Astronomers' Universe

David S. Stevenson

Extreme Explosions

Supernovae, Hypernovae, Magnetars, and Other Unusual Cosmic Blasts

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Preface

Although I was perhaps only 6 or 7 years old at the time, I remember my dad taking me out on cold winter evenings, pointing out the constellations as we walked slowly up the frost-glazed road. This was suburban Glasgow, then a city of one million people, and there was relatively less light pollution and many thousands of stars that were visible. I was immediately intrigued by the differences in brightness and colors of the stars, as much as I was about their twinkling effervescence. Even from a city as big as Glasgow, the sheer beauty of space never failed to amaze me.

I suppose it was my dad's enthusiasm for a night sky – a love born during his time on HMS Orion in the First World War – that really pushed me in this direction. By eight, I had developed an unhealthy love of explosions. Early on my main area of explosive interest, aside from James Bond movies, was volcanoes. However, once I knew that entire stars could blow themselves to pieces, I was never really going to look back. At eight, I had my first book on stars, and even though it was soon chewed to pieces by my pet hamster, it was still heavily thumbed in search of facts about why something as awesome as a star could blow up. By the time I was ten, I had already grasped how stars evolved, understood that there were different types of supernovae, and had absorbed some of the more peculiar aspects of the evolution of the universe.

In my teens, in the 1980s, I realized that there were very few books that extended what I already knew about stars, and although I was subsequently able to access peer-reviewed articles while at Glasgow and Cambridge Universities, it was evident that the number of more advanced titles were limited to the point of virtual non-existence.

The aim of this book is not to produce a comprehensive coverage of supernovae, nor is it going to rehash the general mechanisms of supernovae that can be found elsewhere in abundance. Instead, I wish to take this opportunity to present the more unusual examples of stellar deflagration and detonation that are pouring out of automated searches for supernovae. The science of stellar death has ballooned in the last decade, on the back of decades of theorization and observation. This is an attempt to bring those new understandings to a broader audience. In this title, I have attempted to cover as wide a range of discoveries as possible. However, if you trawl websites such as www.universetoday.com or www.ArXiV.com, you will undoubtedly discover more that I either could not include for reasons of space or continuity or simply was not aware of. However, this book should serve to extend considerably the baseline knowledge of those interested in stars and form a starting point for further personal discovery. I hope you enjoy it.

Nottingham, UK David S. Stevenson

About the Author

David Sinclair Stevenson studied Molecular Biology at Glasgow University before completing his PhD in molecular genetics at the University of Cambridge. Subsequently, David studied and achieved a distinction in Astronomy and Planetary Science, and Geochemistry and Geophysics at the Open University. His peer-reviewed biological research articles from 1999 to 2009 include a paper on the early development of life, "The Origin of Translation," published in the *Journal of Theoretical Biology*.

David's interest in astronomy was encouraged from an early age by his father. This (combined with an interest in explosions!) has led David to research and write about the life and death of stars.

After a stint in academia, David became a teacher but continued to write scientific articles for various publications. He has published numerous articles on the Blackwell Plant Sciences website (2002–2007). "Turning Out the Lights" (an article about red dwarfs) was published in *Popular Astronomy* in 2003, "A Bigger Bang" (about Type Ia supernovae) in *Sky & Telescope* in July 2007, with "Supercharged Supernovae" featuring as the cover story for the October 2011 edition of *Sky & Telescope*. He is currently writing another book for Springer called *Under a Crimson Sun*, on the possibilities of life in red dwarf systems.

David lives in Nottingham in the UK with his wife and family.

Contents

Part I
An Overview of Stellar Evolution

1. The Biology of Supernovae

Introduction

Stars shredded into pieces and nearby planets boiling away are among the images conjured up by the word "supernova." Shockwaves pound outwards and turn rocky asteroids into cometary fluff, driving planetary shards from their orbits and showering neighboring star systems with waves of deadly radiation. It's dramatic stuff. But what really happens inside the blast wave of a supernova, and, more importantly how can we explain all the different forms of explosion that are emerging from automated supernova searches? This book explores these violent and sometimes strange landscapes, populated by the corpses of tortured stars. Recent observations have revealed a wealth of new types of explosion, as well as illuminating the underlying mechanisms of how stars explode.

A traveler of any sort needs a map, a compass and some sort of focal point onto which new discoveries can be pinned. Astronomers employ a number of tools that return the information they require to describe and explain supernovae. This chapter is subdivided into sections that build one upon the other. From these modest beginnings we will emerge in a world like no other, a world of poetic death, schadenfreude and humbling sacrifice.

