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P. C. W. Davies
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The fundamental ingredients of nature

The variety and complexity of physical systems that adorn our universe are so bewildering that the task of discovering simple laws to describe them all appears hopeless. Yet remarkable though it may seem, the fundamental principles that control objects as diverse as atoms and stars are well enough understood that an integrated account can be given of most of the more common systems in the natural world. Our ability to summarize the workings of nature within a single theoretical framework stems from the fact that the really fundamental features of physics are both simple and comprehensive. Theories like quantum mechanics have such enormous predictive power that they explain at a stroke phenomena as dissimilar as the formation of a crystal and the collapse of a neutron star.

The universality of fundamental physics lies behind the account given in the forthcoming chapters. The reader will discover that although the specific details of physical systems can only be determined from complicated analyses, the broad structural features are largely determined from a few elementary considerations. These considerations reveal a universe full of stunning surprises.

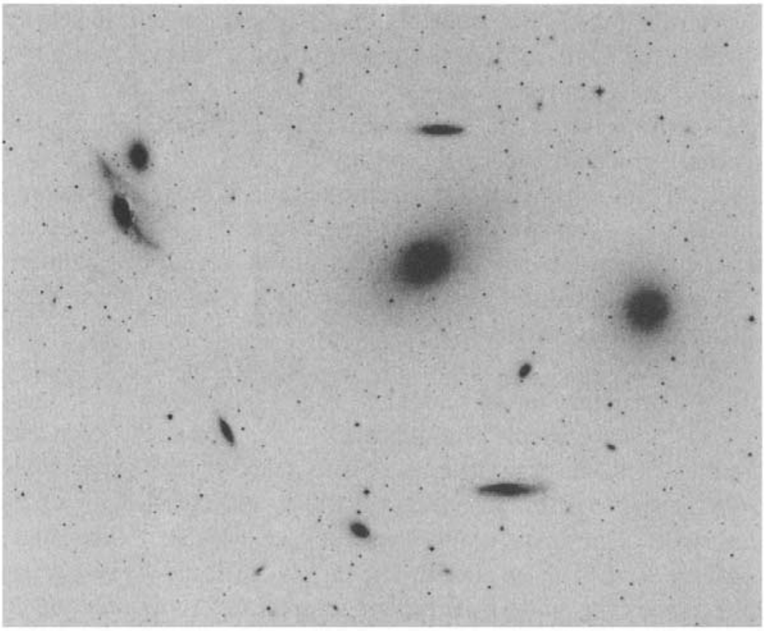
1.1 Structure on all scales

Nature displays a hierarchy of structure. From the smallest known constituents of the atom to the large scale arrangement of the galaxies, we observe systems with characteristic organization and size, each level of structure interlocking with the others in a highly ordered way. What determines the scale of these structures and their relation to one another? Why are galaxies so big and atoms so small? Why are stars so hot and the night sky so dark?

The largest familiar structure is the galaxy, of which our own Milky Way is typical. Containing about 10^{11} stars it is shaped like a plate with a central ball of more densely packed stars. The whole assemblage of stars, together with clouds of gas and some dust grains, slowly rotates. The stars are not distributed uniformly throughout the galaxy, but tend to concentrate in spiral shaped arms. A typical galaxy is about 10^5 light years in diameter.

Galaxies tend to cluster together throughout space in groups ranging from a few dozen to many thousands. There is good observational evidence that above this scale of structure the universe is remarkably uniform in the way that matter and radiation are distributed. The uniformity is both in

Fig. 1. The Virgo cluster of galaxies is one of the nearest clusters to our own Group. (Scale of print 26 arcsec/mm.) Courtesy of the UK Schmidt Telescope Unit, Royal Observatory, Edinburgh

