the new astronomy

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contents

1 the new astronomy

THE 'NEW ASTRONOMY' is a phenomenon of the late twentieth century, and it has completely revolutionised our concept of the Universe. While traditional astronomy was concerned with studying the light – optical radiation – from objects in space, the new astronomy encompasses all the radiations emitted by celestial objects: gamma rays, X-rays, ultraviolet, optical, infrared and radio waves.

The range of light is surprisingly limited. It includes only radiation with wavelengths 30 per cent shorter to 30 per cent longer than the wavelength to which our eyes are most sensitive. The new astronomy covers radiation from extremes which have wavelengths less than one thousand-millionth as long, in the case of the shortest gamma rays, to over a hundred million times longer for the longest radio waves (Fig. 1.2). To make an analogy with sound, traditional astronomy was an effort to understand the symphony of the Universe with ears which could hear only middle C and the two notes immediately adjacent.

The rapid growth of the new astronomy is due partly to the accidental discovery in the 1930s of radio waves from beyond the Earth, which showed that there are non-optical radiations from space. But there have been two major barriers, overcome only in recent decades. First, there are technological problems. We must build new types of telescopes to gather other kinds of radiation, and focus them into an image. We must also develop new detectors to record the image and show it to us in a way we can comprehend. The other is a natural barrier. Earth's atmosphere absorbs most of the radiations from space before they reach the ground, and the new detectors for many wavelengths must be flown well above the atmosphere (Fig. 1.2). These branches of the new astronomy could not be pursued until telescopes could be launched by the rockets, and carried on the satellites, of the 'space age'.

As astronomers have broken the new ground of another

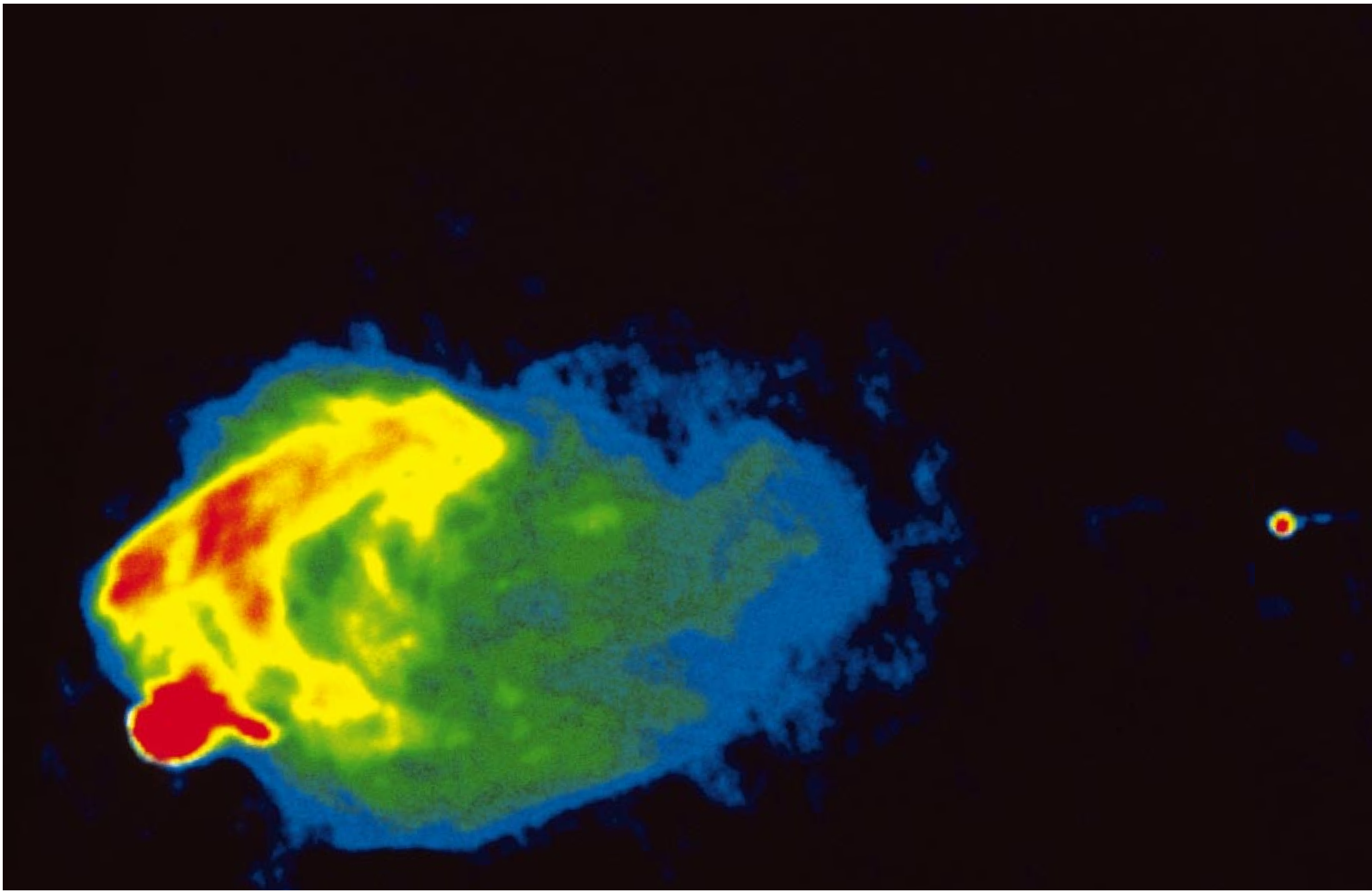
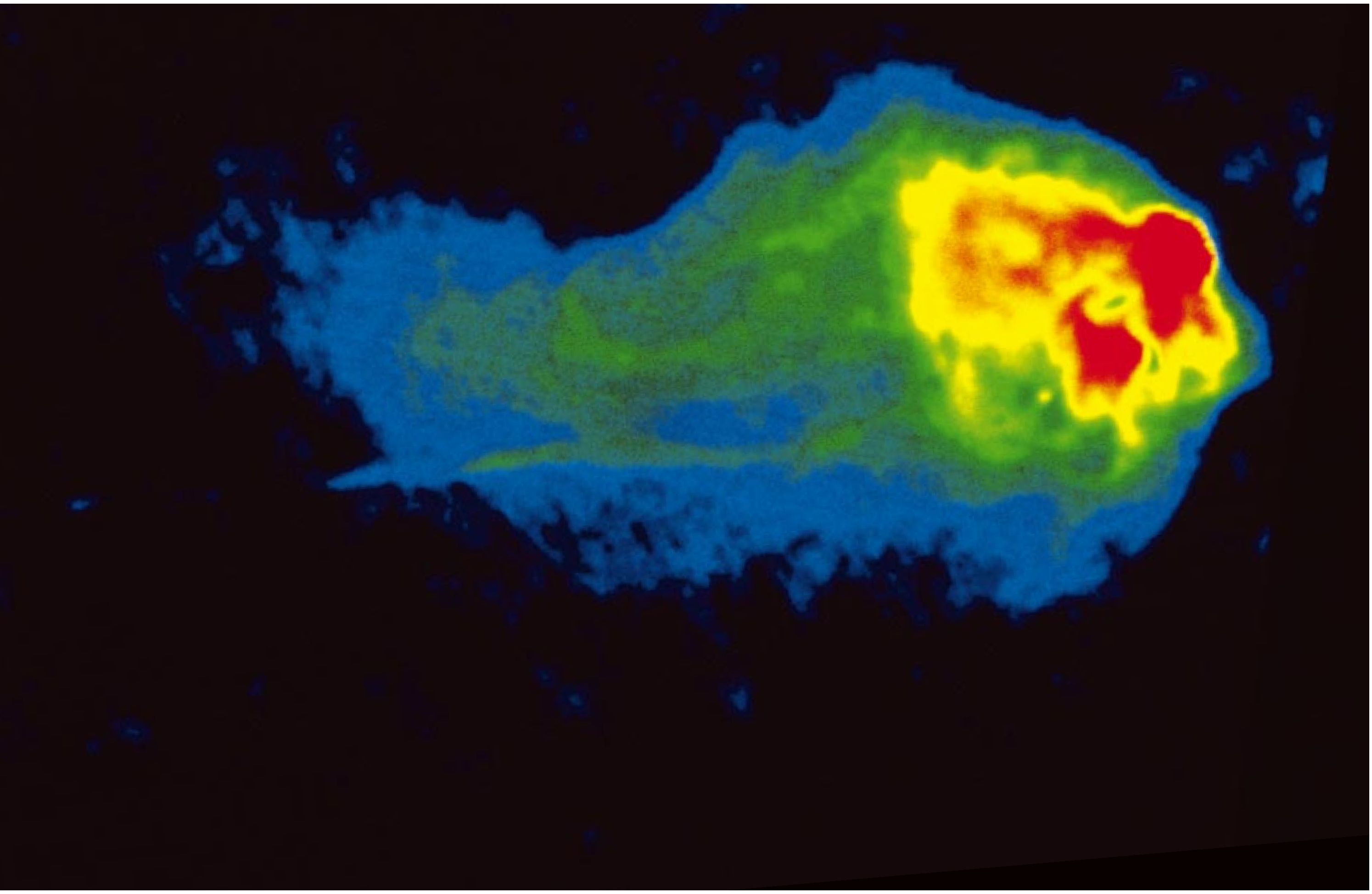


