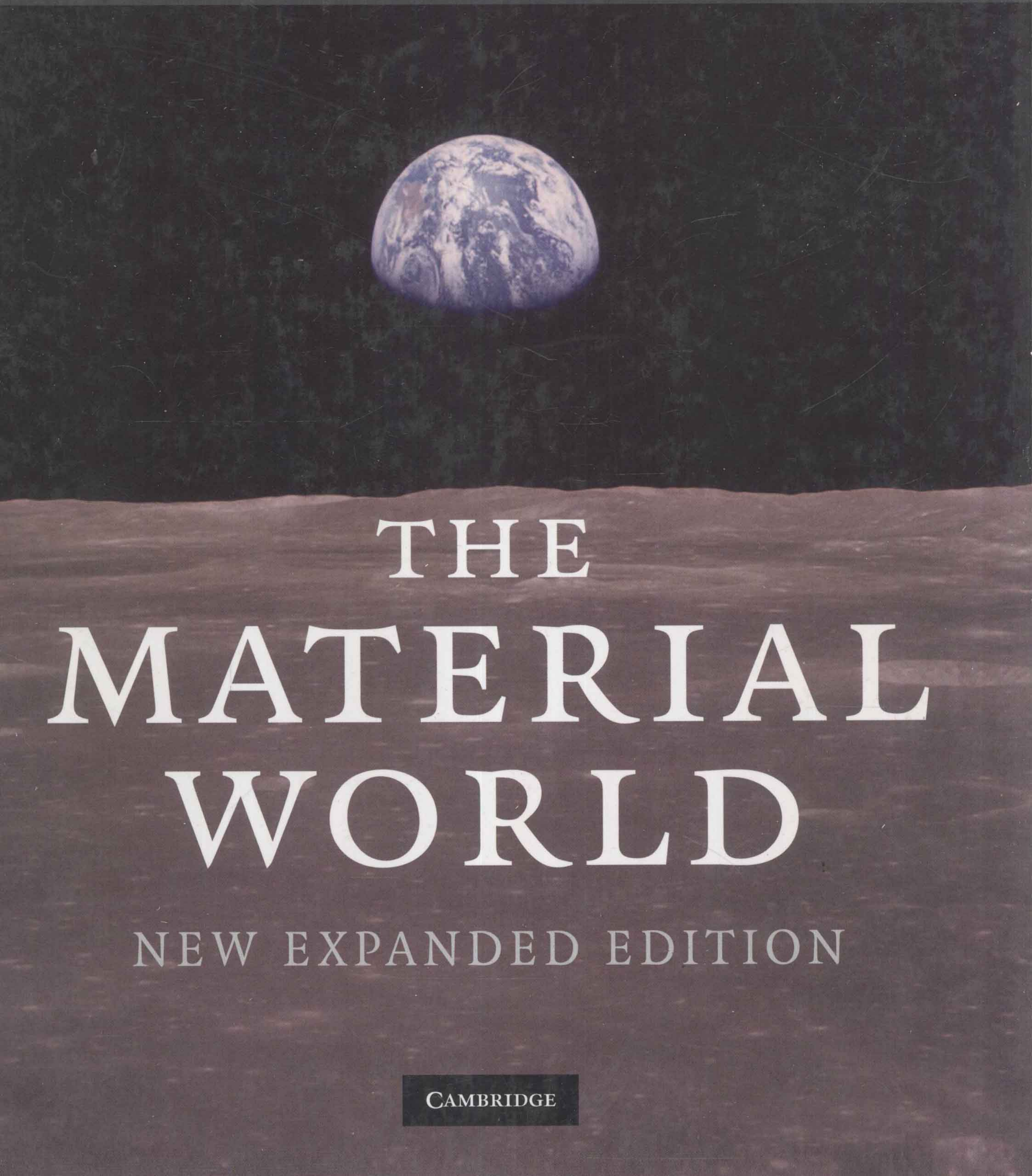
Rodney Cotterill



The Material World

New Expanded Edition

Cambridge

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RODNEY COTTERILL

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The Material World

Rodney Cotterill was a native of the Isle of Wight, and he was educated at University College London, Yale and the Cavendish Laboratory in Cambridge, where he was also a member of Emmanuel College. He researched and taught initially in physics and materials science, subsequently in biophysics, and ultimately in neuroscience, and he was one of the pioneers of computer simulation. He spent periods at Argonne National Laboratory, near Chicago, the University of Tokyo, and the Quantum Protein Centre at the Technical University of Denmark, near Copenhagen. Professor Cotterill was a Fellow of the Royal Danish Academy of Sciences and Letters, and a Member of its præsidium, until his death in June 2007.

