2. The Anatomy of Stellar Life and Death

Stars begin as clouds of gas and dust, called nebulae, with temperatures hovering a few degrees Kelvin above absolute zero (–273 °C). If there is sufficient mass present within the cloud, gravity may overcome resistive forces and cause the cloud to collapse. Resistance against collapse is provided by the internal kinetic energy of the gas and dust particles and by the interstellar magnetic field that permeates the galaxy. Once resistance is overcome, gravity collapses the cloud until it has become hot and dense enough inside to begin fusing hydrogen to helium. At this point a star is born.

Initial Conditions

Each nebula has a minimum mass that determines whether collapse will occur or be retarded by other resistive forces. This mass is called the Jeans mass, named after British physicist James Jeans. Jeans reasoned that a cloud would collapse only if it lacked sufficient internal support against gravity. Clearly the criteria will vary from location to location in the galaxy.

In addition to the effects of magnetism, chemical composition plays a crucial role in the formation of stars. Nebulae composed of pure hydrogen and helium tend to remain massive as they collapse, failing to fragment effectively. The reason for this is a little complex, but note that a large volume of gas has quite a significant amount of internal energy – even if the temperature of the material is very low. As the gas collapses gravitational potential energy is converted to thermal (heat) energy, and this thermal energy causes the gas to resist further collapse. Cooling in primordial gas clouds is, therefore, a relatively inefficient process driven primarily by

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the formation of diatomic hydrogen gas (H_2). Consequently, the nebulae remain fairly massive even as they collapse, and they fail to fragment into smaller, denser and less massive cores. Thus the stars produced from this material tend to be particularly massive, and modeling suggests that this was an important factor in the formation of the first stars in the universe.

Subsequent populations of stars were polluted with elements heavier than helium. These metals are able to efficiently cool clouds of hydrogen and helium, and nebulae tend to fragment into smaller pieces. Metal atoms, and their associated ions, have a large number of potential energy levels associated with the larger number of electrons these elements possess.

If an electron orbiting the nucleus picks up a photon of energy at a short wavelength, the atom absorbs some of the ambient energy within the cloud. However, the electron can subsequently release this energy by dropping down to its original energy shell in smaller, less energetic hops. If the nebula is transparent to these longer wavelengths the energy escapes the cloud and the internal energy is reduced. This allows the cloud to shrink further. The combination of cooling, gravitational collapse and the conservation of angular momentum then dictates how the cloud shrinks and fragments.

With greater cooling and fragmentation, the stars formed from metal-rich gas tend to be smaller than those formed from metal-free or metal-poor gas. However, this is theoretical, and it has to be said, poorly constrained by observation. In 2011 a star, SDSS J102915 + 172927, was discovered in the galactic halo with a low mass and an extremely low metallicity – less than 1 millionth the abundance of metal in the Sun. This EMP (extremely metal poor star) followed the earlier identification of HE0107-5240 in the early part of the last decade.

The presence of such low mass stars threatens the assumption that early stellar generations were more massive – or at least that there is a simple relationship between metallicity and stellar mass function. There was an assumption that interstellar chemistry had to cross some threshold value of metallicity in order to allow for the formation of low mass stars. However, observations of galactic halo stars are increasingly challenging this assumption. Moreover, observations of stellar populations at higher red-shift, i.e., greater age, don't show significant differences in the stellar IMF with increasing age or decreasing metallicity. Finally, observations of metal-poor Population II stars show little evidence for the kinds of explosions predicted for the first metal-free stars. Instead most closely match the elemental abundances seen for conventional core-collapse supernovae, or those with substantial fallback into a central black hole, and with substantial mixing within the stellar envelope. However, the number of very low metallicity stars observed is marginal, and it remains possible that we are only seeing the effect of a few massive stars that are not representative of Population III as a whole.

If the effect of metallicity on stellar birth produces a mixed signal, it appears as though this factor does affect the later evolutionary stages of the star. In this chapter we shall examine how metallicity may influence some particularly lively stellar fireworks.

It is generally agreed that the vast majority of stars form in clusters and associations – looser aggregates of stars. Each cluster may contain up to tens of thousands of members with a few clusters attaining membership in the hundreds of thousands. The vast majority of stars that form are low mass (less than the mass of the Sun), with only a sparse number of massive stars in association with these. In general this picture holds across all of observed interstellar space. The reason for this pattern of star formation is unclear, but it appears to hold across nebulae of varying composition.

A further clear pattern emerges in the distribution of stars that form. The most massive stars form from the densest regions of the parental nebula, with lower mass stars forming further out. Furthermore, in general massive stars are rare to non-existent members of low mass clusters, only appearing when the mass of the cluster as a whole is relatively large. However, there was thought to be a problem with this simple process of massive star formation. Massive stars produce copious radiation and intense stellar winds, and the expectation emerged that these processes would limit star formation by accretion to stars with masses less than a few times that of the Sun. It was assumed that massive stars were formed via collisions between low or intermediate mass stars. This merger model certainly could reproduce massive stars formation, but is it their sole method of creation?

Observations by Henrik Beuther (University of Heidelberg) and Peter Schilke (University of Cologne) of a star-forming region IRAS 19410–2336 revealed that the process of massive stars formation appeared to mirror that of lower mass star formation with a very similar scaling of the mass of protostars. The observations were done in the millimeter (microwave) range where the dusty material comprising the nebula is transparent. This allowed detailed observations of the internal structure of the nebula.

Beuther's and Schilke's work revealed a nebula containing denser portions called cloud cores. Embedded within these cores lay still denser clumps of gas in which the massive protostars were forming, in a hierarchical arrangement akin to a Matryoshka doll. The nebula contained smaller cloud cores, and within these lower mass stars were presumably forming. The process appeared identical for massive protostars and their lesser cousins. Thus, although the merger model is not excluded, these observations suggested that mergers were not necessary to form massive stars.

Mark Krumholz (University of California, Santa Cruz) carried out another study, published in 2009, which detailed in three dimensions the formation of massive stars. This was no mean feat, particularly as earlier, simpler models failed to show accretion by protostars with masses exceeding 20 times that of the Sun. Again the culprit was radiation pressure. At this mass, the radiation produced by the protostar overwhelms the force of gravity, halting further accretion. However, these earlier models assume spherical accretion onto the surface of the protostars, when we are already aware that stars form at the heart of spinning accretion discs.

Modeling in three dimensions took 40 days of computing time on 256 processors. The results were astonishing. Mark Krumholz's model described the first 50,000 years in the life of a protostar. During the first 4,000 years the cloud collapses into a thick disc with the protostar at its heart. During the ensuing 20,000 years, spirals within the disc allow the continued accretion of material onto the protostar. At 17,000 years radiation pressure begins to affect accretion. However, radiation primarily escapes from the rotation poles of the protostar while accretion continues along equatorial regions. By 50,000 years three protostars complete formation with masses of 20, 37 and 44 times that of the Sun. The key to the success of these models was the consideration of accretion in three dimensions. Accretion primarily occurs along the equatorial plane of the protostar, driven by gravity, while winds blow material outward along the polar axis of the protostar.

Despite the success of these models and observations we shouldn't completely discount the role of collisions between protostars. Modeling of star formation revealed a frenetic process of protostar interaction, an occasional merger and, on occasion, an untimely ejection. Particularly dense clusters of stars, those formed from larger and more massive nebulae, seem prone to stellar mergers. The question is how much of this mass these stars can hold onto. At present models tend to show even the most massive star (up to 1,000 times the mass of the Sun) will still be pared down to more modest dimensions by stellar winds. However, much work remains to be done with the influence and extent of stellar mass loss; thus, this remains an open book awaiting further discovery.

The Life of a Star

Once a protostar has formed, gravity continues to contract the object, heating it steadily until nuclear reactions can begin. The lowest mass stars take over 2 billion years to stabilize, but as the mass increases, the time spent growing and maturing decreases. A star with the mass of the Sun spends about 30 million years descending from a nebula, through its protostar phase to the main sequence. But something as massive as 20 or more times the mass of the Sun will spend less than 50,000 years completing this journey. As the core increases in temperature, first deuterium, then lithium is consumed. These are mere burps along the road to stardom and have little or no influence on the process of massive star formation.

Hydrogen will initially fuse through the proton-proton (ppI) chain, but as temperatures continue to climb the CN cycle will engage, driving the production of most of the stellar energy. Once radiation and stellar winds have dispersed a critical mass of material around the star, accretion ceases and stellar winds rip free in all directions, clearing the remaining gases away.

Massive stars are born with high surface temperatures, and the radiation they release is mostly in the form of ultraviolet. This ionizes the remaining gases around the star, forming an emission nebula and revealing the birthing chamber in all its splendor.

Around the brilliant core of the stellar cluster lies those lesser stars, still condensing from the remains of the cloud. Many glorious examples of these nebulae are known, the nebula in Orion perhaps being the most famous. Around the central Trapezium cluster of O-class stars exists a multitude of protostars still surrounded by discs of gas and dust. Many show the impact of radiation from the central Trapezium cluster, with bow shocks around their leading edges and ionization of the gases within the disc.

One wonders if the Sun formed in such circumstances. The nascent Sun descended, contracting and heating, with Jupiter forming from within the swirling disc of gas and dust surrounding it. But before the Sun ignited its engines, a nearby star evolved away from the main sequence, its high mass dictating a short life. The Sun and infant planets breathed a temporary sigh of relief as the ultraviolet radiation that threatened their formation died away. A million years after this star left the main sequence, cooling and brightening as a red supergiant, its core collapsed, triggering a supernova. The shock wave battered the infant Sun but showered it with a glittering gift of radioactive elements that helped heat and differentiate the planets as they condensed around the Sun.