Fig. 1.1 *A radio view of the distant galaxy Cygnus A reveals two huge clouds of magnetism, either side of the galaxy itself. The radio brightness is coded by colour, with the most intense regions shown in red, and successively fainter parts in yellow, green and blue. This radiation, generated by fast electrons*

wavelength region, they have generally started by surveying the sky for sources of this radiation, measuring their brightness and spectra, and making crude maps, often shown as contour diagrams. Only later on are the telescopes and detectors able to produce detailed images of the objects they are observing. As a result, images at wavelengths other than light have only become available since the 1980s. In addition, computer techniques have been developed to process these images. This book brings together a comprehensive collection of pictures which shows the balance of the new astronomy. Optical photographs are not ignored, but take their natural place as just one of the many kinds of view we can now obtain. All the pictures are orientated with North at the top, except where indicated otherwise.

In many cases, the optical picture is the least interesting. Dark clouds of dust in space completely hide the places where stars are born – regions whose details are readily seen at infrared and radio wavelengths. The gas in space is transparent, unseen by optical telescopes, but emits radio waves and gamma rays which makes it brilliant at these wavelengths. Distant clusters of galaxies trap pools of very hot gas, at a temperature of millions of degrees, and these can only be detected by their X-ray emission. Explosions at the centres of powerful galaxies eject beams of electrons which pump up enormous bags of magnetic field – the largest structures in the Universe, but invisible except to astronomers using radio telescopes (Fig. 1.1).

The radiations producing the images in this book go under a variety of names – *X-rays* or radio *waves*, for example – but they are all basically similar in nature, 'waves' consisting of rippling electric and magnetic fields spreading out from a source – be it star, pulsar or quasar. The difference comes in the *wavelength* of the undulation, the distance from 'crest' to 'crest' of the electric wave, visualised very like the succession of waves at sea.



trapped within the magnetic clouds, is completely invisible to an ordinary optical telescope. Conversely, this radio image reveals no sign of the billions of stars that make up the galaxy itself, which lies around the tiny radio source in the centre.