In honour – and *awe* – of the polymaths of bygone days – of the likes of Aristotle, Francis Bacon, Roger Bacon, Robert Boyle, René Descartes, Thomas Edison, Michael Faraday, Benjamin Franklin, Galileo Galilei, Nicholaas Hartsoeker, Hermann von Helmholtz, Christiaan Huygens, Antoine Lavoisier, Gottfried Leibnitz, John Locke, John Tyndall, Thomas Willis, Christopher Wren and Thomas Young – and not the least of Leonardo da Vinci, Robert Hooke, Isaac Newton and Niels Steensen.

With special thanks to Bjørn G Nielsen, Henrik Georg Bohr, Jens Ulrik Madsen, Claus Helix Nielsen and Anetta Claussen, all of whom were instrumental in completing this new edition.

International praise for Rodney Cotterill's

The Material World

'In undertaking to give an account of matter in all its aspects, from the individual atom to the living organism, Rodney Cotterill has done what very few would dare. This is a book that should be in every university science department, every technological firm and every sixth-form college. Let me commend a magnificent achievement.'

Sir Brian Pippard FRS *Interdisciplinary Science Reviews*

'The unity at depth between physics and chemistry, between crystal defects and restriction enzymes, has never been served so well in a popular and visually engaging book.'

Philip Morrison *Scientific American*

'The beautifully produced *The Material World* by Rodney Cotterill should allow teachers and students alike to move away from the narrow traditional education patterns and adopt a broader, more thoughtful approach to science education.'

Sir Tom Blundell FRS *New Scientist*

'This is a grand tour of the sciences. Beautifully written, with a fine poetic turn of phrase, it will be an outstanding source of reference for high school, college and university students, and should find a market among science teachers, science buffs, and young scientists who might be encouraged to range farther afield during their own research careers.'

Graeme O'Neill in *The Canberra Times*

'An instant classic.'

Robert Cahn FRS *Contemporary Physics*

'A godsend to anyone who knows little or no physics, chemistry or biology but would like a picture of the world at the microscopic and atomic levels.'

Carol Rasmussen *New York Library Journal*

'Will it not soon be impossible for one person to grasp the breadth of the topics we call science? Not yet. After several delightful hours with Rodney Cotterill's *The Material World*, I can confirm that at least one polymath survives.'

Peter Goodhew *The Times Educational Supplement*

Preface

In 1855, Heinrich Geissler (1815–1879) devised a vacuum pump based on a column of mercury which functioned as a piston. He and his colleague Julius Plücker (1801–1868) used it to remove most of the air from a glass tube into which two electrical leads had been sealed, and they used this simple apparatus to study electrical discharges in gases. Their experiments, and related ones performed around the same time by Michael Faraday (1791–1867) and John Gassiot (1797–1877), probed the influence of magnetic and electric fields on the glow discharge, and it was established that the light was emitted when 'negative rays' struck the glass of the tube. The discharge tube underwent a succession of design modifications, in the hands of William Crookes (1832–1919), Philipp Lenard (1862–1947) and Jean Perrin (1870–1942), and this field of activity culminated with the discovery of X-rays by Wilhelm Röntgen (1845–1923), in 1895, and of the electron two years later, by Joseph (J.J.) Thomson (1856–1940). These landmarks led, respectively, to investigations of the atomic arrangements in matter and explanations of the forces through which the atoms interact. The repercussions were felt throughout the physical and life sciences. Jens (J. F.) Willumsen (1863–1958) captured the spirit of these pioneering efforts in his 'A Physicist', painted in 1913.

