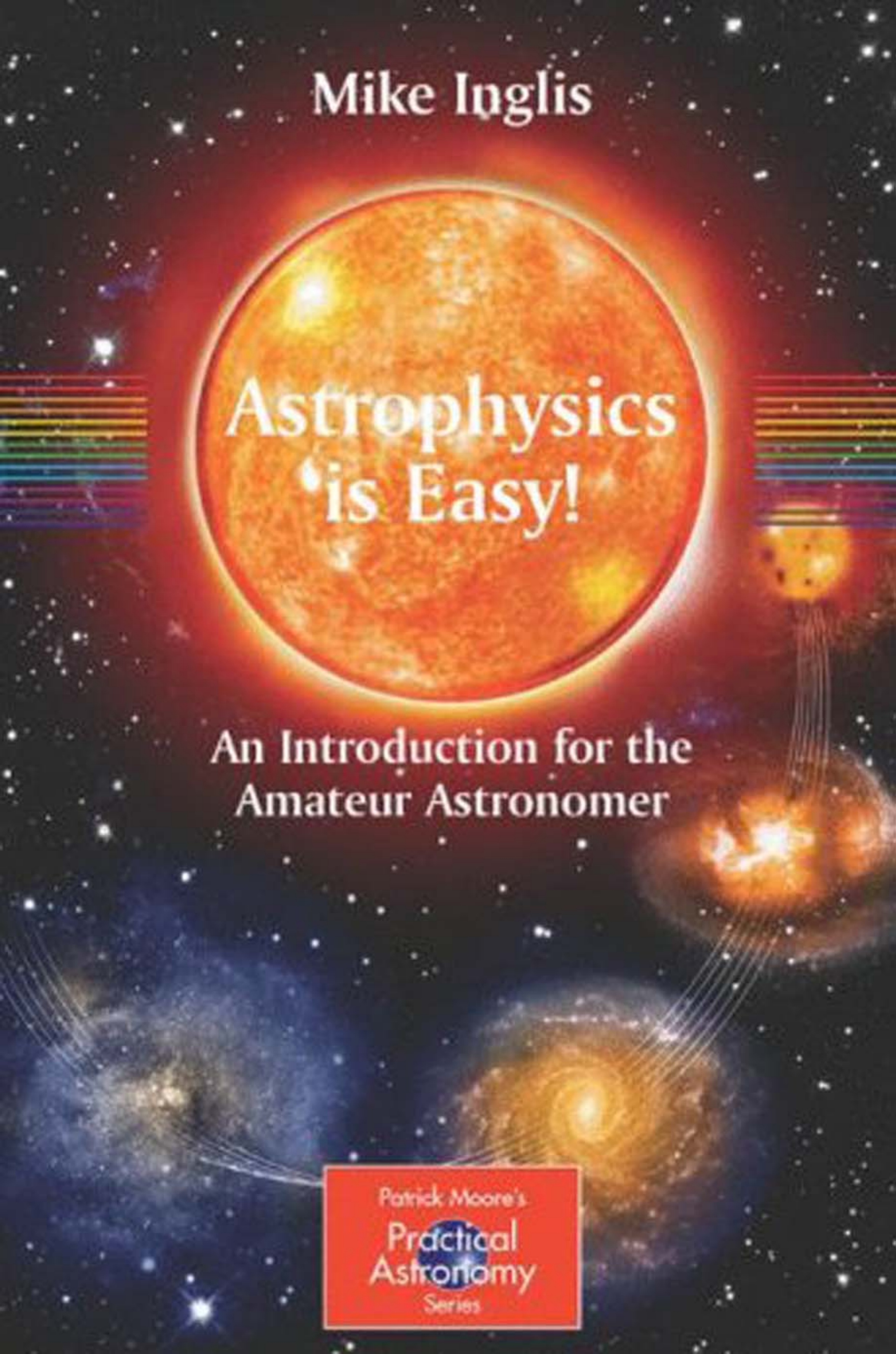

Mike Inglis

Astrophysics is Easy!

An Introduction for the Amateur Astronomer

Patrick Moore's Practical Astronomy Series

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Bob Mizon

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(Continued after Index)

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For Dad and Alan, who are already amongst the stars

Contents

Preface and Thanks

Once again, I took paper to pen, and began a journey to explain the mysterious and beautiful complexities of stars, galaxies, and the material that lies between them. It was a journey that took many roads with many side-turnings as I often spent many long, lonely hours worrying whether I was being too obtuse, or at times patronizing. It is a fact that many amateur astronomers are very knowledgeable of the subject that they pursue with a passion. However, the book eventually came into sight, and this, for me a mammoth task, was completed. You now hold it in your hands!

Throughout the entire process of writing the book, I was lucky enough to have the support of my publisher, Harry Blom, who, as a professional astronomer himself, knows only too well that astronomy authors are a breed apart and need to be pampered and dealt with extreme patience. Thanks, Harry—I owe you a pint. I must also thank my great friend John Watson, also associated with Springer, who gave the initial thumbs-up when I first outlined the idea for the book. John is an amateur astronomer himself, so he knows exactly what should go into a book, and perhaps even more importantly, what should be left out! I also owe you a pint.

I am fortunate to have been taught astronomy by some of the world's leading experts, and it was, and still is, a privilege to know them. In my humble opinion, not only are they superb astronomers, whether theoretical or observational, but also wonderful educators. They are Chris Kitchin, Alan McCall, Iain Nicolson, Robert Forrest, and the late Lou Marsh. They were the best teachers I ever had.

During the time spent writing this book, usually alone, usually at night, usually tired, I had the company of some wonderful musicians whose music is truly sublime. They are Steve Roach, David Sylvian, John Martyn, and the Blue Nile.

Many friends have helped raise my spirits during those times when not all was going right according to the Inglis Master Plan. They listened to me complain, laughed at my jokes, and helped me remain sane—for the most part. So I want to say thank you to my British friends—Pete, Bill, Andy and Stuart—and my new friends here in the USA—Sean and Matt. It is nice to know that beer is the universal lubricant of friendship, whether it is McMullens or Blue Point.

Astronomy is a very important part of my life, but not as important as my family; my brother, Bob, is a great friend and a strong source of support, especially during my formative years as an astronomer. My mother, Myra, is amazing, full of energy, spirit, and laughter, and has been supportive of my dream to be an astronomer since I was knee-high to a tripod. She is truly an example to us all. And of course Karen, my partner. I am not exaggerating when I say this book would not have seen the light of day without her help. *"Diolch Cariad."*

For making my life so much fun, cheers!

Dr. Mike Inglis
Long Island, USA, 2006

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Robert Forrest, of the *University of Hertfordshire Observatory*, UK, for use of his observing notes.

Michael Hurrell and Donald Tinkler of the *South Bayfordbury Astronomical Society*, UK, for use of their observing notes.

In developing a book of this type, which presents a considerable amount of detail, it is nearly impossible to avoid error. If any arise, I apologize for the oversight, and I would be more than happy to hear from you. Also, if you feel that I have omitted a star or galaxy that you think would better describe a certain aspect of astrophysics, please feel free to contact me at: inglism@sunysuffolk.edu. I can't promise to reply to all e-mails, but I will certainly read them.

Overview

To most normal people, astrophysics—the science of stars, galaxies, and the universe we live in—would seem to be a topic suited to a university-level textbook, and so the idea of a guide to astrophysics for the amateur astronomer may not, on first appearance, make any sense. However, let me assure you that anyone can understand how a star is born, lives its life, and dies, how galaxies are thought to evolve and what their shape can tell us about their origins and age, and even how the universe began and how it may end. In fact, very little mathematics is needed, and when it is used, it is only a matter of multiplication, division, subtraction, and addition![1]

What is more, there are many wonderful objects that can be observed in the night sky that will illustrate even the most obtuse astrophysics concepts. All one needs is a willingness to learn and a dark night sky.

Learning about, say, the processes that give rise to star formation, or what happens to a very large star as it dies, or even why some galaxies are spiral in shape whereas others are elliptical can add another level of enjoyment and wonder to an observing session. For instance, many amateur astronomers are familiar with the star *Rigel*, in the constellation *Orion*, but how many of you know that it is a giant star, with a mass more than 40 times that of the Sun, and it is nearly half a million times more luminous than the Sun? How many know that the closest large galaxy, *M31* in Andromeda, has a supermassive black hole lurking at its center with a mass more than 50 million times that of the Sun? Or that the *Orion Nebula,* regarded by many as the premier nebula in the sky, is in fact an enormous stellar nursery where stars are actually being born as you read this book? Knowing details such as these can add another level of enjoyment to your observing sessions.

Each section of this book addresses a specific aspect of astrophysics. The first part focuses on the concepts needed for a complete understanding of the remainder of the book, and as such will be divided into specific topics, such as the brightness, mass, and distance of stars, and so on. Then we will look at the tools of an astronomer, namely spectroscopy. It is true to say that nearly all of what we know about stars and galaxies was and is determined by this important technique. We shall spend a fair amount of time looking at something called the Hertzsprung-Russell diagram; if ever a single concept or diagram could epitomize a star's life (and even a star cluster's life), the *H-R* diagram, as it is known, is the one to do it. It is perhaps the most important and useful concept in all of stellar evolution, and it is fair to say that once you understand the *H-R* diagram, you understand how a star evolves.

Moving on to the objects themselves, we start with the formation of stars from dust and gas clouds, and conclude with the final aspect of a star's life, which can end in a spectacular event known as a supernova, resulting in the formation of a neutron star and perhaps a black hole!

On a grander scale, we delve into galaxies, their shapes (or morphology, as it is called), distribution in space, and origins.

The topics covered are chosen specifically so that examples of objects under discussion can be observed; thus, at every point in our journey, an observing section will describe the objects that best demonstrate the topics discussed. Many of the objects, whether they be stars, nebulae, or galaxies, will be visible with modest optical instruments, and many with the naked eye. In a few exceptional cases, a medium-aperture telescope may be needed. Of course, not all observable objects will be presented, but just a representative few (usually the brightest examples). These examples will allow you to learn about stars, nebulae, and galaxies at your own pace, and they will provide a detailed panorama of the amazing objects that most of us observe on a clear night.

For those of you who have a mathematical mind, some mathematics will be provided in the specially labelled areas. But, take heart and fear not—you do not have to understand any mathematics to be able to read and understand the book; it is only to highlight and further describe the mechanisms and principles of astrophysics. However, if you are comfortable with maths, then I recommend that you read these sections, as they will further your understanding of the various concepts and equip you to determine such parameters as a star's age and lifetime, distance, mass, and brightness. All of the maths presented will be simple, of a level comparable to that of a 4th-year school student, or an 8th-grader. In fact, to make the mathematics simpler, we will use rough (but perfectly acceptable) approximations and perform back-of-the-envelope calculations, which, surprisingly, produce rather accurate answers!

An astute reader will notice immediately that there are no star maps in the book. The reason for this is simple: in previous books that I have written, star maps were included, but their size generated some criticism. Some readers believed the maps were too small, and I tend to agree. To be able to offer large and detailed star maps of every object mentioned in this book would entail a doubling of its size, and probably a tripling of cost. With the plethora of star-map software that is available these days, it is far easier for readers to make their own maps than to present any here.

A final point I wish to emphasize here is that the book can be read in several ways. Certainly, you can start at the beginning and read through to the end. But if you are particularly interested in, say, supernovae and the final stages of a star's life, or in galaxy clusters, there is no reason that you should not go straight to that section. Some of the nomenclature might be unfamiliar, but I have attempted to write the book with enough description that this should not be a problem. Also, many of you will undoubtedly go straight to the observing lists. Read the book in the way that is most enjoyable to you.

Without further ado, let us begin a voyage of discovery…

Note

1. Well, o.k.—we do use powers of ten occasionally, and numbers multiplied by themselves from time to time. But nothing else…honest!

CHAPTER ONE

Tools of the Trade

1.1 Distance

To determine many of the basic parameters of any object in the sky, it is first necessary to determine its proximity to us. We shall see later how this is vitally important because a star's bright appearance in the night sky could signify that it is close to us or that it is an inherently bright star. Conversely, some stars may appear faint because they are at immense distance from us or because they are very faint stars in their own right. We need to be able to determine which is the correct explanation.

Determining distance in astronomy has always been, and continues to be, fraught with difficulty and error. There is still no consensus as to which is the best method, at least for distances to other galaxies and to the farthest edges of our own galaxy—the Milky Way. The oldest method, still used today, is probably the most accurate, especially for determining the distances to stars.

This simple technique is called *Stellar Parallax.* It is basically the angular measurement when the star is observed from two different locations on the Earth's orbit. These two positions are generally six months apart, and so the star will appear to shift its position with respect to the more distant background stars. The parallax (p) of the star observed is equal to half the angle through which its apparent position appears to shift. The larger the parallax (p), the smaller the distance (d) to the star. Figure 1.1 illustrates this concept.

If a star has a measured parallax of 1 arcsecond (1/3600th of a degree) and the baseline is 1 astronomical unit (AU), which is the average distance

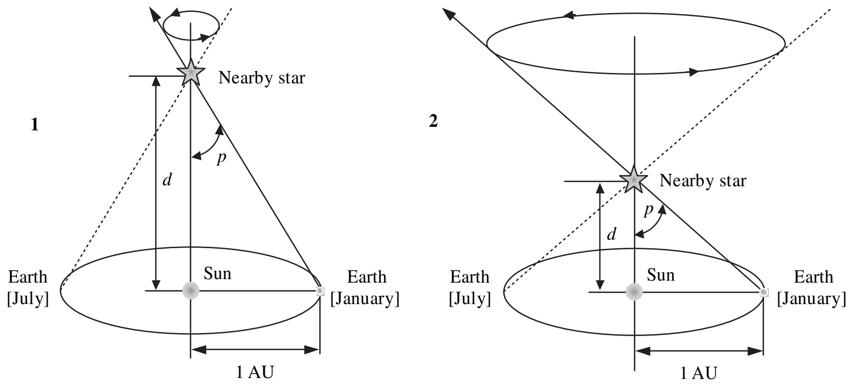


Figure 1.1. Stellar Parallax. (1) The Earth orbits the Sun, and a nearby star shifts its position with respect to the background stars. The parallax (*p*) of the star is the angular measurement of the Earth's orbit as seen from the star. (2) The closer the star, the greater the parallax angle (PA).

from the Earth to the Sun, then the star's distance is 1 parsec (pc)—"the distance of an object that has a **par**allax of one **sec**ond of arc." This is the origin of the term parsec, which is the unit of distance used most frequently in astronomy.[1]

The distance (d) of a star in parsecs is given by the reciprocal of its parallax (p), and is usually expressed as thus:

$$d = \frac{1}{p}$$

Thus, using the above equation, a star with a measured parallax of 0.1 arcseconds is at a distance of 10 pc, and another with a parallax of 0.05 arcseconds is 20 pc distant.

Box 1.1: Relationship between Parallax and Distance

$$d = \frac{1}{p}$$

$d =$ the distance to a star measured in pc
$p =$ the parallax angle of the measured star in arcseconds

This simple relationship is a significant reason that most astronomical distances are expressed in parsecs, rather than light years (l.y.). The brightest star in the night sky is

Sirius (α *Canis Majoris*), which has a parallax of 0.379 arcseconds. Thus, its distance from the Earth is:

$$d = \frac{1}{p} = \frac{1}{0.379} = 2.63\,\text{pc}$$

Note that 1 pc is equivalent to 3.26 l.y. This distance can also be expressed as:

$$d = 2.63 \times \frac{3.26\,\text{l.y.}}{1\,\text{pc}} = 8.6\,\text{l.y.}$$

Surprisingly, all known stars have a parallax angle smaller than 1 arcsecond, and angles smaller than 0.01 arcseconds are very difficult to measure from Earth due to the effects of the atmosphere; this limits the distance measured to about 100 pc (1/0.01). However, the satellite Hipparcos, launched in 1989, was able to measure parallax angles to an accuracy of 0.001 arcseconds, which allowed distances to be determined to about 1000 pc.[2]

But, this great advance in distance determination is useful only for relatively close stars. Most of the stars in the Galaxy are too far for parallax measurements to be taken. Another method must be resorted to.

Many stars actually alter their brightness (these are the variable stars). Several of them play an important role in distance determination. Although we shall discuss their properties in far greater detail later, it is instructive to mention them here.

Two types of variable stars are particularly useful in determining distances. These are the *Cepheid* variable stars and *RR Lyrae* variable stars.[3] Both are classified as *pulsating variables*, which are stars that actually change their diameter over a period of time. The importance of these stars lies in the fact that their average brightnesses, or luminosities,[4] and their periods of variability are linked. The longer the time taken for the star to vary its brightness (the period), the greater the luminosity. This is the justifiably famous *Period–Luminosity* relationship.[5] The period of a star is relatively easy to measure, and this is something that many amateur astronomers still do. Once the period has been measured, you can determine the star's luminosity. By comparing the luminosity, which is a measure of the intrinsic brightness of the star, with the brightness it appears to have in the sky, its distance can be calculated.[6] Using Cepheid as a reference, distances of up to around 60 million l.y. have been determined.

A similar approach is taken with the RR Lyrae stars, which are less luminous than Cepheids and have periods of less than a day. These stars allow distances to about 2 million l.y. to be determined.

Another method of distance determination is that of spectroscopic parallax, whereby determining a star's spectral classification can lead to a measure of its intrinsic luminosity, which can then be compared with its apparent brightness to determine its distance.

There are other distance determination methods used for the objects farthest from us—galaxies. These methods include the Tully Fisher method and the very famous Hubble Law.

All of these methods—Cepheid variable, Tully Fisher, and the Hubble Law—will be addressed in greater detail later in the book.

A final note on distance determination is in order. Do not be fooled into thinking that these methods produce exact measurements. They do not. A small amount of error is inevitable. This error is usually about 10 or 25%, and even an error of 50% is not unheard of. Remember that a 25% error for a star estimated to be at a distance of 4000 l.y. means it could be anywhere from 3000 to 5000 l.y. away. Table 1.1 lists the 20 nearest stars.

Let us now discuss some of the nearest stars in the night sky from an observational point of view. The list (Table 1.1) is by no means complete but includes those stars that are easily seen. Many of the nearest stars are very faint, and thus present an observing challenge; they are not included here.

Throughout the book, I have used the following nomenclature with regard to stars: the first item will be its common name, followed by its scientific designation. The next item will be its position in right ascension and declination. The final item will identify the months when the star is best positioned for observation (the month in bold type is the most favorable time of observation).

The next line will present standard data and information pertinent to the star under discussion: its apparent magnitude, followed by its absolute magnitude, other specific data relating to the star, and, finally, the constellation in which the star resides.

Table 1.1. The 20 nearest stars in the sky

	Star	Distance, l.y.	Constellation
1	Sun	----	----
2	Proxima Centauri	4.22	Centaurus
3	Alpha Centauri A[7]	4.39	Centaurus
4	Barnard's Star	5.94	Ophiuchus
5	Wolf 359	7.8	Leo
6	Lalande 21185	8.31	Ursa Major
7	Sirius A[7]	8.60	Canis Major
8	UV Ceti A[7]	8.7	Cetus
9	Ross 154	9.69	Sagittarius
10	Ross 248	10.3	Andromeda
11	Epsilon Eridani	10.49	Eradinus
12	HD 217987	10.73	Piscis Austrinus
13	Ross 128	10.89	Virgo
14	L 789–6 A[7]	11.2	Aquarius
15	61 Cygni A	11.35	Cygnus
16	Procyon A[7]	11.42	Canis Minoris
17	61 Cygni B	11.43	Cygnus
18	HD173740	11.47	Draco
19	HD 173739	11.64	Draco
20	GX Andromadae[7]	11.64	Andromeda

1.1.1 The Nearest Stars to Us[9]

Proxima Centauri	**V645 Cen**	**$14^h29.7^m$**	**−62°41′**	Mar-**Apr**-May
11.01_vm[8]	**15.45M**	**4.22 l.y.**	**0.772″**	**Centaurus**

This is the second-closest star to the Earth and the closest star to the Solar System, and thus it is included albeit faint. It is a red dwarf star and also a flare star with frequent bursts, having maximum amplitude of around one magnitude. Recent data indicate that it is not, as previously thought, physically associated with *α Centauri*, but is, in fact, on a hyperbolic orbit around the star and just passing through the system.

Sirius A[α Canis Majoris]	**$06^h45.1^m$**	**−16°43′**		Dec-**Jan**-Feb
−1.44 m	**1.45M**	**8.6 l.y.**	**0.379″**	**Canis Major**

Sirius, also known as the Dog Star, is a lovely star to observe. It is the sixth-closest and brightest star in the sky. It is famous among amateur astronomers for the exotic range of colors it exhibits due to the effects of the atmosphere. It also has a dwarf star companion—the first to be discovered. A dazzling sight in any optical device.

Procyon	**α Canis Minoris**	**$07^h39.3^m$**	**+56°13′**	Dec-**Jan**-Feb
0.40 m	**2.68M**	**11.41 l.y.**	**0.283″**	**Canis Minor**

Procyon is the fifteenth-nearest star and the eighth brightest. Like its neighbor *Sirius*, Procyon has a white dwarf companion star, but it is not visible through amateur telescopes.

Barnard′s Star[HD21185]	**$17^h57.8^m$**	**+4°38′**		Apr-**May**-Jun
9.54 m	**13.24M**	**5.94 l.y.**	**0.549″**	**Ophiuchus**

The third-closest star is a red dwarf. What makes this star so famous is that it has the largest proper motion of any star[10]—0.4 arcseconds per year. *Barnard's Star*, also known as *Barnard's Runaway Star*, has a velocity of 140 km per second; at this rate, it would take 150 years for the star to move the distance equivalent to the Moon's diameter across the sky. It has also been thought that the star belonged to the Galaxy's *Halo Population*.

61 Cygni A	**V1803 Cyg**	**$21^h06.9^m$**	**+38°45′**	Jul-**Aug**-Sep
5.20_vm	**7.49M**	**11.35 l.y.**	**0.287″**	**Cygnus**

This is a very nice double star with separation 30.3 arcseconds and a PA of 150° (see section 3.7). Both stars are dwarfs and have a nice orange color. It is famous for being the first star to have its distance measured successfully, by F. W. Bessel in 1838, using stellar parallax.

GX And	**Grb34**	**$00^h18.2^m$**	**+44°01′**	Aug-**Sep**-Oct
8.09_vm	**10.33M**	**11.65 l.y.**	**0.280″**	**Andromeda**

This is one of a noted red dwarf binary system with the primary star itself a spectroscopic double star. Also known as *Groombridge 34 A*, *GX And* is located about 1/4° north of 26 Andromedae.

Lacille	**HD 217987**[11]	**$23^h05.5^m$**	**−35°52′**	Aug-**Sep**-Oct
7.35m	**9.76M**	**10.73 l.y.**	**0.304″**	**Pisces Austrinus**

This is a red dwarf star with the fourth-fastest proper motion of any known star, traversing a distance of nearly 7 arcseconds a year and thus would take about 1000 years to cover the angular distance of the full Moon, which is 1/2°. *Lacille* is in the extreme southeast of the constellation, about 1° SSE of π *Pisces Austrinus*.

UV Ceti	**L726 − 8A**	**$01^h38.8^m$**	**−17°57′**	Sep-**Oct**-Nov
12.56_vm	**15.42M**	**8.56 l.y.**	**0.381″**	**Cetus**

The seventh-closest star is a red dwarf system, which is rather difficult, but not impossible, to observe. The prefix UV indicates that the two components are flare stars; the fainter star is referred to in older texts as "*Luytens Flare Star*" after its discoverer, W. J. Luyten, who first observed it in 1949.

Epsilon Eridani	**HD 22049**	**$03^h32.9^m$**	**−09°77′**	Oct-**Nov**-Dec
3.72m	**6.18M**	**10.49 l.y.**	**0.311″**	**Eridanus**

The tenth-closest star is a naked-eye object. Recent observations indicate that there may be an unseen companion star with a very small mass, approximately 0.048 that of the Sun.

1.2 Brightness and Luminosity

There is an immense number of stars and galaxies in the sky, and for the most part they are powered by the same process that fuels the Sun. This does not mean that they are all alike. Stars differ in many respects, such as mass, size, and so on. One of the most important characteristics is their *luminosity*, *L*. Luminosity is usually measured in *watts* (W), or as a multiple of the Sun's luminosity,[12] $L_\odot$. This is the amount of energy that the star emits each second. However, we cannot measure a star's luminosity directly because its brightness as seen from Earth depends on its distance as well as its true luminosity. For instance, α *Centauri A* and the Sun have similar luminosities, but, in the night sky, α *Centauri A* is a dim point of light because it is about 280,000 times farther from the Earth than the Sun.

To determine the true luminosity of a star, we need to know its *apparent brightness*, which we define as the amount of light reaching the Earth per unit area.[13] As light moves away from the star, it will spread out over increasingly larger regions of space, obeying what is termed an *inverse square law*. If the sun were to be viewed at a distance twice that of the Earth, then it would appear fainter by a factor of $2^2 = 4$. If we view it from a distance 10 times that of the Earth, it would appear 10^2 times fainter. If we were to observe the Sun from the same location as α *Centauri A*, it would be dimmed by $270{,}000^2$, which is 70 billion times!

The inverse square law describes the amount of energy that enters, say, your eye or a detector. Imagine an enormous sphere of radius d, centered on a star. The amount of light that will pass through a square meter of the sphere's surface is the total luminosity (L) divided by the total surface area of the sphere. Now, as the surface area of a sphere is given by the formula $4\pi d^2$, you will understand that, as the sphere increases, d increases, and so does the amount of luminosity. You may understand now why the amount of luminosity that arrives at the Earth from a star is determined by the star's distance.

This quantity, the amount of energy that arrives at our eye, is the apparent brightness mentioned earlier (sometimes just called the brightness of a star). It is measured in watts per square meter (W/m^2).

Box 1.2: The Luminosity Distance Formula

The relationship between distance, brightness, and luminosity is given as:

$$b = \frac{L}{4\pi d^2}$$

where b is the brightness of the star in W/m^2
L is the star's luminosity in W
d is the distance to the star in m

Example:
Let us apply this formula to *Sirius*, which is at a distance of 8.6 l.y.
[Note: 1 l.y. is 9.46×10^{15} m; thus 8.6 l.y. is $8.6 \times 9.46 \times 10^{15} = 8.14 \times 10^{16}$ m]

$$b = \frac{3.86 \times 10^{26}\,\mathrm{W}}{4\pi\,(8.14 \times 10^{16}\,\mathrm{m})^2}$$

$$b = 1 \times 10^{-7}\,\mathrm{W/m^2}$$

This means that, say, a detector of area $1\,\mathrm{m}^2$ (possibly a reflecting telescope) will receive approximately one-ten millionth of a watt!

Astronomers measure a star's brightness with light-sensitive detectors, and this procedure is called *photometry*.

Box 1.3: Luminosity, Distance, and Brightness

To determine a star's luminosity, we need to know its distance and apparent brightness. We can achieve this quite easily by using the Sun as a reference. First, let us rearrange the formula thus:

$$L = 4\pi d^2 b$$

Now, applying this equation to the Sun, whose luminosity is given as $L_\odot$ and distance is $d_\odot$, which is equal to 1 AU, the Sun's apparent brightness ($b_\odot$) is:

$$L_\odot = 4\pi d_\odot{}^2 b_\odot$$

Now let us take the ratio of the two formulas:

$$(L = 4\pi d^2 b)/(L_\odot = 4\pi d_\odot{}^2 b_\odot)$$

which gives us:

$$L/L_\odot = (d/d_\odot)^2 b/b_\odot$$

Therefore, all we need to know to determine a star's distance is how far it is as compared with the Earth-Sun distance, given as $d/d_\odot$, and how bright it is as compared with that of the Sun, given as $b/b_\odot$.

Example:

Let Star 1 be at half the distance of Star 2, and appear twice as bright. Compare the luminosities. First, $d_1/d_2 = 1/2$; similarly, $b_1/b_2 = 2$. Then:

$$\frac{L_1}{L_2} = \left(\frac{1}{2}\right)^2 \times 2 = 0.5$$

This means that Star 1 has only half the luminosity of Star 2, but it appears brighter because it is closer to us.

1.3 Magnitudes

Probably the first thing anyone notices when looking at the night sky is that the stars differ in brightness. A handful are bright, a few others are fairly bright, and the majority are faint. This characteristic, the brightness of a star, is called its *magnitude* (also refers to any other astronomical object that is observed with the naked eye). Magnitude is one of the oldest scientific classifications used today, and it was coined by the Greek astronomer Hipparchus. He classified the brightest stars as first-magnitude stars; those that were about half as bright as first-magnitude stars were called second-magnitude stars, and so on; the sixth-magnitude stars were the faintest he could see.[14] Today, we can see the fainter stars, and so the magnitude range is even greater, down to thirtieth-magnitude. Because the scale relates to how bright a star appears to an observer on Earth, the term is more correctly called *apparent magnitude*, and is denoted by m.

You may have noticed by now that this is a confusing measurement because the brighter objects have smaller values; for example, a star of apparent magnitude +4 (fourth-magnitude) is fainter than a star of apparent magnitude +3 (third-magnitude). Despite the confusion in its usage, apparent magnitude is used universally, and so we are stuck with it. A further point to note is that the classification of stars has undergone revision since Hipparchus's day, and an attempt was made to put the scale on a scientific footing. In the 19th century, astronomers accurately measured the light from stars, and they were able to determine that a first-magnitude star is about 100 times brighter than a sixth-magnitude star, as observed from Earth. To put it another way, it would take 100 sixth-magnitude stars to emit the light of one first-magnitude star. The definition for magnitude scale was then stated to be thus: a difference of 5 magnitudes corresponds exactly to a factor of 100 in brightness (see Table 1.2). A difference in magnitude of 1 corresponds to a factor of 2.512 in brightness. This is shown by the following calculation:

$$2.512 \times 2.512 \times 2.512 \times 2.512 \times 2.512 = (2.512)^5 = 100$$

Using this modern scale, several objects now have negative magnitude. *Sirius*, the brightest star in the sky, has a value of −1.44 m; *Venus* (at brightest) has −4.4 m, the full *Moon* has −12.6 m, and the *Sun* has −26.7 m.

Table 1.2. Magnitude and brightness ratio difference

Magnitude Difference	Brightness Ratio
0.0	1.0
0.1	1.1
0.2	1.2
0.3	1.3
0.4	1.45
0.5	1.6
0.7	1.9
1	2.5
2	6.3
3	16
4	40
5	100
7	630
10	10,000
15	1,000,000
20	10,000,000

Box 1.4: Apparent Magnitude and Brightness Ratio

Both apparent magnitude (m) and absolute magnitude (M) are used by astronomers, and there are several relationships between them. Consider two stars, s_1 and s_2, which have apparent magnitudes m_1 and m_2 and brightnesses b_1 and b_2, respectively. The relationship between them can be written as:

$$m_1 - m_2 = -2.5\log\left(\frac{b_1}{b_2}\right)$$

This means that the *ratio* of their apparent brightnesses (b_1/b_2) corresponds to the *difference* in their apparent magnitudes (m_1–m_2).

Example:

Sirius A has a magnitude of −1.44, while the Sun has a magnitude of −26.8. The ratio of their brightnesses is thus:

$$m_1 - m_2 = -2.5\log\left(\frac{b_1}{b_2}\right)$$

$$-1.44 - (-26.8) = -2.5\log\left(\frac{b_{sirius}}{b_{sun}}\right)$$

$$-10.21 = \log\left(\frac{b_{sirius}}{b_{sun}}\right)$$

$$\left(\frac{b_{sirius}}{b_{sun}}\right) \sim 10^{-10.1} = 7.9 \times 10^{-11} = 1/1.32 \times 10^{10}$$

Thus, *Sirius A* appears 13,200,000,000 times fainter than the Sun, even though it is more luminous (as well as more distant).

The apparent magnitude scale does not tell us whether a star is bright because it is close to us, or faint because it is small or distant; all that the classification tells us is the apparent brightness of the star—that is, the star's brightness as observed with the naked eye or through a telescope. A more precise definition may be that of the *absolute magnitude* (M) of a star; it is defined as the brightness an object would have at a distance of 10 pc. This is an arbitrary distance, derived from stellar parallax, the technique mentioned earlier; nevertheless, it quantifies the brightness of stars in a more rigorous way.[16] As an example, *Deneb*, a lovely star of the summer sky, in the constellation *Cygnus*, has an absolute magnitude of −8.73, making it one of the intrinsically brightest stars, while *Van Biesbroeck's* star has a magnitude of +18.6, making it one of the intrinsically faintest stars known. Table 1.3 shows 20 brightest stars.

Table 1.3. The 20 brightest stars in the sky

	Star	Apparent Magnitude, m	Constellation
1	Sirius	-1.44_v [15]	Canis Major
2	Canopus	-0.62_v	Carina
3	Alpha Centauri	-0.28	Centaurus
4	Arcturus	-0.05_v	Boötes
5	Vega	0.03_v	Lyra
6	Capella	0.08_v	Auriga
7	Rigel	0.18_v	Orion
8	Procyon	0.40	Canis Minor
9	Achernar	0.45_v	Eradinus
10	Betelgeuse	0.45_v	Orion
11	Hadar	0.61_v	Centaurus
12	Altair	0.76_v	Aquila
13	Acrux	0.77	Crux
14	Aldebaran	0.87	Taurus
15	Spica	0.98_v	Virgo
16	Antares	1.05_v	Scorpius
17	Pollux	1.16	Gemini
18	Fomalhaut	1.16	Piscis Austrinus
19	Becrux	1.25_v	Crux
20	Deneb	1.25	Cygnus

Box 1.5: Relationship Between Apparent Magnitude and Absolute Magnitude

The apparent magnitude and absolute magnitude of a star can be used to determine its distance, the formula for which is:

$$m - M = 5 \log d - 5$$

where $m =$ the star's apparent magnitude
$M =$ the star's absolute magnitude
$d =$ the distance to the star (in pc)

The term $m - M$ is referred to as the *distance modulus*.

Example:

Sirius is at a distance of 2.63 pc and has an apparent magnitude of −1.44. Its absolute magnitude can be calculated thus:

$$m - M = 5 \log d - 5$$

$$M = m - 5 \log d + 5$$

$$-1.44 - 5 \log(2.63) + 5$$

$$M \sim 1.46$$

1.3.1 The Brightest Stars

Below is a list of some of the brightest stars in the sky. It is by no means complete. For those interested in observing additional bright stars, I recommend the accompanying volume to this book. Several of the brightest stars have already been mentioned in the section "The Nearest Stars." For the sake of clarity and space, they will not be repeated here.

Pollux	**β Gem**	**$07^h45.3^m$**	**+28°02′**	Dec-**Jan**-Feb
1.16 m	**1.09 M**	**33.72 l.y.**		**Gemini**

This is the brighter of the two famous stars in *Gemini*, the other being *Castor*.

Becrux	**β Crucis**	**$12^h47.7^m$**	**−59°41′**	Mar-**Apr**-May
1.25_v m	**−3.92 M**	**352.1 l.y.**		**Crux**

This star lies in the same field as the glorious *Jewel Box* star cluster. It is a pulsating variable star with a very small change in brightness.

Spica	**α Virginis**	**$13^h25.2^m$**	**−11°10′**	Mar-**Apr**-May
0.98_v m	**−3.55 M**	**262 l.y.**		**Virgo**

The fifteenth-brightest star is a large spectroscopic binary with the companion star lying very close to it, and thus eclipsing it slightly. *Spica* is also a pulsating variable star, though the variability and pulsations are not visible with amateur equipment.

Hadar	**β Centauri**	**$14^h03.8^m$**	**−60°22′**	Mar-**Apr**-May
0.58_v m	**−5.45 M**	**525 l.y.**		**Centaurus**

This is the eleventh-brightest star in the sky, and it is invisible to northern observers because of its low latitude (lying only 4.5° from *α Centauri*). It has a luminosity that is an astonishing 10,000 times that of the Sun. A white star, it has a companion of magnitude 4.1, but it is a difficult double to split, as the companion is only 1.28 arcseconds from the primary.

Arcturus	**α Boötis**	**$14^h15.6^m$**	**+19°11′**	Mar-**Apr**-May
-0.16_v m	**−0.10 M**	**36.7 l.y.**		**Boötes**

The fourth-brightest star in the sky, *Arcturus* is the brightest star north of the celestial equator. It has a lovely orange color and is notable for its peculiar motion through space. Unlike most stars, *Arcturus* is not travelling in the plane of the Milky Way, but instead it is circling the Galactic center in a highly inclined orbit. Calculations predict that it will swoop past the Solar System in several thousand years, moving towards the constellation *Virgo*. Some astronomers believe that, in as little as half a million years, *Arcturus* will disappear from naked-eye visibility. At present, it is about 100 times more luminous than the Sun.

Rigil Kentaurus	**α Centauri**	**$14^h39.6^m$**	**−60°50′**	Apr-**May**-Jun
−0.20 m	**4.07 M**	**4.39 l.y.**		**Centaurus**

The third-brightest star in the sky, *Rigil Kentaurus* is in fact a part of a triple system, with the two brightest components contributing most of the light. The system contains the closest star to the Sun, *Proxima Centauri*. The group also has a very large proper motion (its apparent motion in relation to the background).

Antares	**α Scorpii**	**$16^h29.4^m$**	**−26°26′**	Apr-**May**-Jun
1.06_v m	**−5.28 M**	**604 l.y.**		**Scorpius**

This is a red giant star with a luminosity 6000 times that of the Sun and a diameter hundreds of times larger than the Sun's. What makes this star especially worth watching is the vivid color contrast that is observed between it and its companion star. The star is often described as vivid green when seen with the red of *Antares*. The companion has a magnitude of 5.4, PA of 273°, and lies 2.6″ away.

Vega	**α Lyrae**	**$18^h36.9^m$**	**+38°47′**	Jun-**Jul**-Aug
0.03_v m	**0.58 M**	**25.3 l.y.**		**Lyra**

This is the fifth-brightest star, familiar to northern observers, located high in the summer sky. Although similar to *Sirius* in composition and size, *Vega* is three times as distant, and thus appears fainter. Often described as having a steely-blue color, it was one of the first stars observed to have a disc of dust surrounding it—a possible proto-solar system in formation. *Vega* was the *Pole Star* some 12,000 years ago, and will be again in another 12,000 years.

Altair	**α Aquilae**	**$19^h50.8^m$**	**+08°52′**	Jun-**Jul**-Aug
0.76_v m	**2.20 M**	**16.77 l.y.**		**Aquila**

The twelfth-brightest star, *Altair* has the honour of being the fastest-spinning of the bright stars, completing one revolution in approximately 6 1/2 hours. Such a high speed deforms the star into what is called a flattened ellipsoid, and it is believed that, because of this amazing property, the star may have an equatorial diameter twice that of its polar diameter. The star's color has been reported to be completely white, although some observers see a hint of yellow.

Fomalhaut	**α Pisces Austrini**	**$22^h57.6^m$**	**−29°37′**	Aug-**Sep**-Oct
1.17 m	**1.74 M**	**25.07 l.y.**		**Pisces Austrinus**

The eighteenth-brightest star is a white one, which often appears reddish to northern observers due to the effect of the atmosphere. It lies in a barren area of the sky, and it is remarkable that a star close to it, which is not bound gravitationally yet lies at the same distance from the Earth, is moving through space in a manner and direction similar to *Fomalhaut*. It has been suggested that the two stars are remnants of a star cluster or star association that has long since dispersed. This orange star of magnitude 6.5 lies about 2° south of *Fomalhaut*.

Achernar	**α Eridani**	**$01^h 37.7^m$**	**−57°14′**	Sep-**Oct**-Nov
0.45_v m	**−2.77 M**	**144 l.y.**		**Eridanus**

The ninth-brightest star in the sky lies at the southernmost end of the constellation and too far for northern observers. Among the brightest stars, it is one of the very few with the designation "p" in its stellar classification, indicating that it is a "peculiar" star.

Aldebaran	**α Tauri**	**$04^h 35.9^m$**	**+16°31′**	Oct-**Nov**-Dec
0.87 m	**−0.63 M**	**65.11 l.y.**		**Taurus**

The fourteenth-brightest star appears to be located in the star cluster *Hyades*; however, it is not physically in the cluster at all, lying twice as close as the cluster members. This pale-orange star is approximately 120 times more luminous than the Sun. It is a double star, too, but very difficult to separate due to the extreme faintness of the companion. The companion star, a red dwarf star of magnitude 13.4, lies at a PA of 34° and at a distance of 121.7″.

Rigel	**β Orionis**	**$05^h 14.5^m$**	**−08°12′**	Nov-**Dec**-Jan
-0.18_v m	**−6.69 M**	**773 l.y.**		**Orion**

The seventh-brightest star in the sky, *Rigel* is in fact brighter than *α Orionis*. This supergiant star is one of the most luminous stars in our part of the Galaxy, almost 560,000 times more luminous than the Sun but at a greater distance than any other nearby bright star. Often described as a bluish star, it has a tremendous mass—about 50 times that of the Sun and about 50 times its diameter. It has a close bluish companion at a PA of 202°, apparent magnitude 6.8, and at a distance of 9 arcseconds, which should be visible with a 15 cm telescope, or even a smaller one under excellent observing conditions.

Capella	**α Aurigae**	**$05^h 16.7^m$**	**+46°00′**	Nov-**Dec**-Jan
0.08_v m	**−0.48 M**	**42 l.y.**		**Auriga**

The sixth-brightest star in the sky is, in fact, a spectroscopic double, although it cannot be split in a telescope; however, it has a fainter 10th-magnitude star about 12 arcseconds to the south-east at a PA of 137°. This is a red dwarf star, which is itself a double (only visible in larger telescopes). So, *Capella* is in fact a quadruple system.

Betelgeuse	**α Orionis**	**$05^h 55.2^m$**	**+07°24′**	Nov-**Dec**-Jan
0.45_v m	**−5.14 M**	**427 l.y.**		**Orion**

The tenth-brightest star in the sky, and a favorite to most observers, this orange-red star is a giant variable with an irregular period. Recent observations by the Hubble Space Telescope have shown that it has features on its surface that are similar to Sunspots but much larger, covering perhaps a tenth of the surface.

It also has a companion star, which may be responsible for the non-spherical shape it exhibits. Although a giant star, it has a very low density and a mass 20 times that of the Sun, which together mean that its density is in fact just 0.000000005 times that of the Sun.

1.4 Color

When we look up into the sky at night, we see many stars; all of them are generally white. There are, of course, a few that exhibit distinct colors—*Betelgeuse* (*α Orionis*) is most definitely red, as is *Antares* (*α Scorpi*); *Capella* (*α Aurigae*) is yellow; and *Vega* (*α Lyrae*) is steely blue. However, for the most part, there does not seem to be any great variation in color. Look through binoculars or a telescope, and the situation changes dramatically.[17] Variations in color and hue abound![18]

The color of a star is determined by its *surface temperature*. A red star has a lower temperature than that of a yellow star, which in turn has a lower temperature than that of a blue star. This is an example of what is called the *Wien Law* (See Box 1.6). The law states that low-temperature stars emit most of their energy in the red to infrared part of the spectrum, while much hotter stars emit in the blue to ultraviolet part of the spectrum. Some very hot stars emit most of their energy in the ultraviolet, and so in fact we see only a fraction of their light. Furthermore, many stars emit nearly all of their light in the infrared, and so we do not see them at all. Surprisingly, these low-mass (to be discussed later), low-temperature stars make up about 70% of the stars in our galaxy, but you would never ever see them by going out and observing the sky on a clear night.

An important point to notice here is that hotter objects emit more energy at *all* wavelengths due to the higher average energy of *all* the photons. This is illustrated in Figure 1.2. The graphs demonstrate how the light from three different stars is distributed, depending on the stars' temperature. The colored block represents the visible part of the spectrum. The first plot shows the light that would be measured from a colored star of about 3000 K. Note that the curved line peaks at about 1100 nm, which would make the star appear red. The second plot shows a star of about 5500 K (similar to the Sun's temperature), which peaks in the middle of the visible spectrum, thus looking yellowish. The final plot illustrates a very hot star, of 25,000 K; it peaks at about 400 nm, and so it will appear blue. Thus, the color of a star, from an astronomical viewpoint, depends on where the peak of its curve lies; a short wavelength (the left part of the plot) indicates a hot, bluish-white star, while a longer wavelength (the right part of the plot) indicates a cool, reddish-orange star. The Sun peaks at the green part of the spectrum; since there is a mixture of light from all the other parts of the visible spectrum—the blues, reds, and yellows—we actually observe the Sun as being yellowish-white.

An interesting thing to observe is that a few stars are so hot, possibly in millions of degrees, that they emit energy at very short wavelengths. In fact, they radiate X-rays. These are neutron stars!

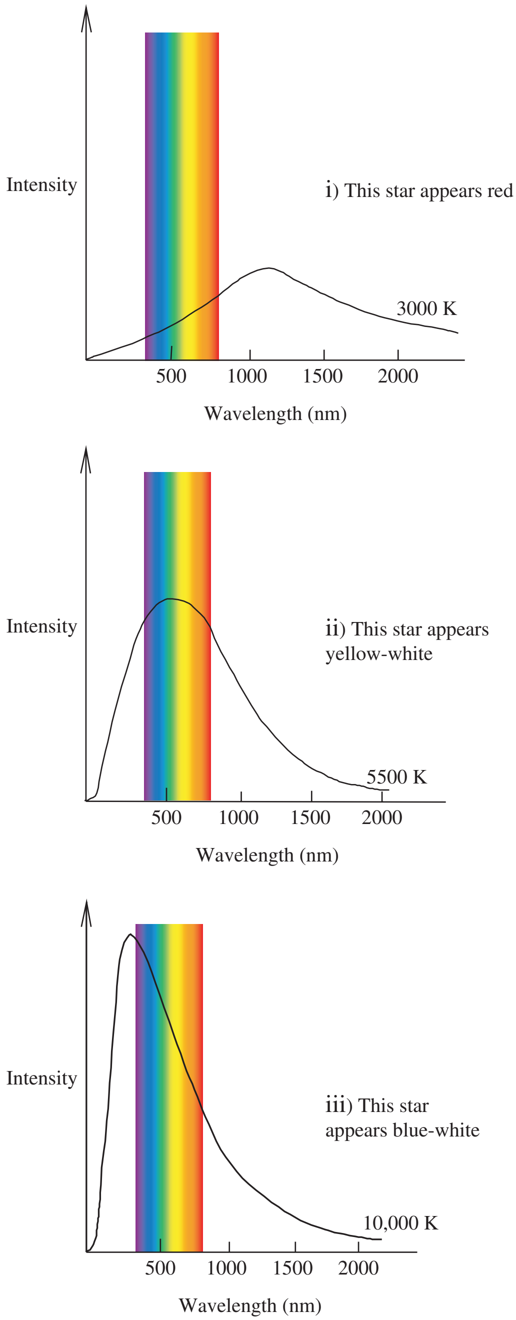


Figure 1.2. Relationship between color and temperature.

Note that when we speak of a star's temperature, we are referring to its surface temperature. The internal temperature cannot be measured directly, and it is usually determined from theoretical temperatures. So, when you read that a star's temperature is 25,000 K, it refers to the surface temperature.[19]

Box 1.6: The Wien Law

Wien's Law can be stated as:

$$\lambda_{max} = \frac{2,900,000}{T(\text{Kelvin})}\,\text{nm}$$

Example:

Two stars, α Canis Majoris and o Ceti, have a temperature of 9200 K and 1900 K, respectively. What are their peak wavelengths?

$$\lambda_{max} = \frac{2,900,000}{9200(\text{Kelvin})}\,\text{nm} = 315\,\text{nm (i.e., in the ultraviolet}^{20})$$

and

$$\lambda_{max} = \frac{2,900,000}{1900(\text{Kelvin})}\,\text{nm} = 1526\,\text{nm (i.e., in the infrared}^{21})$$

Sirius emits a lot of light in the ultraviolet, even though it shines brightly white.

Knowing a star's temperature helps to determine many other characteristics. One scientific description of a star's color is based on the stellar classification, which in turn is dependent upon the star's chemical composition and temperature. A term commonly used by astronomers is *color index*. It is determined by observing a star through two filters, the *B* and *V* filters, which correspond to the wavelengths 440 and 550 nm, respectively, and by measuring its brightness. Subtracting the two values obtained, *B* and *V*, produces the color index. Usually, a blue star will have a negative color index (e.g., −0.3); orange-red stars will have a value greater than 0.0 and upwards to about 3.00, and even greater for very red stars (M6 and greater) [see section 1.8].

Having discussed the colors of stars, let us now look at some examples. I have chosen a representative selection of bright stars. There are, of course, literally thousands of other visible colored stars. The section "The Brightest Stars" offers many examples of stars that exhibit distinct colors. In addition, many double stars (not mentioned here) show very distinct hues and tints. The nomenclature used here is the same as that used previously, except for the addition of the star's temperature and color.[22]

1.4.1 Colored Stars

Bellatrix	**γ Ori**	**$05^h26.2^m$**	**$+06°21'$**	Nov-**Dec**-Jan
1.64 m	**−2.72 M**	**21,450 K**	**Blue**	**Orion**

Also known as the *Amazon Star*, *Bellatrix* appears steely blue. Some observers report a faint nebulosity associated with the star, but it may just be a part of general nebulosity that envelopes much of *Orion*.

Merope	**23 Tau**	**$03^h46.3^m$**	**$+23°57'$**	Oct-**Nov**-Dec
4.14 m	**−1.07 M**	**10,600 K**	**Blue**	**Taurus**

Located within the *Pleiades* star cluster, it gives a breathtaking and spectacular view when seen through binoculars, and the cluster is a highlight of the night sky. Almost all the stars in this cluster are worth observing for their lovely steely-blue color.

Regulus	**α Leo**	**$10^h08.3^m$**	**$+11°58'$**	Jan-**Feb**-Mar
1.36 m	**−0.52 M**	**12,000 K**	**Blue-white**	**Leo**

α Leonis is the handle of the Lion's sickle. It is an easy double star; the companion, an 8th magnitude, orange-red color, is about $3'$ away.

Acrux	**α Crucis**	**$12^h26.6^m$**	**$-63°06'$**	Feb-**Mar**-Apr
0.72[10] m	**−4.19 M**	**28,000/26,000 K**	**White**	**Crux**

Acrux is a double star with components $4''$ apart. Both stars are almost of the same magnitude: 1.4 for α^1 and 1.9 for α^2. The colors of the stars are white and bluish-white, respectively.

Zubeneschamali	**β Lib**	**$15^h17.0^m$**	**$-09°23'$**	Apr-**May**-Jun
2.61 m	**−0.84 M**	**11,000 K**	**Green!**	**Libra**

This is a mysterious star for two reasons: historical records state that it was much brighter than it appears today, and observers of the past 100 years have declared that it is greenish or pale emerald in color. It is one of the rare green-colored stars!

The Sun				**Jan-Dec**
−26.78 m	**4.82 M**	**5800 K**	**Yellow**	**The Zodiac**

The Sun is our closest star, without which no life would have evolved on Earth. It is visible every day throughout the year, unless you happen to live in the UK. **DO NOT OBSERVE THE SUN THROUGH ANY KIND OF OPTICAL EQUIPMENT.**

Garnet Star	**μ Cep21^{h}43.5^m**		**+58°47′**	Jul-**Aug**-Sep
4.08$_v$m	**−7.3M**	**3500 K**	**Orange**	**Cepheus**

Located on the north-eastern edge of the nebulosity IC1396, *Garnet Star*, named by William Herschel, is one of the reddest stars in the sky, having a deep orange or red color, seen against a backdrop of faint white stars. It is a pulsating red giant star, with a period of about 730 days and brightness from 3.4 to 5.1 m.

Hind's Crimson Star	**R Leporis**	**04^{h}59.6^m**	**−14°48′**	Nov-**Dec**-Jan
7.71$_v$m	**1.08M**	**3000 K**[23]	**Red**	**Lepus**

This star, a classic long-period variable, has a period of about 432 days, and varies in brightness between 6.0 and 9.7 m. At maximum brightness, it displays the famous ruddy color that gave it its name. It was discovered in 1845 by J. R. Hind, who described its color as "intense smoky red." This may be the reddest star in the sky. It is also an AGB star (see section 3.15).

1.5 Size and Mass

Stars are at an immense distance from the Earth; no matter how much we magnify a star's image, it will, in all but a handful of cases,[24] remain just a point of light. So how do we determine the size of a star? The answer is quite simple: by measuring both the luminosity (derived from its distance and brightness) and the surface temperature (determined from its spectral type); it is just a matter of manipulating numbers with a few formulas. Using this technique, astronomers have discovered that many stars are much smaller than the Sun, while many others are thousands of times larger.

To accurately determine a star's size, a physical law called the Stefan–Boltzmann Law is used. We will not bother looking at how this law came about, but simply quote it and show how it is used (see Box 1.7). The law states that the amount of energy that a star radiates per second from a square meter of its surface[25] is proportional to the fourth power of the temperature (T) of its surface. Do not let the complexity of this statement distract you. It just tells us that the *energy flux* (F) is proportional to the temperature, which may make sense to you when you think it over. A cool object has lower thermal energy than a hot object.

Now recall what we discussed earlier, that the luminosity of a star is a measure of the energy emitted from its surface every second. This luminosity is, in fact, the flux (F) multiplied by the *number of square meters there are on the star's surface*. If we assume that most stars are spherical (which is not as silly as it sounds because a few stars are not spherical!), then the quantity highlighted in the previous sentence is in fact the surface area of the star. This is given by a very simple formula, which most of us already know: $4\pi R^2$, where R is the radius of the star (taken as the distance from the center of the star to its surface[26]).

Box 1.7: Flux, Luminosity, and Radius

The flux from a star is given by the Stefan–Boltzmann Law:

$$F = \sigma T^4$$

The relationship between flux (F), luminosity (L), and radius (R) of a star is:

$$L = 4\pi R^2 \sigma T^4$$

where L is the star's luminosity in watts (W)
R is its radius in meters (m)
σ is the Stefan–Boltzmann constant; $5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$
T is the star's temperature in Kelvin (K)

The above equations tell us that a coolish star (one with a low surface temperature) will have a low flux, but it might be quite luminous because it could have a very large radius, and thus a large surface area. In a similar vein, a hot star (one with a high surface temperature) might have a low luminosity if it has a small radius, which would mean a low surface area. Now you can see that knowing the temperature alone does not indicate how luminous a star will be—you need its radius, too!

Although we can now determine such parameters as the radius, temperature, luminosity, and brightness of a star, it is often more useful to relate these values to that of the Sun. It would be easier for someone to understand if we said that a star is about 10 times hotter than Sun rather than saying it is 54,000 K. The same applies to L and R.

Box 1.8: Even More about Flux, Luminosity, and Radius

We regard the Sun as a typical star, and so we can relate a star's characteristics to that of the Sun. For instance:

$$L_\odot = 4\,\pi\,R_\odot{}^2 \sigma T_\odot{}^4$$

where $L_\odot$ is the luminosity of the Sun
$R_\odot$ is the Sun's radius
$T_\odot$ is the Sun's temperature

If we divide the luminosity equation for a star by that for the Sun, we get:

$$L/L_{\odot} = (R/R_{\odot})^2(T/T_{\odot})^2$$

The constants σ and 4π have now gone, and we can rearrange the formula to read:

$$R/R_{\odot} = (T_{\odot}/T)^2(L/L_{\odot})^{1/2}$$

where the factor 1/2 indicates a square root.
Now, $R/R_{\odot}$ is the ratio of the star's radius to that of the Sun
$T_{\odot}/T$ is the ratio of the Sun's temperature to that of the star
$L/L_{\odot}$ is the ratio of the star's luminosity to that of the Sun

Example:
Sirius has a temperature of about 9200 K and luminosity of about 23 $L_{\odot}$.
To determine its ratio:

$$R/R_{\odot} = \left(\frac{5800}{9200}\right)^2 \times \sqrt{23} \sim 2$$

Thus, its radius is about twice that of the Sun.

1.5.1 The Biggest Stars

Let us now discuss some examples of giant stars, particularly those that can be seen with the naked eye.

α Herculis	**ADS 10418**	**$17^h14.6^m$**	**+14°23′**	May-**Jun**-Jul
3.5_v, 5.4_vm	**−1.9 M**	**Radius : 2.0 AU**		**Hercules**

A lovely color-contrast double (orange and bluish-green), the star lies at a distance of about 400 l.y. and is a semi-regular, supergiant variable star. The primary star is itself variable, while the secondary is an unresolvable double.

ψ^1 Aurigae	**HD 44537**	**$06^h24.9^m$**	**+49°17′**	Nov-**Dec**-Jan
4.92_vm	**−5.43 M**	**Radius : 3.0 (?) AU**		**Auriga**

This star has an incredible luminosity of over 11, 000 $L_{\odot}$. It is an irregular variable star, the diameter of which is not known. The star is believed to be about 4300 l.y. distant.

η Persei	**ADS 2157**	**$02^h50.7^m$**	**+55°54′**	Oct-**Nov**-Dec
3.8, 8.5 m	**−4 M**	**Radius : 2.0 AU**		**Perseus**

Lying at a distance of about 1300 l.y., this is a lovely double star—gold primary and blue secondary. The primary is a supergiant with a luminosity of over 4000 $L_{\odot}$.

VV Cephei	**HD 208816**	**$21^h\ 56.6^m$**	**+63°37′**	Sep-**Oct**-Nov
5.11 m	**−6.93 M**	**Radius : 8.8 AU**		**Cepheus**

This star has a luminosity between 275,000 and 575,000 $L_\odot$, and it lies at a distance of 2000 l.y. It is one of the famous *eclipsing binary*-type variable stars, with a period of just 20 years or over. The system consists of an *O*-type dwarf and an *M*-type supergiant; if placed at the center of the solar system, this giant star would extend to the orbit of Saturn!