Billions of years later, those distant memories have long since faded, but left their footprint in the ratio of isotopes of magnesium in the rocks that form our terrestrial worlds. Core collapse supernovae make abundant aluminium-26, which decays in a few hundred thousand years to form magnesium-26. Many of the asteroids in the Solar System are rich in this isotope. And since aluminium-26 has a short half-life the only way it could have acquired it is by close proximity to a supernovae. By implication, many other useful elements such as the oxygen in our air, water and rocks; the iron in our blood; and the calcium in our bones may also have come from this same death in the neighborhood.

We may owe much to the death of a massive star.

The Main Sequence

A star is born when the collapsing and heating object reaches the main sequence. The starting position on the main sequence is called the "zero age main sequence," ZAMS for short. Here, the energy produced by nuclear reactions balances the inward pull of gravity. Contraction ceases, and nuclear reactions between hydrogen nuclei provide the necessary energy to stave off gravity's fatal attraction. Stability is achieved. The period the star spends on the main sequence depends critically on the initial mass of the star. This is detailed in the table below.

Stars entering the main sequence emerge at a location set by their mass and to a lesser extent by their chemical composition. Metal-poor stars are found on the sub-dwarf branch (luminosity class VI), but we can effectively ignore them for now because the metal-poor stars in our galaxy are all of low mass. The stars that form the bulk of the thin disc stars in our galaxy and those stars forming today in other parts of the universe fall onto the main sequence (luminosity class V). These stars form a sequence that follows the so-called mass luminosity relationship (Table 2.1).

In outline, a simple relationship exists that links the mass of the star to its luminosity. The relationship works for all stars that fuse hydrogen to helium. However, the precise link between mass and luminosity varies as we ascend the main sequence, and the manner in which energy is created and transported varies (see Chap. 1). For stars with masses exceeding 20 times that of the Sun the relationship is a very simple one. As mass goes up luminosity goes up in turn. Beneath this, at the lower regions of the main sequence, the relationship varies considerably, with different expressions added to tweak the mathematics in line with observations.

The Main Sequence Lifetime

A star will live on the main sequence for as long as it has hydrogen fuel to support it. During its time here, the core converts hydrogen to helium, and the core slowly fills with spent fuel. For the lowest mass stars the helium produced by fusion is continually mixed into the bulk of the star by global convection currents. However, in stars with masses above approximately 0.25 solar masses, convection does not extend throughout the star, and the fuel available to the core is restricted at birth.

In a Sun-like star, with a radiative core, helium settles towards the center of the core throughout the main sequence lifetime. In more massive stars convection mixes the helium

Table 2.1 Main sequence mass and lifetime. One WD refers to a white dwarf with a core dominated by the elements oxygen and neon, while CO refers to a white dwarf with an interior dominated by carbon and oxygen. He WD is a helium-dominated white dwarf

Initial mass	Luminosity L/L. (ZAMS)	T (ZAMS) 10^3 K	Spectral class (ZAMS)	Absolute magnitude (ZAMS)	Time on main Sequence	Total lifespan	Fate (Dependent on mass loss)
120	5,000,000	53	02	–12	3.0	3.9	Black hole
60	700,000	48	03	–8.7	3.5	4.0	Black hole
40	400,000	44	05	–5.6	4.4	5.0	Black hole
20	60,000	35	08	–5.0	8.2	9.0	Neutron star
12	10,000	28	B0.5	–4.0	16	18	Neutron star
7	3,000	21	B2	–1.5	43	48	CO/ONe WD
5	1,000	17	B4	–0.8	94	107	CO WD
3	100	12.2	B7	–0.2	350	440	CO WD
2	25	9.1	A2	1.4	1.16 billion	1.36 billion	CO WD
1.5	7.5	7.1	F3	3.0	2.7 billion	2.9 billion	CO WD
1	1	5.64	G5	5.2	11 billion	12.3 billion	CO WD
0.8	4/5	5.3	K0	6.4	25 billion	27 billion	CO WD
0.3	1/100	3.5	M5	11.6	350 billion	400 billion	He WD

with the remaining hydrogen in the stellar core. However, the end result is a fall in the number of particles present in the core. Four hydrogen atoms have been converted to one helium atom. It should be said, though, that the term "atom" is a tad misleading at the very high temperatures found in the stellar core. All atoms of hydrogen and helium are fully ionized and so consist of free electrons and nuclei.

As the number of particles decreases the pressure provided by their constant movement within the core decreases, and the core is forced to contract to compensate. Gases that contract heat up, and so throughout the main sequence the temperature in the core of a star increases. This accelerates the rate of nuclear reactions, and the luminosity of the star slowly picks up.

Over the last 4.5 billion years the Sun has grown hotter and slightly larger, and is now more luminous in response to this effect; the same is true for more massive stars. As the fuel is consumed the luminosity slowly increases.

The effect is quite subtle in comparison to later changes, but over the main sequence lifetime, low and intermediate mass stars (0.1–1.5 solar masses) slowly migrate up the main sequence over a short distance before moving away from it at greater speed once the fuel has gone. More massive stars move only slightly upwards, but predominantly execute a straight and very rapid run to the cooler portion of the HR diagram before exploding. The difference in behavior reflects the manner in which fuel is consumed and the limited time the star has to respond to changes in fuel availability before other less appealing effects overwhelm the star's sensibilities.

In general the time a star has to spend on the main sequence reflects its mass – although chemical composition is also a factor. Low metallicity stars lose energy more readily to the outside universe and hence have to generate it faster to remain stable against gravity. Thus a low metallicity star lasts for a shorter time than a star of the same mass but with more heavy elements (metals). The basic idea is that the more energy a star gives out, the faster its fuel will be used up and its life terminated.

Thus massive stars live much shorter lives than less massive ones.

Instability on the Main Sequence

We like to think of the main sequence as a happy time for a star. It is producing energy that allows it time to breathe and hold off the debt collector, gravity. However, this cozy textbook picture can be misleading. For many stars processes occurring within the stellar envelope mean that these stars pulsate, and for a few massive ones there is a source on instability within the core.

Many intermediate mass stars fall inside the so-called instability strip – a zone on the HR diagram stretching from the cooler edge of class A through class F on the main sequence and white dwarf cooling tract to class G in the giants, which contains stars that pulsate in a regular manner.

Main sequence stars in class F (~1.25–1.8 solar masses) have one significant behavioral difference from their smaller and larger siblings. These stars are intrinsically variable. Variability is a consequence of changes in the physical behavior of the outer portion of the envelope of the star. In main sequence stars lying in this mass range, the temperature reaches 50,000 K just beneath the photosphere. At this temperature helium becomes doubly ionized (helium atoms lose both of their electrons). Helium atoms can lose two electrons with the second electron coming off as temperatures approach and then exceed 50,000 K.

As any chemist will tell you, removing electrons from helium is a difficult business that requires a lot of energy. Therefore, as temperatures approach those critical for electron removal, the ability of the envelope to lose energy falls away sharply. Available energy becomes trapped in the layer of ionizing gases. Moreover, doubly ionized helium is more opaque to radiation than helium in its singly ionized state.

As radiation becomes trapped in the layer the material expands, causing the star as a whole to inflate. Expansion causes the layer to cool, which reverses the process – electrons recombine with the helium. Opacity drops, radiation can escape and the layer relaxes once more. The ensuing contraction then reverses these steps and the process continues.

The incessant cycling in the ionization state of this relatively thin layer drives expansion and contraction of the envelope, and this, in turn, drives the observed changes in luminosity. These variations in stellar girth and hence brightness can only occur where the layer in which helium ionization is occurring has a particular density. This mechanism drives luminosity changes in Cepheid variables – the stellar cornerstone of much of modern cosmology, used to determine the distances to distant galaxies and hence the expansion rate of the universe.

In 1962 Robert Christy proposed that a variation on this mechanism – pulsation driven by the ionization of hydrogen – might explain cyclical expansion and contraction observed in giant stars such as S U Draconis. In Chap. 3 we will examine the potential impact of these processes on the evolution of the universe's most massive stars.

In stars hotter than class F helium II ionization occurs at too shallow a level to drive the pulsation in the manner described. Helium ionization in A- and B-class stars occurs near the photosphere, and insufficient energy can be stored within the envelope in these stars to drive pulsations. Too great a depth and the star will not pulsate; nor will those in which the mass is too high and the level of overall ionization occurs is considerably greater. The instability strip thus demarcates a zone of stellar mass and temperature where pulsations occur, driven by the ionization of helium. This strip extends from the white dwarf tract (ZZ Ceti variables), through the main sequence and up into the giant branch. Here stars with masses between 5 and 9 times that of the Sun appear as Cepheid variables when evolutionary processes carry them through the instability strip.

An interesting idea is that pulsations, driven by different ionizations, may drive the final changes in the life of low and intermediate mass stars. If you look at planetary nebulae, the complex inner nebula is often surrounded first by an inner layer made up of closely spaced shells, and this in turn is cloaked in a broader, messier outflow. These changes reflect alterations in tempo as the star approaches its final scene in the movie. Perhaps the earlier stages are associated with mass loss driven by the ionization of hydrogen, but as the star loses mass more and more energy can escape by radiation. The star then heats up, and the helium ionization regions approach the stellar surface. This change drives the appearance of more closely spaced shells, which ultimately give way to the final planetary nebula as the remnant star collapses what's left of its envelope onto the nascent white dwarf within.