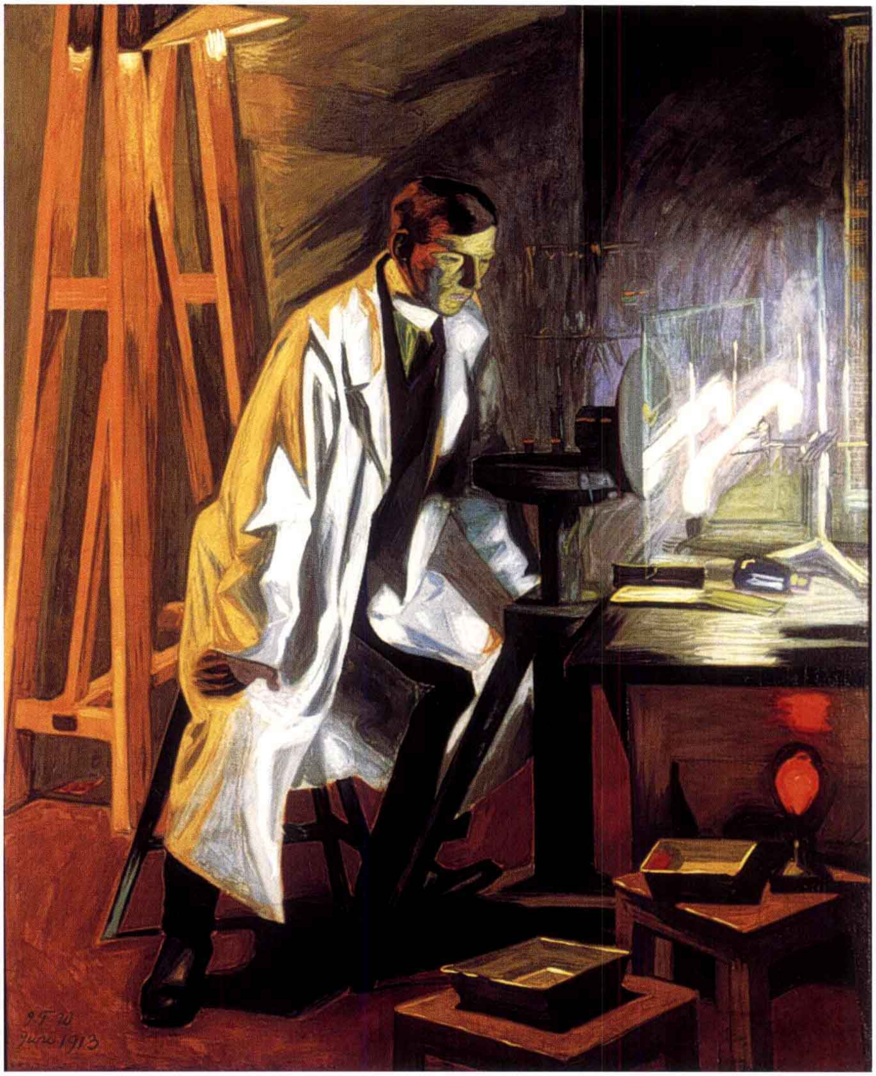
I have written this book for people interested in science who seek a broader picture than is normally found between a single pair of covers. It presents a non-mathematical description of the physics, chemistry and biology of nature's materials. Although it has been written primarily as a self-contained review for the non-specialist, it can also be used as an introduction, to precede more detailed studies of specific substances and phenomena.

The general approach adopted in the text has been to proceed from the relatively simple to the more complex. After the Prologue, which provides the book with a cosmic backdrop, the story starts with single atoms and the groups of atoms known as molecules, and it continues with the cooperative properties of large numbers of atoms. The nature and consequences of symmetry in crystals have been allocated their own chapter, as have those departures from regularity that play a key role in the behaviour of materials. Such imperfections are presented in the context of the inorganic domain, but they have counterparts in the mutations and variations inevitably present in living organisms. Water and the Earth's minerals are so important to our environment that they too have been discussed in separate chapters, and the balance of the book is broadly divided into three parts, each covered in several chapters: inorganic materials, organic non-biological materials, and biological materials. The final chapter is devoted exclusively to the mind.

Nature is not aware of the boundaries between our scientific disciplines, and the areas obscured by professional demarcations are potentially as rich as any established field of scientific inquiry. Some of the most exciting developments in recent times have indeed come through exploration of these twilight zones. Around the middle of the twentieth century, for example, physics impinged upon biology and produced the revolution we now know as molecular biology. It has already changed our approach to the body, and it may ultimately influence our attitude to the mind; if Alexander Pope were alive today, he might feel that the proper study of mankind should involve proteins, lipids and nucleic acids. The individual chapters of this book admittedly reflect current academic divisions, and could seem to reinforce them. I hope that the inclusion of such wide variety in a single volume will be perceived as compensation, and that the unusual association of apparently disparate topics might even reveal new avenues for investigation.

It would be gratifying if the book's provision of a global view could help alleviate the scarcity of time that bedevils so many professionals these days.

The pressures of securing adequate funding have never been greater, and one of the chief casualties has been the time that could have been spent in the library. Those who would have us focus on a narrow range of prestigious projects are no lovers of the diversity so vital to the scientific enterprise. In an era dominated by buzz-words, it is worth bearing in mind that there is hardly a word in this book's index that does not give a buzz to someone or other.


