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Origin of the Universse

Martin J. Rees

'Whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning, endless forms most . . . wonderful have been, and are being evolved.' These concluding words from *The Origin of Species* could serve as a text for later lectures in this series. But I shall be trying to describe what happened *before* the era that Darwin took as his 'simple beginning': to set the Earth in a broader evolutionary context, and trace the origins of its constituent material back to the formation of our Galaxy – right back, indeed, to the first seconds of the so-called 'big bang' that initiated our expanding Universe.

Cosmologists cannot yet offer more than the rudiments of this overall cosmogonic scheme; but what should really surprise us is that there has been any progress at all. 'The most incomprehensible thing about the Universe is that it is comprehensible' is one of Einstein's best-known sayings. It expresses his wonder that the physical laws, which our brains are somehow attuned to make sense of, apparently apply not just in the lab but in the remotest parts of the Universe. This unity and interrelatedness of the physical world must impress all who ponder it. Later on, I shall venture towards some speculative fringes of the subject, but let us start with something quite well understood, the life-cycle of a star like our own Sun.

The Sun and stars

The Sun started life by condensing gravitationally from an interstellar cloud. It continued to contract until its centre became hot enough to ignite nuclear reactions. Gradual conversion of hydrogen into helium then releases enough energy to keep the Sun burning steadily, as a gravitationally confined fusion reactor, for about ten thousand million (ten billion) years. It has been shining for four-and-a-half billion years, and about five billion years from now the hydrogen in its core will run out. It will then swell up to become a red giant, engulfing the inner planets, before settling down to a quiet demise as a white dwarf.

The study of stellar evolution made little progress until the 1930s. Before that

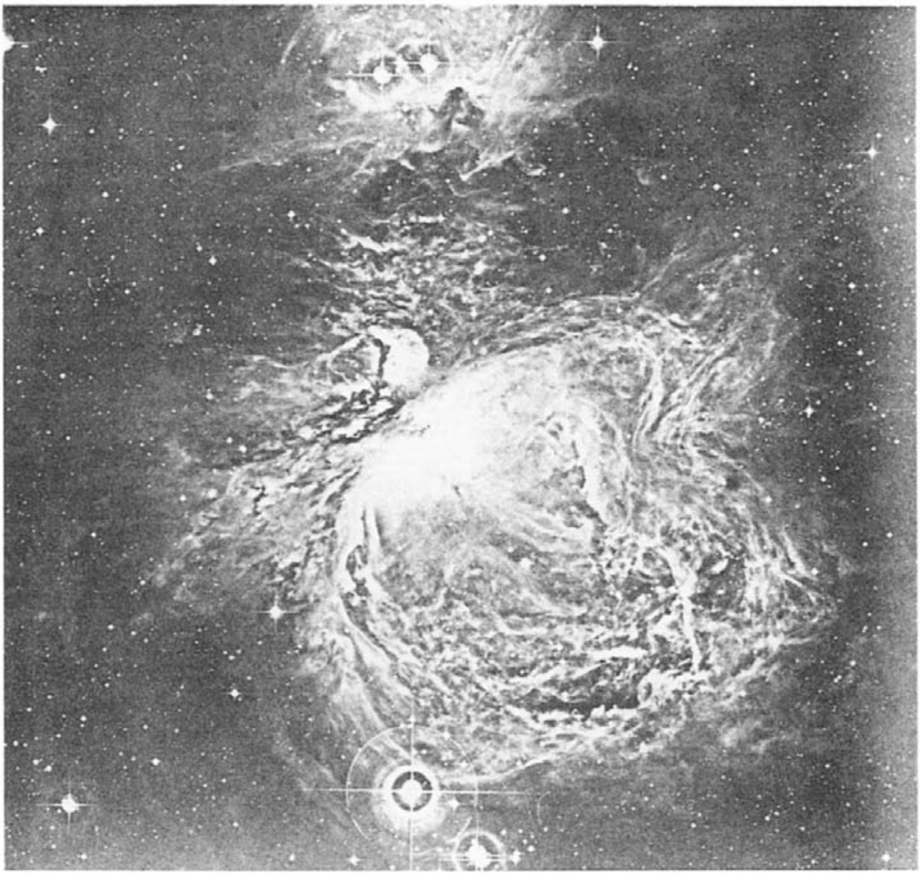

Fig.1.1. The Orion Nebula: a region where stars are now forming.

time, the physics of nuclear reactions was not understood. Indeed, the Sun's age was something that Darwin worried about. Lord Kelvin argued that gravitation must be the prime energy source, and that the Sun must inexorably contract as it loses heat. He calculated that unless sources now unknown to us are 'prepared in the great storehouse of creation', the Sun could last only 20 million years – a period more than ten times shorter than Darwin and the geologists thought comfortable. Only much later did laboratory physics reveal the nuclear fuel that Kelvin could not conceive of.