KQ Puppis	**HD 60414**	**07^h 33.8^m**	**−14°31′**	Sep-**Oct**-Nov
4.82 m	**−5.25 M**	**Radius : 8.8 AU**		**Puppis**

This star has a luminosity of over 9870 $L_\odot$, and it lies at a distance of 3361 l.y.[27] It is believed to be an irregular variable star.

1.6 Star Constituents

Although we shall cover this topic in far greater detail later in the book, it is important that we briefly look at what stars are made of.

A star is an enormous sphere of hot gases. It is as simple, or as complex, as that, whichever way you wish to look at it. Of course, the processes involved in making and maintaining a star are, as expected, very, very complex!

Gases that compose a star are primarily hydrogen (H, the most common element in the universe), helium (He), and some other elements.[28] By and large, most stars are nearly entirely made of hydrogen, less helium, and very small amounts of everything else. This composition is usually about 75% hydrogen, 24% helium, and the remainder metals. This ratio may change, however, since very old stars are nearly all hydrogen and helium with tiny amounts of metals, and very new stars can contain as much as 2–3% metals.

The energy needed to create and maintain a star is produced within the star by nuclear fusion. Two immense forces—very high temperature and strong gravitational force—are at work. Due to very large mass and concomitantly strong gravitational fields, the conditions at the center of the ball of gases are such that the temperature may be about 10 *million* K. At such extremes of pressure and heat, nuclear fusion can occur, by which hydrogen is converted into helium. The outcome of this nuclear reaction is a tiny amount of energy in the form of gamma rays. It may not seem like much, but when billions of these reactions take place every second, the amount of energy liberated is quite substantial…enough, in fact, to make a star shine!

As a star ages, it uses up more and more hydrogen in order to keep the nuclear reactions going. A by-product of this reaction is helium. After quite some time, the amount of hydrogen decreases and helium increases. If conditions are right (which include a higher temperature and a large mass), then helium itself will start to undergo nuclear fusion at the star's core. After a very-long time, helium, in turn, will produce the element carbon as a by-product of the reaction; similarly, if conditions are suitable, carbon, too, will initiate nuclear fusion and produce more energy. An important point to emphasize is that each step requires a higher temperature to begin nuclear reactions, and if a star does not have the conditions necessary to produce this temperature, further reactions will not occur. So, you can see that the "burning" of hydrogen and helium is the source of power for nearly all the stars that we see, and the mass of a star determines how the reactions will proceed.

1.7 Spectra and Spectroscopy

Let us now look at a tool that is central to the topic of astrophysics—spectroscopy and spectra. This is an amazing topic; from just looking at the light from an object, we can say how hot it is, how far away it is, in which direction is it moving,[29] if it is rotating, and (from all these data) infer its age, mass, how long it will live, and so on. In fact, so important is this topic that, from this point on in the book, a star will be referred to by its spectral classification.

Determining a star's classification is a theoretically easy task, although it may be difficult in practice. What is needed is a spectroscope. This is an instrument that helps one look at the light from a star in a special way by utilizing either a prism or a diffraction grating for analysis. You are probably aware that white light is in fact a mixture of many different colors, or wavelengths, and so it is safe to assume that the light from a star is a mixture of colors. Indeed it is, but usually with an added component. Using a spectroscope mounted at the eyepiece end of the telescope,[30] light from a star can be collected and photographed (these days with a CCD camera). The result is something called a spectrum. Many amateur astronomers are now making some good observations of stars' spectra.

Basically, a spectrum is a map of light coming from a star. It consists of all of the emitted light, spread out according to wavelength (color), so that different amounts of light at different wavelengths can be measured. Red stars have a lot of light at the red end of the spectrum, and blue stars have a correspondingly larger amount at the blue end. However, an important point to note is that, in addition to this light, there will be a series of dark lines superimposed upon this rainbow-like array of colors. These are called *absorption lines*, which are formed in the atmosphere of the star. In rare cases, there are bright lines, too, called *emission lines*. Although comparatively rare in stars, these lines are very prominent in nebulae.

The electrons in the atoms located on the surface layers of a star can only have very specific energies, just like the specific heights of the rungs of a ladder. Sometimes, an electron in an atom of, say, hydrogen can be "knocked" from a lower energy level to a higher energy level, maybe by a collision with another atom. Eventually, it will fall down to the lower level. The energy that the atom loses when the electron returns to its original level must go somewhere, and it often goes to emitting a photon of light. This emitted photon has a unique property—it has the exact amount of energy that the electron loses, which in turn means that the photon has a very specific wavelength and frequency.

When hydrogen gas is heated to a high temperature, the number of collisions between atoms can continually bump electrons to higher energy levels, and an *emission line spectrum* results. This consists of the photons that are emitted as each electron falls back to lower levels.

The origins of the absorption lines are due to the differing amounts of elements in the cooler atmosphere of the stars (recall that in addition to hydrogen and helium, there are other elements, or metals, present, but in minute quantities). Not only are photons emitted, but they may also be absorbed. This process causes the electrons to jump up in energy to a higher level. But, this can only happen if the photon has the precise amount of energy required. Too much too little energy, even a minuscule amount, can cause the photon to not interact with the electron.

In hydrogen gas, an electron moving from level 2 to level 1 will emit a photon that has a wavelength of 121.6 nm; an electron absorbing a photon of this wavelength will jump from level 1 to level 2. Such jumps from different levels are called *transitions*. Thus, in the above example, an electron undergoes a transition from level 1 to level 2, with an absorption of a photon of wavelength 121.6 nm. Figure 1.3 shows the allowed energy levels of hydrogen and wavelengths that occur for downward transitions. Also shown are the absorption and emission spectra.

Note in Figure 1.3 that the dark absorption lines and bright emission lines occur at exactly the same wavelengths, regardless of whether the hydrogen is

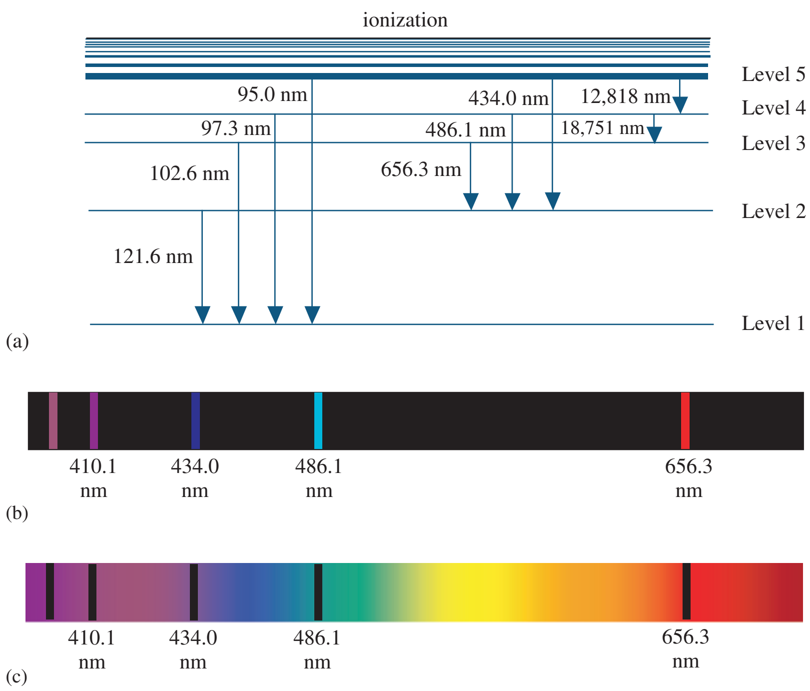


Figure 1.3. Allowed energy levels of hydrogen. (a) The wavelengths of various energy level transitions in hydrogen.[31] (b) Visible emission line spectra showing transitions that occur from high energy levels downward to level 2 for hydrogen. (c) Absorption line spectra showing transitions that arise from energy level 2 to higher levels. These absorption and emission lines of hydrogen are called the *Balmer Lines*.

emitting or absorbing light. Emission lines are simply the result of downward jumps, or transitions, of electrons between the energy levels, while absorption lines are upward transitions.

The energy levels of electrons in each chemical element are unique—a "fingerprint" that results in each element's having its own distinct spectral lines. Hydrogen is a very simple element, with only 1 electron, but in those elements with many electrons and energy levels, the corresponding spectra can be very complex.

The factor that determines whether an absorption line will arise is the temperature of a star's atmosphere. A hot star will have different absorption lines than a cool star. The classification of a star is determined by examining its spectrum and measuring various aspects of the absorption lines. A very important point that I would emphasize is that the observational classification of a star is determined primarily by the temperature of the atmosphere and not the core temperature. The structure of the absorption lines can be examined, and this gives further information on pressure, rotation, and even the presence of a companion star.

1.8 Stellar Classification

We saw earlier that stars are distinguished by their spectra (and thus temperature). Let us now think about the spectral type. For historical reasons, a star's classification is designated by a capital letter which is in order of *decreasing* temperature:[32]

O B A F G K M L R N S

The sequence goes from hot blue stars (types *O* and *A*) to cool red stars (types *K*, *M*, and *L*). In addition, there are rare hot stars called *Wolf-Rayet* stars (classes *WC* and *WN*), exploding stars (*Q*), and peculiar stars (*p*). The star types *R*, *N*, and *S* actually overlap the class *M*, and so *R* and *N* have been reclassified as *C*-type stars, the *C* standing for carbon stars. A new class (*L*) has recently been introduced.[33] Furthermore, the spectral types are divided into ten spectral classes beginning with 0, 1, 2, 3, and so on up to 9. A class A1 star is hotter than a class A8 star, which in turn is hotter than a class F0 star. Furthermore, prefixes and suffixes can be used to illustrate additional features:

a star with emission lines (also called f in some *O*-type stars)	e
metallic lines	m
peculiar spectrum	p
variable spectrum	v
a star with a blue or red shift in the line (e.g., P Cygni stars)	q

For more historical reasons, the spectra of the hotter star of types *O*, *A*, and *B* are sometimes referred to as *early-type* stars, while the cooler ones (*K*, *M*, *L*, *C*, and *S*) are *later-type*. *F* and *G* stars are designated *intermediate-type* stars.

Because the spectral type is so important, it is instructive to explain further how the appearance of a spectrum is affected by its surface temperature. We will consider the *Balmer* lines of hydrogen, mainly because these are by far the easiest to understand. Hydrogen gas makes up 75% of a star, yet the Balmer lines do not always appear in a star's spectrum. The Balmer absorption lines are produced when an electron undergoes a transition from the 2nd energy level to a higher level by absorbing a photon with the correct amount of energy. If, however, the star is hotter than 10,000 K, the photons coming from the star's interior have such a high energy that they can easily knock electrons out of hydrogen atoms in the star's atmosphere. This process is called *ionization*. Now that the hydrogen atom has lost its electrons, it cannot produce absorption lines. So, the Balmer lines will be relatively weak in the spectra of such hot stars (e.g., type-*O* stars, up to type *B*2).

On the other hand, if the atmosphere of a star is cooler than 10,000 K, most of the hydrogen atoms are in the 1st energy state. Many of the photons passing through the atmosphere do not have enough energy to boost the electron from the 1st to the 2nd energy level. Therefore, very few atoms will have electrons in the 2nd level, and only these electrons will absorb the photons characteristic of the Balmer lines. This results in the lines' being almost absent from the spectrum of cool stars, such as *M*0 and *M*2 stars.

For the Balmer lines to be prominent, a star must be hot enough to excite the electrons out of level 1 (also known as the *ground state*), but not so hot that the hydrogen becomes ionized. If a star has a surface temperature of around 9,000 K, it will have the strongest hydrogen lines (e.g., the *A*0 to *A*5 stars).

The Balmer lines of hydrogen become increasingly prominent as you go from type *B*0 to *A*0. From *A*0 through *F* and *G* class, the lines weaken and almost fade away. The Sun, a *G*2 star, has a spectrum dominated by lines of calcium and iron.

Finally, a star can also be classified by its *luminosity*, which is related to its intrinsic brightness, with the following system:

Supergiants[34]	I
Bright giants	II
Giants	III
Subgiants	IV
Dwarfs	V
Subdwarfs	VI
White dwarfs	VII

It is evident that astronomers use a complex and very confusing system! In fact, several classes of spectral type are no longer in use, and the luminosity classification is also open to confusion. It will not surprise you to know that there is even disagreement among astronomers as to whether, for example, a star labelled *F*9 should be reclassified as *G*0! Nevertheless, it is the system generally used, and so it will be adhered to here. Examples of classification are:

Boötes (Arcturus)	K2IIIp
β Orionis (Rigel)	B8Ia
α Aurigae (Capella)	G8 III
P Cygni	B1Iapeq
Sun	G2V

I conclude my discussion on spectral classification by explaining what the spectral type actually *refers* to.[35] You may recall that spectral classification was based on the detection of absorption lines, which in turn depends on the temperature of a star's atmosphere. Thus, the classification relies on the detection of certain elements in a star, giving rise to a temperature determination for that star. The classification is summarized in Table 1.4.

It is interesting to note that the distribution of stars throughout the Galaxy may not be what you assume. A casual glance at the stars in the night sky will give you several *O*- and *B*-type, a few *A*-type, some *F*- and *G*-type, a smattering of *K*, and more *M*-types. You may think that this is a fair picture of the type of distribution throughout the remainder of the Galaxy. You could be wrong! As we shall see in later sections, a vast majority of stars in our Galaxy—over 72% of them—are faint, cool, and red *M*-type stars. The bright and hot *O*-type stars are less than 0.005%. For every *O*-type star, there are about 1.7 million *M*-types!

Let us now look at a few examples:

1.8.1 The Spectral Sequence

–	**HD 93129A**	**$10^h43.9^m$**	**−59°33′**	Jan-**Feb**-Mar
7.0 m	**−7.0 M**	**O3If**		**Carina**

This is an extraordinary star! This supergiant star, lying at a distance of about 11,000 l.y. shines about 5 million times as brightly as the Sun. With a mass of 120 $M_{\odot}$, it is believed to be one of the most luminous stars in the entire Galaxy.

θ Orionis C	**θ Ori**	**$05^h35.3^m$**	**−05°23′**	Nov-**Dec**-Jan
4.96 m	**−5.04 M**	**O6**		**Orion**

A member of the famous Trapezium multiple star system in the Orion Nebula, this is a fairly new star, maybe several thousand years old, and as a consequence most of its light is emitted at ultraviolet wavelengths. It has a temperature of about 45,000 K and a diameter 10 times that of the Sun.

15 Monocerotis	**HD 47839**	**$06^h40.9^m$**	**+09°54′**	Nov-**Dec**-Jan
4.66_v m	**−2.3 M**	**O7**		**Monoceros**

Both a visual binary and a variable star, 15 *Monocerotis* is located in the star cluster *NGC 2264*, which in turn is encased in a diffuse nebula.

Plaskett′s Star	**HD 47129**	**$06^h37.4^m$**	**+06°08′**	Nov-**Dec**-Jan
6.05 m	**−3.54 M**	**O8**		**Monoceros**

Table 1.4. Spectral Classification

Spectral Type	Absorption Lines	Temperature, K	Color	Notes	Brightest Wavelength (Color)	Examples
O	ionized helium (HeII)	35,000+	blue-white	massive, short-lived	< 97 nm (ultra-violet)	Stars of Orion's Belt
B	neutral helium first appearance of hydrogen	20,000	blue-white	massive and luminous	97–290 nm (ultraviolet)	Rigel
A	hydrogen lines singly ionized metals	10,000	white	up to 100 times more luminous than the Sun	290–390 nm (violet)	Sirius
F	ionized calcium (CaII), weak hydrogen	7,000	yellow-white		390–480 nm (blue)	Polaris
G	CaII prominent, very weak hydrogen	6,000	yellow	Sun is G-type	480–580 nm (yellow)	Alpha Centauri A, Sun
K	neutral metals, faint hydrogen, hydrocarbon bands	4,000–4,700	orange		580–830 nm (red)	Arcturus
M	molecular bands, titanium oxide (TiO)	2,500–3,000	red	most prolific stars in Galaxy	> 830 nm (infrared)	Proxima Centauri, Betel-geuse

Plaskett's Star is actually composed of two stars and is a spectroscopic binary system with an estimated mass of approximately 110 times that of the Sun, making it one of the most massive known objects.

GammaK Cassiopeiae	**γ Cas**	**$00^h56.7^m$**	**+60°43′**	Sep-**Oct**-Nov
2.15_vm	**−4.22 M**	**B0 IV**		**Cassiopeia**

This peculiar star has bright emission lines in its spectrum, indicating that it ejects material in periodic outbursts. It is the middle star of the familiar W-shape of *Cassiopeia*.

Mirzim	**β CMa**	**$06^h22.7^m$**	**−17°57′**	Nov-**Dec**-Jan
1.98_vm	**−3.96 M**	**B1 II**		**Canis Major**

Mirzim is the prototype of a class of variable stars now classified as *β Cepheid* stars, which are pulsating variables. The magnitude variation, however, is too small to be observed visually.

Algenib	**γ Peg**	**$00^h13.2^m$**	**+15°11′**	Aug-**Sep**-Oct
2.83_vm	**−2.22 M**	**B2 V**		**Pegasus**

Algenib is a member of the type *βCMa* (Canis Majoris) variable star and is the south-eastern corner star of the famed square of Pegasus.

Achernar	**α Eri**	**$01^h37.7^m$**	**−57°14′**	Sep-**Oct**-Nov
0.45_vm	**−2.77 M**	**B3 V**		**Eradinus**

Achernar is a hot and blue star. It lies so far south, it can never be seen from the UK.

Aludra	**η CMa**	**$07^h24.1^m$**	**−29°18′**	Dec-**Jan**-Feb
2.45 m	**7.51 M**	**B5 I**		**Canis Major**

This is a highly luminous supergiant with an estimated luminosity 50,000 times that of the Sun.

Electra	**17Tau**	**$03^h44.9^m$**	**+24°07′**	Oct-**Nov**-Dec
3.72 m	**−1.56 M**	**B6 III**		**Taurus**

Electra is located within the *Pleiades* star cluster.

Alcyone	**η Tauri**	**$03^h47.5^m$**	**+24°06′**	Oct-**Nov**-Dec
2.85 m	**−02.41 M**	**B7 III**		**Taurus**

Alcyone is the brightest star in the Pleiades star cluster, with a luminosity of about 350 times that of the Sun.

Maia	**20 Tauri**	**$03^h45.8^m$**	**+24°22′**	Oct-**Nov**-Dec
3.87 m	**−1.344 M**	**B8 III**		**Taurus**

This is yet another lovely blue star in the Pleiades cluster. *Maia* has a luminosity about eight times that of the Sun.

Eta Sagitai	**ε Sgr**	**$18^h24.2^m$**	**−34°23′**	May-**Jun**-Jul
1.79 m	**−1.44 M**	**B9.5 III**		**Sagittarius**

This is a brilliant orange star at a distance of 125 l.y. with a luminosity 250 times that of the Sun's.

Nu Draconis[1]	**ν^1 Dra**	**$17^h32.2^m$**	**+55°11′**	May-**Jun**-Jul
4.89 m	**2.48 M**	**Am**		**Draco**

This is a classic double star system visible through binoculars or a small telescope. The stars are nearly identical in magnitude and stellar class and have a lovely white color.

Alhena	**γ Gem**	**$06^h37.7^m$**	**+16°23′**	Nov-**Dec**-Jan
1.93 m	**−0.60 M**	**A0 IV**		**Gemini**

The star is relatively close at 58 l.y. with a luminosity 160 times that of the Sun.

Castor	**α Gem**	**$07^h34.6^m$**	**+31°53′**	Dec-**Jan**-Feb
1.43 m	**0.94 M**	**A1 V**		**Gemini**

Castor is a part of the famous multiple star system and a fainter brother to *Pollux*. The visible magnitude stated here is the result of combining the magnitudes of the two brighter components of the system, 1.9 and 2.9.

Deneb	**α Cyg**	**$20^h41.3^m$**	**+45°17′**	Jul-**Aug**-Sep
1.25_v m	**−8.73[36] M**	**A2 I**		**Cygnus**

This is the faintest star of the *Summer Triangle* (the others being *Altair* and *Vega*). *Deneb* is a supergiant star with definite pale-blue color. It is the prototype of a class of pulsating variable stars.

Denebola	**β Leo**	**$11^h49.1^m$**	**+14°34′**	Feb-**Mar**-Apr
2.14_v m	**1.92 M**	**A3 V**		**Leo**

This star, along with several of its companion stars, is visible through a variety of instruments. The star has just recently been designated a variable.

Delta Leonis	**δ Leo**	**$11^h14.1^m$**	**+20°31′**	Feb-**Mar**-Apr
2.56 m	**1.32 M**	**A4 V**		**Leo**

Also called *Zozma*, *Delta Leonis* lies at a distance of 80 l.y. with a luminosity 50 times that of the Sun.

Ras Alhague	**α Oph**	**$17^h34.9^m$**	**+12°34′**	May-**Jun**-Jul
2.08 m	**1.30 M**	**A5 III**		**Ophiucus**

This is an interesting star for several reasons. It shows the same motions through space as several other stars in the *Ursa Major Group*. It also shows interstellar absorption lines in its spectrum. Finally, its measurements show an oscillation (or wobble) in proper motion, which would indicate an unseen companion star.

2 Mon	**HD 40536**	**05^{h}59.1^m**	**−09°33′**	Nov-**Dec**-Jan
5.01 m	**0.02 M**	**A6**		**Monoceros**

The star lies at a distance of over 1900 l.y. with a luminosity 5000 times that of the Sun.

Alderamin	**α Cep**	**21^{h}18.6^m**	**+62°35′**	Jul-**Aug**-Sep
2.45 m	**1.58 M**	**A7 IV**		**Cepheus**

This is a rapidly rotating star, which results in its spectral lines becoming broad and less clear. It also has the dubious distinction of becoming the Pole Star in 7500 A.D.

Gamma Herculis	**γ Her**	**16^{h}21.8^m**	**+19°09′**	Apr-**May**-Jun
3.74 m	**−0.15 M**	**A9 III**		**Hercules**

This is an optical double system, lying at a distance of 144 l.y., with a luminosity 46 times that of the Sun.

Canopus	**α Car**	**06^{h}23.9^m**	**−52°41′**	Nov-**Dec**-Jan
−0.62 m	**−5.53 M**	**F0 I**		**Carina**

This is the second brightest star in the sky. Its color is often reported as orange or yellow, as it is usually seen low down in the sky, and hence it is more likely to be affected by the atmosphere. Its true color is white.

b Velorum	**HD 74180**	**08^{h}40.6^m**	**−46°39′**	Dec-**Jan**-Feb
3.84 m	**−6.12 M**	**F3 I**		**Vela**

This star is unremarkable except that its luminosity is estimated to be 180,000 times that of the Sun!

Zubenelgenubi	**α^1 Lib**	**14^{h}50.7^m**	**−15°60′**	Apr-**May**-Jun
5.15 m	**3.28 M**	**F4 IV**		**Libra**

An easily resolvable double star, α^1 is a spectroscopic binary. The colors are a nice faint yellow and pale blue.

Algenib	**α Per**	**03^{h}24.3^m**	**+49°52′**	Oct-**Nov**-Dec
1.79 m	**−4.5 M**	**F5 I**		**Perseus**

The star lies within *Melotte 20*, a loosely bound stellar association, also known as *Perseus OB–3* or *Alpha Persei Association.* About 75 stars with magnitude 10 or below are contained within this group. These are stellar infants, 50 million years old, lying 550 l.y. away. The metallic lines increase through the *F* class, especially the *H* and *K* lines of ionized calcium.

Polaris	**α UMi**	**02^{h}31.8^m**	**+89°16′**	Sep-**Oct**-Nov
1.97$_v$m	**−3.64 M**	**F7 I**		**Ursa Minor**

Polaris is an interesting and famous star, yet it is only the 49th brightest star in the sky. It is a *Cepheid Variable* type II star (the *W Virginis* class), and a binary star (the companion reported as being pale blue).The star is expected to move closest to the celestial pole in 2102 A.D.

β Vir	**HD 102870**	**$11^h50.7^m$**	**+01°46′**	Feb-**Mar**-Apr
3.59m	**3.40M**	**F8 V**		**Virgo**

A close star at 34 l.y., *β Vir* is just three times as luminous as the Sun.

Sadal Suud	**β Aqr**	**$21^h31.6^m$**	**−05°34′**	Jul-**Aug**-Sep
2.90m	**−3.47M**	**G0 I**		**Aquarius**

A giant star and a close twin to *α Aqr*, *Sadal Suud* lies at a distance of 990 l.y. and is 5000 times more luminous than the Sun.

Sadal Melik	**α Aqr**	**$22^h05.8^m$**	**−00°19′**	Jul-**Aug**-Sep
2.95m	**−3.88M**	**G2 I**		**Aquarius**

Although it has the same spectral class and surface temperature as that of the Sun, *α Aqr* is a giant star, whereas the Sun is a main-sequence star.

Ras Algethi	**α^2 Her**	**$17^h14.7^m$**	**+14°23′**	May-**Jun**-Jul
5.37m	**0.03M**	**G5 III**		**Hercules**

This is a beautiful double star with colors of ruddy orange and bluish green. The spectral class refers to the primary star of α^2 *Her*, which is a spectroscopic double, and thus visually inseparable with any telescope.

Algeiba	**γ^2Leo**	**$10^h19.9^m$**	**+19°50′**	Jan-**Feb**-Mar
3.64m	**0.72M**	**G7 III**		**Leo**

Algeiba is a famous double star. Most observers report an orange or yellow color, but some report the G7 star as greenish.

β LMi	**HD 90537**	**$10^h27.8^m$**	**+36°42′**	Jan-**Feb**-Mar
4.20m	**0.9M**	**G8 III**		**Leo Minor**

A constellation in which no star is given the classification *α*, *β LMi* has the misfortune not being the brightest star in the constellation, the honor of which goes to *46 LMi*.

β Cet	**HD 4128**	**$00^h43.6^m$**	**−17°59′**	Sep-**Oct**-Nov
2.04m	**−0.30 M**	**G9.5 III**		**Cetus**

This star lies at a distance of 60 l.y. with luminosity 42 times that of the Sun.

Gienah	**ε Cyg**	**$20^h46.2^m$**	**+33°58′**	Jul-**Aug**-Sep
2.48m	**0.76M**	**K0 III**		**Cygnus**

Marking the eastern arm of the *Northern Cross*, *Gienah* is a spectroscopic binary. In the *K*-class stars, the metallic lines are becoming more prominent than the hydrogen lines.

ν^2 CMa	**HD 47205**	**$06^h36.7^m$**	**−19°15′**	Nov-**Dec**-Jan
3.95m	**2.46M**	**K1 III**		**Canis Major**

This star lies at a distance of 60 l.y. with luminosity seven times that of the Sun.

Enif	**ε Peg**	**$21^h44.2^m$**	**+09°52′**	Jul-**Aug**-Sep
2.38_vm	**−4.19 M**	**K2 I**		**Pegasus**

This star lies at a distance of 740 l.y. with luminosity 7,450 times that of the Sun. The two faint stars in the same field of view have been mistakenly classified as companions, but on analysis they have been proved to be stars in the line of sight.

Almach	**γ^1 And**	**$02^h03.9^m$**	**+42°20′**	Sep-**Oct**-Nov
2.33m	**−2.86 M**	**K3 III**		**Andromeda**

This is a famous binary star whose colors are golden and blue, although some observers see orange and greenish-blue. Nevertheless, the fainter companion is hot enough to show a truly blue color. It is also a binary in its own right, but not observable through amateur instruments.

ζ^2 Sco	**HD 152334**	**$16^h54.6^m$**	**−42°22′**	May-**Jun**-Jul
3.62 m	**0.3 M**	**K4 III**		**Scorpius**

The brighter of the two stars in this naked-eye optical double star system, the orange supergiant star contrasts nicely with its slightly fainter blue supergiant companion.

ν^1 Boö	**HD 138481**	**$15^h30.9^m$**	**+40°50′**	Apr-**May**-Jun
5.04m	**−2.10 M**	**K5 III**		**Boötes**

The star lies at a distance of 385 l.y. and has a luminosity 104 times that of the Sun (see also *Aldebaran*).

Mirach	**β And**	**$01^h09.7^m$**	**+35°37′**	Sep-**Oct**-Nov
2.07m	**−1.86 M**	**M0 III**		**Andromeda**

In this stellar class, the bands of titanium oxide are strengthening. This red giant star is suspected to be slightly variable, like so many other stars of the same type. In the field of view is the Galaxy *NGC 404*.

Antares	**α Sco**	**$16^h29.4^m$**	**−26°26′**	Apr-**May**-Jun
1.06_vm	**−5.28 M**	**M1 I**		**Scorpio**

This giant star, measuring 600 times the diameter of the Sun, has a glorious fiery red color, contrasting nicely with its fainter green companion.

Scheat	**β Peg**	**$23^h03.8^m$**	**+28°45′**	Aug-**Sep**-Oct
2.44_vm	**−1.49 M**	**M2 II**		**Pegasus**

Marking the north-western corner of the *Square of Pegasus*, *Scheat* is a red, irregular variable star. It was noted for having been one of the first stars to have its diameter (0.021″) measured by the technique of interferometry. Being a variable star, its size oscillates to a maximum diameter of 160 times that of the Sun.

Eta Persei	**η Per**	**$02^h50.7^m$**	**+55°54′**	Oct-**Nov**-Dec
3.77m	**−4.28 M**	**M3 I**		**Perseus**

This yellowish star is an easily resolved double-star system. The color contrasts nicely with its blue companion.

Gacrux	**γ^A Crucis**	**$12^h31.2^m$**	**−57°07′**	Feb-**Mar**-Apr
1.59m	**−0.56 M**	**M4 III**		**Crux**

The top star of the *Southern Cross*, *Gacrux* is a giant star. γ^A and γ^B do not form a true binary since they are apparently moving in different directions.

Ras Algethi	**α^1 Her**	**$17^h14.6^m$**	**+14°23′**	May-**Jun**-Jul
3.03_vm	**−2.32 M**	**M5 II**		**Hercules**

A fine double-star system. The M5 semi-regular star is an orange supergiant, which contrasts with its companion, a blue-green giant. It must be pointed out that this double star can be resolved only with a telescope (not with binoculars), as the two stars are less than 5″ apart. The change in brightness may be attributed to actual physical changes to the star as it increases and decreases in diameter.

Mira (at maximum)	**o Cet**	**$02^h19.3^m$**	**−02°59′**	Sep-**Oct**-Nov
2.00_vm	**−3.54 M**	**M5**		**Cetus**

For details on *Mira*, see the section "Long Period Variables."

Mira (at minimum)	**o Cet**	**$02^h19.3^m$**	**−02°59′**	Sep-**Oct**-Nov
10_vm	**−0.5 M**	**M9**		**Cetus**

For details on *Mira*, see the section "Long Period Variables."

θ Apodis	**HD 122250**	**$14^h05.3^m$**	**−76°48′**	Mar-**Apr**-May
5.69_vm	**−0.67 M**	**M6.5 III**		**Apus**

This is a semi-regular variable with a period of 119 days in the range of 5th to nearly 8th magnitude. The titanium bands are now at their strongest.

1.9 The Hertzsprung–Russell Diagram

We have already covered many topics in our description of a star's basic characteristics, such as its mass, radius, spectral type, and temperature. Let us now put all these parameters together to get a picture of how a star evolves. It is often quite useful in many subjects to represent the data about a group of objects in the form of a graph. Many of us are familiar with graphs or have seen, for example, one that shows height as a function of age, or temperature as a function of time. A similar approach has been pursued to study the characteristics of stars. A graph that is used universally is called *The Hertzsprung–Russell Diagram*. It is, without a doubt, one of the most important and useful diagrams in the study of astronomy.

In 1911, the Danish astronomer Ejnar Hertzsprung plotted the absolute magnitude of stars (a measure of their luminosities) against their colors (a measure of their temperature). Later, in 1913, the American astronomer Henry Norris Russell independently plotted spectral types (another way to measure temperature) against absolute magnitude. They both realized that certain unsuspected patterns began to emerge, and furthermore, an understanding of these patterns was *crucial* to the study of stars. In recognition of the pioneering work of these astronomers, the graph was known as the *Hertzsprung–Russell Diagram*, or *H-R* diagram. Figure 1.4 is a typical *H-R* diagram. Each dot on the diagram represents a star whose properties, such as spectral type and luminosity, have been determined. Note the key features of the diagram:

- The horizontal axis represents stellar temperature or, equivalently, the spectral type.
- The temperature increases from right to left. This is because Hertzsprung and Russell originally based their diagram on the spectral sequence OBAFGKM, where hot *O*-type stars are on the left and cool *M*-type stars on the right.
- The vertical axis represents stellar luminosity measured in the unit of Sun's luminosity, $L_\odot$.
- The luminosities cover a wide range, so the diagram makes use of the logarithmic scale, whereby each tick mark on the vertical axis represents a luminosity 10 times larger than the prior one.
- Each dot on the *H-R* diagram represents the spectral type and luminosity of a single star. For example, the dot representing the Sun corresponds to its spectral type G2 with luminosity $L_\odot = 1$.

Note that because luminosity increases upward in the diagram and surface temperature increases leftward, stars near the upper left corner are hot and luminous. Similarly, stars near the upper right corner are cool and luminous; stars near the lower right corner are cool and dim; and finally stars near the lower left corner are hot and dim.

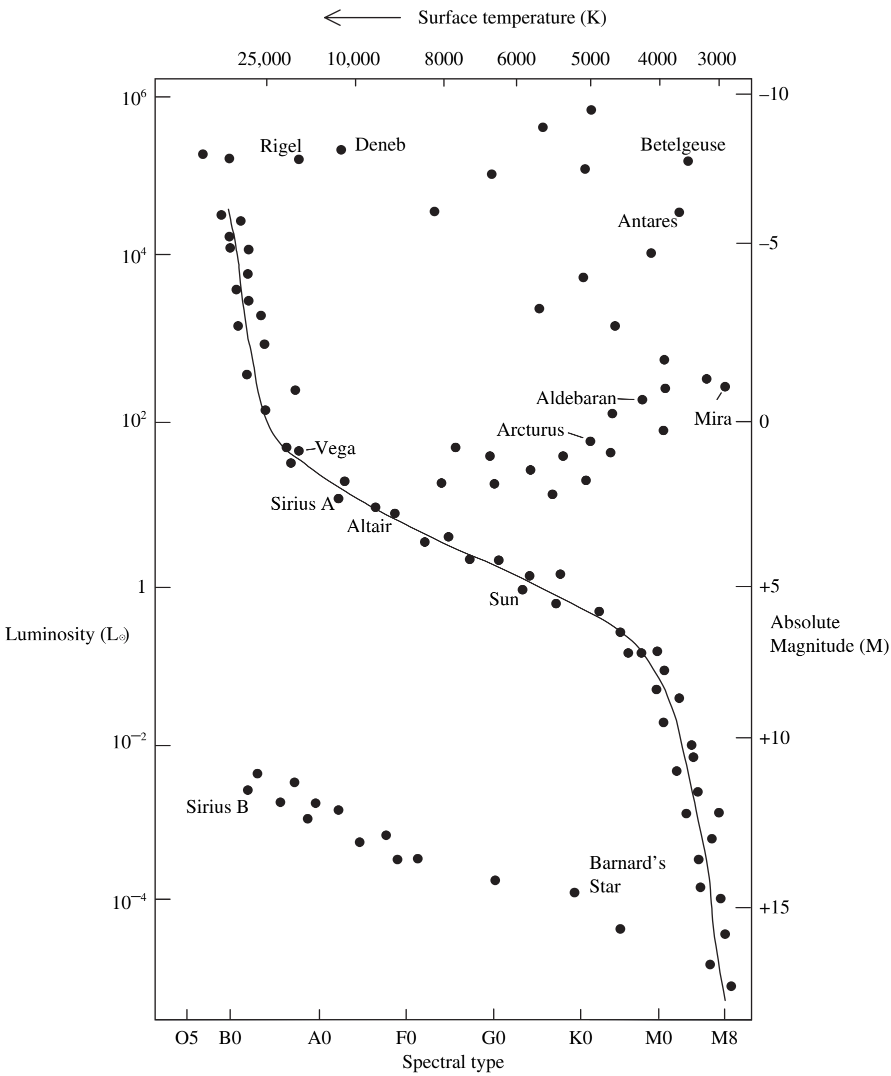


Figure 1.4. The Hertzsprung–Russell Diagram. Luminosity is plotted against spectral type for a selection of stars. Some of the brighter stars are shown. Each dot represents a star whose spectral type and luminosity have been determined. Note how the data are grouped in just a few regions, indicating a correlation. The main sequence is the continuous blue line. Surface temperature and absolute magnitude are also shown.

1.10 The *H-R* Diagram and Stellar Radius

The *H-R* diagram can directly provide important information about the radius of stars, because the luminosity of a star depends on both its surface temperature and surface area, or radius. You may recall that the surface temperature determines the amount of power emitted by the star *per unit area*. Thus, a higher temperature means a greater power output per unit area. So, if two stars have the same temperature, the larger star may be more luminous than the other. Stellar radii must perforce increase as we go from the high-temperature, low-luminosity corner on the lower left of the *H-R* diagram to the low-temperature, high-luminosity upper right corner. This is shown in Figure 1.5.

The first thing to notice on the *H-R* diagram is that the data points (or stars) are not scattered at random but appear to fall into distinct regions. This would imply that surface temperature (or spectral type) and luminosity are related! The several groupings can be described as thus:

- The band that stretches diagonally across the *H-R* diagram is called the *Main Sequence*, and it represents about 90% of the stars in the night sky. It extends from hot and luminous blue stars in the upper left corner to cool and dim red stars in the bottom right. Any star located in this part of the *H-R* diagram is called a *main-sequence star*. Note that the Sun is a main-sequence star (spectral type G2, absolute magnitude +4.8, luminosity $1\,L_\odot$). We shall see later in the book that stars on the main sequence are undergoing *hydrogen-burning* (thermonuclear fusion, which converts hydrogen to helium) in their cores.
- Stars in the upper right are called *giants*. These stars are both cool and luminous. Recall from an earlier section that we discussed the *Stefan–Boltzmann* Law, which states that a cool star will radiate much less energy per surface area than a hot star. Hence, for these stars to appear as luminous as they look, they must be immense, and so they are called giants. They may be anywhere from 10 to 100 times as big as the Sun. Figure 1.5 shows this, where stellar radii have been added to the *H-R* diagram. Most giant stars are about 100 to 1000 times more luminous than the Sun and have temperatures of 3000 to 6000 K. Many of the cooler members of this class are reddish and have temperatures of 3000 to 4000 K—these are often referred to as *red giants*. Some examples of red giants are *Arcturus* in *Boötes* and *Aldebaran* in *Taurus*.
- At the extreme upper right corner are a few stars that are even bigger than the giants. These are the s*upergiants*, which have radii up to $1000\,R_\odot$. Giants and supergiants make up about 1% of stars in the night sky. *Antares* in *Scorpius* and *Betelgeuse* in *Orion* are two fine examples of supergiant stars. Nuclear fusion taking place in supergiant stars is significantly different in both character and position than the reactions taking place in the stars on the main sequence.

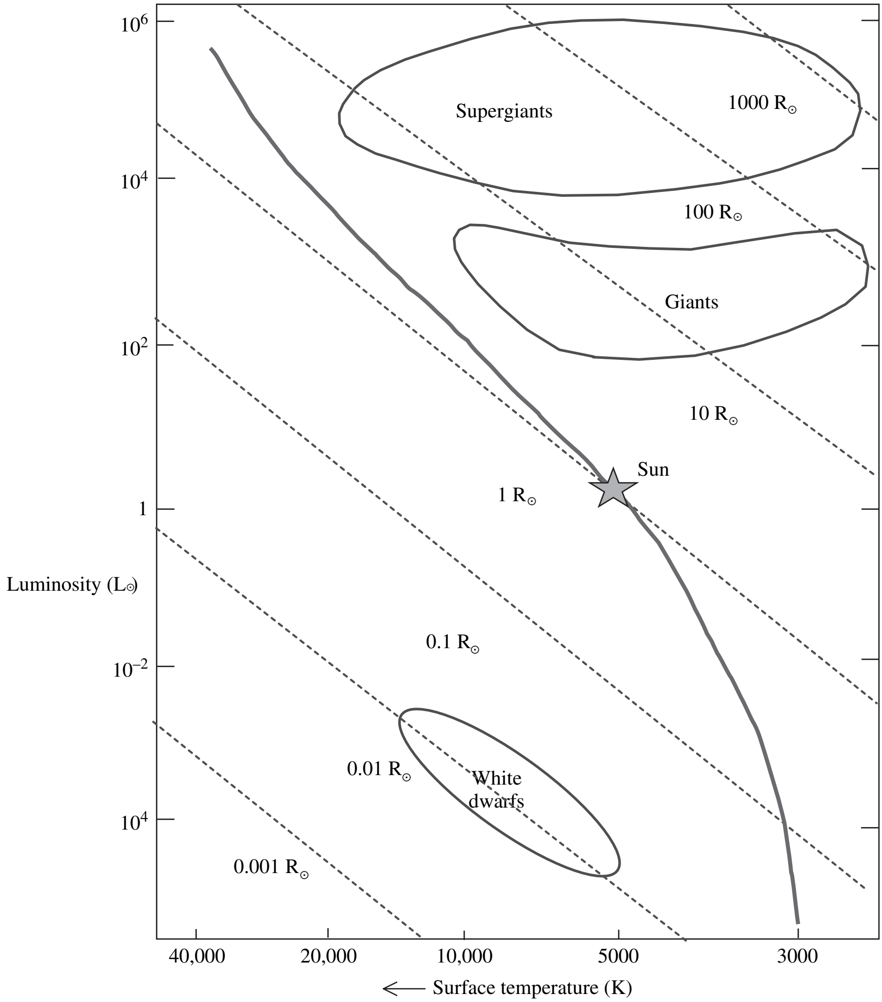


Figure 1.5. Size of stars on an *H-R* diagram. Stellar luminosity against surface temperature. The dashed diagonal lines indicate stars of different radii. At a given radius, the surface temperature increases (moving from right to left), and luminosity increases. Notice the main sequence and the Sun's position on it. A very average star.

- Stars in the lower left of the *H-R* diagram are much smaller in radius and appear white. These are the *white dwarf* stars. As we see from the *H-R* diagram, they are hot stars with low luminosities; therefore, they must be small and hence the name dwarf stars. They are faint stars, and so they can be seen only with telescopes. They are approximately the same size as the Earth. There are no nuclear reactions within white dwarfs; rather, they are the still-glowing remnants of giant stars. White dwarfs account for about 9% of stars in the night sky.

1.11 The *H-R* Diagram and Stellar Luminosity

The temperature of a star determines which spectral lines are most prominent in its spectrum. Therefore, classifying a star by its spectral type is essentially the same as by its temperature. A quick look at an *H*-*R* diagram will reveal that stars can have similar temperatures but in fact very different luminosities.

Consider this example: a white dwarf star may have a temperature of 7000 K; so do a main-sequence star, a giant, and a supergiant. It all depends on its luminosity. Therefore, by examining a star's spectral lines, one can determine which category the star belongs to. A rule of thumb (for stars of spectral types *B* through *F*) is: the more luminous the star, the narrower the lines of hydrogen. The theory behind the phenomenon is quite complex, but suffice to say that these measurable differences in spectra are due to differences in stars' atmospheres where absorption lines are produced. The density and pressure of hot gases in the atmosphere affect the absorption lines and hydrogen in particular. If the pressure and density are high, hydrogen atoms collide more frequently, and they interact with other atoms in the gas. The collisions cause the energy levels in hydrogen atoms to shift, resulting in broadened hydrogen spectral lines.

In a giant luminous star, the atmosphere will have a very low pressure and density because the star's mass is spread over such an enormous volume. Therefore, the atoms (and ions) are relatively far apart. This means that collisions between atoms are far less frequent, which produces narrow hydrogen lines. In a main-sequence star, the atmosphere is denser than a giant or supergiant, with collisions occurring more frequently, thereby producing broader hydrogen lines.

In an earlier section on "Stellar Classification," we saw that we can ascribe to a star a luminosity class. We can use it here to describe the region of the *H*-*R* diagram where a star of a particular luminosity will fall. This is shown in Figure 1.6.

Knowing both the spectral type and luminosity of a star would help an astronomer to instantly know where on the main sequence it lies. For instance, a G2 V star is a main-sequence star with a luminosity of 1 $L_\odot$ and a surface temperature of about 5700 K. In a similar vein, *Aldebaran* is a K5 III star, which means that it is a red giant star with a luminosity of 375 $L_\odot$ and a surface temperature of about 4000 K.

1.12 The *H-R* Diagram and Stellar Mass

The most common trait of main-sequence stars is that, just like the Sun, they undergo nuclear fusion at their cores to convert hydrogen to helium. Since most stars spend much part of their lives doing this, it naturally follows that a majority of stars spend their time somewhere on the main sequence. Even a cursory look

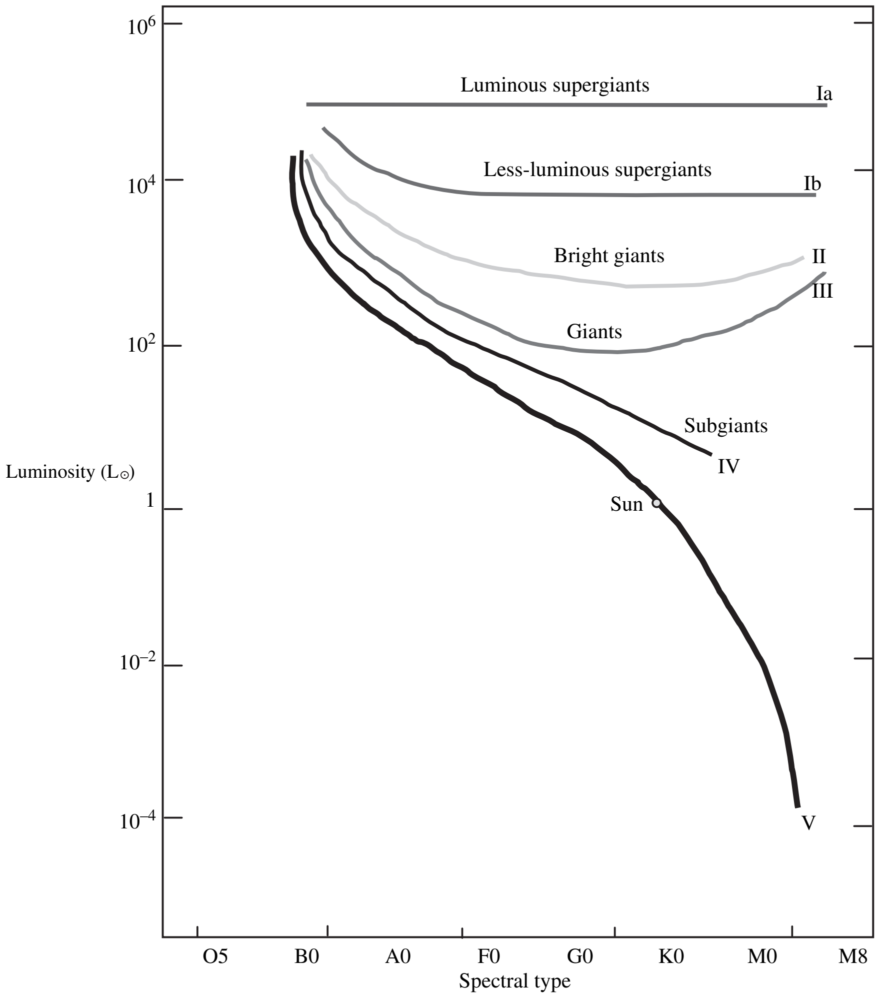


Figure 1.6. Luminosity classes. Dividing the *H-R* diagram according to luminosity classes allows distinctions to be made between giant and supergiant stars.

at the *H-R* diagram can tell you that an enormous range of luminosities and temperatures are covered.

The question that may arise is, why such a large range?

Astronomers have determined the masses of stars using binary star systems, and they discovered that a star's mass increases as it moves upward along the main sequence (Figure 1.7). The *O*-type stars, which are hot and luminous stars, at the upper part of the diagram can have masses as high as 100 times that of the Sun—100 $M_{\odot}$. At the other end of the main sequence, the cool and faint

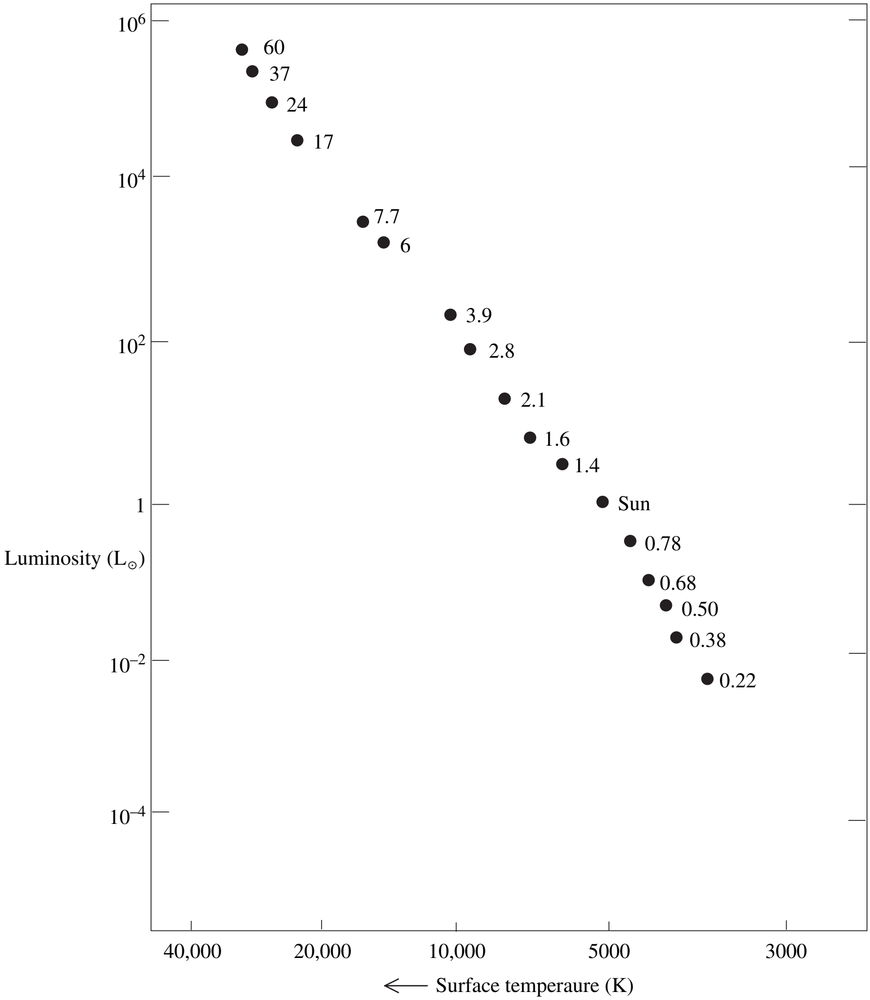


Figure 1.7. Mass and the main sequence. Each filled-in circle is a main-sequence star. The number is the star's mass in solar masses ($M_\odot$). As you move up the main sequence (from lower right to upper left), the mass, luminosity, and temperature increase.

stars have masses as low as 0.1 time that of the Sun—0.1 $M_\odot$.[37] This orderly distribution of stellar masses along the main sequence tells us that *mass* is the most important attribute of a hydrogen-burning star. Mass has a direct effect on a star's luminosity because the weight of a star's outer layers will determine how fast the hydrogen-to-helium nuclear reaction will proceed in the core. A 10 $M_\odot$ star on the main sequence will be more than 1000 times more luminous than the Sun (i.e., 1000 $L_\odot$).

However, the mass–surface temperature relationship is just a little more subtle than the preceding paragraph indicated. Generally, very high luminous stars must either be very large or have a very high temperature, or even a combination of both. Stars on the top left corner of the main sequence are some thousands of times more luminous than the Sun, but they are only about 10 times larger than the Sun. Therefore, their surface temperatures must be significantly hotter than that of the Sun to account for such high luminosities. Bearing this relationship in mind, we can now say that main-sequence stars that are more massive than the Sun must have correspondingly higher temperatures, while those with lower masses must have lower surface temperatures. Thus, you can now understand why the main sequence on the *H-R* diagram goes diagonally from upper left to the lower right.

The *H-R* diagram is one of the most fundamental tools in astronomy. We will use it throughout the remainder of this book, as it provides a means to determine the many paths that stars take during their lives—from star birth to star death.

Notes

1. One parsec is equal to 3.26 light years, 3.09×10^{13} km, or 206265 AU. 1 AU is 149,597,870 km.
2. Nearly 200 previously unobserved stars were discovered, the nearest about 18 l.y. away. In addition, several hundred stars originally believed to be within 75 l.y. were in fact found to be much farther away.
3. The most famous Cepheid variable star is *Polaris*, the North Star. It varies its visual brightness by about 10% in just under 4 days. Recent data show that the variability is decreasing, and the star may, at some point in the future, cease to pulsate. We shall discuss Polaris and other important variable stars in detail in a later section.
4. We shall discuss the meaning of the term luminosity later. For the time being, think of it as the star's brightness.
5. The Period–Luminosity relationship was discovered by Henrietta Leavitt in 1908 while working at the Harvard College Observatory. She studied photographs of the Magellanic Clouds and found more than 1700 variable stars.
6. The relationship between the apparent brightness of a star and its intrinsic brightness will be discussed in the next section.
7. This signifies that the star is in fact part of a double star system, and the distance quoted is for components *A* and *B*.
8. The star, and thus the magnitude, is variable.
9. Most of the nearest stars are very faint, so only the brighter ones will be mentioned here. Exceptions to this will be made, however, if the object has an important role in astronomy. A companion book to this one—*Field Guide to the Deep Sky Objects*—provides much more information and detail regarding the nearest stars. Furthermore, the *Field Guide* addresses many techniques to enhance your observational skills, such as dark adaption, averted vision, etc.

10. The proper motion of a star is its apparent motion across the sky.
11. The HD signifies it is the 217987th object in the Henry Draper Catalogue.
12. One watt is equal to 1 joule per second. The Sun's luminosity is 3.86×10^{26} W. It is often designated by the symbol $L_\odot$.
13. The scientific term for apparent brightness is *flux*.
14. Observers have reported that, under excellent conditions and with very dark skies, objects down to magnitude 8 can be seen with the naked eye.
15. Many stars are variable, so the value for their apparent magnitude will change. The suffix v indicates a variable star, and the value given is the mean value.
16. It shouldn't come as any surprise to you to learn that there are several other magnitude definitions that rely on a star's brightness when observed at a different wavelength—the U, B, and V system. There is also a scale based on photographic plates, the *photographic magnitude*, m_{pg}, and the *photovisual magnitude*, m_{pv}. Finally, there is the *bolometric magnitude*, m_{BOL}, which is a measure of all the radiation emitted from an object.
17. The eye does not recognize color at low light levels. This is why at night, with the naked eye, we see only shades of grey, white, and black.
18. The most important factor determining the color of a star you see is you—the observer! It is purely a matter of physiological and psychological influences. What one observer describes as a blue star, another may describe as a white star; or one may see an orange star, while another observes the same star as yellow. You might even observe a star to have different color when using different telescopes or magnifications, and atmospheric conditions certainly have a role to play.
19. From here on, when I mention temperature, I am referring to the surface temperature, unless indicated otherwise.
20. This star is the brightest in the night sky. It is, of course, *Sirius*.
21. This is the most famous irregular variable star, *Mira*.
22. Remember that a star's color is observer-dependent! What one person sees as yellow, another sees as white. Do not be surprised if you see a different color to that mentioned.
23. The real temperature of the star is still undetermined.
24. A few stars, such as Betelgeuse, have had their radii determined by a technique known as interferometry. For the vast majority of stars, the technique is not applicable, either due to distance or faintness.
25. To be accurate, the law refers to a black-body, which is something that emits thermal radiation. Thus, thermal radiation is blackbody radiation. It can be applied to a star because, to all intents and purposes, a star's surface behaves like a black-body.
26. No doubt some of you are already asking, "Where is the surface of a star? A star is made of gas." Fear not…all will be revealed in later chapters.
27. There is some uncertainty about this value.
28. Astronomers call every element other than hydrogen and helium a metal. It's odd, I agree, but don't worry about it—just accept it.
29. We can only easily deduce whether an object is moving away from us or toward us. To measure if it is moving laterally to us requires some complicated measurements.

30. Some spectroscopes place the prism or grating in front of the telescope, and thus the light from *every* star in the field of view is analyzed simultaneously. This is called an *objective spectroscope*. The drawback is the considerable loss of detail (i.e., information about the stars), but initial measurements can be made.
31. The transitions shown are only a few of the many that occur.
32. The reason that stars follow the order OBAFGKM was discovered by a brilliant astronomer, Cecilia Payne-Gaposchkin. She found that all stars are made primarily of hydrogen and helium and that a star's surface temperature determines the strength of its spectral lines. For instance, O stars have weak hydrogen lines because, due to their high temperature, nearly all the hydrogen is ionized. Thus, without an electron to "jump" between energy levels, ionized hydrogen can neither emit nor absorb light. On the other hand, M stars are cool enough for molecules to form, resulting in strong molecular absorption lines.
33. As we shall see later, these are stars with very low temperatures—1900 to 1500 K. Many astronomers now believe these are the infamous brown dwarfs.
34. These can be further classified into Ia and Ib, with Ia the brighter.
35. Usually only the classes O, A, B, F, G, K, and M are listed. The other classes are used and defined as and when they are needed.
36. This value is in question. The data are awaiting reassessment.
37. Over the past several years, astronomers have discovered that the low-mass, faint M-type dwarf stars are far more numerous than other star types. We have just not been able to see them up until now.