We begin our journey with the tools to navigate: stellar spectra, the Hertzsprung-Russell diagram, photometry and a brief guide to stellar structure and function.

Spectra: Chemical Portraits of Stars

Spectroscopy can be thought of as the study of the "chemistry of light." When white light is passed through a prism or diffraction grating the light is split into its respective colors. Each chemical

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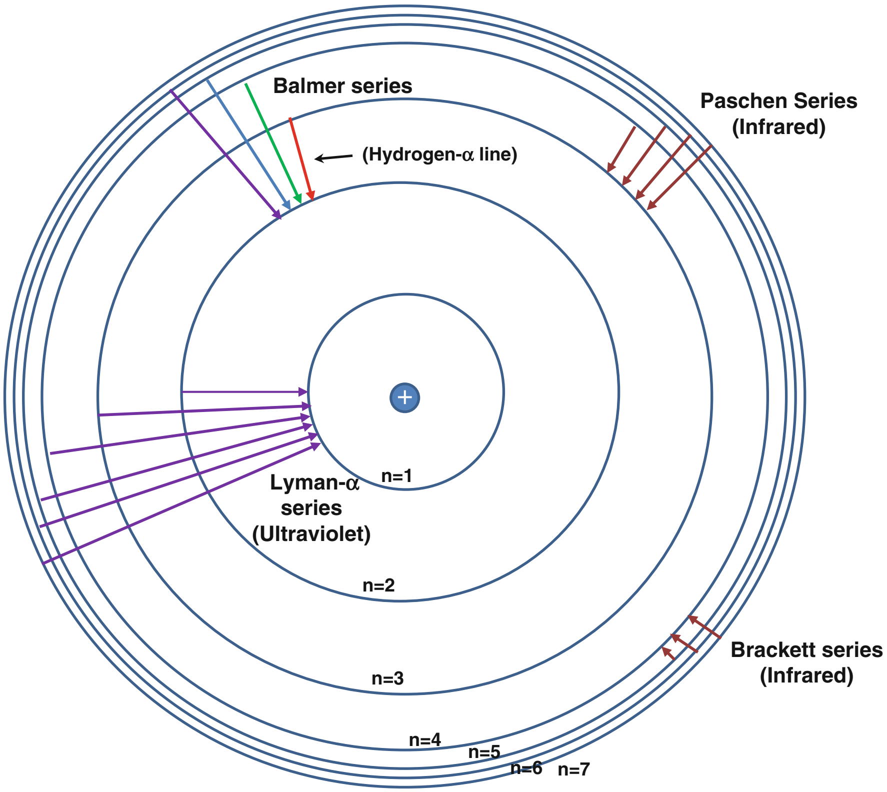

Fig. 1.1 Energy levels in a hydrogen atom. If electrons drop to the first level (n = 1) from the outer, higher energy levels they emit an ultraviolet photon. The well-known Balmer emission series (hydrogen-α) is produced when electrons drop from upper level three to the lower second level. Corresponding upward movements generate absorption features

element has a distinctive and unique spectroscopic signature. Although significantly lower in intensity than sunlight, starlight can also be split this way. The resulting spectrum gives a unique chemical signature for the star (Fig. 1.1).

Spectra come in three broad flavors: absorption, continuous and emission. A continuous spectrum is a bland rainbow of color produced by a chemically mixed source of light such as the surface, or photosphere, of a star. Where the light passes through intervening material an absorption spectrum of dark bands, called Fraunhofer lines, are observed. Finally, where light is emitted by excited gas this light is broken into bright bands called emission spectra.

Only the hottest stars or strongly irradiated gas produces emission lines. But what are these bands and how are they produced?

To answer this innocuous question we need to take a brief tour of the atom. In standard high school textbooks the atom is a Solar System in miniature, with planetary electrons orbiting a nuclear Sun. However, unlike planets whose orbits wobble and stretch, electrons experience an odd, restricted life. Electrons exist around the nucleus in specific energy levels or shells. Leaving aside the peculiarities of quantum physics, electrons remain in these shells with specific energies, unless they absorb or emit energy.

Now, not any energy will suffice. Electrons are picky. Thinking somewhat anthropomorphically, if the electron wants to move up one or more energy levels it must absorb a specific packet or quanta of energy – a photon with the correct frequency.

The energy levels are separated by specific energy amounts, and the absorbed photon must match the energy if the electron is to hop up. The electron can also move down a level by emitting a photon of light. This photon will exactly match the difference in the energy of the levels the electron has traversed.