Stars are so long lived compared with astronomers that we only have, in effect, a single 'snapshot' of each one. But the fact that there are so many of them makes up for this; and we *can* check our theories, just as we could infer the life-cycle of a tree by one day's observation of a forest. Of special interest are places like the Orion Nebula (Figure 1.1), where even now stars, perhaps with new solar systems, are condensing from glowing gas clouds; and star clusters (Figure 1.2), containing stars of different sizes which are thought to have formed at the same time.

Not everything in the cosmos happens slowly. Stars heavier than the Sun

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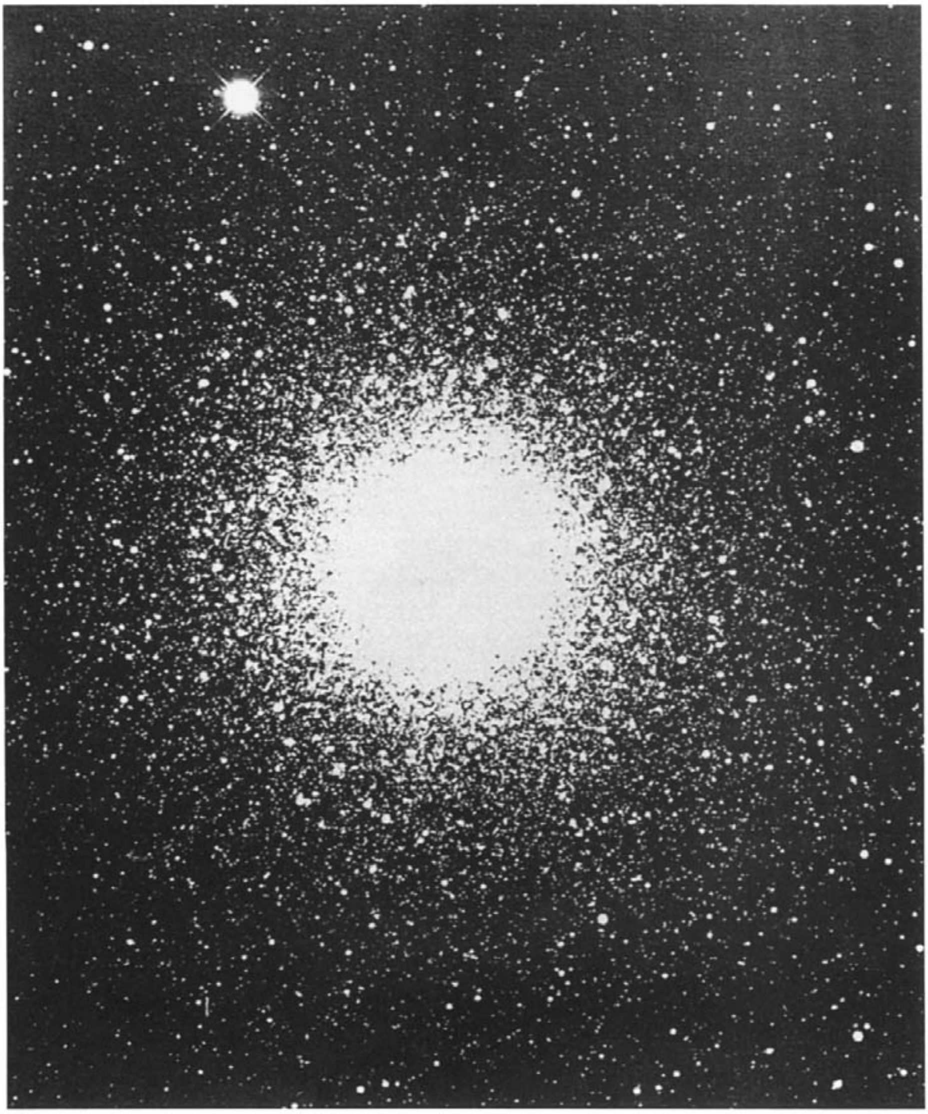