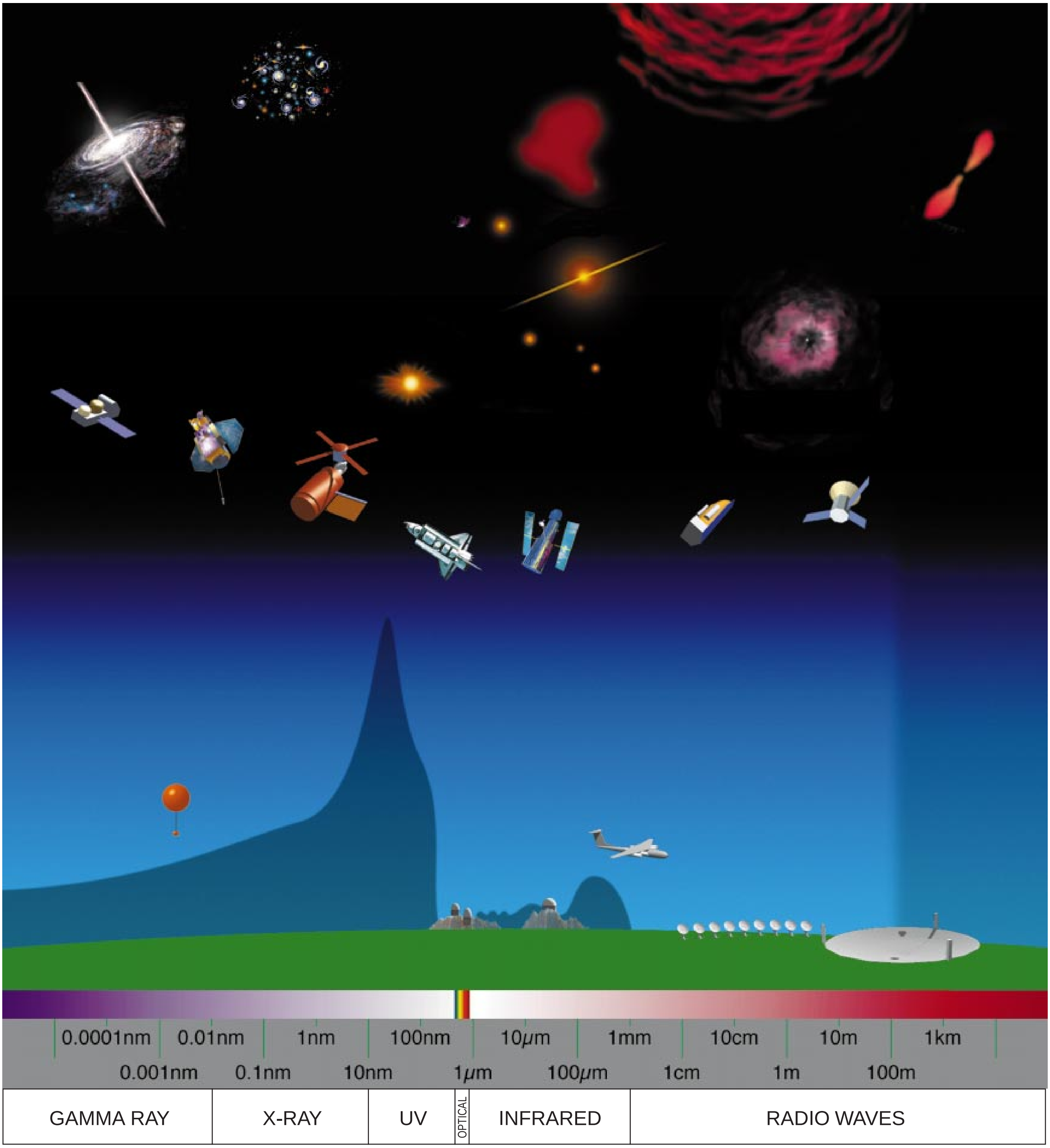


Fig. 1.2 *Astronomers have developed instruments to examine all kinds of radiation from the Universe, ranging in wavelength from the shortest gamma rays (far left) through optical ('rainbow' spectrum) to the longest radio waves (far right). The Earth's atmosphere blocks almost all these wavelengths, however, leaving just two clear 'windows' where astronomers can observe the Universe with telescopes sited at sea-level: the optical window (centre) and the radio window (right), containing the Very Large Array and the Arecibo radio telescope. The long-wavelength side of the radio window is closed by the ionosphere, which reflects long radio waves back to space. Lying between the radio and optical windows is infrared radiation, which is absorbed by water vapour and carbon dioxide in the lower atmosphere: some infrared wavelengths can be observed from high mountain tops or aircraft. To the shorter side of the optical window, ultraviolet (UV) is absorbed by the ozone layer, while gas atoms and molecules in the upper atmosphere block X-rays and gamma rays from space. Astronomers have built satellites to observe almost all these wavelengths unimpeded by the atmosphere (left to right: Compton Gamma Ray Observatory, Rosat, Skylab, Astro, Hubble Space Telescope, Infrared Space Observatory, Cosmic Background Explorer).*

The multiwavelength view has revealed an unsuspected cosmos. At the shortest wavelengths, the sky is dominated by quasars and other 'active galaxies', and by superhot gas in clusters of galaxies. Ultraviolet astronomy has shed new light on the outer layers of our Sun and other stars. Infrared telescopes have laid bare the cool clouds which are the birthplace of stars, many emitting powerful streams of gas. At radio wavelengths, we can observe the remnants of supernova explosions, the vast clouds of electrons and magnetism ejected by distant galaxies and the glow of radiation from the Big Bang.