CHAPTER TWO

The Interstellar Medium

2.1 Introduction

When we look up into the night sky, we see stars, and not much else. So we get the impression that between the stars, space is empty. There does not seem to be any sort of material that lies between one star and another. At the same time, we know intuitively that this cannot be true, for if space were empty, from what did stars form? This then leads us to the conclusion that perhaps space is not quite so empty, but filled with some sort of material that, to our eyes, is all but invisible yet is responsible for providing the source material for stars.

In fact, space is anything but empty; it is filled with gas and dust. This is known as the *Interstellar Medium* (ISM). The ISM is made up of gas (mainly hydrogen) and dust (which accounts for about 1% of the mass of gas). The dust, not to be confused with dust on Earth, consists of other elements that are not hydrogen, such as carbon, silicon, and so on, and their compounds, CO, HCN, and so on.

The material that makes up the ISM is not spread evenly throughout space; there are regions that are dense and regions that are not so dense. Similarly, there are areas of the ISM that are hot and other areas that are cooler. Thus, the two most important parameters concerning the ISM are the temperature and a quantity we call the number density (n). The latter is just the number of particles per unit volume (per cubic meter), and it can be individual atoms, neutral, ionized, combined in molecules, or a mixture of all four. Because there is far more hydrogen in the ISM than anything else, we can say, to a good approximation, that the particle density (n) is the number of hydrogen atoms per cubic meter, and this we call n_H.[1]

The important point to realize is the enormous range of temperatures and number densities that occur in the ISM. There can be as few as 100 particles per cubic meter ($n = 100\,m^{-3}$) to about 10^{17} per cubic meter ($n = 10^{17}\,m^{-3}$). Similarly, the temperature can be as low as 10 K and as high as a few million K. To get a feel for these ranges, look at Figure 2.1 It shows the ranges of temperature and number density, and the names we give to the correspondingly different regions in the ISM.

Let us look at this diagram in more detail; what we call the *intercloud medium*, whether hot or warm, actually accounts for most of the ISM. The interesting thing is that all other regions of the ISM are located within the intercloud medium. The regions are:

Hot intercloud medium—this is widespread and, although hot, of extremely low density, and consisting mainly of ionized hydrogen. Fortunately for amateur

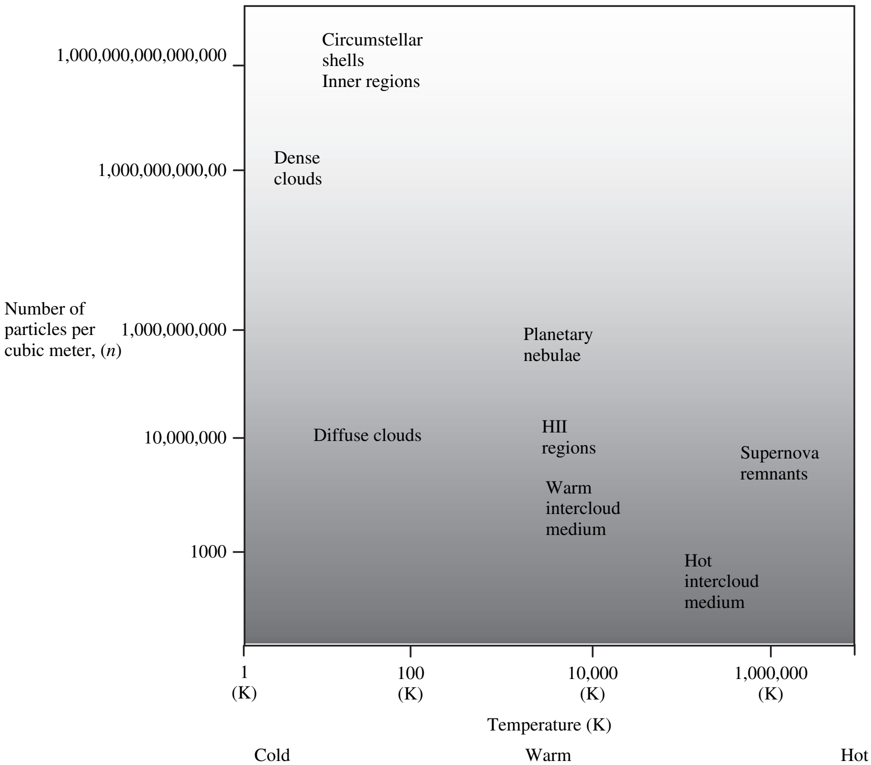


Figure 2.1. Regions in the interstellar medium.

astronomers, it does not obscure our view of space, as we can see through it. For similar reasons, the *warm intercloud medium* is also transparent.

All other regions on the diagram (and, thus, in the ISM) present a much more visual aspect and so are important to us as observers. They can be divided into two groups: the regions in the ISM that are concerned with star formation, namely the *diffuse* and *dense clouds* and the *HII regions*,[2] and those that deal with star death—*planetary nebulae*, *supernova remnants*, and *circumstellar shells.*

We shall discuss all these regions in considerable detail in this and later chapters because they are objects of interest to the amateur astronomer…all, that is, except for the diffuse clouds, as these are transparent to visible light. There are, however, methods to allow observations of these clouds; radio astronomy to measure the hydrogen 21 cm line, microwave telescopes to measure the CO molecule, and infrared telescopes to measure the far infrared emission of the dust.

As an astronomer, you will have already observed the interstellar medium, but perhaps without realizing it. As previously mentioned, the ISM is composed of gas (mainly hydrogen),[3] and dust, so it is, from an observer's viewpoint, invisible; however, there are places in the Galaxy where certain conditions tend to aggregate the material, and these denser-than-average regions are indeed visible to the amateur astronomer. We know them as *nebulae*.

2.2 Nebulae

Nebulae are actually disparate in nature, even though many of them have a rather similar appearance. They are associated with the areas of star formation,[4] cover several aspects of a star's life, and end with the process of star death. This section will just cover three main types of nebulae: emission, reflecting, and dark, all associated with the birth of a star. In addition, we are fortunate from an observing point of view, because these objects abound in the night sky, and some are spectacular objects indeed.

2.3 Emission Nebulae

These clouds of gas are associated with very hot O- and B-type stars, which produce immense amounts of ultraviolet radiation. They typically have masses of about 100 to 10,000 solar masses. This huge mass, however, is usually spread over a correspondingly large area (possibly a few l.y. across), so the actual density of the gas is extremely low (maybe only a few thousand hydrogen atoms per cubic centimeter). Usually, these very luminous stars are actually born within and from the material of the clouds, and so many *emission* nebulae are "stellar nurseries." Radiation from the stars causes the gas (usually hydrogen) to undergo a process called *fluorescence*, and it is this process that is responsible for the glow observed from the gas clouds.

The energy provided by ultraviolet radiation from the young and hot stars ionizes the hydrogen. In other words, energy—in this case, in the form of ultraviolet radiation—is absorbed by the atom and transferred to an electron that is sitting comfortably in what is called an energy level or orbital shell.[5] Having gained extra energy, the electron can leave the energy level it is in, and in some instances actually break free from the atom. When an atom loses an electron, the process is called *ionization*.

If electrons are broken free from their parent atoms, the hydrogen cloud will contain some hydrogen atoms without electrons—ionized hydrogen (also known as protons), and a corresponding number of free electrons. Eventually,[6] the electrons recombine with the atoms, but an electron cannot just settle down back to the state it was originally in before it absorbed the extra energy—it has to lose the extra energy that the ultraviolet imparted. For this to happen, the electron moves down the atomic energy levels until it reaches its original level, losing energy as it goes. In hydrogen (the most common gas in the nebula), an electron moving down from the third energy level to the second emits a photon of light at 656.3 nm (see Section 1.7).

This is the origin of the famous "hydrogen alpha line," usually written as *H-alpha*, and pronounced "aitch alpha." It is a lovely red-pink color and is responsible for all the pink and red glowing gas clouds seen in photographs of emission nebulae.[7]

When electrons move down from other energy levels within the atom, other specific wavelengths of light are emitted. For instance, when an electron moves from the second level to the first, it emits a photon in the ultraviolet part of the spectrum. This particular wavelength is called the *Lyman alpha line* of hydrogen, which is in the ultraviolet part of the spectrum.

It is this process of atoms' absorbing radiation to ionize a gas, with electrons subsequently cascading down the energy levels of an atom, that is responsible for nearly all of the light we see from emission nebulae. If a gas cloud is particularly dense, the oxygen gas in it may be ionized, and the resulting recombination of the electron and atom produces the doubly ionized lines, at wavelengths of 495.9 and 500.7 nm.[8]

Emission nebulae are sometimes called *HII regions*, pronounced "aitch two." This astrophysical term refers to hydrogen that has lost one electron by ionization. The term HI, or "aitch one," refers to hydrogen that is unaffected by any radiation (i.e., neutral hydrogen). The doubly ionized oxygen line mentioned above is termed OIII ("oh three"); the "doubly" means that *two* of the outermost electrons have been lost from the atom by ionization.[9]

The shape of an emission nebula is dependent on several factors: the amount of radiation available, the density of the gas cloud, and the amount of gas available for ionization. When there is a significant amount of radiation, coupled with a small and low-density cloud, then all of the cloud will likely be ionized, and thus the resulting *HII* region will be of an irregular shape—just the shape of the cloud itself. If the cloud of gas is large and dense, however, then the radiation can penetrate only to a certain distance before it is used up—that is, there is only a fixed amount of radiation available for ionization. In this case, the *HII* region will be a sphere,[10] often surrounded by the remaining gas cloud, which is not fluorescing. Many of the emission regions that are irregular in shape include M42 (the *Orion Nebula*), M8 (the *Lagoon Nebula*), and M17 in *Sagittarius*. Two of those exhibiting a circular shape, and thus are in fact spherical, are M20 (the *Trifid Nebula*) and NGC 2237 (the *Rosette Nebula*).

After a suitable period of time, usually several million years, the group of young O- and B-type stars located at the center of the nebulae will be producing so much radiation that they can in effect sweep away the residual gas and dust clouds that surround them. This produces a "bubble" of clear space surrounding the cluster of stars. Several emission regions show this. For example, *NGC 6276* and *M*78 show the star cluster residing in a circular clear area within the larger emission nebula.

Let us now look at a few examples of the brighter emission nebulae. Note, however, that from an observational viewpoint, many of the emission nebulae are faint and have a low surface brightness, making them not exactly difficult objects to observe but rather featureless and indistinct (though in some instances the brighter nebulae do show several easily seen features). Therefore, clear nights and clean optics are a high priority.

The photographic brightness (as seen on the photographic plates from the Palomar Observatory Sky Survey (POSS) is assigned a value from 1 through 6; those nebulae rated at 1 are just barely detectable on the plate, while those quoted at a value of 6 are easily seen on the photographic plate, and this number is just the measure of the difficulty (or ease) of observation, and is given the symbol ❅. The size of an object is also given (in arcseconds), and is indicated by the symbol ⊕. Where a value of ⊕ is given as x⇆y, the object is approximately x arcseconds long by y arcseconds wide.

2.3.1 Brightest Emission Nebulae

Gum 4	**NGC 2359**	**$07^h18.6^m$**	**−13°12′**	Dec–**Jan**–Feb
❅2–5	**⊕9⇆6′**			**Canis Major**

Also known as the *Duck Nebula*, this is a bright emission consisting of two patches of nebulosity, with the northern patch being the larger and less dense. Try using an OIII filter to improve the appearance of the emission nebula, showing the delicate filamentary nature.

Messier 20	**NGC 6514**	**$18^h02.3^m$**	**−23°02′**	May–**Jun**–Jul
❅1–5	**⊕20⇆20′**			**Sagittarius**

Also known as the *Trifid Nebula*, this emission nebula can be glimpsed as a small hazy patch of nebulosity and is easy to see, along with its famous three dark lanes, which give it its name and which radiate outwards from the central object: an O8-type star, which is the power source for the nebula. The northern nebulosity is in fact a reflection nebula, and so it is harder to observe.

Messier 8	**NGC 6523**	**$18^h03.8^m$**	**−24° 23′**	May–**Jun**–Jul
❅1–5	**⊕45⇆30′**			**Sagittarius**

Also known as the *Lagoon Nebula*, this is the premier emission nebula of the summer sky. Binoculars will show a vast expanse of glowing green-blue gas split by a very prominent dark lane, whereas telescopes of aperture 30 cm will show much more intricate and delicate detail, including many dark bands. The Lagoon Nebula is located in the *Sagittarius–Carina Spiral Arm* of our Galaxy, at a distance of 5400 l.y.

Messier 17	**NGC 6618**	$\mathbf{18^h20.8^m}$	**−16°11′**	May–**Jun**–Jul
❋1–5	**⊕20⇆16′**			**Sagittarius**

Also known as the *Swan* or *Omega Nebula*. This is a magnificent object to see through binoculars, and perhaps a rival to the Orion Nebula, M42, for the summer sky. Not often observed by amateurs, as it is low down in the sky from, say, UK latitudes. With telescopes, the detail of the nebula becomes apparent, and with the addition of a light filter, it can in some instances surpass M42. Certainly, it has many more dark and light patches than its winter cousin, although it definitely requires an OIII filter for the regions to be fully appreciated.

Messier 16	**IC 4703**	$\mathbf{18^h18.6^m}$	**−13°58′**	May–**Jun**–Jul
❋1–5	**⊕35⇆30′**			**Serpens Cauda**

Also known as the *Star Queen* or *Eagle Nebula*, a famous though not often observed nebula. As usual, the use of a filter enhances its visibility. The "Black Pillar" and associated nebulosity are difficult to see, even though they are portrayed in many beautiful photographs (a prime example of astronomical imagery fooling the amateur into thinking that these justifiably impressive objects can easily be seen through a telescope). Nevertheless, it can be spotted by an astute observer under near-perfect conditions.

Caldwell 27	**NGC 6888**	$\mathbf{20^h12.0^m}$	**+38°21′**	Jun–**Jul**–Aug
❋1–5	**⊕18′⇆13′**			**Cygnus**

Also known as the *Crescent Nebula*, this difficult nebula is included here as it is a prime example of several relevant phenomena associated with star formation. With good conditions, the emission nebula will live up to its name, having an oval shape with a gap in the ring on its southeastern side. The nebula is known as a *Stellar Wind Bubble*, and it is the result of a fast-moving stellar wind from a *Wolf–Rayet* star that is sweeping up all the material previously ejected during its red giant stage.

–	**IC 5067–70**	$\mathbf{20^h50.8^m}$	**+44°21′**	Jul–**Aug**–Sep
❋1–5	**⊕25⇆10′**			**Cygnus**

Also known as the *Pelican Nebula*, this nebula, close to the *North American Nebula* (see the entry below), has been reported to be visible to the naked eye and is easily glimpsed in binoculars as a triangular, faint, and hazy patch of light. Remember, it can be seen best with averted vision and the use of light filters.

Caldwell 20	**NGC 7000**	$\mathbf{20^h58.8^m}$	**+44°12′**	Jul–**Aug**–Sep
❋1–5	**⊕120⇆100′**			**Cygnus**

Also known as the *North America Nebula*. It is located just west of *Deneb* and is a magnificent site in binoculars, melding, as it does, into the stunning star fields of *Cygnus*. Provided you know where and what to look for, the nebula is visible to the naked eye. The dark nebula lying between it and the *Pelican Nebula* is responsible for their characteristic shape. Until recently, *Deneb* was thought to be the star responsible for providing the energy to make the nebula glow, but recent research points to several unseen stars' being the power sources.

–	**IC 1396**	**$21^h39.1^m$**	**+57°30′**	Jul–**Aug**–Sep
❅3–5	**⊕170⇆40′**			**Cepheus/Cygnus**

One of the few emission nebulae visible to the naked eye (under perfect seeing conditions, of course!) and easily spotted in binoculars, it is an enormous patch of nebulosity, over 3°, spreading south of the orange star *Mu* (μ) *Cephei*. As usual, a telescope will lessen the impact of the nebula but the use of filters will help to locate knots, patches of brighter nebulosity, and dark dust lanes. The use of dark adaption and averted vision will enhance the observation of this giant emission nebula.

Caldwell 19	**IC 5146**	**$21^h53.4^m$**	**+47°16′**	Jul–**Aug**–Sep
❅3–5	**⊕12|12′**			**Cygnus**

Also known as the *Cocoon Nebula*, *Caldwell 19* has a low surface brightness and appears as nothing more than a hazy amorphous glow surrounding two 9th-magnitude stars. The dark nebula *Barnard 168* (at the end of which the Cocoon lies) is surprisingly easy to find and can thus act as a pointer to the more elusive emission nebula. The whole area is a vast stellar nursery, and recent infrared research indicates the presence of many new protostars.

Caldwell 11	**NGC 7635**	**$23^h20.7^m$**	**+61°12′**	Aug–**Sep**–Oct
❅1–5	**⊕16⇆9′**			**Cassiopeia**

Also known as the *Bubble Nebula*, this is a very faint nebula, even in telescopes of aperture 20 cm. An 8th-magnitude star within the emission nebula and a nearby 7th-magnitude star hinder its detection due to their combined glare. Research suggests that a strong stellar wind from a star pushes the material out (creating the "Bubble") and heats up a nearby *Molecular Cloud*, which in turn ionizes the "Bubble."

–	**NGC 604**	**$01^h33.9^m$**	**+30°39′**	Sep–**Oct**–Nov
❅3–5	**⊕60⇆35′**			**Triangulum**

Now for something very special: the brightest emission nebula that can be glimpsed. It is actually in another galaxy—M33 in Triangulum. It appears as a faint hazy glow some 10′ northeast of M33's core. Oddly enough, due to M33's low surface brightness (which often makes it a difficult object to find), the emission nebula may be visible while the galaxy is not! It is estimated to be about 1000 times bigger than the *Orion Nebula*.

Caldwell 49 **NGC 2237–3906^{h}32.3^{m}** **+05°03′** Nov**–Dec–**Jan
✺1–5 **⊕80⇆60′** **Monoceros**

Also known as the *Rosette Nebula*, this is a giant emission nebula that has the dubious reputation of being very difficult to observe. But this is wrong—on clear nights it can be seen with binoculars. Over 1° in diameter, it covers an area of sky four times larger than a full Moon! With a large aperture and light filters, the complexity of the nebula becomes readily apparent, and under perfect seeing conditions dark dust lanes can be glimpsed. The brightest parts of the emission nebula have their own NGC numbers: *2237, 2238*, *2239*, and *2246*. It is a young nebula, perhaps only half a million years old, and star formation may still be occurring within it. Photographs show that the central area contains the star cluster *NGC 2244*, along with the "empty" cavity caused by the hot young stars blowing the dust and gas away. Also known as the *Rosette Molecular Complex (RMC)*.

– **NGC 2024** **05^{h}40.7^{m}** **02°27′** Nov**–Dec–**Jan
✺2–5 **⊕30⇆30** **Orion**

This nebula lies next to the famous star *Zeta Orionis*, which is unfortunate as the glare from the star makes observation difficult. It can, however, be glimpsed in binoculars as an unevenly shaped hazy and faint patch to the east of the star, provided the star is placed out of the field of view. With large telescopes and filters, the emission nebula is a striking object and has a shape reminiscent of a maple leaf.

Caldwell 46 **NGC 2261** **06^{h}39.2^{m}** **+08°44′** Nov**–Dec–**Jan
✺1–5 **⊕3.5⇆1.5′** **Monoceros**

Also known as *Hubble's Variable Nebula*, *Caldwell 46* is easily seen in telescopes of 10 cm as a small, comet-like nebula, which can be seen even from the suburbs. Larger apertures just amplify what is seen with little detailed visibility. What we see is the result of a very young and hot star clearing away the debris from which it was formed. The star *R Monocerotis* (buried within the nebula and thus invisible to us) emits material from its polar regions, and we see the north polar emissions, with the southern emission blocked from view by an accretion disc. The variability of the nebula, reported in 1916 by Edwin Hubble, is due to a shadowing effect caused by clouds of dust drifting near the stars. It was also the first object to be officially photographed with the 200-inch Hale Telescope.

– **NGC 1554–55** **04^{h}21.8^{m}** **+19°32′** Oct**–Nov–**Dec
✺2–5 **⊕1⇆7 variable′** **Taurus**

Also known as *Hind's Variable Nebula*. I decided to include this object despite its difficulty to locate and observe because it is so interesting. This famous but incredibly faint emission nebula is located to the west of the famous star *T Tauri*, the prototype for a class of variable star. The nebula was much brighter in the past, but it is now an exceedingly difficult object to locate. With a large aperture, it will appear as a small faint hazy patch. When (and if!) located, it does bear higher magnification well. It may become brighter in the future, so it is worth looking for in the hope that it makes a reappearance.

2.4 Dark Nebulae

Dark nebulae (also known as *dense clouds*, briefly mentioned earlier in the chapter) by nature differ from other nebulae in one major respect: they do not shine. In fact, when you observe them, you are actually not seeing them by any light-emitting process, but rather for their light-blocking ability. They are vast clouds of gas molecules, such as H_2, HCN, OH, CO, and CS, as well as *dust grains*. These grains, however, bear no resemblance to the dust we see on Earth. They are microscopic in size, believed to be in the region of 20 to 30 nm. However, ice (either water ice—H_2O—or ammonia ice—NH_3) may condense on them, forming a "mantle," which then increases their size up to 300 nm. Dust grains are shaped like long spindles, and in some cases, they rotate. The actual composition of the grains is a topic of vigorous debate, but they are believed to be made, in various unknown amounts, from carbon in the form of graphite, along with silicon carbides, and silicates of magnesium and aluminium.

The formation of the dust grains is spectacular! They are believed to have been formed in the outer regions of stars—in particular, the cool supergiants, and the *R Corona Borealis*-type stars. Dense molecular clouds are also a possible formation site. The temperature of the grains is thought to be about 10 to 100 K, which is cool enough to allow the formation of molecules. In a typical dark nebula, there may be anywhere from 10^4 to 10^9 particles made up of atoms, various molecules, and dust grains.

Due to their vast size, the nebulae appear dark and so are very effective at scattering all the light, with the result that hardly anything reaches the naked eye. The process of scattering the light is so effective that, for instance, visible light emitted from the center of our Galaxy is nearly 100% extinguished by the dust clouds between us and its center. This is why the appearance of the central region in *visible light* is still a mystery. The scattering and absorption of light is known as *extinction*. Do not be confused by thinking that these clouds of dust grains are very dense objects. They are not. Most of the material in the cloud is molecular hydrogen (along with carbon monoxide, which is responsible for their radio emission), and the resulting density is low. There is also some evidence to suggest that the dust grains present in the clouds have different properties to those in the interstellar medium.

Many dark nebulae are actually interacting with their environs, as witnessed by the spectacular images taken by the Hubble Space Telescope of M16 in *Serpens*.

The images show dust clouds containing dense regions, or globules, resisting the radiation pressure from close, hot young stars, with the result that many of the globules are trailing long tails of material. The area near the *Horsehead Nebula* in *Orion* is also famous for its image of the radiation from the supergiant stars of *Orion's Belt* impacting on the dark clouds to either side of the Horsehead, with the result that material is ionized and streaming from the cloud's surface.

Most dark clouds have vastly different shapes, and this is for several reasons. It may be that the cloud was originally spherical in shape, and thus it would have presented a circular image to us, but hot stars in its environment disrupted this by radiation pressure and stellar winds. Shock fronts from nearby supernovae can also have an impact. The gravitational effects from other clouds, stars, and even that of the Milky Way itself all have a role to play in determining the shape of a cloud. It is also believed that magnetic fields may have some limited effect. As many of these dark clouds are part of a much larger star-forming region, the new stars will themselves influence and alter their shape.

Let us now look at a few examples of dark nebulae. The "opacity" of a dark nebulae is a measure of how opaque the cloud is to light, and thus how dark it will appear. There is a rough classification system that can be used; a value of 1 for a dark nebula indicates that it very slightly attenuates the starlight from the background Milky Way; conversely, a value of 6 means that the cloud is nearly black, and it is given in the symbol ✦. Observing dark nebulae can be a very frustrating pastime. The best advice I can offer is to always use the lowest possible magnification. This will enhance the contrast between the dark nebula and the background star field. If a high magnification is used, the contrast will be lost, and you will only see the area surrounding the dark nebula, not the nebula itself. Dark skies are a must with these objects, as even a hint of light pollution makes their detection an impossible task.

2.4.1 Famous Dark Nebulae

Barnard 228	—	**$15^h45.5^m$**	**−34°24′**	Apr—**May**—Jun
✦6	**⊕240⇆20′**			**Lupus**

This is a long band of dark nebula, easily spotted in binoculars as lying halfway between *Psi* (ψ) and *Chi* (χ) *Lupi.* It is best seen in low-power, large-aperture binoculars, as it stands out well against the rich background of star field.

Barnard 59, 65–7	**LDN 1773**	**$17^h21.0^m$**	**−27°23′**	May—**Jun**—Jul
✦6	**⊕300⇆60′**			**Ophiuchus**

Also known as the *Pipe Nebula* (*Stem*) and *Lynds Dark Nebula 1773*, this large dark nebula is visible to the naked eye because it stands out against a star-studded field and is best viewed with lower-power binoculars. With the unaided eye, it appears as a straight line, but under magnification its many variations can be glimpsed.

Barnard 78 **LDN 42** **$17^h33.0^m$** **−26°30′** May–**Jun**–Jul
✦5 **⊕200⇆150′** **Ophiuchus**

Also known as the *Pipe Nebula* (*Bowl*). This is part of the same dark nebula as above. The bowl appears as a jagged formation, covering over 9°. The whole region is studded with dark nebulae and is thought to be part of the same complex as that which encompasses *Rho* (ρ) *Ophiuchi* and *Antares*, which are more than 700 l.y. away from it.

Barnard 86 **LDN 93** **$18^h03.0^m$** **−27°53′** May–**Jun**–Jul
✦5 **⊕6′** **Sagittarius**

Also known as the *Ink Spot*, *Barnard 86* is located within the *Great Sagittarius Star Cloud*. It is a near-perfect example of a dark nebula, appearing as a completely opaque blot against the background stars.

Barnard 87, 65–7 **LDN 1771** **$18^h04.3^m$** **−32°30′** May–**Jun**–Jul
✦4 **⊕12′** **Sagittarius/Ophiuchus**

Also known as the *Parrot Nebula*, this is not a distinct nebula, but it stands out because of its location within a stunning background of stars. Visible in binoculars as a small, circular dark patch, it is best seen in a small telescope of about 10 to 15 cm.

Lynds 906 **$20^h40.0^m$** **+42°00′** Jul–**Aug**–Sep
✦5 **⊕ – –** **Cygnus**

Also known as the *Northern Coalsack*, this is probably the largest dark nebula of the northern sky. It is an immense region, easily visible on clear, moonless nights just south of *Deneb* and lying just at the northern boundary of the *Great Rift*, a collection of several dark nebulae that bisects the *Milky Way*. The Rift is part of a spiral arm of our Galaxy.

Barnard 352 **$20^h57.1^m$** **+45°54′** Jul–**Aug**–Sep
✦5 **⊕20⇆10′** **Cygnus**

Visible in binoculars as a well-defined triangular dark nebula, this is part of the much more famous *North American Nebula*; this dark part is located to the north.

Barnard 33 **$05^h40.9^m$** **−02°28′** Nov–**Dec**–Jan
✦4 **⊕6⇆4′** **Orion**

Also known as the *Horsehead Nebula*. Often photographed, but rarely observed, this famous nebula is very difficult to see. It is a small dark nebula that is seen in silhouette against the dim glow of the emission nebula *IC 434*. Both are very faint and require perfect seeing conditions. Such is the elusiveness of this object that even telescopes of 40 cm are not guaranteed a view. Dark adaption and averted vision, along with the judicious use of filters, may result in its detection, so have a go!

2.5 Reflection Nebulae

The final classification of nebulae is *reflection nebulae*. As the name suggests, these nebulae shine by the lights reflected from the stars within them, or from nearby stars. Like the emission nebulae, these vast clouds consist of both gas and dust, but in this case, the concentration of dust is far less than that found in emission nebulae. One of the characteristics of particles, or grains that are so small (in proportion to the wavelength of light), is their property of selectively scattering light of a particular wavelength. If a beam of white light shines upon a cloud containing the grains, the blue light is scattered in all directions, a phenomenon similar to that seen in the Earth's sky[11] (hence its blue color). This is one reason that reflection nebulae appear so blue in photographs; it is just the blue wavelengths of the light from (usually) hot blue stars nearby. To be scientifically accurate, the nebulae should be called scattering nebulae instead of reflection nebulae, but the name has stuck. An interesting property of the scattered light is that the scattering process itself polarizes the light, which is useful in the studies of grain composition and structure.

But that's not all…if a star that lies behind a dust cloud is observed, some of its blue light is removed by the process discussed above, and an effect known as *interstellar reddening* occurs, which makes the light from the star appear redder than it actually is. This leads to a further phenomenon associated with dust grains called *interstellar extinction*, which should be mentioned because it affects all observations. Astronomers noticed that the light from distant star clusters was fainter than expected, and this was due to dust lying between us and the cluster. This in fact makes all objects fainter than they actually are and leads to an underestimation of their luminosity and an overestimation of their distance. Thus, interstellar extinction must be taken into account when making detained measurements.

Several reflection nebulae reside within the same gas clouds as emission nebulae. The Trifid nebula is a perfect example. The inner parts of the nebula are glowing with a telltale pink color, indicative of the ionization process responsible for the emission, whereas further out from the center, the edge material is definitely blue, signposting the scattering nature of the nebula. Visually, reflection nebulae are very faint objects with a low surface brightness, so they are not easy targets. Most require large-aperture telescopes with moderate magnification to be seen, but a few are visible in binoculars and small telescopes. Note that excellent seeing conditions and very dark skies are required.

2.5.1 Brightest Reflection Nebulae

–	**NGC 1435**	**03^{h}46.1^m**	**+23°47′**	Oct–**Nov**–Dec
✺**2–5**	**⊕30⇆30′**			**Taurus**

Also known as *Tempel's Nebula*, this faint patch of reflection nebula is located within the most famous star cluster in the sky—the Pleiades. The nebula itself surrounds the star *Merope*, one of the brighter members of the cluster, and under perfect conditions can be glimpsed with binoculars. Several other members of the cluster are also enshrouded by nebulosity, but these require exceptionally clear nights and, incidentally, clean optics, as even the slightest smear on, say, a pair of binoculars will reduce the chances to nil.

Caldwell 31	**IC 405**	**05^{h}16.2^m**	**+34°16′**	Nov–**Dec**–Jan
✺**2–5**	**⊕30⇆19′**			**Auriga**

Also known as the *Flaming Star Nebula*, this is a very challenging reflection nebula to observe. It is actually several nebulae, including *IC 405, 410*, and 417, plus the variable star *AE Aurigae*. The use of narrow-band filters will be justified with this reflection nebula, as they will highlight the various components.

2.6 Molecular Clouds

We have seen that interstellar space is filled with gas and dust, and that in certain locations, concentrations of this material gives rise to nebulae. But the location of these nebulae are not, as one might expect, entirely random. The areas that give rise to star formation are called *Molecular Clouds*. These clouds are cold, perhaps only a few degrees above absolute zero, and occupy enormous regions of space. Due to the conditions within them, molecular clouds allow the formation of several molecules [e.g., carbon monoxide (CO), water (H_2O), and hydrogen molecules (H_2)[12]]. Although the most abundant molecule in a cloud, molecular hydrogen is very difficult to observe because of the low temperature. On the other hand, CO can be detected when certain portions of the cloud are 10–30 K above absolute zero. It is these molecules that allowed molecular clouds to be discovered by two radio astronomers—Philip Solomons and Nicholas Scoville—who, in 1974, found traces of the carbon monoxide molecule in the Galaxy.

Molecular clouds are truly gigantic and contain vast amounts of hydrogen. They can have masses from 10^5 to 2×10^6 solar masses, and diameters anywhere from 12 to 120 pc, or about 40 to 350 l.y. The total mass of molecular clouds in our Galaxy is thought to be about 5 billion solar masses.[13] But even though these molecular clouds are so vast, do not be fooled into thinking that we are talking about something that resembles, in structure, conditions similar to a foggy day, with hydrogen and dust being so dense that you hardly see anything in front of you. If we could go inside one of these clouds, there would be about 200 or 300 hydrogen molecules per cubic centimeter. This is not a lot, even though it is several thousand times greater than the average density of matter in our Galaxy. Even more staggering, it is 10^{17} times less dense than the air we breathe.

Astronomers have deduced that molecular clouds and CO emission are intimately linked, and by looking at the areas in our Galaxy where CO emission originates, we are in fact looking at those areas where star formation is taking place. Because the molecular clouds are, by comparison with the rest of the ISM, heavy and dense, they tend to settle toward the central layers of the Milky Way. This has produced a phenomenon we have all seen—the dark bands running through the Milky Way. Surprisingly, it was found that the molecular clouds in which star formation occurs outline the spiral arms of the Galaxy and lie about 1000 pc apart, strung out along the arms rather like pearls on a necklace.[14] However, spiral arms of galaxies are not the only place where star formation can occur. There are several other mechanisms that can give rise to stars, as we shall see in the chapter on stars.

2.7 Protostars

I have included the topic of protostars in this chapter and not the following because we are still discussing large, diffuse clouds of gas and dust, albeit briefly, before they are turned into proper stars. So let's begin by looking at the mechanisms by which stars are believed to have been formed.

We have discussed the fact that space is full of gas and dust, and that local concentrations of this material give rise to nebulae. But how do stars form in these regions? It may seem obvious in hindsight that a star will form in those clouds where the gas and dust are particularly dense and thus will allow gravity to attract the particles. An additional factor that will assist in formation is a very low temperature of the cloud. A cold cloud means that the (thermal) pressure of the ISM is low. A cold temperature is not only helpful but in fact a prerequisite, as clouds have a high (thermal) pressure, which tends to overcome any gravitational collapse. It is a delicate balancing act between gravity and pressure, whereby if gravity dominates, stars form.

From our earlier discussion in the book, you should have realized by now that there is only one place where conditions like those just mentioned arise: the dark nebulae. As the cloud contracts, pressure and gravity permitting, the dust and gas cloud becomes very opaque and the precursor region to star formation. These regions are often called *Barnard objects*, after the astronomer who first catalogued them, Edward Barnard.[15] There are also even smaller objects, sometimes located within a Barnard object. These resemble small, spherical dark blobs of matter and are referred to as *Bok globules*, named after astronomer Bart Bok. It may help you to think of a Bok globule as a Barnard object but with its outer layers, which are the less-dense regions, dispersed.

Radio measurements of Bok globules indicate that their internal temperature is a very low 10 K, and their density, although only about 100 to 20,000 particles (dust grains, gas atoms, and molecules) per cubic centimeter, is considerably greater than that found in the ISM. The size of these objects can vary considerably; there are no standard sizes, but on average, a Bok globule is about 1 pc in diameter, ranging anywhere from 1 to 1000 $M_\odot$. The larger Barnard object, on the other hand, can have a mass of about 10,000 $M_\odot$, with a diameter of about 10 pc. As you can imagine, the sizes of these objects vary greatly and are determined by the local conditions in the ISM.

Now, if conditions permit, the densest areas within these objects and globules will further contract under gravitational attraction. A consequence of this contraction is the heating up of the blob material; however, the cloud can radiate this thermal energy away, and in doing so prevent the pressure from building up enough to resist the contraction. During the early phase of collapse, the temperature remains below 100 K, and the thermal energy is transported from the warmer interior to the exterior of the cloud by convection, causing the cloud to glow in infrared radiation. This ongoing collapse has the effect of increasing the cloud's density, but this makes it difficult for the radiation to escape from the object. Consequently, the central regions of the cloud become opaque, which traps nearly all the thermal energy produced by the gravitational collapse. Trapping the energy results in a dramatic increase in both pressure and temperature. The ever-increasing pressure fights back against the overpowering crush of gravity, and the now-denser fragment of cloud becomes a *protostar*—the seed from which a star is born. At this stage, a protostar may resemble a star, but it is not really a star, as no nuclear reactions occur in its core.

The time taken for the above scenario to occur can be extremely short, in an astronomical sense—maybe of the order of a few thousand years. The protostar is still quite large. For example, after, say, 1000 years, a protostar of 1 $M_\odot$ can be 20 times larger than the Sun's radius, $R_\odot$, and about 100 times as luminous, 100 $L_\odot$.

2.8 The Jeans Criterion

You might think from the previous sections that star formation is a pretty straightforward process, and that if there is enough material (i.e., gas and dust) and a long enough period of time, the only possible outcome is the formation of a star. You would be wrong!

Remember that an interstellar cloud, however large (or small), performs a delicate balancing act between the gravitational attraction from all the cloud's particles, which is trying to collapse the cloud, and the thermal energy (think of it as the cloud's heat), which is trying to resist this collapse. If one is more dominant than the other, a star may form.

The question to ask yourself is, "What decides whether gravity wins?" This is where the *Jeans Criterion*[16] comes into play. In a cloud with a specific density, temperature, and mass, these criteria describe the small-sized cloud and its minimum mass where gravity could overcome the thermal pressure and so result in collapse. As you can imagine, some quite involved equations are used; however, we can make approximations of them (see Box 2.1).

The critical mass of the cloud is known as the *Jeans Mass*, M_J, and the critical size, the *Jeans Length* R_J. The Jeans Mass is the mass of the cloud whose radius is the Jeans Length.

From the above description, you can see that there are a few conditions that make cloud collapse more likely: the cloud has a very low temperature (the cooler the cloud, the better the chances of collapse), and the cloud is more dense (a dense cloud has a better chance of collapse than one that is very thinly spread out). Thus, the dark, dense clouds discussed earlier would be ideal locations for cloud collapse. Indeed, in the darkest, densest clouds, only a few solar masses of material are necessary for collapse.

Some dense, dark clouds have within them even denser areas, called clumps and cores, which may have masses ranging from 0.3 to 10^3 solar masses, and thus can satisfy the Jeans Criterion on their own. So now we have the situation of a large, dense, dark cloud's collapsing, while inside it, there are clumps collapsing, as well!

But, as you can imagine, things are far more complicated than the picture I have just drawn for you. As clouds, cores, and clumps collapse, they tend to warm up. This acts to inhibit the gravitational collapse; however, this brief hiccup is overcome, and collapse continues.

One point that needs to be mentioned is that most of the diffuse clouds in the ISM are not close to the Jeans Criterion, so some sort of mechanism, or trigger, is needed to change the conditions. In fact, what is needed is something that will increase a cloud's density (i.e., an event that will compress the cloud material into a smaller volume of space).[17] Once a trigger pushes the cloud closer to, and possibly over, the Jeans limits, then cloud collapse can begin (we discuss these possible triggers later in the book).

Finally, imagine a massive cloud that does not initially satisfy the Jeans Criterion, but then something causes the cloud to collapse. Areas within the large cloud may now satisfy the criteria and so they themselves start to contract. In a cloud of several hundred to several thousand solar masses, there can be a lot of clumps, and this *fragmentation*, as it is called, could eventually give rise to a cluster of stars. Thus, this may be a possible scenario for the formation of open star clusters.

The Jeans Criterion is a good starting point in the description of cloud collapse, and today there exist far more sophisticated models that perhaps more accurately describe what is going on. Nevertheless, as a starting point, they adequately describe the possible beginning of star formation (see Box 2.1).

Let us now move on to those objects we (hopefully) can see each and every night—stars.

Box 2.1: The Jeans Length and Jeans Mass

The Jeans Length is approximately given by:

$$R_J \approx \left(kT/Gm^2n\right)^{1/2}$$

k is Boltzmann constant $= 1.3806 \times 10^{-23}\ \mathrm{JK}^{-1}$
T is temperature in K

G is gravitational constant $= 6.67 \times 10^{-11}\ \mathrm{Nm^2\,kg^{-2}}$
m is mass of hydrogen atom $= 1.67 \times 10^{-27}$ kg
n is number of particles (number density)

Example:
If an interstellar cloud has a temperature of 50 K, and there are 10^{11} hydrogen atoms per cubic meter, determine the Jeans Length and Jeans Mass.
Using the above formula, we get:

$$R_J \approx \left[\frac{(1.38 \times 10^{-23}) \times (50)}{(6.67 \times 10^{-11}) \times (1.67 \times 10^{-27})^2 \times (10^{11})}\right]^{1/2}$$

$$R_J \approx 6 \times 10^{15}\ \mathrm{m}$$
$$\approx 0.2\ \mathrm{pc}$$

The Jeans Mass can easily be estimated by multiplying the density by the volume:

$$M_J = (4\pi/3)(1.67 \times 10^{-27})(10^{11})(6 \times 10^{15})^3$$
$$1.5 \times 10^{32}\ \mathrm{kg}$$
$$\approx 76\ \mathrm{M}_\odot$$

Thus, in a cloud with a temperature of 50 K that has 10^{11} atoms per cubic meter, 76 solar masses of material is the minimum amount needed for gravitation to overcome any thermal pressure, with a radius of about 0.2 pc.

Notes

1. An important distinction is that n is not the same as the number of hydrogen atoms per cubic meter. If the hydrogen is in a molecular form, H_2, then the number of separate particles is $n_H/2$.
2. HII is pronounced "aitch 2."
3. Recall that the ISM is made up of about 74% hydrogen (by mass), 25% helium, and the rest metals.
4. And in some cases, star death, namely supernova remnants, covered later.
5. Our simple model of an atom has a central nucleus with electrons orbiting around it, somewhat like planets orbiting a Sun. Electrons with a lot of energy are in the outer orbits, while electrons with less energy are closer to the nucleus. Not all orbits are allowed by quantum mechanics: to move up to higher energy levels, electrons need a very specific amount of energy; too much or too little, and an electron will not move.
6. The time spent before recombining is very short—millionths of seconds—but also depends on the amount of radiation present and the density of the gas cloud.
7. Unfortunately, the red glow is usually too weak to be seen at the eyepiece.

8. These lines are a rich blue-green color and, under good seeing conditions and with clean optics, can be glimpsed in the *Orion Nebula*, M42.
9. In some astrophysical contexts, such as in the center of quasars, conditions exist that can give rise to terms such as Fe23. The amount of radiation is so phenomenal that the atom of iron (Fe) has been ionized to such an extent, it has lost 22 of its electrons!
10. This is often called the Stromgren sphere, named after the astronomer Bengt Stromgren, who did some pioneering work on *HII* regions.
11. Note that scattering of water molecules, and not dust, is responsible for the blue sky on Earth.
12. Other molecules such as ammonia (NH_3) and alcohol (CH_3OH!!!) have also been detected.
13. In areas where the average density exceeds, say, a million solar masses, clouds referred to as *Giant Molecular Clouds* can form.
14. Molecular clouds can be found outside of spiral arms, but current ideas suggest that the spiral arms are regions where matter is concentrated, due to gravitational forces. The molecular clouds pass through the arms and are "squeezed." This dense region then gives rise to star-forming regions.
15. See the section on dark nebulae for observable examples of Barnard objects.
16. James Jeans (1877–1946) was a British astronomer, and the first person to mathematically describe the necessary conditions for star collapse.
17. At this point, the increase in density is thought to be a more important condition than a commensurate increase in temperature.

CHAPTER THREE

Stars

3.1 The Birth of a Star

A newly born star can be thought of as having been born when the core temperature of the protostar reaches about 10 million K. At this temperature, hydrogen fusion can occur efficiently by the *proton-proton chain*.[1] The moment the ignition fusion process occurs will halt any further gravitational collapse of the protostar. The star's interior structure stabilizes, with the thermal energy created by nuclear fusion maintaining a balance between gravity and pressure. This important act of balancing is called *gravitational equilibrium*.[2] It is also sometimes referred to as *hydrostatic equilibrium*. The star is now a hydrogen-burning main-sequence star.

The time taken for the formation of a protostar to the birth of a main-sequence star depends on the star's mass. This is an important point to emphasize. A star's mass determines a lot! A handy reference to remember is that *massive stars do everything faster!* A high-mass protostar may collapse in only a million years or less, while a star with a mass of $\approx 1\,M_{\odot}$ could take around 50 million years. A star with a very small mass, say, an M-type star, could take well over 100 million years to collapse. This means that very massive stars in a young star cluster may be born, live, and die before the very smallest stars finish their infant years!

The changes, or transitions, that occur to a protostar's luminosity and surface temperature can be shown on a special *H-R* diagram. This is known as an *evolutionary track*, or a *lifetrack*, of a star.[3] Each point along the star's track represents its luminosity and temperature at some point during its life, and so it shows us how the protostar's appearance changes due to changes in its interior. Figure 3.1 shows the evolutionary tracks for several protostars of different masses, from 0.5 $M_\odot$ to 15 $M_\odot$ (it is important to realize that these evolutionary tracks are theoretical models, and the predictions are only as good as theory;[4] they seem to work very well and are being improved all the time). Recall that protostars are relatively cool, and so the tracks all begin at the right side of the *H-R* diagram. However, subsequent evolution is very different for stars of differing mass.

The evolutionary lifetracks of seven protostars are shown. Also identified are the stages reached after an indicated number of years of evolution (dashed lines). The mass shown for each protostar is the final mass when it becomes a main-sequence star. Note that the greater the mass, the higher the temperature and luminosity.

As an example of an evolutionary lifetrack for a protostar, we shall look at the lifetrack for a 1 $M_\odot$, rather like the Sun. This period in the star's life has 4 very distinct phases:

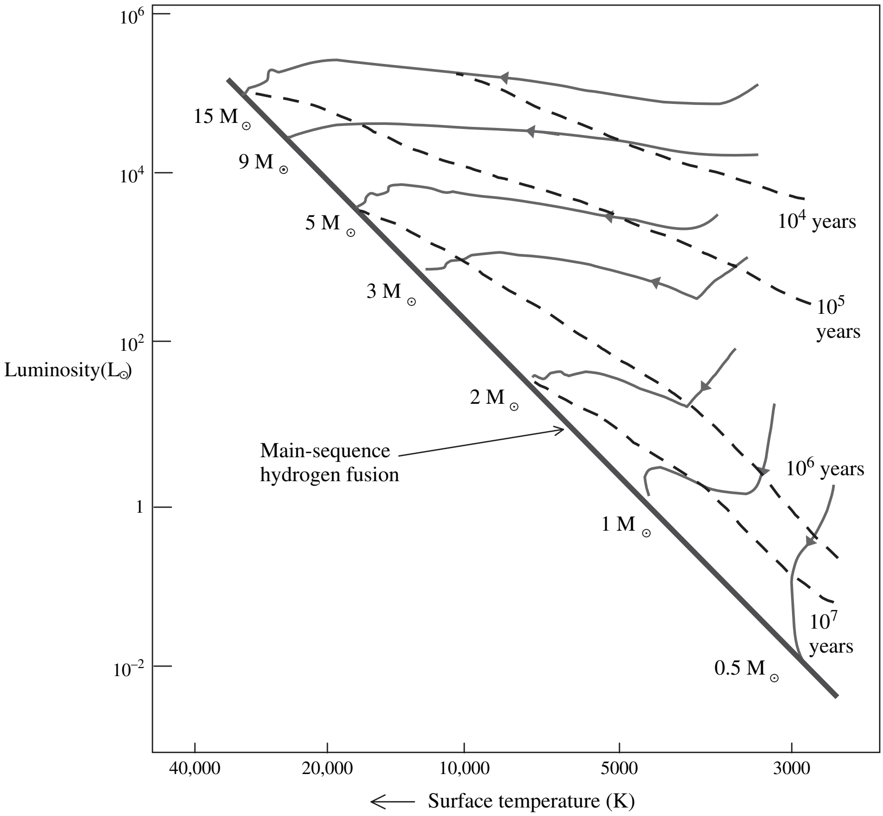


Figure 3.1. Pre-main-sequence lifetracks.

Phase 1: The protostar forms from a cloud of cold gas and thus is on the far right side of the *H*-*R* diagram; however, its surface area is enormous, and so its luminosity can be very large—it may be 100 times more than luminous when it becomes a star.

Phase 2: Due to its large luminosity, the young protostar rapidly loses the energy it generated via gravitational collapse, and so further collapse proceeds at a relatively rapid rate. Its surface temperature increases slightly during the next several million years, but its diminishing size reduces the luminosity. The evolutionary track now progresses almost vertically downward on the *H*-*R* diagram.

Phase 3: Now that the core temperature has reached 10 million K, hydrogen nuclei fuse into helium. The rate of nuclear fusion, however, is not sufficient to halt the collapse of the star, although it is slowed down considerably. As the star shrinks, its surface temperature increases. The process of shrinking and heating will result in a small increase in luminosity over the next 10 million years. The evolutionary track now progresses leftward and slightly upward on the *H*-*R* diagram.

Phase 4: Both the rate of nuclear fusion and the core temperature increase over the next tens of millions of years. Once the rate of fusion is high enough, gravitational equilibrium is achieved, and fusion becomes self-sustaining. The result is that the star settles onto the hydrogen-burning main sequence (see fig 3.2).

From the viewpoint of an observer, this stage of stellar evolution does not present itself with many visible objects. Even though the luminosity of such

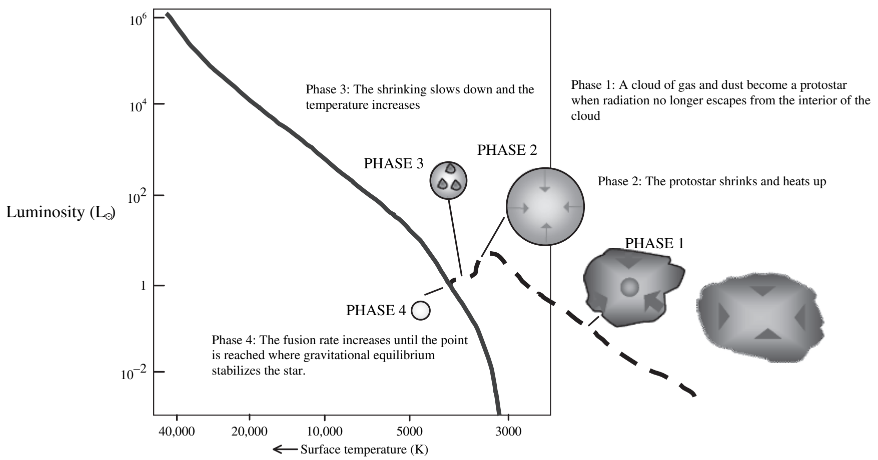


Figure 3.2. The evolutionary track of a protostar.

objects is very high, we will never see one. The reason is obvious: they are enshrouded within vast clouds of interstellar dust, which, if you recall, are very efficient at blocking out light. The dust in the vicinity of a protostar, often called a *cocoon nebula*, absorbs the light, and so it is very difficult to observe at visible wavelengths.[5] On the other hand, they can be seen at infrared wavelengths… but this does not really help us, as visual observational astronomers on Earth.

3.2 Pre-Main-Sequence Evolution and the Effect of Mass

The previous sections explained how a cloud can contract and become a protostar. In fact, due to the immense amount of material in a molecular cloud, it is believed that rather than an individual protostar being formed, several are formed as a star cluster. However, there is a small problem with this scenario; at the time of writing this book, there is no satisfactory explanation for protostars of differing masses actually forming within the same cloud. What are the processes that govern the clumping and fragmentation of the cloud into protostars of widely differing masses? Even though we cannot explain the process, we can at least observe its results.

Let us begin this section by looking at how protostars of differing mass are believed to have been formed. We'll begin with a star of $1\,M_{\odot}$, a star just like Sun. The outer layers of such a protostar are cool and opaque,[6] which means that energy released as radiation due to the shrinkage of the inner layers cannot reach the surface. Thus, the only way of moving this energy toward the surface layers must be by the less-efficient and slower method of *convection*. The result of this process is that the temperature remains more or less constant as the protostar shrinks, while the luminosity decreases because the radius decreases,[7] and the evolutionary track moves downward on the *H*-*R* diagram. This is depicted in Figure 3.1.

I said previously that the surface temperature remains roughly constant during this phase, but conditions inside the protostar are far from unchanging. The internal temperature starts to increase during this time, and the interior becomes ionized. This reduces the opacity within the protostar and allows the transfer of energy by radiation in the interior regions, and by convection in the outer layers. This process is the one that is ongoing within the Sun today. The net result of these changes is that energy can escape much more easily from the protostar, and thus the luminosity increases. This increase in energy transport is represented by the evolutionary track's bending upward (meaning higher luminosity) and to the left (higher temperature). After an interval of a few million years, the temperature within the protostar is high enough—10 million K—for nuclear fusion to begin and, eventually, enough heat and associated internal pressure are created so as to balance the gravitational contraction of the star. We can say that at this point, hydrostatic equilibrium has been reached, and the protostar has reached the main sequence—it is now a main-sequence star.

As to be expected, a more massive protostar will evolve in a different way. Protostars with a mass of about or greater than $4\,M_{\odot}$ contract and heat up at a more rapid rate, and so the hydrogen-burning phase begins earlier. The net result is that the luminosity stabilizes at approximately its final value, but the surface temperature continues to increase as the protostar continues to shrink. The evolutionary track of such a high-mass protostar illustrates this on the *H-R* diagram; the luminosity is nearly horizontal (meaning nearly constant luminosity) from right to left (increasing surface temperature). This is especially true for the stars at mass $9\,M_\odot$ and $15\,M_\odot$.

An increase in mass will result in a corresponding increase in pressure and temperature in the interior of a star. This is very significant because it means that in very massive stars, there is a much greater temperature difference between the core and its outer layers as compared to, say, the Sun. This allows convection to occur much deeper into the star's interior regions. In contrast, the massive star will have very low-density outer layers, and so energy flow in these regions is more easily performed by radiative methods than by convective methods. Thus, stars on the main sequence with a mass greater than about $4\,M_\odot$ will have convective interiors and radiative outer layers, while stars less than about $4\,M_\odot$ will have radiative interior regions and convective outer layers.

At the very low end of the mass scale, stars that have a mass less than about $0.8\,M_\odot$ have a very different internal structure. In these objects, the interior temperature of the protostar is insufficient to ionize the inner region, which is thus too opaque to allow energy transport by radiation. The only possible method to transport the energy to the outer layers is by convection. In these stars, convective methods are the only means of energy transport. Examples of the interior structures of low-mass, high-mass, and very low-mass stars are shown in Figure 3.3.

Energy flows from the core by convection in the inner regions and by radiation in the outer layers in stars of mass greater than $4\,M_\odot$.

Energy flows outward from the core by radiative means in inner regions and by convection in outer layers in stars with a mass of less than $4\,M_\odot$ and greater than $0.8\,M_\odot$.

Energy flows outward by convection throughout the interior of the stars with a mass of less than $0.8\,M_\odot$.

A very important point to make here is that all the evolutionary tracks shown in Figure 3.1 end at the main sequence. Thus, the main sequence represents those stars in which nuclear fusion reactions are producing energy by converting hydrogen to helium. For the large majority of stars, this is a stable situation, and this endpoint on the main sequence can be represented by a *Mass-Luminosity Relationship*, which is shown in Figure 3.4. What this diagram implies is that the hot bright blue stars are the most massive, while the cool faint red stars are the least massive.[8] Thus, the *H-R* diagram is a progression not only in luminosity and temperature but in mass, as well. This can be succinctly summed up as "*the greater the mass, the greater the luminosity.*"

For stars on the main sequence, there is a ratio between the mass and luminosity. Basically, the more massive the star, the greater its luminosity. A star of mass $10\,M_\odot$ has about $3000\,L_\odot$; a star of mass $0.1\,M_\odot$ has a luminosity of only $0.001\,L_\odot$.

Now that we have discussed how stars are formed, and how star birth is depicted in the *H-R* diagram, it is important that I emphasize two factors that

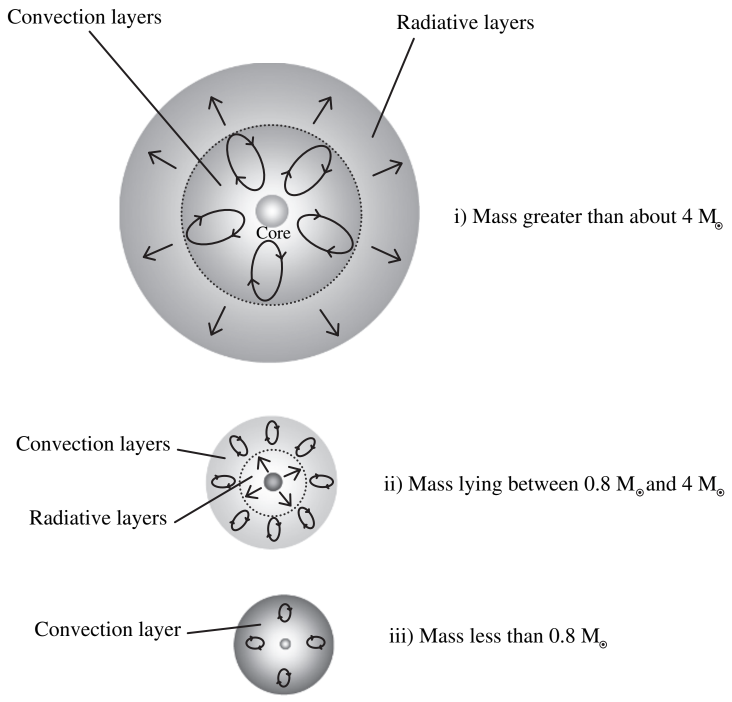


Figure 3.3. Mass of main-sequence stars.

