8 The science and beauty of nebulae

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Spectacular astronomical images of clusters of blue stars deeply embedded in vibrant clouds of dusty gas have become abundant over the last decade. Collected using space telescopes and a new generation of ground-based instruments, these pictures awe us with their glorious landscapes of multicoloured gas sculpted to form swirls and filaments. Black misshapen blobs and tenuous drifts of dust are seen in silhouette against the glow of the gas, and the whole is peppered with aggregations of brilliant, bright blue stars. Many of these vistas are by now familiar to the layperson (for example, the 'pillars of creation' shown in Figure 8.1), who is able to appreciate their beauty without necessarily requiring comprehension of what is being portrayed. In this chapter I shall revisit such images with the aim of deconstructing them in order to explain the science that underlies the beauty.

The interstellar medium

We live in a spiral galaxy, flattened out to form a giant frisbee slowly wheeling in space, with our own Sun just one of two hundred thousand million stars all bound together by their mutual gravity. A central bulge of stars is surrounded by an extended flat disc that contains the spiral arms, which are traced by conspicuous clusters of young blue stars (see the Whirlpool Galaxy, shown in Figure 8.2). We live within such a spiral arm, about halfway from the centre to the edge of our own galaxy, the Milky Way. The clusters of stars most apparent in our night sky – such as the Pleiades, or the double star cluster in Perseus – are prominent because they are physically close to us, located in neighbouring spiral arms. As we will learn later, blue stars such as those seen in these clusters are hot, massive, and the most recently formed. But whilst they are the

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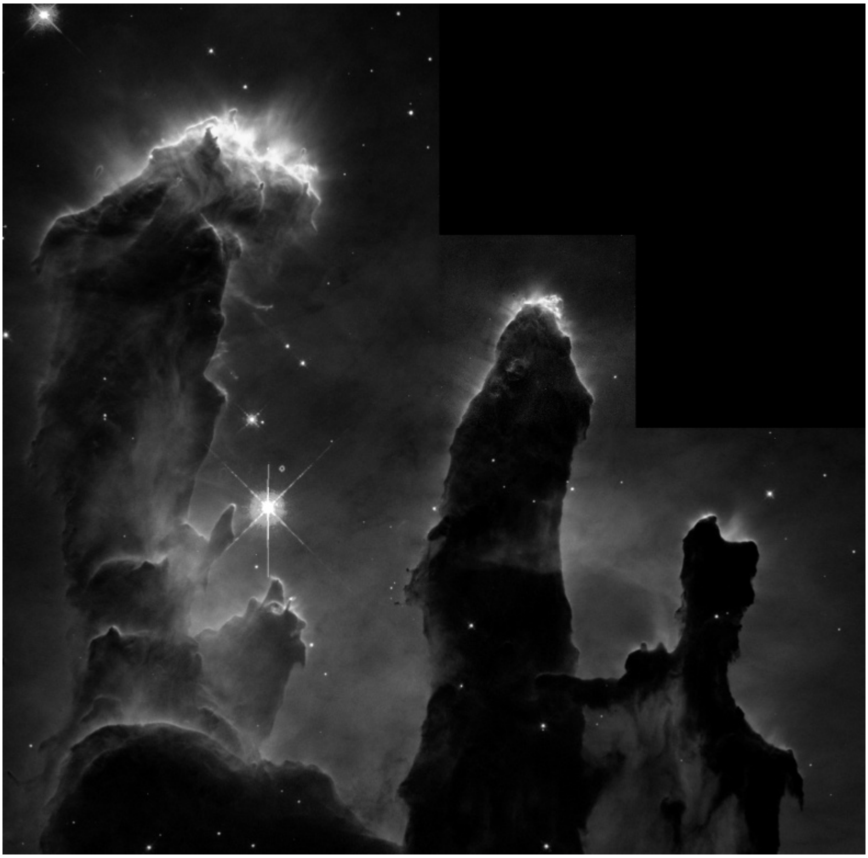

FIGURE 8.1. The 'pillars of creation' in the Eagle Nebula. Long towers of interstellar gas and dust emerge from the walls of the Eagle Nebula seen in silhouette against the glow of background emission. For colour images of the figures appearing in this chapter, see www.darwin.cam.ac.uk/lectures/beauty.
Credit: NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University).

most obvious feature to draw the eye and delineate the structure, a galaxy does not consist solely of stars. It is easy to dismiss the void between the stars as being only empty space; even though it might be millions of times emptier than the best vacuum that we can achieve in a laboratory on Earth, it is not completely devoid of matter. Interstellar space abounds with atoms and molecules of gas, alongside tiny solid particles that we

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FIGURE 8.2. The 'Whirlpool' spiral galaxy. Our face-on view of the disc of the 'Whirlpool' spiral galaxy clearly shows the spiral arms delineated by bright blue star clusters, pink emission nebula and dark obscuring dust lanes.
Credit: NASA, ESA, S. Beckwith (STScI), and the Hubble Heritage Team (STScI/AURA).

refer to as 'dust'. This material is very sparsely distributed – perhaps only a few dozen atoms would be contained in a scoop of space the volume of a can of drink – but a lot of matter can be tucked away within the enormous volumes lying between the stars. This gas and dust comprise what we call the *interstellar medium.*

All the gas within our galaxy has a mass that is only around a tenth of that contained in stars. Most of the gas is primordial hydrogen and helium, formed at the very beginning of the Universe but not yet incorporated into the formation of the stars of our Milky Way. This is mixed with a trace of heavier elements, such as carbon, oxygen and iron, which were cooked up in the interiors of massive stars and then flung out into space when the stars exploded at the ends of their lives. These gas clouds of interstellar matter are of fundamental importance to us all, as they are the reservoir from which new stars are born – along with the planets around those stars and, of course, any life forms living on those planets. It is the interstellar medium that forms the focus for this chapter: a story that concerns not only stars, but also the gaseous clouds that lie in between the stars in space, which are revealed in *nebulae*.