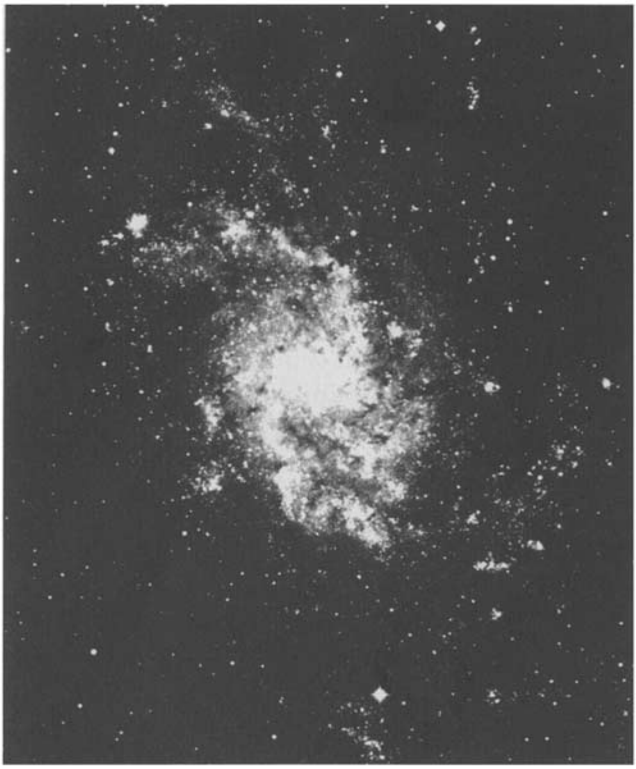


orientation about us (isotropy) and from region to region in distance from us (homogeneity).

The entire assemblage of clusters of galaxies is not, of course, at rest. The force of gravity is forever trying to coalesce the dispersed material into more compact clumps, so that all matter is engaged in a struggle between gravity and the opposing forces of dispersal. In relatively small objects, such as stars and planets, gravity has partially won the struggle. The density of material in these objects is about 10^{30} times higher than the average cosmic density of matter.

The larger systems – galaxies and clusters of galaxies – have

Fig. 2. A typical spiral galaxy, in the constellation Triangulum. Our own Milky Way galaxy would have a similar appearance from afar.



avoided collapse because they are rotating, and orbiting around each other. Gravitational implosion is counterbalanced by centrifugal effects. In addition to this, the clusters of galaxies are prevented from falling together by the fact that the entire universe is engaged in a systematic pattern of expansion, each cluster gradually moving away from its neighbours. The expansion of the universe, discovered by Edwin Hubble in the 1920s, is a cornerstone of modern cosmology, and is best envisaged as the continual swelling or stretching of space itself. As the space between galaxies expands, so the galaxies grow further apart.

As with the distribution of matter, this expansion is unexpectedly uniform throughout the universe. Because the universe on the very large scale is so uniform in its arrangement, the motion of the whole assembly can be characterized by a single parameter: the rate at which two typical galaxies a certain distance apart are separating. This is called the Hubble constant, denoted H, and its value is often quoted by astronomers as about 50 kilometers per second per megaparsec, which means that two galaxies, say, 10 megaparsecs (about 30 million light years) apart, are receding from each other at about 500 kilometers per second. In more familiar units $H \simeq 10^{-18}\ \mathrm{s}^{-1}$.

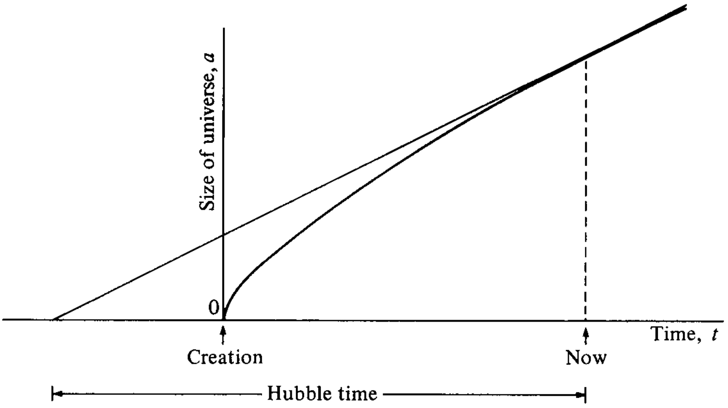
If the galaxies are currently moving apart then they must have been closer together in the past. The units of H are those of velocity/distance, which is inverse time; inverting H therefore yields a fundamental unit of time – the Hubble time – by which to gauge cosmological change. The value of H^{-1} is about 10^{10} years, which implies that 10^{10} years ago the large scale structure of the universe must have been very different from today, with the galaxies crowded much closer together.