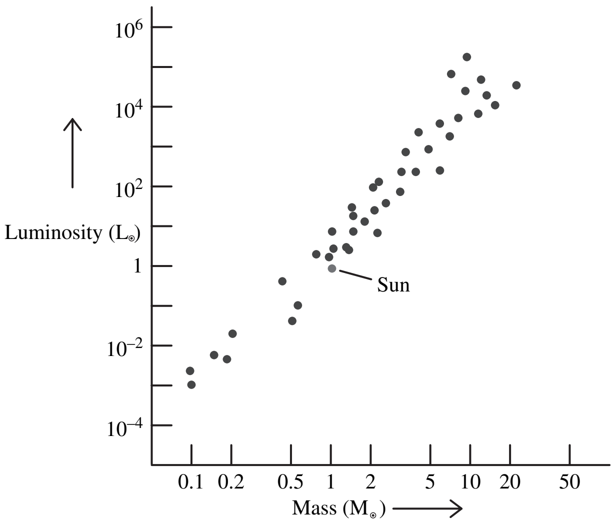


Figure 3.4. Mass-luminosity relationship.

can cause confusion. First, if you look at the evolutionary track of protostars, several of them, especially the high-mass protostars, begin in the upper-right region. But they *are not red giant stars*! The red stars are at a stage in their lives that occurs only *after* being a main-sequence star. The second point to note is that most stars spend *most* of their lives on the main sequence and only a relatively brief time as protostars. For example, a $1\,M_{\odot}$ protostar takes about 20 million years to become a main-sequence star, while a $12\,M_{\odot}$ may only take 20,000 years. In contrast, a star like the Sun has been a main-sequence star for nearly 5 billion years and will remain one for another 5 billion!

One final point is that the masses of stars have limits. Using theoretical models, astronomers have deduced that stars above ≈ 150–$200\,M_{\odot}$ cannot form; they generate so much energy that gravity cannot contain their internal pressure. These stars literally tear themselves apart. At the other end of the scale, there is also, not surprisingly, a lower limit. Those stars with a mass of less than $0.08\,M_{\odot}$[9] can never achieve the 10 million K core temperature necessary to initiate nuclear fusion. So, what is actually formed can be thought of as a "failed star," which will slowly radiate away all of its internal energy, gradually cooling with time. These objects have been called *Brown dwarfs* and seem to occupy a strange area between what we think of as a planet and a star. Brown dwarfs radiate in infrared, making them very difficult to detect. The first known detection was in 1995 of *Gliese 229B*, a $0.05\,M_{\odot}$ object. Many astronomers believe these small, elusive objects are far more common than previously thought and may in fact be the most common form of ordinary matter[10] in the universe.

From an observational point of view, this period in a star's life does not present us with many observable opportunities. The protostars are cocooned within vast clouds of gas and dust and are therefore invisible to us. Some objects are, of course, visible if infrared telescopes are used. However, it is always worthwhile to look at areas of the night sky where we know such objects exist, even though they cannot be seen. We can always use our imagination as we gaze at them, knowing that hidden deep in these clouds are stars in the process of being formed. One such location is, of course, the *Orion Nebula*.

Messier 42	**NGC1976**	**$05^h35.4^m$**	**$-05°27'$**	Nov—**Dec**—Jan
✺**1–5**	⊕**65⇆60′**			**Orion**

Also known as the *Orion Nebula*. This is the premier emission nebula and one of the most magnificent objects in the sky. It is part of the vast Orion complex, which contains star-forming regions, molecular clouds, and all sorts of nebulae! Visible to the naked eye as a barely resolved patch of light, it shows detail from the smallest aperture upwards. In binoculars, its pearly glow will show the structure in detail, and in telescopes of aperture 10 cm, the whole field will be filled. The entire nebulosity is glowing due to the light (and thus energy) provided by the famous *Trapezium* stars located within it. These stars are stellar power houses, pouring forth vast amounts of energy, and they are fairly new stars. What is also readily seen along with the glowing nebula are the dark, apparently empty and starless regions. These are still part of the huge complex of dust and gas but are not glowing by the process of fluorescence—instead, they are vast clouds of obscuring dust (the dark nebulae mentioned previously). The emission nebula is one of the few that show definite color. Many observers report seeing a greenish glow, along with pale grey and blue, but to observe any color besides gray will require excellent observing conditions. Also, amateurs state that with very large apertures of 35 cm, a pinkish glow can be seen. Located within the nebula are the famous *Kleinmann–Low Sources* and the *Becklin–Neugebauer Object*, which are believed to be dust-enshrouded young stars. The whole nebula complex is a vast stellar nursery. M42 is at a distance of 1700 l.y. and about 40 l.y. in diameter. Try to spend a long time observing this object—you will benefit from it, and many observers just let the nebula drift into the field of view.

3.3 Mass Loss and Gain

3.3.1 T Tauri Stars

After reading the previous sections, you may have gotten the idea that star formation is simply a matter of material falling inward due to gravity. In fact, most of the material that makes up a cloud is ejected into space and never forms stars at all. This ejected material can help sweep away the gas and dust surrounding the young stars and make them visible to us. Several examples of such a process can be seen in the *Rosette Nebula*, the *Triffid Nebula,* and the *Bubble Nebula*, mentioned earlier.

There are also examples of individual objects that eject material into space during this aspect of a star's birth. These are called *T Tauri stars*, which are protostars whose luminosity can change irregularly in a matter of just a few days, and which also have both absorption and emission lines in their spectrum. In addition, due to the conflict between gravitational contraction and hydrogen-burning in these first stages of main-sequence stability, the element lithium is produced. Spectral lines of lithium are a signature of protostars of the T Tauri type. The masses of these stars are less than about $3\,M_\odot$ and they seem to be about 1 million years old. If placed on an *H-R* diagram, they would be on the right–hand side of the main sequence. By analyzing the emission lines, we can see that surrounding these protostars are very thin clouds of very hot gas, which the protostar has ejected into space with a speed of about $80\,km\ s^{-1}(300,000\,km\ h^{-1})$. A T Tauri star bears a superficial resemblance to the Sun in that it will exhibit a spectral type of F, G, or K, with a surface temperature of 4000–8000 K.

Over a period of a year, a typical T Tauri star would have ejected about 10^{-8} to 10^{-7} solar masses. You may think that this is a very small amount, but compared with the Sun, which loses about $10^{-4}\,M_\odot$ a year, it is significant. This phase of a protostar, called the T Tauri phase, can last as long as 10 million years, during which it can eject roughly $1\,M_\odot$ of material. A consequence of this is that the mass of the final main-sequence star is very much less than the mass it started with. As these are objects associated with star birth, they are often, if not always, found near or in the Milky Way.

Other young stars with masses greater than $3\,M_\odot$ do not vary in luminosity like T Tauri stars; they do eject mass, however, due to the extremely high radiation pressure at their surfaces. This class of star is called *Ae* or *Be* stars. Stars greater than 10 $M_\odot$ will reach the main sequence before the surrounding dust and gas from which they have been formed will have had a chance to disperse, and so these stars are often detected as highly luminous infrared objects located within the molecular clouds.

Fortunately, as observers, there are several visible examples of T Tauri stars. They are, however, extremely faint, and so only the archetypal one is mentioned below.

T Tauri	**$04^h22.0^m$ +19°32′**	Oct–**Nov**–Dec
8.5––13.6$_v$m	**dGe–K1e**	**Taurus**

This star is about 1.8° west and slightlynorth of *ε (epsilon) Tauri*, the northernmost bright star in the famous "v" shape of the *Hyades* star cluster. Discovered in 1852 by J. Hind (who also discovered the associated nebula—*Hind's Variable Nebula*). The star varies irregularly in several aspects: the brightness varies from about 8th to 13th magnitude, the period, with a range from a few weeks to perhaps a few months, and the spectrum varying from G4 to G8. Oddly enough, the variation in spectral type does not necessarily correlate with variability in magnitude. T Tauri and the nebula lie within the *Taurus Dark Cloud Complex*, within which there are numerous but faint, variable nebulae and recently formed stars (other T Tauri and similar stars are *VV Tauri* and *FU Orionis*).[11]

3.3.2 Discs and Winds

One aspect of protostar formation that came as a surprise to astronomers in the late twentieth century was a curious phenomenon observed in many young stars, including the T Tauri stars mentioned above. It involves a loss of mass, once again, but the loss is directed out from the young star in two jets; these are very narrow, usually flowing out along the rotation axis of the star and in opposite directions. This outflowing jet is referred to as a *bipolar outflow*. The material is moving with a velocity that can reach several hundred kilometers per second, and it sometimes interacts with the surrounding debris left over from star formation to form clumpy knots of material called *Herbig-Haro objects*. The lifetime of such a phenomenon is relatively short, maybe from 10,000 to 100,000 years. The mechanism that forms these jets is not yet fully understood, although it is believed to involve magnetic fields.

We have discussed mass loss in a protostar, but there exists a mechanism that can add mass to the normal star-formation process. Recall that a protostar is formed from falling gas and dust due to gravity. As clouds of denser material clump together, the protostar nebula will begin to rotate. This is a consequence of physics, and it is called the *Conservation of Angular Momentum*. The material will flatten itself out and form a disc, or *protostellar disc*, as it is called. The gas and dust particles within the nebula collide and spin inwards onto the forming protostar, thus adding to its mass. This process is often called *accretion,* and the build-up of material into the ever faster-rotating disc is called the *circumstellar accretion disc*.

The interactions between the magnetic fields, the jets, and the accretion disc are to slow down the protostar's rotation, which would explain why most stars have a much slower spin than protostars of similar mass.

Since the 1990s, the discovery of accretion discs around new stars led astronomers to speculate that these are the precursors to possible planetary formation. Many of these splendid objects were discovered in Orion but are, naturally, unobservable for the amateur astronomer.

3.4 Clusters and Groups of Stars

Stars do not form in isolation.[12] You do not get one star forming here, and perhaps another forming overthere! A dark nebulae can contain the material that could form hundreds of stars, and so stars tend to form in groups, or clusters.

3.4.1 Galactic Star Clusters

The stars that form out of the same cloud of material will not necessarily all have the same mass. Far from it — the masses will differ, and, as a consequence, reach the main sequence at different times. As I mentioned earlier, high-mass stars evolve faster than low-mass stars, and so at a time when these high-mass stars are shining brightly as stars in their own right, the low-mass protostars may still be cocooned within their dusty mantles. Consequently, the intense radiation emitted by the new, hot, and bright stars may disturb the normal evolution of the low-mass stars, and so reduce their final mass.

Over time, however, the stellar nursery of young stars will gradually disperse. Calculations predict that massive stars have much shorter life-spans than smaller, less massive ones, so you can easily see that some stars (the more massive ones) do not live long enough to escape their birthplace, whereas a smaller star, say, of solar mass size, will in most cases easily escape from its stellar birthplace.

It's worth noting that, in relation to stars of mass about equal to that of the Sun, where there may be several thousand objects, the combined gravitational attraction of so many stars may slow down the dispersion of the group. It really depends on the star density and mass of the particular cluster. Thus, the most dense or closely packed clusters that contain solar-mass-sized stars will be the ones that contain the oldest population of stars, while the most open clusters will have the youngest star population.

Open clusters, or *galactic clusters*, as they are sometimes called, are collections of young stars containing anywhere from a dozen members to hundreds. A few of them (for example, *Messier 11* in Scutum) contain an impressive number of stars, equalling that of globular clusters, while others seem little more than a faint grouping set against the background star field. Such is the variety of open clusters that they come in all shapes and sizes. Several are over a degree in size and their full impact can only be seen by using binoculars, as a telescope has too narrow a field of view. An example of such a large cluster is *Messier 44* in Cancer. Then there are tiny clusters, seemingly nothing more than compact multiple stars, as is the case with *IC 4996* in Cygnus. In some cases, all the members of the cluster are equally bright, such as *Caldwell 71* in Puppis; but there are others that consist of only a few bright members accompanied by several fainter companions, as is the case of *Messier 29* in Cygnus. The stars that make up an open cluster are called *Population I* stars, which are metal-rich and usually found in or near the spiral arms of the Galaxy.

The size of a cluster can vary from a few dozen l.y., as in the case of *NGC 255* in Cassiopeia, to about 70 l.y., as in either component of *Caldwell 14*, the Perseus Double Cluster.

The reason for the varied and disparate appearances of open clusters is the circumstances of their births. It is the interstellar cloud that determines both the number and type of stars that are born within it. Factors such as the size, density, turbulence, temperature, and magnetic field all play a role as the deciding parameters in star birth. In the case of *giant molecular clouds*, or GMCs, the conditions can give rise to both O- and B-type giant stars along with solar-type dwarf stars—whereas in *small molecular clouds* (SMCs), only solar-type stars will be formed, with none of the luminous B-type stars. An example of an SMC is the *Taurus Dark Cloud*, which lies just beyond the Pleiades.

By observing a star cluster, we can study in detail the process of star formation and interaction between low- and high-mass stars. As an example, look at Figure 3.5, which shows the *H-R* diagram for the cluster *NGC 226*4, located in *Monoceros*. Note that all the high-mass stars, which are the hottest stars, with a temperature of about 20,000 K, have already reached the main sequence, while those with temperatures at about 10,000 K or below have not. These low-mass and cooler stars are in the latter stages of pre-main-sequence star formation, with nuclear fusion just about beginning at their cores. Astronomers can compare this *H-R* diagram with the theoretical models, and they have deduced that this particular cluster is very young, only two million years old.

This young star cluster is about 800 pc from Earth and contains many T Tauri stars. Each dot is a star whose temperature and luminosity have been measured.

By comparison, we can look at the *H-R* diagram for a very famous cluster—the *Pleiades* star cluster, Figure 3.6. We can see right away that the cluster must be older than NGC 2264 because most of the stars are already on the main sequence. From studying the Pleiades *H-R* diagram, astronomers believe that the cluster could be about 50 million years old. Also look at the area on the *H-R* diagram with a temperature of about 10,500 K and luminosities ranging from 10 to $10^2 L_\odot$. You will see a few stars that do not seem to lie on the main sequence. This is not the case because they are still in the process of being formed; on the contrary, these massive stars have left the main sequence. They were among the first to be formed and thus are the oldest, and they are now evolving into a different kind of star. As we shall see later, all the hydrogen at the center of these stars has been used up,[13] and helium-burning is now proceeding.

This is a much older cluster, around 50 million years. Most, if not all, of the low-mass cool stars have reached the main sequence, which implies that hydrogen-burning has started in their cores.

An interesting aspect of open clusters is their distribution in the night sky. You may be forgiven in thinking that they are randomly distributed across the

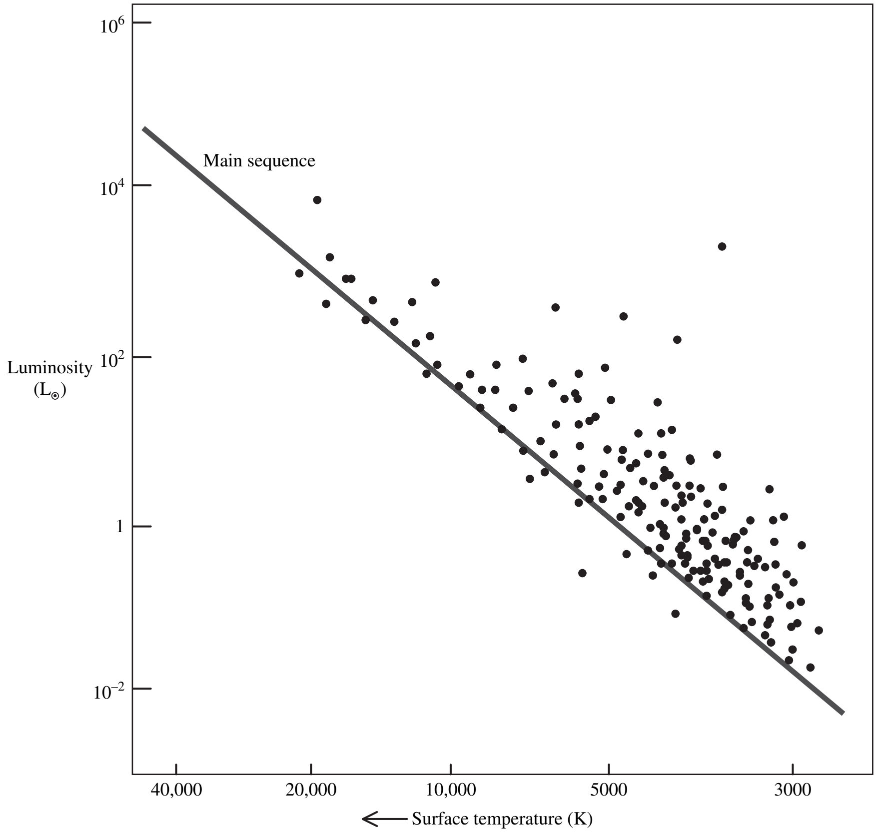


Figure 3.5. *H-R* diagram of star cluster NGC 2264.

sky, but surveys show that although well over a thousand clusters have been discovered, only a few are observed to be at distances greater than 25° above or below the galactic equator. Some parts of the sky are very rich in clusters—e.g., *Cassiopeia* and *Puppis*—and this is due to the absence of dust lying along these lines of sight, allowing us to see across the spiral plane of our Galaxy. Many of the clusters mentioned here actually lie in different spiral arms, and so as you observe them, you are actually looking at different parts of the spiral structure of our Galaxy.

I mentioned earlier that stars are not born in isolation. Nor are they born simultaneously. Recall that the more massive a star, the faster it contracts and becomes stable, thus joining the main sequence; this results in some clusters' having bright young O and B main-sequence stars, while at the same time containing low-mass members, which may still be in the process of gravitational contraction (for example, the star cluster at the center of the *Lagoon Nebula)*. In a few cases, the star production in a cluster is at a very early stage, with only a

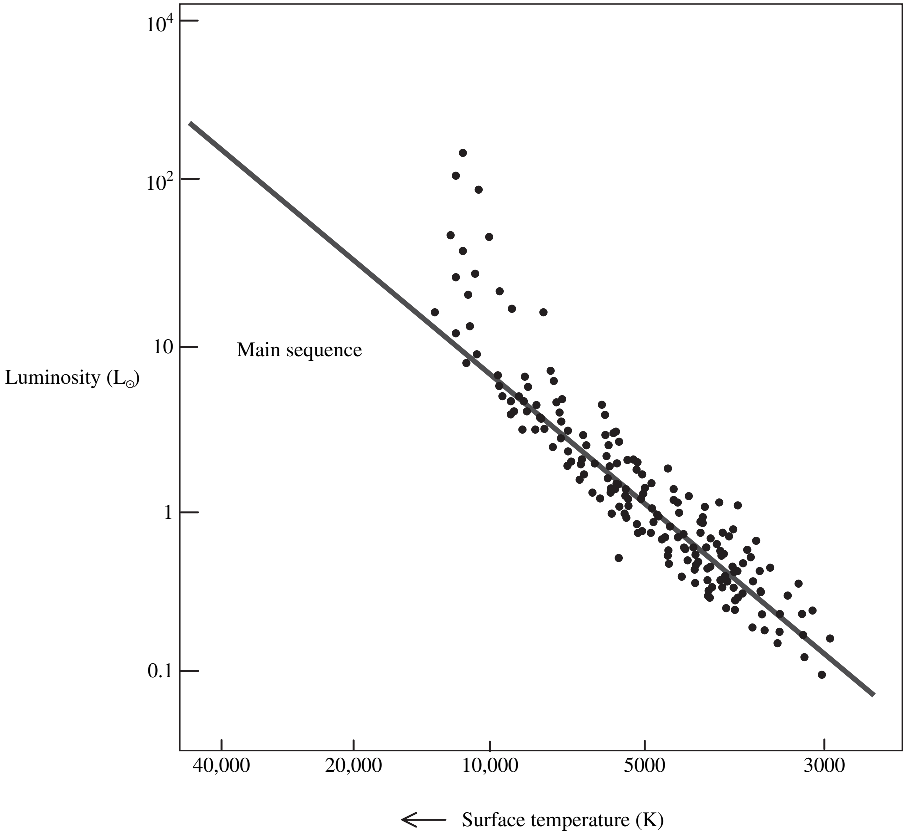


Figure 3.6. *H-R* diagram of the Pleiades star cluster.

few stars visible; the majority are still in the process of contraction and hidden within the interstellar cloud.

A perfect example of such a process is the open cluster within *Messier 42*, the *Orion Nebula*. The stars within the cluster, the *Trapezium*, are the brightest, youngest, and most massive stars in what will eventually become a large cluster containing many A-, F-, and G-type stars. However, the majority are blanketed by the dust and gas clouds and are only detectable by their infrared radiation.

As time passes, the dust and gas surrounding a new cluster will be blown away by the radiation from the O-type stars, resulting in the cluster's becoming visible in its entirety, such as in the case of the young cluster *Caldwell 76* in *Scorpius*.

Once a cluster has formed, it will remain more or less unchanged for at least a few million years, but then changes within the cluster may occur. Two processes are responsible for changes within any given cluster. The evolution of open clusters depends on both the initial stellar content of the group and the ever-pervasive pull of gravity. If a cluster contains O-, B-, and A-type stars, these stars will eventually become supernovae, leaving the cluster with slower-evolving, less-massive, and less-luminous members of type A and M stars. A famous example of such a cluster is *Caldwell 94*, the *Jewel Box* in *Crux,* which is the highlight of the southern sky, and, alas, unobservable to northern hemisphere observers. However, these, too, will become supernovae, with the result that the most luminous members of a cluster will, one by one, disappear over time. This does not necessarily mean the demise of a cluster, especially those that have many tens or hundreds of members. But some, which consist of only a few bright stars, will seem to meld into the background star field. However, even those clusters that have survived the demise of their brighter members will eventually begin to feel the effect of a force that pervades everywhere—the Galaxy's gravitational field. As time passes, the cluster will be affected by the influence of other globular clusters and the interstellar matter itself, as well as the tidal force of the Galaxy. The cumulative effect of all of these encounters will be that some of the less-massive members of the cluster acquire enough velocity to escape from the cluster. Thus, given enough time, a cluster will fade and disperse. (Take heart, as this is not likely to happen in the near future so that you would notice: the *Hyades* star cluster, even after having lost most of its K- and M-type dwarf stars, is still with us after 600 million years!).

For the amateur, observing open clusters is a very rewarding experience, as they are readily observable, from naked-eye clusters to those visible only in larger telescopes. Many of them are best viewed with binoculars, especially the larger clusters that are of an appreciable angular size. Furthermore, nearly all have double or triple stars within the cluster, and so, regardless of magnification, there is always something interesting to be seen.

From the preceding chapter, you know that color in observed stars is best seen when contrasted with a companion(s). Thus, an open cluster presents a perfect opportunity for observing star colors. Many clusters, such as *Pleiades*, are all a lovely steely blue color. On the other hand, *Caldwell 10* in Cassiopeia has contrasting bluish stars along with a nice orange star. Other clusters have a solitary yellowish or ruddy orange star along with fainter white ones, such as *Messier 6* in Scorpius. An often-striking characteristic of open clusters is the apparent chains of stars that are seen. Many clusters have stars that arc across apparently empty voids, as in *Messier41* in Canis Major.

Because open clusters display such a wealth of characteristics, different parameters are assigned to a cluster that describe its shape and content. For instance, a designation called the *Trumpler* type is often used. It is a three-part designation that describes the cluster's degree of concentration—that is, from a packed cluster to one that is evenly distributed, the range in brightness of the stars within the cluster, and finally the richness of the cluster from poor (fewer than 50 stars) to rich (more than 100). The full classification is:

Trumpler Classification for Star Clusters
Concentration

I	Detached—strong concentration of stars toward the center.
II	Detached—weak concentration of stars toward the center.
III	Detached—no concentration of stars toward the center.
IV	Poor detachment from background star field.

Range of brightness

1 Small range.
2 Moderate range.
3 Large range.

Richness of cluster

p Poor (with fewer than 50 stars).
m Moderate (with 50–100 stars).
r Rich (with more than 100 stars).
n Cluster within nebulosity.

Two points that can often cause problems need to be mentioned: the *magnitude* and *size* of the cluster. The quoted magnitude of a cluster may be the result of only a few bright stars, or, on the other hand, may be the result of a large number of faint stars. Also, the diameter of a cluster is often misleading, as in most cases it has been calculated from photographic plates, which, as experienced amateurs will know, bear little resemblance to what is seen at the eyepiece.

Although magnitudes and diameters may be quoted in the text, do treat them with a certain amount of caution.

In the descriptions given below, the first line lists the name, the position, and the approximate midnight transit time; the second line presents the visual magnitude (the combined magnitude of all stars in cluster), the object size in arcminutes ⊕, the approximate number of stars in the cluster (bear in mind that the number of stars seen will depend on magnification and aperture and will increase when large apertures are used, thus the number quoted is an estimate using modest aperture), the Trumpler designation, and the level of difficulty (based on the magnitude, size, and ease of finding the cluster).

3.4.1.1 Bright Star Clusters

Messier 41	**NGC 2287**	**$06^h47.0^m$**	**−20°44′**	Dec–**Jan**–Feb
4.5m	**⊕38′**	**70**	**II3 m**	**Canis Major**

Easily visible to the naked eye on clear nights as a cloudy spot slightly larger in size than the full moon. Contains blue B-type giant stars, as well as several K-type giants. Current research indicates that the cluster is about 100 million years old and occupies a volume of space 80 l.y. in diameter.

Caldwell 64	**NGC 2362**	**$07^h18.8^m$**	**−24°57′**	Dec–**Jan**–Feb
4.1m	**⊕8′**	**60**	**I3 p n**	**Canis Major**

A very nice cluster, tightly packed, and easily seen with small binoculars. The glare from *τCMa* tends to overwhelm the majority of stars, but the cluster becomes truly impressive with telescopic apertures; the bigger the aperture, the more stunning the vista. It is believed to be very young—only a couple of million years old—and thus has the distinction of being the youngest cluster in our Galaxy. Contains O- and B-type giant stars.

Messier 48	**NGC 2548**	**$08^h13.8^m$**	**−05°48′**	Dec**–Jan–**Feb
5.8m	**⊕55′**	**80**	**I3 r**	**Hydra**

Located in a rather empty part of the constellation Hydra, this is believed to be the missing Messier object. It is a nice cluster and can be viewed both in binoculars and small telescopes. In the former, about a dozen stars are seen, with a pleasing triangular asterism at its center, while the latter will show a rather nice but large group of about 50 stars. Many amateurs often find the cluster difficult to locate for the reason mentioned above, but also for the fact that within a few degrees of M48 is another nameless, but brighter, cluster of stars, which is often mistakenly identified as M48. Some observers claim that this nameless group of stars is in fact the correct missing Messier object, and not the one which now bears the name.

Messier 44	**NGC 2632**	**$08^h40.1^m$**	**+19°59′**	Dec**–Jan–**Feb
3.1m	**⊕95′**	**60**	**II2 m**	**Cancer**

A famous cluster called *Praesepe* (the Manger) or the *Beehive.* One of the largest and brightest open clusters from the viewpoint of an observer. An old cluster, about 700 million years, distance 500 l.y., with the same space motion and velocity as the *Hyades*, which suggests a common origin for the two clusters. A nice triple star, *Burnham 584*, is located within M44, located just south of the cluster's center. A unique Messier object in that it is brighter than the stars of the constellation within which it resides. Due to its large angular size in the sky, it is best seen through binoculars or a low-power eyepiece.

Caldwell 54	**NGC 2506**	**$08^h00.2^m$**	**−10°47′**	Dec**–Jan–**Feb
7.6m	**⊕7′**	**100**	**I2 r**	**Monoceros**

A nice rich and concentrated cluster best seen with a telescope, but one that is often overlooked due to its faintness, even though it is just visible in binoculars. Includes many 11th- and 12th-magnitude stars. It is a very old cluster, about 2 billion years, and contains several *blue stragglers*. These are old stars that nevertheless have the spectrum signatures of young stars. This paradox was solved when research indicated that the young-looking stars are the result of a merger of two old stars.

Messier 67	**NGC 2682**	**$08^h50.4^m$**	**+11°49′**	Jan**–Feb–**Mar
6.9m	**⊕30′**	**200**	**II2 m**	**Cancer**

Often overlooked because of its proximity to M44, it is nevertheless very pleasing. However, the stars which it is composed of are faint, and so in binoculars it will be unresolved and seen as a faint misty glow. At a distance of 2500 l.y. it is believed to be very old, possibly 9 billion years, and thus has had time to move from the Galactic Plane, the usual abode of open clusters, to a distance of about 1600 l.y. off the plane.

Caldwell 76	**NGC 6231**	**$16^h54.0^m$**	**−41°48′**	May**–Jun–**Jul
2.6m	**⊕14′**	**100**	**I3 p**	**Scorpius**

A superb cluster located in an awe-inspiring region of the sky. Brighter by 2.5 magnitudes than its northern cousins, the double cluster in *Perseus*. The cluster is full of spectacular stars: very hot and luminous O-type and B0-type giants and supergiants, a couple of *Wolf–Rayet* stars, and ξ^{-1} *Scorpii*, which is a B1.5 Ia extreme supergiant star with a luminosity nearly 280,000 times that of the Sun! The cluster is thought to be a member of the stellar association[14] *Sco OB1*, with an estimated age of 3 million years. A wonderful object to view in binoculars and telescopes, the cluster contains many blue, orange, and yellow stars. It lies between μ^{1+2} *Scorpii* and ξ^{-1} *Scorpii,* an area rich in spectacular views.

Trumpler 24	**Harvard 12**	**$16^h57.0^m$**	**−40°40′**	May–**Jun**–Jul
8.6m	**⊕60′**	**100**	**IV2 pn**	**Scorpius**

A loose and scattered cluster, set against the backdrop of the Milky Way. It is, along with nearby *Collinder 316*, the core of the *Scorpius OB1* stellar association.

Messier 7	**NGC 6475**	**$17^h53.9^m$**	**−34°49′**	May–**Jun**–Jul
3.3m	**⊕80′**	**80**	**I3 r**	**Scorpius**

An enormous and spectacular cluster. It presents a fine spectacle in binoculars and telescopes, containing more than 80 blue–white and pale yellow stars. It is only just over 800 l.y. away, but it is over 200 million years old. Many of the stars are around 6th and 7th magnitude and thus should be resolvable with the naked eye.

Messier 24[15]		**$18^h16.5^m$**	**−18°50′**	May–**Jun**–Jul
2.5m	**⊕95′ x 35′**			**Sagittarius**

Another superb object for binoculars. This is the *Small Sagittarius Star Cloud*, visible to the naked eye on clear nights, and nearly four times the angular size of the Moon. The cluster is in fact part of the *Norma Spiral Arm* of our Galaxy, located about 15,000 l.y. from us. The faint background glow from innumerable unresolved stars is a backdrop to a breathtaking display of 6th- to 10th-magnitude stars. It also includes several dark nebulae which adds to the three-dimensional impression. Many regard the cluster as truly a showpiece of the sky.

Messier 16	**NGC 6611**	**$18^h18.8^m$**	**−13°47′**	May–**Jun**–Jul
6.0m	**⊕22′**	**50**	**II3 mn**	**Serpens Cauda**

A fine large cluster easily seen with binoculars. It is about 7000 l.y. away, located in the *Sagittarius–Carina Spiral Arm* of the Galaxy. Its hot O-type stars provide the energy for the *Eagle Nebula*, within which the cluster is embedded.

Messier 25	**IC 4725**	**$18^h31.6^m$**	**−19°15′**	May–**Jun**–Jul
4.6m	**⊕32′**	**40**	**I3 m**	**Sagittarius**

Visible to the naked eye, this is a pleasing cluster suitable for binocular observation. It contains several star chains and is also noteworthy for small areas of dark nebulosity that seem to blanket out areas within the cluster, but you will need perfect conditions to appreciate these. Unique for two reasons: it is the only Messier object referenced in the *Index Catalogue* (IC), and it is one of the few clusters to contain a *cepheid*-type variable star—*U Sagittarii*. The star displays a magnitude change from 6.3 to 7.1 over a period of 6 days and 18 hours.

Messier 11	**NGC 6705**	**$18^h51.1^m$**	**−06°16′**	Jun–**Jul**–Aug
5.8m	**⊕13′**	**200**	**I2 r**	**Scutum**

Also known as the *Wild Duck Cluster*, this is a gem of an object. Although it is visible with binoculars as a small, tightly compact group reminiscent of a globular cluster, they do not do it justice. With telescopes, its full majesty becomes apparent. Containing many hundreds of stars, it is a very impressive cluster. It takes high magnification, as well, where many more of its 700 members become visible. At the top of the cluster is a glorious pale yellow-tinted star.

–	**IC 1396**	**$21^h39.1^m$**	**+57°30′**	Jul–**Aug**–Sep
3.7m	**⊕50′**	**40**	**II mn**	**Cepheus**

Although a telescope of at least 20 cm is needed to truly view this cluster, it is nevertheless worth searching for. It lies south of *Herschel's Garnet Star* and is rich but compressed. What makes this so special, however, is that it is cocooned within a very large and bright nebula.

Caldwell 13	**NGC 457**	**$01^h19.1^m$**	**+58°20**	Sep–**Oct**–Nov
6.4m	**⊕13′**	**80**	**I3 r**	**Cassiopeia**

This is a wonderful cluster and can be considered as one of the finest in Cassiopeia. Easily seen in binoculars as two southward-arcing chains of stars, surrounded by many fainter components. The gorgeous blue and yellow double, *φ Cass*, and a lovely red star, *HD 7902*, lie within the cluster. Located at a distance of about 8000 l.y., this young cluster is located within the *Perseus Spiral Arm* of our Galaxy.

Caldwell 14	**NGC 869**	**$02^h19.0^m$**	**+57°09′**	Sep–**Oct**–Nov
5.3m	**⊕29′**	**200**	**I3 r**	**Perseus**
	NGC 884	**$02^h22.4^m$**	**+57°07′**	
6.1m	**⊕29′**	**115**	**II2 p**	

The famous *Double Cluster* in *Perseus* is a highlight of the northern-hemisphere winter sky. Strangely, never catalogued by Messier. Visible to the naked eye and best seen using a low-power, wide-field optical system. But whatever system is used, the views are marvellous. *NGC 869* has about 200 members, while *NGC 884* has about 150. Both are composed of A-type and B-type supergiant stars with many nice red giant stars. However, the systems are dissimilar; NGC 869 is 5.6 million years old (at a distance of 7200 l.y.), whereas NGC 884 is younger at 3.2 million (at a distance of 7500 l.y.). But be advised that in astrophysics, distance and age determination are error prone! Also, it was found that nearly half the stars are variables of the type B, indicating that they are young stars with possible circumstellar discs of dust. Both are part of the *Perseus OB1 Association*[16] from which the *Perseus Spiral Arm* of the Galaxy has been named. Do not rush these clusters, but spend a long time observing both of them and the background star fields.

Messier 45	**Melotte 22**	**$03^h47.0^m$**	**+24°07′**	Oct–**Nov**–Dec
1.2m	**⊕110′**	**100**	**I3 r**	**Taurus**

Without a doubt, the sky's premier star cluster. The *Seven Sisters* or *Pleiades* is beautiful however you observe it—naked eye, through binoculars, or with a telescope. To see all the members at one go will require binoculars or a rich-field telescope. Consisting of more than 100 stars, spanning an area four times that of the full Moon, it will never cease to amaze people. It is often stated that from an urban location, 6 to 7 stars may be glimpsed with the naked eye. However, it may come as a surprise to many of you that it has 10 stars brighter than 6th magnitude, and that seasoned amateurs with perfect conditions have reported 18 being visible with the naked eye. It lies at a distance of 410 l.y., is about 20 million years old (although some report it as 70 million), and is the 4th-nearest cluster. *Messier 45* contains many stunning blue and white B-type giants. The cluster contains many double and multiple stars. Under perfect conditions with exceptionally clean optics, the faint nebula NGC 1435, the *Merope Nebula* surrounding the star of the same name (*Merope* – 23 Tauri), can be glimpsed and was described by W. Tempel in 1859 as "a breath on a mirror." However, this and the nebulosity associated with the other Pleiades are not, as they were once thought to be the remnants of the original progenitor dust and gas cloud. The cluster is just passing through an edge of the *Taurus Dark Cloud Complex*. It is moving through space at a velocity of about 40 kilometers a second, so by 32,000 AD, it will have moved an angular distance equal to that of the full Moon. The cluster contains the stars *Pleione, Atlas, Alcyone, Merope, Maia, Electra, Celaeno, Taygeta, and Asterope*. A true celestial showpiece.

Caldwell 41	**Melotte 25**	**$04^h27.0^m$**	**+16°00′**	Oct–**Nov**–Dec
0.5m	**⊕330′**	**40**	**II3 m**	**Taurus**

Also known as the *Hyades*. The nearest cluster after the *Ursa Major Moving Stream*, lying at a distance of 151 l.y. with an age of about 625 million years. Even though the cluster is widely dispersed both in space and over the sky, it nevertheless is gravitationally bound, with the more massive stars lying at its center. Best seen with binoculars due to the large extent of the cluster—over $5^{1/2^\circ}$. Hundreds of stars are visible, including the fine orange giant stars γ, δ, ε, and θ^{-1} *Tauri*. *Aldebaran*, the lovely orange K-type giant star, is not a true member of the cluster, but it is a foreground star only 70 l.y. away. Visible even from light-polluted urban areas—a rarity!

Collinder 69	–	**$05^h35.1^m$**	**+09°56′**	Nov–**Dec**–Jan
2.8m	**⊕65′**	**20**	**II3 pn**	**Orion**

This cluster surrounds the 3rd-magnitude star λ *Orionis* and includes φ^{-1} and φ^{-2} *Orionis*, both 4th-magnitude. Encircling the cluster is the very faint emission nebula *Sharpless 2–264*, only visible using averted vision and an OIII filter with extremely dark skies. Perfect for binoculars.

Messier 37	**NGC 2099**	**05^{h}52.4^m**	**+32°33′**	Nov–**Dec**–Jan
5.6m	**⊕ 20′**	**150**	**II1 r**	**Auriga**

The finest cluster in *Auriga*. Contains many A-type stars and several red giants. Visible at all apertures, from a soft glow with a few stars in binoculars to a fine, star-studded field in medium-aperture telescopes. In small telescopes using a low magnification, it can appear as a globular cluster. The central star is colored a lovely deep red, although several observers report it as a much paler red, which may indicate that it is a variable star. Visible to the naked eye.

Collinder 81	**NGC 2158**	**06^{h}07.5^m**	**+24°06′**	Nov–**Dec**–Jan
8.6m	**⊕ 5′**	**70**	**II3 r**	**Gemini**

Lying at a distance of 16,000 l.y., this is one of the most distant clusters visible using small telescopes, and lying at the edge of the Galaxy. It needs a 20 cm telescope to be resolved, and even then only a few stars will be visible against a background glow. It is a very tight, compact grouping of stars, and something of an astronomical problem. Some astronomers class it as intermediate between an open cluster and a globular cluster, and it is believed to be about 800 million years old, making it very old as open clusters go.

3.4.2 Stellar Associations and Streams

There exists another type of grouping of stars, which is much more ephemeral and spread over a large region of the sky, and although not strictly associated with star formation, it is, however, an integral part of star evolution. Furthermore, as this book is dealing with both the evolution *and* observational properties of stars, I think it wise to mention it here.

A stellar association is a loosely bound group of very young stars. They may still be swathed in the dust and gas cloud within which they formed, and star formation may still be occurring within the cloud. They differ from open clusters in their enormity, covering both a sizable angular area of the night sky and at the same time encompassing a comparably large volume in space. As an illustration of this huge size, the *Scorpius-Centaurus Association* is about 700 by 760 l.y. in extent, and it covers about 80°.

There are three types of stellar associations:

OB associations, containing very luminous O- and B-type main-sequence, giant, and supergiant stars.

B associations, containing only B-type main-sequence and giant stars but with an absence of O-type stars. These associations are just older versions of the OB association, and thus the faster-evolving O-type stars have been lost to the group as supernovae.

T associations, which are groupings of T Tauri-type stars. These are irregular variable stars that are still contracting and evolving toward being A-, F-, and G-type main-sequence stars. As they are still in their infancy, more often than not they will be shrouded in dark dust clouds, and those that are visible will be embedded in small reflection and emission nebulae (see Chapter 4).

The OB associations are truly enormous objects, often covering many hundreds of l.y. This is a consequence of the fact that massive O- and B-type stars can only be formed within the giant molecular clouds which are themselves hundreds of l.y. across. On the other hand, the T associations are much smaller affairs, perhaps only a few l.y. in diameter. In some cases, the T association is itself located within or near an OB association.

The lifetime of an association is comparatively short. The very luminous O-type stars are soon lost to the group as supernovae, and, as usual, the ever-pervasive gravitational effects of the Galaxy soon disrupt the association. The coherence and identity of the group can only exist for as long as the brighter components stay in the same general area of a spiral arm, as well as having a similar space motion through the Galaxy. As time passes, the B-type stars will disappear through stellar evolution, and the remaining A-type and later stars will now be spread over an enormous volume of space, and the only common factor among them will be their motion through space. At that point, the association is called a *stellar stream*. An example of such a stream and one that often surprises the amateur (it did me!) is the *Ursa Major Stream*. This is an enormous group of stars, with five central stars of Ursa Major (The Plough) being its most concentrated and brightest members. The stream is also known as *The Sirius Supercluster* after its brightest member. The Sun actually lies within this stream (more information about this fascinating stream can be found below).

3.4.2.1 Bright Stellar Associations and Streams

The Orion Association, 1600 l.y.

This association includes most of the stars in the constellation down to 3.5 magnitude, except for γ *Orionis* and π^3 *Orionis*. Also included are several 4th-, 5th-, and 6th-magnitude stars. The wonderful nebula M42 is also part of this spectacular association. Several other nebulae (including dark, reflection, and emission nebulae) are all located within a vast *Giant Molecular Cloud*, which is the birthplace of all the O- and B-type supergiant, giant, and main-sequence stars in Orion. The association is believed to be 800 l.y. across and 1000 l.y. deep. By looking at this association, you are in fact looking deep into our own spiral arm, which, incidentally, is called the *Cygnus-Carina Arm*.

The Scorpius-Centaurus Association, 550 l.y.

A much older, but closer association than the Orion association. It includes most of the stars of 1st, 2nd, and 3rd magnitude in Scorpius down through Lupus and Centaurus to Crux. Classed as a B-type association because it lacks O-type stars, its angular size on the sky is about 80°. It is estimated to be 750 × 300 l.y. in size, and 400 l.y. deep, with the center of the association midway between *α Lupi* and *ζ Centauri*. Its elongated shape is thought to be the result of rotational stresses induced by its rotation about the Galactic center. Bright stars in this association include *Ophiuchi*, *β*, *ν*, *δ* and *σ Scorpii*, *α*, *γ Lupi*, *ε*, *δ*, *μ* and *ε Centauri*, and *β Crucis*.

The Zeta Persei Association, 1300 l.y.

Also known as *Per OB2*, this association includes *ζ* and *ξ Persei*, as well as 40, 42, and *o Persei*. The California nebula, *NGC 1499*, is also within this association.

The Ursa Major Stream, 75 l.y.

As briefly mentioned earlier in this section, this stream includes the five central stars of the Plough. It is spread over a vast area of sky, approximately 24°, and is about 20 × 30 l.y. in extent. It includes as members *Sirius* (*α Canis Majoris*), *α Coronae Borealis*, *δ Leonis*, *β Eridani*, *δ Aquarii*, and *β Serpentis*. Due to the predominance of A1 and A0 stars within the association, its age has been estimated at 300 million years.

The Hyades Stream

There is some evidence (although it is not fully agreed upon) that the Ursa Major stream is itself within a much older and larger stream. This older component includes *M44, Praesepe* in Cancer, and the *Hyades* in Taurus, with these two open clusters being the core of a very large but loose grouping of stars. Included within this are *Capella* (*α Aurigae*), *α Canum Venaticorum*[1], *δ Cassiopeiae,* and *λ Ursae Majoris*. The stream extends to over 200 l.y. beyond the Hyades star cluster, and 300 l.y. behind the Sun. Thus, the Sun lies within this stream.[1]

The Alpha Persei Stream 540 l.y.

Also known as *Melotte 20*, this is a group of about 100 stars, including *α Persei*, *ψ Persei, 29*, and *34 Persei*. The stars *δ* and *ε Persei* are believed to be among its most outlying members, as they also share the same space motion as the main groups of stars. The inner region of the stream is measured to be over 33 l.y. in length, the distance between 29 and *ψ Persei.*

3.5 Star Formation Triggers

We have seen how stars are formed from clouds of dust and gas, and how these clouds clump together under the force of gravity to form protostars. In addition, the evolution of a protostar to a main sequence depends on the initial mass of the protostar and so determines where it will arrive on the main sequence. But one thing we have not yet addressed is what *causes* a protostar to form in the first place! This is the topic of the final part of this section.

The mechanisms that provide the "triggers" for star formation have three very disparate origins:

- The spiral arms of a galaxy
- Expanding HII regions
- Supernovae

We mentioned earlier in this section that the spiral arms of galaxies are a prime location for star formation because the gas and dust clouds temporarily "pile up" as they orbit around the center of a galaxy.[17] In such a spiral arm, the molecular clouds are compressed as it passes through the region. In the molecular cloud's densest regions, vigorous star formation can then occur.

Massive stars, such as O-type and B-type stars, emit immense amounts of radiation, usually in the ultraviolet part of the spectrum. This, in turn, causes the surrounding gas to ionize, and an HII region is formed within the larger molecular cloud. The strong stellar winds and ultraviolet radiation that O- and B-type stars possess can carve out a cavity within the molecular cloud into which the HII region expands. The stellar wind is moving at such a high velocity that it is supersonic (i.e., faster than the speed of sound in that particular region). A shock wave associated with this supersonically expanding HII region then collides with the rest of the molecular cloud. In doing so, it compresses the cloud, and so further star formation occurs. The new O- and B-type stars that result from this induce further star formation, but at the same time, the precursor O- and B-type stars that originally started the procedure may well have dispersed by this point. In this manner, an OB association "devours" a molecular cloud, leaving older stars in its wake.

The Orion Nebula is one example of such a mechanism, where the four stars of the Trapezium are ionizing the surrounding material. The nebula itself is at the edge of a giant molecular cloud, some $500,000\,M_{\odot}$.

The final mechanism which is believed to induce further star formation is a *supernova*. As we shall see in later sections, a supernova is the death of a star and results in a catastrophic explosion, usually blowing the star to bits! What is important to us at this stage is that the outer layers of the star are ejected into space at incredible speeds, may be several thousand kilometers per second! This shock wave, an expanding shell of material, will be moving at supersonic velocities and, in a similar manner as mentioned above, will impact the material in the interstellar medium, and in doing so will compress and heat it. In doing so, it will stimulate further star formation.

We have now covered the amazing processes involved in star formation, from vast clouds of dust and gas to glowing spheres of nuclear fusion—the birth of a star. However, do not think that we know all there is to know about star birth because we do not! For instance, a spiral arm that passes through a giant molecular cloud tends to produce giant O- and B-type stars, whereas the stars induced by supernovae shock waves are predominantly A-, F-, G-, and K-type stars. Also, in our home Galaxy, there often seems to be a lot of dust associated with star formation that shields the newly born stars from the destructive effects of ultraviolet radiation from other hot stars that are close by. However, in a nearby galaxy—*The Large Magellanic Cloud*[18] (LMC)—it has been observed that young OB associations have hardly any dust at all! Nevertheless, what we do know is amazing and involves mechanisms from star death to the rotation of galaxies.

Most of the stars that we observe in the night sky have one thing in common: they are on the main sequence. There are, of course, exceptions. *Betelgeuse* has left the main sequence and has become a red giant star; the hydrogen-burning at the center of its core has stopped, and now helium is burning by fusion processes. Also, *Sirius B* has evolved far from the main sequence and has become a white dwarf star, with no nuclear fusion occurring within it. But for the large majority, the main sequence is a stable time, with only small changes in mass and luminosity occurring. However, as a star ages, changes occur in the way energy is formed, and this in turn affects its size and thus its luminosity, and so the star leaves the main sequence to begin the next phase of its life. The remaining material in this chapter will look at these periods in a star's life, whether it is a small, low-mass, and cool star or a bright, high-mass, and hot star.

Before we look at the many types of stars on the main sequence, it will be helpful (and indeed necessary) for us to look at the nearest star to us—the Sun. After all, astronomers have been studying the closest star to us for a long time now, and so we have a good idea of what is going on.[19] In looking at the Sun in detail, we will be able to see how energy is produced in the core and how this energy is transported to the surface, and then to us on the Earth! We can then look at other stars and compare and contrast them with what we know about the Sun.

3.6 The Sun—The Nearest Star

In this section, we shall look at the Sun bearing in mind it is a star on the main sequence. Therefore, I shall not discuss in any depth topics such as sunspots, the sunspot cycle, and so on.[20] Instead, we will concentrate on the internal structure, the means of energy production, and the manner in which energy is transported from its source to us on Earth. With this approach, it is possible to use the Sun as a benchmark with which to compare stars of differing size.

Due to the advances not only in astronomy but in computing as well, astronomers have been able to determine the conditions inside the Sun by solving several equations that describe how the temperature, mass, luminosity, and pressure change with distance from the center of the Sun. To solve them, we need to know the mechanisms by which energy is transported throughout the Sun, either by radiation or convection, the chemical composition of the Sun, and the rate of energy production at any specific distance from its center. Now although the equations are simple to solve, computers are needed, so we will just say that the results seem to match the observations, which is always a good test for any theory.

3.6.1 From the Core to the Surface

The Sun's internal structure is shown in Figure 3.7. The visible surface of the Sun, called the photosphere, has a temperature of about 5800 K, and although it may look like a well-defined surface from the Earth, it is in fact a gas less dense than the Earth's atmosphere. Both the density and temperature increase steadily as we progress from the surface to the core. Beneath the photosphere is a very turbulent area called the *convection zone*, where energy generated in the core travels upward, transported by rising columns of hot gas and the falling of cool gas. This process is called *convection*. So the photosphere is in fact the top of the convection zone. Descending deeper through the convection zone, the pressure and density increase quite substantially, along with the temperature. The density is far greater than that of water, but remember that we are still talking about gas, albeit one in a very strange state. A gas under these extreme conditions of temperature and/or pressure is usually called *plasma*.[21] The temperature in this region is about 2 million K, and the solar plasma absorbs the photons.

About one-third of the way down to the center, the very turbulent convection zone gives way to the more stable plasma of the *radiation zone*. Here the energy is transported outward primarily by photons of X-ray radiation. The temperature in this region is now about 10,000,000 K. At the central region, the core of the Sun, the temperature is now 15,000,000 K, and it is here that hydrogen is being transformed to helium. The pressure in this region is nearly 200 billion times the surface pressure found on the Earth. The central temperature and pressure are both impressive, with the core compressed to a density of about 150,000 kg m^3, which is about 150 times the density of water. It may come as a surprise to some people that essentially all of the Sun's energy is produced in the inner 25% of its radius, which corresponds to about 1.5% of its volume. This is a consequence of the very acute temperature sensitivity of nuclear reactions. If we were to actually go to a point about 1/4 the distance from the center of the Sun to its surface, the temperature would have fallen to about 8,000,000 K, and at

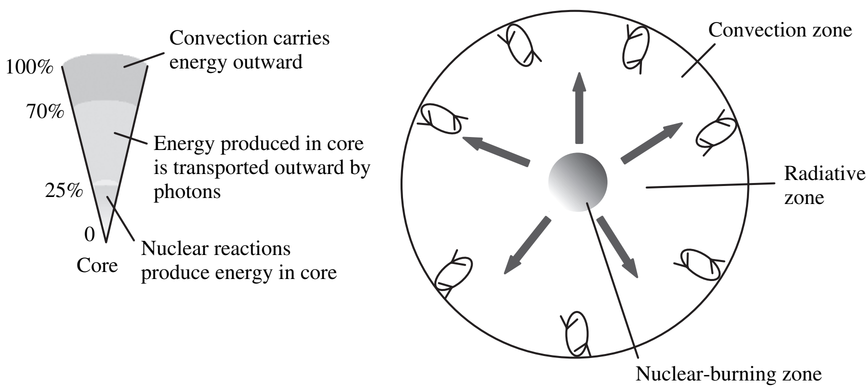


Figure 3.7. The internal structure of the Sun.

this lower temperature nuclear fusion energy production would have fallen to practically zero. So, virtually no energy is produced beyond the inner 25% of the solar radius.

At the surface of the Sun, each kilogram of gas contains about 71% hydrogen, whereas in the core, the percentage of hydrogen will be much lower, around 34%. The reason for this is obvious—hydrogen has been the fuel for nuclear fusion for the past 4.6 billion years. The total power output of the Sun, which is its luminosity, is a staggering 3.8×10^{26} joules per second. This may not mean much to most of us, but if we could somehow capture all of this energy, for even one second, it would be sufficient to meet all current energy demands for the human race for the next 50,000 years! But remember, only a tiny fraction of this reaches the Earth, as it is all dispersed *in all directions* into space.

The current model of energy production in the Sun is that in which nuclear fusion is the generator. It is a source so efficient that the Sun will shine for 10 billion years, and as it is only 4.6 billion years old at the moment, it has a long way to go! This current model of solar-energy generation means that the Sun's size will generally be stable, maintained by a balance between the competing forces of gravity pulling inward and pressure pushing outward. This balance between forces is called *hydrostatic equilibrium* (or sometimes *gravitational equilibrium*). What this means is that at any given point within the Sun, the weight of the overlying material is supported by the underlying pressure. You may think that this is a simple concept, and so it is, but it maintains the integrity of the Sun, as well as most stars in the universe. When one or the other of the forces gains the upper hand, however, the consequences are spectacular, as we shall see in a later section. The hydrostatic equilibrium in the Sun means the pressure increases with the depth; this makes the Sun extremely hot and dense in its core.

The efficiency with which the energy is transported outward by radiation is strongly influenced by the opacity of the gas through which the photons flow. The opacity describes the ability of a substance to stop the flow of photons. For instance, when the opacity is low (think of it as a clear day), photons are able to travel much greater distance between emission and re-absorption than when the opacity is high (a foggy, hazy day). If opacity is low, the transportation of energy by photons is very efficient. But when the opacity is high, the efficiency is reduced, which leads to an inefficient flow of energy and a higher rate of temperature decline.

3.6.2 The Proton-Proton Chain

To explain the Sun's energy, we need a process that involves the most abundant element in the Sun, hydrogen. The fusion of hydrogen into helium was first proposed in 1920 by the British astronomer A. S. Eddington, although the details were not fully understood until 1940.

Hydrogen, which is the lightest element, has a nucleus consisting of just one proton. The nucleus of helium, however, has four nuclear particles—two protons and two neutrons. So four hydrogen nuclei are needed to make one helium nucleus. But we cannot expect four protons to collide and instantly make a helium nucleus. This is unlikely to happen, as it has never happened before—not even once—in the history of the universe. What happens instead is a series of reactions involving two reactions at a time. This series of reactions is called the *proton-proton chain*.[22] The reactions begin with an interaction between two protons that must come within 10^{-15} meters of each other for a nuclear reaction to occur. There is a small problem, however, as protons are positively charged, and, just like magnets, repel each other. The result of this mutual repulsion is that most collisions between protons do not result in any reaction; instead, the two protons deflect each other and move apart. At room temperature, there is absolutely no possibility that two protons would collide with enough energy to get close enough to instigate a reaction.

So, for any reactions to occur, we need conditions that will allow protons to move at very high velocities; these conditions exist in the center of the Sun (and, of course, stars). At the core of the Sun, the temperature is 15 million K, and a typical proton will be travelling at about 1 million kilometers per hour. But even at this fantastic speed, the likelihood of a reaction occurring is very small. If we could watch a single proton to see how long it would take before it eventually reacted with another proton in nuclear fusion, we would be waiting for about 5 billion years! The important point here is that there are so many protons in the Sun's core, every second 10^{34} of them can undergo a reaction.

The sequence of steps in the proton-proton chain is shown in Figure 3.8.

Step 1: Two protons fuse to form a nucleus consisting of one proton and one neutron. This is the isotope of hydrogen called *deuterium* (^{2}H). The other products formed are a positively charged electron, called a *positron* (β^+), and a *neutrino* (ν), a minuscule particle with a tiny mass. The positron

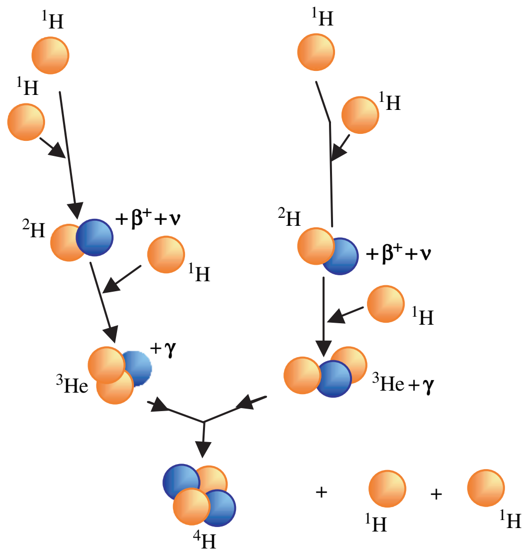


Figure 3.8. The reactions of the proton-proton chain.

does not last long, however; it soon meets up with an ordinary electron, and the result is the creation of two gamma rays that are rapidly absorbed by the surrounding gas, which consequently heats up. What happens to the neutrino? We shall discuss that later.

Step 2: The deuterium now fuses with a proton, producing a helium nucleus (^3He) and gamma rays. The ^3He nucleus consists of two protons and one neutron, whereas an ordinary helium nucleus has two protons and two neutrons. This step of producing ^3He from a deuteron occurs very rapidly, so that a typical deuteron in the core of the Sun will survive for only 4 seconds before reacting with a proton.

Step 3: Usually, the final reaction in the proton-proton chain requires the addition of another neutron to the ^3He nuclei, thereby making normal ^4He. This final step can proceed in several ways, with the most common involving a collision of two ^3He nuclei. Each of these ^3He nuclei resulted from a prior, separate occurrence of step 2 somewhere else in the core. The final result is a normal ^4He nucleus and two protons. On average, a ^3He nucleus must wait 4 million years before it participates in this reaction.

