravitation is what keeps our atmosphere from drifting away from the Earth into space. It is because of gravity that when we lie on the beach we do not fall off, but cling to the surface of our planet like magnets to a refrigerator door. You might then ask how it is that the Moon, attracted by the Earth, does not fall on us? It is precisely because it is in orbit around the Earth that it does not, the gravitational force being balanced by the centrifugal force (the same applies to spacecraft in orbit). This is also what keeps the Earth from falling into the Sun. Should the Earth suddenly stop in its orbit – don't worry it cannot happen – then it would fall toward the Sun with ever-increasing speed, to be consumed after a voyage of only three months' duration. The Earth attracts each of us toward its center and this is what we call our weight. We do not fall toward the center because the ground prevents this, except when we