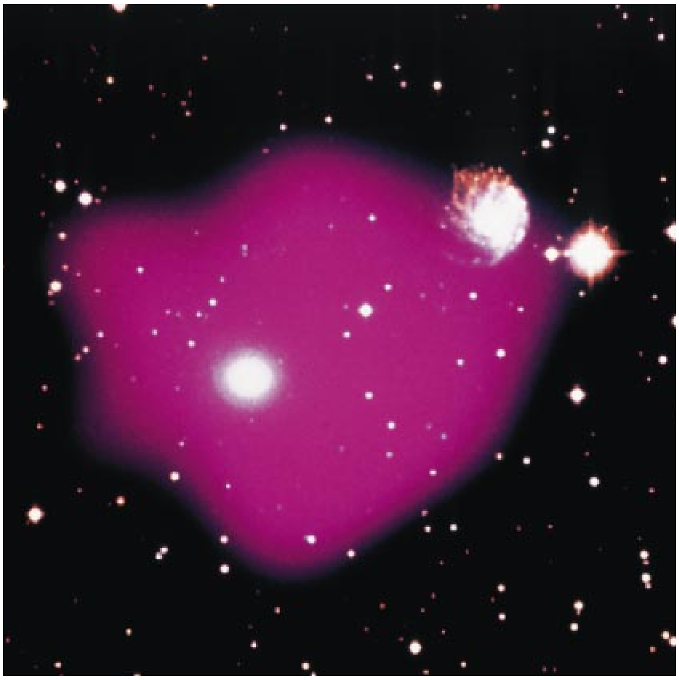


Fig. 1.3 *Clusters of galaxies contain pools of ultrahot gas that are 'visible' only at X-ray wavelengths. This image combines an optical photograph of the cluster centred on the galaxy NGC 2300 with an X-ray view of the same region of sky (magenta). The pool of X-ray emitting gas is at a temperature of 10 million degrees, but is too tenuous to destroy the galaxies that swim in it. By combining multi-wavelength views, astronomers can learn more than each individually reveals. Optical observations can indicate the gravitational pull of these galaxies: it is not enough to trap the hot gas detected at X-ray wavelengths. So the cluster must contain a huge amount of 'dark matter', which is invisible at any wavelength.*

Visible light is radiation of an 'intermediate' wavelength – about 500 nanometres (one nanometre is a millionth of a millimetre). In everyday terms, the waves are certainly short: over a hundred wavecrests would be needed to span the thickness of this page. The human eye perceives light of different wavelengths as the various colours of the rainbow: red light has the longest waves, around 700 nanometres from crest to crest; and blue-violet is the shortest, with wavelengths of about 400 nanometres. Although these limits to visible light dictate what the human eye can see at the telescope, professional astronomers now use light-detectors that cover a rather wider span. 'Optical astronomy' is generally considered to cover the range from 310 to 1000 nanometres (1 micrometre).

Radiation with shorter wavelengths is invisible to the eye. The range of radiations with wavelengths from 310 down to 10 nanometres is the *ultraviolet*. These are the rays in sunlight which tan our skins; for the astronomer, they are the 'light' from the hottest stars. During its passage through space ultraviolet radiation is imprinted with invaluable information about the tenuous gases between the stars.

At shorter wavelengths than the ultraviolet are the *X-rays*, whose crest-to-crest distance ranges from 10 down to only 0.01 nanometres – the latter is about one-tenth the size of an atom. X-rays from space are the hallmark of superheated gases, at a temperature of over a million degrees. X-ray sources can be the hot gases thrown out by exploding stars, or rings of gas falling down on to a pulsar or a black hole; they can be the hot gases of a quasar explosion, or the huge pools of gas which fill whole clusters of galaxies (Fig. 1.3).

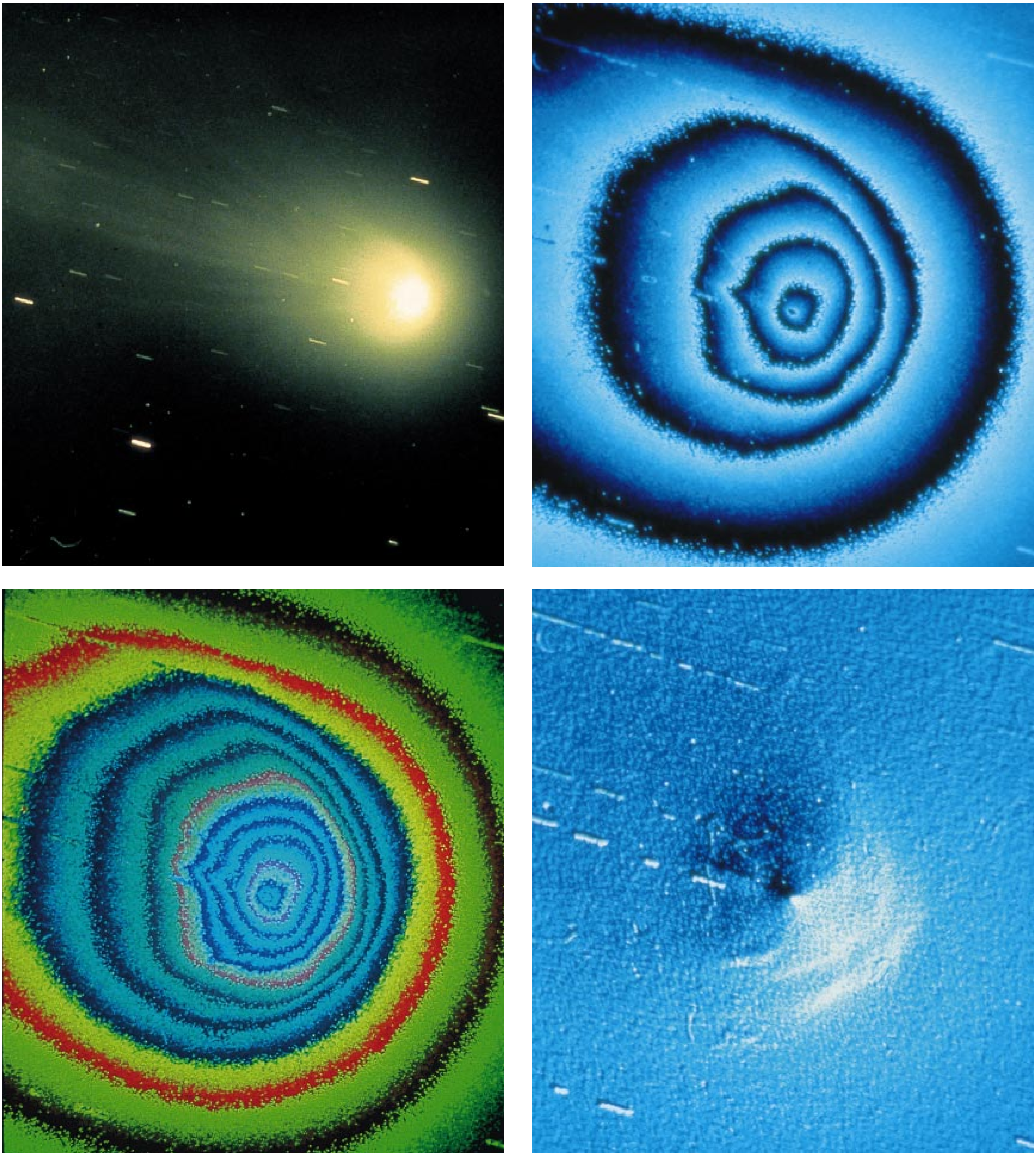
Even shorter are the *gamma* rays – a name which encompasses all radiation whose wavelength is less than 0.01 nanometres. These come from the most action-packed of astronomical objects: from the compact pulsars, and the superexplosions of distant quasars. And gamma rays can spring from nuclear reactions, in regions of space where tremendously fast electrons and protons cannon into atoms in space and provoke nuclear reactions similar to those in the artificial particle accelerators which physicists use to probe the ultimate constituents of matter.