Some of this gas is accommodated in a widespread inter-cloud atmosphere, very sparsely distributed and at temperatures of millions of degrees, so incredibly hot that it cannot be detected other than at X-ray wavelengths. Invisible and transparent at lower energy wavebands, this X-ray gas is not relevant to our discussion. Embedded within the hot atmosphere are far cooler, denser clouds that contain a comparable amount of the mass but inhabit a far smaller volume. Such diffuse cold clouds encompass the entire disc of our galaxy and extend out beyond the visible spiral arms. The gas in these clouds is so cold (at temperatures of tens to hundreds of degrees above absolute zero) that matter is mostly in the form of neutral hydrogen atoms, detectable only in the radio waveband and again transparent to our eyes. But if the neutral atoms are heated by a flood of energetic ultraviolet photons from a nearby young star, they store and re-radiate this energy as light, causing the gas to glow with radiation. It is at this point that the gas clouds become apparent as the distinctive pinky-red nebulae that accompany the blue star clusters lining the spiral arms (Figure 8.2).

An aside on the colours in the images

The only way astronomers can learn about distant cosmic objects out beyond the Solar System is through the light they emit. Everything we know about the stars, nebulae and distant galaxies is inferred from how we analyse and interpret that light. There are many colours of light, each corresponding to a different wavelength. In the optical band, this is easily

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demonstrated by the way that sunlight can be dispersed into a rainbow using a prism. Beyond this rainbow lie the exotic realms of the infrared, the radio, the ultraviolet and X-ray wavebands, all containing far more colours that are completely undetectable except with specialist telescopes and instruments. All stars such as the Sun emit many colours continuously to give a *spectrum* of colour. Individual atoms contained in a diffuse cloud emit light very differently, however, giving off only very specific colours, each of a particular wavelength.

An atom is composed of a cloud of electrons surrounding a central more massive nucleus; these electrons can only inhabit specific energy levels, like books that are constrained to sit only on shelves in a bookcase. If illuminated by a source of energetic light, an atom can absorb energy and store it by temporarily raising one or more of its electrons to higher energy levels. When the energy is released later in the form of a photon of light, the amount available depends on the difference between the electron energy levels. This in turn is a well-defined quantity, crucially dependent on the atomic structure of that element. Thus the photons liberated by an atom can only have certain energies, which correspond to specific wavelengths. In this way, the colours radiated by gas atoms of each element produce a unique fingerprint, revealed in sharp spikes of colour within a spectrum known as emission lines. Analysis of these lines can tell much about the chemical composition of an emitting cloud, and the details of relative strengths of lines of different colour can inform us about the density and temperature of the gas. The nebulae in images of all galaxies are predominantly a pinky-red, as it is the dominant colour emitted by excited hydrogen, by far and away the most common element in the Universe. Additional colours such as blue and green are produced by atoms of many other common elements, including nitrogen, oxygen, neon and sulphur.

When using images to study astronomical objects, astronomers do not obtain the data with a camera that collects all the light at once. Instead, separate images are taken of the object, each viewed through a succession of filters to isolate specific bands of colour. Wide filters let a broad range of colour through and are used for imaging the stars, which emit colour at a continuous range of wavelengths: the balance of light between red, green and blue wide filters can allow us to distinguish the colours of

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the stars. Narrow filters are used to isolate specific colours that can trace the light from particular excited atoms within a gas cloud. Most commonly a narrow red filter is used to detail the distribution of the hydrogen present, although many other wavebands are commonly in use. The final image is compiled from matching observations which are usually obtained through a range of both broad and narrow filters, all of which are colourized appropriately before being combined. The variety of colours represented will thus depend on how many different filters were used to form the composite. The simplest details are obtained with a wide blue filter (to pinpoint the blue stars) and a narrow red filter (to map out the accompanying gas cloud); far more complex multi-coloured maps are only possible with long dedicated observations through a whole host of different filters.

Many of the visible-light images that are publicly available have been constructed with a view to faithfully recreating the 'true' colour of the light emitted. The brightness of the diffuse gaseous structures is usually exaggerated, as only short exposures through a wide filter are necessary to bring out the location of bright stars, but much longer exposures are required to include faint wisps of a surrounding nebula. This means that viewing a nebula by eye, even through a very powerful telescope, is far less spectacular than the images might suggest. The mismatch is compounded by the fact that the cells in the retina of the eye that are most sensitive to faint diffuse structures are those that are least responsive to colour. Obviously, images that are collected from other (non-optical) emission, such as the infrared or X-ray, must be portrayed using 'false' colours so we can view them. When such images are accommodated within a visible image for comparative purposes, it can lead to a portrayal that may not be 'true' but is at least accurate in spirit. For example, if an image incorporates near-infrared light, this band would most likely be coloured red, and the colours given to the optical images shifted blueward, retaining an informative and coherent sense of the comparative colour.