Fig.1.2. A globular star cluster: a self-gravitating system of several hundred thousand coeval stars.

evolve faster, and some expire violently as supernovae. The best-known instance is the Crab Nebula, the expanding debris of a stellar explosion seen and recorded by oriental astronomers in AD 1054. In July of that year, Yang Wei Te, the Chinese 'chief calendrical computer' (the counterpart of our Astronomer Royal, presumably), reported to the Emperor that a 'guest star' had appeared. This star faded after a few months, leaving a remnant behind (Figure 1.3). Supernova explosions signify the violent end-point of stellar evolution, when a star too massive to become a white dwarf exhausts its available nuclear

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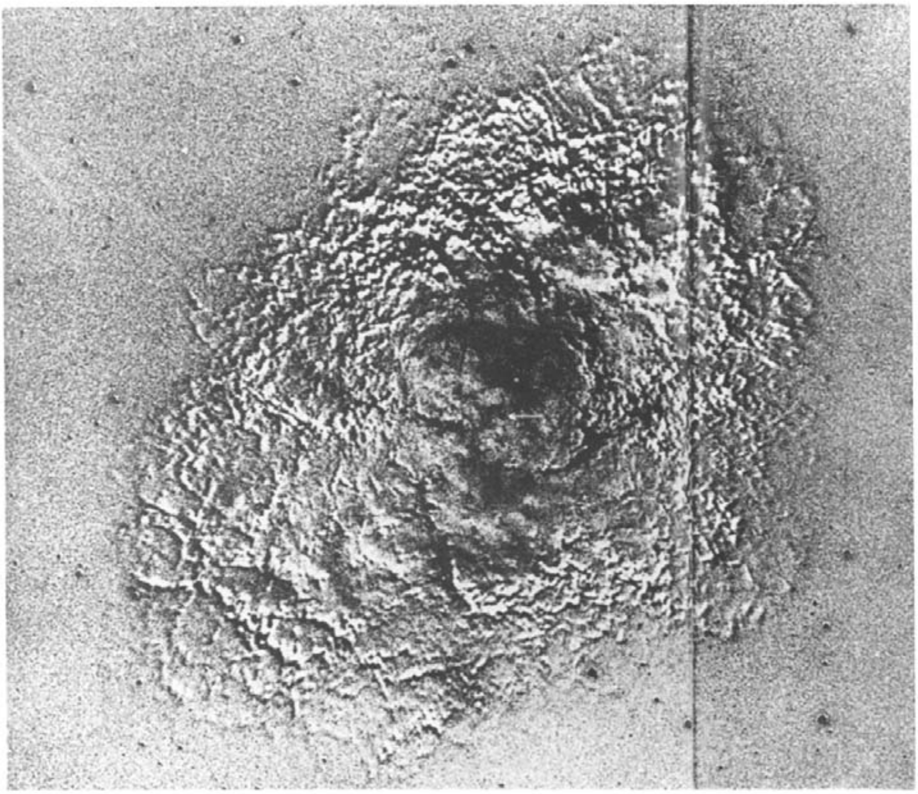

Fig.1.3. The Crab Nebula. This picture shows a positive print of the nebula superposed on a negative taken 15 years earlier. The 'bas relief' appearance of the filaments is graphic evidence that the nebula, which lies at a distance of about 5000 light years, has been expanding (at speeds of order 1000 km s^{-1}) since the supernova event in AD 1054.

energy. The star then faces an energy crisis. Its core catastrophically implodes, releasing so much gravitational energy that the outer layers are blown off. The centre of the star collapses to form a spinning neutron star (pulsar) only about 10 km across.

Supernovae may seem remote and irrelevant to our own origins. But on the contrary, only by studying the births of stars, and the explosive way they die, can we tackle such an everyday question as where the atoms we are made of came from. The respective abundances of the elements of the periodic table can be measured in the Solar System, and inferred spectroscopically in stars and nebulae. The proportions in which the elements occur display regularities from place to place which certainly demand some explanation (Figure 1.4).