As the universe slowly expands, so the intergalactic gravitational forces operate to restrain the dispersal of the galaxies. One would therefore expect the expansion rate H to be gradually slowing down, much as a vertically propelled projectile gradually decelerates. There is indeed some observational evidence that the cosmological expansion rate is diminishing.

If one accepts the idea of a decelerating cosmos, then it follows that 10^{10} years ago the expansion rate was higher than now. Going backwards in time, one expects an accelerating rate of expansion in order for the galaxies to escape falling together under their mutual gravity. Extrapolating as far back as one can, it seems that about 18 billion years ago the universe was infinitely compressed, and expanding infinitely rapidly. This dense, explosive phase is popularly called the big bang, and because it began a finite time ago it is generally held to describe the actual creation of the universe.

Fig. 3 shows how a typical volume of space (for example a cubic light year as measured today) has expanded from nothing since the big bang. Notice the rapid deceleration of the expansion rate in the early stages, followed by the steady decline, expected to continue in the future. This diminishing deceleration is due to the fact that gravity weakens with separation. As the galaxies become more dispersed so the

Fig. 3. The expanding universe. Space is continually swelling, thereby diluting the density of matter and sweeping the galaxies apart from each other. The curve shows how the diameter of a typical spherical volume of space grows at a diminishing rate. The present expansion rate, H, defined as $\dot{a}/a$, where a is the radius of some typical spherical volume of space, is given by the tangent to the curve at the instant marked 'now'. It yields a characteristic time, H^{-1}, called the Hubble time, which is about one and a half times the age of the universe.



intergalactic gravitational forces diminish their restraint on the expansion. Because of the early rapid deceleration in the expansion rate, the Hubble time, H^{-1}, is roughly the same (to within a factor of about $\frac{3}{2}$) as the age of the universe. Note that H is therefore not actually a constant, in spite of its name.

Although the galaxies appear to be islands of glowing matter surrounded by vast chasms of empty space, the intergalactic regions are not totally void. There is undoubtedly some tenuous dark or transparent matter there. More important, all of space, including these superficially empty chasms, is filled with heat radiation. This radiation bathes the entire universe in a rather feeble glow – the temperature is about 3 K. It is the extreme isotropy of this cosmic background heat radiation as received on Earth that provides such good evidence of the large scale uniformity of the universe, for the heat radiation has travelled unimpeded over cosmological distances, and would have carried the imprint of any large scale irregularities.

One of the fundamental mysteries of modern cosmology is why the temperature of the cosmic heat radiation is 3 K rather than some other value. In fact, as the universe expands, the temperature falls. However, the ratio of the number of thermal photons to the number of, say, protons or electrons, in some large volume of space, is unchanged by the cosmic expansion (this will be shown in detail in Section 2.4). The photon/proton ratio is denoted by S, and has a value of about 10^9. Evidently, photons are considerably more numerous than atoms.

Turning now to length scales smaller than galaxies one identifies the most familiar structures in the universe: stars. Stars are held in equilibrium by the balance of their own gravitational force, which tries to shrink them, with thermally generated internal pressure sustained by nuclear reactions in the interior. The smaller, cooler planets overcome their self-gravity by solid state forces which are basically electric in origin. Stars are frequently found in clusters of up to a million in number.