Emission nebulae

A typical pink emission nebula in our galaxy is the Rosette Nebula (Figure 8.3). Lying about 5,000 light years distant from Earth (where one light year – despite the name! – is a distance of 9.5 million million

FIGURE 8.3. The cavity in the Rosette Nebula. A central cluster of young stars illuminates the layers of gas and dust in the nebula around them.
Credit: NASA, the DSS-II and GSC-II Consortia.

kilometres; the distance that light travels in one year), this roughly spherical nebula spans around a hundred light years from one side to another. It is thus an immense structure, particularly when one considers that the Sun's nearest neighbour is around four light years away from us. A cluster of hot blue stars dominates the centre of the pink Rosette. These condensed from denser pockets of material within a diffuse cloud some four million years ago, and they now illuminate and heat the surrounding remnants of gas to give off hydrogen's characteristic pink glow. The young blue stars themselves inhabit a low-density cavity within the nebula, caused as their heat warmed the gas in the immediate vicinity so that it expanded and pushed back the surroundings to create a bubble. This effect is enhanced both by the radiation pressure of the stellar light (whereby energetic photons impart a push on matter) and by the physical winds of charged particles that stream continually from the surfaces of young stars. These both act to erode the walls of the newly formed cavity around the stars.

Introducing dust

Not only are there gas atoms occupying the space between the stars, but mixed in with the gas are small solid particles, called dust grains. With a characteristic size of around one micro-metre, these are about one-thousandth the width of a human hair, or the size of particles in cigarette smoke. The dust is made of carbonates (mostly in the form of graphite) and silicates – literally, soot and sand – and, if very cold, the grains can be coated with the frozen ice of water, ammonia or carbon dioxide. The total mass in such grains is only about one hundredth of that contained in all the stars. Despite the tiny grain size and low total mass, once collected into clouds that can stretch from tens to hundreds of light years across, the cumulative effect of the dust is sufficient to completely block the light from stars or gas clouds in the background. This effect is apparent from the striking dark rifts seen alongside the spiral arms of an external galaxy (Figure 8.2); as the dust clouds are largely confined to the plane of the disc, they block out so much light that a spiral galaxy seen edge-on can appear as if cut in two. Given that we live in the disc, we have an edge-on view of our own galaxy, which is why its stars are spread across the sky to form the band we call the Milky Way. The obscuration produced by the accompanying dust clouds is particularly pronounced in the southern hemisphere, where the night sky is directed towards the constellation of Sagittarius and the centre of our galaxy. Broad swathes of obscuration are apparent against the band of the Milky Way, and individual structures such as the Coalsack Nebula (close to the constellation of the Southern Cross) create large dark voids in the backdrop of stars.

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The chemistry for the creation of dust grains requires a reasonably cool environment, such as that found in the extended outer layers of a star in a late stage of its evolution. The dust is then dispersed into the local interstellar medium when the star blows itself apart at the end of its life. The dust and gas coexist, with the grains embedded deep within the cold diffuse clouds; thus, the dust is another important component of nebulae. When dust is mixed with the cold gas in particularly dense concentrations, the high level of obscuration make such pockets appear as small opaque knots, known as globules, against the pink glimmer from the gas. The high density of dust grains in these small clouds not only prevents the light of the nearby stars from passing through the cloud, but the absorption also protects the core of the cloud from the stars' heat. Without an internal heat source, the temperature in the densest parts of the cloud can drop to only a few degrees above absolute zero. Under these conditions, the atoms in a cloud join up to form molecules on the surfaces of the grains – most commonly hydrogen, but also many more complex molecules such as water, ammonia and methanol. These *molecular clouds* have typical sizes from a few to fifty light years, and contain a mass of up to one thousand times that of the Sun. Although the molecular clouds are denser than, and embedded within, the diffuse clouds, they are still nowhere near as dense as the air that we breathe. In the images, the silhouettes of the dark globules very often show a jagged structure, which reveals how the light and winds from the nearby massive stars have a harsh corrosive effect that erodes from the outside.

One of the most familiar constellations in the winter sky is Orion the hunter, clearly marked out by some of the brightest stars in the sky. Far less obvious to stargazers is the fact that Orion also marks the direction of a giant diffuse cloud, some 1,500 light years away, that stretches from shoulder to toe across the constellation. Its most obvious manifestation is at the Great Orion Nebula, which marks the position of the hunter's sword, and is the only emission nebula visible to the unaided eye. The full extent of the complex network of nebulae in this region is only revealed in deep telescopic images taken through filters that emphasize the light from excited hydrogen gas. One famous example is the Horsehead Nebula, which sits just below and to the

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side of Alnitak, the lowest of the three stars that make up Orion's belt. In the visible waveband, the presence of a lurking dust cloud can be sensed by a sudden depopulation in the number of background stars and the luminous pink glow that is emitted by gas streaming away at the edge of the cloud irradiated by starlight. An outcropping of dense dusty material produces the silhouette of the eponymous horse's head (Figure 8.4). The topside of the Horsehead Nebula has a crisp edge, which shows where the stellar winds and radiation are steadily carving into the cloud at the *working surface*. To the left along this edge a bright glimmer reveals where a young star is breaking free from