β-Cephei Variables

Further up the main sequence are another set of variable stars, the β-Cepheids. These have masses between 10 and 20 times that of the Sun and are thus hot, blue, B-class stars with surface temperatures exceeding 18,000 °K. In these stars helium is doubly ionized throughout the bulk of the star, and this cannot provide the sort of pressure-valve mechanism seen in F-class instability strip stars. Instead these hot stars pulsate because iron and similar relatively massive elements acts as the valve. In a manner analogous to helium at lower temperatures, when iron is sufficiently heated electrons are driven off the metal (which is already partially ionized at these high temperatures). Progressive ionization of this iron then allows energy to flow through from the interior to the exterior of the star, and the star can breathe a sigh of relief, contracting inwards. However, once the energy has passed through and the layer containing iron ions cools, some of the liberated electrons recombine with the ions and trap energy once more, causing renewed expansion and the pattern to repeat. Many O and B stars show this pattern of variability, and it is proving rather useful to astronomers (Fig. 2.1).

As stars pulsate the pattern of pulsation reflects their internal structure. Pulsations generate internal waves that course through the star like giant earthquakes. And just like on Earth, seismic waves can be used to investigate the planet's deep interior. Astronomers have used this technique, known as astroseismology, to probe the interiors of many stars, the Sun included. For example, astroseismological observations of the ten solar mass B-star HD129929 and the 20 solar mass O-class star HD46202 reveal that convection within the heart of these stars overshoots the edge of the core. This implies that additional hydrogen from the base of the stellar envelope could be brought down into the core, affecting the core's mass and potentially lengthening the time the star has to fuse hydrogen – the star's main sequence lifetime.

In still more massive stars, a second mechanism comes into play that generates pulsations within the star. The so-called epsilon (ε)- or Eddington mechanism was first evoked in the 1930s to explain the pulsations of Cepheid variables. However, subsequent work indicated that the kappa mechanism described above was the

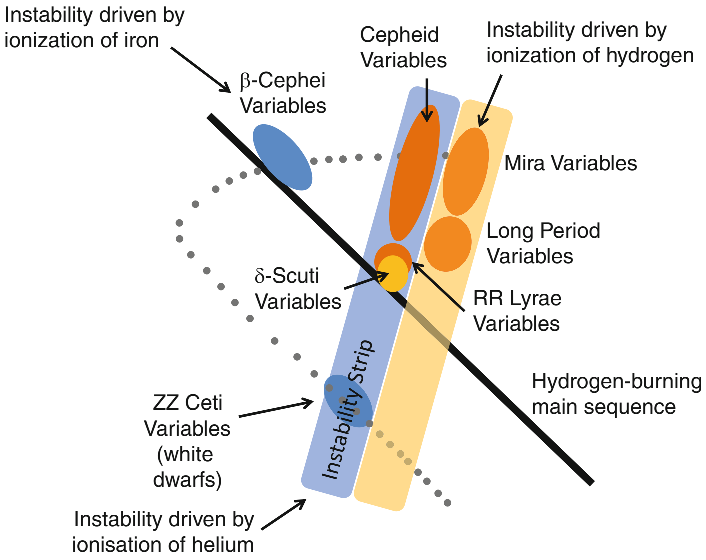

Fig. 2.1 Variable stars and the HR diagram. Stars in the instability strip pulsate because of ionization of helium just under the surface of the stars. β-Cepheids pulsate because of radiation periodically trapped and released by a layer of partly ionized iron some distance under the surface of the star

root cause of Cepheid instability. However, in stars with masses in excess of 60 times that of the Sun, a type of instability associated with the production of nuclear energy sets in. This epsilon mechanism causes small but noticeable changes in the luminosity of massive O and hydrogen-deficient Wolf-Rayet (WR) stars.

In 1992 it was reported that the WR star WR40, or HD96548, pulsated with a period of 627 s (or a little over 10 min). This period was in keeping with theoretical predictions of pulsations driven by the ε-mechanism. Of importance, although the change in magnitude was slight (0.005 magnitudes), this type of pulsation may be an important factor in driving mass loss in these very massive stars. In turn a simple pulsation may affect the type of death the most massive stars can undergo.

Therefore, although we like to think of the main sequence as the quiet time for a star, many stars, and probably all of the most massive stars, undergo pulsations that affect them and potentially foreshorten their lives. The main sequence is not so quiet.

Throughout the main sequence massive stars rapidly deplete their inventory of core hydrogen by the CN cycle. At somewhat higher temperatures hydrogen is also consumed by a final ring of reactions called the CNO cycle. This succession branches off the CN cycle, producing a slightly different set of isotopes, but ultimately helium is the end-product.

As the abundance of hydrogen falls to less than 1 % of the mass of the core, insufficient energy is generated by fusion, the temperature gradient declines and convection ceases. All remaining hydrogen is rapidly destroyed, and the core begins to contract.

As Above, So Below

Over the ensuing 50,000–100,000 years, depending on mass, the star expands and cools as the helium-rich core contracts and heats up. Luminosity remains roughly constant for these massive stars, during this transit, which is in stark contrast to Sun-like stars, which steadily grow brighter.

The dichotomy is explained by the behavior of the hydrogen-free core. Stars like the Sun consume only about 10 % of their mass during the main sequence phase. The helium core that is left over sets the luminosity of the star. As the Sun's core contracts, hydrogen fusion switches on in a shell around it, adding fresh helium to the core and thus increasing its mass. As the mass increases so does the luminosity of the star. These stars thus ascend the red giant branch. They do this quite slowly over hundreds of millions of years. All stars with masses of less than 2.25 times that of the Sun follow the same route and pile up at the same location on the HR diagram. This location is set by a mass of helium roughly half that of the Sun (0.5 solar masses). At that point helium fusion sets in, and the stars depart the red giant branch for a few tens of millions of years.

Massive stars (indeed all stars with masses exceeding 2.25 solar masses) already have helium core masses exceeding 0.5 solar masses. Therefore, as their helium cores contract and heat up, the concomitant expansion of their hydrogen envelope drives a cooling trend on the HR diagram but not an increase in the brightness of the star, its luminosity. These stars merely head to cooler climes before helium fusion sets in and the star embarks on the next phase of its life.

During this first expansion of the star, helium can be dredged out of the core as the zone in which convection is occurring in the envelope extends downwards. As it reaches what was the edge of the former core helium, along with isotopes of nitrogen, appear at the stellar surface. These elements were produced earlier by hydrogen fusion, through the CNO cycles. This, first dredge up as it is known, can be a useful diagnostic tool allowing astronomers to tell that the star has moved on from the main phase of its life to something a little more dramatic.

The transition to giant-hood is brief, which accounts for the scarcity of stars between classes O and B, and the cool red giant and supergiant classes. Stars spend so little of their lives here that they are unlikely to get caught in the act of transformation. The HR gap is thus a conspicuous feature of the HR diagram but one that is readily explained by models of stellar evolution.

Helium Ignition and Subsequent Evolution

Helium fusion kicks in with relative passivity in massive stars. Once the helium core has heated to temperatures in excess of 100 million degrees Kelvin, it ignites gently. At this point helium begins a frantic three-way fusion reaction that produces first carbon and then oxygen. The triple-alpha reaction, as it is known, releases roughly one-tenth the energy produced by hydrogen fusion. All subsequent phases of fusion release proportionately less energy in turn. Why?

Nuclear fusion converts a small fraction of the mass of the parent nuclei into energy, via the eponymous equation $E = mc^2$. The energy liberated is called binding energy, and it is a fraction of the energy in the nucleus of the atom that links the component quarks together. Hydrogen fusion converts approximately 0.7 % of the mass of the four hydrogen atoms into energy. However, considerably less binding energy is liberated when helium fuses in threes (Figs. 2.2 and 2.3).

Indeed, close inspection of the diagrams here reveals that only one-tenth the energy is available to the star. One might then reasonably expect that helium fusion lasts for a tenth the time the hydrogen fusion did. After all, if a tenth of the energy is available then the star must use it ten times faster to get the same bang for

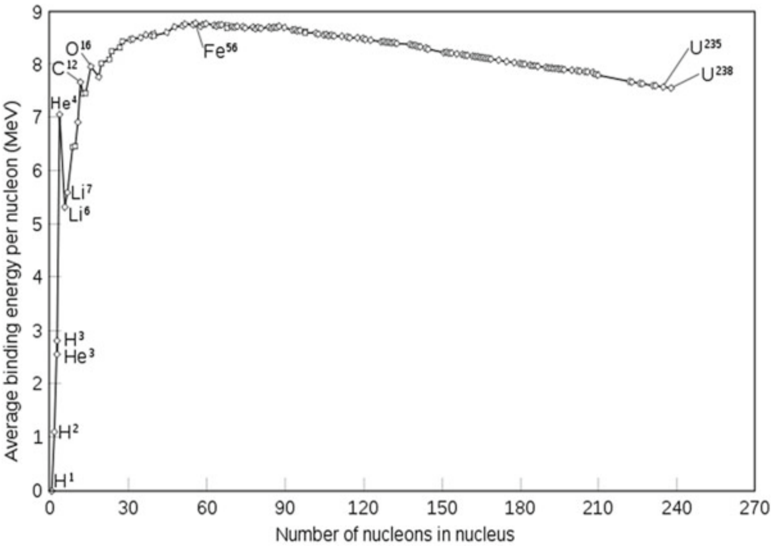

Fig. 2.2 Nuclear binding energy showing the change in binding energy with increasing mass of nucleons (protons and neutrons) in the nucleus of the atom. Hydrogen fusion to form helium releases approximately ten times the energy of helium fusion to form carbon (Image Source: Wikipedia Commons)