Reducing in scale still further, one encounters large living

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organisms (including man), representing the most developed structures, in terms of complexity, yet known. Passing on down in size through cells and biologically active chain molecules such as DNA, one reaches the level of atoms, now known to be composite systems with their own internal structure.

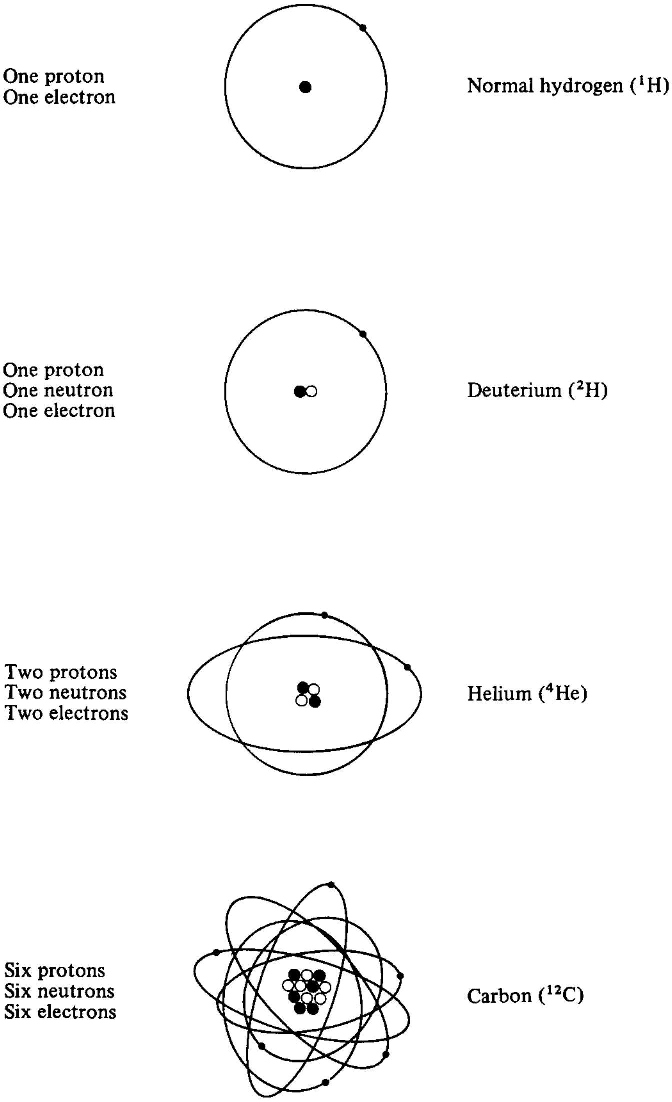
The nuclei of atoms consist of two types of particles: electrically charged protons, and neutrons. Both have a mass of about 10^{-27} kg. In isolation, neutrons decay, with an average lifetime of a few minutes, into protons and electrons. In addition, another particle is emitted, called an antineutrino (the antiparticle of a neutrino – see Section 1.3). Neutrinos are electrically neutral, possess little or no mass, and interact so weakly with ordinary matter that they easily pass right through the Earth. Neutrinos are therefore extremely elusive, and only since the Second World War has their existence been unequivocally confirmed. They nevertheless play an important role in the structure of the universe.

The proton is the fundamental building block of nuclear structure (see Fig. 4). The chemical elements are determined by the numbers of protons contained in the nucleus. The nucleus of the simplest element, hydrogen, consists of a single proton. An isotope of hydrogen, called deuterium, has a neutron and proton stuck together. The nuclear charge is therefore the same as for ordinary hydrogen, but the nucleus is roughly twice as massive.

The next simplest element is helium, which in its normal form contains two protons and two neutrons. Continuing upwards, lithium has three protons, beryllium four, etc. Important elements are carbon, with six protons, oxygen with eight, iron with 26 and uranium with 92. Heavy elements, such as uranium, usually contain about one and a half times as many neutrons as protons. Many are radioactive. Elements heavier than uranium decay with average lifetimes less than the age of the Earth, so are not found in abundance on Earth.