Given enough energy, the electron can shake free of its bonds and escape the atomic nucleus altogether. This process, called ionization, allows the electron the freedom to absorb subsequent photons with any energy.

Absorption of photons by electrons gives rise to the dark Fraunhofer lines. Each element has a unique set of protons and (in the neutral state) an equal number of electrons that characterizes the chemistry of that atom. Consequently, the movement of electrons between atomic shells formulates a unique signature of absorption or emission that is evident in the spectrum of the light source or gas through which the light traverses.

An observer examining the light from the star, peering through the cloud, will see these absorptions as an absorption spectrum. Conversely an astronomer able to observe the gas without interference from light directly from the parent star will see only the light emitted by the same electrons as they lose energy and drop back down energy levels. This will produce an emission spectrum. In reality on Earth we can see all three of these from the same object (or at least the vicinity of the illuminating object) by blocking out portions of starlight entering the telescope's spectroscope. The end result can be a detailed chemical portrait of the star and its surroundings. Knowledge of this sort is essential, as we shall see that some stars have a deft knack of shedding their skin as they age. In these evolutions, the pupal case is often as important as the beast that emerges from underneath as they reveal the inner workings of the star in the period running up to its death.

Conversely, atoms with very excited, energetic electrons can calm down by electrons leaping down energy levels and emitting photons of light that correspond to the difference in energy levels. These liberated photons constitute the building blocks of the emission spectra – the bright lines on an otherwise dark background. Similarly, if light is emitted by a cloud of diffuse, hot gas it will also display emission lines. O-type stars, the hottest and most luminous in the universe, are sufficiently energetic to display emission lines corresponding to hydrogen and helium in their spectra. Any hydrogen or helium in their vicinity may also be ionized by the profuse emission of ultraviolet light from their surfaces. Consequently, the nebulae from which they form, and so frequently are associated with them, show prominent emission of hydrogen-alpha (Balmer) and Lyman-alpha lines and glow a profuse red. As a result O-type stars, buried within nebulosity and clusters of lesser stars, may be spotted over cosmological distances by the effect they have on nearby nebulosity. The Orion Nebula is perhaps the most famous nearby example powered by a small, tight cluster of O-type stars – the Trapezium. Many others are known (Fig. 1.2).

Consider this further. Imagine you are an electron and you're stuck on the ground floor of a building. You receive a package to deliver to the top floor. Now, you could take the stairs, but it's a long way to the top floor where the package needs posting. So, you take the elevator. The package is your photon, the particle of radiant energy that you collect to elevate you to the top floor. You absorb your photon, take your package and rise up the building in the elevator. In terms of the spectrum you could go all the way to the top if the photon is energetic enough, and a dark band will appear corresponding to this transition in the electron's energy. However, you could be left wanting and only have enough energy to reach the second floor. A different band, representing lower energy, will appear in the spectrum.

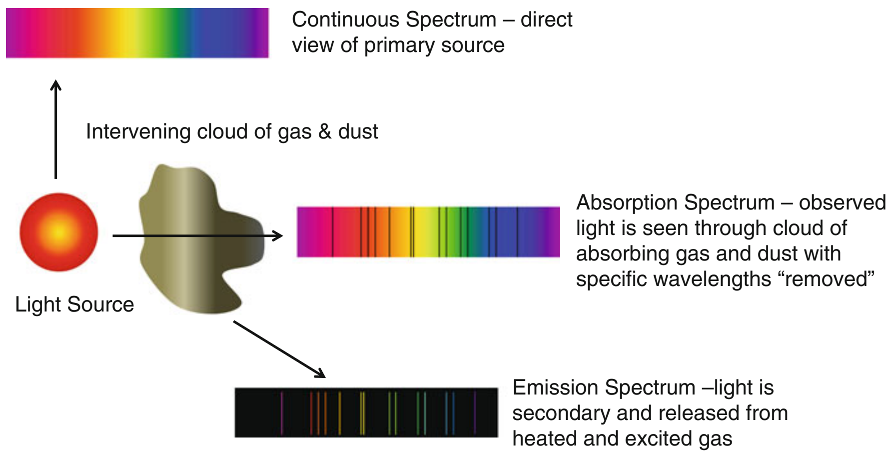

Fig. 1.2 The formation of different kinds of spectra. This is dependent on the viewing angle of the light source and the presence of any intervening material that is excited by short wavelength radiation or collisions

OK, let's say the photon packed enough punch to get you all the way to the top floor. At the top you take a rest, drop off your photon and drop all the way back down again. The photon emitted will exactly correspond to the one absorbed in terms of its energy. In which case, you might see an emission spectrum forming a mirror image of the absorption spectrum, but viewed at a different angle.