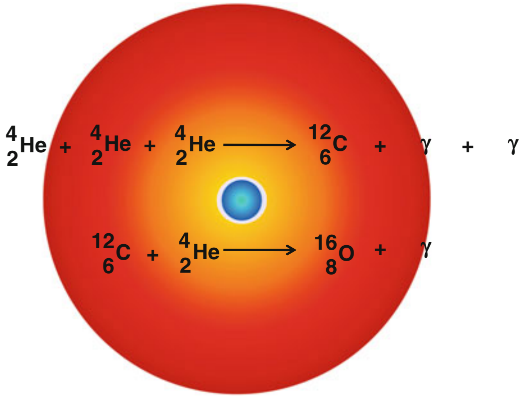

Fig. 2.3 The triple-alpha reaction. In evolved stars helium reaches temperatures in excess of 100 million Kelvin and fuses in threes to make carbon-12. At later times carbon-12 can pick up another helium nucleus and transform into oxygen-16. Each reaction releases gamma rays

its bucks. However, helium fusion is limited by one other factor: the speed of the reactions. Helium fuses to carbon and oxygen with even greater temperature sensitivity than hydrogen. A 2 % increase in temperature causes a doubling in the rate (rate varies with T^{40}). The very high rate of reactions means that nuclear fusion lasts only 150 million years or so for the Sun – compared with 11 billion years fusing hydrogen. For a massive star, helium fusion lasts between 100,000 and 1 million years, with a time that decreases with increasing mass.

For stars of between 0.5 solar masses (depending on the mass lost through stellar winds) to seven times that of the Sun, this is as far as nuclear fusion goes. The star has insufficient reserves of gravitational potential energy to raise its core temperatures high enough to fuse the carbon or oxygen produced by helium fusion. The star stops its ascent of the fusion ladder. Stellar winds then terminate the evolution of the star by the removal of the stellar envelope as a planetary nebula. The core shrinks and begins a protracted period of cooling as a white dwarf. This is the end for single, low and intermediate mass stars.

Stars with masses exceeding seven times that of the Sun generate core temperatures in excess of 800 million K. This is sufficient to allow carbon nuclei to combine in pairs directly to form neon. Carbon fusion produces even less energy than helium fusion and so lasts even less time. After only a few hundred years all the carbon is exhausted, and the star attempts to repeat the trick again (Fig. 2.4).

With the exception of a narrow window in mass of 9–9.25 solar masses, stars with masses above nine times that of the Sun initiate neon fusion and begin the final death-dive. Neon fusion lasts 12 months at most in stars with masses above 20 times that of the Sun and generates paltry amounts of energy, per unit mass, compared to the original stock of hydrogen. When that card has been played oxygen burning occurs for several months until silicon and sulfur are produced. Those stars in the range of 9–9.25 solar masses terminate fusion at the carbon-fusion stage, leaving either an oxygen-neon-magnesium white dwarf or they expire as supernovae. The latter is still a contentious issue, but is returned to in Chap. 6 (Figs. 2.5 and 2.6).

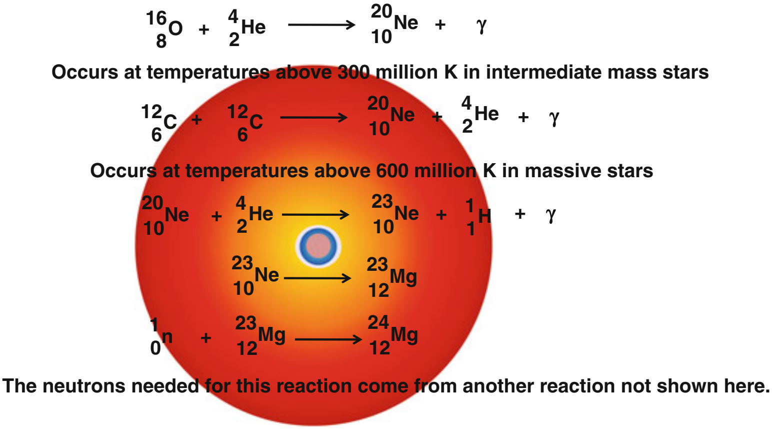

Fig. 2.4 The fusion of carbon to make neon and magnesium. With the exception of the top reaction these occur in the cores of massive stars where temperatures exceed 800 million Kelvin. These reactions are fairly complex, with a variety of products that are ultimately dominated by neon with lesser amounts of magnesium

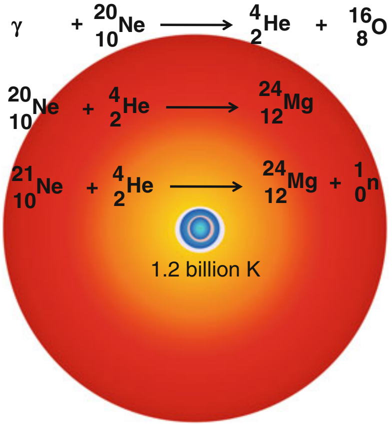

Fig. 2.5 Neon fusion occurs at temperatures around 1,200 million Kelvin. The reactions are a little complex, but magnesium is the ultimate product, along with neutrons. These free neutrons are soaked up in the reaction shown in Fig. 2.4 that also produces magnesium in the cooler shell above this one

For the most massive stars silicon fusion represents the final desperate act. Very little useful energy is released, and within a day more than a Sun's mass of silicon has been turned unproductively into iron. Any attempt to fuse iron is futile. As temperatures rise,

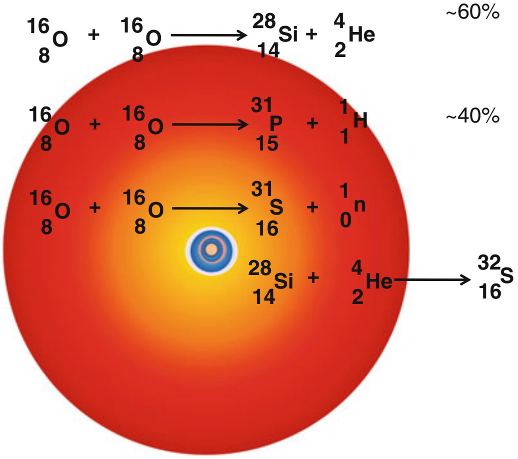

Fig. 2.6 Oxygen fusion. At temperatures around 1,500 million Kelvin oxygen fuses to make silicon and sulfur. The phosphorous shown here is converted into sulphur so that around 60 % of the core becomes silicon while the remainder is sulfur

iron doesn't fuse; it simply soaks up energy from the core. Were fusion possible, the outcome would be cooling of the core and the end of the reactions (Fig. 2.7).

Throughout the latter stages of nuclear burning the amount of energy released as ghost-like neutrinos accelerates. For a star born with 20 solar masses the luminosity in neutrinos rises by nearly one million fold from hydrogen to silicon burning. Most of these losses come from the creation and annihilation of positrons and electrons from energetic gamma rays. During the annihilation, some products end up as neutrino-antineutrino pairs rather than gamma rays. This is wasted energy that zips merrily out of the dying star. Consequently, the star is forced to contract its core further, raising the temperature and the rate of nuclear burning to compensate for the loss. But higher temperatures accelerate the process and a vicious, and self-destructive, cycle ensues.

Indeed, the mere act of pair production (electron-positron pairs) robs the star of some of its critical support, further hastening core collapse, temperature increase and enhancement in the rate of nuclear burning. For stars with less than 50 or so solar masses in their helium cores, pair production is not fatal in itself. However, later on pair production can have unfortunate effects for stars more massive than this limit.

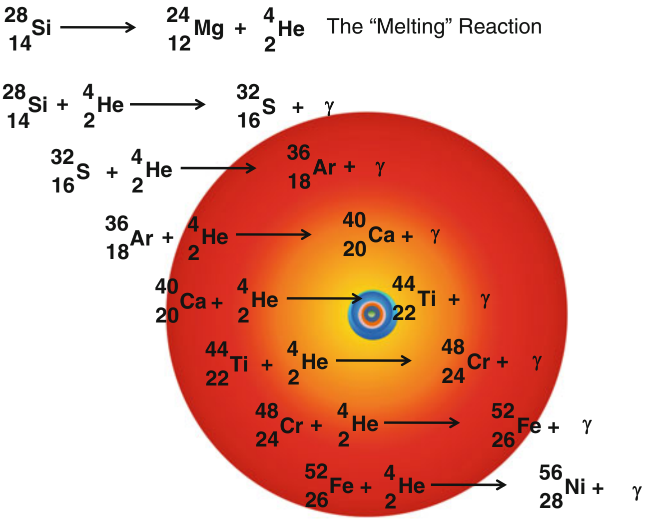

Fig. 2.7 Silicon fusion. Something of a misnomer, silicon fusion involves both its annihilation through the action of energetic gamma rays and a barrage of reactions where silicon serves as the scaffold for the assembly of iron and nickel. In the cores of massive stars energetic gamma rays break up silicon, releasing alpha particles. These are added to other silicon nuclei in a ladder of reactions that ultimately produce nickel-56. Silicon melts at temperatures above 2.7 billion Kelvin. Temperatures are higher in more massive stars and the resulting iron core can grow faster and larger before it implodes

Stages in the Life of a 25 Solar Mass Star

Burning phase	Required temperature (degree Kelvin)	Required mean density (gm per cubic cm)	Duration
-------------	---------------------	---------------------	-------------
Hydrogen burning	4×10^7	5	7,000,000 years
Helium burning	2×10^8	700	700,000 years
Carbon burning	6×10^8	200,000	600 years
Neon burning	1.2×10^9	4 million	1 year
Oxygen burning	1.5×10^9	10 million	6 months
Silicon burning	2.7×10^9	30 million	1 day

The increase in luminosity in the form of neutrinos provides the second explanation for the rapid decrease in the stellar burning time with each new fuel. The combination of lower productive energy release and the amount of total energy available causes the star to rush faster and faster headlong toward its grave. Each nuclear hit gives less return than the last.