The symbol ν indicates a neutrino, the β^+ indicates a positron, and γ indicates a photon. The orange sphere represents protons, and blue indicates neutrons.

The net result of the chain of reaction is:

$$6\,^1H \rightarrow {}^4He + 2\,^1H + 26.72\,\text{MeV}$$

Although it takes six protons to make one helium nucleus, there is a net loss of only four protons because two are regenerated in the final step. Because the six protons are more massive than the two protons and a helium nucleus, mass is lost in the proton-proton chain and converted to energy. Each resulting ^4He nucleus has a mass that is slightly less than the combined mass of the four protons that created it (by about 0.7%). The energy produced by a single proton-proton chain reaction is 26.27 MeV, and although the units are unfamiliar to you, this converts to about one ten-millionth of the amount of energy needed to lift a drop of water. As you can see, this is not a lot of energy; overall, however, the Sun converts about 600 million tons of hydrogen into 596 million tons of helium every second. The *missing* 4 million tons of matter are converted to energy in accordance with the famous equation formulated by Einstein: $E = mc^2$. The neutrinos carry off about 2% of this energy and rarely interact with matter and so pass straight out into space. The remaining energy emerges as kinetic energy of the nuclei and as radiative energy of the gamma rays.

Box 3.1: Mass and Energy Conversion in the Sun

It is easy to calculate how much mass the Sun loses through nuclear fusion. First let us look at the input and output masses of the proton-proton chain A single proton has a mass of 1.6726×10^{-27} kg, so four protons have a mass of 6.693×10^{-27} kg.

A single ^{4}He nucleus has a mass of only 6.645×10^{-27} kg, which is slightly less than the mass of four protons. In other words:

$$6.69 \times 10^{-27}\,\text{kg} - 6.643 \times 10^{-27}\,\text{kg} = 4.8 \times 10^{-29}\,\text{kg}$$

This is only 0.7% or 0.007 of the original mass, so if 1 kg of hydrogen fuses, the resulting helium weighs 993 grams, and 7 grams of mass are turned into energy. To calculate the amount of energy for a single reaction, let us use Einstein's famous equation, $E = mc^2$.

$$E = mc^2 = \left(4.8 \times 10^{-29}\,\text{kg}\right)\left(3.0 \times 10^8\,\text{ms}^{-1}\right)^2 = 4.3 \times 10^{-12}\,\text{joules}$$

This is the tiny amount of energy created by the formation of one helium atom. It is so small, it would only power a 10-watt light bulb for half a trillionth of a second.

Let us now see how much total energy is produced when hydrogen is converted to helium every second. We know that only 0.7% of the mass of hydrogen is fused:

$$E = mc^2 = (0.7\,\text{kg})\left(3.0 \times 10^8\,\text{ms}^{-1}\right)^2 = 6.3 \times 10^{14}\,\text{joules}$$

However, the Sun's luminosity is 3.9 10^{26} J/s, thus hydrogen must be consumed at a rate:

$$\frac{\left(3.9 \times 10^{26}\ \text{joules per second}\right)}{\left(6.3 \times 10^{14}\ \text{joules per second}\right)} = 6 \times 10^{11}\,\text{kg/s}$$

So the Sun fuses 600 million metric tons of hydrogen each second, with 596 tons fused into helium and the remaining 4 million becoming energy.

3.6.3 Energy Transport from the Core to the Surface

Energy produced in the central region of the Sun flows outward toward the surface. If the Sun were transparent, the photons, or gamma rays, emitted by the extremely hot gases in the core would travel straight out at the speed of light, 2 seconds after being emitted. The Sun's gases, however, are not very transparent, and so a typical photon only travels about 10^{-6} meters before it is re-absorbed. In being absorbed, it heats up the surrounding gases, which in turn emit photons, which are then subsequently re-absorbed. The emitted photon will not necessarily be emitted in an outward direction but rather a totally random direction, which means that at least 10^{25} absorptions and re-emissions occur before energy reaches the surface. This slow, outward migration of photons is often called a *random walk*.

This process means that there is a considerable time delay before energy produced at the core reaches the surface. On an average, about 170,000 years will pass before energy created at the core eventually reaches the surface.[23]

Furthermore, the energy produced in one second does not erupt from the surface all in one go; it appears that it is radiated from the surface over a period of more than 100,000 years. Some energy appears in about 120,000 years, while other energy takes 220,000 years. But the bulk of it is emitted after 170,000 years.

This tells us two things about the Sun. First, when we observe the light emitted by the Sun, we learn nothing about what is going on in the core *at that moment*. All we can say is that energy was created in the core thousands of years ago. The second point is that if energy generation were to suddenly cease in the core for, say, a day, or even a hundred years, we would not notice it because by the time the energy flowed to the surface, it would have been averaged out over more than 100,000 years. This implies that the brightness of the Sun is very insensitive to changes in the energy production rate.

The above processes occur in some form or other in many of the stars on the main sequence. As we shall see, more massive stars carry their energy outward in a different manner, and the energy is created in a slightly different way. We shall now look at other stars and how they are placed on the main sequence.

Observing the Sun is a very popular pastime for amateur astronomers, but let me say now that you should NEVER OBSERVE, OR EVEN LOOK AT, THE SUN WITH THE NAKED EYE OR THROUGH A TELESCOPE. It is exceedingly dangerous, and you must have specially made equipment to do so. So do not do it. Instead, project the Sun onto a card. There are several excellent books on solar observing, and I highly recommend a very recent one by Chris Kitchin, called "Observing the Sun."

3.7 Binary Stars and Stellar Mass

3.7.1 Binary Stars

Binary stars, or as they are sometimes called, double stars, are stars that may appear to the naked eye to be just one star, but on observation with either binoculars or telescopes resolve themselves into two stars. Indeed, some apparently single stars turn out to be several stars! Many appear as double stars due to their position in the same line of sight as seen from the Earth, and these are called *optical doubles*. It may well be that the two stars are separated in space by a vast distance.

Others, however, are actually gravitationally bound and may orbit around each other over a period of days, or even years. These systems are the ones we will discuss here.[24]

The classification of some binary stars is quite complex. For instance, many cannot be resolved by even the largest telescopes and are called *Spectroscopic Binaries*, the double component only being fully understood when the spectra are analyzed. Others are *Eclipsing Binaries,* such as *Algol* (β Persei), where one star moves during its orbit in front of its companion, thus brightening and dimming the light observed. A third type is the *Astrometric Binary*, such as Sirius (α Canis Majoris), where the companion star may only be detected by its influence on the motion of the primary star. As this book is concerned with objects that can be observed visually, I will concentrate on binary stars that are physically associated and can be split with either the naked eye or with the use of some sort of optical equipment.

What makes binary stars so important to astronomers is that by observing their motion,[25] as they dance around each other, it is possible to determine their mass. This is, of course, vitally important in determining the evolutionary processes of stars.

Terminology must now be introduced that is specific to visual binary star observation. The brighter of the two stars is usually called the *primary* star, while the fainter is called the *secondary* (in some texts it may be called the companion, and both terms will be used throughout this book). This terminology is employed regardless of how massive either star is or whether the brighter is in fact the less luminous of the two but simply appears brighter.

Perhaps the most important terms used in visual binary star work are the *separation* and *position angle* (PA). The separation is the angular distance between the two stars, usually in seconds of arc, and is measured from the brighter star to the fainter. The position angle is a somewhat more difficult concept to understand. It is the relative position of one star, usually the secondary, with respect to the primary, and it is measured in degrees, with 0° at due north, 90° at due east, 180° at due south, 270° at due west, and back to 0°. It is best described by an example: using Figure 3.9, the double star γ Virginis, with components of magnitude 3.5 and 3.5, has a separation of 1.8″ (arcsecs) at a PA of 267°

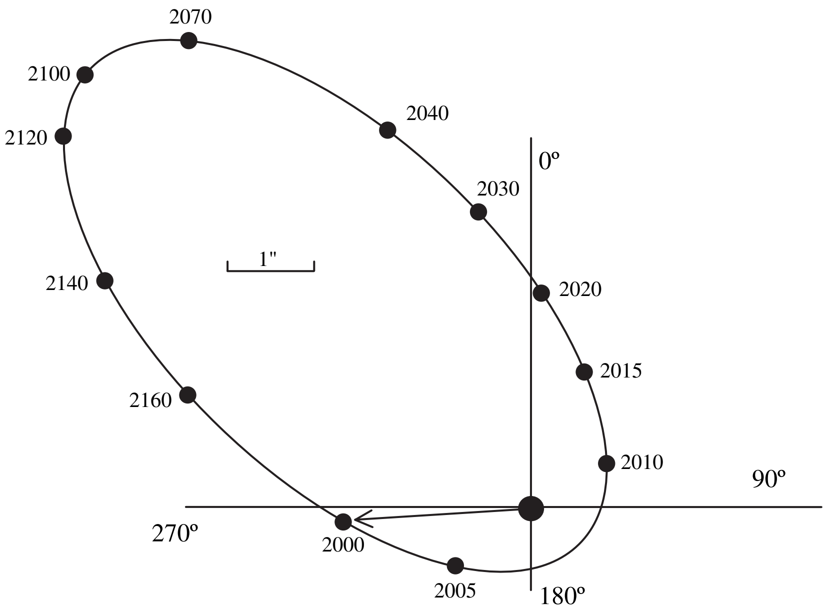


Figure 3.9. Separation and position angle of γ Virginis.

(epoch 2000.0). Note that the secondary star is the one always placed somewhere on the orbit, the primary star is at the center of the perpendicular lines, and the separation and PA of any double star are constantly changing and should be quoted for the year observed. Some stars (where the period is very long) will have no appreciable change in PA for several years; others, however, will change from year to year.

It is worth mentioning again that although your optical equipment, including your eyes, should in theory be able to resolve many of the binaries listed here,[26] there are several factors that will constrain the resolution (e.g., the seeing conditions, light pollution, dark adaption, your temperament, etc.). Thus, if you cannot initially resolve a double star, do not despair, but move onto another and return to the one in question at another date. Also recall that the colors ascribed to a star will not necessarily be the colors you see; they are just indicators of the general color, and in fact, as you will see from the text, many observers disagree on several stars' colors.

Presented below is a brief list of several stars that will, as an initial indicator, help you to determine the resolution of both yourself and your binoculars/telescope.[27] All of the positions quoted are for the primary star.

3.7.1.1 Visual Binary Stars

μ Canis Majoris	**ADS 5605**	**$06^h56.1^m$**	**−14°03′**	**January 4**
5.3, 8.6 m	**P.A. 340°;**	**Sep.3.0″**	**Spec.G5**	**moderate**

Two stars of differing brightness that nevertheless present a glorious double of orange and blue.

ξ Ursae Majoris	**ADS 8119**	**$11^h18.2^m$**	**+31°32′**	**March 12**
4.3, 4.8 m	**P.A.273°;**	**Sep.1.8″**	**Spec. G0**	**very difficult**

Discovered by William Herschel in 1780, this is a close pair of pale yellow stars. It also has the distinction of being the first binary system to have its orbit calculated by Savary in 1828. Both components are also spectroscopic binaries.

ζ Ursae Majoris	**ADS 8891**	**$13^h23.9^m$**	**+54°56′**	**April 12**
2.3, 4.0 m	**P.A.152°;**	**Sep.14.4″**	**Spec. A2 A2**	**very easy**

Part of the famous double *Mizar* and *Alcor* (80 *U*Ma). Visible to the naked eye. Nice in binoculars. A small telescope will resolve Mizar's 4th-magnitude companion. Alcor and both members of Mizar are themselves spectroscopic binaries. Thus, there are six stars in the system. Mizar also has several other distinctions: the first double to be discovered by telescope (by Riccioli in 1650), the first to be photographed (by Bond in 1857), and the first spectroscopic binary to be detected (by Pickering in 1889).

α CVn	**ADS 8706**	**$12^h56.0^m$**	**+38°19′**	**April 5**
2.9, 5.5 m	**P.A.229°;**	**Sep.19.4″**	**Spec.A0**	**easy**

Also known as *Cor Caroli*, the stars of this system are separated by a distance equivalent to 5 solar system widths—770 astronomical units! The two stars are yellowish in small instruments; however, with large aperture, subtle tints become apparent and have been called flushed white and pale lilac or pale yellow and fawn!

ε Boötis	**ADS 9372**	**$13^h45.0^m$**	**+27°04′**	**April 18**
2.5, 4.9m	**P.A.339°; Sep. 2.8″**		**Spec. K0 A0**	**moderate**

Also known as *Mirak*. A wonderful contrast of gold and green stars has also been reported to be yellow and blue. Difficult with apertures of about 7.5 cm, and even a challenge for beginners with apertures of 15.0 cm. With small telescopes, a high power is needed to resolve them.

β Lyrae	**ADS 11745**	**$18^h50.1^m$**	**+33°22′**	**July 4**
3.4_v, 8.6m	**P.A.149°; Sep. 45.7″**		**Spec. B9**	**easy**

This pair of white stars is a challenging double for binoculars. β^1 is also an eclipsing binary. A fascinating situation occurs due to the gravitational effects of the components of β^1: the stars are distorted from their spherical shapes into ellipsoids.

β Cygni	**ADS 12540**	**$19^h30.7^m$**	**+27°58′**	**July 14**
3.1, 5.1m	**P.A.54°; Sep. 34.4″**		**Spec. K3 B8**	**easy**

Thought by many to be the finest double in the skies, Albireo is a golden-yellow primary and blue secondary against the backdrop of the myriad of fainter stars of the Milky Way. Easy to locate at the foot of the Northern Cross.

ε Lyrae	**ADS 11635**	**$18^h44.3^m$**	**−39°40′**	**July 2**
5.4, 6.5m	**P.A. 357°; Sep. 2.6″**		**Spec. A2 F4**	**easy/moderate**
5.1, 5.3m	**P.A. 94°; Sep. 2.3″**			**easy/moderate**

The famous *Double-Double*, easily split, but to resolve the components of each star, ε^1 (magnitude 4.7) and ε^2 (magnitude 4.6), requires a high power. The stars themselves are at a P.A. 173°, separated by 208″, which is near the naked-eye limit, and some keen-eyed observers report being able to resolve them under perfect seeing conditions. However, there is fierce debate among amateurs—some say the double is difficult to resolve, others the opposite. All stars are white- or cream–white-colored. A highlight of the summer sky.

61 Cygni	**ADS 14636**	**$21^h06.9^m$**	**−38°45′**	**August 8**
5.2, 6.0 m	**P.A. 150°; Sep. 30.3″**		**Spec. K5 K7**	**easy**

Best seen with binoculars (but sometimes a challenge, if conditions are poor), which seem to emphasize the vibrant colors of these stars, both orange–red. Famous for being the first star to have its distance measured by the technique of parallax. The German astronomer Friedrich Bessel determined its distance to be 10.3 l.y.; modern measurements give a figure of 11.36. Also has an unseen third component, which has the mass of 8 Jupiters, and a very large proper motion.

α Ursae Minoris	**ADS 1477**	**$02^h31.8^m$**	**+89°16′**	**October 29**
2.0, 8.2m		**P.A. 218°; Sep.18.4″**	**Spec. F8**	**easy**

Possibly the most famous star in the sky. *Polaris*, or the *Pole Star,* is located less than a degree from the celestial pole and is a nice double consisting of a yellowish primary and a faint whitish-blue secondary. The primary is also a Population II cepheid variable and a spectroscopic binary. Although claims have been made to the effect that the system can be resolved in an aperture as small as 4.0 cm, at least 6.0 cm will be required to split it clearly

o^2 Eradini	**ADS 3093**	**$04^h15.2^m$**	**−07°39′**	**November 24**
4.4, 9.5m	**P.A.104°; Sep. 83″**		**Spec. WD**	**easy/moderate**

A challenge to split with binoculars. What makes this system so interesting is that the secondary is the brightest *white dwarf* star visible from Earth.

3.7.2 The Masses of Orbiting Stars

It may come as no surprise to you that the mass of a star can be determined. However, the question that needs to be asked is "how"? Well, usually, we need to use binary stars, as well as the laws of Kepler and Newton.

Kepler's law, which demonstrates how the time required for a planet orbiting the Sun is related to its distance from the Sun, can be modified to describe the motion of any two bodies that orbit around each other. The person who first did this was the great Isaac Newton. To find the mass of the stars in a visual binary, we must first determine their orbits by observing them over several years. This might take a few years, or even tens of years, but eventually we can determine the time needed for one star to completely orbit the other. This period of time is called P. By using a plot of the orbit, and forearmed with the system's distance from the Sun, we can then measure the semimajor axis,[28] a, of one star from the other. An important point to note here is that this method only gives us the combined mass of the stars, not their individual masses. To achieve that, we need to go one step further.

From the above description, we can easily determine the combined masses of two stars orbiting each other. To determine individual stellar masses, however, we determine how much one star moves relative to the other. For instance, if one star is much more massive than the other, then it will hardly move at all relative to the less-massive star; the less-massive star will do all of the orbiting in the system in a manner reminiscent of planets orbiting the Sun. To be accurate, we should really say that the stars (and, incidentally, the planets and Sun) orbit about their common center of mass, or center of gravity. In fact, they "wobble."[29]

The masses of stars are not so similar to that of, say, the Sun and Jupiter, where 99% of the mass is in the Sun, so they orbit the center of mass that is more or less equidistant from both of them. This center of mass is found along a line joining the two stars at a position that depends on the stars' masses. Think of it as the balance point on a child's see-saw. If one star is four times as massive as the other, the balance point will be four times closer to the more massive star. If the two stars have mass M_A and M_B, their distances from the center of mass (the balance point) are a_A and a_B,[30] with the larger mass having the smaller distance from the center of mass. So, for example, if the two stars have equal mass, or $M_A = M_B$, then $a_A = a_B$, and they orbit a point that is exactly halfway between them. On the other hand, if star B is four times less massive than star $A(M_B = 1/4 \times M_A)$, star B orbits four times farther from the center of mass than star A $(a_B = 4 \times a_A)$. Again, using the image of a see-saw, an adult weighing four times as much as a child must sit four times closer to the pivot as a child.

In this manner, stellar masses can be determined, and using sophisticated techniques, the masses of double-star systems that cannot be optically resolved can also be measured. Using these and other techniques, we have determined that stellar mass ranges from about 0.08 $M_\odot$ to 50 $M_\odot$. Of course, there are larger stars, but these are few and far between.

Box 3.2: Determining Stellar Mass

Consider the orbits of the double-star system of Sirius A and Sirius B.

The two stars have an orbital period, P, of 50.1 years and an average semimajor axis, a, of 19.6 astronomical units. To determine their combined mass, $M_A + M_B$, we use the modified form of Kepler's Law:

$$M_A + M_B = \frac{a^3}{P^2}$$

Inserting the measured values for P and a, we get:

$$M_A + M_B = \frac{19.8^3}{50.1^2} \approx \frac{7762}{2510} \cong 3.1\,M_\odot.$$

Thus, the combined mass of Sirius A and Sirius B is approximately 3.1 $M_\odot$. In reality, the orbit of the system is very eccentric, or elliptical, and so the distance between them varies from 31.5 AU to 8.1 AU and back again. Using this information, and data gained from spectroscopic studies, we can determine that the mass of Sirius A is 2.12 $M_\odot$, and that of Sirius B 1.03 $M_\odot$.

3.8 Lifetimes of Main-Sequence Stars

We have covered topics that describe how a star forms, how the mass of stars can be determined by observing binary-star systems, and how long it takes to become a star. Now we shall discuss how long a star will remain on the main sequence, and then look at what happens due to changes in its internal structure.

The stars that are on the main sequence are fundamentally alike in their cores because it is here that stars convert hydrogen to helium. This process is called *core hydrogen-burning*. The *main-sequence lifetime* is the amount of time a star spends consuming hydrogen in its core, and so the main-sequence lifetime will depend on the star's internal structure, and evolution. A newly born star is often referred to as a *zero-age-main-sequence-star*, or *zams* for short. There is a subtle but important difference between a *zams* star and a main-sequence star. During its long life on the main sequence, a star will undergo changes to its radius, surface temperature, and luminosity due to the core hydrogen-burning. The nuclear reactions alter the percentage of elements within the core. Initially, it would have had, say, in the case of the Sun, about 74% hydrogen, 25% helium, and 1% metals, but now, after a period of 4.6 million years, the core has a much greater mass of helium than that of hydrogen at its core.

Due to the hydrogen-burning at the core, the total number of atomic nuclei decreases with time, and so with fewer particles in the core to provide the internal pressure, the core will shrink very slightly under the weight of the star's outer layers. This has an effect on the star's appearance. The outer layers expand and become brighter. This may seem odd to you; if the core shrinks, why doesn't the star shrink? The explanation is very simple: the core shrinkage increases its density and temperature, which causes the hydrogen nuclei to collide with each other much more often, which in turn increases the rate of hydrogen-burning. The resulting increase of core pressure causes the star's outer layers to expand slightly, and as luminosity is related to the surface area of a star, the increase of the star's size will result in an increase in luminosity. In addition, the surface temperature will increase. In the case of the Sun, astronomers have calculated that its luminosity has increased by 40%, its radius by 6%, and its surface temperature by 300 K, all during the past 4.6 billion years.

As a star ages on the main sequence, the increase of energy flowing from its core will also heat the surrounding area, and this will cause hydrogen-burning to begin in this surrounding layer. As this can be thought of as "new" fuel for the star, its lifetime can be lengthened by a few million years for a main-sequence star.

The one factor that determines how long a star will remain on the main sequence is its mass. Basically, it can be summed up in a few words: *Low-mass stars have much longer lifetimes than high-mass stars*. Figure 3.10 illustrates this nicely.

High-mass stars are extremely bright, and their lifetimes are very short. This means that they are using up their reserve of hydrogen in the core at a very high rate. Thus, even though an O- or B-type star is much more massive, and thus contains more hydrogen than, say, a less-massive M-type star, it will use up its hydrogen much sooner. It may only take a few million years for O- or B-type stars to use up their supply of hydrogen, whereas for low-mass M-type stars, it may take hundreds of billions of years. Think about that for a second. The lifetime of an M-type star may be *longer than the present age of the universe*![31] Table 3.1 shows how the mass of a star relates to temperature and spectral class.

The differing lifetimes of stars can be easily seen by looking at star clusters. Massive stars have shorter lifetimes than less-massive stars, and so a star cluster's *H-R* diagram will give information on the evolution of the stars in

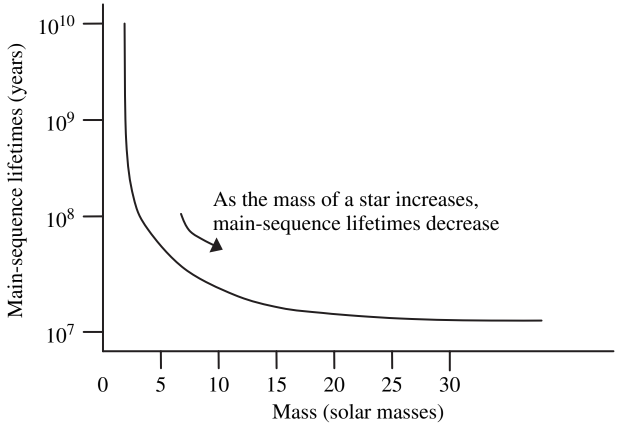


Figure 3.10. Main-sequence lifetimes for stars of different mass.

the cluster. Such a diagram will show a main sequence that lacks O-type stars, which are the most massive, then A-type, and so on and so forth as the cluster ages. Figure 3.11 shows this erosion of main-sequence stars by comparing the *H-R* diagrams of several different star clusters. In every case, some stars will have left the main sequence to become red giants,[32] or they are already red giants.

The temperature and spectral type of the very hot stars that are left on the main sequence are used to determine the age of a star cluster. Suppose the hottest star on the main sequence is an A0-type star, with the much hotter, and more-massive stars already evolved to red giants. We know that A0 stars have a main-sequence lifetime of about 100 million years, so we can say with some confidence that the star cluster is about 100 million years old.

Generally, the more massive the star, the faster it goes through all of its phases, so we are fortunate to be able to observe stars in the main-sequence phase, as they remain in it for such a long time. It is also very easy to estimate a star's lifetime if we know its mass.

Table 3.1. Mass, spectral class, and main-sequence lifetimes

Mass, $M_\odot$	Temperature, K	Spectral Class	Luminosity, $L_\odot$	Main-Sequence Lifetime, 10^6 years
25	35,000	O	80,000	3
15	30,000	B	10,000	11
3	11,000	A	60	640
1.5	7000	F	5	3600
1	6000	G	1	10,000
0.75	5000	K	0.5	20,000
0.5	4000	M	0.03	56,000

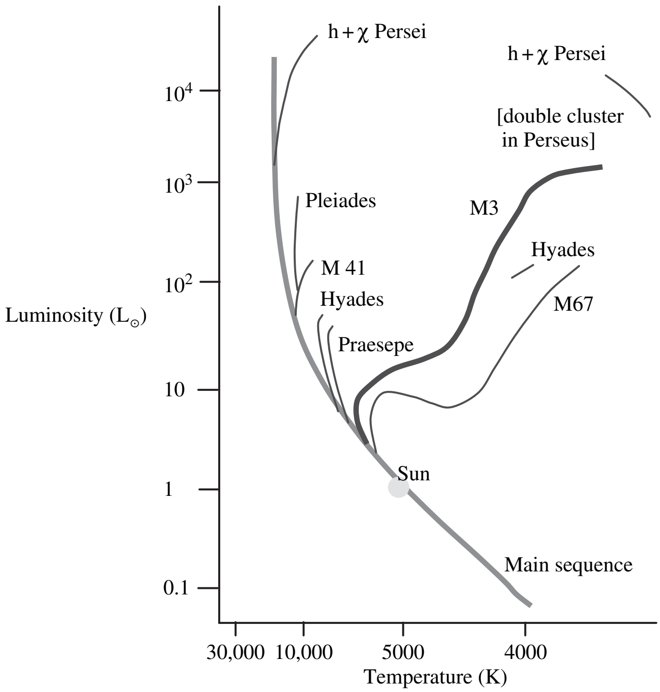


Figure 3.11. *H-R* diagrams for several star clusters of different ages.

There are many stars on the main sequence that can be observed. The brightest of these have already been mentioned in previous sections; they include: *Regulas, Vega, Sirius A, Procyon A, the Sun*, and *Barnard's Star*, to name a few.

Box 3.3: Main-Sequence Lifetimes

The duration a star remains on the main sequence is very easy to calculate. There is an approximate relationship between the mass of a star and its lifetime:

$$t = \frac{1}{M^{2.5}} = \frac{1}{M^2\sqrt{M}}$$

Astronomers usually relate the main-sequence lifetime to the Sun (a typical $1\,M_\odot$ star), which is believed to be 10^{10} years, or ten billion years.

For example, the main-sequence lifetime of Sirius, a $2.12\,M_\odot$, star will be:

$$\frac{1}{2.12^{2.5}} = \frac{1}{2.12^2\sqrt{2.12}} = \frac{1}{6.54} \text{ solar lifetimes}$$

So, a Sirius will burn hydrogen in its core for about $1/6.54 \times 10^{10}$ years, or about 1.5 billion years.

On the other hand, a main-sequence star with a mass of $0.5\,M_{\odot}$ will have a lifetime of:

$$\frac{1}{0.5^{2.5}} = \frac{1}{0.5^{2}\sqrt{0.5}} = \frac{1}{0.177} = 5.66\,\text{solar lifetimes}$$

which is about 56 billion years.

3.9 Red Giant Stars

Although the amount of hydrogen in a star's core is vast, it is not infinite, and so, after a *very long time*, the production of energy will cease when the central supply of hydrogen is used up. Throughout the length of time that nuclear fusion has been taking place, the hydrogen has been transformed into helium, by way of the proton-proton chain, and without this source of energy, the star uses gravitational contraction to supply its energy needs. Thus, the core will start to cool down, which means that the pressure also decreases, with the result that the outer layers of the star begin to weigh down on the core and compress it. This has the effect of causing the temperature within the core to rise again, and for heat to flow outward from the core. Note that although a tremendous amount of heat is formed now, it is not due to nuclear reactions but to gravitational energy being converted into thermal energy.

In a relatively short time, astronomically speaking, the region around the star's hydrogen-depleted core will become hot enough to begin nuclear fusion of hydrogen into helium, in a thin shell around the core, in a process called *shell hydrogen-burning*. This is shown in Figure 3.12.

The core will consist of helium, but the outer layers are hydrogen rich. The shell, where energy production occurs, is relatively thin. [Note: figure to scale.]

For a star like the Sun, this hydrogen-consuming shell develops almost immediately from the moment nuclear fusion stops in the core, and so the supply of energy is more or less constant. For massive stars, there can be an interval of perhaps a few thousand years to a few million years from the end of the core nuclear-fusion phase to the beginning of the shell hydrogen-burning phase.

The new supply of energy, and thus heat, has the effect of causing the rate of shell hydrogen-burning to increase, and so it begins to eat further into the surrounding hydrogen. The helium that is the by-product of the hydrogen fusion in the shell falls to the center of the star, where, along with the helium already there, it heats up as the core continues to contract and increase its mass. In the case of, say, a $1\,M_{\odot}$ star, the core will be compressed to as much as one-third of its original size. The result of this core compression is an increase in the temperature, from about 15 million K to nearly 100 million K.

Now, most of what has happened in this stage of a star's life has occurred inside of it and so was invisible to our eyes. Nevertheless, it does have effects

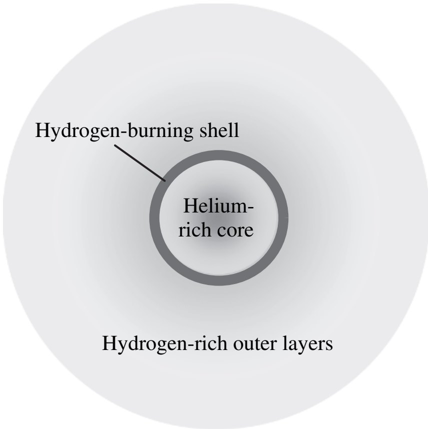


Figure 3.12. Star with shell hydrogen-burning.

on a star's structure that can drastically alter its appearance. The star's outer layers expand as the core contracts. With the increased flow of heat from the contracting core, and the ever-expanding shell of hydrogen-burning, the star's luminosity increases quite substantially. This causes the star's internal pressure to increase and makes the outer layers of the star expand to many times their original radius. The tremendous expansion actually causes the outer layers to cool, even though the inner core temperature has risen dramatically. The new, much-expanded, and cooler outer layers can reach temperatures as low as 3500 K and will glow with a very distinctive reddish tint, as can be explained by Wien's Law (mentioned earlier). The star has now become a *red giant* star.

So, we can now see that red giant stars are former main-sequence stars that have evolved into a new phase of their lives.

Due to the large diameter and thus weaker surface gravity of the red giant, quite a substantial amount of *mass loss* can occur. This means that gases can escape from the surface of a red giant star. Such an effect is relatively easy to observe by looking at the absorption lines produced in the star's spectrum. Calculations and measurements have shown that a typical red giant star can lose $10^{-7}\,M_{\odot}$ each year. Compare this with the much-smaller $10^{-17}\,M_{\odot}$ that the Sun loses each year. From this, we can see that as a star evolves from the main sequence to the red-giant stage, it can lose quite a lot of its mass. The evolutionary track from the main sequence to the red-giant phase for stars of differing mass is shown in Figure 3.13.

The dotted lines indicate time scales of 10, 50, 100 million, and 1 billion years. You can see that a star of about 15 solar masses leaves the main sequence (the shaded area) about 100 times earlier than a star of 1.5 solar masses.

There are many wonderful red giant stars that are observable in the night sky. We have already mentioned a few of these in earlier sections—*Capella A*,

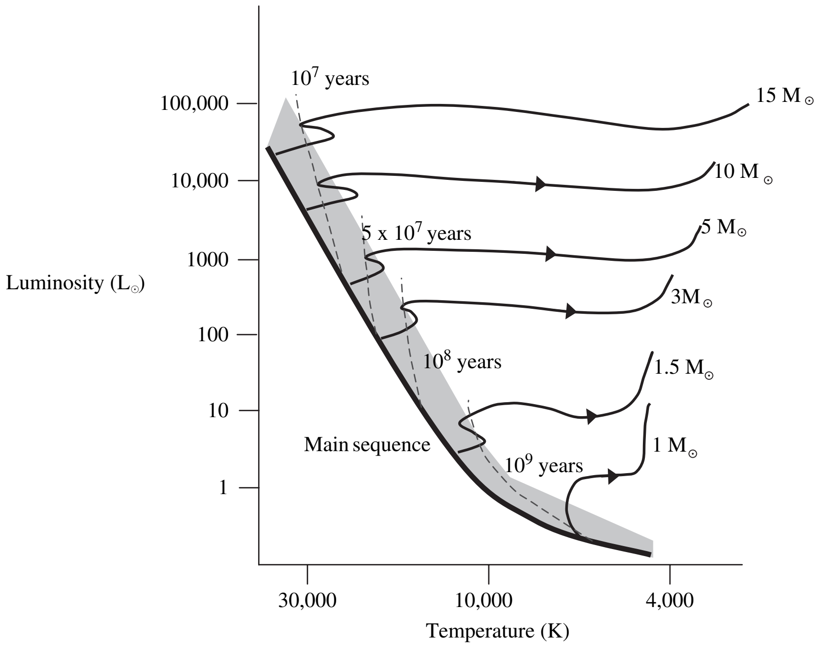


Figure 3.13. Evolutionary tracks from the main sequence to the red-giant phase for stars of different mass.

Arcturus, Aldebaran, Pollux, Mirach, R Leporis, and Mira. But there are several other, lesser-known red giant stars, which are also worth observing.

3.9.1 Bright Red Giant Stars

RS Cyg	**HD 192443**	**$20^h13.3^m$**	**+38°44′**	Jun–**Jul**–Aug
8.1_vm	**B–V:3.3**	**C5**		**Cygnus**

A red giant star with a persistent periodicity, class SRA, it has a period of 417.39 days, with a magnitude range of 6.5 to 9.5 m. A strange star where the light curve can vary appreciably, with the maxima sometimes doubling a deep red-colored star.

R Aqr	**HD 222800**	**$23^h43.8^m$**	**−15°17′**	Jul–**Aug**–Sep
5.8_v m	**B–V:1.5**	**M4 pe**	**2500**	**Aquarius**

This is a symbiotic double star and is classed as a *Z Andromedae*-type star. *R Aqr* is a nice red giant, which, incidentally, has a small, blue (thus, very hot) companion star. Due to its variable nature, its magnitude can fall to 11.5, and so it can be somewhat difficult to locate. It is believed to lie at a distance of about 640 l.y.

R Cas	**HD 224490**	**$23^h58.4^m$**	**+51°23′**	Sep–**Oct**–Nov
5.5_v m	**B-V : 1.5**	**M7 IIIe**	**2000**	**Cassiopeia**

This is a Mira-type variable star with quite a large magnitude range, say 5.5–13.0m. It is estimated to lie at a distance of 350 l.y. Its surface temperature of only 2000 K is still a matter of speculation.

R Leo	**HD 84748**	**$09^h47.6^m$**	**+11°26′**	Jan–**Feb**–Mar
6.02_v m	**B-V : 1.5**	**M8 IIIe**	**2000**	**Leo**

A very bright Mira-type variable star and a favorite among amateur astronomers. Again, like so many other red giants, its low temperature of 200 K is in some doubt. Its color is deep red. This star is often cited as being a perfect introductory star for those who wish to observe a variable star. It is also an AGB star.

Note that as a star ages and moves from the main sequence to the red-giant stage, its spectral type will also change. For instance, the Sun, at present a G-type star, will gradually change its spectral class to K, and then to a warm M-type star. It may even become an M2- or M3-type with the temperature falling to about 3200 K. Similarly, stars of different masses will also change their spectral type.

Finally, for this section, it is worth noting in passing that there are two red giant phases. Which one a star will follow depends, as I am sure you will have guessed by now, on its mass, and can lead to the formation of *supergiant* stars. We will discuss these in another section.

3.10 Helium-Burning and the Helium Flash

Most of the stars with a mass greater than, or equal to, the Sun's will eventually become red giants. But how energy is produced in the star after it has reached the red-giant phase depends on its mass. We shall look at these two stages, beginning with how the helium in its core produces energy.

3.10.1 Helium-Burning

Helium can be thought of as the "ash" left over from the hydrogen-burning reactions, and can in fact be used as the fuel for another nuclear fusion reaction, which, this time, uses helium. This is the *helium-burning* phase. As a star approaches and becomes a red giant, its core temperature is too low to initiate helium-burning. But the hydrogen-burning shell that surrounds the dormant helium core adds mass to the core, with the result that it contracts further, becomes denser, and increases the temperature substantially.[33] Something else happens as the temperature increases—the electrons in the gas become degenerate. Electron degeneracy is a very important process and is explained in greater detail in the appendices. When the electrons become degenerate, they in effect resist any further contraction of the core, and the internal temperature of the core will no longer affect the internal pressure.

As the hydrogen shell continues to burn, the degenerate core grows even hotter, and when it reaches 100 million K, and has a mass of about $0.6\,M_{\odot}$ (i.e., the inner 60% of the hydrogen in the star has been converted to helium), *core helium-burning* begins, converting helium into carbon, and producing nuclear energy. During this stage of a star's life, it can be nearly 1 AU in radius and almost 1000 times as luminous as the Sun. By now the old star has once again obtained a central energy source for the first time since it left the main sequence.

The helium-burning in the core fuses three helium nuclei to form a carbon nuclei and is called the *triple α process*. This occurs in two steps. In the first step, two helium nuclei combine to form an isotope of beryllium:

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be}$$

This isotope of beryllium is very unstable and very quickly breaks into two helium nuclei. But in the extreme conditions in the core, a third helium nucleus may strike the ^{8}Be nucleus before it has had a chance to break up. If this happens, a stable isotope of carbon is formed, and energy is released as a gamma-ray photon (γ):

$$^{8}\mathrm{Be} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

The phrase "triple α" comes about because helium nuclei are also called alpha particles.[34] The carbon nuclei formed in this process can also fuse with additional helium nuclei, producing a stable isotope of oxygen, and supply additional energy:

$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma$$

So the "ash" of helium-burning is carbon and oxygen. This process is very interesting, as you will note that both of these isotopes of oxygen and carbon are the most abundant forms and in fact make up the majority of carbon atoms in our bodies, as well as the oxygen we breathe. We will explore this fascinating piece of information in greater depth later in this book.

The formation of carbon and oxygen not only provides more energy but also re-establishes thermal equilibrium in the core of the star. This prevents the core from any further contraction due to gravity. The duration of time a red giant will spend burning helium in its core is about 20% as long as the time it spent burning hydrogen on the main sequence. The Sun, for example, will only spend 2 billion years in the helium-burning phase.

3.10.2 The Helium Flash

As I mentioned earlier, the mass of a star will direct how helium-burning begins in a red giant star. In a high-mass star (that is, with a mass greater than

2–3 $M_\odot$), the helium-burning begins gradually as the temperature in the core approaches 100 million K. The triple α process is initiated, but it occurs before the electrons become degenerate. However, in low-mass stars (that is, with a mass less than 2–3 $M_\odot$), the helium-burning stage can begin suddenly, in a process called the *helium flash*. This stage, the helium flash, occurs due to the most unusual conditions found in the core of a low-mass star as it becomes a red giant.

The energy produced by helium-burning heats up the core of the star and raises its temperature. Now, in normal circumstances, this would result in an increase of pressure that would lead to an expansion and subsequent cooling of the core. This explains why nuclear reactions do not usually cause a rapid increase in the central temperature of a star. But we must remember that the gas in the core of a 1 $M_\odot$ red giant is far from normal; it is a gas of degenerate electrons. This means that any temperature increase that the helium-burning produces does not increase the internal pressure. What the rise in temperature does is to strongly affect the rate at which the triple α process occurs. A doubling of the temperature will increase the triple α production rate by about 1 billion times.

The energy that is produced by the triple α process heats up the core, and its temperature begins to rise even more. This increase and the subsequent rise in energy production can cause the temperature to reach an amazing 300 million K. Due to the rapid heating of the core, a nearly explosive consumption of helium occurs, and this is the helium flash mentioned earlier. At the peak of the helium flash, the core of the star has, very briefly, an energy output that is some 10^{11} to 10^{14} times solar luminosity. This converts to a rate of energy output that is about 100 times greater than the entire Milky Way.

Eventually, however, the high temperature becomes so high that the electrons in the core can no longer remain degenerate. They then behave normally for electrons in a gas, with the result that the star's core expands, which ends the helium flash. These events occur very quickly, so the helium flash is over in a matter of seconds, and the star's core settles down to a steady rate of helium-burning.

An important point to make here is that whether the helium flash occurs or does not occur, the start of helium-burning actually reduces the star's luminosity. Here's what happens: the superheated core expands, and this core expansion pushes the hydrogen-burning shell outward, lowering its temperature and burning rate. The result is that even though the star has both helium fusion in its core and a shell of hydrogen-burning taking place simultaneously, the total energy production falls from its peak during the red-giant phase. This reduced total energy output of the star therefore reduces the luminosity and allows its outer layers to contract from their peak size during the red-giant phase. As the outer layers contract, the star's surface temperature will increase slightly.

The helium-burning in the core lasts for a relatively short time, however, and from calculations we can make an estimate of this time. For, say, a 1 $M_\odot$ star like the Sun, the period after the helium flash will only last about 100 million years, which is 1% of its main-sequence lifetime.

3.11 Star Clusters, Red Giants, and the *H-R* Diagram

At this point in our story of stellar evolution, it is a good idea to take stock of what we have learned so far. We have discussed how stars are formed before moving onto the main sequence. Their lifetime on the main sequence depends on their mass; massive stars have shorter lives. The red-giant phase is next, along with a change in the hydrogen, and helium-burning within the star's core. To put all of this together in one coherent picture is useful, as we can see how a star develops from the moment of its birth; so we shall do just that by looking at the *H-R* diagram for stars that have just started their main-sequence lifetimes and those that are in the red-giant phase.

Stars that have just emerged from the protostar stage and are about to join the main sequence are burning hydrogen steadily and have attained hydrostatic equilibrium. These stars are often referred to as *zero-age* main-sequence stars and lie along a line on the *H-R* diagram called the *zero-age main sequence*, or *ZAMS*. This is shown on the *H-R* diagram in Figure 3.14 as a green line. Over time, which can be relatively short or exceptionally long, depending on the star's mass, the hydrogen in the core is converted to helium, and the luminosity increases. This is accompanied by an increase in the star's diameter, and so the star moves on the *H-R* diagram away from the ZAMS. This explains why the main sequence is actually more of a broad band, rather than, as often portrayed, a thin line.

The light grey line in Figure 3.14 represents those stars in which the hydrogen has been used up in the core and so nuclear fusion has ceased. As you can see, high-mass stars, $3\,M_\odot$, $5\,M_\odot$, and $10\,M_\odot$, then move rapidly from left (high temperature) to right (low temperature) across the *H-R* diagram. What is happening here is a decrease in surface temperature, but the surface area is increasing, so its overall luminosity remains fairly constant (i.e., an approximately horizontal line). In this phase, the core is contracting and outer layers expanding as energy flows from the hydrogen-burning shell.

High-mass stars with core helium-burning exhibit sharp downward turns in the red-giant region of the *H-R* diagram. Low-mass stars have a helium flash at their cores (red stars).

The evolutionary track of the high-mass stars then makes an upward turn to the upper-right section of the *H-R* diagram. This occurs just before the onset of core helium-burning. After the start of helium-burning, the core expands, the outer layers contract, and the evolutionary track of the star falls from these high, albeit temporary, luminosities. Notice how the tracks wander back and forth on the *H-R* diagram. This represents the stars' adjusting to their new energy supplies.

The low-mass stars, $1\,M_\odot$ and $1.5\,M_\odot$, behave in a somewhat different manner. The start of helium-burning is marked by the helium flash, indicated by the red stars in the diagram. The star shrinks and becomes less luminous after the helium flash, although the surface temperatures rises. This occurs because the reduction in luminosity is proportionally less than the reduction in size. So now

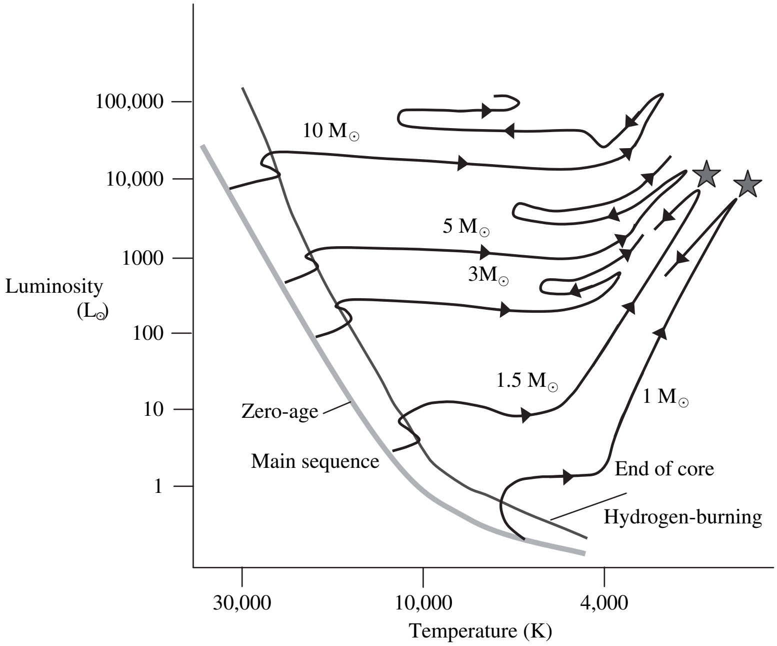


Figure 3.14. Post-main-sequence evolutionary track for several stars of different masses.

the evolutionary tracks move down (lower luminosity) the *H-R* diagram, and to the left (hotter) region.

We can observe the evolution of stars from birth to helium-burning by looking at young star clusters and comparing the actual observations with theoretical calculations. But there exists another astronomical grouping of stars that contain many, maybe millions, of very old post-main-sequence stars—globular clusters. These are the subject of our next section.

3.12 Post-Main-Sequence Star Clusters: The Globular Clusters

In the night sky there are many compact and spherical collections of stars. These stars clusters are called *globular clusters*. These are metal-poor stars and are usually to be found in a spherical distribution around the galactic center at a radius of about 200 l.y. Furthermore, the number of globular clusters increases significantly the closer one gets to the galactic cente. This means that particular constellations which are located in a direction toward the galactic bulge have a high concentration of globular clusters within them, such as *Sagittarius* and *Scorpius*.

The origin and evolution of a globular cluster is very different from that of an open or galactic cluster. All the stars in a globular cluster are very old, with the result that any star earlier than a G- or F-type star will have already left the main sequence and be moving toward the red-giant stage of its life. In fact, new star formation no longer takes place within any globular clusters in our Galaxy, and they are believed to be our Galaxy's oldest structures. In fact, the youngest of the globular clusters is still far older than the oldest open cluster. The origin of globular clusters is a scene of fierce debate and research, with the current models predicting that they may have been formed within the proto-galaxy clouds that went to make up our Galaxy.

As previously mentioned, globular clusters are old, as they contain no high-mass main-sequence stars, and this can be shown on a special kind of *H-R* diagram called a *color-magnitude diagram.* On a color-magnitude diagram, the apparent brightness is plotted against the color ratio for many of the stars in a cluster (see Figure 3.15). The color ratio of a star can tell you the surface temperature, and if we assume that all the stars in a cluster lie at the same distance from us, their relative brightness can tell us their relative luminosities.

Even a cursory glance at such a color-magnitude diagram will tell you something strange has happened. In fact, you will see that the upper half of the main sequence has disappeared. This means that all of the high-mass stars in a globular cluster have evolved into red giants, a long time ago. What remains are the low-mass main-sequence stars that are very slowly turning into red giants.

One thing that is very apparent on the diagram is a grouping of stars that lie on a horizontal band toward the center-left of the diagram. This is called the *horizontal branch,* while the stars in this area are the *horizontal-branch stars.* These stars are low-mass, post-helium-flash stars of about $50\,L_{\odot}$, in which there are both core helium-burning and shell hydrogen-burning. In the future, these stars will move back toward the red-giant region as the fuel is devoured.

A star that has had its surface temperature and visual magnitude determined is represented by a black dot. All the stars in M3 lie at approximately the same distance from us (32,000 l.y.), so their magnitudes are a direct measurement of their luminosities. The asymptotic giant branch is described in a later section.

One very practical use of the *H-R* diagram is to estimate the age of a star cluster. With a very young star cluster, most, if not all, of the stars are on or near the main sequence. As it ages, however, the stars will move away from the main sequence, with the high-mass, high-luminosity stars being the first to become red-giant stars. As time passes, the main sequence will get increasingly shorter. The top of the main sequence, which remains after the specified time, can be used to determine the cluster's age and is called the *turnoff point*. The stars that are at the turnoff point are those that are just exhausting the hydrogen in their cores, so the main-sequence lifetime is in fact the age of the star cluster. An example of the *H-R* diagram for open star clusters showing their turnoff points is shown in Figure 3.16.

The time for the turnoff point is shown as a horizontal gray line. For example, the cluster M41 has a turnoff point near the 10^8 year point, so the cluster is about 100,000,000 years old.

From an observational point of view, globular clusters can be a challenge. Many are visible in optical instruments, from binoculars to telescopes, and a

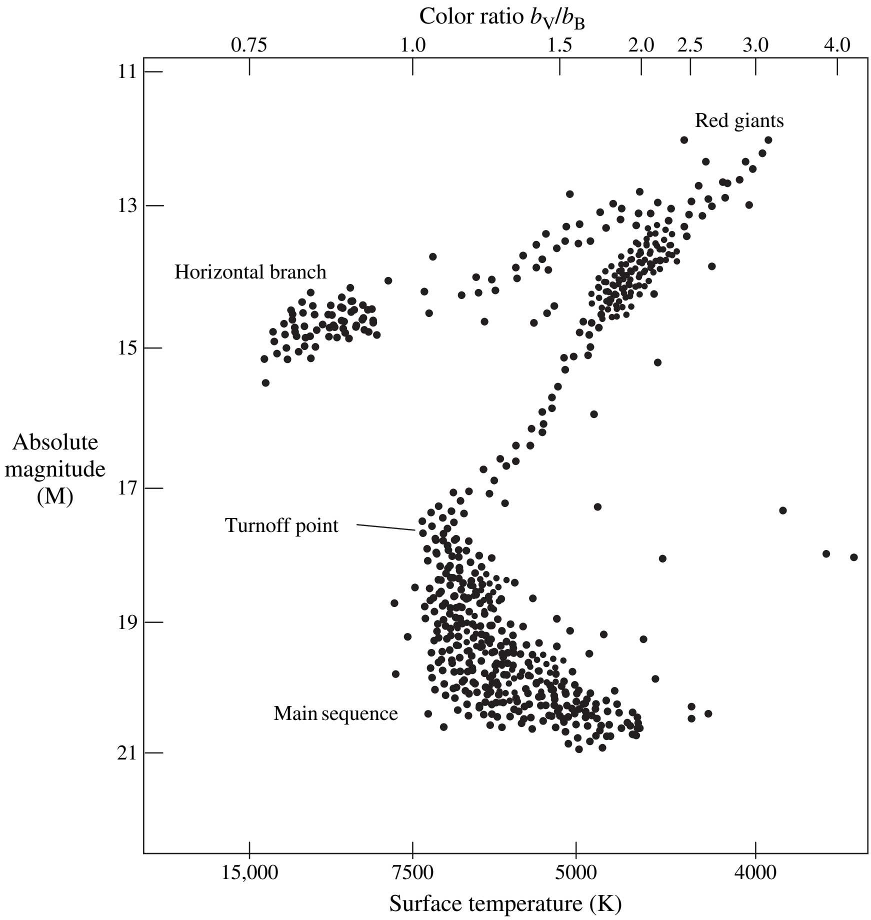


Figure 3.15. Color-magnitude diagram for the globular cluster M3.

few are even visible to the naked eye. There are about 150 globular clusters, ranging in size from 60 to 150 l.y. in diameter. They all lie at vast distances from the Sun and are about 60,000 l.y. from the *Galactic plane*. The nearest globular clusters (for example, *Caldwell 86* in Ara) lie at a distance of over 6000 l.y., and thus the clusters are difficult objects for small telescopes. They cannot be seen; rather, any structure within the cluster will be difficult to observe. Even the brightest and biggest globular will require apertures of at least 15 cm for individual stars to be resolved. However, if large-aperture telescopes are used, these objects are magnificent. Some globular clusters have dense concentrations toward their center, while others may appear as rather compact open clusters. In some cases, it is difficult to say where the globular cluster peters out and the background stars begin.

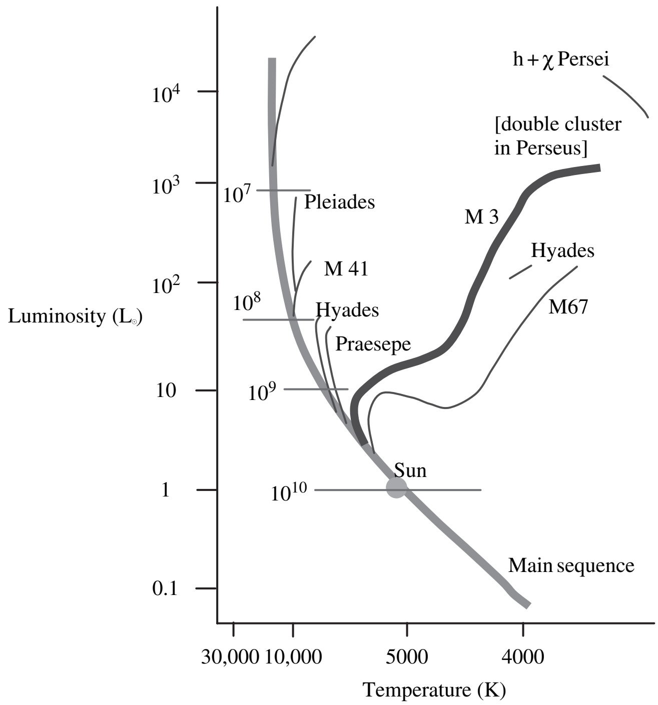


Figure 3.16. *H-R* diagram for star clusters showing the turnoff point.

As in the case of open clusters, there exists a classification system, the *Shapley-Sawyer Concentration Class*, where Class I globular clusters are the most star-dense and Class XII the least. The ability of an amateur to resolve the stars in a globular actually depends on how condensed the cluster is, and so the scheme will be used in the descriptions, but it is really useful only for those amateurs who have large-aperture instruments. Nevertheless, the observation of these clusters, which are among the oldest objects visible to amateurs, can provide you with breathtaking, almost three-dimensional aspects.

The many globular clusters listed below are just a few of the literally hundreds that can be observed and are meant to be just a representative sample. The ⊕ indicates the approximate size of the cluster.

3.12.1 Bright Globular Clusters

Messier 68	**NGC 4590**	**$12^h39.5^m$**	**−26°45′**	Mar–**Apr**–May
7.7m	**⊕ 12′**		**X**	**Hydra**

Appearing only as a small, hazy patch in binoculars, this is a nice cluster in telescopes, with an uneven core and faint halo. A definite challenge to naked-eye observers, where perfect seeing conditions will be needed. Use averted vision and make sure that your eyes are well and truly dark-adapted.

Messier 3	**NGC 5272**	**13^{h}42.2^m**	**+28°23′**	Mar—**Apr**—May
5.9m	**⊕ 16′**		**VI**	**Canes Venatici**

A good test for the naked eye. If using giant binoculars with perfect seeing conditions, some stars may be resolved. A beautiful and stunning cluster in telescopes, it easily rivals *M13* in *Hercules*. It definitely shows pale colored tints, and reported colors include yellow, blue, and even green; in fact, it is often quoted as the most colorful globular in the northern sky. Full of structure and detail, including several dark and mysterious tiny patches. Many of the stars in the cluster are also variable. One of the three brightest clusters in the northern hemisphere is located at a distance of about 35,000 l.y.

Messier 5	**NGC 5904**	**15^h 18.6^m**	**+02°05′**	Apr—**May**—Jun
5.7m	**⊕ 17.4′**		**V**	**Serpens**

Easily seen as a disc with binoculars and with large telescopes, the view is breathtaking—presenting an almost three-dimensional vista. One of the few colored globulars, with a faint, pale yellow outer region surrounding a blue-tinted interior. It gets even better with higher magnification, and stars become more apparent. Possibly containing over half a million stars, this is one of the finest clusters in the northern hemisphere; many say it is *the* finest.

Messier 4	**NGC 6121**	**16^{h}23.6^m**	**−26°32′**	Apr—**May**—Jun
5.8m	**⊕ 26.3′**		**IX**	**Scorpius**

A superb object, presenting a spectacle in all optical instruments, and even visible to the naked eye. But it does lie very close to the star Antares, so the glare of the latter may prove a problem in its detection. Telescopes of all apertures show detail and structure within the cluster, and the use of high magnification will prove beneficial; but what is more noticeable is the bright lane of stars that runs through the cluster's center. The closest globular to the Earth at 6,500 l.y. (although *NGC 6397* in *Ara* may be closer), and about 10 billion years old.

Messier 13	**NGC 6205**	**16^h 41.7^m**	**+36°28′**	May—**Jun**—Jul
5.7m	**⊕ 16.5′**		**V**	**Hercules**

Also known as the *Hercules Cluster*. A splendid object and the premier cluster of the northern hemisphere. Visible to the naked eye, it has a hazy appearance in binoculars; with telescopes, however, it is magnificent, with a dense core surrounded by a sphere of a diamond-dust-like array of stars. In larger telescopes, several dark bands can be seen bisecting the cluster. It appears bright because it is close to us, at only 23,000 l.y., and also because it is inherently bright, shining at a luminosity equivalent to more than 250,000 Suns. At only 140 l.y. in diameter, the stars must be very crowded, with several stars per cubic light year, a density 500 times that of our vicinity.