However, you fancy a change. On your way up you spotted some interesting things on different floors, so instead of going down straightaway, you pop out of the elevator onto different, intermediary hallways and landings before continuing your journey. Each time you drop off at an intermediate floor a photon of energy corresponding to the difference in energy levels is released. Since there are many different floors on the way down the chances are you will pop out at any number of these before returning to the lobby. Consequently, it is highly unlikely that the emission spectrum would directly mirror any absorption spectrum. There are simply too many possible other floors onto which an electron could emerge on its way back to the lobby. However, the emission spectrum would still carry the chemical fingerprint allowing the material's identification. The bands produced, whether absorption or emission, will still form the same unique chemical fingerprint for whatever chemical element is present.

In reality, unless the gas has a simple composition, the identification of all the bands may be very complex, indeed. As well as simple chemical elements, molecules, such as carbon monoxide or metal oxides in some stars, produce a myriad of complex absorption bands that can make the task of identifying the chemical composition vexing to say the least. In addition bands can be split in two if strong magnetic fields are present. Finally, stellar rotation and strong gravity can stretch or move some bands subtly around the spectrum, further complicating the process of chemical fingerprinting.

A case in point was the unusual supernovae SN 2005ap. Although a few absorption bands were noted in this supernova's spectrum, it wasn't until astronomer Robert Quimby realized that adjusting the spectrum for cosmological red shift meant that the explosion spectrum could be aligned with other, unusual blasts. At that point some of the chemical elements present were matched up to reference spectra and the problem was solved. When you look at the relatively simple spectrum of SN 2005ap you can appreciate how even a simple problem can cause confusion.

Photometry: Behavioral Studies of Stellar Death

Photometry is the measurement of the intensity, or flux, of energy in the form of electromagnetic radiation. The electromagnetic spectrum spans from radio waves at the lowest energy and frequencies through visible and ultraviolet all the way to the most energetic and highest frequency radiation – gamma rays. The majority of photometric examination of stars occurs from the near infrared through visible to the near ultraviolet. This is, in part, an historical situation, as stellar observations were most commonly done in or near to the visible portion of the electromagnetic spectrum. However, most stars emit the bulk of their radiation at visible wavelengths, hence the propensity of analyses at these wavelengths.

There are, however, many clear exceptions. The hottest stars (classes O and B) emit a large proportion of their energy in the ultraviolet range, while cool stars emit the bulk of their energy at infrared wavelengths. This means that measurements taken solely

Table 1.1 Pre-existing filter bands used in photometry and their corresponding wavelengths

Filter letter	Effective wavelength midpoint l_{eff} for standard filter	Description
Ultraviolet		
U	365 nm	"U" stands for ultraviolet
Visible		
B	445 nm	"B" stands for blue
V	551 nm	"V" stands for visual
G		"G" stands for green (visual)
R	658 nm	"R" stands for red
Infrared		
I	806 nm	"I" stands for infrared

in the visible portion of the electromagnetic spectrum will grossly underestimate the total energy (or flux) emitted by the object.

Nowadays, photometry is or can be done across the entire electromagnetic spectrum, but using a diverse set of instruments that are ground- and space-based. Past measurements of flux were initially executed utilizing specific photoelectric cells that measured the radiant energy striking each cell. However, with the advent of charge-coupled devices (CCD) multiple wavelengths can be examined simultaneously. Whereas in the past observations were made with single targets, CCD technology allows multiple targets to be imaged and analyzed simultaneously – vastly accelerating the acquisition of information. This has had an unprecedented effect on the rate of information gathering. One only has to look at the acceleration in the discovery of supernovae over the last decade. Various automated telescopic systems, employing CCD technology, now churn out hundreds of supernovae sightings per year. This has greatly expanded our pool of data and subsequently our understanding of the exotica present beyond the boundaries of our galaxy (Table 1.1).

The HR Diagram

Through the latter half of the nineteenth century and into the early part of this century sufficient numbers of stars were observed to begin the process of dissecting their morphology and gaining a better understanding of their underlying biology. Initial work by Father Angelo Secchi in the 1860s organized five broad groups of stars based on similarities and differences in their spectra. In the 1890s Henry Draper became the first person to photograph absorption spectra. Published in the Harvard Annals the work is part of the Henry Draper Memorial. Extending from this many astronomers will be familiar with stars bearing the prefix "HD," a derivation from his name. Work by Williamina Paton Fleming and Edward Charles Pickering fine-tuned and extended the classification scheme of Secchi, based on the spectroscopic analysis by Draper. Further work by Antonia Maury and later Annie Cannon refined the system further; Cannon's work eventually creating the classic O, B, A, F, G, K, M system that we know today.