As the last stages of nuclear burning are reached the interior of the star resembles an onion. The analogy with onions has become somewhat wearisome. Russian Matryoshka dolls are far more enlightening The inner iron core nestles within narrow shells of silicon and oxygen, which in turn snuggly settle within thicker layers of neon, carbon and helium, working outwards from the center. On the outside a layer of hydrogen persists – at least for single stars with masses of less than 25–30 times the mass of the Sun. Larger stars, or those in close binary partnerships, may shed their hydrogen (and sometimes helium) layers, exposing the hidden, former core.

Death of a Star

Once the core fills with more than 1.44 solar masses of iron the density and temperature reach a critical point at which energetic gamma rays begin to rip the iron nuclei apart. This process, called photodisintegration (meaning destruction by light), reverses the reactions that occurred over the preceding hundred thousand years or so. Iron becomes hydrogen, helium and neutrons. The next stage takes a lot longer to describe than it takes to happen. You may take a minute to read this paragraph, but in far less than a second the iron core is obliterated and its tattered remains implode.

During photodisintegration gamma rays split the nuclei down into smaller fragments; the process requires energy – the energy used by the star to support itself against gravity. In the final moments, as the soup of particles crushes inward at more than 70,000 km/s, electrons merge with the nuclei, further draining support from the moribund core. The products of this merger are neutrons and a sea of neutrinos that pour out of the core of the star, whipping away 99 % of the core's internal energy. However, the journey of these neutrinos, normally a peaceful and non-taxing ride, is severely hampered by the extreme densities of matter found

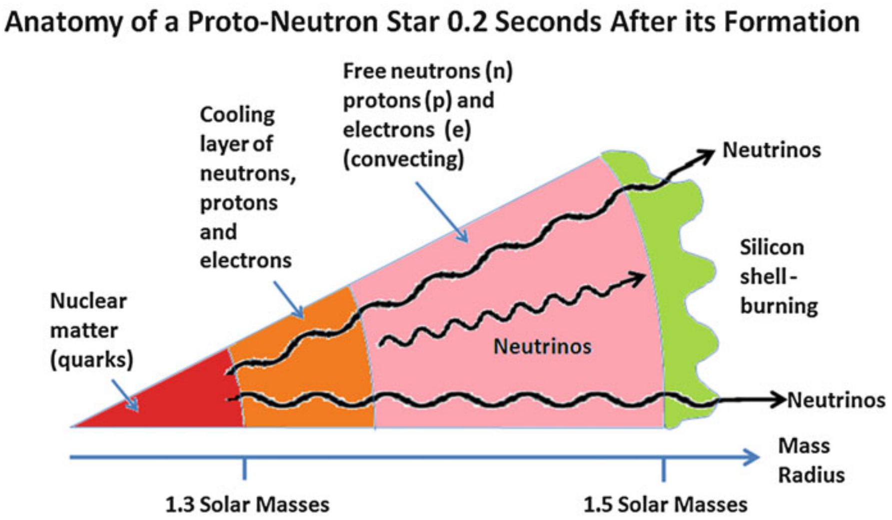

Fig. 2.8 0.2 s after the core collapses, the young, or proto, neutron star has a temperature in the hundreds of billions and is cooling quickly through the release of neutrinos. These particles can become trapped beneath the infalling silicon and oxygen shells and re-invigorate the stalled shockwave that lies near its outer surface 200 km above the center of the star. On the surface of the proto-neutron star silicon burning and other nuclear reactions continue

within the imploded core. Instead of wistfully departing the scene of the crime, they are briefly trapped within the carnage. It is this that leads to the next stage of the unfolding drama.

In the earliest models of core collapse, the formation of the neutron star was accompanied by a bounce as the material compressing into the proto-neutron star (as this hot, young object is called) overshot and bounced back outwards. However, it soon became clear that the energy of this bounce was insufficient to overcome the sheer weight of in-falling material in the overlying silicon and oxygen shells. The shockwave stopped in a fraction of a second, having traversed a pitiful 250 km or so from the ravaged surface of the proto-neutron star. Something else was needed to re-launch this failed shockwave (Fig. 2.8).

An initial solution to this conundrum came in the unlikely guise of the ephemeral neutrino. Neutrinos become shackled to the material within the dense stellar core. The neutron-rich matter forming the inner core boils at over 500 billion degrees Kelvin, and as the matter settles, neutrinos pour outward, impacting the collapsing silicon and oxygen shells surrounding the core.

Initially, in the 1980s, it was proposed that these escaping neutrinos would simply impart enough energy to the overlying silicon and oxygen shells and re-launch the stalled shockwave. However, the two-dimensional models used to justify this conclusion were too simplistic. Later three-dimensional versions of these seemed to falter.

In the early-1990s computer modeling by Adam Burrows (University of Arizona) indicated that the shockwave could be re-launched by the neutrinos but using a very different mechanism from a simple shove. Published in 1993, this model demonstrated that violent heating could drive convection-like plumes that ascended from above the edge of the neutron star – and they also dredged iron upwards from the deep interior to higher, cooler layers. Initially seen as a puzzling observation in SN 1987A, the presence of iron at early times indicated far more mixing between layers than was demonstrable in early modeling of supernovae. Thus convection seemed a reasonable starting point for an explosion, something that was also subsequently observed in laser-induced explosions in the lab.

However, these models were still done in two-dimensions, and it wasn't clear if they would apply to a more realistic three-dimensional structure such as a star. Further work with a class of explosions driven by so-called electron capture suggests that this mechanism might work for lower mass progenitor stars (9–9.25 solar masses). Electron capture probably drives the collapse of lower mass oxygen, neon and magnesium cores, rather than the more massive iron cores discussed here (Chap. 6). However, more recent work has indicated that the convection-driven mechanism is unable to drive explosions in more massive stars. There is simply too much mass in the overlying oxygen shell, and the process of convection delivers too little energy to drive it outward.

A further eclectic supernova model involved sound as the detonating mechanism. Again this work came from the University of Arizona, and the basic idea is fairly simple. Collapse of material onto the neutron star is an uneven and violent process; after all, material is imploding at 70,000 km/s. In this sonic model all the internal hullabaloo kicks off sound waves that rattle around in the collapsing core of the star, eventually causing the proto-neutron star to wiggle rather aggressively. Somewhat akin to watching the crowd at a 1970s punk concert, wavelike motion eventually sets in inside the material, which then initiates a shockwave that pushes out preferentially in one direction. Given the right amount of wiggling, the model indicated that the shockwave could drive violent expansion in one direction, and rather usefully also launch the neutron star through the expanding debris with a birth-kick – something that is observed in a number of supernova remnants.

However, is this real deal? At the moment no one is really sure. As yet we haven't exhausted all the possible players in this drama. As we already know stars rotate and possess magnetic fields. Indeed many of the sorts of B- and O-class stars that give rise to supernovae seem to possess relatively strong magnetic fields, and even those that do not should create such fields as the core of the star collapses inward.

Recall the physical property of rotating bodies: angular momentum. As a star's core collapses inwards angular momentum is conserved, and contraction must be accompanied by an increase in the rotation speed. Indeed, very basic calculations suggest that a freshly minted neutron star should spin at over 1,000 revolutions per second. Fast enough to dry your clothes in no time at all. However, neutron stars observed in supernova remnants spin nowhere near as fast as this. Typical speeds top out at a few tens of revolutions per second. For example the Crab pulsar spins at 33 times per second, and this is relatively nifty for a young neutron star. The question then arises, if they were born spinning much faster than this, where did all the extra spin go?

Astronomers have already observed young protostars ejecting material in jets and outflows from their rotation poles as they accrete material from their surroundings. This process allows the star to shed angular momentum effectively and collimate (or direct) magnetized outflows from the disc of matter surrounding them. In principle the proto-neutron star could do the same thing. Within the core of the star, matter accreting onto the proto-neutron star could spin it up and drive jets outwards along the star's rotation or magnetic axis. In addition, hot winds driven by nuclear reactions and neutrino emission within the accretion disc surrounding the proto-neutron star could also help drive material away from the collapsing core. Finally, the presence of a strong magnetic field within the proto-neutron star and any surrounding disc could launch jets of material outwards into the surroundings.

In reality all, some or none of these mechanisms could be at work, and it will undoubtedly take a lot of work and observation to discriminate between these models or their successors. Despite 50 years of work, in many ways the process of untangling the complexity of an imploding star is still in its infancy. However, one is reminded of Henry Louis Mencken's adage, "For every complex problem there is an answer that is clear, simple, and wrong." Keep watching for more complexity.