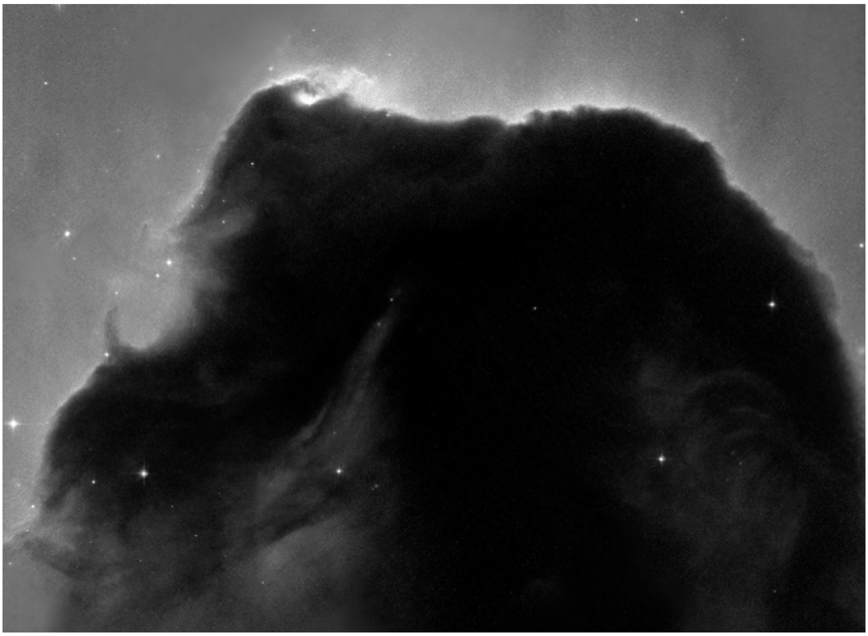

FIGURE 8.4. The top of the Horsehead Nebula. The 'Horsehead' is shaped from a cold dark cloud of gas and dust, illuminated by bright stars beyond the top of the image, which are also eroding gas at the top 'working edge' of the cloud. Stars seen through the cloud are clearly reddened in colour, and to the top left a new star is breaking free of its confines.
Credit: NASA, NOAO, ESA and The Hubble Heritage Team (STScI/AURA), with acknowledgement to K. Noll, C. Luginbuhl and F. Hamilton.

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the cloud: a first indication that star formation is associated with the denser, dustier regions of a cloud.

The stars seen through the cloud appear much redder in colour than those viewed along clearer lines of sight to either side of the cloud. As it diminishes the light from background stars, dust also changes the colour of that light, making it redder, by a process of scattering. Photons can collide with particles of dust and cause them to deviate from their original path and travel in random directions. Light is scattered most efficiently by particles of a smaller size than its wavelength; the typical size of interstellar dust grains means that they are most effective at scattering the bluer (smaller) wavelengths. So when a star's light passes through a dusty cloud en route to the observer, the blue colours of this light are preferentially scattered away and no longer reach us. Only the redder portion of the starlight emerges from the other side of the cloud. This scattering is a similar process to that which gives us red sunrises and sunsets here on Earth. When it is close to the horizon, we observe the Sun through more of the dense portion of our atmosphere (that closer to the Earth's surface), which results in increased scattering by molecules of air, and the blue light is lost; this turns the Sun much redder than when it is at higher altitudes. The effect is enhanced when the atmosphere contains extra localized scattering particles, such as ash or dust. During the day we see all the blue light that is continually scattered out of sunlight in all directions as our sky. In the same way that this scattered blue light renders the atmosphere visible to us here on Earth, scattered blue light can also render a dust cloud visible. A bright star that is not hot enough to excite the gas atoms to glow can still have its blue light scattered by dust, to reveal the surrounding cloud as a distinctly blue *reflection nebula*. The obvious blue hue of the Pleiades is due not just to the colour of the forty to fifty stars that make up the young cluster, but also to the way that their light is scattered by a neighbouring dust cloud. Other stunning examples include the Iris Nebula, where a dusty cloud morphs from a veil of obscuration to a glowing blue ghost around a bright star, and the Witch's Head Nebula, which scatters blue light from the nearby bright star Rigel to reveal its distinctive profile.

Infrared radiation from dust

The dust can, however, also be detected directly. The energy of the absorbed photons raises the temperature of dust grains to a few tens or hundreds of degrees above absolute zero. Objects at this temperature (including humans!) radiate brightly at infrared wavelengths, and so do the grains of dust. Thus, dark obscuring clouds that block the light of stars in optical images are incandescent when observed with an infrared telescope and their inherent structures and shapes are revealed. Given that the longer (i.e. the redder) the wavelength of light the better it can travel through dust relatively unimpeded, any infrared light given off by stars tucked inside dusty clouds can escape – unlike visible radiation. Infrared observations can thus penetrate through a dusty cloud to reveal new clusters of stars that are still forming deep within the denser, obscured parts of a nebula. It is also through the infrared emission that we can verify both the origin of the dust and the presence of the molecules. One of the largest and most luminous known stars is VY Canis Majoris, a red supergiant star near the end of its life. It is currently ejecting huge quantities of material from its outer layers into interstellar space, forming a large extended cloud. The distribution of the colours of the infrared light emitted provides information on the properties of the dust grains that produce the broad-band radiation, and prominent spikes of infrared colour can be identified with many different molecules, particularly carbon monoxide and water.