J F W
June 1913

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Stand still you ever-moving spheres of heaven, that time may cease, and midnight never come.
Christopher Marlowe (1564–1593)
Faustus

Prologue

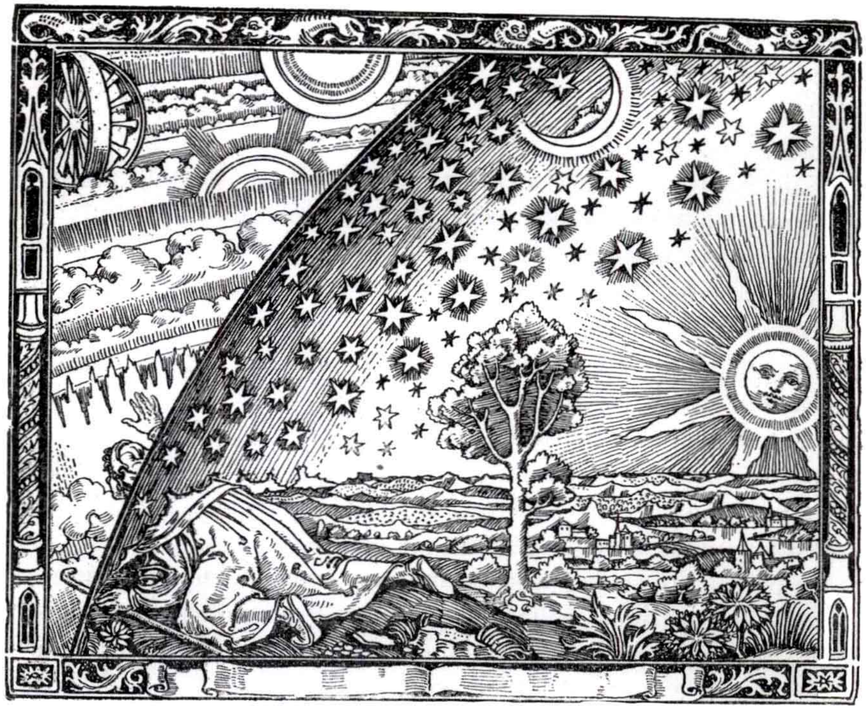
There is broad scientific agreement that the *Universe* came into existence about 13 700 000 000 years ago, as a result of the largest-ever explosion. In the briefest of instants, the explosion created all the *matter* and *energy* that has ever existed, and although matter and energy are interconvertible, as Albert Einstein's *special theory of relativity* tells us, their sum has remained constant ever since. Fred Hoyle referred to this cataclysmic event as the *big bang* – facetiously in fact, because he advocated the now-defunct rival idea of *continuous creation*. In 1948, Hoyle, Hermann Bondi and Thomas Gold had put forward the idea that the Universe is in a *steady state*, that it had no beginning, and that it will have no end. There is now strong evidence that the big bang did take place, as first surmised by Georges Lemaître in 1927, and thus that the Universe certainly did have a beginning. It remains a moot point, however, as to whether it will have an end.

One might speculate as to what was present in the cosmos before the primordial explosion, but Stephen Hawking has argued that such a question would be incorrectly posed, and therefore futile. According to his theory, the big bang created *time* itself, and it thus coincided with what could be called a *pole in time*. Just as it would be meaningless to ask which direction is North when one is standing on the North Pole – pointing upward would merely indicate the direction of increasing altitude – so is it meaningless to ask what came before the big bang.

The huge explosion created a prodigious number of *elementary particles* of matter, which immediately started to fly apart from one another, as do gas molecules in the more familiar type of explosion. But the moving particles were travelling through the vacuum of *space*, and they have continued to do so ever since. The Universe has always been expanding, therefore, but that is not to say that it is featureless and inert. On the contrary, the various *fundamental forces* – of which there are just four – have contrived to cause clustering of particles on a number of very different scales of distance. The shortest-ranged of these forces, the so-called *weak nuclear force* and *strong nuclear force*, created *nuclear matter*, the most common example being the tiny clumps of it present in *atomic nuclei*, while the longer-ranged *electromagnetic force* was responsible for the formation of *atoms* themselves.

The *gravitational force* is by far the weakest of the four, but given the great amount of mass and time at its disposal, it was sufficient to gradually produce the very large clusters of atoms we now call heavenly bodies. The composition of some of these is such that the interconversion predicted by Einstein's theory comes into play, and *thermonuclear reactions* convert matter into vast amounts of energy. These bodies are *stars*, and the one closest to

It was natural for early astronomers to assume that the various heavenly bodies revolve around the Earth, the latter remaining fixed in position. This picture looks like a sixteenth century woodcut at first glance, and it seems to show a person succumbing to curiosity regarding what lies beyond the firmament of fixed stars, as well as the Sun and Moon. It was actually produced fairly recently, however, by Camille Flammarion (1842–1925), an enthusiastic popularizer of science. Published in his book *L'Atmosphère*, in 1888, it is a tongue-in-cheek depiction of a medieval missionary's claim to have found the point at which the sky touches the earth.