Messier 10	**NGC 6254**	**16^h 57.1^m**	**−04°06′**	May—**Jun**—Jul
6.6m	**⊕ 15′**		**VII**	**Ophiucus**

Similar to *M12*, but slightly brighter and more concentrated. It lies close to the orange star *30 Ophiuchi* (spectral type K4, magnitude 5), and so if you locate this star, then by using averted vision M10 should be easily seen. Under medium aperture and magnification, several colored components have been reported: a pale blue-tinted outer region surrounding a very faint pink area, with a yellow star at the cluster's center.

Messier 19	**NGC 6273**	**$17^h02.6^m$**	**−26°16′**	May—**Jun**—Jul
6.7m	**⊕ 13.5′**		**VIII**	**Ophiucus**

A splendid, albeit faint, cluster when viewed through a telescope. Although a challenge to resolve, it is nevertheless a colorful object, reported as having both faint orange and blue stars, while the overall color of the cluster is a creamy white.

Messier 9	**NGC 6333**	**$17^h19.2^m$**	**−18°31′**	May—**Jun**—Jul
7.6m	**⊕ 9.3′**		**VII**	**Ophiucus**

Visible in binoculars, this is a small cluster with a brighter core. The cluster is one of the nearest to the center of our Galaxy and is in a region conspicuous for its dark nebulae, including *Barnard 64*; it may be that the entire region is swathed in interstellar dust, which gives rise to the cluster's dim appearance. It lies about 19,000 l.y. away.

Messier 22	**NGC 6656**	**$18^h36.4^m$**	**−23°54′**	May—**Jun**—Jul
5.1m	**⊕ 24′**		**VII**	**Sagittarius**

A truly spectacular globular cluster, visible under perfect conditions to the naked eye. Low-power eyepieces will show a hazy spot of light, while high power will resolve a few stars. Often passed over by northern hemisphere observers due to its low declination. Only 10,000 l.y. away, nearly twice as close as *M13*.

Messier 92	**NGC 6341**	**$17^h17.1^m$**	**+43°08′**	May—**Jun**—Jul
6.4m	**⊕ 11′**		**IV**	**Hercules**

A beautiful cluster, often overshadowed by its more illustrious neighbor, M13. In binoculars, it will appear as a small hazy patch, but in 20 cm telescopes its true beauty becomes apparent, with a bright, strongly concentrated core. It also has several very distinct dark lanes running across the face of the cluster. A very old cluster, 25,000 l.y. distant.

Messier 54	**NGC 6715**	**$18^h55.1^m$**	**−30°29′**	Jun—**Jul**—Aug
7.6m	**⊕ 9.1′**		**III**	**Sagittarius**

It has a colorful aspect—a pale blue outer region and pale yellow inner core. Recent research has found that the cluster was originally related to the *Sagittarius Dwarf Galaxy*, but the gravitational attraction of our Galaxy has pulled the globular from its parent. Among the globular clusters in the Messier catalogue, it is one of the densest, as well as the most distant.

Messier 15	**NGC 7078**	**$21^h30.0^m$**	**+12°10′**	Jul—**Aug**—Sep
6.4m	**⊕ 12′**		**IV**	**Pegasus**

An impressive cluster in telescopes, it can be glimpsed with the naked eye. It does, however, under medium magnification and aperture, show considerable detail, such as dark lanes, arcs of stars, and a noticeable asymmetry. It is one of the few globulars that have a planetary nebula located within it—*Pease-1*, which is seen only in apertures of 30 cm and greater. The cluster is also an X-ray source.

3.13 Pulsating Stars

We saw earlier that there are stars far more massive than the Sun that contract, and move horizontally across the *H-R* diagram, while at the same time they get hotter but remain at a constant luminosity. As they move across the *H-R* diagram, they can also become unstable and vary in size. Some stars change their size quite considerably, alternatively shrinking and expanding as their surface moves in and out. As the stars vary in size, so does their brightness. These stars are the *pulsating variable stars*. There exist several classes of pulsating variable stars, but we will just discuss the main types: the *long-period variables*, the *Cepheid variables*, and the *RR Lyrae* stars. Figure 3.17 shows where on the *H-R* diagram these pulsating stars reside.

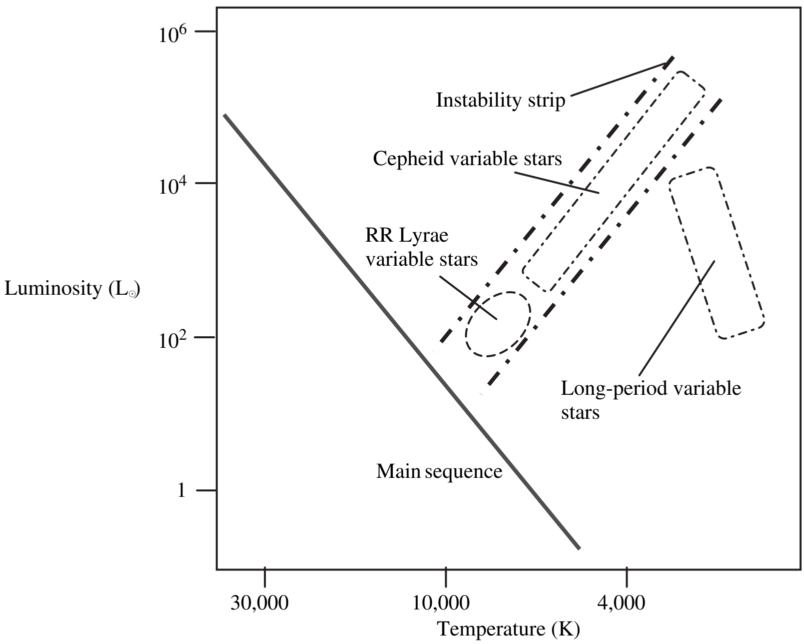


Figure 3.17. Variable stars on the *H-R* diagram.

3.13.1 Why Do Stars Pulsate?

You may think that the pulsations of a star are caused by variations in the rate of energy production deep in its core. You would be wrong, however, as the rate of nuclear fusion remains constant in a pulsating star. Astronomers have realized that the variations are caused by changes in the rate at which energy can *escape* from the star. The explanation is surprisingly simple, but somewhat involved, so I shall go through the various stages in some detail.

Imagine a normal star, where there is a balance between the downward-pulling force of gravity and the upward force of pressure (i.e., the star is in hydrostatic equilibrium). Now picture a star where the pressure in the outer layers *exceeds* the force of gravity in those layers. In such a scenario, the star's outer layers would begin to expand (see Figure 3.18 for a schematic of this process). As the star expands, its gravity will naturally fall, but the pressure force will fall at a faster rate. A time would then come when the star will have expanded to a larger size where, once again, hydrostatic equilibrium would reign. But this does not necessarily mean that the star would stop expanding. The inertia of the outward-moving outer layers will carry the expansion past the balance point. By the time gravity will have brought everything to a stop, the pressure would now be too small to balance the gravity, and so the outer layers would begin to fall inward. At this point gravity will rise again, but less than the pressure will. The outer layers will fall past the balance point until eventually the force of pressure would prevent any further fall, and so would come to a halt. And this is where we came in—the pulsations would start all over again.

You can think of a pulsating star behaving just like a spring with a heavy weight attached to it. If you pull down on the weight and then let it go, the spring will oscillate around the point at which the tension in the spring and the force of gravity are in balance. After a while, however, friction in the spring will dampen the oscillations unless the spring is given a little push upwards each time it reaches the bottom of an oscillation. In a pulsating star, for the pulsations to continue, and not to die out, the star also needs an outward push each time it contracts to its minimum size. Discovering what causes that extra push was a challenge to astronomers of the twentieth century.

The first person to develop an idea of what was happening was the British astronomer Arthur Eddington in 1914. He suggested that a star (in this case, a Cepheid variable) pulsated because its opacity increases more when the gas is compressed than when it is expanded. Heat is trapped in the outer layers if a star is compressed, which increases the internal pressure; this, in turn, pushes upward the outer layers. As the star expands, the heat will escape and so the internal pressure falls, and the star's surface drops inward.

In 1960, the American astronomer John Cox further developed the idea and proved that helium is the key to a Cepheid's pulsations. When a star contracts, the gas beneath its surface gets hotter, but the extra heat does not raise the temperature; instead, it ionizes the helium. This ionized helium is very good at absorbing radiation. In other words, it becomes more opaque and absorbs the radiant energy flowing outward through it, toward the surface. This trapped heat

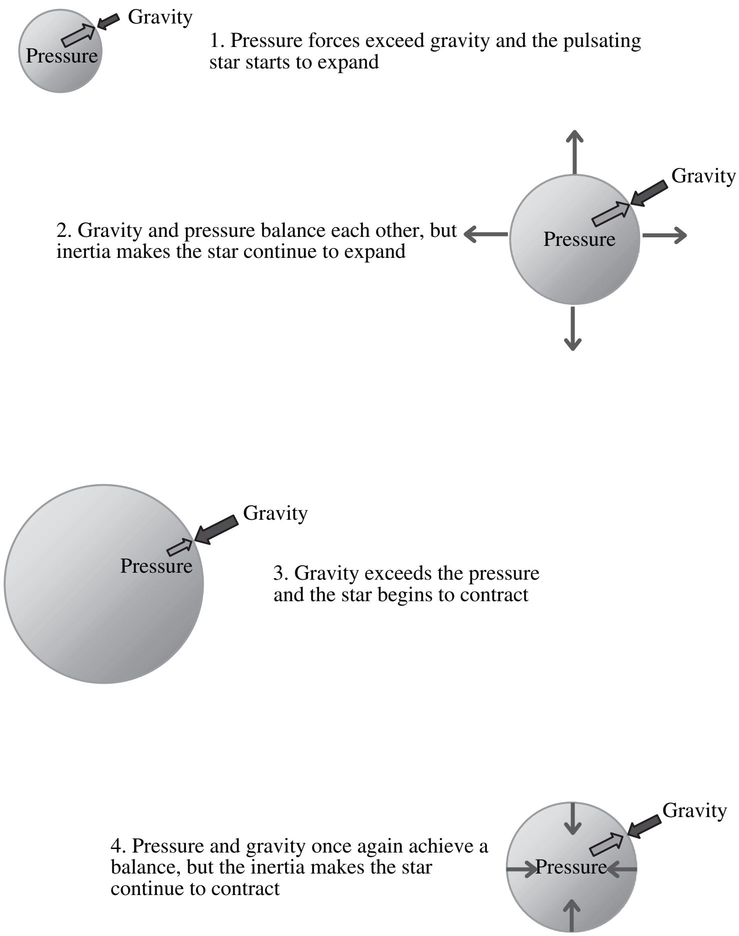


Figure 3.18. Gravity and pressure during the pulsation cycle of a pulsating star.

makes the star expand. This, then, provides the "push" that propels the surface layers of the star back outward. As the star expands, electrons and helium ions recombine, and this causes the gas to become more transparent (i.e., its opacity falls, and so the stored energy escapes).

For a star to be susceptible to pulsations, it must have a layer beneath its surface in which the helium is partially ionized. The existence of such a layer will depend not only on the size and mass of a star, but also on its surface temperature, which, in most cases, will be in the range of 5000 to 8000 K. There is a region on the *H-R* diagram where such an area exists, and it is the location of the pulsating stars. It is called the *instability strip*. In this region are found the Cepheid variable and RR Lyrae stars.

3.13.2 Cepheid Variables and the Period-Luminosity Relationship

Cepheid variables are named after *δ Cephei*, which was the first star of its type to be discovered. It is a yellow giant star that varies by a factor of two in brightness over 5.5 days.[35] Figure 3.19 shows the variations of *δ Cephei* in luminosity, size, and temperature.

You will notice immediately that its luminosity and temperature have a maximum value when its size has a minimum value, and vice-versa; its size is at maximum when its luminosity and temperature are at minimum. Cepheids are very important for astronomers for two reasons. They can be seen at extreme distances, perhaps as great as a few million pc. This is because they are very luminous, with a range from a few hundred to a few tens of thousands of solar luminosity (i.e., $100\,L_\odot$ to $10,000\,L_\odot$). Second, there exists a relationship between the period of a Cepheid and its average luminosity. The very faintest Cepheids (which are in fact hundreds of times brighter than the Sun) pulsate with a very rapid period of only one or two days, while the brightest (as much as 30,000 times brighter than the Sun) have a much slower period of about 100 days. The correlation between the pulsation period and luminosity is called the *period-luminosity relationship*. If a star can be identified as a Cepheid, and its period measured, then its luminosity and absolute magnitude can be determined. This can then be used, along with its apparent magnitude, to determine its distance.

The amount of metals in a Cepheid star's outer layers will determine how it pulsates. This occurs because the metals can have a substantial effect on the opacity of the gas. They can then be classified according to their metal content. If

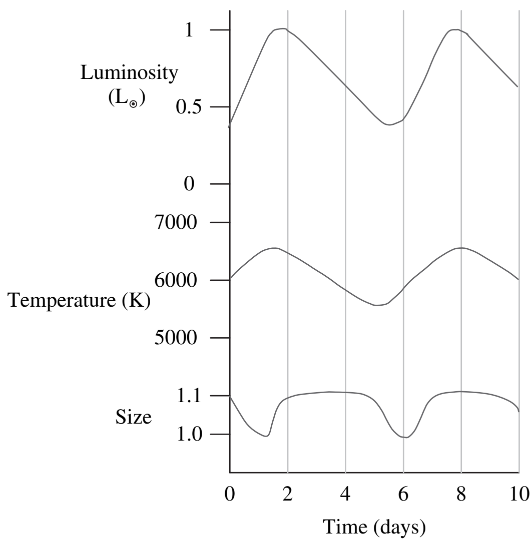


Figure 3.19. The size, temperature, and luminosity of δ Cephei during one period.

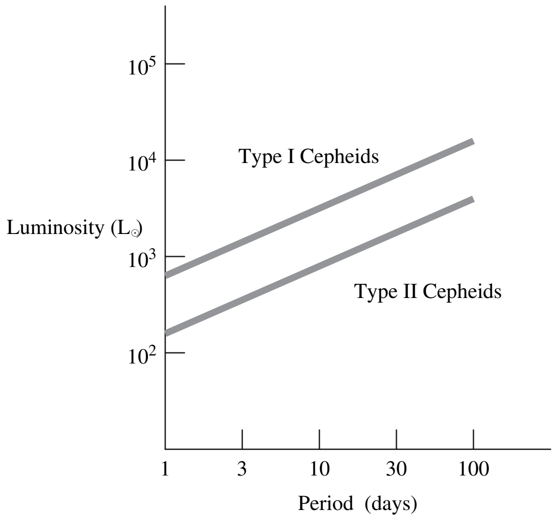


Figure 3.20. Period-luminosity relationship for the two types of Cepheid variable star.

a Cepheid is a metal-rich *Population I* star,[36] it is called a *Type I Cepheid*, and if it is a metal-poor *Population II* star, it is called a *Type II Cepheid*. Figure 3.20 shows a period-luminosity diagram for the two types of Cepheids. So, an astronomer must first determine what type of Cepheid he or she is observing before the period-luminosity relationship can be applied.

3.13.3 Cepheids: Temperature and Mass

The period-luminosity relationship comes about because the more massive stars are also the most luminous stars as they cross the *H-R* diagram during core helium-burning. These massive stars are also larger in size and lower in density during this period of core-helium-burning, and the period with which a star pulsates is larger for lower densities; so, the massive pulsating stars have greater luminosities and longer periods. This is shown in Figure 3.21.

We have seen that old, high-mass stars have evolutionary tracks that cross back and forth in the *H-R* diagram, and thus will intercept the upper end of the instability strip. Such stars become Cepheids when the helium ionizes at just the right depth to drive the pulsations. Those stars on the left (high temperature) of the instability strip will have helium ionization occurring too close to the surface and will involve only a small fraction of the star's mass. The stars on the right (low-temperature) side will have convection in the star's outer layers, and this will prevent the storage of the heat necessary to drive the pulsations. Thus, Cepheid variable stars can only exist in a very narrow temperature range.

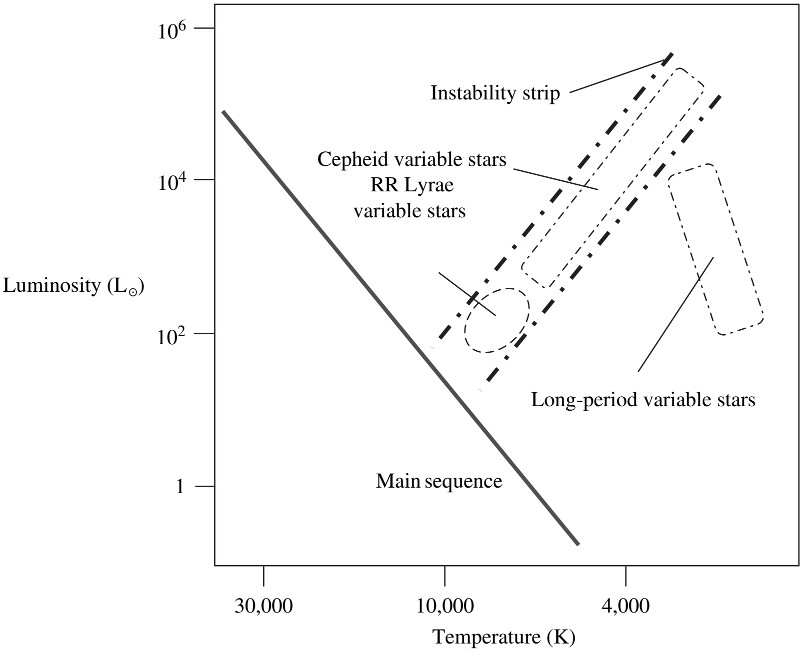


Figure 3.21. Instability strip and evolutionary tracks for stars of different mass.

3.13.4 RR Lyrae and Long-Period Variable Stars

The faintest and hottest stars on the instability strip are the *RR Lyrae stars*. These stars have a much lower mass than Cepheids. After the helium flash occurs, their evolutionary tracks pass across the lower end of the instability track as they move across the horizontal branch of the *H*-*R* diagram. The RR Lyraes, named after the prototype in the constellation *Lyra*, all have periods shorter than Cepheids, of about 1.5 hours to 1 day. They are small and dense stars compared with the Cepheids (but are nearly 10 times larger and about 100 times more luminous than the Sun). The RR Lyrae region of the instability strip is in fact a segment of the horizontal branch. They are all metal-poor Population II stars, and so many are found in globular clusters.

The *long-period variables* are cool red giant stars that can vary by as much as a factor of 100, in a period of months or even years. Many have surface temperatures of about 3500 K and average luminosities in a range of 10 to as much as $10,000\,L_\odot$. They're placed on the middle right-hand side of the *H*-*R* diagram. Many are periodic, but there are also a few that are not. A famous example of a periodic long-period variable star is *Mira* (*o* Ceti) in *Cetus*. A famous non-periodic long-period variable star is *Betelgeuse* (α Orionis) in *Orion*. It may come as a surprise to you to know that we do not fully understand why some cool red giant stars become long-period variable stars.

There are many pulsating stars that can be observed by the amateur astronomer, and in fact several organizations exist throughout the world that cater specifically to this pastime.[37] However, I shall just describe the brightest members of each of the three aforementioned classes: Cepheid, RR Lyrae, and long-period variable stars. All that is needed in observing these stars is a degree of patience, as the changes in magnitude can take as little as a few days to several hundred days, and, of course, clear skies.

The nomenclature used in this list is the same as that used before, with a few changes. The apparent magnitude range of the variable is given, along with its period in days.

3.13.5 Bright Cepheid Variables

δ Cephei	**HD 213306**	**$22^h29.1^m$**	**+58°25′**	Jul–**Aug**–Sep
3.48–4.37 m	**−3.32M**	**5.37 days**	**F3–G3**	**Cepheus**

This is the prototype star of the classic short-period pulsating variables known as Cepheids. It was discovered in 1784 by the British amateur astronomer John Goodricke. It is a favorite with amateurs, as several bright stars also lie in the vicinity—*Epsilon* (ε) *Persei* (4.2m), *Zeta* (ζ) *Persei* (3.4m), *Zeta* (ζ) *Cephei* (3.35m), and *Eta* (η) *Cephei* (3.43m). The behavior of the star is as follows: it will brighten for about 1 1/2 days and will then fade for 4 days, with a period of 5 days, 8 hours, and 48.2 minutes. Delta Cephei is also a famous double star, with the secondary star (6.3m) an attractive white color, which contrasts nicely with the yellowish tint of the primary.

η Aquilae	**HD 187929**	**$19^h52.5^m$**	**+01°00′**	Jun–**Jul**–Aug
3.48–4.39m	**−3.91M**	**7.17 days**	**F6 – G4**	**Aquila**

This is a nice Cepheid to observe, as its variability can be seen with the naked eye. The rise to brightest magnitude takes 2 days, and thereafter slowly fades. The nearby star *Beta* β *Aquilae* (3.71 m) is often used as a comparison. It is the third-brightest Cepheid (in apparent magnitude), after *Delta Cephei* and *Polaris*. The actual period is 7 days, 4 hours, 14 minutes, and 23 seconds!

RT Aurigae	**HD 45412**	**$06^h28.6^m$**	**+30°29′**	Nov–**Dec**–Jan
5.29–6.6m	**−2.65M**	**3.73 days**	**F5 – G0**	**Auriga**

Also known as *48 Aurigae*, this star was discovered to be a variable in 1905 by T. Astbury, who was a member of the British Astronomical Association. The rise to maximum takes 1½ days, with a diminishing over 2½ days. Easy to observe in binoculars, it lies midway between *Epsilon* (ε) *Geminorum* (3.06 m) and *Theta* (θ) *Auragae* (2.65 m). The period has been measured to an astounding accuracy to be 3.728261 days!

α Ursae Minoris	**ADS 1477**	**$02^h31.8^m$**	**+89°16′**	Sep–**Oct**–Nov
1.92–2.07 m	**−3.64 M**	**3.97 days**	**F7 : Iib–Iiv**	**Ursa Minor**

Possibly the most famous star in the sky. *Polaris*, or the *Pole star*, is located less than a degree from the celestial pole. It is one of the Type II Cepheids, which are also known as *W Virginis* variable stars. The magnitude changes are very small and therefore not really detectable with the naked eye. Polaris also consists of double color, namely a yellowish primary and a faint whitish-blue secondary at a magnitude of 8.2. The primary is also a Population II Cepheid variable and a spectroscopic binary. Although claims have been made to the effect that the system can be resolved in an aperture as small as 4.0 cm, at least 6.0 cm will be required to split it clearly. Will be closest to the actual pole in 2102 A.D.

Other Cepheid variable stars that can be observed with amateur equipment are: *U Aquilae, Y Ophiuchi, W Sagittae, SU Cassiopeiae, T Monocerotis*, and *T Vulpeculae*.

3.13.6 Bright RR Lyrae Variables

RR Lyrae	**HD 182989**	**$19^h 25.3^m$**	**+42°47′**	Jun–**Jul**–Aug
7.06-8.12m	**1.13 M**	**0.567 days**	**see text below***	**Lyra**

This is the prototype of the RR Lyrae class of pulsating variable stars. These are similar to Cepheids but have shorter periods and lower luminosities. There are no naked-eye members of this class of variable, and *RR Lyrae* is the brightest member. There is a very rapid rise to maximum, with the light of the star doubling in less than 30 minutes, with a slower falling in magnitude. From an observational viewpoint, it is a nice white star, although detailed measurements have shown that it does become blue as it increases in brightness. There is some considerable debate as to the changes in spectral type that accompany the variability. *One source quotes A8–F7, while the other is A2–F1. Take your pick. There is also some indication that there is another variability period along with the shorter one, which lasts about 41 days.

Other RR Lyrae variable stars are: *RV Arietis*, *RW Arietis*, and *V467 Sagittari*; however, all of these stars are faint and so will present a considerable challenge to observers.

3.13.7 Long-Period Variables

Mira	**o Cet**	**$02^h 19.3^m$**	**−02°59′**	Sep–**Oct**–Nov
2.00-10m	**−3.54M**	**331.96 days**	**M9–M6e**	**Cetus**

An important star, and maybe the first variable star ever observed. Written records certainly exist as far back as 1596. The prototype of the long-period pulsating variable, it varies from 3rd to 10th magnitude over a period of 332 days, and it is an ideal star for the first-time variable star observer. At minimum, the star is a deeper red color, but, of course, fainter. It now has a lower temperature of 1900 K. The period, however, is subject to irregularities, as is its magnitude, and can be longer, or shorter, than the quoted average of 332 days. It has been observed for maximum light to reach 1st magnitude, similar to *Aldebaran*! One of the oddities about *Mira* is that the change in spectral class does not occur exactly with maximum, but rather a few days later! Another oddity is that when Mira is at its faintest, it apparently is also at its largest, when you would think the opposite to be true. A reason for this has been put forward recently: the star produces titanium oxide in its atmosphere as it cools and expands. The compound then acts as a filter, blocking out the light. The name *Mira* is Arabic for "wonderful star."

Other Mira-type stars are *R Leonis* and *R Leporis*, both of which have been described in earlier sections.

3.14 The Death of Stars

Stars live for millions, billions, and even hundreds of billions of years,[38] and so you may be thinking how on Earth can we know anything about how a star dies? After all, we have only been on a planet that is about 4.5 billion years old and studying astronomy for about 10,000 years. Well, fortunately for us, it is nevertheless possible to observe the many disparate ways in which a star can end its life.

Once again, it is the mass of a star that decides how it will end its life, and the results are spectacular and sometimes very strange indeed. Low-mass stars can end their lives in a comparatively gentle manner, forming beautiful, and apparently delicate structures that we know as *planetary nebulae*, before proceeding to small and ever-cooling white dwarf stars. At the other end of the scale, high-mass stars tend to end their lives in a far more spectacular fashion by exploding! These are the rare *supernovae*.

We begin our journey by looking at stars that have a low mass.

3.15 The Asymptotic Giant Branch

Let's recap briefly how low-mass stars (and by this I mean stars with a mass of about $4\,M_\odot$ and less), behave after leaving the main sequence. When core hydrogen-burning ceases, the core will shrink, and this heats up the surrounding hydrogen gas, and so hydrogen-shell burning begins. The outer layers of the star will expand but also cool, and so the star becomes a red giant. The post-main-sequence star will move up and to the right on the *H-R* diagram as its luminosity increases and temperature falls. We can say that the star now lies on the *red-giant branch* of the *H-R* diagram. The next stage involves the onset of helium-burning in the core. If a star has a high mass (greater than about $2–3\,M_\odot$), then this starts gradually, but if the star has a lower mass, this stage begins suddenly, in what is called the helium flash. But no matter which way it starts, a result of the helium-burning is that the core actually cools down, with a resulting slight decrease in luminosity. The outer layers of the star also contract a little, heating up in the process, and so the evolutionary track of the red giant now moves left across the *H-R* diagram. The luminosity during this phase remains more or less constant, so the path is nearly horizontal, and so is called the *horizontal branch*. Stars on the horizontal branch are stars in which helium-burning is occurring in the core, which in turn is surrounded by a shell of hydrogen-burning. Many such stars are often found in globular clusters.

We can now look at the next stage of a star's life. Recall from Section 3.10.1 that by-products of the triple α process are the elements carbon and oxygen. So after a suitably long period of time, maybe 100 million years, we could expect all of the helium in the core to have been converted into carbon and oxygen. This would mean that core-helium-burning would cease. A similar process to that (which was explained in Section 3.10.2) then begins. The absence of nuclear fusion results in a contraction of the core because there is no energy source to provide the internal pressure necessary to balance the force of gravity. The core contraction is stopped, however, by degenerate electron pressure, which is something we met earlier. A result of the core-contraction is a release of heat into the helium gas surrounding the core, and so helium-burning begins in a thin shell around the carbon–oxygen core. This is aptly called *shell helium-burning*.

Now an extraordinary thing happens: the star enters a second red-giant phase. It is as if history has repeated itself. Stars become red giants at the end of their main-sequence lifetimes. The shell hydrogen-burning phase provides energy, causing the outer layers of the star to expand and cool. In a similar fashion, the energy from the helium-burning shell also causes the outer layers to expand, and so the low-mass star rises into the red-giant region of the *H-R* diagram for a second time. But this time it has an even greater luminosity.

This phase of a star's life is often called the *asymptotic giant branch* phase, or *AGB*. Thus, these stars are called AGB stars and are on the *asymptotic giant branch* of the main sequence.

The structure of an AGB star is shown in Figure 3.22. Its central region is a degenerate carbon–oxygen mix surrounded by a helium-burning shell, which in turn is surrounded by a helium-rich shell. This is further surrounded by a hydrogen-burning shell. All of this is further encompassed by a hydrogen-rich outer layer. What is truly remarkable is the size of these objects. The core region is about the same size as the Earth, while the hydrogen envelope is immense. It can be as large as the orbit of the Earth! When the star has aged, however, the outer layers, which are expanding, cause the hydrogen-burning shell to also expand and thus cool, and so the nuclear reactions occurring therein may cease, albeit temporarily.

The luminosity of these stars can be very high indeed. For example, a $1\,M_\odot$ AGB star may eventually attain a luminosity of $10,000\,L_\odot$. Compare this with the luminosity of only $1000\,L_\odot$ it is achieves when it reaches the helium-flash phase, and the poor $1\,L_\odot$ when it resides on the main sequence. It is sobering to think ahead and imagine what will happen when the Sun becomes an AGB star in about 8 billion years from now!

There are many AGB stars that can be observed by amateurs, and in fact we have already mentioned and described several of them: the archetypal AGB star is *Mira* (o Ceti), but there are also *R Leonis*, *R Leporis*, *R Aquarii*, and

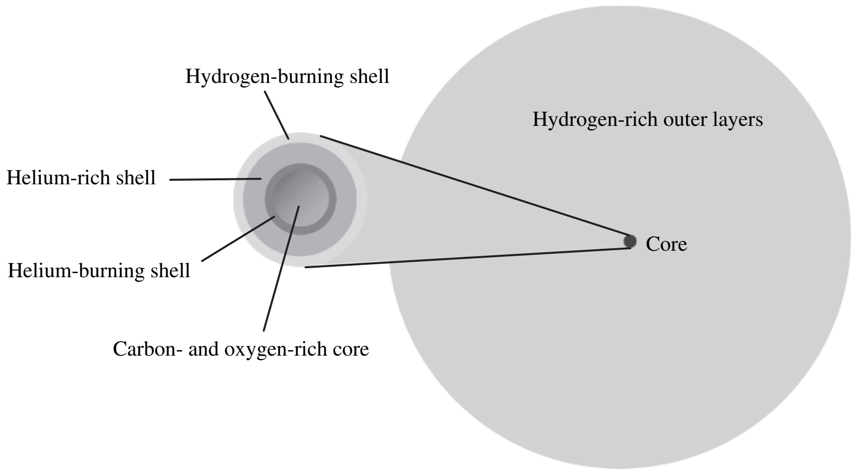


Figure 3.22. The structure of an AGB star.

R Cassiopea. In addition, there are a few others, although they are somewhat fainter. These include *χ Cygni*, *W Hydrae*, *S Pegasi*, and *TT Monocerotis.*

3.16 Dredge-Ups

We have seen that energy and heat are transported from a star's core to the surface by two methods: convection and radiation. Convection is the motion of the star's gases moving upwards toward the surface, and then cooling of the gases so that it falls downwards. This method of energy transfer is very important in giant stars. Radiation, or radiative diffusion as it is also sometimes called, is the transfer of energy using electromagnetic radiation, and is only important when the gases in a star are transparent (the opacity is low). When a star ages and leaves the main sequence, the convective zone can increase substantially in size, and sometimes extend right down to the core. This means that the heavy elements, or metals, that are formed there can be carried to the star's surface by convection. This process has the very unglamorous name of *dredge-up*. The *first dredge-up* begins when the star becomes a red giant for the first time (i.e., core hydrogen-burning phase has stopped). The by-products of the CNO[39] cycle of hydrogen are transported to the surface because the convective zone now reaches deep into the core regions. A *second dredge-up* begins when the helium-burning phase ends. Then, during the AGB phase, a *third dredge-up* occurs, but only if the mass of the star is greater than $2\,M_{\odot}$, when a large amount of newly formed carbon is carried to the star's surface. The spectrum of a star that has such a carbon-enriched surface exhibits very prominent absorption bands of carbon-rich elements, such as C_2, CH, and CN. Such stars that have undergone a third dredge-up are often called *carbon stars*.

3.17 Mass Loss and Stellar Winds

As a star continues to rise up the AGB, it increases in both brightness and size, and, consequently, it develops a very strong stellar wind. This blows the star's outer layers into interstellar space. Thus, the star undergoes a substantial mass loss during this phase, maybe as much as 10^{-4} $M_{\odot}$ per year (this is about 1000 times greater than the mass loss of a red giant star, and about 10 billion times the mass loss of the present-day Sun). The cause of these extreme stellar winds is still a puzzle, although the surface gravity of AGB stars is very low because the stars are so large; thus, any sort of disturbance on the star surface is capable of expelling material outwards. The outer layers of the star flow outward at 10 km per second (about 2% of the speed of the solar wind), cooling as they move from the star. Dust particles can thus form in the cooler surrounding gas formed out of the ejected carbon-rich molecules. In fact, it is believed that tiny grains of soot are formed! Many carbon stars have been observed, surrounded by cocoons of carbon-rich matter. In some cases, the dust cloud is so thick that it can totally obscure the star, absorbing all the emitted radiation. The dust then heats up, and re-emits the energy, but this time in the infrared.

3.18 Infrared Stars

It may come as a surprise to know that AGB stars, which can have luminosities 10,000 times that of the Sun, were, until the 1960s, hardly known. The reason for this is simple: the dust that surrounds the star, and re-emits the radiation, is so cool that the reradiated energy is almost entirely in the infrared part of the spectrum. This is, of course, invisible to the naked eye, and it has only been explored in detail in the past 30 years. This is shown in Figure 3.23. These stars

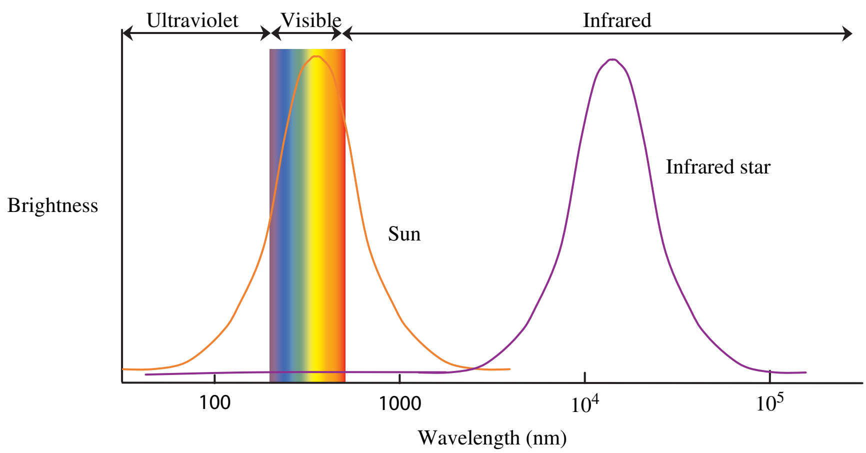


Figure 3.23. The spectra of an infrared star compared with the Sun.

are very faint, or even invisible in the visible part of the spectrum. By comparison, the Sun is very bright in the visible part of the spectrum, and very faint in the infrared. The surface of an infrared star can be thought of as starting at the surface layer of the dust cloud, and for some AGB stars, this can have a radius as much as 500 AU, which is about 10 times the size of the Solar System. These outer layers of the star are extremely tenuous and hold only a fraction of its total mass. The vast majority of the mass is in the carbon-oxygen core and the energy-forming layers that surround it. So, we can picture an infrared star as having a very small and dense central part and an enormous, low-density outer layer.

Most of the energy emitted by the Sun is in the visible part of the spectrum. In comparison, nearly all of the energy radiated from the dust surrounding an infrared star is invisible to the naked eye.

3.19 The End of an AGB Star's Life

As it ages, an AGB star continues to grow in size and increase its luminosity, along with an increase in the rate at which it loses mass. As mentioned earlier, the mass loss can be $10^{-4}\,M_{\odot}$ per year, which means that if the Sun lost mass at this rate, it would only last for 10,000 years. So, obviously, even giant stars cannot carry on this way for very long. If a star has a mass of less than about $8\,M_{\odot}$, its stellar wind will soon strip away the outer layers almost down to the degenerate core. Therefore, a loss of the outer layers would signal the end of the AGB phase. For stars that are greater than $8\,M_{\odot}$, the end of the AGB phase arrives in a much more spectacular event—a supernova…which will be discussed in a later section.

I would like to end this section on the AGB part of a star's life with a sobering and amazing thought. Carbon stars enrich the interstellar medium with not only carbon, but with some nitrogen and oxygen, as well. In fact, carbon can only be formed by the triple α process that occurs in helium-burning, and carbon stars are the main means by which the element carbon is dispersed throughout the interstellar medium. The part that always amazes me is when I consider that the carbon in my body, and in fact in the body of every living creature on the Earth, was formed many billions of years ago, inside a giant star undergoing the triple α process. It was then dredged up to the star's surface and expelled into space. Later, by some means, it formed the precursor to the Solar System and made the Sun and planets, and all life on the Earth.

We are made of the stuff of stars!

One of the benefits of a carbon star, from the point of view of an observer, is that many of the rare carbon stars are visible in the night sky with amateur instruments. We have already come across a few of these: *R Leporis, RS Cygni*, and *19 Piscium*. But there are several more that are worth seeking out, and I have listed those on the following pages. The one aspect of these stars that will be immediately apparent to you is their color; all of them are strongly red colored. They are, in fact, the reddest stars visible to the amateur astronomer.

3.19.1 Bright Carbon Stars

X Cnc	**HD 76221**	**$08^h55.4^m$**	**+17°14′**	Jan–**Feb**–Mar
6.12_vm	**B–V: 2.97**	**C6**		**Cancer**

An extremely orange star, this semi-regular variable star, classification SRB, has a period of 180 to 195 days and has been observed to range in magnitude from 5.6 to 7.5.

La Superba	**Y CVn**	**$12^h45.1^m$**	**+45°26′**	Mar–**Apr**-May
5.4_vm	**B–V: 2.9**	**C7**		**Canes Venatici**

The color of this star (red) is best seen through binoculars or a small telescope. With a period of 159 days and varying in magnitude between 4.9 and 6.0 m, this red giant has a diameter of 400 million kilometres.

V Pav	**HD 160435**	**$17^h43.3^m$**	**−57°43′**	May–**Jun**–Jul
6.65_vm	**B–V: 2.45**	**C5**		**Pavo**

A red giant variable star, class SRB, varying in brightness from 6.3 to 8.2 m over a period of 225.4 days. It also has a secondary period of about 3735 days. A glorious deep-red color.

V Aql	**HD 177336**	**$19^h04.4^m$**	**−05°41′**	Jun–**Jul**–Aug
7.5_vm	**B–V: 5.46**	**C5**		**Aquila**

A semi-regular variable star with a period of about 350 days, varying in magnitude from 6.6 to 8.1 m. A very deep red in color.

S Cephei	**HD 206362**	**$21^h35.2^m$**	**+78°37′**	Jul–**Aug**–Sep
7.9_vm	**B–V: 2.7**	**C6**		**Cepheus**

A moderately difficult star to observe due to its magnitude range of 7 to 12 m; nevertheless, it has a very high color index, making it one of the reddest stars in the sky, if not *the* reddest. Its red color immediately strikes you and, once seen, is never forgotten.

R Scl	**HD 8879**	**$01^h26.9^m$**	**−32°33′**	Sep–**Oct**–Nov
5.79_vm	**B–V: 1.4**	**C6**		**Sculptor**

A semi-regular-period variable star, with a period ranging between 140 and 146 days; it varies in brightness from 5.0 to 6.5.

U Cam		**$03^h41.8^m$**	**+62°39′**	Oct–**Nov**–Dec
8.3_vm	**B–V: 4.9**	**N7**		**Camelopardalis**

A semi-regular variable star, period 412 days with a magnitude range of 7.7 to 9.5 m. It has a very deep red color.

W Ori	**HD 32736**	**$05^h0.4^m$**	**+01°11′**	Nov–**Dec**–Jan
6.3_vm	**B–V: 3.33**	**N5**		**Orion**

A red giant variable star, classification SRB, with a period of 212 days, although a secondary period of 2450 days is believed to occur. Varies in magnitude from 5.5 to 7.7m. A deep-red star.

R Corona Borealis	**HD 141527**	**$15^h48.6^m$**	**+28°09′**	Apr–**May**–Jun
5.89_vm	**B–V:0.608**	**G0I ab:pe**		**Corona Borealis**

Although not strictly a carbon star, *R Cor Bor*, as it is known affectionately, should be mentioned here. It is the prototype variable star of the class RCB. What makes this star so special is that it is an irregular variable, usually seen at maximum brightness, but then suddenly fading down to 12th magnitude, which can last for several weeks, months, or even as long as a year.[40] Then, just as suddenly, it can return to its normal brightness. The reason for this strange behavior is that carbon grains condense out in the star's atmosphere, thus blocking out the light from the star. Radiation then causes the grains to dissipate, and so the star returns to its usual magnitude. The cycle then begins again with the grains building up over time. Other stars that show a similar behavior are *RY Sagittarii* (6.5 m), *SU Tauri* (10 m), and *S Apodis* (10 m).

3.20 Planetary Nebulae

At the end of the AGB phase, all that will remain of a star is the degenerate core of carbon and oxygen, surrounded by a thin shell in which hydrogen-burning occurs. The dust ejected during the AGB phase will be moving outward at tens of kilometers per second. As the debris moves away, the hot, dense, and small core of the star will become visible. The aging star will also undergo a series of bursts in luminosity, and during each burst, eject a shell of material into interstellar space. The star now begins to move rapidly toward the left of the *H-R* diagram, at an approximately constant luminosity but at an increasing temperature. It will only take, say, a few thousand years for the surface temperature to reach 30,000 K. Some stars achieve temperatures of 100,000 K. At these high temperatures, the exposed core of the star will emit prodigious amounts of ultraviolet radiation, which can excite and ionize the expanding shell of gas. The shell of ionized and heated gas will begin to glow and produce what is called a *planetary nebula*.

We know that as the helium in the helium-burning shell is depleted, the pressure that supports the dormant hydrogen-burning shell decreases. Therefore, the hydrogen-burning shell contracts and heats up, thereby initiating hydrogen-burning. This newly started hydrogen-burning creates helium, which falls down upon the temporarily dormant helium-burning shell. If the shell temperature reaches a specific value, it reignites in what is called the helium-shell flash, similar to (but less intense than) the helium flash that occurs in the evolution of low-mass stars. The newly created energy pushes the hydrogen-burning shell outward, cooling it as it does so, which results in a cessation of the hydrogen-burning, and the shell becomes dormant once again. The process then starts all over again.

The luminosity of the AGB star increases quite substantially when the helium shell flash occurs, although it is only for a relatively short time. This short-lived burst is called a *thermal pulse*. After a thermal pulse has occurred, the star resumes its former appearance until enough helium builds to allow another thermal pulse to occur. With each thermal pulse, the mass of the degenerate core, consisting of carbon and oxygen, will increase. For the very massive stars, the thermal pulse occurs in the very deep interior of the star and produces only a slight, temporary change in luminosity. For a star of mass $1\,M_\odot$, a thermal pulse would be close enough to the surface to cause the luminosity to increase by a factor of 10 and last about 100 years. The time between thermal pulses varies depending on the star's mass, but calculations predict that they would occur at ever-decreasing intervals, perhaps as short as 100,000 to 300,000 years, while the luminosity of the star during this time would slowly increase overall.

Significant mass loss can also occur during thermal pulses. A star's outer layers can separate completely from the carbon- and oxygen-rich core, and as the ejected material disperses into space, grains of dust can condense out of the cooling gas. The radiation from the very hot core can propel the dust grains farther, and so the star sheds its outer layers completely. In this manner, a star of mass, say, $1\,M_\odot$ can lose about 40% of its mass. Even more mass is lost by the massive stars. As the dying star loses its outer layers, the hot core is exposed and it illuminates the surrounding dust and gas cloud.

The evolution of the remaining core is itself of interest as it progresses rapidly to its final state. There are two factors that can influence the rate at which the core evolves. First, due to the star's extreme luminosity (which can be as high as $100,000\,L_\odot$), it consumes its hydrogen at a very fast rate. Second, little hydrogen remains in the thin hydrogen-burning shell that surrounds the degenerate core, so there is hardly any fuel left to be consumed. The central stars of some planetary nebulae have as little as a few millionths of a solar mass of hydrogen left to burn, and so they fade very rapidly. In fact, some can have their luminosities decrease by as much as 90% in as little as 100 years, whereas others may require a bit longer, perhaps a few thousand years. As the source of ionizing photons decreases over time, the planetary nebulae grow darker and eventually fade away.

Planetary Nebulae[41] are some of the most interesting and beautiful objects in the sky, and they have a lot to offer to the amateur. They range across the whole of the observational spectrum: some are easy to find in binoculars, while others require a large aperture, patience, and maybe even specialized filters to be distinguished from the background star fields. These small shells of gas, the atmosphere of stars come in a variety of shapes, sizes, and brightnesses. Many have a hot central star within the nebula, which is visible in amateur equipment and is the power source, providing the energy for the gas to glow.

Several nebulae have a multiple-shell appearance, and this is thought to be due to the red giant experiencing several periods of pulsation where the material escapes from the star. The strong stellar winds and magnetic fields of the star are also thought to be responsible for the many observed exotic shapes of the nebulae. Planetary nebulae are only a fleeting feature in our Galaxy; after only a few tens of thousands of years, they will have dissipated into interstellar space, and so no longer exist. Thus, the planetary nebulae we observe today cannot be older than about 60,000 years. However, this aspect of a star's evolution is apparently very common, and there are more than 1400 planetary nebulae in our part of the Galaxy alone!

Visually, the nebulae are one of the few deep sky objects that actually appear colored. About 90% of their light comes from the doubly-ionized oxygen line, OIII, at wavelengths 495.9 nm and 5000.7 nm. This is characteristic of blue-green color and, it so happens, the color at which the dark-adapted eye is at its most sensitive. Specialized light filters are also extremely useful for observing planetaries, as they isolate the OIII light in particular, increasing the contrast between the nebulae and the sky background, thus markedly improving the nebulae's visibility.

Such is the variety of shapes and sizes that there is something to offer all types of observers. Some planetaries are so tiny that even at high magnification, using large-aperture telescopes, the nebulae will still appear starlike. Others are much larger. For instance, the *Helix Nebula*, *Caldwell 63*, is half the size of the full Moon but can only be observed with low magnification and perhaps only in binoculars, as any higher magnification will lower its contrast to such an extent that it will simply disappear from view. Many, such as the *Dumbbell Nebula,* M27, in *Vulpecula*, exhibit a bipolar shape. Still others show ring shapes, such as the ever-popular *Ring Nebula, M57*, in *Lyra*.

An interesting aspect is the possibility of observing the central stars of the nebulae. These are very small subdwarf and dwarf stars. They are similar to main-sequence stars of types O and B, but, as they are running down their nuclear reactions, or in some cases, no longer producing energy by nuclear reactions, they are consequently fainter and smaller. These two characteristics make observation very difficult. The brightest central star is possibly that of *NGC 1514* in *Taurus*, at 9.4 magnitude, but the majority are at magnitude 10 or fainter.

There is a classification system called the *Vorontsoz-Vellyaminov Classification System*, which can be used to describe the appearance of a planetary. Although it is of limited use, it will be used here.

Planetary Nebulae Morphology Types

1 Starlike
2 Smooth disc-like appearance
    a. bright toward center
    b. uniform brightness
    c. possible faint ring structure
3 Irregular disc-like appearance
    a. irregular brightness distribution
    b. possible faint ring structure
4 Definite ring structure
5 Irregular shape
6 Unclassified shape*
    * can be a combination of two classifications,
    (e.g., 4 + 3, ring and irregular disc)

The usual information is given for each object, with the addition of morphology class [⊙] and central star brightness [❅]. In addition, the magnitude quoted is the magnitude of the planetary nebula as if it were a source point. This last parameter can often be confusing, so even if a nebula has a quoted magnitude of, say, 8, it may be much fainter than this and, consequently, hard to find.

3.20.1 Bright Planetary Nebulae

Caldwell 39	**NGC 2392**	**$07^h29.2^m$**	**+20°55′**	Dec–**Jan**–Feb
8.6m	**⊕15″**	**⊙3b+3b**	**❅9.8**	**Gemini**

Also known as the *Eskimo Nebula*. This is a small but famous planetary nebula, which can be seen as a pale blue dot in a telescope of 10 cm, although it can be glimpsed in binoculars as the apparent southern half of a double star. Higher magnification will resolve the central star and the beginning of its characteristic "Eskimo" face. With an aperture of 20 cm, the blue disc becomes apparent. Research indicates that we are seeing the planetary nebula pole-on, although this is by no means certain. Its distance is also uncertain, with values ranging from 1600 to 7500 l.y.

Caldwell 59	**NGC 3242**	**$10^h24.8^m$**	**−18°38′**	Jan–**Feb**–Mar
8.4m	**⊕16″**	**⊙4+3b**	**❅12.1**	**Hydra**

Also known as the *Ghost of Jupiter*. One of the brighter planetary nebulae and the brightest in the spring sky for northern observers, this is a fine sight in small telescopes. Visible in binoculars as a tiny blue disc. With an aperture of 10 cm, the blue color becomes more pronounced along with its disc, which is approximately the same size as that of Jupiter in a similar aperture. The central star has a reported temperature of about 100,000 K.

Messier 97	**NGC 3587**	**$11^h14.8^m$**	**+55°01′**	Feb–**Mar**–Apr
9.9m	**⊕ 194″**	**⊙3a**	**❅16**	**Ursa Major**

Also known as the *Owl Nebula*. Not visible in binoculars due to its low surface brightness; apertures of at least 20 cm will be needed to glimpse the "eyes" of the nebula. At about 10 cm aperture, the planetary nebula will appear as a very pale blue-tinted circular disc, although the topic of color in regard to this particular planetary nebula is in question.

Caldwell 6	**NGC 6543**	**$17^h58.6^m$**	**+66°38′**	May–**Jun**–Jul
8.3m	**⊕18|350″**	**⊙3a+2**	**❅11**	**Draco**

Also known as the *Cat's Eye Nebula*. This is seen as a bright oval planetary nebula with a fine blue–green color. Caldwell 6 is one of the planetary nebula that became famous after the HST published its image. Visible even in a telescope of 10 cm, but a large telescope (20 cm) will show some faint structure, while to observe the central star requires a 40 cm aperture. The incredibly beautiful and complex structure is thought to be the result of a binary system, with the central star classified as a *Wolf–Rayet* star.

Messier 57	**NGC 6720**	**$18^h53.6^m$**	**+33°02′**	Jun–**Jul**–Aug
8.8m	**⊕71′**	**⊙4+3**	**❅15.3**	**Lyra**

Also known as the *Ring Nebula*. The most famous of all planetary nebulae, surprisingly—and pleasantly—visible in binoculars. However, it will not be resolved into the famous "smoke-ring" shape seen so often in color photographs; it will, rather, resemble an out-of-focus star. It is just resolved in telescopes of about 10 cm aperture, and at 20 cm the classic smoke-ring shape becomes apparent. At high magnification (and larger aperture), the Ring Nebula is truly spectacular. The inner region will be seen to be faintly hazy, but a large aperture and perfect conditions will be needed to see the central star.

Caldwell 15	**NGC 6826**	**$19^h44.8^m$**	**+50°31′**	Jun–**Jul**–Aug
8.8m	**⊕ 25″**	**⊙ 3a+2**	**❋ 11**	**Cygnus**

Also known as the *Blinking Planetary*. A difficult planetary nebula to locate, but well worth the effort. The blinking effect is solely due to the physiological structure of the eye. If you stare at the central star long enough, the planetary nebula will fade from view. At this point, should you move the eye away from the star, the planetary nebula will "blink" back into view at the periphery of your vision. Although not visible in amateur telescopes, the planetary nebula is made up of two components: an inner region consisting of a bright shell and two *ansae* (delicate protuberances from either side), and a halo that is delicate in structure with a bright shell.

Messier 27	**NGC 6853**	**$19^h59.6^m$**	**+22°43′**	Jun–**Jul**–Aug
7.3m	**⊕ 348″**	**⊙ 3+2**	**❋ 13.8**	**Vulpecula**

Also known as the *Dumbbell Nebula*. This famous planetary nebula can be seen in small binoculars as a box-shaped hazy patch, and many amateurs consider it the sky's premier planetary nebula. In apertures of 20 cm, the classic dumbbell shape is apparent, with the brighter parts appearing as wedge shapes that spread out to the north and south of the planetary nebula's center, and a central star may be glimpsed.

Herschel 16	**NGC 6905**	**$20^h22.4^m$**	**+20°05′**	Jun–**Jul**–Aug
11.1m	**⊕ 40″**	**⊙ 3+3**	**❋ 15.5**	**Delphinus**

Also known as the *Blue Flash Nebula*. The true nature of this planetary nebula only becomes apparent at apertures of at least 20 cm, when the lovely blue color is seen. The central star can be seen only under good seeing conditions.

Caldwell 55	**NGC 7009**	**$21^h04.2^m$**	**−11°22′**	Jul–**Aug**–Sep
8.3m	**⊕ 25″**	**⊙ 4+6**	**❋ 12.78**	**Aquarius**

Also known as the *Saturn Nebula*. Although it can be glimpsed in small apertures, a telescope of at least 25 cm is needed to see the striking morphology of the planetary nebula that gives it its name. There are extensions, or ansae, on either side of the disc, along an east–west direction, which can be seen under perfect seeing conditions. High magnification is also justified in this case. Recent theory predicts a companion to the central star, which may be the cause of the peculiar shape.

Caldwell 63	**NGC 7293**	**$22^h29.6^m$**	**−20°48′**	Jul–**Aug**–Sep
6.3m	**⊕ 770″**	**⊙ 4+3**	**❋ 13.5**	**Aquarius**

Also known as the *Helix Nebula*. Thought to be the closest planetary nebula to the Earth, at about 450 l.y., it has an angular size of over 1/4°—half that of the full Moon. However, it has a very low surface brightness, and is thus notoriously difficult to locate. With an aperture of 10 cm, low magnification is necessary, and averted vision is useful to glimpse the central star. The use of an OIII filter will drastically improve the image.

Caldwell 22	**NGC 7662**	**$23^h25.9^m$**	**+42°33′**	Aug–**Sep**–Oct
8.6m	**⊕ 12″**	**⊙ 4+3**	**❋ 13.2**	**Andromeda**

Also known as the *Blue Snowball*. This planetary nebula is visible in binoculars due to its striking blue color, but it will only appear stellar-like. Research indicates that the planetary nebula has a structure similar to that seen in the striking HST image of the Helix Nebula, showing *Fast Low-Ionization Emission Regions* (Fliers). These are clumps of above-average-density gas ejected from the central star before it formed the planetary nebula.

Messier 76	**NGC 650**	**$01^h42.4^m$**	**+51°34′**	Sep–**Oct**–Nov
10.1m	**⊕ 65″**	**⊙ 3+6**	**❋ 15.9**	**Perseus**

Also known as the *Little Dumbbell Nebula.* This is a small planetary nebula that shows a definite non-symmetrical shape. In small telescopes of aperture 10 cm, and using averted vision, two distinct "nodes" or protuberances can be seen. With apertures of around 30 cm, the planetary nebula will appear as two bright but small discs that are in contact. Even larger telescopes will show considerably more detail.

Herschel 53	**NGC 1501**	**$04^h07.0^m$**	**+60°55′**	Oct–**Nov**–Dec
11.5m	**⊕ 52′**	**⊙ 3**	**❋ 14.5**	**Camelopardalis**

Also called the *Oyster Nebula*. A blue planetary nebula, easily seen in telescopes of 20 cm and glimpsed in apertures of 10 cm. With a larger aperture, some structure can be glimpsed, and many observers liken this planetary nebula to that of the *Eskimo Nebula*.

3.21 White Dwarf Stars

We now look at the endpoint for low-mass stars, and it is a very strange end indeed. We have seen that stars with a mass of less than $4\,M_\odot$ never manage to produce the internal pressure and temperature necessary to provide the means to burn the carbon and oxygen in the core. What happens instead is an ejection of the star's outer layers, leaving behind the very hot carbon-oxygen-rich core. In such a scenario, the core has stopped producing energy by nuclear fusion and so just cools down, admittedly over a vast time scale. These cooling relics are called *white dwarf* stars. In many instances, they are no bigger than the Earth.

3.21.1 Electron Degeneracy

Experience tells us that as the mass of an object increases, so does its size, and this applies for many astronomical objects, such as stars on the main sequence. However, the opposite is true for white dwarfs. The more massive a white dwarf star, the smaller it is. This contrary behavior has to do with the electron structure of the material of the white dwarf. Increasing the density of an object will lead to an increase in pressure, as observed in main-sequence stars, but the pressure in a white dwarf star (which is, remember, the core of a once-much-larger star) is produced by degenerative electrons.[42] This electron degenerate pressure supports the star. An increase in density, however, also leads to an increase in gravity. For the white dwarf star, this increased gravity will exceed the increase in pressure, and so the star will contract. As it gets smaller, both the gravity and pressure increase further and come into balance with each other, but at a smaller size for the white dwarf. This means the more massive a white dwarf star, the smaller it is. As an example, a $0.5\,M_{\odot}$ white dwarf star is about 90% larger than the Earth, whereas a $1\,M_{\odot}$ white dwarf star is only about 50% larger than the Earth. If the white dwarf is $1.3\,M_{\odot}$, then it is only 40% as large as the Earth.