Complex chemical elements are an inevitable by-product of the nuclear reactions that provide the power in ordinary stars. A massive star develops a kind of onion-skin structure, where the inner hotter shells are 'cooked' further up the periodic table (Figure 1.5). The final explosion ejects most of this

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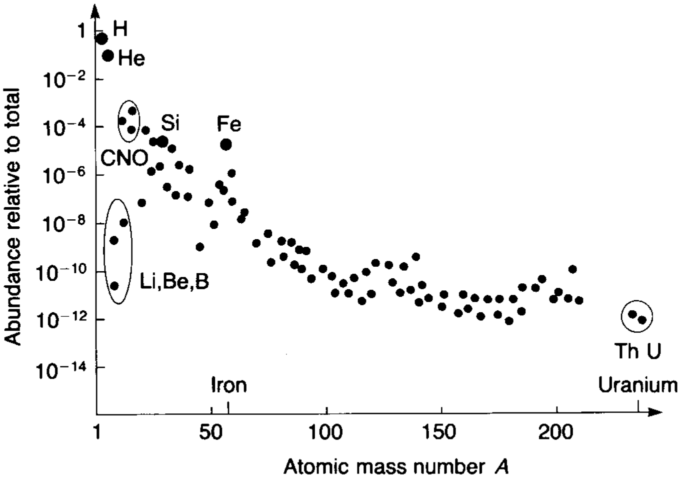

Fig.1.4. The abundances of the chemical elements in the Solar System are here plotted (on a logarithmic scale) as a function of atomic number. Note that only 2 per cent of all the matter is in elements heavier than hydrogen and helium. The relative abundances of the heavy elements are fairly standardized throughout the galaxy; in some of the oldest stars, however, these elements are all depleted relative to hydrogen and helium compared to abundance measurements in the Solar System (i.e. much less than 2 per cent of the total). No objects have been found to contain less than 23–25 per cent (by mass) of helium. It is believed that the material emerging from the 'big bang' was essentially just hydrogen and helium, and that heavier elements were synthesized in stars over the lifetime of the galaxy.

processed material. All the carbon, nitrogen, oxygen and iron on the Earth could have been manufactured in stars that exhausted their fuel supply and exploded before the Sun formed. The Solar System would then have condensed from gas contaminated by the debris ejected from earlier generations of stars. These processes of cosmic nucleogenesis can account for the observed proportions of different elements – why oxygen is common but gold and uranium are rare – and how they came to be in our Solar System.

Each atom on Earth can be traced back to stars that died before the Solar System formed. A carbon atom, forged in the core of a massive star and ejected when this exploded as a supernova, may spend hundreds of millions of years wandering in interstellar space. It may then find itself in a dense cloud which contracts into a new generation of stars. It could then be once again in a stellar interior, where it is transmuted into a still heavier element. Alternatively, it may find itself out on the boundary of a new solar system in a planet, and maybe eventually in a human cell. We are literally made of the ashes of long-dead stars.

This concept of *stellar nucleosynthesis*, due primarily to Hoyle, Fowler and Cameron, is one of the triumphs of astrophysics in the last 40 years. It sets our Solar System in a kind of ecological scheme involving the entire Milky Way galaxy. The particular mix of elements that we find around us is not *ad hoc*, but

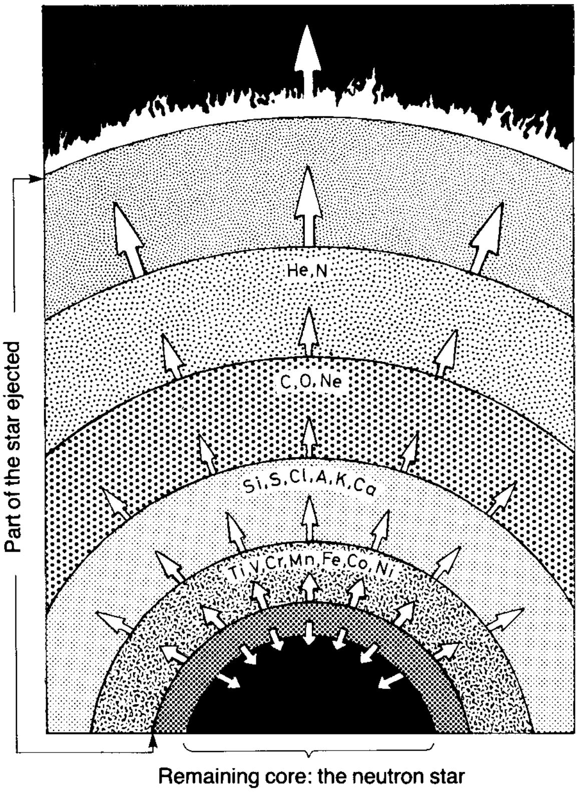

Fig.1.5. The structure of a massive star before the final supernova outburst. The hotter inner shells have been processed further up the periodic table; this releases progressively more energy until the material is converted into iron ($A = 56$), the most tightly bound nucleus. Endothermic nuclear reactions occurring behind the shock wave that blows off the star's outer layers (explosive nucleosynthesis) can synthesize small quantities of elements beyond the 'iron peak' (see Figure 1.4).

the outcome of transmutation and recycling processes, whose starting-point is a young galaxy containing only the lightest elements. One thing this scheme could not explain, however, was helium – why this makes up so much of the mass of all stars, young or old. We shall come back to that later.