Many of the most dramatic features within a nebula are caused by stellar winds and light pushing on the dust grains at the working edge of the nebula. The smaller, lighter dust particles exposed to this are pushed away most easily; the more massive particles or those that are embedded in the very dense concentrations are least affected and most resistant to erosion. Nowhere is this more evident than in the heart of the Eagle Nebula, 7,000 light years away in the next inner spiral arm of our Milky Way. A cluster of stars formed at the core of a large dusty cloud of gas some five million years ago and are now surrounded by a cavity with glowing walls of gas, which is excited by the radiation from the hot young stars. Pillars protrude from these walls, and all point inwards in the direction of the star cluster; the most famous of these are known affectionately as the ‘pillars of creation’ (Figure 8.1). These long tall towers of cold gas and dust rise up to heights of ten light years and show up in silhouette against the glow of the background gas emission. The shape of these towering pillars is a characteristic signature of the erosion process. The energetic ultraviolet radiation lights up the exposed surface of a cavity wall, and heats it so that sparse diffuse gas is boiled away. Strong stellar winds and radiation also push on all the matter, and this steady erosion is resisted only by the coldest, densest clumps of gas and dust. Remaining in place, they can provide shelter much like an umbrella, shielding the less dense regions behind them from the corrosive effects of the stars. Thus protected, long towers of gas are left in the shadow of the densest clumps, while their surroundings are steadily burnt away. Such dusty pillars can be found in all nebulae; the Horsehead is one (Figure 8.4) and less prominent examples can be seen to the top right of the Rosette Nebula (Figure 8.3). All point radially towards the source of the radiation (the stellar cluster at the centre of the nebula). Even smaller outcrops along the sides of the pillars are shaped to form fingers pointing in the same direction. At the very top of each pillar, exposed material is continually eroded until only the very densest pockets are left behind to eventually break free and float as individual dense globules. Several can be seen escaping from the top of the left-most pillar in the Eagle Nebula (Figure 8.1). Each globule is much wider than the Solar System, and they provide the next step in the story of nebulae. To see where they lead us, we must move to the Great Orion Nebula in the sword of Orion, where a variety of similar features at a later stage of their development can be observed.

Star birth

The Orion Nebula is one of the greatest local star formation regions, ‘only’ 1,600 light years away from us. It was created when a star cluster carved out a cavity that has broken through the nearside edge of a dark molecular cloud, enabling us to peer inside. Infrared observations reveal thick layers of surrounding dust that hides the presence of at least a thousand very young stars. Imaging of the immediate environs of the most prominent of these – the Trapezium of stars well known to amateur

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observers – reveals isolated small dark globules with a flattened egg shape. They are seen either as opaque silhouettes against the bright hydrogen gas emission, or sometimes illuminated by the young stars. These dusty cocoons are the next stage in the development of the blobs that are evident in the Eagle Nebula and are left behind when all of the lighter, fluffier material around them was eroded away. Each cocoon has a size several times that of the Solar System. Denser than their surroundings, they are in the process of collapsing inwards under gravity and are becoming steadily more concentrated and thus opaque to visible light. Infrared observations that can peer into the cocoons show many to contain a single proto-star buried deep at the core: these dusty globules are where stars are born. As matter falls together under gravity at the very core of the cocoon, it gains energy and heats up; as more and more matter is accreted, the central condensation can reach temperatures of some millions of degrees. At this point the material at the centre is hot enough to commence nuclear fusion – the energy-producing process that powers a star and enables it to resist the further inward pull of gravity. A proto-star is formed, and soon it begins to pour out a combination of light, heat, jets and winds that will eventually break through the immediate surroundings to reveal the newly born star to the outside universe.

The formation of the star does not use all of the matter that constitutes its nest; it does not need to accrete all of the cloud to reach sufficient temperature to switch on. The remaining dusty material surrounds the star and forms a ring-shaped proto-planetary disc – or *proplyd*, a very early stage in the formation of a planetary system. When such proplyds were first discovered (in the mid-1990s) around many of the newly forming stars in Orion, it was the first concrete evidence that planetary systems around stars other than our Sun could be common. (Certainly, we believe that our own Solar System formed from a cocoon such as these, some 4.5 billion years ago.) A proplyd is shaped into a flat disc because it is not stationary. A globule will inherit any incipient rotation inherent in its parent cloud. The rotation speed is greatly amplified as it shrinks in size due to gravitational collapse, and the spinning mass of the cloud flattens out. The star at the core of the proplyd will be formed as a spinning body. As the proto-star begins to radiate, it erodes the cocoon and morphs it into a thick ring of gas and dust that will – over the next hundred million years or so – evolve into the accompanying planets. Whether the proplyds we observe in Orion will form planetary systems that really resemble our own is far less certain. The high-resolution images show that they are suffering heavy erosion from the outside as well. The energetic radiation and winds given off by the massive young stars forming the Trapezium are pushing on the gas and dust of the proplyds, shaping them more like wind socks or comet tails that stream away from the source of the blast. The outer layers of the proplyds are stripped such that any planetary systems formed would be made up of only a tight core of planets wrapped around their host sun.

Star death

Clearly the nebulae that we study reveal much about the connection between the interstellar medium and the formation of stars. But nebulae are, of course, also intimately associated with stars at the other end of their life cycles. Once a star has ignited at the centre of a cocoon, the whole of its existence is a battle against the inevitable inward pull of gravity. It supports itself against its collapse by fusing atomic nuclei of relatively low mass together, in a long and complicated chain of nuclear reactions. In this way the star both gradually stockpiles nuclei of much greater mass and obtains a source of internal energy to make it shine and to resist gravity. This continues until the star effectively runs out of appropriate fuel, which then leaves gravity to claim its victory. What happens to the star at that point depends mainly upon its mass.