3.21.2 The Chandrasekhar Limit

White dwarf stars have a very unusual mass-radius relationship, shown in Figure 3.24. As you can see, the more degenerate matter you put into a white dwarf star, the smaller it gets. However, you cannot do this ad infinitum, as there is a maximum mass that a white dwarf can have. This mass, which is about $1.4\,M_{\odot}$, is called the *Chandrasekhar limit*, named after the Indian scientist who first seriously studied the behavior of white dwarfs. It is the mass for which the

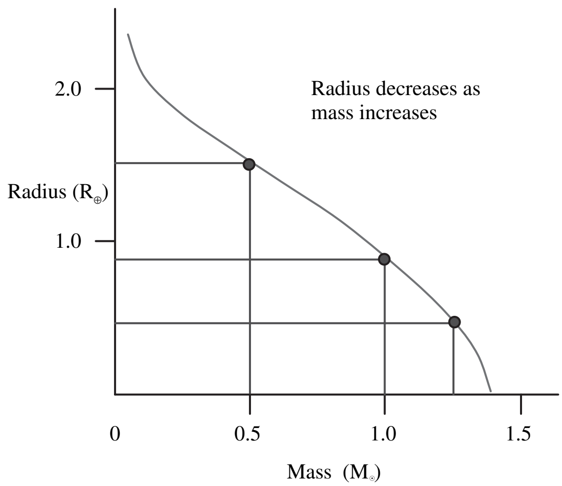


Figure 3.24. Mass-radius relationship for white dwarf stars.

mass-radius relationship drops to zero, so that a white dwarf star with a mass equal to the Chandrasekhar limit will shrink to a very small size. But no star with a mass greater than 1.4 $M_\odot$ can be supported against the crush of gravity by the pressure of the degenerate electrons. This means that the main-sequence stars of types O, B, and A, which have masses greater than the Chandrasekhar limit, will need to shed mass if they are to become white dwarf stars. This they do while becoming AGB stars, as we saw earlier. But not all stars do achieve the necessary mass loss, and in such cases where the contraction cannot be stopped by degenerate electrons, the stars collapse even further to become neutron stars, and perhaps even black holes.

The radius is given in terms of the Earth's radius. The more massive a white dwarf, the smaller it will be. Note that on this graph, the size of a white dwarf will fall to zero if it has a mass of 1.4 $M_\odot$.

A question that is often asked is, "What is a white dwarf star made of?" The answer is surprising. The matter making up the white dwarf star consists mostly of ionized oxygen and carbon atoms, which are floating in a sea of fast-moving degenerate electrons. As the star continues to cool, the particles in this matter slow down, resulting in electric forces between the ions beginning to dominate the random thermal motions they may have originally had. These ions no longer move freely through the white dwarf but are aligned in orderly rows, rather like a giant crystal lattice. It is appropriate to think of the white dwarf as being "solid," with the degenerate electrons still moving freely in the crystal lattice, just as electrons move in, say, a copper wire. Another interesting point to make is that a diamond is a crystal lattice of carbon, so a cooling white dwarf star can also be thought of as a (sort of) giant spherical diamond. The density in a white dwarf star is immense, typically 10^9 kg m^{-3}. This is about one million times the density of water. One of the statistics astronomers like to throw out is that one teaspoon of white dwarf matter weighs about 5.5 tons, equal to the weight of an elephant...providing, of course, that you could get a teaspoon of the matter to the Earth in the first place.

3.21.3 White Dwarf Evolution

When a white dwarf shrinks to its ultimate size, it will no longer have fuel available for nuclear fusion. It will, however, still have a very hot core and a large reservoir of residual heat. For example, the surface temperature of a famous white dwarf star, *Sirius B*, is about 30,000 K. Time will pass, and with it, the white dwarf will cool down as it radiates its heat into space. As it does so, it will also grow dimmer, as shown in Figure 3.25, where white dwarf stars of differing mass are plotted on an *H-R* diagram. The more massive a white dwarf star, the smaller its surface area vs. less-massive white dwarfs. This means that massive white dwarfs are less luminous for a given temperature, so their evolutionary tracks are below those of the less-massive white dwarf stars.

Theoretical models of the evolution of white dwarfs have been constructed and they show that a white dwarf with a mass of 0.6 $M_\odot$ will fade to 0.1 $L_\odot$ in about 20 million years. Any further reductions in luminosity take progressively longer

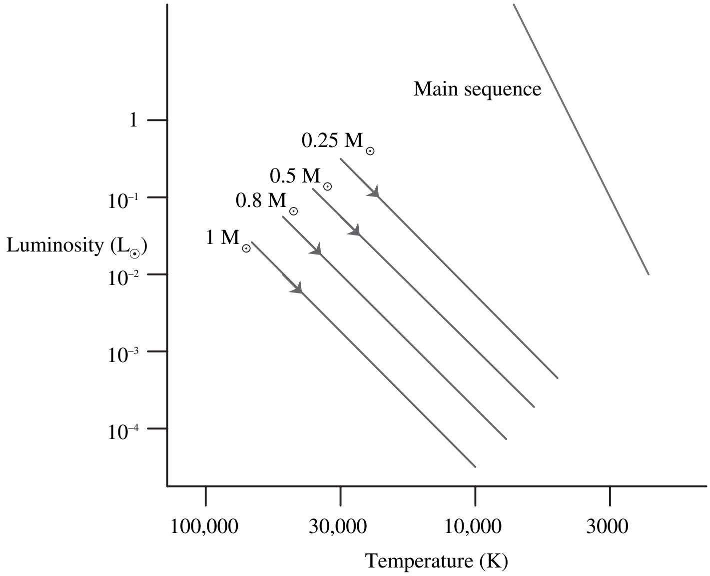


Figure 3.25. White dwarf evolutionary tracks.

amounts of time. This means that it will take 300 million years to fade to about $0.01\,L_\odot$, and a billion years to get to $0.001\,L_\odot$. It will take about 6 billion years for the white dwarf to reach a luminosity of $0.0001\,L_\odot$. At this point, the white dwarf will have the same temperature and color of the Sun. It will be so faint, however, that unless it were within a few pc of the Earth, it would be undetectable. Those white dwarf stars with masses greater than $0.6\,M_\odot$ have more internal heat and so will take an even longer time to cool down and grow faint.

In the case of the Sun, it will eject most of its mass into space and eventually end up about the same size as the Earth, but its luminosity will change dramatically, perhaps only achieving one-tenth the brightness it presently has. As it ages further, it will continue to grow even fainter. When about 5 billion years have passed, the Sun will only be able to achieve one ten-thousandth of its present luminosity. As time passes into the unimaginable future, it will simply fade from view!

A white dwarf will cool and grow fainter, so it moves downwards and to the right on the *H-R* diagram. The more massive a white dwarf, the smaller and fainter it will be. Therefore, the track for a $1\,M_\odot$ white dwarf will lie below the track for less-massive white dwarfs. Note that although a white dwarf may have the same temperature as a main-sequence star, it will be fainter because it is small, and thus has a smaller surface area.

3.21.4 White Dwarf Origins

It is now believed that most, if not all, white dwarfs have evolved directly from the central stars of planetary nebulae. These, in turn, are the former cores of

AGB stars. We saw earlier that during the AGB phase, a star will lose much of its mass via a cool stellar wind. If the star strips away sufficient mass to one that is lower than the Chandrasekhar limit, a carbon-oxygen rich core of matter surrounded by a very thin layer of helium-rich gas is the result. In some cases, there may even be a thin outer layer of hydrogen-rich gas. The star and expelled gas are now a planetary nebula, and at the moment nuclear fusion ends, a white dwarf is born.[43] But even though theory matches well with observations, there is still uncertainty as to the mass that the star may have originally been to lose enough mass to become a white dwarf star. Current ideas suggest a mass limit of $8\,M_{\odot}$. Those main-sequence stars that have a mass between 2 and $8\,M_{\odot}$ produce white dwarfs of mass 0.7 and $1.4\,M_{\odot}$, whereas main-sequence stars less than $2\,M_{\odot}$ produce white dwarfs of mass 0.6 to $07\,M_{\odot}$. If a white dwarf star has a mass less than $0.6\,M_{\odot}$, the progenitor main-sequence star will have a mass less than $1\,M_{\odot}$. What is incredible about these lower-mass stars is that their main-sequence lifetimes are so incredibly long, the universe is not yet old enough for them to have evolved into white dwarf stars. This means that there are no white dwarf stars with a mass less than about $0.6\,M_{\odot}$. The timescale for the evolution from giant star to white dwarf can take between 10,000 and 100,000 years.

Due to their faintness and small size, white dwarf stars present a challenge to observers. There are, of course, many of them in the night sky, and those amateur astronomers with large telescopes of, say, aperture 25 cm in diameter and larger will have no problem locating and observing them. On the other hand, there are a handful that, given the right conditions, can be seen with much more modest instruments. These are the ones I shall outline below. The symbol ⊕ indicates the size of the white dwarf star as compared with the Earth (thus, $0.5_{\oplus}$ would mean that it is half the size of the Earth).

3.21.5 Bright White Dwarf Stars

Sirius B		**06^{h}45.1^m**	**−16°43′**	Dec–**Jan**–Feb
8.4m	**11.2M**	**0.92$_{\oplus}$**	**27,000 K**	**Canis Majoris**

The companion star to the brightest star in the sky (*Sirius*) is a white dwarf known as the *Pup*, the first ever to be discovered. It is a difficult, though not impossible, star to observe for two main reasons. First, it is overcome by the dazzling primary star, and so the light from Sirius often needs to be blocked out by some means. In fact, if *Sirius B* were not a companion to Sirius, it would be easily visible in binoculars. Second, its orbit changes over a period of 50 years. This means that at certain times it will be too close to Sirius to be detected with amateur instruments. The next time it will be at maximum separation is the year 2025.

Procyon B	α **Canis Minoris**	**07^{h}39.3^m**	**+05°13′**	Dec–**Jan**–Feb
10.9m	**13.2M**	**1.05$_{\oplus}$**	**8700 K**	**Canis Minoris**

This dwarf star is not easily visible in small amateur telescopes, having a magnitude of 10.8 and a mean separation of 5 arcsecs. Note that it has a low temperature compared with other white dwarfs. It is the second-closest white dwarf to the Earth. A challenge to observers.

o^2 **Eradani 40**	**Eridani B**	**$04^h15.2^m$**	**−07°39′**	Oct–**Nov**–Dec
9.5m	**11.0M**	**1.48$_\oplus$**	**14,000 K**	**Eridanus**

Even though this is a challenge to split with binoculars, it is nevertheless the easiest white dwarf star to observe. The star will be in a prime observing position relative to its brighter primary star for the next 50 years or so. What makes this system so interesting is that the secondary is the brightest white dwarf star visible from Earth. In addition, under high magnification, the white dwarf will be seen to have a companion star of its own—a red dwarf star! All in all, a nice triple star system.

Van Maanen's Star Wolf 28		**$00^h49.1^m$**	**+05°25′**	Aug-**Sep**-Oct
12.3m	**14.1M**	**0.9(?)$_\oplus$**	**6000 K**	**Pisces**

One of the few stars visible to amateurs, it is a close white dwarf, at only 13.8 l.y. distant. It is located about 2° south of *δ (delta) Piscium*. Discovered by A. Van Maanen in 1917 due to its large proper motion of 2.98 arcsecs per year.

3.22 High-Mass Stars and Nuclear Burning

We now turn our attention to high-mass stars. As you have probably surmised by now, the death throes of these stars are very different than and spectacular compared with those of low-mass stars.

Throughout the entire life of a low-mass star (that is, one that is less than 4 $M_\odot$), only two nuclear reactions occur: hydrogen-burning and helium-burning, and the only elements besides hydrogen and helium that are formed are carbon and oxygen. Stars that have a zero-age mass greater than 4 $M_\odot$ begin their lives in a similar manner, but theory predicts that due to the increased mass, and therefore higher temperatures involved, other nuclear reactions will occur. The tremendous crush of gravity is so overwhelming that degeneracy pressure is never allowed to come into play. The carbon-oxygen core is more massive than the Chandrasekhar limit of 1.4 $M_\odot$, and so the degenerate pressure cannot stop the core from contracting and heating.

The nuclear reactions that take place in the star's final phase of its life are very complex, with many different reactions occurring simultaneously. But the simplest sequence of fusion involves what is termed *helium capture*; this is the fusing of helium into progressively heavier elements.[44] The core continues to collapse with an accompanying rise in temperature to about 600 million K. At this high temperature, the helium capture can give rise to *carbon-burning*, and the carbon can be fused into heavier elements. The elements oxygen, neon, sodium, and magnesium are produced. The carbon fusion provides a new source of energy that, albeit temporarily, restores the balance between pressure and gravity. If the star, however, has a mass greater than $8\,M_{\odot}$, even further reactions can occur. In this phase, the carbon-burning may only last a few hundred years. As the core contracts further, the core temperature reaches 1 billion K, and *neon-burning* begins. In this manner, the neon produced by the earlier carbon-burning reaction is used up, but at the same time, there is an increase in the amount of oxygen, and magnesium in the star's core. This reaction lasts as little as 1 year. As you can imagine, with each stage of element burning, higher temperatures are reached, and further reactions occur; oxygen-burning will occur when the reaches 1.5 billion K, with the production of sulphur. *Silicon-burning* can also occur if the core reaches the staggering temperature of 2.7 billion K. This reaction produces several nuclei, from sulphur to iron.

Despite the very dramatic events that are occurring inside the high-mass star, its outward appearance changes only slowly. When each stage of core nuclear fusion stops, the surrounding shell-burning intensifies and therefore inflates the star's outer layers. Then, each time the core flares up again and begins further reactions, the outer layers may contract slightly. This results in the evolutionary track of the star zigzagging across the top of the *H-R* diagram.

Some of the reactions that occur also release neutrons, which are particles similar to protons, but they do not have an electric charge. This neutrality means that they can, and do, collide with positively charged nuclei and combine with them. The absorption of neutrons by nuclei is termed *neutron capture*. In this way, many elements and isotopes that are not produced directly in the fusion reactions are produced.

Each stage during this phase of a high-mass star's life helps to initiate the subsequent phase. As each phase ends due to the star's using up the specific fuel in its core, gravity will cause the core to contract to an ever-higher density and temperature, which in turn is responsible for starting the next phase of nuclear-burning. In effect, you can think of each stage burning the "ash" of the previous one.

An interesting point to make here is that we tend to think of astronomical events taking place over many millions of years. However, theoretical calculations have shown that when we are dealing with high-mass stars, events can proceed at a very fast pace, with each successive stage of nuclear-burning proceeding at an ever-increasing rate. One calculation has been made in detail for $20–25\,M_{\odot}$ zero-age stars, and the results are very surprising. The carbon-burning stage can last for about 600 years, while the neon-burning stage can be as short as 1 year. Then things start to speed up! The oxygen-burning lasts only 6 months, and the silicon-burning only 1 day!

At each phase of core-burning, a new shell of material is formed around the core of the high-mass star, and after several such stages, say, a very massive star of mass $20–25\,M_{\odot}$, the internal structure of the star can resemble an onion (shown in Figure 3.26).

Nuclear reactions are taking place in several different shells simultaneously, and the energy released does so at such a rapid rate that the star's outer layers can expand to an immense size. The star can now be called a *supergiant* star. The luminosity and temperature of such stars are much higher than those of a mere giant star.

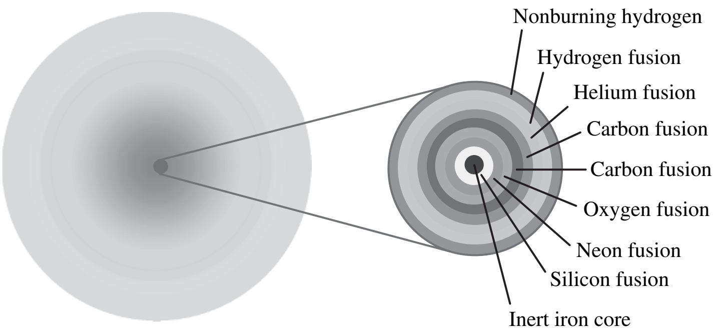


Figure 3.26. The multiple-layer structure of an old high-mass star.

Many of the brightest stars in the night sky are supergiants. These include *Rigel* and *Betelgeuse* in *Orion* and *Arcturus* in *Scorpius*. Rigel has a temperature of 11,000 K, while Betelgeuse is only 3700 K (or even cooler) and is an example of a "red supergiant." Thus, although Betelgeuse is cooler, it must be correspondingly larger for it to be as bright as Rigel. Oddly enough, red supergiants are rare, perhaps even rarer than the O-type stars. One current estimate predicts that there is only one red supergiant star for every million stars in the Milky Way, and only about 200 have ever been studied.

What makes these stars stand out is their immense size. The radius of Betelgeuse has been measured to be about 700 times that of the Sun, or 3.6 astronomical units. This can be better appreciated this way: if it were placed in the Solar System, it would extend past the asteroid belt to about half-way between the orbits of Mars and Jupiter. Antares would extend nearly to Jupiter! Alpha Herculis is only 2 astronomical units in radius. The record, however, must go to *VV Cephei*, which is an eclipsing binary star. Its radius is a staggering 1900 times that of the Sun, or 8.8 astronomical units. This means that it would nearly extend to Saturn.

As I mentioned earlier, supergiant stars are quite rare, but fortunately for observers, there are some we can see with the naked eye. These are listed below.

3.22.1 Bright Supergiant Stars

CE Tauri	**HD 36389**	**$05^h32.2^m$**	**+18°35′**	Nov–**Dec**–Jan
4.38m	**−6M**	**M 2 Iab**		**Taurus**

Also known as *119 Tauri*, this star has a radius of 2.9 astronomical units and lies about 2000 l.y. from us. It has the odd distinction of being classified as both a semi-regular and irregular variable star, meaning it is an erratic variable star, and so its period is difficult to predict with any certainty. It lies within a field of stars of similar brightness, which makes it difficult to locate unless a good star atlas is handy.

Mu Geminorum	**HD 44478**	**$06^h12.3^m$**	**+22°54′**	Nov–**Dec**–Jan
6.51m	**−4.09M**	**M2 Iab**		**Gemini**

Part of the *Gem OB1* stellar association, is at the limit of naked-eye visibility as observed from an urban location. It lies at a distance of 4900 l.y.

Other stars that are supergiants and were mentioned in earlier sections are: Rigel, Betelgeuse, Antares, Mu Cephei, Eta Persei, ψ^{-1} Aurigae, and VV Cephei.

Before we leave supergiant stars, I should mention a class of stars that are similar to supergiants, and these are the *Wolf-Rayet* stars. These are very hot, very luminous supergiant stars, similar to O-type stars, but they have very strange spectra that show only emission lines and, strangely enough, no hydrogen lines. Wolf-Rayet stars are believed to be precursors to the formation of planetary nebulae. They are few and far between, with perhaps only 1000 in our Galaxy. They have a terrific mass loss, and images from large telescopes show these stars surrounded by rich clouds of ejected material. Fortunately for us, there is a very bright example that can be easily observed.

γ^2 Vel	**HD 68273**	**$08^h09.5^m$**	**−47°20′**	Dec−**Jan**−Feb
1.99_vm	**0.05 M**	**WC 8**		**Vela**

The brightest and closest of all *Wolf–Rayet* stars. γ^2 *Vel* is an easy double, colors white and greenish-white.

This aspect of a supergiant's life, whereby several layers of nuclear-burning occur, resembling the layers of an onion, cannot go on forever, as there is only a finite amount of material to burn. Thus, a point comes when the high-mass star undergoes yet another change, but this time, with catastrophic consequences. It is star death, but in a spectacular manner—a *supernova*.

3.23 Iron, Supernovae, and the Formation of the Elements

When nuclei in the core collide and fuse, energy is emitted, and it is this energy flowing from the core and surrounding shells of nuclear-burning that supports the tremendous weight of material making up a star. The energy is a consequence of the strong nuclear force of attraction between neutrons and protons, or *nucleons*, as they are sometimes called. But you may recall that protons also repel each other by what is called the weak electric force. This has profound consequences for the life of the high-mass star.

Up to this point, energy has been released (i.e., the energy has been output, but, due to the repulsive effect, if any protons are added to nuclei larger than iron, which has itself 26 protons, then energy must be input to the system). What this means is that any nuclei greater than iron will not release any energy. Therefore, the various stages of nuclear-burning end with the production of silicon. After that, iron can be formed, but there will be no release of energy associated with its formation. The result is an iron-rich core that has no nuclear reactions taking place within it.

Of course, surrounding this inert core of iron will be the various shells of nuclear burning.[45] However, this is a state of affairs that cannot continue for much longer.

Astronomers use a variety of techniques to find out about the life of a star. Observations are made, and then theoretical models are devised so that they fit the observations. In the case of supernovae, it can be said that most, if not all, of what we know about supernovae comes from theoretical and mathematical calculations. After all, it is not easy to see what is happening in the central regions of a star! You will also see that we are now talking about densities, pressures, and velocities that will stagger our comprehension. With this in mind, note that the following descriptions of the events in a high-mass star are theoretical predictions, albeit ones that seem to fit the observations.[46]

During these final days of a star, the core of inert iron, in which there are no nuclear reactions taking place, is surrounded by shells of silicon, oxygen, neon, carbon, helium, and hydrogen. The core, which can be thought of as essentially a white dwarf star surrounded by the outer layers of a red giant star, is supported by the pressure of its degenerate electrons. There is a limit to the mass of a white dwarf star—the Chandrasekhar limit—and so when the core surpasses this limit, its weight becomes too great to be supported by the degenerate electrons and it collapses.

A consequence of the core contraction is an increase in the density, which in turn gives rise to a process called neutronization. This is a process where-by electrons react with the protons in the iron nuclei to form neutrons. This is shown below.

$$e^- + p \rightarrow n + \nu$$

Each neutronization reaction will also produce a neutrino. Now more and more electrons will react with the protons, and so there are fewer left to support the core, and so resist the compression. This results in a speeding up of the contraction and actually could be better termed a collapse of the core. It only takes about a second for the core to collapse from a radius of thousands of kilometers to about 50 km. Then, in only a few seconds, it shrinks down to a 5-kilometer radius. The core temperature also increases during this time to about 500 million K. The gravitational energy released as a result of the core collapse is equal to the Sun's luminosity for several billion years. Most of this energy is in the form of neutrinos, but some is also in the form of gamma rays, which are created due to the extremely hot core temperature. These gamma ray photons in turn have so much energy that when they collide with the iron nuclei, the nuclei are broken down into alpha particles (which are ^{4}He nuclei). This process is called *photo-disintegration*.

After a short interval of time, which is thought to be about 0.25 seconds, the central 0.6 to 0.8 $M_\odot$ of the collapsing core will reach a density equal to that of atomic nuclei, that is, some 4×10^{27} kg m^{-3}. At this point, the neutrons become degenerate and strongly resist any further attempts of compression. To get an idea of what this density means, the Earth would have to be compressed to a sphere 300 meters in diameter. For all intents and purposes, the core of the star can now be thought of as a neutron star, and the innermost part of the core suddenly becomes rigid, and the contraction abruptly halts. This innermost part actually rebounds outward and pushes back against the rest of the infalling core, driving it outward in a pressure wave. This is called the *core bounce*, and it is illustrated in Figure 3.27.

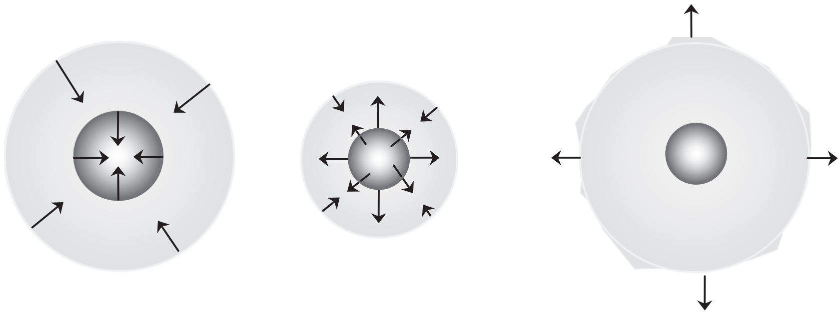


Figure 3.27. Evolution of a supernova explosion.

The core also cools at this stage, and this causes the pressure to decrease significantly in those regions that surround the core. If you recall, there is a balancing act between the pressure pushing upward and gravity falling downward, and a consequence of this reduced pressure is that the material surrounding the core now falls inward at a velocity close to 15% of the speed of light. This inward-moving material encounters the outward-moving pressure wave, which, incidentally, can be moving at one-sixth the speed of light. In just a fraction of a second, the falling material now moves back outward toward the star's surface.

Surprisingly enough, this wave of pressure would soon die out, long before it reached the surface of the star, if it were not for the fact that helping it along is the immense number of neutrinos that are trying to escape the star's core. The upward-moving wave of pressure speeds up as it encounters the less-dense regions of the star and achieves a speed in excess of the speed of sound in the star's outer regions. The pressure wave now behaves like a shock wave.

These neutrinos actually escape from the star in a few seconds, but it takes a few hours for the shock wave to reach the surface. Most of the material of the star is pushed outward by this shock wave and is expelled from the star at many thousands of kilometers per second. The energy released during this event is a staggering 10^{46} J, which is 100 times more than the entire output of the Sun during the last 4.6 billion years. It will surprise you to know that the visible light we observe is only about 1% of the total energy released during the event.

Recent studies have proposed that up to 96% of the material making up the star may be ejected into the interstellar medium that, of course, will be used in future generations of star formation. But before this matter is ejected, it is compressed to such a degree that new nuclear reactions can occur within it, and it is these reactions that form all the elements that are heavier than iron. Elements such as tin, zinc, gold, mercury, lead, and uranium, to name a few, are produced, and this has profound implications because it means that the stuff that makes up the Solar System, the Earth, and in fact us, was formed long ago in a supernova.

The expansion of the star's surface due to the shock wave is the cause of the tremendous increase in luminosity that we observe, but after several months, the surface will cool, and so the brightness will fade. During this later-stage time, the main source of the supernova's light is in fact the radioactive decay of nickel and cobalt nuclei, which were produced in the supernovae event. These decaying nuclei are able to keep the supernova shining for many years.

As an observer, it would be delightful if you could go out and just pick a supernovae a that you wish to look at. Life is not like that, however from a statistical point of view, there should be about 100 supernovae a year in our Galaxy, and so you would think that you would have a good chance of observing one. The most recent bright supernova, in 1987, was in fact in another galaxy completely—The Large Magellanic Cloud—and the last bright one in our Galaxy was seen several hundred years ago. So why is this? The answer is simple. As we have seen in earlier sections, our Galaxy is filled with dust and gas, and it is this material that blocks out the light from any supernova that may be occurring. That is not to say that we will never see a supernova—far from it; but we cannot predict with any certainty when one will occur, although there are a few stars that we should keep an eye on: Betelgeuse and Eta Carinae.

We can, however, see the remains of a supernova, the *supernova remnant*.

3.23.1 Supernova Remnants

The supernova remnant (usually abbreviated to SNR) represents the debris of the explosion, the layers of the star that have been hurled into space, and the remains of the core that will now be a *neutron star*. The visibility of the remnant actually depends on several factors: its age, whether there is an energy source to continue making it shine, and the original type of supernova explosion.

As the remnant ages, its velocity will decrease, usually from 10,000 km s^{-1} to maybe 200 km s^{-1}. It will, of course, fade during this time. A few SNRs have a neutron star at their center that provides a replenishing source of energy to the far-flung material. The classic archetypal SNR that undergoes this process is the *Crab Nebula*, *M1* in Taurus. What we see is the radiation produced by electrons travelling at velocities near the speed of light as they circle around magnetic fields. This radiation is called *Synchrotron radiation* and is the pearly, faint glow we observe. Some SNRs glow as the speeding material impacts dust grains and atoms in interstellar space, while others emit radiation as a consequence of the tremendous kinetic energies of the exploding star material.

Caldwell 34	**NGC 6960**	**$20^h45.7^m$**	**+30°43′**	Jul–**Aug**–Sep
•3–5	**⊕70|6′**			**Cygnus**

Also known as the *Veil Nebula* (*Western Section*). This is the western portion of the *Great Cygnus Loop*, which is the remnant of a supernova that occurred about 30,000 years ago. It is easy to locate because it is close to the star *52 Cygni*, though the glare from this star makes it difficult to see. The nebulosity we observe is the result of the shockwave from the supernova explosion's impacting on the much-denser interstellar medium. The actual remains of the star have not been detected.

Caldwell 33	**NGC 6992**	**$20^h56.4^m$**	**+31°43′**	Jul–**Aug**–Sep
•2–5	**⊕60|8′**			**Cygnus**

Also known as the *Veil Nebula* (*Eastern Section*). A spectacular object when viewed under good conditions. It is the only part of the loop that can be seen in binoculars and has also also been described as looking like a fish hook. Using a telescope, it becomes apparent why the nebula has been named the *Filamentary Nebula,* as lacy, delicate strands will be seen. However, there is a downside: it is notoriously difficult to find. Patience, clear skies, and a good star atlas will help. A showpiece of the summer sky (when you have finally found it).

–	**IC 2118**	**$05^h06.9^m$**	**−07°13′**	Nov–**Dec**–Jan
•3–5	**⊕180|60′**			**Eridanus**

Also known as the *Witch Head Nebula*. This is a very faint patch of nebulosity, which is apparently the last of a very old supernova remnant. It resembles a long ribbon of material, which can be glimpsed with binoculars. It is glowing by reflecting the light of nearby *Rigel*. Very rarely mentioned in observing guides.

Messier 1	**NGC 1952**	**$05^h34.5^m$**	**+22°01′**	Nov–**Dec**–Jan
•1–5	**⊕6|4′**			**Taurus**

Also known as the *Crab Nebula*. The most famous supernova remnant in the sky, it can be glimpsed in binoculars as an oval light of plain appearance. With telescopes of aperture 20 cm, it becomes a ghostly patch of grey light. In 1968, in its center was discovered the *Crab Pulsar*, the source of the energy responsible for the pearly glow observed, a rapidly rotating neutron star that has also been optically detected. The Crab Nebula is a type of supernova remnant called a *plerion*, which, however, is far from common among supernova remnants.

Sharpless 2–276		**$05^h56.0^m$**	**−02°00′***y*	Nov–**Dec**–Jan
•6.5 ?	**⊕600′**			**Orion**

Also known as *Barnard's Loop*. It seems to be the remains of a very old supernova. Often mentioned in books, but very rarely observed, this is a huge arcing loop of gas located to the east of the constellation Orion. It encloses both the sword and belt of Orion, and if it were a complete circle, it would be about 10° in diameter. The eastern part of the loop is well defined, but the western part is exceedingly difficult to locate and has never to my knowledge been seen visually. Needless to say, perfect conditions and very dark skies will greatly heighten the chances of its being seen.

3.23.2 Supernova Types

Before we bid a fond farewell to Supernovae, and say hello to the final phase of a star's life, I should mention (albeit briefly) that there are two types of supernovae. The classification system used to distinguish the two types is a rather obtuse (for the non-professional astronomer) system based upon whether the supernova has emission lines of hydrogen in its spectrum. *Type I* supernovae do not have these lines, whereas *Type II* do. The supernova we have previously discussed is a Type II supernova. This class of supernova involves the final death throes of a massive star. These stars, as we have seen, have quite a lot of hydrogen left in their outer layers, hence the classification as a Type II. Type I stars, on the other hand, do not have hydrogen emission lines and can be further divided into Types Ia, Ib, and Ic. Type Ia has absorption lines of ionized silicon, and Types Ib and Ic do not. The difference between Ib and Ic is also a spectroscopic one, in that the former has a helium absorption line, whereas the latter does not.

There is a further twist to this story. Types Ib, Ic, and II are massive stars, but Type I stars have had their outer layers stripped away either by a strong stellar wind or by the action of a nearby star (so that the progenitor supernova star is in fact part of a binary star system), and mass is transferred from one star to another. Furthermore, all three are usually found near sites of star formation. This is to be expected, as we know that massive stars have short lives, and so we do not expect them to move far from their birthplace.

Type I supernovae are a different beast altogether. They are usually (but not always) found in galaxies where star formation may be minimal or has even stopped altogether. You can now see that this implies that they originate not from the final phases of massive stars, as described above, but from some other, new phenomenon. Actually, in an earlier section, we discussed stars that are the originators of Type Ia supernovae. These are white dwarf stars that literally explode by thermonuclear reactions. Now, you may think that this is contradictory to what you read earlier, where I said that white dwarf stars do not have any nuclear reactions occurring within them. This is absolutely correct, but in this case, the carbon-rich white dwarf star is part of a binary system where the other star is a red giant.

Recall that as a red giant star evolves, its outer layers expand and it can overflow what is called its *Roche Lobe*. This is the region around a star in which the gravity of the star dominates. Any matter within the Roche Lobe is gravitationally bound to the star, but if the Roche Lobe is filled, then matter can overcome the gravitational attraction of the star and in fact "flow" or be transferred to a companion star.[47] This material then falls onto the white dwarf star. A consequence of this extra material is that the Chandrasekhar limit can be reached, and the increase in pressure will cause carbon-burning to commence deep in the star's interior. This is, of course, accompanied by a resulting increase in temperature.

Normally, this temperature increase would mean a further increase in pressure, resulting in an expansion of the white dwarf, resulting in the star's cooling down, and the carbon burnings ceasing. However, as we have seen, white dwarfs are not normal. They are made of degenerate matter, which means that the increase of temperature results in the carbon-burning reactions proceeding at an ever-increasing rate. This is reminiscent of the helium flash process seen in low-mass stars mentioned earlier. The temperature soon gets so high that the electrons in the white dwarf become non-degenerate, and, simply put, the white dwarf blows itself to bits!

So, we can see that Type I supernovae involve nuclear energy and emit more energy in the form of electromagnetic radiation,[48] whereas Type II involve gravitational energy and emit an enormous number of neutrinos.

All of this, of course, has no bearing on the amateur astronomer who wishes to observe a supernova, as this will not help or hinder you. Nevertheless, it is important to know in case you read in journals or on the WWW that the latest supernovae is of Type Ib (or Ic or Ia or even Type II).

We now move on to the final phase of a star's life, the end result of millions, and even billions, of years of stellar evolution, the end of a long journey.

3.24 The End Result of High-Mass Stars' Evolution: Pulsars, Neutron Stars, and Black Holes

3.24.1 Pulsars and Neutron Stars

The endpoint of a star's life is now in sight, and although these objects are probably forever beyond the vision of amateur astronomers, it is important that we discuss them for the sake of completeness. These objects are either very small (maybe 10 km in radius) or invisible, so for all intents and purposes they are not observable with amateur equipment.[49] They represent the conclusion of a star's evolution and until fairly recently, had never been seen, only predicted. The fascinating properties of these objects could fill a book in itself, so I shall just briefly describe those properties that are relevant to the evolutionary story.

Recall that in a Type II supernova the central $0.6\,M_{\odot}$ of the collapsing core has a density equal to that of the nuclei of atoms, and the neutrons become degenerate. This central core region has become a *neutron star*. In fact, after a supernova explosion has flung all the outer layers of the star into space, what remains (usually) is just the central core region. These neutron stars were actually predicted as far back as 1939 by Robert Oppenheimer and George Volkoff, who calculated the properties of a star made entirely of neutrons.

The actual structure of the star is not completely known, but there are many theoretical models that accurately describe the observations. Many of their properties are similar to those of white dwarf stars. For instance, an increase in the mass of a neutron star will result in a decrease in radius, with a range of radii from 10–15 km. The mass of a neutron star can be from $1.5–2.7\,M_{\odot}$.

But, of course, these figures depend on the calculation being used at the time. Nevertheless, they give a good picture of the star.

Two properties of neutron stars that we can describe in confidence are its rotation and magnetic field. A neutron star rotates at a very rapid rate, as many as hundreds and even thousands of times per second. It does this because of a law of physics called the *conservation of angular momentum*. Although it is a complicated law, it is easy to visualize. Just picture an ice skater spinning around; as she pulls in with her arms, she spins faster. It is the same with the neutron star. The Sun rotates about once every 30 days, but if it were shrunk to the size of a neutron star, it would have a rotation rate of 1000 times per second. We also know that every star has a magnetic field, but imagine compressing that field to the size of a neutron star with the result that it would be enormous. Again, using the Sun as an example, its magnetic field would increase by 10 billion times if it shrunk to the size of a neutron star. The strength of the field of a typical star is about 1 tesla, whereas in a neutron star it can be as high as 100 million tesla.

Some neutron stars are believed to be in a binary system, and material can be transferred from the companion star onto the magnetic pole regions of the neutron star with the matter travelling at perhaps nearly half the speed of light. The material literally crashes onto the star and results in "hot spots." The temperature of these hot spots is high, in the range 10^8 K, and can result in the emission of X-rays. In fact, to casually say they emit X-rays is misleading, as the amount of X-ray emission is tremendous. The total amount of X-ray luminosity can be as high as 10^{31} watts, nearly 100,000 times greater than the total amount of energy emitted by the Sun at ALL wavelengths! These *x-ray bursters* typically flare up and last from a few hours to a few days. Each burst lasts only a few seconds, but then declines in energy and brightness. This type of binary system is called an *X-ray binary pulsar*, and examples are *Hercules X-1* and *Centaurus X-3*.

This leads rather nicely to the subject of *pulsars*. In 1967, a young graduate student at Cambridge (Jocelyn Bell) discovered a source of very evenly spaced pulses of radio emission. The period of the pulses was 1.337 seconds and was very constant to an accuracy of about 1 part in 10 million. The object, designated *PSR 1919 + 21*, was the first pulsar discovered! The problem was trying to explain what this object was. Some theories predicted a neutron star that pulsated in a manner similar to that of a Cepheid variable star, where its size actually changed. One proposal even suggested that these pulsars were in fact messages from an alien civilization. Not surprisingly, this last idea was discounted. Another model was that of a rotating white dwarf star. All of these plausible explanations were eventually discounted and the correct one accepted.

The generally accepted model of a pulsar is one in which the magnetic axis of the neutron star is tipped with respect to its rotation axis. Very energetic particles travel along the magnetic field lines and are literally beamed out from the magnetic poles. As the neutron star rotates around its rotation axis, the beamed radiation sweeps across the Earth and the pulse detected. In some instances, two pulses can be observed per rotation if the beams from both magnetic poles sweep past the Earth. As time passes, the period of a pulsar increases. For instance, a pulsar with a period of 1 second will slow down to a rate of 2 seconds in 30 million years. One observational point to make is that although we know of many pulsars, there are none that have periods of, say, 5 seconds or longer; this would imply that the pulse mechanism must cease after a period of time. So, neutron stars only exist as pulsars for the first tens of millions of years after the supernova explosion.

I mentioned earlier that neutron stars are the remains from a supernova explosion, and that pulsars are rotating neutron stars. So, we would expect to find pulsars at the center of supernova remnants, or SNRs. We do, but so far there are only 3 known SNRs with associated pulsars. There are two reasons for this. To detect a pulsar, the beams have to sweep past the Earth, and if they do not we will not detect them. Second, the supernova remnant will only last a relatively short time, perhaps 100,000 years, before it merges into the interstellar medium and disappears from view. On the other hand, a pulsar can last for millions of years. So, many of the pulsars we observe now are old, with their SNRs having dispersed.

An example of a pulsar at the center of an SNR, and probably the most famous, is the one in the *Crab Nebula* designated *PSR 0531-21*. In fact, the energy from the pulsar is responsible for the pearly glow and appearance of the nebula, and it is caused by synchrotron radiation produced by high-velocity electrons spiralling around the magnetic field. An SNR that has a filled-in appearance as opposed to a shell-like appearance is termed a *plerion*.

I mentioned in the section on white dwarfs that there is a limit to a white dwarf's mass (the Chandrasekhar limit), beyond which the star cannot support the weight of the material making it up. Not surprisingly, there is also a limit to the mass a neutron star can support. Current estimates put this figure at about 2–3 $M_{\odot}$. In some supernovae, the most massive outer layers may not have been dispersed into space during the explosion, and matter may fall back onto the already-dense core. This extra material may push the neutron star core above its limit, and neutron degeneracy pressure will not be able to fend off gravity.

The core will continue to collapse catastrophically, and not even the increasing temperature and pressure can halt the inevitable result. In fact, according to Einstein's famous equation, $E = mc^2$, energy is equivalent to mass and so the energy associated with the incredible pressure and temperatures concentrated in the now-tiny core acts like additional mass, thus hastening the collapse. To the best of our knowledge, nothing can stop the crush of gravity. The core collapses without end, forming a *black hole*. We have reached the end of a star's life.

3.24.2 Black Holes

We now discuss an object that everyone has heard about, but not many really understand—a black hole. It is one of those things that has gripped the public's imagination, what with its fabled inescapable pull of gravity and its possible use as a means of stellar transportation. However, it will surely come as a surprise to many of you to know that although a rigorous description of a black hole would entail a thorough background in Tensor Calculus and General Relativity, the broad description of such an exotic object is quite simple, and it is very easy to calculate a few of its basic characteristics. Let us begin.

Following the previous section's description of the formation of a neutron star and subsequent supernova, if the core of the star contains about 3 or more solar masses, nothing will stop its collapse even beyond the neutron degeneracy stage. In fact, the core will collapse to an object with zero radius! Consider this statement for a moment. Something with zero radius has no physical size; it is not very tiny, or even really, really tiny. It has no size at all.

The core collapses, and thus its density, and thus surface gravity increase. If it collapses to zero size, then the gravity becomes infinite, and that is a lot of gravity. This entity, which has no physical size yet has infinite gravity, is called a *singularity*.

Before we go any further, we need to make a slight detour to discuss *escape velocity*. This is the velocity an object needs to escape the pull of gravity of a celestial object. For instance, a spaceship has to go about 11 kilometers per second to escape from the Earth. What dictates the value for the escape velocity depends on two things: the mass of the celestial body and the distance from the object escaping to the center of the celestial body. Thus, if something were very massive, or very small, then the escape velocity would increase. A point may be reached when even light, which is the fastest-moving thing in the universe, may not be able to achieve escape velocity, and since the light would never escape, the object would never be seen.[50]

Let us return now to the singularity. There will be an area of space (usually spherical) surrounding the singularity where the escape velocity will be so high, light cannot escape. This sphere of space within which the escape velocity is equal to, or higher than, the escape velocity of light is what we call a *black hole*.[51]

Thus, inside a black hole, you would have to go faster than light to escape its gravitational pull; outside a black hole, you would not. The boundary between these two regions is called the *event horizon*; any event that occurs within the horizon is forever invisible to an outside observer.

To fully understand how and why black holes exist as I said earlier is beyond the scope of this book, but we should mention that the great scientist Albert Einstein and his theory of General Relativity really started the whole ball rolling. He was the first person to combine space and time into a single entity—space-time—and it is his equations that showed that gravity can be portrayed as a curvature of space-time. Astronomer Karl Schwarzschild used and solved Einstein's equations to give the first-ever general relativistic description of a black hole. We now call them *Schwarzschild black holes*, as his solutions are for non-rotating, electrically neutral black holes, to distinguish them from rotating, charged black holes!

What Schwarzschild showed is that, if the conditions are right (say, if matter is packed into a small enough volume of space) then the space-time can curve back on itself. This means that an object (or light) can follow a path (also known as a *geodesic*) into a black hole, but inside the black hole, the curvature of space-time is so extreme, there exists no path leading out. Once in, you stay in!

The event horizon is the boundary between the universe and the forever-isolated region of extreme curved space-time,[52] also known as a black hole. The radius of the black hole, that is, the distance from the singularity to the event horizon, is called the *Schwarzschild Radius*, R_S.

We now have our full description of a black hole: the singularity, the Schwarzschild Radius, and the event horizon.

One point that I think must be made is that many people believe, erroneously, that black holes will just vacuum you up regardless of your distance from them. This is wrong. For instance, if the Sun were to suddenly turn into a black hole, of radius 3 km, the orbits of the planets would not change. It would get dark and very cold, I admit, but the gravitational pull would remain the same. The gravitational effect of a black hole only becomes extreme if one gets very close to it. Provided we are at a reasonable distance away, there is nothing, relatively speaking, to worry about.[53]

There remains, however, one small problem: if black holes are literally invisible to us, how can we ever detect them?

We do this by looking for the effect that they have on objects nearby! First, search for a star whose motion, determined by measuring the Doppler shift in its spectrum, indicates that it is a member of a binary star. (The Doppler shift is the change in the appearance of light from an object that is moving away from or toward an observer.) If it proves possible to see both stars, give up on that object. The search is for a binary system where one companion is invisible, no matter how powerful the telescope used. However, just because it is unseen does not mean it is a black hole candidate; it may just be too faint to be seen, or the glare from the companion may swamp out its light. It could even be a neutron star.

Thus, further evidence is needed to determine if the invisible companion has a mass greater than that allowable for a neutron star. Kepler's laws are used at this point to determine whether the star, or rather the invisible object, has a mass greater than 3 solar masses. If this is so, then the unseen companion may be a black hole. Further information is still needed, however, and this may appear in the form of X-rays, which can arise either from material flowing from one star into the black hole or from an accretion disc that has formed around the black hole. Either way, the presence of X-ray emission is a good indicator that a black hole may be the unseen companion object.

Of course, the measurements as just stated are a bit more complicated than this. For instance, it is known that neutron stars can emit X-rays and have an accretion disc. So, careful analysis of the data is necessary. However, a few candidates are known, and one is even visible to the amateur astronomer…or perhaps I should say that the companion star to the black hole is visible!

Box 3.4: The Size of a Black Hole

To determine the approximate radius of a black hole, known as the Schwarzschild radius (R_{Sch}), we need to know the progenitor mass, in terms of the Sun's mass, $M_{\odot}$.

The radius is given by the very simple formula:

$$R_{Sch} \sim 3\,M_{\odot}$$

where R_{Sch} is in kilometers.

Example:

Betelgeuse, in the constellation Orion, has a mass of $\sim 20\,M_\odot$. Determine the radius of a black hole that may form when the star eventually dies.

$$R_{Sch} \sim 3\,M_\odot$$
$$R_{Sch} \sim 3 \times 20$$
$$\sim 60\,\text{km}$$

Thus, a $20\,M_\odot$ star could form a black hole of diameter 120 km.

The point at which Einsteinian Gravity takes over from Newtonian Gravity

At a large distance, a black hole exerts a gravitational force according to Newton's Law. However, a point is reached whereby Newton's Laws are no longer valid, and the gravitational effects are now explained using Einstein's General Relativity. The distance from a black hole where this change occurs is approximately $3\,R_{Sch}$.

Example:

Betelgeuse could form a black hole with a Schwarzschild radius of approximately 60 km. At what distance from the black hole does gravity increase from what Newton's Law predicts?

Using the above formula, this distance is approximately $3\,R_{Sch}$, thus:

$$\sim 3 \times 60$$
$$= 180\,\text{km}$$

At 180 km from the black hole, the gravitational force will increase to considerably more than that predicted by Newton's Law.

Cygnus X—1 HDE 226868 $19^h 58.4^m$ 35°12′ July 21

This is one of the strongest X-ray sources in the sky and possibly the most convincing candidate for a black hole. Its position is coincident with the star *HDE 226868*, which is a B0Ib supergiant of magnitude 9. It lies about 0.5° ENE of *Eta Cygni*. It is a very hot star, of around 30,000 K, and analysis shows it is a binary with a period of about 5.6 days. Observations by satellite have detected variations in the X-ray emission on a time scale of less than 50 milliseconds. The estimated mass of the unseen black hole companion is in the range of 6 to 15 solar masses. This would mean that it has a maximum diameter of about 45 km.

Other black hole binary systems are:

Star	Type	Orbital Period days	Black Hole Mass Estimates M_{Sun}
LMC X-3	B main sequence	1.7	4 to 11
V616 Mon	K main sequence	7.8	4 to 15
V404 Cyg	K main sequence	6.5	> 6
Nova Sco 1994	F main sequence	2.4	4 to 15
Nova Velorum	M dwarf	0.29	4 to 8

We have finished our brief, but fascinating look at the lives of stars. It is now time to look at bigger things—Galaxies!

Notes

1. We discuss the proton-proton chain in much greater detail in the sections on the Sun and the main sequence.
2. See the section on the Sun for a full discussion on gravitational equilibrium.
3. When astronomers refer to a star's following a specific evolutionary track, or moving on an *H-R* diagram, what they really mean is the star's luminosity and/or temperature changes. Thus, the position of the star on the *H-R* diagram will change.
4. The theoretical calculations were developed by the Japanese astrophysicist C. Hayashi, and the phase a protostar undergoes before it reaches the main sequence is called the *Hayashi Phase*.
5. There are a few examples of nebulae in which protostars are currently forming and which are observable in the section on emission nebulae. You will not, however, see protostars, just the region within which they reside.
6. We shall see in a later section why the Sun is opaque.
7. Recall from an earlier section that the luminosity is proportional to the square of the radius and to the fourth power of the surface temperature.
8. There is no mass-luminosity relationship for white dwarfs, giant stars, or supergiant stars.
9. This figure of $0.08\,M_{\odot}$ is about 80 times the mass of Jupiter.
10. By "ordinary" I mean matter composed of atoms, to distinguish it from "dark matter," whatever that may be!
11. Stars named after the FU Orionis prototype are also worth observing. It is now believed that the activity of FU Orionis (and similar stars) is related to the T Tauri variables. T Tauri variations may result from instabilities within and interactions with the surrounding accretion disk. FU Orionis activity is caused by a dramatic increase in instability due to the dumping of large amounts of material onto an accompanying star. Many astronomers believe that all T Tauri stars probably go through FU Orionis-type behavior at least once in their development.
12. During 2006, research indicated that some stars do form in isolation. However, the consensus outlined above is the one we will adopt.

13. Remember that hydrogen-burning is a characteristic of stars on the main sequence.
14. See next section.
15. Located within Sagittarius are numerous open clusters. Only the brightest are listed here.
16. See Section 3.4.2 in this chapter for a discussion on stellar associations.
17. We are talking about spiral galaxies here, not elliptical. Elliptical galaxies are believed to be the results of mergers between spiral galaxies where the rate of star formation is very low. For further details see chapter 4.
18. It isn't a cloud at all; this is just the name that ancient astronomers gave the galaxy before they knew what it really was!
19. This is, of course, an exaggeration, as it is only in the last ten years that astronomers have solved (possibly!) the problem of the solar neutrino, as we shall see in a later section.
20. There are many excellent books available that are devoted totally to the Sun (see appendices for a list of suitable texts).
21. A plasma is a collection of positively charged ions and free electrons.
22. In stars that are more massive than the Sun, the fusion of helium occurs via a different series of reactions called the CNO cycle. We shall discuss this later.
23. This means that averaged over the distance from the core to the surface, a "photon" travels about 0.5 m per hour, or about 20 times slower than a snail.
24. For a very detailed listing of beautiful double and multiple stars, see "Field Guide to Deep Sky Objects" by the author.
25. This is regardless of whether the binary star system is a visual, spectroscopic, eclipsing, or astrometric binary star system.
26. There are literally thousands of double, triple, and multiple star systems in the sky, all within reach of the amateur astronomer. The list that follows is a taste of what awaits the observer. If your favorite star is omitted, I apologize, but to include them all would be impossible.
27. Note that the position angle and separation are quoted for epoch 2000.0. With double stars that have small periods, these figures will change appreciably.
28. The semimajor axis is a term used in elliptical orbits (as nearly all orbits are). It is defined as half of the longer axis of an ellipse, and it is the average separation of the two stars.
29. It is this wobble that is used to detect unseen planets around stars!
30. Note that $a_A + a_B$ add up to the semimajor axis, a, as used in Kepler's Law.
31. We shall discuss this remarkable fact in later sections.
32. See the next section for a discussion on red giant stars.
33. Recall that for hydrogen-burning to start, the temperature has to reach about 10 million K, whereas for helium-burning, the temperature has to achieve a staggering 100 million K.
34. If you are a particle physicist!
35. The time for a star to complete one cycle in its brightness variation is called its period. Thus, for δ Cephei, its period is 5.5 days.

36. *Population I* stars are bright supergiant stars, main-sequence stars with high luminosity, such as O- and B-type stars, and members of young open star clusters. Molecular clouds are often found in the same location as Population I stars. They are usually located in the disc of a galaxy and concentrated in the spiral arms, following nearly, but not always, circular orbits. Population I stars include stars with a range of ages, maybe 10 billion years old, or one year old. *Population II* stars, on the other hand, are usually old stars. Examples include *RR Lyrae* stars and the central stars of *planetary nebulae*. This type of star has no correlation with the location of the spiral arms. They are also found in globular clusters, which are almost entirely in the halo and central bulge of the Galaxy. Therefore, they represent the oldest stars, which formed very early in the history of the Galaxy.
37. A list of organizations is in the index.
38. Current theories predict that low-mass M-type stars will stay on the main sequence for trillions of years!!!
39. In stars that are hotter and have a higher mass than the Sun, the chain of reactions that leads to hydrogen fusion is called the CNO cycle, where C, N, and O stand for carbon, nitrogen, and oxygen, respectively. The amount of energy produced in this reaction is exactly the same as that produced by the proton-proton reaction discussed earlier, but it occurs at a much more rapid rate.
40. On one occasion, it remained at minimum magnitude for 10 years!
41. The name "Planetary Nebulae" was first applied to these objects by Herschell, who thought that the nebulae looked like Jupiter when seen in a telescope.
42. See Appendix 1 for a full explanation of degeneracy.
43. Recent observations have detected a star *(V4334 Sagittarii)* that was well on its way to being a white dwarf when it underwent a final helium flash, grew to red-giant size once again, and is now ejecting more gas. Another star that has shown similar behavior is *V605 Aquilae*.
44. Some helium nuclei do remain in the star's core, but these are insufficient to initiate helium-burning to any great degree.
45. The entire energy-producing region in the star is now in a volume about the same size as the Earth. —one million times smaller in radius than the size of the star.
46. Do not think that astronomers know everything about supernovae. Prior to the famous supernovae in 1987 ("SN1987A"), astronomers believed that only red supergiants could form supernovae. They were put into some confusion when it was discovered that the progenitor star of SN1987 was a blue supergiant!
47. The subject of binary stars, Roche Lobes, and other assorted ephemera could fill a book in itself! Any interested readers will find references to books on such topics in the appendices.
48. As there is no core collapse in a Type I supernova, there will be no neutrinos emitted.
49. No doubt I shall soon be corrected on this point, when an amateur images the Crab Nebula Pulsar. It is only a matter of time!

50. In 1783, the British astronomer Rev. John Mitchell realized that using Newton's Laws of Gravity, a situation could occur whereby an object 500 times the radius of the Sun but with the same density would have an escape velocity greater than the speed of light! Although he didn't know it, he was talking about a black hole.
51. In some cases, a supernova remnant that does not have a central pulsar or neutron star may have a black hole at its center.
52. There are some relativists who propose that in an unimaginably distant future, black holes could "evaporate." We will be long gone for this issue to worry us.
53. That is, if we ignore the immense amount of radiation being formed around a black hole, and the debris from stars that have been literally torn apart.

CHAPTER FOUR

Galaxies

4.1 Introduction

We now discuss objects that every amateur astronomer has usually seen at least a handful of—*galaxies*.[1]

However, for a majority of amateurs, galaxies tend to remain faint and elusive objects, and I would not be far wrong if I said that perhaps only 15 to 20 galaxies are ever observed by 99% of amateur astronomers. It often comes as a surprise to know that, with the proper optical system and optimum seeing conditions (and a copy of this book), there are in fact many more that are within the reach of even the smallest telescopes or binoculars. In fact, a few are even visible to the naked eye if you know where to look!

Galaxies are vast, immense collections of stars, gases, and dust. Indeed, they are the source of all stars, because stars are not born outside of galaxies.[2] The number of stars in galaxies varies considerably; for instance, in some giant galaxies, there may be over a trillion (10^{12}) stars—a number that may stagger your mind. On the other hand, in small dwarf galaxies, such as *Leo I*, there may be only a few hundred thousand.

4.2 Galaxy Types

Galaxies come in a variety of shapes and sizes, but the vast majority can be grouped into a few distinct classifications. When astronomers first began studying galaxies, the most obvious characteristic that immediately became apparent was their shape, or morphology. Broadly speaking, galaxies can be classified into three major categories:

Spiral galaxies appear as flat white discs with yellowish bulges at their centers. The disc regions are occupied by dust and cool gas, interspersed with hotter ionized gas, as is the case in the Milky Way. Their most obvious characteristic is the beautiful spiral arms.

Elliptical galaxies are somewhat redder and more rounded in appearance like a football.[3] Compared with spiral galaxies, ellipticals contain far less cool gas and dust, but very much more hot ionized gas.

Galaxies that appear neither disc-like nor rounded are classified as *irregular galaxies*.

Some spiral galaxies exhibit a straight bar of stars that cuts across the center with spiral arms curling away from the ends of the bars. Galaxies with these features are known as *barred spiral* galaxies. Galaxies that possess discs but not spiral arms are called *lenticular* galaxies, because they look lens-shaped when seen edge-on.

The classification system is further subdivided and specialized to take account of, for instance, the brightness of the nuclear region (the tight compact central region of the galaxy), the tightness of the spiral arms, and so on.

4.3 Galaxy Structure

At this point, I think it will be helpful to describe in a little more detail the structure of a galaxy, which will, albeit in a small way, provide some insight into why galaxies appear the way they do. The books mentioned in the appendix will have a much more detailed coverage of this topic along with discussions on the origin and formation of galaxies.

Spiral galaxies have a thin *disc* extending outward from a *central bulge*. The bulge merges smoothly into the *halo*, which can extend to a radius in excess of 100,000 l.y. Both the bulge and halo make up the *spheroidal component*. There are no clear boundaries as to what divides this component up into its constituent parts, but a ball-park figure often used is that stars within 10,000 l.y. of the center can be considered to be bulge stars, whereas those outside this radius are members of the halo.