It was the simplicity of this system of spectral classification that led Ejnar Hertzsprung (University of Leiden in the Netherlands) to realize that some of the stars were grouped according to luminosity. Some stars within one classification showed significantly lower "proper motion" (motion relative to the background stars) compared to others in the same class. This schism indicated that those with lower proper motion had to be further away from us than those stars showing the greater proper motion. Hence, these stars had to be significantly more luminous in order to appear equally bright.

Shortly thereafter, around 1911, Hertzsprung and separately in 1913, Henry Norris Russell (Princeton University), published subtly different but compatible diagrams. Hertzsprung's compared luminosity (absolute magnitude as the dependent variable) with color (Hertzsprung) and Russell's absolute magnitude with spectral type. However, as spectral type is a property of surface temperature, the two diagrams are effectively the same – hence the name Hertzsprung-Russell (or HR) diagram.

The eponymous chemistry tool, the Periodic Table, is an exquisite implement for dissecting and characterizing the chemical elements that make up our universe. It is such an easy tool to use, with elements grouped according to their properties, masses and atomic numbers. New elements can easily be slotted in, and clear patterns emerge linking elements in their groups. The underlying physics driving their chemical behaviors is also easy to determine with only a cursory examination of the Periodic Table.

Yet for all its finery, the Periodic Table still lacks the elegant simplicity of the HR diagram. Obviously it is worth recognizing that the 110 plus elements have a lot more inherent complexity compared to a star, but even so one could argue that the HR diagram is a more elegant tool than the Periodic Table. The virtue of this construct lies in its utter simplicity, its clear lack of obvious sophistication. Only two variables are present: color (or temperature), serving as the independent variable, and luminosity, functioning as the dependent. There is nothing else to this, and yet it is central to our understanding of all stars. The HR diagram is a blissfully simplistic representation that forms the backdrop for so much activity in astronomy.

The absolute magnitude scale is logarithmic, with each decrease in number corresponding to a jump in luminosity by a few times. Thus a star with an absolute magnitude of –1 is ten times brighter at the chosen waveband than a star with an absolute magnitude of 0.

Once constructed, the Hertzsprung-Russell diagram clearly demonstrated Hertzsprung's observed schism between dwarf and giant stars. They formed two distinct groups on the initial plots. The dwarfs formed a relatively smooth curve from top left (hot and luminous) to bottom right (cool and red), while the giants formed a separate locus positioned on the top right of the diagram (cool and red but luminous). There was a smudging of stars linking the two loci but above which few stars were present. This Hertzsprung gap is located in the region between spectral classes A5 and G0 and between +1 and –3 absolute magnitudes (i.e., between the top of the main sequence and the giants in a portion called the horizontal branch). It turns out that there is a fundamental reason for this gap: stars evolve so quickly from main sequence to red giant branch at this luminosity that they are rarely observed making this transition.

The study of stellar evolution tends to modify the HR diagram, converting the inferred parameter of temperature or spectral

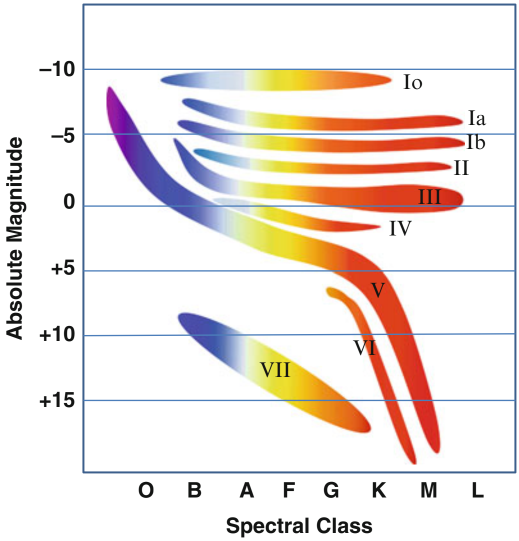

Fig. 1.3 The HR diagram in a more modern guise showing luminosity classes I through to VIII. *Io* hypergiants, *Ia* bright supergiants, *Ib* dimmer supergiants, *II* bright giants, *III* red giants, *IV* sub-giants, *V* main sequence, *VI* sub-dwarfs, *VII* white dwarfs. As well as inclusion of terms such as hypergiant and sub-dwarf, spectral classes L and T (showing lithium and methane respectively) have been added. These are primarily populated by brown dwarfs ("failed stars"), although a few bona fide hydrogen burning red dwarfs lie at the brighter end of class L – and the odd red giant. (Class T is omitted)

class into a photometric factor "B-V". This allows the flux of light at specific spectral wavelengths to be used as a reliable indicator of temperature, but one which is also numerical and hence easy to plot on a computer. These B-V versus absolute magnitude plots are referred to as color magnitude diagrams (Fig. 1.3).