Planetary nebulae

A star with a mass similar to that of our Sun can live for about ten billion years before the fuel supplies at its very core are depleted. There are various stages within its life cycle: while it spends most of its time most simply burning hydrogen to helium, in later years it swells to become a *red giant*. The star is not sufficiently massive or hot, however, to proceed significantly with the further fusion processes that produce more energy and create heavier elements. As the nuclear fusion dies away the gravity of the star begins to squeeze the inner core, causing it to collapse rapidly

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and heat up again as it does so. The collapse is halted when the outward pressure produced by the motion of the electrons in the densely packed material is enough to resist gravity, and the core forms a *white dwarf*. During its initial collapse the sharp increase in the core's temperature rapidly heats the outer layers of the star, and they are driven away in an outward wind, to form a surrounding bubble-like shell known as a *planetary nebula*. The uncovered white dwarf at its centre will eventually cool and fade over many millions of years, but in the mean time its radiation heats and excites the gases in the nebula. The atoms in the shell glow and are visible as beautiful bubble-like structures. One of the simplest is the Ring Nebula (Figure 8.5), an easy target for the amateur astronomer, which lies in the constellation of Lyra. The spherical shell formed from the outer layers is illuminated by the compact white dwarf clearly seen as a white dot at the centre. Faint radial fingers of obscuration can be seen mixed in with the gas: these are composed of the dust that was formed during the star's final red giant phase and later thrown in the outer layers of its atmosphere. A planetary nebula is relatively transitory – as it expands it will disperse into space over a period of several thousand years, cooling down and fading as it does so.

While visible, such structures provide the opportunity for the observation and modelling of processes that can occur during the last few thousand years in the life of a Sun-like star. Few are as simple as the Ring Nebula. Some show far more intricate structures, such as the complex webbing apparent in the Spirograph Nebula, or the bipolar lobes that spread out from the white dwarf to form the suitably named Hourglass, Ant or Butterfly Nebulae. One of the most complex planetary nebulae known is the famous Cat's Eye, which is shaped from ten concentric gas shells that were blown off in a sequence of regular pulses at 1,500-year intervals. The regular pattern of shells is disturbed by the passage of two high-velocity jets and wind bubbles that emerged later from the dying star. As with many of these nebulae, a wider-angle view reveals much larger, very faint haloes of matter thrown off at far earlier episodes of the star's evolution, some five to ten thousand years previously. Certainly it would appear that many stars do not end their lives in a simple spherically symmetric 'textbook' manner. Planetary nebulae may also have the development of

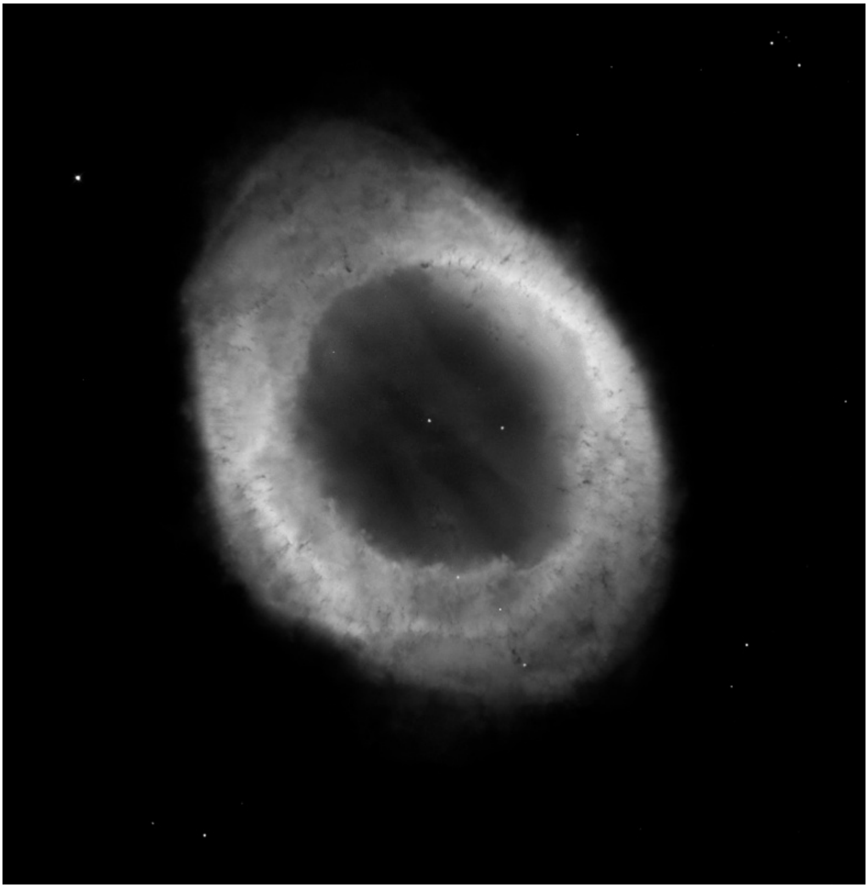

FIGURE 8.5. The Ring Nebula. The Ring Nebula is a planetary nebula, a shell formed from the outer layers of a star, shed at the end of its life, and expanding away into space. The central core of the dying star is a white dwarf, which can be seen as a white dot at the centre of the ring. The whole structure is about one light year across.
Credit: The Hubble Heritage Team (AURA/STScI/NASA).

their structures influenced by any dusty layers shrugged off by the star earlier on, which can produce an inhomogeneous environment that moulds an asymmetric expansion of the gas layers. Shapes can also be complicated by the presence of a close companion star or strong magnetic fields contained within the expelled material.