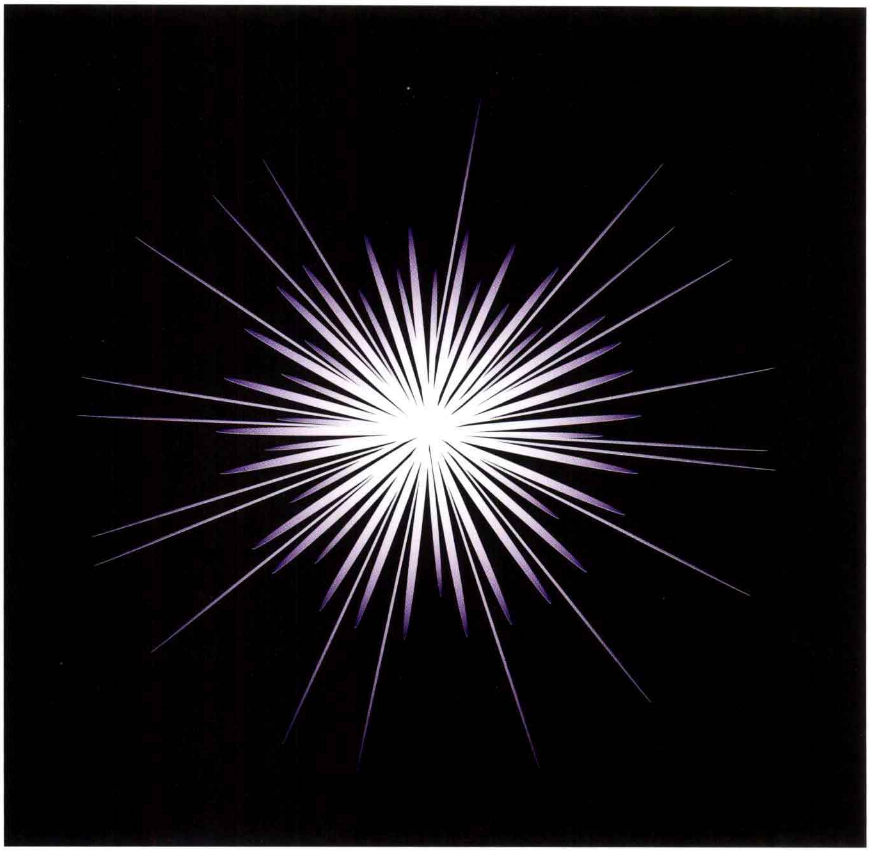


Un missionnaire du moyen âge raconte qu'il avait trouvé le point où le ciel et la Terre se touchent...

us – *the Sun* – is so bright that it is visible during the day. Indeed, it *creates* the day! It provides us with light and heat. All the other stars are so far away that their radiations are visible only during the night. Our Sun is surrounded by a number of smaller bodies – *the planets* – which do not generate light, but they reflect it and this makes most of them visible to the naked eye during darkness. Some planets have even smaller bodies revolving around *them*, and the larger of these are known as *moons*. Planets have also been discovered revolving around some of the other stars, and there has been much speculation about whether they too support living organisms. There has indeed been speculation about whether life existed at earlier times on other planets in our own *solar system*, *Mars* in particular.

Solar systems are not the largest manifestations of gravity at work. It transpires that such systems are themselves clustered into what are known as *galaxies*, and the galaxy of which our own solar system is a member contains approximately 10 000 000 000 stars. It is a typical example of a *spiral galaxy*. It has a central stellar cluster and the remainder of its stars are distributed among a number of 'arms', which spiral out from the centre. Our own solar system is located in one of the arms, and this is why we see more of the other stars when we look in a certain direction at the night sky. We call this dense region the *Milky Way*, which is indeed the name given to our galaxy itself. Certain other stars in our galaxy are so close that they appear particularly bright, and are thus easily identifiable. The night sky seems to be a two-dimensional dome – the *firmament* – but the various stars really lie at different distances. This causes some of them to appear grouped together as *constellations*, which acquired names reflecting their fanciful similarities to familiar objects and animals. There is a seven-star constellation variously

There is general scientific agreement that the Universe was created about fourteen thousand million years ago, as a result of the largest-ever explosion. Fred Hoyle (1915–2001), an advocate of the rival theory of continuous creation, referred to this cataclysmic event as the *big bang* – humorously, because he did not believe that it ever took place. The picture shown here is, of course, just an artists's impression. In reality, there would have been nothing to see because the wavelengths involved were much shorter than those of the visible spectrum.



known as the Great Bear (*Ursa major*), the Plough, the Drinking Gourd or the Big Dipper, for example. Early observers of the firmament divided it into twelve more or less equally spaced zones, each containing a constellation, the number twelve being roughly compatible with the approximately twelve full moons in each year. These constellations become prominent at various times of the year, always in the same sequence, and gave rise to the *signs of the zodiac*. This early rationalization in *astronomy* was subsequently embraced by *astrology*, according to which date of birth dictates traits in a person's character.