Naturally, the diagram has evolved over time. During the 1940s the current system of luminosity classes O through to VII emerged. This MK luminosity system was completed by Morgan, Keenan and Kellman (hence the abbreviation "MK") in 1943 and is still in use today. It extended the original dwarf and giant groupings to six luminosity classes (see above). The giants have been subdivided into the following classes: "sub-giants – IV," "giants- III," "bright giants – II," "supergiants I" and lastly "hypergiants – O," each with increasing luminosity. All of the stars populating these regions of the HR diagram are more "evolved" and have left the portion of the diagram where stars fuse hydrogen into helium as a main energy source.

Dissecting the diagram from top left to bottom right is the main sequence – the region containing 90 % of the stars in the universe. This is also called class V. Main sequence stars fuse hydrogen to helium, a process that powers them for most of their lives. Running alongside the main sequence, from class G to M, is a parallel and more sparsely populated band of stars called the sub-dwarfs, or class VI. These are metal-poor stars that form an extension to the main sequence, comprising hydrogen-burning stars.

The supergiant locus (luminosity class I) has also been broken into two further subdivisions, Ia and Ib, with Ia forming the brighter clump. Descending numerically each class is brighter than the last, but with some overlap of the edges between these. Stars, after all, are not simple creatures, and like living things, the more you look at them the more blurred the boundaries become between classes. Consequently, a simple inspection of the HR diagram won't necessarily tell you what is happening to a star bearing particular characteristics.

An interesting biological example of a classification quandary in exists in parasites. They move around and behave like animal cells, and they lack the canonical cell walls of plant cells. Yet, if you look closely at the cells of the intracellular parasite plasmodium – the pathogenic cause of malaria – you will spot a cellular structure that is derived from a chloroplast. Chloroplasts are the site of photosynthesis, a classic plant trait. So is a plasmodium cell plant or animal?

A rather analogous example of this problem was revealed by the star Capella. Capella is actually two closely paired yellow giant stars and a more distant pair of red dwarf stars. The giant stars orbit one another so closely it took the power of spectroscopy to separate the partners in Capella's intricate dance. Capella's component stars were first resolved using interferometry in 1919 by John Anderson and Francis Pease at the Mount Wilson Observatory. This was the first interferometric measurement of any object outside the Solar System.

The Capella giants Aa and Ab have similar brightness and surface temperatures, which poses a problem for stellar evolution. How do two stars appear to evolve at the same time? After all, it is highly unlikely that they were born with identical masses. Even a slight initial difference would cause their paths to diverge as they age. Yet if we refer solely to the HR diagram as a guide to these stars, both appear to have reached the same evolutionary point at the same time.

The HR diagram offered few clues to this mystery. Both stars are rarities found at the red end of the HR gap and appear to have similar masses. Capella Aa weighs in at 2.7 solar masses, while Ab is slightly hotter and smaller, weighing in at 2.6 solar masses. Their luminosities are 79 and 78 times that of the Sun, respectively – uncannily close matches to one another. The question then repeats: Why are these stars so similar? Is this a simple fluke? The answer appears to lie in the internal state of each star. The slightly more massive Capella Aa appears to have completed its first ascent of the red giant branch and is now burning helium in its core. This has caused the star to contract, heat up and return to the yellow portion of the HR diagram. Ab, by contrast, with its lower mass, is lagging behind and is still on route from the main sequence to the giant branch. It is purely coincidental that both stars appear to be passing each other at the same location in the HR diagram. They are merely ships passing in the night.

A cursory inspection of the diagram didn't reveal this information. Instead the solution lay in the analysis of the chemical composition of the stars through spectroscopy. Star Aa has an envelope depleted in the element lithium. This element is readily destroyed in the hot interior of stars by nuclear fusion. However, the type of star Capella Aa came from would have probably resembled Sirius. As we shall see shortly, these stars cannot drag material from their outer layers down towards the core, where it is hot enough to fuse lithium. However, once these stars leave the main sequence and become red giants this process happens readily, destroying any lithium present. Capella Aa is depleted in lithium but Ab is not, suggesting that Aa has already become a red giant but Ab has not. The HR diagram thus offers clues to the evolutionary state of a star, but without additional information, certain mysteries will remain unsolved.