Moving the other way in wavelength, to radiations longer than those of light, we come into the realm of the infrared. These rays have wavelengths between 1 micrometre and 1 millimetre. We think of infrared in everyday life as being heat radiation – the rays from an electric fire, for example. For astronomers, infrared radiation is the signature of the cooler objects in the Universe. An electric fire, at a temperature of a few hundred degrees Celsius, is rather cool on the cosmic scale, where an average star has a temperature of several thousand degrees and some gas clouds have multi-million degree temperatures. Objects at room temperature produce infrared radiation too. We are constantly surrounded by this radiation on Earth, so we do not notice it. But an infrared astronomer can pick up the radiation from a planet which is at everyday temperatures, and even below.

In fact, all objects produce radiation of some kind, and the lower the temperature the longer the wavelength of the resulting radiation. The hot filament of a light bulb naturally glows visible light; an electric fire with shorter wavelength infrared; and our bodies with longer wavelength infrared. Objects which are cooled down until they almost reach the absolute zero of temperature (–273.15°C) emit infrared radiation so long that it technically falls into the region of radio waves. Our view of the sky at different wavelengths is in many ways a portrait of different temperatures; and to the astronomer it makes more sense to measure temperatures upwards from absolute zero – instead of the rather arbitrary Celsius system which is based on the melting point of ice and the boiling point of water at sea-level on our own planet. *Absolute temperatures* thus start at absolute zero: 0 K – where the symbol K stands for degrees Kelvin, named after the physicist Lord Kelvin who first realised the advantages of using absolute temperatures in science. The melting point of ice (0°C) is about 273 K; room temperature roughly 300 K; and the boiling point of water about 373 K – to convert Celsius temperatures into absolute, add 273.15. The absolute scale is actually easier to visualise in one way, because it has no negative temperatures – nothing can be colder than absolute zero.

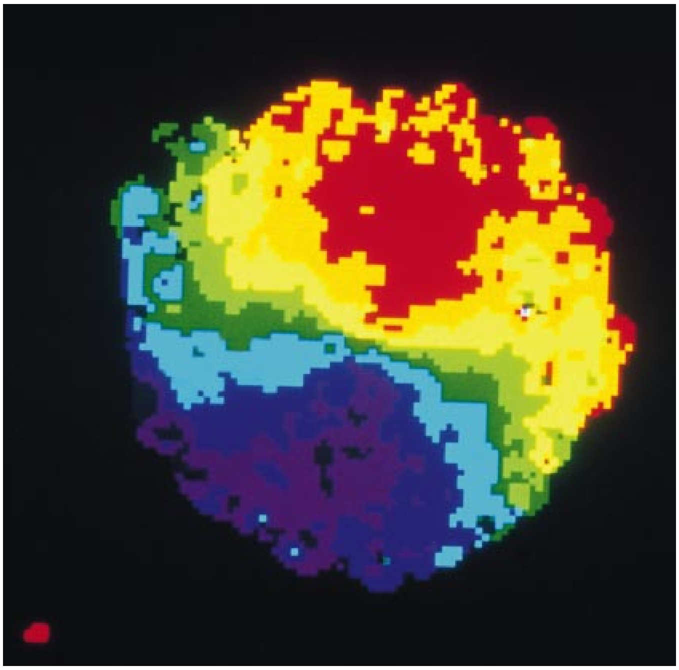
Infrared astronomers can 'see' cool clouds of dust in space, which are invisible at other wavelengths. These hidden dust clouds are the spawning ground for new stars, and infrared astronomers are privileged to see the first signs of starbirth.

Beyond the region of the infrared lies the last type of radiation. *Radio waves* cover a huge range of wavelengths: technically, they are radiation with a wavelength greater than 1 millimetre. Radio astronomers regularly observe the sky at wavelengths of a few millimetres or a few centimetres, but a few radio telescopes are designed to pick



Figs. 1.4-1.7 *'New astronomy' techniques of computer processing have been applied here to an old photograph of Halley's Comet, to bring out hidden details. The original photograph,* **Fig. 1.4** *(top left), was taken in Egypt on 25 May 1910. It shows details in the tail, but relatively little of the structure of the bright head. Four photographs taken that night have been scanned by a small light spot, and their electronic images added by computer to produce the remaining displays (each of which also shows four sections of several star images, trailed as the camera followed the moving comet). In* **Fig. 1.5** *(top right), brighter levels of the image have been coded by paler shades of blue, up to a level (white) where the coding jumps back to black, and then works up to white again. A succession of such jumps produces the dark and light fringes, like contour lines, surrounding a peak at the brightest, central part of the comet's head. This technique shows clearly a small jet, extending behind (to the left of) the head.* **Fig. 1.6** *(lower left) shows the same data, but with many more contour levels, and coded in several colours. The extra contours help to indicate the limited extent of the jet. The apparently three-dimensional image,* **Fig. 1.7**, *has been made by shifting the electronically stored image slightly, then subtracting the shifted image from the original. The comet's head appears as a peak, lit from the lower right, with apparent height indicating brightness. The technique reduces large scale contrasts, and emphasises small scale details. As well as the jet, Fig. 1.7 reveals bright arcs of gas in front of the comet's head (lower right), which are not easily seen in the other representations of the photograph.*

Fig. 1.8 *Colour-coding for velocity reveals how galaxy NGC 1073 is spinning. Regions moving away from us most rapidly are in red, those moving towards us at highest speed are in purple. Intermediate velocities are in orange, yellow, green and blue. These radio observations were made at a wavelength of 21 cm, which is emitted by hydrogen gas in the galaxy. Any motion of the gas along the line of sight causes a slight change in the wavelength, by the Doppler effect. The galaxy is tilted along a line from lower left to upper right, where the velocities towards or away from us reach their maximum values.*



up waves as long as several metres – or even several kilometres. Natural radio broadcasters in the Universe are usually places of unbridled violence, where high-speed electrons – negatively charged subatomic particles – are whirled about in intense magnetic fields.