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Supernova remnants

Much more massive stars (around eight times the mass of our Sun) have a very different life. With more mass comes far more gravity to be overpowered, so the star has to produce far more outward energy from the nuclear fusion. This requires it to undergo a much higher rate of fusion processes at much higher temperatures. In the real world of physics – in contrast to the common perception of blue as 'cold' and red as 'hot' – hotter objects emit bluer, more energetic radiation than the yellowy-red colour of cooler stars such as our Sun. Thus an astronomer immediately recognizes that any blue stars in an image are both massive and very hot. In addition, blue stars can always be identified as young stars. Producing more energy, they consume fuel at a much faster rate. Even though they start with far more mass, the rapidity with which it is devoured means that stars with a mass over ten times that of our Sun only live for some tens of millions of years. The more massive the star, the shorter its lifetime. A convoluted chain of nuclear reactions can be supported at these much higher temperatures, which results in the core of the star being completely converted to much heavier elements, up to and including iron. Once a star has created iron (the most tightly bound nucleus) it can no longer extract energy via fusion, and it abruptly runs out of power. The final collapse from gravity is rapid and dramatic, and results in a complete disruption of the star in a *supernova* explosion. During this disruption an intense flood of neutrons is released, and these bombard ions and atoms within the resulting debris, thus enabling the rapid formation of elements much heavier than iron.

When a much higher mass (and hence higher gravity) drives the collapse of the star, the atoms in the core are squeezed beyond the point where electron pressure is sufficient to resist gravity. Within each atom, electrons are now forced onto protons to create neutrons, and the incompressibility of this population of neutrons can hold up the star against further collapse. The remnant core comes to rest as an incredibly dense, and tiny, neutron star. But if the mass in the original giant star exceeded twenty-five solar masses, it is a completely different story. The final gravitational collapse of the core pushes past the neutron pressure, and there is no process that can any longer support

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the star. The matter in the core will continue falling inwards under gravity, and turn it into one of the oddest objects in the Universe: a black hole.

The supernova explosion blasts off the outer layers of the star to generate a tide of debris, which expands away at over half a million kilometres an hour. The rapidly moving shell of matter sweeps up the surrounding interstellar medium, compressing and collapsing the material in front of it into thin sheets and filaments. Shocks are generated as the blast-wave collides with its environs, and the energy that is released heats the gas in the filaments to temperatures of millions of degrees. As this material in the shell cools, the atoms radiate away the energy and trace a filigree network of filaments up to hundreds of light years across. Such a supernova remnant remains visible long after the initial explosion and can persist for tens of thousands of years. The Crab Nebula (Figure 8.6) is the nearby (6,500 light years from Earth) remnant of a supernova explosion that was recorded as a bright 'guest star' by Chinese astronomers over a thousand years ago. Today the shreds of debris form a cloud around 10 light years in diameter, still expanding from the centre at over 1,000 kilometres a second.

During this process, all of the heavier elements created – whether during the massive star's life or at its violent death – become mixed in with the primordial gas of the interstellar medium and subtly enrich its chemical composition. But it is these same diffuse gas clouds, now seeded with a trace of heavy elements, that will one day collapse to form another generation of new stars. As the history of the Galaxy proceeds, subsequent generations of star birth and death have a cumulative effect, slowly increasing the proportion of heavy elements present. The interstellar medium is dynamic, with star birth and death occurring all of the time, very often in close proximity. Any given nebula will be dominated by a cluster of young massive stars sitting in the cavity they have created around them. Their radiation is eroding the walls of the molecular hydrogen cloud around them to form giant dusty pillars and in the process isolating small dark globules, some of which are already collapsing into proplyds around proto-stars. The most massive stars of a cluster are the first to explode as a supernova, and the heavy elements that they release will become incorporated into future generations of

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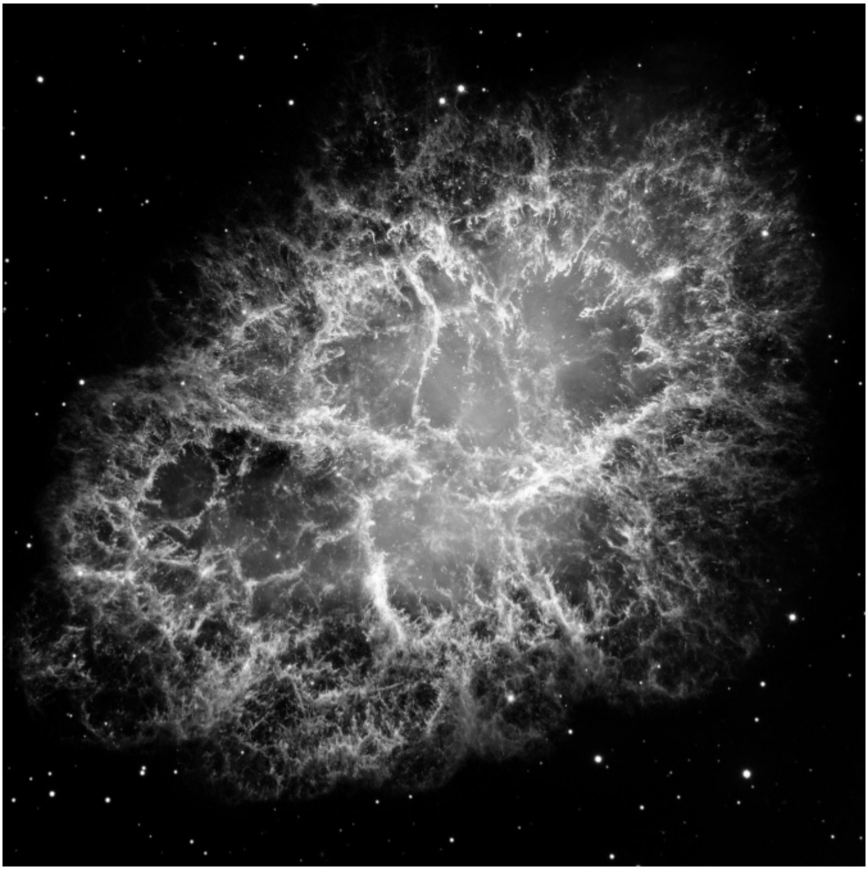