As a final coda to the HR diagram a little quirk must be emphasized. The orientation of the independent variable on the horizontal axis is inverted. Any high school boy or girl will tell you numbers increase along the axis, away from the origin. The HR diagram retains an idiosyncrasy of its inception based on spectral class. The highest temperatures are found closest to the origin – the point where the vertical axis intercepts it. In the color-magnitude diagram, this is corrected with numerical values increasing rightwards, away from the origin, but the location of the luminosity classes and their orientation is retained.

Quirks aside, the HR diagram remains a magnificent tool and central to modern astronomy teachings.

The Power Sources of Nuclear Reactions in Stars

Stars on the main sequence convert hydrogen into helium by the process of nuclear fusion. In outline, hydrogen combines in fours to make one helium atom. These reactions require high temperatures and high densities to flourish; therefore, they are generally limited to the stellar core, where temperatures are highest.

In the lowest mass stars nuclear fusion is a very sluggish process, and a star with one tenth the mass of the Sun will take nearly 6 trillion years to use up its fuel reserves. The Sun has greater reserves of fuel than a low mass star, but because it is more massive its core is hotter, and at higher temperatures nuclear reactions run through the fuel reserves a lot faster.

This is a general rule for all stars: the greater the mass the faster the fuel is used up. Stellar lifetimes extend from a little more than 10 trillion years for the lowest mass stars (approximately 0.075 solar masses) to less than 5 million years for the most massive (greater than 100 solar masses). Clearly this is a non-linear relationship, with three orders of magnitude in stellar mass equating to six orders of magnitude of stellar lifetime. The reason for this discrepancy is two-fold. For one thing, stars get hotter as their mass increases. Nuclear reactions are very sensitive to temperature, and only slight increases in temperature give very large increases in the rate of nuclear burning. This means massive stars burn fuel faster. Secondly, massive stars burn their hydrogen

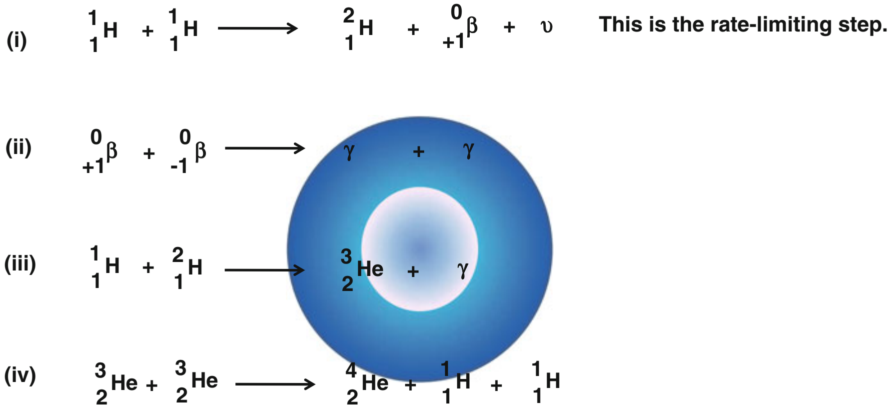

FIG. 1.4 The Proton-Proton-I (PPI-I) chain. This series of reactions convert hydrogen into helium in four, sequential reactions. The first step limits these reactions to stars with more than 75 times the mass of Jupiter. The third step can occur in brown dwarfs with more than 13 Jupiter-masses, at temperatures above 700,000 K. β represents a positron, γ a gamma ray and υ a neutrino

fuel in a different manner from lower mass stars. The details will be described shortly, but the mechanism of hydrogen fusion in massive stars is more efficient and fuel is consumed more quickly than in low mass stars. These two effects contribute to a rapid decrease in stellar longevity as mass increases.

The Proton-Proton Chain of Low Mass Stars

There are three proton-proton chains in reality, but concentrating on that used most abundantly, the system can be outlined as follows. In the first step (which is also rate-limiting) hydrogen (a single proton) combines in pairs to form an isotope of hydrogen called deuterium, plus a particle of antimatter called a positron. The positron soon meets an electron and is annihilated, releasing two gamma rays (Fig. 1.4).

Deuterium, with one proton and one neutron, then combines at a much faster rate with another proton to form helium-3 plus a gamma ray. Lastly, pairs of helium-3 combine to form helium-4, plus two protons. The energy liberated is enormous and comes in the form of particle motion and the emitted gamma rays.