The telescopes used to observe and detect these radiations are described in the odd-numbered chapters. The results themselves are shown in the even-numbered chapters, with the images obtained at different wavelengths displayed as pictures. These images are routinely stored in a computer, and processed in a wide variety of ways, as discussed in more detail in Chapters 3 and 7.

Using the imaging-processing capabilities of the computer, displayed on the screen, astronomers can employ colour coding to bring out the mass of information in each image. Colour in reality comprises light of different wavelengths. When images are obtained at a wavelength in, for example, the X-ray or radio range, colour has no real meaning, and we can use colour coding in a variety of new and exciting ways (Figs. 1.4–1.7). Colour is employed in three main ways in this book.

Observations at different wavelengths, combined into a single image, can be colour coded according to the wavelength. This technique is often used in infrared astronomy, where astronomers make observations of the same object at different wavelengths to reveal differences in temperature. Blue generally represents the shortest-wavelength view, green an intermediate wavelength and red the image at the longest wavelength.

Alternatively, colour coding can show velocity. The speed of a gas cloud is revealed in observations of a single spectral line from atoms or molecules of gas, usually obtained at radio wavelengths. By convention, gas coming toward us is shown in blue, and the colours shade through to red for gas moving away (Fig. 1.8).

But colour coding is most commonly used to show intensity. This technique is widely used at all wavelengths – including optical, when black-and white-images are processed by computer. We can assign different colours, chosen at will, to the various levels of brightness in the picture. The technique is now pretty familiar not just to astronomers but to anyone who watches a pop video!

The results are not only picturesque. They overcome one of the problems of photographic representation, that it is impossible to show details in both the faintest part of a galaxy or nebula, and the brightest – which may be over a thousand times more brilliant. If the former are shown in a photograph, the bright regions are 'burnt out'; while a short exposure to reveal details in the bright regions would not show the faint parts at all. Intensity colour coding shows details of both bright and faint regions simultaneously, in different colours.

The new images often resemble works of art, with the Universe's natural artistry aided by the imagination of the astronomer at the computer. But the astronomer's main task is not to capture the unseen beauty of space, but to use this new information to help understand the structure and scale of the Universe, and how it is changing as time goes by.

In relation to the modern view of the Universe, our planet Earth is a mere speck along with the other eight planets circling the Sun. The planets range in size from Pluto, whose diameter is one-sixth of Earth's, to Jupiter with a diameter of eleven Earths. Saturn is almost as large as Jupiter, and these 'giants' of our Solar System are orbited by 18 and 16 moons, respectively.

Despite the size of the giant planets, they lie so far away that astronomers find it difficult to see details on them. The Earth orbits the Sun at an average distance of 150 million kilometres, but Jupiter's orbit is over five times larger, and Saturn's nearly twice as big again. So these worlds appear very small in our sky: although our unaided eyes can see them shining brightly in reflected sunlight, they seem to be no more than points of light. It needs a telescope to show their globes, and Saturn's encircling girdle of rings.

Astronomers measure the apparent size of objects in the sky in terms of *degrees of angle* (°), and their subdivisions *arcminutes* and *arcseconds*: there are 60 arcminutes to one degree, and 60 arcseconds to one arcminute. This traditional system is undoubtedly cumbersome, but it becomes easier to understand if we take some examples. The entire sky is 180° across, from one horizon up to the zenith and down to the opposite horizon. Most of the traditional constellation patterns are around 20° across: the figure of the 'hunter' Orion (Fig. 4.2), for example, stands 15° tall. The Moon is surprisingly small. Because it shines so brightly, and appears large when it is near the horizon, the Moon looks as though it should cover quite an area of sky; but in fact it is only half a degree across (30 arcminutes). It would take over three hundred Moons, put side-by-side, to stretch across the sky.

Our eyes cannot see details any finer than one or two arcminutes (about 1⁄20 the size of the Moon), and the planets