Fallback

In the outlined scenario, by some as yet unknown mechanism, a successful outgoing shockwave is launched. Within a day this penetrates the surface of the doomed star, scattering it to the four winds. However, what happens if the proto-neutron star doesn't impart enough kick to the material? In principle, if the stellar envelope is sufficiently massive, and particularly if it is densely packed, the outgoing shockwave may fail to puncture the star. In this case material would move outwards, albeit briefly; then either some or all of it would reverse its trajectory and begin raining back onto the newly formed neutron star. What would happen then? Work on so-called fallback has been modeled extensively over the decades, with some of the more recent work carried out by Stan Woosley (University of California, Santa Cruz), Chris Fryer (University of Arizona) and Andrew MacFadyen (New York University).

In stars with initial masses of over 30–40 times that of the Sun, stellar evolution produces a hydrogen-depleted object called a Wolf-Rayet star. We have encountered these already, but a few basic properties are worth reconsidering. Unlike a classic red supergiant, these objects may have only 10–20 times the mass of the Sun, but because they have shed their hydrogen-rich envelopes, these helium or carbon and oxygen-rich stars are small, dense and very hot. Modeling suggests that when core collapse occurs in these dense objects the shockwave is insufficiently powerful to push aside all of the material within the star. Instead a sizable proportion (up to a few solar masses) falls back onto the neutron star, triggering its implosion. The outcome is a stellar mass black hole: an object with 5–15 times the mass of the Sun squeezed into an area several kilometers across.

What happens next is in the realms of theory and computer simulation, but the suggestion is that the black hole may then accrete the bulk of the star through an accretion disc while simultaneously launching jets outwards through what remains. These jets may be visible as X-ray or gamma ray bursts, visible over cosmological distances (Chap. 4).

Depending on the nature of the collapse, and the amount of energy imparted to the surrounding material before the black hole formed, in principle some of the star may escape the clutches of the nascent black hole and become visible either as a supernova or in the form of jets directed towards us. Theory suggests that the supernova may be faint if little material escapes the clutches of the black hole. However, at least in some instances supernovae generated this way may be bright enough to observe over large distances.

Perhaps the most famous of these was the relatively close by SN 1998bw, associated with gamma ray burst GRB 980425. This Type Ic (hydrogen and helium deficient) supernova was particularly energetic, producing a disproportionately large quantity of radioactive nickel and a strong radio signal. The large mass of nickel (0.5 solar masses) suggested that in this explosion rather a large amount of material near the core managed to escape the nascent black hole. Other black holes, such as that found in Cygnus X-1, appear to have formed without much in the way of an explosion. So it appears that the formation of a black hole may be a very capricious process leading to very different outcomes for the parent star.

Observations of extreme metal-poor stars (EMPs) within the galactic halo indicate that their chemical compositions match the expected debris from supernovae that have substantial fallback. Work by Hideyuki Umeda and Ken'ichi Nomoto suggests that the composition of some EMPs can be produced by Population III stars that die in supernovae with substantial mixing and fallback onto the central stellar mass black hole. These supernovae lose most of the iron group elements, silicon and much of their oxygen into the maw of the growing black hole, while carbon and the products of helium and hydrogen fusion largely escape into interstellar space. Although clearly the output of a computer simulation, it is interesting that the model reproduces observations.

The Neutron Star

The product of core collapse for stars with initial masses of less than 25–40 times that of the Sun is an unusual object – the neutron star. Weighing in at roughly one and a half times the mass of the Sun but with a radius of only 10–15 km, it initially boils at over 500 billion degrees Kelvin. Its surface is a poor imitation of the original iron core of the once brilliant star, consisting of distorted iron group nuclei in a sea of electrons. Beneath this solid upper crust (perhaps 0.3–0.5 km thick) lies a 1–2 km lower crust of neutron rich material, primarily neutrons and electrons with some residual iron group nuclei. This layer lies atop a liquid mantle made of neutrons with a smattering of electrons and protons. Deeper still, within the central 3 km of the object, is a mysterious core consisting of neutrons, free quarks and gluons or maybe more exotic matter. The overall density is equivalent to, or exceeds that of, the nucleus of the atom – a stunning 100 trillion grams per cubic centimeter. One teaspoon would weigh in at roughly 100 million metric tons!

The gravitational field strength of this diminutive star is nearly 100 billion times that of Earth, and a spaceship taking off from one of these – were this possible – would need to reach one third the speed of light if it wished to escape the star's intense gravitational maw. Consequently, any object falling onto one of these objects releases rather a lot of gravitational potential energy upon impact. Gas, unfortunate enough to end up within the sphere of influence of a neutron star, impacts the surface, releasing a blast of X-rays.

Some unexpected observations were made of the central neutron star in the Cassiopeia A supernova remnant, observations best explained by nuclear reactions. The Cassiopeia A supernova remnant is approximately 300 years old, and the central neutron star appears to have a carbon atmosphere. Although it is possible that the carbon was accreted from the supernova remnant, it is unlikely that this would be the only element to be drawn to the neutron star. After all, hydrogen and helium are more abundant. Instead the suggestion was that hydrogen and helium, accreted from the surrounding remnant, underwent nuclear reactions and produced the carbon seen today. Observations of young neutrons stars would show if this was commonplace, as the reactions will release copious amounts of hard X-rays and gamma rays at characteristic wavelengths.

Aside from the high density and associated intense gravitational field, young neutron stars are intensely magnetic. A typical magnetic field strength is on the order of a trillion times that seen on Earth, or 10^{12} G. This field, coupled to the rapid rotation of the neutron star, readily accelerates particles embedded within the stellar atmosphere. Electrons spiraling within the magnetic field release primarily synchrotron radiation, but not exclusively at radio wavelengths. The 1,000 year old Crab pulsar also releases pulses of visible synchrotron radiation, and some, including the Crab pulsar, release pulses of X-rays. These pulses can be used to measure the rotation rate of the host neutron star, and rates have been found to vary from once every few seconds up to hundreds of revolutions per second for some old, "recycled" pulsars. Young pulsars, such as the Crab or Vela, spin at 10–30 revolutions per second. The Crab pulsar spins once on its axis every 33 milliseconds, and sensitive measurements confirm that it is slowly decelerating.

Why does it spin so quickly and why is it decelerating? Remember the conservation of angular momentum. As the core of the parent star shrank, its speed of rotation had to accelerate in order to conserve its momentum. Initially, this led to very high rotation rates, perhaps 200 times per second. However, as we saw, the braking of the magnetic field against the expanding debris in the supernova and the interstellar field leads to deceleration. A young neutron star decelerates by between 10^{-10} and 10^{-21} s for each rotation – not much, you may think, but after a million years or so this amounts to a few percent of the rotation of the star. With the declining rate of rotation falls the strength of the magnetic field. At some point the strength of the magnetic field falls below a critical threshold, and the star stops pulsing. It isn't clear entirely where this is, but it may lie somewhere near 100 million gauss, or approximately 100 million times the field strength around Earth.

Although neutron stars are born exceedingly hot, they cool quickly. Their surface area to volume ratio is high, but the density of the material resists cooling by standard electromagnetic radiation. Instead it falls to the elf-like neutrino to do the job of cooling the star. Over a few hundred years following inception, the temperature of the star falls from nearly one trillion degrees down to a few hundred million – a factor of 10,000. Meanwhile the surface temperature falls to around a few million by this point. The Cassiopeia A neutron star has already cooled to just over two million Kelvin within the last 300 years.

A recent paper by Dany Page suggested that the enhanced rate of cooling in this neutron star was due to the commencement of super-fluid behavior within the neutron star mantle. Super-fluidity is a property observed in some highly chilled gases on Earth. Despite the extreme heat and pressure, within the neutron star the neutrons can behave as a super fluid. Unusual quantum interactions between the neutrons allow them to move as though there is no friction between them. This allows convection to transport heat with high efficiency, thus cooling the core of the neutron star quickly. Although super-fluidity is predicted for neutron star interiors, exactly how this affects their properties is still in the realms of theory and speculation. The enhanced cooling rate seen in the Cassiopeia A remnant neutron star may be one of the first testable demonstrations of the role of super-fluidity within a neutron star.

A few neutron stars are born with peculiar magnetic fields that dwarf the heady strength achieved in more conventional pulsars by more than a factor of a hundred. These magnetars have fields so intense that iron nuclei in their crusts will be distorted into cigar shapes. Fields 100–1,000 times the strengths seen in a pulsar require an unusual mechanism to form them. The likely scenario involves a proto-neutron star spinning at more than 200 times per second. In this hot, fast rotating body a dynamo effect can develop that produces a field with a strength of 10^{15} times that of Earth. Such magnetars have fields so intense that they rapidly brake the rotation to less than once per second. Although sluggish in terms of rotation, the magnetic energy contained within these strange stars can warp and crack the surface of the neutron star, leading to the release of energy in a massive starquake.

Visible as a blast of gamma rays across galactic distances, these magnetars appear as soft-gamma ray repeaters, SGRs for short. Only a handful are known, along with a similarly paltry number of related but lower energy anomalous X-ray repeaters. Quite why some neutron stars are born as magnetars is unknown, but this may come down to the rotation of the parent star or perhaps even the mass of the star that gave rise to them. Certainly, to form a magnetar it seems likely that they must have inherited excess angular momentum from their parent star – but quite how this will relate to the properties of the progenitor are still unclear.

Magnetars may hold the key to some of the universe's most brilliant supernovae. We shall return to these eclectic beasts in Chap. 9.

The Fate of the Surrounding Star

What of the parent star itself? We already know it's doomed, but how does its demise demonstrate itself to the outside universe?