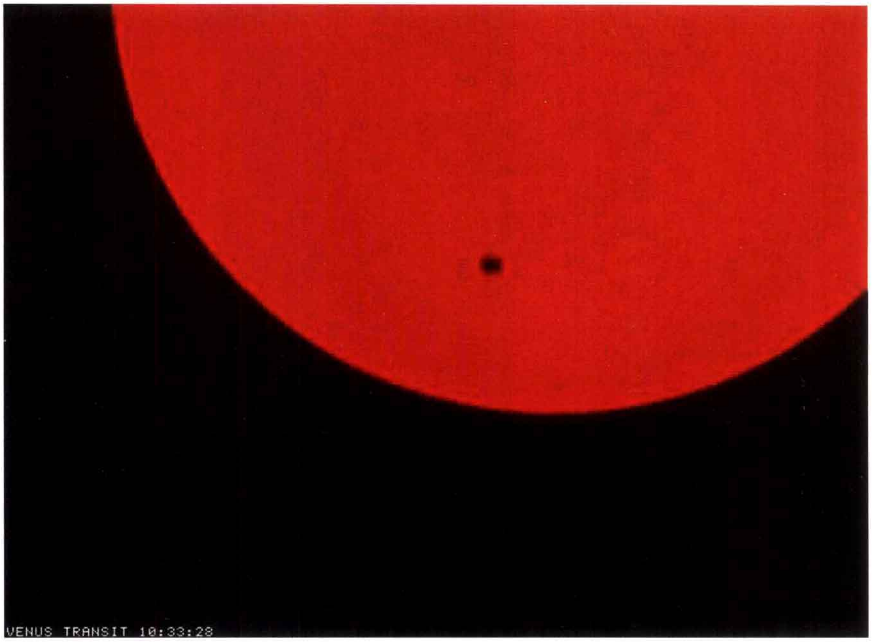
Galaxies lying farther away from us naturally appear smaller, and are visible as entire objects. The apparent density of matter – stars and the material from which they are being formed – is then so large that the distant galaxy appears as a luminous cloud, or *nebula*. A famous example is the nebula that seems to lie in the constellation of Andromeda, but is really very much farther away. The typical galaxy is an extremely large structure; the Milky Way measures about 1 000 000 000 000 000 000 kilometres in diameter. A good idea of the vastness of the Universe is provided by the fact that it contains more than 1 000 000 000 galaxies. If we wished to write down the total mass of the Universe, in kilograms, we would have to write 1 followed by forty-one zeros. Such large numbers are more conveniently written in the short-hand *decimal exponent notation*, that mass then becoming simply 10^{41} kg. We will take advantage of this notation in the rest of the book.

Energy

Energy is the capacity for doing *work*, and it comes in various forms, which are always associated with *matter*, the one exception being *radiant energy*. The most fundamental distinction among the various forms is between *potential energy* and *kinetic energy*, the latter being associated with *motion*. But even this neat categorization is blurred by the fact that all matter in the Universe is perpetually in motion through space. Potential energy thus refers to the capacity for doing work that stems from the *relative* positions of particles of matter. The blacksmith's raised hammer, when held stationary, has unvarying potential energy relative to the target object it will subsequently strike, even though both hammer and target are hurtling through space at the same velocity. The various forms of energy are interconvertible, the conversion *always* requiring the presence of matter, even when one of the forms is radiant energy. *Electrical energy* is a form of potential energy that derives from the electrical charges – some positive, some negative – on interacting particles of matter, and *chemical energy* is one manifestation of this. *Nuclear energy* is produced by somewhat similar interactions between the particles in atomic nuclei. *Thermal energy* stems from the motions of the particles in a solid, liquid or gas, and is thus a form of kinetic energy. The heat produced by the blacksmith's hammer when it strikes its target is a familiar example. The unit of energy is the *joule* (named for James Joule, 1818–1889).

The remarkably weak *gravitational force* really comes into its own over very large distances because of its long-ranged nature; in fact, gravitational attraction appears to stretch out toward infinity. The resulting forces between the heavenly bodies profoundly influence their motions. Indeed, they also cause them. A body's *state of motion* is said to remain constant either if it is at rest or if its velocity – that is to say its speed along a given direction – remains unchanged. As Robert Hooke, and more rigorously Isaac Newton, argued, the application of a force changes the state of motion, speeding it up or slowing it down according to whether the force lies in a direction that promotes acceleration or retardation. In our own solar system, for example, the gravitational force between the massive central Sun and a given planet causes the latter to be constantly attracted toward the former (and vice versa, but let us ignore that minor factor). This does not send the planet crashing into the Sun, however, because it also has a velocity that lies tangential to its *orbit*, and this produces the counterbalancing *centrifugal force* that permits stability to prevail. Our familiarity with *artificial satellites* permits us to appreciate the underlying principles, so we are not surprised when such a device does indeed come crashing down to Earth if its speed falls below the necessary value.