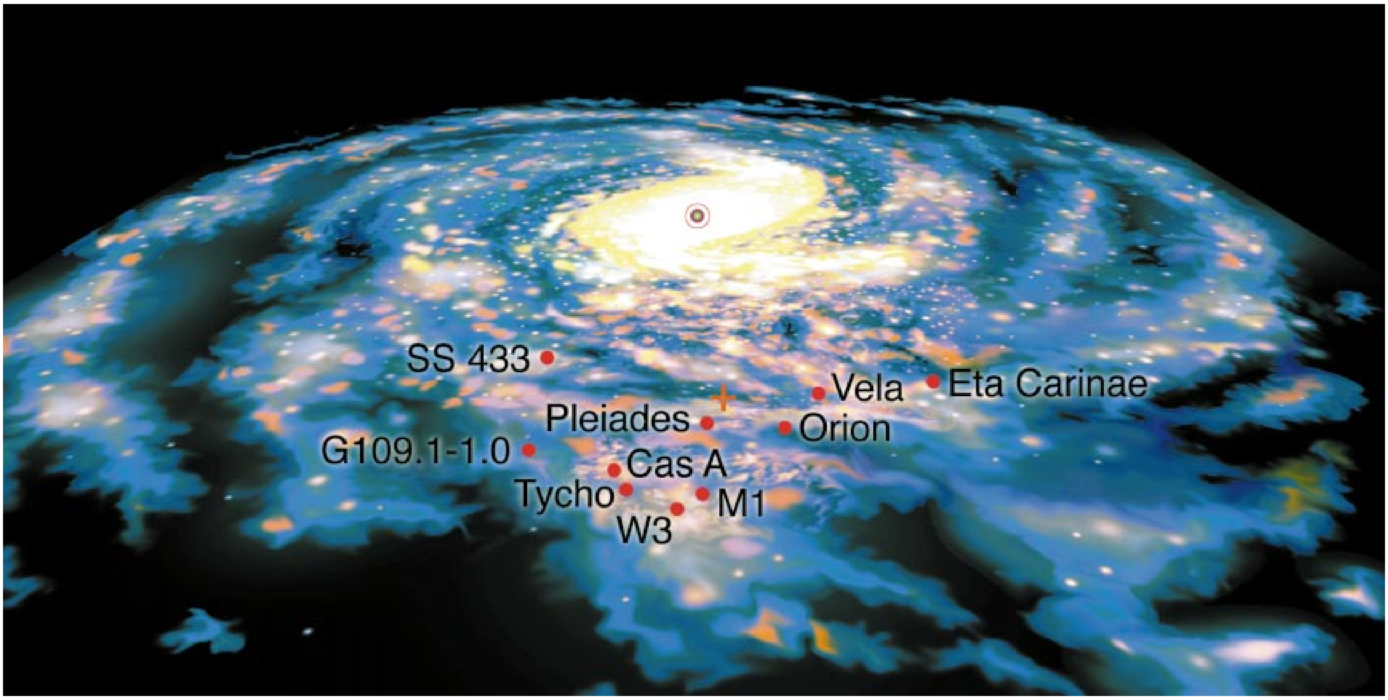


Fig. 1.9 *On the outskirts of the Milky Way Galaxy lie the Sun and Solar System (marked as +), which feature in Chapter 2. Other inhabitants of the Galaxy appear in later even-numbered chapters. Chapter 4 includes the starbirth regions W3 and Orion, the powerful young star Eta Carinae and the Pleiades (a clutch of newly-born stars). Supernova remnants, the gaseous remains of long-expired stars, are featured in Chapter 6: G109.1-1.0, SS 433, Cassiopeia A, Tycho's supernova remnant, the Crab Nebula (M1) and the Vela supernova remnant. Chapter 8 covers the Milky Way itself, and the galactic centre (circled), some 25 000 light years from the Sun.*

all appear smaller than this. Even when the Earth is closest to Jupiter, the giant planet appears just under an arcminute across and Saturn only 20 arcseconds in size. Even the largest optical telescopes on Earth can see detail only as fine as an arcsecond or so, whatever magnification is used, because the images are blurred by Earth's atmosphere. So, ironically enough, astronomers have problems in examining even our nearest neighbours in space. These worlds are close enough, though, to be reached by unmanned spaceprobes, and the last three decades have seen their details revealed by dozens of these craft – from Mariner 10 which visited scorched Mercury, closest to the Sun, to the two Voyagers which have photographed in amazing detail four giant planets: vast Jupiter, ringed Saturn, tipped-up Uranus and remote Neptune.

On the everyday scale, Neptune is a very distant world. Lying some 4500 million kilometres away, it is so far off that the radio signals from Voyager 2 – travelling at the speed of light – took over four hours to reach the Earth. Until 1999, Neptune is the outermost planet, because Pluto follows an oval path that has currently brought it closer to the Sun than Neptune.

But even Neptune's distance shrinks into insignificance once we look out to the stars. The nearest star, Proxima Centauri (part of the Alpha Centauri star triplet), lies a quarter of a million times farther away than Neptune and Pluto – over 40 million million kilometres. Such distances are just too large to comprehend, and the figures themselves become unwieldy in size.

Astronomers cope with star distances by discarding the kilometre as their standard length. A more convenient unit is the distance that a beam of light (or any other radiation) travels in one year. This standard length, the *light year*, works out to just under ten million million kilometres. So Proxima Centauri is about 4 1/4 light years away. With this new unit, star distances become more comprehensible. We can compare star distances, and construct a scale model in our minds, even if the distances themselves are too large for the human mind to encompass.

The bright star Sirius lies about twice as far away as Proxima Centauri, at 8.6 light years. It too is nearby on the cosmic scale; its neighbours as seen in the sky, Betelgeuse and Rigel in Orion, are far more distant, lying at 310 and 910 light years. They only appear bright in our skies because they are truly brilliant stars, each shining as brightly as thousands of Suns.

Optical astronomers have a rather archaic system for describing the apparent brightness of stars and other celestial objects as seen from the Earth. In this *magnitude* system, the faintest stars visible to the naked eye are of magnitude 6; while brighter stars have *smaller* magnitude numbers. A star of magnitude 1 – like Betelgeuse – is a hundred times brighter than a magnitude 6 star; the brightest star, Sirius, is ten times brighter still, and it has a negative magnitude: –1.4. Going brighter still, the Sun has a magnitude of –26.7!

Our Sun is, in fact, a typical star – middle-weight, middle-aged – born some 4600 million years ago. It appears exceptionally bright simply because it is near to us, and it is special to us on Earth because it supplies us with bountiful light and heat. The Sun is special to astronomers too, because its proximity means that we can study an average star in close-up detail. Conversely, investigations of other stars which are younger and older can tell us of the Sun's past, and of its likely future.

Starbirth occurs because space between the stars is not entirely empty. There is tenuous *interstellar gas*, composed mainly of hydrogen, with tiny flecks of dark solid dust