Galaxies and their active nuclei

Let us now extend our horizons to the extragalactic realm. It has been clear since the 1920s that our Milky Way, with its 10^{11} stars and scale of about a hundred thousand light years, is just one galaxy, similar to millions of others visible with large telescopes.

Galaxies are held in equilibrium by a balance between gravity, which tends to draw the stars together, and the countervailing effect of the stellar motions,

Fig.1.6. A disc galaxy, viewed at an oblique angle.

which if gravity did not act would cause the galaxy to fly apart. In some galaxies, our own among them, stars move in nearly circular orbit in giant discs (Figure 1.6). In others, the less photogenic ellipticals (Figure 1.7), the stars are swarming around in more random directions, each feeling the gravitational pull of all the others.

Our understanding of galactic morphology is tentative, maybe at the same

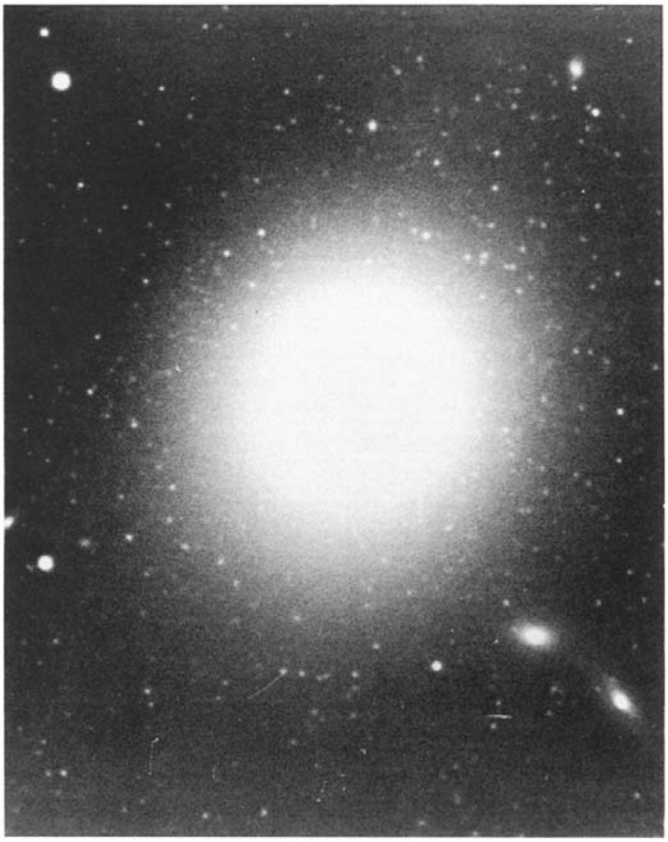

Fig.1.7. An elliptical galaxy.

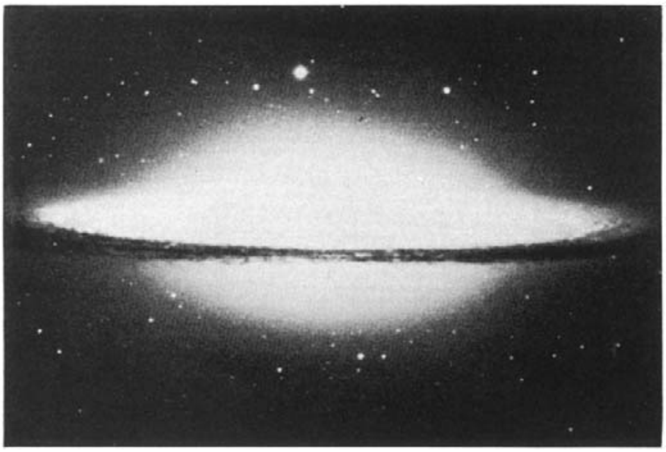

Fig 1.8. The Sombrero galaxy – displaying a hybrid of disc and bulge morphology.