Orbital stability is in fact a relative thing, and one must always ask *For how long?* One theory of the origin of the Earth's single Moon runs as follows. There was formerly an additional planet, *Theia*, which had a mass comparable to that of Mars and an orbit close to that of the Earth. The consequent perturbation of Theia's motion caused its orbit to become chaotic, and the two planets ultimately collided, with the generation of so much energy that both bodies melted. Within about an hour, the remains of the totally disrupted Theia were hurled into an irregular orbit around the now-molten Earth, with Theia's iron core located about 50 000 km from the Earth's centre. This situation too was unstable, and the huge lump of iron crashed into the Earth's surface, within about a day after the initial impact. It penetrated deep within our planet's mass and became permanently incorporated in it. Gravitational attraction then ensured that the remnant debris gradually condensed to produce our Moon, initially in an orbit lying at just 22 000 km, Three of the bodies in our solar system can come between the Earth and the Sun: Mercury, Venus and our own Moon. The latter can thereby cause a total eclipse if it is suitably positioned, the eclipse otherwise merely being partial. (Leonardo da Vinci, 1452–1519, demonstrated the underlying principle, using simple geometry.) Eclipses by Mercury and Venus are only ever partial because the angle subtended at the Earth's surface by either of these planets is very much smaller than that subtended by the Sun. Partial eclipses by Mercury are relatively frequent, because that planet's frequency of revolution about the Sun is relatively large; there was a so-called *Mercury passage* in 2003, for example. The rarest of all types of eclipse is the *Venus passage;* such partial eclipses occur in pairs – about eight years apart – less than once a century. The Venus passage shown here took place on 8 June 2004, and it was the first such event since 1882. No living person had ever before seen such a thing. The passage took six hours and twenty minutes, and the next three passages will occur in 2012 (6 June), 2117 and 2125. Astronomers of earlier times used such passages to check their calculations of planetary sizes and distances.



but now in a stable one at 384 400 km. There is much evidence to support this remarkable theory. The iron-depleted Moon (radius 1738 km) has a density of only 3.34 g/cm^3 (grams per cubic centimetre), whereas the Earth (mean radius 6368 km) has a density of 5.52 g/cm^3. It must be stressed, however, that this fascinating story is nevertheless just conjecture.

On the cosmic scale, then, gravitational influences make motion the norm. *Everything* is perpetually moving! The Moon revolves around the Earth at a speed of about 3600 km/h (kilometres per hour), while the Earth's speed around the Sun (roughly 1.5×10^8 km away) is about 10^5 km/h. And our galaxy is rotating too. This is why its arms do not merely radiate out from the centre like the straight spokes of a wheel; they are a series of vast spirals, and this gives the Milky Way the overall form of a gigantic vortex. It is because of this rotation that the Earth has an additional speed, relative to the Universe, of almost 10^6 km/h. Such relative motions were a constant source of wonderment among the scientists of former times, and some museums can boast an antique *orrery*, in which the planetary movements around the Sun are duplicated in a small-scale clockwork model. Modern counterparts of such devices are to be seen in today's *planetariums*, which additionally reproduce stellar movements.

Gravity also plays a key role in the ultimate fate of each star. Stars vary considerably in size, and also in the surface temperature generated by the thermonuclear reactions in their interiors. These temperatures lie in the approximate range 3000 to 30 000 °C, our Sun being on the cool side with its roughly 6000 °C. This nevertheless makes it hotter than the type of star known as a *red giant*, but it is colder than a so-called *white dwarf*. A white dwarf has the equivalent of a solar mass within the size of the Earth, so it is a million times denser than the Sun. The radiation generated by those thermonuclear reactions produces a force on the constituent particles that counterbalances the inwardly directed gravity. As the reactions weaken, over thousands of millions of years, gravity gradually predominates, pulling the

This typical example of a spiral galaxy was photographed with the Very Large Telescope at the European Southern Observatory on September 21, 1998. It has been given the designation NGC 1232, and it is located about 20 degrees south of the celestial equator, in the constellation of Eridanus, which means the river. Its distance from the Earth is about 100 million light-years. This picture is actually a composite of three individual exposures in the ultra violet, blue and red wave regions, respectively.