Being a particle of fundamental importance, the proton's properties are of special significance for nuclear (and ultimately atomic and chemical) physics. These properties

Fig. 4. The chemical elements. The chemistry of an atom is determined by the nuclear charge (numbers of protons) which in normal form is exactly balanced by the numbers of electrons. When an atom loses electrons it is described as being *ionized*. The outer electrons help form the bonds that stick atoms together into molecules. The heaviest, most complex atoms contain about 250 nuclear particles and about 90 electrons.



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include its mass, electric charge and size. The size of a proton is a rather subtle concept which will be discussed in Section 1.3. For now we take it to be about 10^{-15} m. This distance can be converted to a fundamental unit of time: the duration for light to cross the proton. The speed of light is the fastest rate at which information can travel and is therefore of special significance. The light travel time across a proton is about 10^{-24} s. Physically this is the smallest interval required for a proton to behave in an integrated way as a single entity.

We therefore now have two natural time scales: the Hubble time, $t_H \sim 10^{10}$ years, and the nuclear time, denoted $t_N \sim 10^{-24}$ s. Their ratio is the impressively large number 10^{41}. The origin of this number, and why it is so big, will be an important topic in the coming chapters.

1.2 The forces of nature

As far as we know, all the various natural phenomena are controlled by just four fundamental forces: gravity, electromagnetism, and two nuclear forces called weak and strong. In recent years attempts have been made to describe these forces by a single mathematical theory. This so-called unification programme has interwoven the weak nuclear force with the electromagnetic force, and more recently made progress in incorporating the strong nuclear force too (see Table 1).

Gravity is familiar in daily life. It acts universally between all material bodies in the universe, and to good approximation (in the case of stars and planets) declines with distance in accordance with Isaac Newton's famous inverse square law. For two idealized point masses, each experiences a force directly towards the other mass of strength

$$F_{\text{grav}} = -\frac{Gm_1 m_2}{r^2}. \tag{1.1}$$

In this formula the negative sign indicates a force of attraction, r is the separation of the two bodies (the size of the bodies is assumed to be small relative to r), m_1 and m_2 are their respective masses. The constant G is universal and has an important significance. It controls the strength of the gravitational forces exerted by the masses. If m_1 and m_2 are taken to be some standard mass, say 1 kg each, and r a standard distance, say 1 m, then the observed force of attraction is 6.7×10^{-11} N. If G were larger, then this force would be larger in proportion. The assertion that G is a universal constant is the claim that, wherever in the universe, or at whatever point in history, one were to measure the force between two 1 kg masses at 1 m separation, then the result would always be 6.7×10^{-11} N. The quantity G must therefore be set alongside the other fundamental quantities as an important constant of nature that determines the structure of gravitating systems.

This century, Newton's theory of gravity has been replaced by a new theory, called the general theory of relativity, due to Albert Einstein. Although the results of general relativity differ somewhat from those of Newton's theory in the case of strong gravitational fields, the two theories coincide in the weak field limit, far from the gravitating bodies. Thus Newton's inverse square law, and the significance of the constant G, remain valid in Einstein's theory.

Table 1. *The forces of nature*

Electricity	Electromagnetism (Maxwell 1860)	Electroweak force (Weinberg, Salam 1967)	Grand unified theories (1980)	Superunified theory (1990?)
Magnetism				
Weak nuclear force				
Strong nuclear force				
Gravity				

Ever closer scrutiny reveals that all of nature's disparate forces are really manifestations of a very small number – perhaps one – of fundamental forces. All known interactions can ultimately be reduced to just four basic types: electromagnetic, gravitational and two nuclear. The electromagnetic and weak nuclear forces, while physically very different in their operation, are actually two aspects of a single, unified, electroweak force. Recent advances suggest that the strong nuclear force, very different again in character, can also be brought in to this scheme in a grand unified theory (GUT) Gravity alone remains to be incorporated.