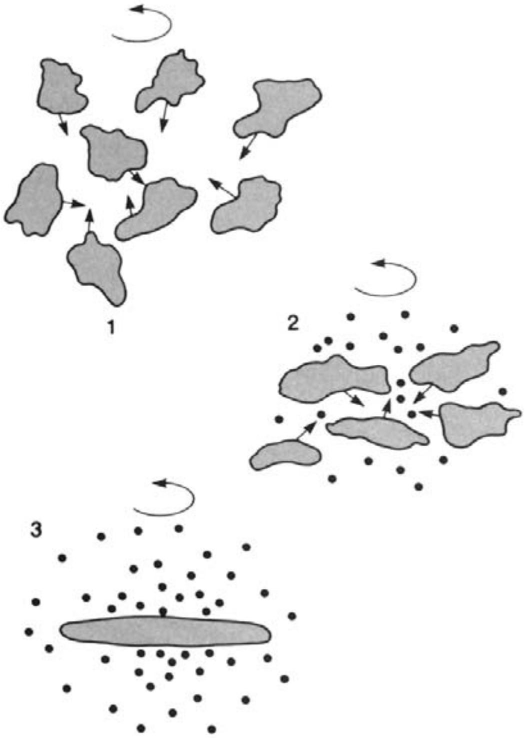

Fig.1.9. Schematic diagram showing three stages in the collapse of a protogalactic cloud with initial mass 10^{11}–10^{12} $M_\odot$ and radius exceeding 10^5 light years. This cloud would have irregular substructure (depicted here as a number of 'subclouds'). The subclouds merge and dissipate energy when they collide; stars, on the other hand, are most unlikely to collide. Stars that condensed out during the infall would retain complex three-dimensional orbits; but those that formed later, from gas that had already settled into a disc, would have more 'ordered' near-circular orbits predominantly in the plane of the disc. The resultant morphology (elliptical or disc-like) then depends on whether the timescale for star formation is shorter or longer than the collapse time. (There is, however, an alternative scheme for forming at least some elliptical galaxies. It could be that most galaxies form as discs, and that ellipticals result from *mergers* of disc systems that occur at a later stage.)

level as the theory of individual stars was 50 years ago: there is much boisterous debate and several competing theories, but little consensus on the details. There is, however, a widely adopted scenario that accounts qualitatively for the two basic types – discs and ellipticals (Figure 1.8). Let us suppose that all galaxies started their lives as huge turbulent gas clouds contracting under their own gravitation, and gradually fragmenting into stars (as depicted in Figure 1.9). The collapse of such a gas cloud is highly dissipative, in the sense that any two globules that collide will radiate their relative energy via shock waves, and will merge. The end result of the collapse of a rotating gas cloud will be a disc. This is the lowest energy state that such a cloud can reach if it loses energy but not its angular momentum. *Stars*, on the other hand, do not collide with each other, and cannot dissipate energy in the same fashion as gas clouds. This suggests that the *rate of conversion of gas into stars* is the crucial feature determining the type of galaxy that results. Ellipticals will be those in which the conversion is fast, so that most stars have already formed before the gas has had time to settle down in a disc. Contariwise, the disc galaxies will be those in which most star formation is delayed until the gas has already settled into a disc. The origin of these giant gas clouds is a cosmological question. But, given such clouds, the physics that determines galactic morphology is nothing more exotic or highbrow than Newtonian gravity and gas dynamics. This does not, of course, make the phenomena easy to quantify, any more than weather prediction is easy.

Some peculiar galaxies, though, are more than just a 'pile' of stars, and harbour intense superstellar activity in their centres. Nearby galaxies such as Centaurus A show this phenomenon in a mild way (Figure 1.10). But most extreme are the quasars, where a small region no bigger than the Solar System outshines the entire surrounding galaxy, and the so-called radio galaxies, whose most conspicuous output is not visible light, but radio waves. In such galaxies, where the central power exceeds a million supernova explosions in unison, gas and stars have accumulated in the centre, until gravity overwhelms all other forces and a *black hole* forms. Here we need more highbrow physics, Einstein's general relativity (the theory that 'matter tells space how to curve, and space tells matter how to move'). The genesis of this theory was unusual: Einstein was not motivated by any observational enigma but, rather, by the quest for simplicity and unity; it was invented almost prematurely in 1915, when any prospects of observing strong field gravity seemed remote. But ever

Fig.1.10. Centaurus A: a relatively nearby galaxy with an active nucleus, which is a radio source.