particles into an ever-decreasing radius. (This is a simplification of the actual situation, but it is adequate for our purposes.) Various scenarios are then possible. Some heavy stars become mechanically unstable, throbbing with alternating increases and decreases of radius until there is a huge explosion known as a *supernova*. The average-sized star is ultimately shrunk by gravity down to a stable and very dense sphere, and it becomes a white dwarf. But if the initial mass is sufficiently large, the collapse proceeds further and the end product is a *neutron star. Pulsars* are believed to be rapidly rotating neutron stars which emit radiation along specific directions, this being detectable on Earth as periodic bursts of energy. A neutron star has the equivalent of a solar mass within a sphere of radius 10 km, so it is 10^9 times denser than a white dwarf and 10^{15} denser than the Sun. Even this does not exhaust the possibilities. If the initial mass is somewhat larger still, gravity shrinks the star into a *black hole*, from which nothing can escape – not even light itself! We can understand how this situation arises by recalling that the speed of an artificial satellite must increase with decreasing distance from the Earth's surface, if it is to remain in stable orbit. If the Earth had a larger mass, the required speed would increase. The concentration of mass in a black hole is so large that even a particle of light, which travels at the fastest possible speed, cannot stay in orbit. During recent years, it has been discovered that there is a black hole located at the very centre of our own galaxy. It is several million times more massive than our Sun. It is a sobering thought that this black hole had been in existence for millions of years before our species emerged.

The metric system
In order to avoid spelling out large and small numbers, it is more convenient to use the decade power notation. Examples are: $1000 = 10^3$; $1\,000\,000\,000 = 10^9$; $1/1\,000\,000 = 0.000\,001 = 10^{-6}$.

Decimal multiples for certain powers have been given standard prefixes and symbols. These are indicated in the following table.

Factor	Prefix	Symbol
10	deca-	da
10^2	hecto-	h
10^3	kilo-	k
10^6	mega-	M
10^9	giga-	G
10^{12}	tera-	T
10^{15}	peta-	P
10^{18}	exa-	E
10^{21}	zetta-	Z
10^{24}	yotta-	Y
10^{-1}	deci-	d
10^{-2}	centi-	c
10^{-3}	milli-	m
10^{-6}	micro	μ
10^{-9}	nano-	n
10^{-12}	pico-	p
10^{-15}	femto-	f
10^{-18}	atto-	a
10^{-21}	zepto-	z
10^{-24}	yocto-	y

How do we know all these things? The key appears in this Prologue's first sentence; our knowledge is scientific. But what *is* science, that we should place such confidence in it? *Science*, according to John Ziman's admirably straightforward definition, is nothing more than *public knowledge*. And the word public indicates that we must limit ourselves to knowledge about which there is some sort of consensus. At the dawn of mankind's independence from the other mammals, this consensus would have existed only on the local scale of the tribe, and it must have been dominated by the immediate needs of sheer survival. The world of those early humans was surely an inhospitable place. Some of the animals being killed for food were ferocious and the hunt must occasionally have gone wrong. External stimuli were very much to the fore, even before humans were able to apply names to such threats – even before there was any form of language. Non-animal stimuli would also have been forcing themselves on the anxious human psyche. Lightning, thunder, storm-force winds, flash floods, landslides, forest fires, the Northern and Southern Lights, earthquakes, tidal waves and volcanoes must all have been terrifying.

An early feature of the consensus was the threat posed by things not immediately visible. A predator would often be heard in the undergrowth before it sprang into view. This inevitably extrapolated to threats detectable by the senses which happened to remain latent. In the most spectacular cases, such as those we have just identified, the latency stretched beyond the lifespan of the individual, and this must have been the harbinger of mankind's preoccupation with the supernatural; the seeds of *religion* were surely being planted very early in mankind's history. The influence would have been particularly strong when the unseen thing could be likened to something familiar. Lightning looks as if it could be a scaled-up version of the sparks generated by struck flint, for example, so this paved the way for Thor's hammer and anvil. And when that god's voice bellowed, there were claps of thunder. The tendency to anthropomorphize things is also seen in the idea that earthquakes were caused by the footfalls of unseen giants. High winds, similarly, were generated when these huge beings expelled air. One can see such wisdom depicted in ancient maps, human figures with puckered lips and puffed-out cheeks frequently being located at the four corners. Such myths may now seem humorous, but we should bear in mind that the general acceptance of unseen influences would subsequently lead to what was surely mankind's greatest intellectual achievement: the realization that there are things – objects and agencies – that lie beyond the reach of the unaided senses. This massive step forward was later to provide the dynamo for much of our industry, and it was going to revolutionize medicine by making us appreciate that illness can be caused by things invisible to the naked eye. But the more immediate result was the emergence of mankind's aspiration to emulate the unseen gods' immortality – to share their apparently eternal life.

It ought to be stressed that such a desire was – and still is – entirely consistent with one of the animal kingdom's most basic urges: the survival instinct. In species not possessing consciousness, this instinct influences behaviour in an automatic fashion. In mankind, it is augmented by the power of reason, but there was – and again still is – an understandable tendency to hold those beliefs which provide most comfort. And here we begin to glimpse the great parting of the ways, because science has no truck with comfort. When the evidence has accumulated, and been duly evaluated, the resulting new