Within the immediate vicinity of the core, neutrons and other fragments of atoms punch into the surrounding silicon shell. Violent nuclear reactions generate a large quantity of radioactive iron, cobalt and nickel. In addition to these atoms, somewhere in this mêlée the soup of particles generates every other element in the Periodic Table upwards, through lead and uranium, towards an unknown summit. Above this, as this shockwave moves outward, it compresses and heats the various shells of material triggering a final wave of nuclear reactions.

For Type Ic supernovae, the shock wave finally leaves the star at the surface of the carbon shell, or a short way through an outer carbon-enriched helium layer after a few hours. These stars are relatively small, perhaps the diameter of the Sun. For Type Ib supernovae, the star is larger, perhaps a hundred times that of the Sun. Here, the shockwave continues expanding outwards until it exits through the more massive helium shell. And finally, for the bulkiest (if not the most massive) red supergiant stars, the shockwave ploughs onwards at 7,000–10,000 km per second before, perhaps a day later, leaving the hydrogen-rich outer envelope of the star. The progenitors of these Type II supernovae are perhaps 500–1,000

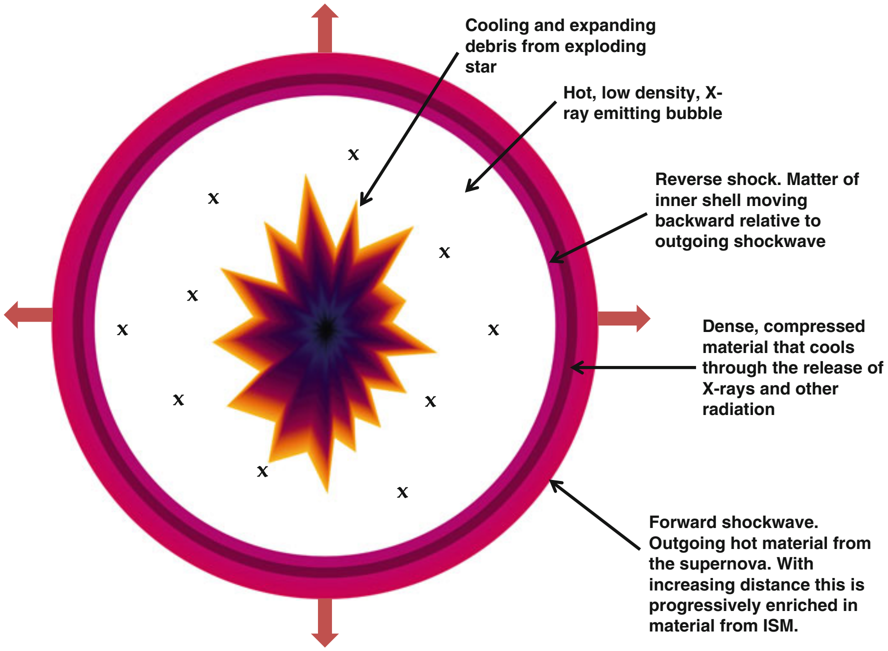

Fig. 2.9 The structure of a supernova shockwave

times wider than the Sun, hence the lengthy delay between the inception of the shockwave and its exit from the star. Even at a nifty click of 10,000 km per second the shockwave takes many hours to blitz the star's outer layers. Conversely, the progenitors of Type Ic supernovae may be only a few times the diameter of the Sun and take correspondingly less time to reach the stellar surface (Fig. 2.9).

What would the emerging shockwave look like? Probably not a smoothly penetrating sheet, for a start. The shockwave will undoubtedly be very uneven, and if it is driven by jets from deep within the star, will have a very aspherical shape. There is ample evidence that a large proportion of core-collapse supernovae are aspherical, many bearing witness to the effects of jets.

As the shockwave passes through material it imparts considerable energy which heats and expands the material. As the shockwave approaches the stellar photosphere, heating raises the temperature to hundreds of thousands of degrees Kelvin causing the material to emit copious amounts of X-rays and ultraviolet light (Fig. 2.10).

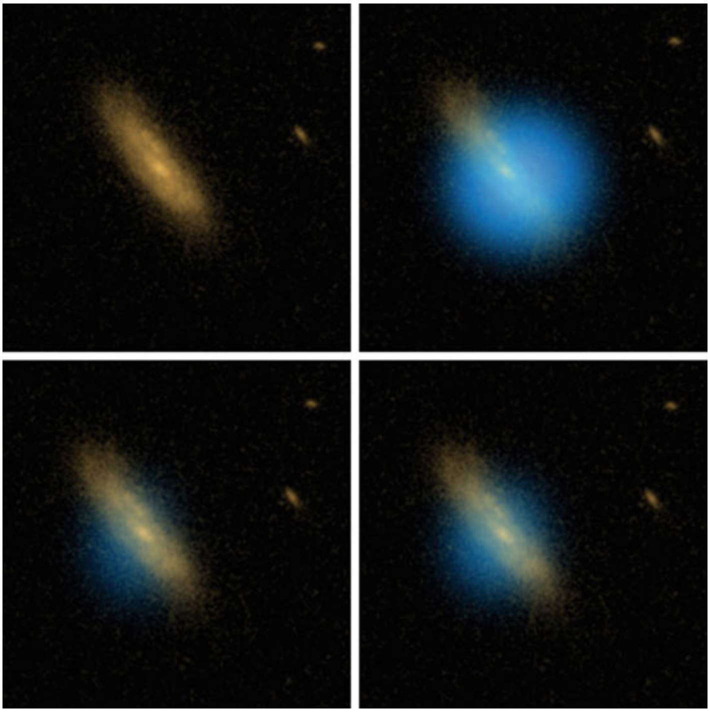

Fig. 2.10 Shock breakout in SNLS-04D2dc, detected as an ultraviolet flash by GALEX. (Images courtesy of NASA/HST/COSMOS/GALE)

In 2008 the Supernova Legacy Survey detected an explosion dubbed SNLS-04D2dc (Fig. 2.10). With some careful detective work the team combed archived ultraviolet images gathered by GALEX (NASA's Galaxy Evolution Explorer) taken during the previous few weeks. Diligence paid off, and a series of images were obtained that rev-ealed the death throes of a red supergiant as the supernova shockwave punched through the surface of the star and out into the giant's extended atmosphere. The supernova was an unremarkable Type II-P event, but this was the first time the shockwave had been seen punching out through this type of star.

A few months previously a similar event in a more compact progenitor was observed. This was associated with the Type Ibc supernova, SN 2008D. A Type Ibc explosion is one that initially displays helium in its spectrum, but later morphs into a helium-free event. Shock breakout through this compact star generated a pulse of X-rays detected by NASA's SWIFT telescope. The detection of this breakout, associated with this supernova, was serendipitous – a chance discovery, one which may not easily be repeated. The Supernova Legacy work was more akin to detective work but with a bit of luck in that the GALEX happened to be looking in the right place at the tight time.

Formation of Supernova Remnants

Following shock breakout the expanding debris immediately begins to cool. Energy is provided by the decay of elements synthesized in the explosion and, in some instances, by the interaction of the expanding debris with any surrounding material. However, it is worth considering the explosion itself, for it is very easy to misunderstand what has just happened to the material in the star.

It is easy to imagine that the shockwave, moving at over 10,000 km per second, simply lifts material ahead of it. However, instead it is a little bit more like the wave moving through a stadium crowd. The shockwave moves through and accelerates the bulk of the material but to a speed less than the wave as a whole is moving. The material accelerates to above the escape velocity of the star, but the shock wave is constantly moving outwards ahead of this mass of accelerated material. As a result, the shockwave moves away from the star, interacting with anything in its path, compressing and accelerating it. Lagging increasingly far behind is the expanding debris of the star. A small fraction of the star (less than 1 solar mass) moves bodily with the shockwave, out from the stellar surface and off into interstellar space, with the bulk of the material following more slowly behind this wave.

This can be seen in recent Hubble images of the SN 1987A supernova remnant (below). Behind the outgoing shock, expanding material, encountering the shockwave, generates a reverse shock that propagates backward, relative to the outgoing forward shock. This reverse shock slows the expansion of the remnant and can contribute to fallback onto the central object left by the explosion (Fig. 2.11).

After the shock has broken out in a typical Type II supernova, the expanding mass of debris brightens as its surface area expands. This phase lasts for perhaps 1 month. After this, cooling

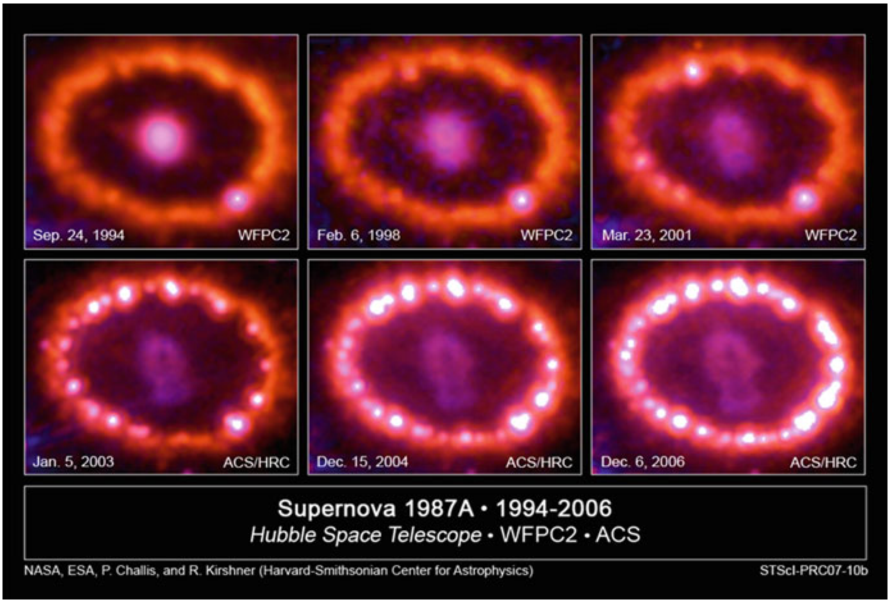

Fig. 2.11 Successive images in the evolution of SN 1987A. In the first image (*top left*) the shockwave from the explosion lies between the central *purple* supernova and the ring of material ejected prior to the supernova. By the time the *lower left* image is taken the shockwave has begun a strong interaction with the ring of material, but the supernova remnant (*purplish in color*) is clearly lagging behind (Image source: Hubble/NASA.)

begins to offset expansion and the luminosity falls. When the visible surface of the supernova has expanded to approximately 20 billion kilometers it becomes transparent, and the light produced drops dramatically. Plotting the visible light using photometric techniques captured from the explosion allows astronomers to construct light curves that provide valuable clues to the inner workings of the explosion. A light curve is usually a plot of visible magnitudes below maximum light versus time measured in days (Fig. 2.12).