FIGURE 8.6. The Crab Nebula. The Crab Nebula is a six-light-year-wide nebula formed from the debris of a massive star's supernova explosion that occurred around a thousand years ago. The central core of the star has collapsed down to form a neutron star at the centre of the nebula.
Credit: NASA, ESA, J. Hester and A. Loll (Arizona State University).

stars to be born out of this cloud. In this way, all of the heavy chemical elements that form the Earth and our bodies were originally created deep in the heart of massive stars, many billions of years ago. Sometimes the supernova blast is even responsible for triggering the next generation of stars.

The triggers for star formation

We observe star formation to be ongoing throughout the disc of our Galaxy. But many of these gas clouds are primordial and have existed for billions of years. What causes them to collapse to form stars only now? To understand this, we have to examine how and why the process of star formation starts.

Every atom or molecule in a gas cloud is pulled on by the combined gravitational attraction of its neighbouring particles. The slightest over-density of matter in a diffuse cloud will make the gravity slightly stronger in one location, and as this over-density condenses, its increased mass results in an increased gravitational pull on its surroundings, which in turn attracts more matter, so it becomes denser, more massive and gravitationally stronger ... and so a runaway process of gravitational collapse is triggered. Gravity squeezes the matter tighter and hotter until the point where nuclear fusion – and thus star birth – is triggered. But all matter in a gas cloud, even if it is only a few degrees above absolute zero, is in continuous motion. The constant jiggling and movement of particles produces a net outward pressure, which, if large enough, enables the particles in a cloud to resist the local pull of its own gravity. So whether or not a cloud of a certain size will collapse to form stars is dictated by a delicate balance between its density and temperature. A threshold density is required to overcome the thermal pressure, and this threshold is higher the warmer the cloud. (There are other factors, such as the strength of any magnetic field threading through the gas, or the amount of rotation present, that can also act to inhibit a cloud's collapse under gravity.) Thus the conditions for star formation are most favourable in the very coolest and densest regions of the interstellar medium, such as the cold dusty globules. There are many invisible cold gas clouds that have not collapsed yet – they can exist undisturbed for hundreds of millions of years if the material in them is either too sparse or too hot to condense spontaneously under gravity. Either the temperature or the density of the cloud has to change substantially to cause it to collapse to form stars. A rapid decrease in temperature across portions of a cloud is nearly impossible to effect, but a quick increase in density can be achieved by a variety of physical processes, all of which can push on the gas and squeeze it.

Star formation is endemic throughout the flat disc of our Galaxy, as evinced by the plethora of blue-star clusters. The exact source of the spiral pattern is not well understood, but it is thought to be due to a 'density wave' that slowly sweeps round the disc, perhaps caused by the way that gas clouds will occasionally bunch together as they rotate around the centre of the Galaxy. The density wave squeezes the gas clouds as it passes, triggering star formation and leaving a long arc of newly formed star clusters in its wake. Compression of gas clouds can exist on smaller, more local, scales as well. The winds and radiation streaming from the surface of very young stars hollow out a cavity – either round an individual massive star, or a combined effort around a cluster of stars such as those in the Rosette Nebula (Figure 8.3). The material excavated piles up to form a thick layer and in the process is compressed, which makes the cavity walls an ideal location for a new region of star birth. The infrared images clearly show large, embryonic stars within these walls, and, in particular, stars located deep inside the tips of the pillars that branch from them.

One of the best examples of a nebula that shows three successive generations of star formation is the Heart and Soul Nebula, a structure that spans 300 light years, around 6,500 light years away. The ages of the stars are observed as systematically younger with increasing distance from the centre of the 'Soul' side of the nebula. Isolated blue stars seen right at the centre of the large cavity are the only remaining survivors from the first clusters of stars to form from the surrounding molecular cloud – any more massive companions have long since lived out their lives. Some young star clusters lie further from the centre: these are a second generation that were prompted to collapse from the compression of gas clouds by the winds, radiation pressure and subsequent supernova blast waves from the original star clusters. Many of the stars in these clusters are accompanied by (rather wind-blown) proplyds. Finally, infrared observations reveal a third generation of young stars and proto-stars, all still embedded within the cavity walls and towering dust pillars. In this way, a dynamic cycle of star birth and star death ripples out from the core of a nebula, enriching and triggering subsequent generations.

Final comment

This chapter has discussed images that many people find both beautiful and awe-inspiring, which were all created from data collected in the pursuit of scientific knowledge; I hope that a better explanation of the underlying science has only enhanced their beauty in the eye of the beholder.

Acknowledgements

There are many more beautiful images of star clusters and nebulae available for the reader to explore and marvel at, all created from the observations of both professional and amateur astronomers around the world. These continue to provide inspiration for my own fascination for astronomy. Two suggestions of starter websites for the interested reader are the Astronomy Picture of the Day at *apod.nasa.gov* and the Heritage Gallery of *Hubble Space Telescope* images at *heritage.stsci.edu*.