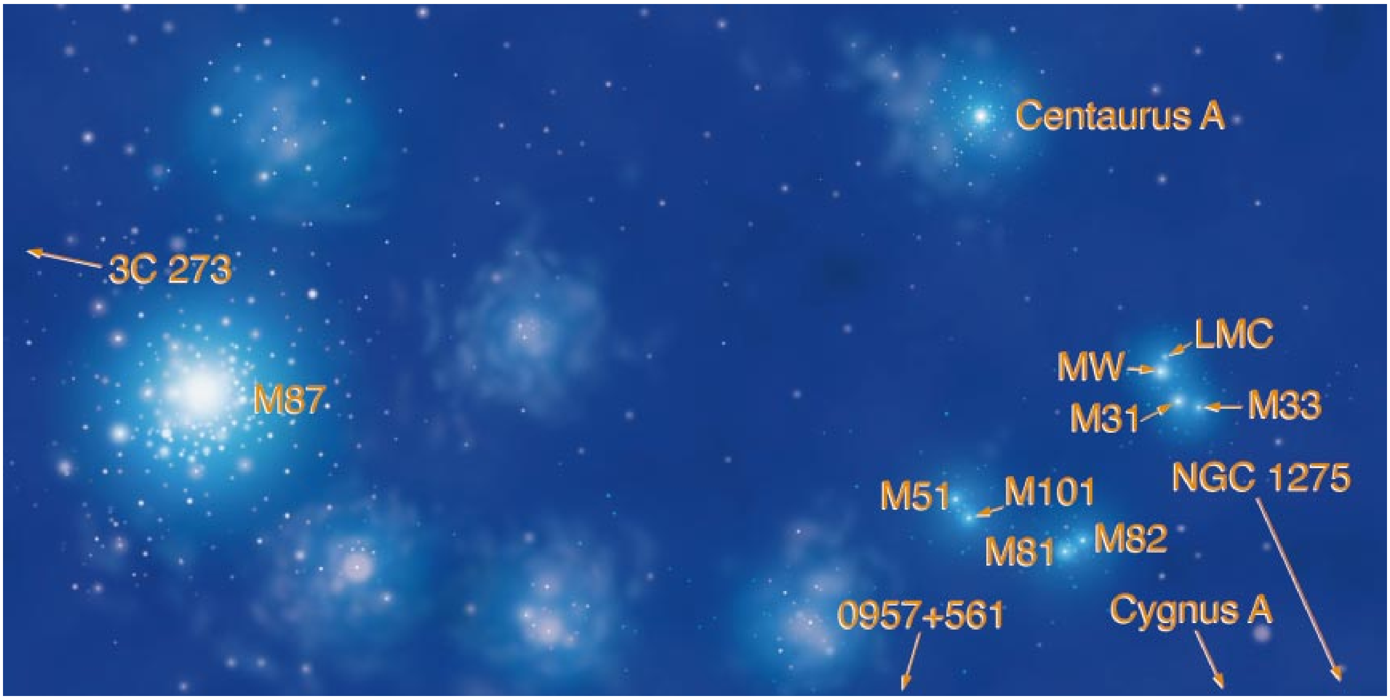


Fig. 1.10 *Our Galaxy, the Milky Way (MW), and its companion the Large Magellanic Cloud (LMC) are scrutinised in Chapter 8. With the Andromeda Galaxy (M31) and the smaller spiral M33 they comprise the major galaxies of our Local Group. Two neighbouring groups include M51, M81, M82 and M101. Chapter 10 covers these six relatively normal galaxies. Further afield lie more exotic cosmic beasts, described in Chapter 12. They include the radio galaxies Centaurus A, M87 (in the Virgo Cluster), NGC 1275 (in the Perseus Cluster) and Cygnus A, along with the quasar 3C 273 and the gravitational mirage seen as the 'twin quasar' (marked as 0957+561).*

mixed in. In places, this gas and dust is compressed into sombre dark clouds. Within these, the interstellar matter is compressed by its own gravity into gradually-shrinking spheres, which heat up until they burst into radiance as new stars. The brilliant young stars light up the surrounding tatters of gas as a glowing *nebula*, like the famous Orion Nebula (Figs. 4.10–4.17), a mass of seething fluorescent gases lying some 1600 light years from us.

Eventually, all stars die. They lose their outer gases, either in gentle cosmic 'smoke rings' or in violent supernova explosions; while their cores collapse to form tiny, compact – and very strange – objects. These cores weigh roughly as much as the Sun, but they can shrink down to the size of a planet to form a *white dwarf* star; even smaller as a *neutron star* or pulsar; or even collapse completely to form a *black hole*, whose gravitational field is so powerful that no radiation can escape from it.

Stars are grouped into huge star-islands, or *galaxies*. Our Sun (and the other stars and nebulae mentioned so far) is a member of the *Milky Way Galaxy* (Fig. 1.9), a collection of around 200 000 million stars – along with nebulae and collapsed star-corpses. The stars are arranged into a huge disc, some 100 000 light years across, all orbiting around the Milky Way's centre where the disc of stars is thicker. Our Sun, with its family of planets, lies about two-thirds of the way to the edge of the Galaxy.

The Milky Way's nearest neighbours are two smaller galaxies, the Large Magellanic Cloud and the Small Magellanic Cloud. They can only be seen from the Earth's southern hemisphere, and the two Clouds were first described by the Portuguese navigator Ferdinand Magellan as he circumnavigated the Earth in 1521. Farther away lies the great Andromeda Galaxy, dimly visible from the Earth's northern hemisphere in autumn and winter months. At 2¼ million light years distance, it is the farthest object we can see with the naked eye.

But telescopes can reveal many other, much more remote galaxies (Fig. 1.10), their intrinsic brilliance dimmed by their enormous distances. While the Andromeda Galaxy has a magnitude of five, rather brighter than the naked eye limit, modern telescopes, coupled with sensitive electronic detectors, can 'see' galaxies almost a billion times fainter, around magnitude 30. Such galaxies lie over 10 000 million light years away from us. Within this vast region of space, the latest telescopes can pick out thousands of millions of galaxies. Many of them are clumped together into huge clusters, each cluster stretching over millions of light years.

Amongst this multitude of galaxies, a few display an intensely bright core, the site of a stupendous explosion – an explosion which can be a thousand times brighter than the galaxy itself. If the galaxy is extremely remote we cannot see anything but this central explosion – and astronomers have called such objects *quasars*. These exploding galaxy cores are so bright that astronomers can see them farther away than any other object in the Universe. The most distant quasars lie some 12 000 million light years away from us. The quasar explosions generate huge quantities of radio waves and X-rays too, and some of the many radio sources and X-ray sources discovered recently are probably quasars even more remote.

Centuries of observations with the eye and optical telescope have revealed the framework of the Universe, but their information on the planets, stars and galaxies has turned out to be only superficial. The story of the life and death of stars, of galaxies and of the Universe itself has only become apparent in recent years, with the advent of the new astronomy.