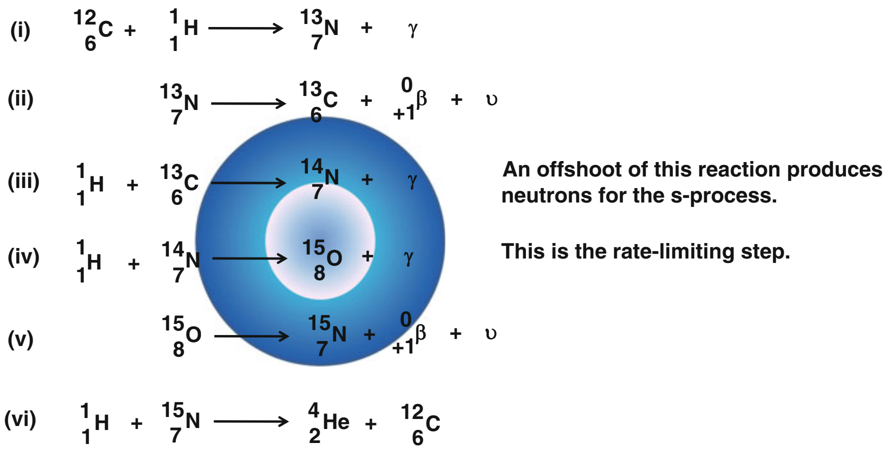

FIG 1.5 The carbon-nitrogen (CN) cycle consists of a series of reactions in which hydrogen is added sequentially to a carbon-12 seed nucleus. The CN cycle releases energy at a far higher rate than the proton-proton chain and is far more sensitive to temperature than these reactions. β represents a positron, γ a gamma ray and υ a neutrino. Some of the intermediates are unstable and release positrons. These reactions are useful on Earth as the source of positrons for PET (Positron Emission Tomography) scans. On white dwarf stars in binary systems that are burning hydrogen, annihilation of positrons with electrons releases copious heat. This leads to a runaway in the rate of nuclear reactions, which in turn leads to a nova explosion

The Carbon-Nitrogen Cycle

The majority of the stars dealt with in the second section of this book last only 3–10 million years at most, squandering their vast fuel reserves in the cosmological blink of an eye. The highly efficient carbon-nitrogen cycle powers this gluttony. Here, carbon-12, with 6 protons and 6 neutrons, fuses with a proton forming nitrogen-13. This decays, releasing a positron forming carbon-13. Carbon-13 fuses with another proton, forming nitrogen-14. These steps are fairly fast (Fig. 1.5).

Next, at a much slower pace, nitrogen-14 fuses with another proton, its third, forming an unstable oxygen-15 isotope, which also decays, releasing another positron. The product, nitrogen-15, finally fuses with a fourth proton, forming helium-4, while regenerating carbon-12 once more. Both positrons annihilate with electrons liberating energy in the form of gamma rays.

Once the stellar interior exhausts its supply of hydrogen, stars with masses exceeding half that of the Sun can go on to fuse their helium reserves to make carbon and oxygen. Even more massive stars, those with initial masses greater than seven times that of the Sun (the exact limit is a little uncertain) can fuse carbon to make neon and magnesium. Above 9 solar masses stars can create elements up to iron through direct nuclear fusion. The other chemical elements have more interesting origins that we shall return to later.

Nuclear fusion releases most of its energy as gamma rays – high energy electromagnetic waves, or if you prefer, photons (particles of light). Either term is an acceptable means of describing a gamma ray, because light likes to behave as particles and as waves.

The Chemical Composition of Stars

Stars vary significantly in their composition. *Significant* is an interesting word in science. It conjures up other words such as "large," "enormous" or "gargantuan." In reality, significant means different in a manner that can be distinguished via statistical analysis. For a star a difference of anything starting at 0.1 % can be significant (but is hardly spectacular numerically).

Variations in stellar composition only become extreme later in their lives as much of their initial stock of hydrogen is used up. Subtle variations in the initial makeup of the star can have profound effects on their subsequent evolution. This is especially true for massive stars – those with initial masses greater than 9 solar masses. Alterations in the amount of heavier elements can drastically affect how much mass the star holds on to as it ages, and this in turn affects how the star dies.

When a star is born its chemical composition, or chemotype, is set by the composition of the gas from which it forms. On a few occasions the star can be polluted by a close companion star, but leaving this aside it is the cloud of gas and dust from which the star is born that determines much of its subsequent fate.

The first stars born in the universe were made solely of hydrogen and helium, with a faint whiff of lithium, beryllium and boron.