During the first 25 days or so, after peak brightness, luminosity typically falls by 0.008 magnitudes per day on average. However from day 25–75 many Type II supernovae display a plateau in their light curve and are known as Type II-P explosions as a result. During this curious phase, hydrogen, abundant in Type II events, is initially very hot (more than 7,000 °K). However, as it cools

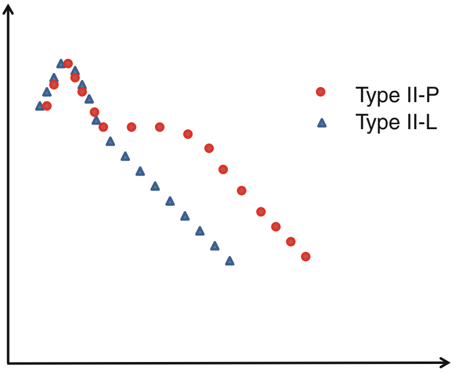

Fig. 2.12 A comparison of the light curves of Type II-P (Plateau) supernovae and Type II-L (Linear) supernovae

electrons can recombine with free nuclei and release a photon of light. This process continues until the temperature has fallen to less than 4,000 °K and the hydrogen is fully recombined as neutral gas. As the material is heated by radioactive decay internally, this process begins from the outside and works its way inward until the hydrogen is exhausted. However, this inward shrinkage is balanced initially by the expansion of the stellar debris, thus producing near constant light during the process. This explains the peculiar curve.

Stars with proportionately smaller (less voluminous) hydrogen envelopes will have smaller plateaus until this part of the light curve disappears altogether in stars with little or no hydrogen. Supernovae that display hydrogen but only in small amounts may appear as so-called Type II-L, or linear supernovae, as their curves are not punctuated by the plateau. Type II-L explosions consequently show more rapid decays in their light curves (around 0.012 magnitudes per day). In some instances limited amounts of hydrogen cause the supernova to transform from Type II to Type Ib events, and SN 1993J is a well-characterized example of this. Analysis later confirmed that SN 1993J has a massive, close companion star that appears to have removed much of the supernova progenitor's hydrogen envelope immediately before the explosion.

Messages From a Retreating Front

An informative feature of supernovae is the manner in which the expanding remnant undergoes various transitions as it expands and cools. At very early stages the photosphere of the supernova is moving outward with the shock-heated debris and illuminates only the outermost portion of the shattered star. However, as the material cools the photosphere, the virtual surface from which light escapes retreats inside this cocoon. This reveals progressively deeper and deeper layers as the light-emitting surface of the photosphere retreats further and further inside the expanding remnant. Elements forged at every layer of our broken Matryoshka doll appear, one after another as the light from the retreating front is absorbed by material lying ahead of it. Thus the interior of the star is opened much like peeling layer after layer of an onion. Not only does this reveal the inner architecture of the star but it can reveal how the star blew up. Close scrutiny of this process has allowed astronomers to understand how much mixing occurs inside the doomed star as the shockwave punches through the star. Such examination of SN 1987A showed that nickel-rich debris from the stellar core was present at far higher levels than expected, indicating thorough mixing.

Following the plateau phase the supernova continues to fade, but the decline is initially dictated by the decay of radioactive nickel-56 and cobalt-56, and much later by the decay of longer-lived radioactive isotopes such as titanium-44. Nickel-56 is abundantly synthesized in supernovae, as we have seen, but decays very quickly, with a half-life of 6.1 days to produce cobalt-56. This latter nuclide decays with a half-life of 77 days, and the decline in output from it principally governs the terminal decline in supernova luminosity. Decay of these nuclei is by positron and gamma emission. The primary gamma rays, and those produced by the annihilation of positrons, heat the expanding stellar material, causing it to glow.

Typical yields of radioactive nickel are on the order of 0.07 solar masses, but some core-collapse supernovae produce rather a lot more than this. SN 1998bw produced an estimated 0.5 solar masses; a typical Type Ia supernova produces 0.7 solar masses of radioactive nickel. These numbers seem rather abstract, so it's better to put them another way. If we go for the figure of 0.07 solar masses, typical of a Type II-P event, this is equivalent to 1.4×10^{29} kg – or 50,000 times the mass of Earth, give or take a few Mount Everests. Remember this is all in the form of a single radioactive element that is decaying and releasing energy.

SN 1987A, despite more than a few well-discussed oddities, beautifully confirmed many of the theories of supernovae. SN 1987A was peculiar because the progenitor was a compact blue supergiant star rather than a red supergiant, expanding if not contradicting the initial models of the day. The compact nature of the progenitor produced a slightly distorted light curve that essentially rose to a plateau and then declined, rather than peaking first. More energy went into detonating the star, rather than heating and driving material outward. Perhaps most significantly, a pulse of neutrinos was detected at the time of the explosion, confirming that a neutron star had formed. Finally, the production of radioactive elements by the explosion was observed at very early times, confirming models of nucleosynthesis. As previously mentioned, SN 1987A also revealed that heavier nuclei from deep within the star could be mixed upwards in the explosion, appearing at earlier than expected times in the spectrum of the explosion. This may be evidence of jets or plumes directed outward from the core of the star during the earliest stages of the explosion. Clearly, more work remains to be done in this area.

A typical Type II explosion releases approximately 10^{46} J of energy. Almost 99 % of this is in the form of neutrinos, but this still leaves a whopping 10^{44} J in kinetic energy and 10^{42} J in the form of electromagnetic radiation. Although the electromagnetic energy is disperses fairly quickly, the kinetic energy is a lot harder to dispose of. Initially, the kinetic energy in the debris expands freely – although, as we'll see, Type IIn explosions are exceptions to this rule. A typical core-collapse supernova may shed 5–10 solar masses of material. However, the bulk of the kinetic energy is carried by a much smaller fraction of this (maybe 0.25 solar masses). This small fraction constitutes the outgoing shockwave that will readily sweep up any material it encounters.

Given the low densities of material in space, this process may take hundreds of years to plough up a significant mass of material. However, what is swept up is violently heated to millions of degrees Kelvin. Material in the shell is thus both highly ionized and is a copious source of X-rays. At the shock interface electrons in the gas are accelerated and release synchrotron radiation primarily in the form of radio waves. Type II supernovae (particularly Type II-P) are usually strong emitters of radio waves. Thermonuclear Type Ia supernovae tend to be radio emission-free.

Some of the super-heated gas within the shell is able to fall back and cross behind the shock, forming a low density hot bubble of X-ray emitting gas. Over time this bubble grows as the shockwave moves outward at thousands of kilometers per second.

Over the ensuing millennia, the shockwave expands and the amount of kinetic energy present per unit mass in the debris falls. Moreover, the amount of matter in the shell is increasing, which further reduces the share of kinetic energy between particles. The shell thus begins a protracted period of deceleration. As the kinetic energy falls, the temperature begins to fall, and the amount of ionization decreases. The shell begins to falter in its advance. At a critical point, tens of thousands of years after the initial explosion, the matter in the shockwave has insufficient energy to continue bulldozing its surroundings. At this point, the light begins to go out, and the shocked material merges with the surrounding interstellar medium (ISM). All that remains is a ghostly pall of metal-enriched debris, ready to collapse again to form a new generation of stars.

By contrast material within the shocked bubble has such a low density that it is very difficult to cool by recombination. Thus supernovae-driven bubbles can remain in place for millions of years and extend beyond 1,000 light years in diameter. In galaxies like our own, not only do supernovae enrich their surroundings chemically, they mix and expel copious amounts of material from the galactic disc into the halo. In a large galaxy like ours, this is of only short-term interest, as this material remains trapped by our galaxy's gravitational field. However, in small galaxies, supernovae can drastically alter the fate of the galaxy by driving star-forming material out of the galaxy into intergalactic space. This can lead to the cessation of further rounds of star formation and end what was a fertile period in the galaxy's history.

In gas-poor elliptical galaxies, supernovae may also drive a galactic wind, whereby the shockwaves from explosions expand freely in the gas-poor medium and push outward into intergalactic space. Such activity may explain, in part, why elliptical galaxies support such feeble rates of star formation.

Conclusions

We've explored the basic ingredients for massive star formation and death and broached upon the areas where supernovae may affect galactic environments. With a basic foundation in supernova biology we are now ready to embark on the main focus of this book: the life and death of the most massive stars in the universe and some of the more enigmatic explosions stars produce when they die.

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