The *disc component* of a spiral galaxy cuts through both the halo and the bulge, and can, in a large spiral galaxy such as the Milky Way, extend 50,000 l.y. from the center. The disc area of all spirals contains a mixture of gas and dust, called the *interstellar medium*, but the amounts and proportions of the gas, whether atomic, ionized, or molecular, will be different from galaxy to galaxy.

4.4 Stellar Populations

The stars contained within a spiral galaxy can also be classified by where they reside. Those that lie in the disc region are called *Population I* stars and are often young, hot, and blue stars; those in the bulge region are old, red giant stars called *Population II* stars. This is why photographs often show the spiral arms colored blue, due to the Population I stars, with the bulge colored orange because of the Population II stars. The spiral arms may also be dotted with pink and red HII regions,[4] areas of star formation. Thus, new stars are usually formed in the spiral arms of galaxies, seldom in the bulge.

About 75% of large galaxies in the observable universe are apparently spiral or lenticular. Some spiral galaxies can be found in a loose collection of other spirals—this is known as a *group*—spread over several million light years. Our Galaxy, the Milky Way, is a member of the *Local Group*.

Elliptical galaxies differ significantly from spirals in that they do not have a significant disc component. Therefore, an elliptical has only the spheroidal component. The interstellar medium is also different from that in spirals; it is a mixture of low-density, hot, X-ray-emitting gas. Contrary to what you may read in some books, ellipticals do possess a little gas and dust, and some have a small gaseous disc at their center, which is believed to be the remains of spiral galaxies that the elliptical has consumed.

The stars in the spheroidal population of elliptical galaxies give a clue to possible star formation, if any. Such stars are orange and red; the absence of blue stars indicates that they are old, and that star formation occurred a long time ago.

Elliptical galaxies are often found in large clusters of galaxies, usually located near their center. They make up about 15% of the large galaxies found outside the clusters, but about 50% of the large galaxies within a cluster. Very small galaxies, called *dwarf elliptical galaxies*, are often found accompanying large spiral ones. A perfect example of such an arrangement, and one that is visible to an amateur, is the *Great Andromeda Galaxy*, M31, which is a classic spiral galaxy, and its attendants, M32 and M110, both dwarf ellipticals.

Several galaxies can be observed to not belong to either the spiral or the elliptical category. These are irregular galaxies, which more or less include all those galaxies that do not easily fall into the two previous classes. They include small galaxies, such as the Magellanic Clouds,[5] and those galaxies that are peculiar due to tidal interactions. These systems of galaxies are usually white and dusty, as spirals are, though there the resemblance ends. Deep imaging has shown that more distant galaxies are irregular, which indicates that this type of galaxy was more common when the universe was much younger.

4.5 Hubble Classification of Galaxies

The famous American astronomer Edwin Hubble was the first to put the many disparate types of galaxies into some sort of order. The *Hubble Classification*, as it is now known, was used as a means of categorizing a galaxy. Further amendments have, of course, been made, particularly by the astronomer Gerald de Vaucouleurs.

Basically, the classification is as follows. An upper-case letter followed by either a number or a lower-case letter is assigned to the galaxy in question, and this identifies its morphology. For instance, in the case of an elliptical galaxy, the letter E is used followed by a number. The larger the number, the flatter the galaxy. An E0 galaxy is round, whereas an E7 galaxy is very elongated. There exists a subgroup for the ellipticals with the following nomenclature: D signifies a diffuse halo, c is a supergiant galaxy, and d represents a dwarf galaxy. Thus, some of the largest elliptical galaxies have a cD classification.

A spiral galaxy is assigned the letter S, but it can also be assigned SA to signify that it is an ordinary spiral, or SB where B indicates that it has a bar. It is then followed by a lower-case letter: a, b, c, or d. Intermediate classes also exist, namely, ab, bc, cd, dm, and m. The lower-case letters a to d indicate the size of the bulge region, the dustiness of the disc, and the tightness of the spiral arms, while m denotes a stage where the spiral shape is barely discernible. An Sa galaxy will usually have a large bulge, a modest amount of dust, and tightly wound arms, whereas an Sd galaxy will have a small bulge and very loosely wound arms. An SBc galaxy will have both a bar and a small bulge.

Galaxies that are intermediate between spirals and ellipticals, called the *Lenticular* galaxies, are classified as SOs; for instance, SAOs those that are ordinary, and SBϕs those that are barred. In addition, for galaxies intermediate between types S and SB, there is the classification SAB. Both lenticular and spiral galaxies can be surrounded by an outer ring, and the spiral arms can nearly close upon themselves, thus forming a pseudo-ring. These new features are classified as R and R', respectively.

Finally, there are classifications for galaxies that do not easily fall into any of the above three! These include Pec, for peculiar galaxies, which have a distorted form. Some galaxies have an irregular morphology, classed as Irr. They can also be further classified as unstructured, IA, and barred, IB. Dwarf galaxies are classified as d. The difference between a Pec and an Irr can be very small, but it appears that a peculiar galaxy is one that may have suffered considerable tidal distortion for the passage of another galaxy nearby.

The Hubble classification system can be represented by a simple diagram (Figure 4.1); note, however, that the diagram and the classification generally do not represent an evolutionary sequence. Galaxies do not start as ellipticals and then progress to be spirals, though there is some evidence that the reverse is true.

The classification system can be confusing (an understatement!), and the system and descriptions outlined above are by no means complete—there are further subdivisions to all the classes. But do not let that worry you—the complete system is only of relevance to those astrophysicists who study galaxies; to the observer the important point is whether the galaxy is elliptical or spiral and, if spiral, it is barred. In a few galaxies where the spiral or elliptical structure is very apparent, the subdivisions of, say, E1, E2 and Sa, Sb, SBa, and so on, will be useful. Like most things in observational astronomy, it will all become easier with continued use.

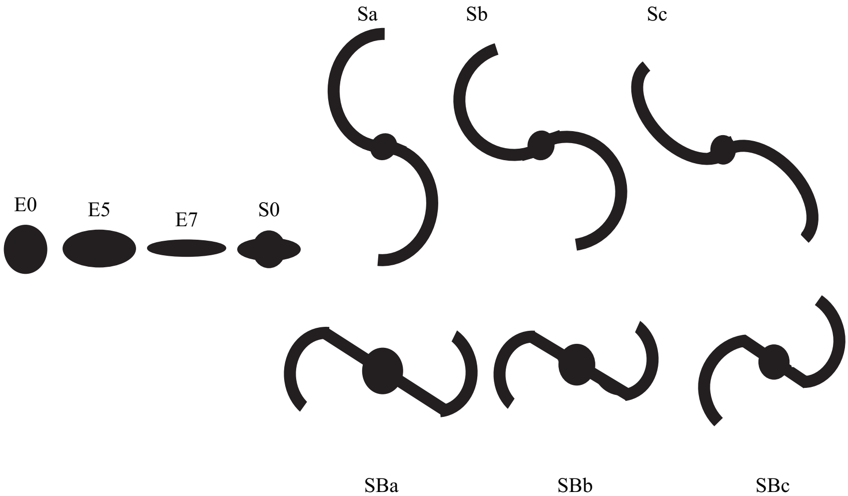


Figure 4.1. Hubble's tuning fork diagram showing the main galaxy types.

Sometimes the classification system may be of no apparent use at all, such as when a galaxy is inclined to our line of sight. The galaxy M83, which is a nice spiral galaxy, is face-on to us, and thus the classic spiral shape is very apparent. However, the galaxy NGC 891, which is classified as a spiral, will just appear as a thin streak of light because the galaxy is edge-on to us, and so the spiral shape will not be visible.

However, finding galaxies that present an edge-on or nearly edge-on perspective adds another element to the pleasure of locating and observing these faint objects.

4.6 Observing Galaxies

To an amateur astronomer, observing galaxies can present something of a dilemma. In astronomical magazines and books, you are bombarded with images of galaxies, their spiral arms resplendent and multi-colored, speckled throughout with distinct pink HII regions. However, when you look at that same galaxy through your telescope, all you can see is a pale tiny blob!

It is true that in nearly every case, especially from an urban location, the galaxy will be faint and indistinct. Only with the largest telescopes and the darkest possible skies can you see any real structure. But take heart! You will be astonished at what you can actually see with the naked eye with practice from the right location. I recall that, during my visit to the wilder parts of Turkey, on several occasions under utterly dark skies, I was able to see M31 in Andromeda and M33 in Triangulum in such amazing detail that even today the memory takes my breath away. With just my naked eye, I was able to trace M31 to nearly 2½° across the sky, and M33 was a huge amorphous glow. Also, had I known enough about how to look, I would have been able to see several other galaxies with the naked eye; unfortunately I was under the common misapprehension that the naked-eye limit is about 6th magnitude, but I now know that, with extremely dark skies and light-adapted vision, magnitude 8 is more likely the limit.

The purpose of this anecdote is to remind you that, in order to see faint galaxies and detail therein, dark skies are indispensable. With very dark skies, and armed with just a pair of binoculars, many galaxies are within reach. If you have a telescope, the number increases dramatically.

As usual, dark skies and dark-adapted and averted vision will help in tracking down and seeing galaxies. Clean optics will also greatly aid you in your observations. Dust and smears of grease will reduce a surprising amount of light that reaches your eyes, and in particular will reduce the contrast.

Generally, galaxies that have a brightness greater than 13th magnitude are usually visible through telescopes of aperture 15 cm, and telescopes of aperture 30 cm will help you see down to about 14.5 magnitude. There are, of course, galaxies with much brighter magnitudes than these, and so they can be visible with much smaller instruments. In some cases, only the brightest part of a galaxy will be visible—perhaps its core (nuclear region), and the spiral part unobservable.

To be able to trace the finer details of the spiral arms of galaxies, and to locate the bulge area, faint halo, and HII regions, you will invariably need a large-aperture telescope. However, if the purpose of your observing is just to locate these elusive objects, and to be amazed that the light that is entering your eye may have begun its journey over 100 million years ago, then there is a plethora of galaxies awaiting you.[6]

The usual nomenclature applies in the following descriptions, but with some changes. Galaxies are *extended objects*, which means that they cover an appreciable part of the sky: in some cases a few degrees, in others only a few arc minutes. The light from the galaxy is therefore "spread out," and thus the quoted magnitude will be the magnitude of the galaxy as if it were the "size" of a star; this magnitude is often termed the *integrated magnitude*. This can cause confusion, as a galaxy with, say, a magnitude of 8 will appear fainter than an 8th-magnitude star, and in some cases, where possible, the surface brightness of a galaxy will be given. This will give a better idea of what the overall magnitude of the galaxy will be. For instance, Messier 64, the Black Eye Galaxy, has a magnitude of 8.5, whereas its surface brightness is 12.4. The surface brightness will be given in italics after the quoted magnitude; for example, the magnitude and surface magnitude of M64 will appear like this: 8.5m [*12.4m*].

Following on from the previous paragraph, the designation "easy," "moderate," or "difficult" takes into account not only the brightness of the galaxy but also the area of the sky the galaxy spans. Thus, a galaxy may be bright with, say, a magnitude of 8, which, under normal circumstances, would be visible with binoculars and designated as "easy"; however, if it covers a significant amount of the sky (and thus its surface brightness is low, making it more difficult to observe) I would designate it "moderate."

In addition, spiral galaxies can exhibit a variety of views, depending on their inclination to the Solar System. Some will appear face-on, others at a slight angle, and a few completely edge-on. As an indicator of inclination, the following symbols will be used:

Face-on:
Slight inclination:
Edge-on:

Finally, the Hubble classification of galaxies I outlined earlier will also be used.

4.6.1 Spiral Galaxies

Caldwell 7	**NGC 2403**	**$07^h\ 36.9^m$**	**+65°35′**	**January 14**
8.5m [*13.9m*]	**17.8′| 10.0′**		**SAB(s)cd**	**easy**

This is one of the brightest galaxies, which was omitted from the Messier catalogue, and is often left out of an observer's schedule. When observed through binoculars, it appears as a large, oval hazy patch with a brighter central region. With averted vision and an aperture of about 20 cm, faint hints of a spiral arm will become apparent. Larger apertures will, of course, present even further detail. It is not a member of the *Local Group of Galaxies*[7] but believed to be a member of the M81–M82 group. It was the first galaxy outside the Local Group to have Cepheid[8] variable stars discovered within it, and the current estimate of its distance is 11.5 million l.y.

Messier 81	**NGC 3031**	**$09^h\ 55.6^m$**	**+69°04′**	**February 18**
6.9m [*13.0m*]	**26′|14′**		**SA(s)ab**	**easy**

A spectacular object! With binoculars, it will show a distinct oval form, and with high-power binoculars, the nuclear region will easily stand out from the spiral arms. A telescope can show considerably more detail, and it is one of the grandest spiral galaxies on view. With an aperture of about 15 cm, traces of several of the spiral arms will be glimpsed. A real challenge, however, is to locate this galaxy with the naked eye. Several observers have reported seeing it in dark skies. If you happen to glimpse it without any optical aid, you are probably looking at one of the farthest objects[9] that can be seen with the naked eye, lying at a distance of some 4.5 million l.y. M81 is partner galaxy to M82, and both of these spectacular objects can be glimpsed in the same field of view.

Caldwell 48	**NGC 2775**	**$09^h\ 10.3^m$**	**+07°02′**	**February 7**
10.1m [*13.1m*]	**5.0′|4.0′**		**SA(R)ab**	**moderate**

A difficult object for binoculars, this galaxy is observable only through a telescope. With an aperture of about 20 cm, you will see the galaxy as a large blob. However, detail within the object is conspicuously absent, but a brighter core and fainter outer region can be resolved. The absence of detail (e.g., spiral arm dust and gas) has been attributed to an early era of star formation, which used up all the material. The evidence for this was found in the galaxy's spectrum, which that lacked emission lines because these lines are usually caused by star-forming regions in and around the spiral arms.

Messier 96	**NGC 3368**	**$10^h\ 46.8^m$**	**+11°49′**	**March 3**
9.2m [*12.9m*]	**7.6′|5.2′**		**SAB(rs)ab**	**easy**

This faint galaxy can be seen through binoculars as a faint, hazy oval patch of light. What you would observe is, in fact, just the bright central nucleus of the galaxy, as the spiral arms are too faint to be resolved. Telescopes will bring out further detail, and with good conditions the spiral arm features can be seen. There is some controversy over M96, as recent measurements of its distance show that it is 38 million l.y, which is 60% greater than the previous value. It forms a nice triangle with two other galaxies, M95 and M105.

Messier 65	**NGC 3623**	**11^h 18.9^m**	**+13°05′**	**March 12**
9.3m [*12.4m*]	**9.8′|2.9′**		**SAB(rs)a**	**easy**

Visible through binoculars, *Messier 65* is one half of the most famous galaxy pair in the sky, after M81 and M82. Along with M66, it shows up quite well with low-power optics. It appears as a nice oval patch of light, and with higher magnification both spiral arms and a dust lane can be glimpsed. However, it is often difficult to observe, as the brightness of its background tends to interfere with the galaxy details. A nice challenge for observers in an urban location.

Messier 66	**NGC 3627**	**11^h 20.2^m**	**+12°59′**	**March 12**
9.0m [*12.5m*]	**9.1′|4.2′**		**SA(s)b**	**easy**

The other half of the galaxy duo mentioned above. This is a bright galaxy, easily seen through binoculars, where its distinct elliptical shape and bright center can be resolved. With telescopes, the oval shape of the nucleus becomes apparent, and with higher magnification a spiral arm and dark patch can be seen. Large-aperture telescopes will show considerable detail, consisting of dark and light patches.

Messier 106	**NGC 4258**	**12^h 19.0^m**	**+47°18′**	**March 27**
8.3m [*13.8m*]	**18.6′|7.2′**		**SAB(s)bc**	**easy**

The galaxy appears as a large glow when seen through binoculars and has a distinct elliptical shape. Large binoculars reveal the presence of the nucleus. With telescopes of small aperture (10 cm) and low magnification, the spiral arms become apparent, and with higher magnification further detail can be seen. This galaxy needs a large aperture and magnification to reveal any amount of detail. The galaxy is nearly face-on to us, but a cloud of gas and dust surrounding the nucleus is apparently edge-on. Furthermore, there is evidence that a *black hole* resides at the core!

Messier 88	**NGC 4501**	**12^h 32.0^m**	**+14°25′**	**March 30**
9.6m [*12.6m*]	**6.9′|3.7′**		**SA(rs)b**	**easy**

It is a fine galaxy, observable through binoculars, with a bright nucleus and a faint hazy glow surrounding it caused by the spiral arms. However, a problem is that the galaxy is located in a barren patch of the sky, making its location difficult. But, with a telescope of medium aperture, say 20 cm, its structure becomes visible. The spiral arms and nucleus can be resolved with averted vision.

Caldwell 38	**NGC 4565**	**12^h 36.3^m**	**+25°59′**	**March 31**
9.6m [*13.5m*]	**15.5′|1.9′**		**SA(s)bsp**	**easy**

It is a striking example of an edge-on galaxy; with small binoculars, the classic spindle shape can be seen against the background of stars, and with large ones, the central core region can be seen. With a telescope of aperture 15 cm, the lovely edge-on shape becomes even clearer, along with its star-like nucleus. The dust lane is observable only with apertures of at least 20 cm. It is thought to be a massive galaxy, similar to the Milky Way, with its dust lane the equivalent of *The Great Rift*.

Messier 98	**NGC 4192**	**12^h 13.8^m**	**+14°54′**	**March 25**
10.1m [*13.2m*]	**9.8′|2.8′**		**SAB(s)ab**	**moderate**

This faint galaxy lies at the edge of the great *Coma–Virgo Cluster*, an area studded with galaxies both faint and bright. It is a difficult object to locate and requires a small telescope of at least 10 cm aperture. It is highly inclined to us and has a very elongated shape. With excellent seeing conditions, a higher magnification would show spectacular spiral arms and dust lanes, and rarely the entire halo can be seen to surround the galaxy. It is an excellent object to observe but requires skill and patience to see any detail in it, especially from an urban location.

Messier 99	**NGC 4254**	**12^h 18.8^m**	**+14°25′**	**March 27**
9.9m [*13.0m*]	**5.4′|4.7′**		**SA(s)c**	**moderate**

A difficult object for binoculars; its circular disc shape can be resolved only in dark skies. With a telescope of aperture 10 cm, the galaxy will remain a hazy round patch, but a small nucleus may be visible. Higher magnification and perhaps greater aperture will show two spiral arms. However, M99 is one of those galaxies whose likelihood of showing detail depends greatly on the seeing conditions. Try observing on a clear night and then on an average night, and compare your observations. M99 lies at a distance of about 55 million l.y. and is one of the galaxies within the *Coma–Virgo Cluster*.[10]

Messier 61	**NGC 4303**	**12^h 21.9^m**	**+04°28′**	**March 28**
9.6m [*13.4m*]	**6.5′|5.8′**		**SAB(rs)bc**	**moderate**

A difficult object for binoculars, you would see nothing more than a small faint circular patch of light even in dark skies. For small-telescope users, however, it is a delight, although it is small and difficult to locate. It is an ideal open-faced spiral galaxy. The use of averted vision is a must for this object, when the nucleus and any spiral arm detail become apparent. A nice addition is the fact that the galaxy is located within the *Virgo Cluster* of galaxies, and you may notice several faint and indistinct glows in the same field of view as M61, depending on the limit of your vision. These are probably unresolved galaxies!

Caldwell 36	**NGC 4559**	**12^h 35.9^m**	**+27°57′**	**March 31**
9.8m [*13.9m*]	**13.0′|5.2′**		**SAB(rs)cd**	**moderate**

A member of the *Virgo Cluster*, this is often overlooked. Not really a binocular object, it is perfect for small telescopes. With a 20 cm aperture, the clear oval shape will be resolved, along with a brightening of the nucleus. A perceptible hint of further detail may also be glimpsed. Larger apertures show considerably more detail.

Caldwell 40	**NGC 3626**	**11^h 20.1^m**	**+18°21′**	**March 12**
11.0m [*12.8m*]	**2.8′|2.0′**		**(R)SA(rs)**	**difficult**

This galaxy is virtually unknown among amateurs. It lies close to several brighter Messier objects, and is often mistaken for NGC 3607. Nevertheless, it is worth searching for. It is a featureless oval patch of light, and you will need an aperture of at least 20 cm to resolve this object. What makes it special, however, is that it is a *multispin* galaxy. This means the molecular and ionized gas is rotating around the galaxy in the direction opposite to that of its stars. The origin of this phenomenon is unknown, but one school of thought suggests that the galaxy recently collided, assimilating a huge gas cloud with a mass of about one billion solar masses.

Caldwell 26	**NGC 4244**	**12^h 17.5^m**	**+37°48′**	**March 26**
10.4m [*14.0m*]	**18.5′|2.3′**		**SA(s)cd:sp**	**difficult**

This is one of those needle-like galaxies that can be seen with amateur instruments. The edge-on galaxy is exceedingly thin, and you will need an aperture of at least 20 cm to locate and observe it. It has a faint but easily resolvable star-like nucleus, but detail within the galaxy is very rarely seen, even with larger apertures. It has a Hubble classification similar to that of M33, the *Pinwheel Galaxy* in Triangulum. When such a galaxy is seen edge-on, the tiny nucleus and loose, open arms give it its indistinct appearance.

Messier 58	**NGC 4579**	**12^h 37.7^m**	**+11°49′**	**April 1**
9.6m [*13.0m*]	**5.9′|4.7′**		**SAB(rs)b**	**easy**

This galaxy will appear as a faint, hazy patch of light with a barely discernible nucleus when observed through binoculars. You may also glimpse in the same field of view the galaxies M59 and M60. A telescope with aperture 10 cm will show some structure in the halo, along with faint patches of light and dark. There are some reports that a 20 cm telescope will allow the bar connecting the spiral arms to the nucleus to be resolved. It has about the same mass as the Milky Way and is about 95,000 l.y. in diameter.

Messier 104	**NGC 4594**	**12^h 40.0^m**	**−11°37′**	**April 1**
8.0m [*11.6m*]	**8.7′|3.5′**		**SA(s)asp**	**easy**

Also known as the *Sombrero Galaxy*, it is an extragalactic treasure! It gives a marvellous sight with almost all binoculars and telescopes. With small binoculars, it will reveal itself as an oval disc, which increases in brightness toward the center. Large binoculars will, however, reveal its true beauty. The dark dust lane that cuts across the galaxy becomes readily apparent. Looking though a telescope, even more detail can be brought out. With a 10 cm aperture, a bright core can be seen, along with the long, spindle-like dust lane. With higher magnification, the spiral arms stand out. Large apertures and higher magnifications will reveal a wealth of detail. It was the first galaxy, other than the Milky Way, to have its rotation determined.

Messier 94	**NGC 4736**	**12^h 50.9^m**	**+41°07′**	**April 4**
8.2m [*13.0m*]	**11.2′|9.1′**		**(R)SA(r)ab**	**easy**

This galaxy is visible through binoculars and will appear as a small circular hazy patch with a star-like nucleus. Telescopes will reveal some structure, possibly a faint spiral arm. Several observers have reported that a central ring can be seen near the core, which gives it an appearance very similar to M64, the Black Eye Galaxy. A further elliptical ring has been reported outside the edge of the galaxy. Needless to say, exceptionally dark skies will help one observe this elusive feature.

Messier 64	**NGC 4826**	**12^h 56.7^m**	**+21°41′**	**April 5**
8.5m [*12.4m*]	**9.3′|5.4′**		**(R)SA(rs)ab**	**easy**

Also known as the *Black Eye Galaxy*, this famous galaxy can be seen through small binoculars as an oval hazy patch with a slightly brighter center. The striking feature that gave the galaxy its name has been reported to be visible through large binoculars on very dark nights. Small telescopes show a very bright nucleus encased in a patch of glowing light. The "eye" is a vast dust lane, some 40,000 l.y. in diameter. There is considerable debate as to whether the "eye" can be seen through small instruments. Some observers report that an aperture as small as 6 cm will resolve it, while others claim at least 20 cm is needed. What was concluded is that a high-magnification instrument is necessary. There is further controversy as to whether the nucleus is star-like or not. It may be that magnification plays an important role here.

Messier 63	**NGC 5055**	**13^h 15.8^m**	**+42°02′**	**April 10**
8.6m [*13.6m*]	**12.6′|7.2′**		**SA(rs)bc**	**easy**

Also known as the *Sunflower Galaxy*, this object is somewhat difficult for binoculars, even though it has a fairly bright magnitude. In small binoculars, it will just appear as a faint patch of light, and with large binoculars, the classic oval shape will become apparent. Telescopes reveal a lot of detail, including many faint and detailed spiral arms.

Messier 51	**NGC 5194**	**13^h 29.9^m**	**+47°12′**	**April 14**
8.4m [*13.1m*]	**11.2′|6.9′**		**SA(s)bcP**	**easy**

Also known as the *Whirlpool Galaxy*, this famous galaxy is easily visible with binoculars. It appears as a small glowing patch of light with a bright, star-like nucleus. Many now believe that M51 is the finest example of a face-on spiral galaxy. What makes this galaxy so special is the small, irregular, satellite galaxy *NGC 5195*, which is close to it. Deep photographs reveal that the galaxies are physically connected with a bridge of material, but unfortunately this satellite galaxy cannot be seen through most binoculars; even with giant binoculars, it appears only as a slight bump on the side of M51. With small telescopes (10 cm), not a lot of detail is visible, except perhaps the slightest hint of spiral structure. With an aperture of 25 cm, much more detail can be resolved: spiral arms, structure within the arms, and dark patches. A matter of debate, however, is whether the bridge connecting M51 to NGC 5195 can be seen with small telescopes. Some observers claim that it can be seen with 10 cm aperture; others claim that at least 30 cm is needed. What everyone would agree upon is that absolute, perfect transparency is needed, as even the slightest haze or dust in the atmosphere will make observations much more difficult.

Messier 83	**NGC 5236**	**13^h 37.0^m**	**−29°52′**	**April 16**
7.5m [*13.2m*]	**12.9′|11.5′**		**SAB(s)c**	**easy**

Often overlooked by observers, this is a nice galaxy located within the star fields of Hydra, and it is a showpiece for small telescopes. With binoculars, it will appear as a hazy patch of light with a bright, star-like nucleus. With telescopes, much more detail can be seen, including spiral arms, dust lanes, bright knots, and even detail within the nucleus. It is one of those objects that merits several observing sessions. Also, it ties with M81 as one of the farthest objects visible to the naked eye, at about 4.5 million l.y. As it is located too far to the south, there may be a problem for observers from the UK in locating it.

Caldwell 30	**NGC 7331**	**22^h 37.1^m**	**+34°25′**	**August 30**
9.5m [*13.5m*]	**11.4′|4.0′**		**SA(s)bc**	**easy**

This is the brightest galaxy in Pegasus. With binoculars, it will appear as a faint patch of light with a brighter core. A telescope of 20 cm will show its structure in a little more detail. Apparently, this galaxy is similar to M31 but lies much farther from us, at a distance of 50 million l.y. There is also some debate as to whether this galaxy is linked with the famous *Stephen's Quintet* (see the section on "Groups and Clusters of Galaxies").

Caldwell 43	**NGC 7814**	**00^h 03.2^m**	**+16°08′**	**September 21**
10.6m [*13.3m*]	**6.3′|3.0′**		**SA(s)ab:sp**	**moderate**

This is no binocular object, but nevertheless a splendid sight with larger-aperture telescopes. It is a fine example of an edge-on galaxy and bears many similarities to its better-known cousin, M104. It can be easily seen with a telescope of aperture 20 cm, but it often provokes debate among amateurs as to whether its dust lane can be seen with small telescopes. Some profess to have seen it with 20 cm, but others claim that at least 40 cm is needed. Try observing with as high a power it can take, as this may help you resolve this dilemma.

Messier 31	**NGC 224**	**00^h 42.7^m**	**+41°16′**	**October 1**
3.4m [*13.6m*]	**3°| 1°**		**Sb**	**easy**

Also known as the *Andromeda Galaxy*, this most famous galaxy in the sky is also the most often visited one and is always a first observing object for the beginner. It can be visible to the naked eye, even on those nights when the conditions are far from perfect. Many naked-eye observers claim to have seen the galaxy spread over at least 2½° of sky, but this depends on the transparency. With binoculars, it presents a splendid view, and the galactic halo is easily seen, along with the bright nucleus. Large binoculars may even show one or two dust lanes. Using averted vision and a very dark sky, several amateurs report that the galaxy can be traced to about 3° of the sky with telescopes of aperture 10 cm. With larger telescopes, a wealth of detail becomes visible. With an aperture of about 20 cm, a star-like nucleus is apparent, cocooned within several elliptical haloes. Another striking feature is the dust lanes, especially the one running along its north-western edge. Many observers are often disappointed when they observe M31, as the photographs they see in books actually belie what they can see at the eyepiece. M31 is so big that any telescope cannot really encompass all there is to show. Observing this wonderful galaxy with patience will reward you with a lot of surprises. Spend several nights observing the galaxy, and choose a dark night in a country location. It really is a spectacular galaxy. It contains about 300 million stars with a diameter of 130,000 l.y., and it is among the largest galaxies known. It is the largest member of the *Local Group*. In older texts, it is often referred to as the *Great Nebula in Andromeda*.

Caldwell 65	**NGC 253**	**00^h 47.6^m**	**−25°17′**	**October 3**
7.2m [*12.6m*]	**25.0′|7.0′**		**SAB(s)c**	**easy**

This is a wonderful object and is often referred to as the southern hemisphere's answer to the *Andromeda Galaxy*. It can be easily seen with binoculars as a long, spindle-shaped glow with a bright nucleus. With large binoculars, some structure can be glimpsed under absolutely perfect conditions. Its size makes it impressive, as it is as wide as the Moon and around a third as thick. Any telescope, even as small as 6 cm, will suffice to see this object. Larger apertures will reveal more detail, and with averted vision the spiral arms can be glimpsed. Several reports suggest that considerable mottling can be seen within the galaxy with a 15 cm telescope. It has the dubious honor of being one of the dustiest galaxies known, as well as one that is undergoing a period of frenetic star formation in its nuclear regions.

Caldwell 70	**NGC 300**	**00^h 54.9^m**	**−37°40′**	**October 4**
8.1m [*14.7m*]	**20.0′|15.0′**		**SA(s)d**	**easy**

A difficult object to locate due to its very low surface brightness, it will present a considerable challenge with binoculars. Nevertheless, once located, it can be an impressive object. With a 20 cm-aperture telescope, the nucleus can readily be seen engulfed in the unresolved haze of the spiral arms. Larger telescopes will resolve some further detail. This galaxy lies at a close distance of about 7 million l.y.

Messier 33	**NGC 598**	**01^h 33.9^m**	**+30°39′**	**October 14**
5.7m [*14.2m*]	**71′|42′**		**SA(s)cd**	**easy**

Also known as the *Pinwheel Galaxy*, it is a famous galaxy for several reasons. It is, without doubt, one of the most impressive examples of a face-on spiral. However, it is also one of the most difficult galaxies to locate. Many amateur astronomers have never seen it, but others have had no trouble locating it. The problem arises from its having such a large surface area. Although it has an integrated magnitude of 5.7, it spreads the light out to such an extent that it appears very faint. As a result, the galaxy may be all but invisible with telescopes, whereas it can be easily seen with binoculars. It will look like a large, very faint cloud with a slight brightening at its center. In addition, there are several reports of its being visible to the naked eye; I testify to this, and it was strikingly visible from a totally dark night under perfect conditions, when it was impossible to see it otherwise! With a telescope of aperture 10 cm, several spiral arms can be glimpsed arcing from the very small nucleus. With large telescopes, a plethora of detail becomes visible, such as star clusters, stellar associations, and nebulae, all located within the galaxy.[11] This truly is a spectacular galaxy.

Caldwell 62	**NGC 247**	**00^h 47.1^m**	**−20°45′**	**October 2**
9.1m [*14.1m*]	**20.0′|7.0′**		**SAB(s)**	**moderate**

This galaxy is barely discernible with large binoculars, where it is seen as an elongated hazy patch of light with a brighter nucleus. However, it lies low down in the skies, and so is often neglected by UK observers. With larger-aperture telescopes, its mottled appearance becomes visible, along with the brighter, southern part of the galaxy. The northern part is much fainter and will require averted vision and clear skies for observation. The galaxy was thought to be a member of the *Sculptor Group* of galaxies, but recently doubts have arisen, as the most recent estimates of its distance put it at about 13.5 million l.y., which is twice the distance of the cluster.

Caldwell 23	**NGC 891**	**02^h 22.6^m**	**−42°20′**	**October 27**
9.9m [*13.8m*]	**14.0′|3.0′**		**SA(s)sp**	**moderate**

This is a fine example of an edge-on galaxy, and it is thought by many to be the finest galaxy. With binoculars, it is just visible as a hazy but distinct elongated smudge. With a telescope of aperture 20 cm, its spindle shape is very apparent, and with a larger aperture the distinctive dust lane will be resolved.

4.6.2 Barred Spiral Galaxies

Messier 95	**NGC 3351**	**10^h 44.0^m**	**+11°42′**	**March 3**
9.7m [*13.5m*]	**7.4′|5.0′**		**SB(R)b**	**moderate**

This is a faint galaxy, which shows little, if any, detail in binoculars. It will just appear as a hazy patch, lying in the same field of view as M96. With a telescope of at least 15 cm, some structure can be glimpsed, with larger apertures showing the distinctive bar feature. There is some debate as to the real magnitude of the galaxy, with some observers putting it at 9.2 m.

Messier 108	**NGC 3556**	**11^h 11.5^m**	**+55°40′**	**March 10**
10.0m [*13.0m*]	**8.7′|2.2′**		**SB(s)cdsp**	**moderate**

This galaxy is visible with binoculars as a very faint streak of light. The central condensation has been reported to be visible with an 8 cm telescope. Larger apertures show a surprising amount of detail with considerable mottling and structure. This is a very small galaxy, just one-twentieth the mass of the Milky Way, lacking a central bulge. Although it was a recent addition to Messier's list, he was aware that the galaxy existed, but for some reason, he just did not include it.

Messier 109	**NGC 3992**	**11^h 57.6^m**	**+53°23′**	**March 21**
9.8m [*13.5m*]	**7.6′|4.7′**		**SB(rs)bc**	**moderate**

Another recent addition to the Messier catalogue, this galaxy can be glimpsed with binoculars, providing the conditions are right. With low-power and small–aperture telescopes, it is evident that you are looking at a galaxy, but no further detail can be seen. High-power and larger-aperture telescopes can show some structure, such as the core and halo regions. The central bar also becomes prominent with aperture around 25 cm. This is the penultimate Messier object.

Caldwell 3	**NGC 4236**	**12^h 16.7^m**	**+69°27′**	**March 26**
9.6m [*14.7m*]	**23.0′|8.0′**		**SB(s)dm**	**difficult**

Although this is a large galaxy, it is very faint and so difficult to locate. In addition, as it is edge-on to us, it presents a very slim view, and so spiral arm features are absent. With aperture around 20 cm, its distinctive spindle shape is conspicuous. It is a nice galaxy for those who would like to test the limits of a small telescope as well as their observing skill. It lies at a distance of about 10 million l.y.

Messier 91	**NGC 4548**	**12^h 35.4^m**	**+14°30′**	**March 31**
10.1m [*13.3m*]	**5.4′|4.3′**		**SB(rs)b**	**difficult**

Now it is time for a mystery! If you try to locate M91 from Messier's original notes, you may make an interesting discovery. There is nothing there! Most observers agree that Messier made a mistake, and that in fact the galaxy NGC 4548, what he originally observed, was incorrectly plotted. The galaxy is a faint object, and telescopes of medium aperture will be needed to see any detail; yet it may be visible with aperture of 10 cm as a faint, hazy circular patch.

Caldwell 32	**NGC 4631**	**12^h 42.1^m**	**+32°32′**	**April 2**
9.2m [*13.3m*]	**17.0′|3.5′**		**SB(s)dsp**	**moderate**

Surprisingly an often neglected galaxy, it has a lot to offer. Visible with binoculars as a faint elongated object, you will really need a telescope to appreciate its beauty. It is a very big galaxy; due to its appearance, it was unofficially nicknamed the *Whale Galaxy*. Its eastern end is appreciably thicker than its western end, hence the name. This aspect can be seen with an aperture of 20 cm, and larger telescopes will show further detail, such as patches of light and dark, along with two prominent knots. On the northern side of the galaxy is a faint 12th-magnitude star, which, providing the seeing is good, will act as a pointer to a faint companion galaxy. Several theories have arisen as to the cause of its strange and disturbed appearance. The most probable reason is tidal interactions with several nearby galaxies.

Caldwell 72	**NGC 55**	**00^h 15.1^m**	**−39°13′**	**September 24**
7.9m [*13.5m*]	**25.0′|4.1′**		**SB(s)m:sp**	**easy**

Although this galaxy lies so far to the south it is invisible from the northern hemisphere, it still warrants inclusion. With binoculars, it appears as a faint spindle-shaped object, and large binoculars hint at some delicate structure. Telescopes show even more detail, and it is one of the few galaxies for which an H-alpha filter will highlight its HII regions.

Caldwell 44	**NGC 7479**	**23^h 04.9^m**	**+12°19′**	**September 7**
10.9m [*13.6m*]	**4.4′|3.4′**		**SB(s)c**	**moderate**

This faint galaxy can be glimpsed with a small telescope of aperture 8 cm as a smudge, but do not expect any more detail. With aperture around 20 cm, the central bar will be visible, along with a suggestion of some structure. The spiral arms at the end of the bar will need at least a 30 cm telescope, but some observers claim to have seen them with a 25 cm aperture under perfect seeing conditions. The nucleus can be easily resolved, however. It has the honor, among some amateur astronomers, of being the finest barred spiral on offer for the northern hemisphere. It lies at about 100 million l.y. from us.

–	**NGC 1365**	**03^h 33.6^m**	**−36°08′**	**November 14**
9.5m [*13.7m*]	**9.8′|5.5′**		**(R)SB(s)b**	**moderate**

This is a very impressive galaxy, easily visible with binoculars as an elongated hazy object with a brighter center. With a telescope having aperture as small as 8 cm, its origin is obvious, and larger apertures will show considerably more detail. Although not visible from the UK, it should be a nice observing target from the USA.

4.6.3 Elliptical Galaxies

Messier 84	**NGC 4374**	**12^h 25.1^m**	**+12°53′**	**March 28**
9.1m [*12.3m*]	**6.5′|5.6′**		**E1**	**easy**

Located close to the Virgo Cluster of galaxies, it presents a small oval patch of light when seen through binoculars. The bright nuclei can be glimpsed under favorable conditions. As with most ellipticals observed with amateur telescopes, there is never much detail seen in the galaxy; most remain as smooth objects with little structure and perhaps only a brightening of the core is all that is ever resolved. Nevertheless, they make observing objects worthwhile. There seems to be some debate as to whether M84 is in fact an E1 galaxy or an S0, which is a galaxy between an elliptical and a spiral. It is located in the *Virgo Cluster* at about 55 million l.y. The area around M86 is full of very faint galaxies, and although only a handful will show any perceptible detail, it is nevertheless worthwhile sweeping the area for these most elusive objects.

Messier 86	**NGC 4406**	**12^h 26.6^m**	**+12°57′**	**March 29**
8.9m [*13.9m*]	**8.9′|5.8′**		**E3**	**easy**

A companion and very similar in appearance to M84, this is the brighter of the two, with M86 being perhaps slightly brighter with a less condensed core. It is generally visible with binoculars and telescopes of all sizes. Similar to the above, the area is full of galaxies, and with patience, many of them can be seen in a dark sky.

Messier 49	**NGC 4472**	**12^h 29.8^m**	**+08°00′**	**March 30**
8.4m [*12.9m*]	**10.2′|8.3′**		**E2**	**easy**

This is the second-brightest galaxy in Virgo. It can be easily spotted with binoculars as a featureless, oval patch of light. Although most ellipticals are rather featureless, M49 stands out quite well with higher magnification and large aperture, and some resolution can be seen in the nuclear area too. It seems to have a bright nucleus surrounded by a diffuse core region, which in turn is surrounded by a rather diffuse halo. Some observers report that the nucleus shows a mottled appearance under magnification. The galaxy is at the center of a subcluster of galaxies called the *Virgo Cloud*, which in turn is part of the much larger *Virgo Cluster*. In addition, the elliptical galaxy is cocooned in an envelope of hot gas at a temperature of about 10,000,000 K. At such a high temperature, X-rays are formed, which may be detected with an X-ray telescope.

Messier 89	**NGC 4552**	**12^h 35.7^m**	**+12°33′**	**March 31**
9.7m [*12.3m*]	**5.1′|4.7′**		**E0**	**moderate**

It is a difficult galaxy to locate with binoculars, especially if the seeing conditions are far from ideal. If, however, located, it would appear as just a small hazy spot of light. With a telescope and medium magnification, a bright and well-defined nucleus can be seen enveloped by the mistiness of the halo. With a large aperture and magnification, some mottling has been reported on the halo, but again, the atmospheric conditions may limit observability. In the same field of view as M89 is the spiral galaxy M90. Both are members of the *Virgo Cluster*.

Messier 59	**NGC 4621**	**12^h 42.0^m**	**+11°39′**	**April 2**
9.6m [*12.5m*]	**5.4′|3.7′**		**E5**	**moderate**

Although visible with binoculars, this galaxy will pose a challenge to most observers. It will probably need the use of averted vision to be spied, and dark adaption will undoubtedly be needed. However, telescopically, M59 is rather nice, as it is one of the few ellipticals that seem to show detail. It has a star-like nucleus, and some observers report a faint mottled appearance, although it could be an effect of foreground stars being seen against the oval of the galaxy. It would be interesting to find out whether this is correct. Try observing it under excellent conditions to see if you can detect any features. Also in the same field of view is the elliptical galaxy M60.

Caldwell 52	**NGC 4697**	**12^h 48.6^m**	**−05°48′**	**April 3**
9.2m [*12.7m*]	**6.0′|3.8′**		**E6**	**moderate**

This is a nice galaxy, but often ignored and left out from most observing schedules. Although it is rather bland in appearance, it stands out well against the background star field. Not really a binocular object, it is featureless telescopically, but with a large aperture, some brightness can be seen at its core. It is a dominant member of a small cluster of galaxies, which lies at a distance of about 60 million l.y.

Caldwell 35	**NGC 4889**	**13^h 00.1^m**	**+27°58′**	**April 6**
11.5m [*13.4m*]	**2.8′|2.0′**		**E4**	**difficult**

This is worth seeking out, as it is at a distance of about 350 million l.y. With a telescope of at least 20 cm aperture and excellent seeing conditions, you can glimpse this tiny object. It has a bright core, surrounded by the usual faint halo. It is a dominant member of the *Coma Galaxy Cluster*, which contains about 1000 galaxies (several of which can be seen through large-aperture telescopes of at least 40 cm). The cluster itself is made of many elliptical galaxies and S0-type galaxies. Apparently, this galaxy was the result of a merger of two older clusters. Observing any of these galaxies is a feat indeed, but worth the effort.

Caldwell 18	**NGC 185**	**00^h 38.9^m**	**+48°20′**	**September 30**
9.2m [*14.3m*]	**12′|10′**		**dE0**	**moderate**

This is another companion galaxy to M31, as mentioned earlier. However, this is easier to locate and observe than M31. With a telescope of 10 cm, it can just be glimpsed, whereas with 20 cm, it is easily seen. It remains featureless even with larger apertures (40 cm), but shows a perceptibly brighter core. Several reports suggest that, with a very large aperture of 75 cm, some resolution of the galaxy becomes apparent. It is a dwarf elliptical galaxy.

Caldwell 17	**NGC 147**	**00^h 33.1^m**	**+48°30′**	**September 29**
9.5m [*14.5m*]	**13′|8.1′**		**dE4**	**difficult**

Located in *Cassiopeia*, this is classified as a *dwarf elliptical galaxy*. Although not for from M31, the *Andromeda Galaxy*, it is in fact a companion to that famous galaxy. It is difficult to locate and observe except in very dark skies. It has been suggested that a minimum of 20 cm aperture is needed to see this galaxy; however, under excellent seeing conditions, a 10 cm telescope is sufficient and averted vision is necessary. The moral of this story is that dark skies are essential to see faint objects. Increased aperture as well as higher magnification will help its nuclear region become visible. A member of the *Local Group*, it is one of more than 30 galaxies that are believed to be companions to either M31 or the Milky Way.

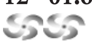
Messier 110	**NGC 205**	**00^h 40.4^m**	**+41°41′**	**October 1**
8.0m [*13.9m*]	**21.9′|11.0′**		**E5P**	**easy**

M110 is the final entry in the Messier catalogue, added to the original list in 1967. It is the second satellite galaxy of M31, and although it has a brighter magnitude than that of M32 (the first satellite), it has a much lower surface brightness. Consequently, it is much harder to see. However, it is visible with large binoculars, but will appear only as a very faint, featureless glow northwest of M31. With a telescope, it shows a surprising amount of detail, and a higher magnification will bring out its mottled nucleus. In addition, it shows details that are peculiar for an elliptical galaxy and visible to the amateur; look for dark patches near a bright center. Strangely enough, they are reminiscent of features normally found in a spiral galaxy. Of course, exceptionally dark skies and perfect seeing and transparency will be needed, but with a telescope of even modest aperture, say 10 cm, and a high magnification, they can be readily seen.

4.6.4 Lenticular Galaxies

Caldwell 53	**NGC 3115**	**10^h 05.2^m**	**−07°43′**	**February 21**
8.9m [*12.6m*]	**8.3′|3.2′**		**SOsp**	**easy**

Also known as the *Spindle Galaxy*, this galaxy is often overlooked, which is unfortunate because it is a fine example of its type, as well as being quite bright. With binoculars, it will appear as a small, faint elongated cloud, and with large binoculars, it will display the characteristic lens shape. It can be easily located with telescopes because of its high surface brightness. With telescopes of aperture 20 cm, it will appear as a featureless oval cloud, with perhaps a slight brightening toward its center. As it is classed as an SO-type galaxy, it will not show any further detail, even with larger apertures. It is a very big galaxy, about five times larger than the Milky Way. It is also one of the most favored objects that is purported to have a black hole at its center.

Caldwell 60/61	**NGC 4038/9**	**12^h 01.6^m**	**−18°51′**	**March 22**
10.3/10.6*m* [14.4*m*]	**7.6′|4.9′**		**Sp S(B)p**	**moderate**

They are known as the *Antennae* or *Ring-Tail Galaxies*. Together, they probably make one of the most famous objects in the entire sky, but few amateurs ever observe it, believing it to be too faint. A telescopic object, it will appear as an asymmetrical blur through apertures of about 20 cm. Larger apertures will hint at its detailed structure, and with a 25 cm aperture, it will resemble the shape of an apostrophe. With an aperture of about 30 cm, along with medium or high magnification, you will resolve both the objects involved, and it would be a worthwhile project to try with a different group of telescopes and observers to see just how much detail can be resolved. It is one of those celestial objects that are so familiar from photographs that your perception of what you actually see will be tainted by what you expect to see. Nevertheless, it is a wonderful object. Sadly, it is very low down for UK observers, so perfect observing conditions will be necessary. The marvellous shape of the Antennae was the result of spiral galaxies passing close by each other, and that tidal interaction caused material to be dispersed. Observe the amazing long tails that can be seen from deep images of these galaxies. Furthermore, recent work has shown that the interaction has led to a vast bout of star formation. Also, it has encouraged astronomers to put forward the idea that spiral galaxies evolve into elliptical galaxies after such an encounter.

Messier 85	**NGC 4382**	**12^h 25.4^m**	**+18°11′**	**March 28**
9.1m [*13.0m*]	**7.1′|5.5′**		**SA(s)OP**	**moderate**

This is a bright galaxy that can be glimpsed with binoculars on clear nights. With large binoculars, it is even easier, where it will show a star-like nucleus surrounded by the faint glow of the halo. A telescope will just magnify the rather featureless aspect, though a few observers report that, at high magnification, some faint detail can be glimpsed to the south of the nucleus, which may be a trace of some spiral structure. Also, there is an indication of a faint blue tint to the galaxy.

Caldwell 21	**NGC 4449**	**12^h 28.1^m**	**+44°05′**	**March 29**
9.6m [*12.5m*]	**6.0′|4.5′**		**IBm**	**moderate**

A member of the *Canes Venaticorum Group* of galaxies, this is a faint and frequently ignored object. Its irregular shape is often mistaken for a comet. Under good skies, a telescope of 20 cm aperture will easily discern its fan-shaped morphology along with its faint nucleus. Larger telescopes will, of course, resolve the galaxy with a considerable amount of detail. An interesting point is that several HII regions are visible, especially one at the northern corner of the open fan shape. It is apparently a site of much ongoing star formation, and it is similar in many ways to the *Large Magellanic Cloud*.

Caldwell 57	**NGC 6822**	**19^h 44.9^m**	**−14°48′**	**July 18**
8.8m [*14.2m*]	**20.0′|10.0′**		**IB(s)m**	**moderate**

Also known as *Barnard's Galaxy*, this is a challenge for binoculars. Even though it is a fairly bright galaxy, it has a low surface brightness and hence is difficult to locate. Once located, however, it will just appear as indistinct glow running east to west. This is in fact the bar of the galaxy. Strangely enough, it is one of those objects that are easier to locate using a small aperture (say 10 cm) rather than large. Nevertheless, dark skies are essential to locate this galaxy.

Caldwell 51	**IC 1613**	**01^h 04.8^m**	**+02°07′**	**October 7**
9.2m [−]	**11.0′|9.0′**		**dIA**	**moderate**

A very difficult galaxy to observe, a few observers report that it is visible through large binoculars as a very faint hazy glow, while others claim that a minimum of

20 cm aperture is needed. Whatever you choose, one thing is paramount—a dark sky. A member of the *Local Group*, it is similar in many respects to *Caldwell 57*. It is also an old galaxy that is still forming stars.

4.7 Active Galaxies and AGNs

We now discuss a type of galaxy that has become very prominent in astrophysical research over the past 20 years or so—*Active Galaxies* and *Active Galactic Nuclei*, or *AGNs*.

The story begins in the 1950s, when radio astronomers began to detect galaxies that emitted vast amounts of radio energy, in some cases as much as 10 million times more radio energy than a normal galaxy would. Later on, when space-borne telescopes made an appearance, it was found that there exist galaxies that emit incredible amounts of energy in the infrared, ultraviolet, and X-ray. These are the active galaxies. Subsequent observations have shown that most of this "extra" energy is emitted from the central regions of the galaxies, and so this is the explanation for the term active galactic nuclei.

The different types of active galaxies are legion! In fact, there was a time when it seemed that every time an active galaxy was discovered, it could be put into its own individual class. But we now know different.[12] For instance, there are:[13]

Seyfert Galaxies, types 1 and 2 [and 1.6, 1.7, 1.8, & 1.9!]
LINERS [low-ionization nuclear emission line regions]
LLAGN [low-luminosity AGN]
Radio-loud AGN
Radio-quiet AGN
BLAZERS, consisting of *BL Lacs* and *OVVs* [optically violent variables]
Flat spectrum radio quasars (FSRQs)
Steep spectrum radio quasars (SSRQs)
*Starburst*s
QSOs and *Quasars*, these two being the most extreme types of AGNs
Phew!
So what is really going on?

The answer is quite simple. At the center of the galaxy is a supermassive black hole surrounded by an accretion disc. This disc is very hot toward the black hole but cooler farther out. Theoretical studies suggest that the inner part of the disc can be very narrow, and that the black hole is hidden deep within this narrow central area. The outer part of the disc is believed to be a large, dense torus-shaped object consisting of dusty gas. Material falls into the black hole via the accretion disc, and prestigious amounts of energy are emitted. Sometimes this energy is focused into jets, as in Messier 87, which we can sometimes see. Moreover, this energy causes nearby clouds of fast-moving hydrogen to emit very strongly in the hydrogen alpha wavelength; other circumstances give rise to clouds farther away from the center emitting light, too.

Broadly speaking, the type of active galaxy (or AGN) that we see depends on how the accretion disc is inclined to our line of sight. If we can see the inner regions, it could be a Seyfert 1 active galaxy. If the inner region is obscured from view, it may be a Seyfert type 2. It is important to realize that even though we may see a galaxy face-on, it does not necessarily mean we can see the active nucleus face-on. The accretion disc may be inclined at a very steep angle to the plane of the galaxy, as in Centaurus A. Figure 4.2 attempts to demonstrate this.

As I mentioned earlier, the source for all the energy in active galaxies is believed to be the supermassive black holes that lurk at their centers. Further observations suggest that most active galaxies are interacting or merging with nearby smaller galaxies, and these events provide a source of material than can feed the central supermassive black hole. This leads nicely to the idea that galaxies that are not interacting with a companion, or have not done so in the recent past, will not have material flowing into the black hole, and thus will not be active. And indeed, this is what we see.

A certain type of AGN that has profound consequences on both galaxy evolution and cosmology are the Quasars, also known as quasi-stellar objects, or QSOs. It is important that we briefly discuss them here. The story begins in 1963,

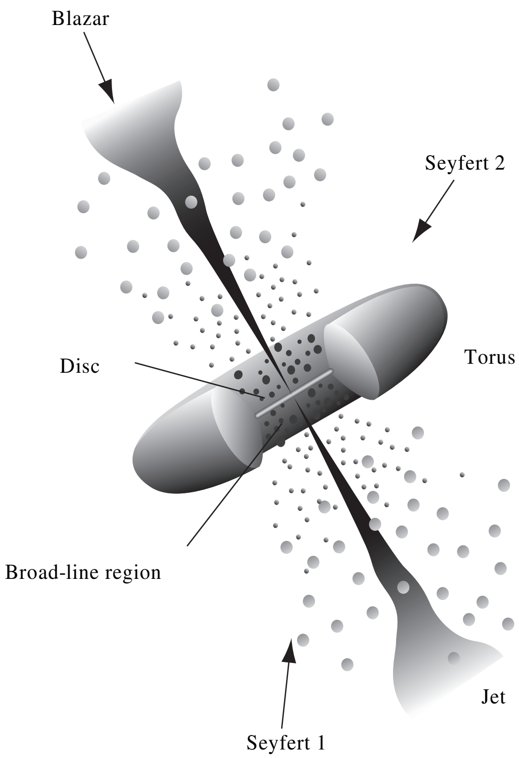


Figure 4.2. Diagrammatical form of the unified theory of active galactic nuclei.

when Maarten Schmidt at Hale Observatories managed to identify some previously unknown spectral lines in a supposedly stellar spectrum. He discovered that the unknown lines were in fact hydrogen lines, but with large redshift. For the object he was looking at, 3C 273, he measured a redshift of 15.8%. This is not particularly large as redshifts go, but soon after, quasars with larger redshifts were discovered. "So what?", you may ask! Well, the significance is that these quasars are very far from us, as evident from their redshifts; however, they appear bright in photographs, in fact, like stars, and hence the quasi-stellar nomenclature. To be so easily seen,[14] and yet at immense distances from us, quasars must be very luminous, perhaps as much as 10 to 1000 times as luminous as a galaxy. Thus, quasars must be superluminous.

Another important factor appears now; some quasars fluctuate in brightness in only a few months, and since an object cannot alter its brightness appreciably in less time than it takes light to cross its diameter, then these quasars must be very small objects, perhaps not more than a few light-months in diameter. What can possibly make quasars have nearly 1000 times more energy than all the stars in a galaxy, yet be so small? You guessed it—a supermassive black hole.

We now know that quasars are the nuclei of galaxies that lie at tremendous distances from us, and thus must be objects that formed in the early universe. Deep images suggest that quasars contain supermassive black holes, and these young galaxies are distorted, and many have close companions. The activity we observe is possibly initiated by interactions between the host and companion galaxies.

It is a nice aspect of observational astrophysics. Several active galaxies can be easily observed by amateur astronomers, as the brief list that follows would indicate.

4.7.1 Brightest Active Galaxies

Caldwell 29	**NGC 5005**	**13^h 10.9^m**	**+37°03′**	**April 9**
9.8m [*12.6m*]	**6.3′|3.0′**		**SAB(rs)bc**	**easy**

This galaxy is not a binocular object, and so telescopes of about 15 cm aperture will reveal it only as an oval patch with a bright nucleus. The galaxy does not have any conspicuous spiral arms, and so even with large-aperture telescopes further detail will be sparse, and only a slight irregularity in overall brightness will be resolved. Although it is similar to the Milky Way, what makes this galaxy special is that it is an *active galaxy* of a class called *LINER* (*L*ow *I*onization *N*uclear *E*mission-line *R*egion). At the center of the galaxy is some sort of mechanism that gives rise to both the observed spectral lines and a radio source. It may be due to massive stars called *warmers*, or an accretion disc around a *black hole*.

Messier 77	**NGC 1068**	**02^h 42.7^m**	**−00°01′**	**November 1**
8.9m [*13.2 m*]	**7.1′|6.0′**		**(R)SA(rs)b**	**easy**

This is a famous galaxy for several reasons. With binoculars, it is visible just as a hazy patch of light; under excellent seeing conditions, a faint star-like nucleus may be glimpsed. With telescopes of aperture about 10 cm or greater, and providing that dark skies are available, the spiral arms can be glimpsed. What makes this galaxy so special is that it is the archetypal *active galaxy* of a class known as *Seyferts*. Its uniqueness was discovered in the middle of the twentieth century by *Carl Seyfert*, who noticed that it had very prominent emission lines. These are due to the high velocity of gas close to the nucleus of the galaxy. The high speed of the gas, in the order of 350 kilometers per second, is believed to be due to the influence of a massive black hole. M77 is in fact classified as a *Seyfert II* galaxy, which indicates that it has only narrow emission lines. Seyferts are distant cousins of the famous *quasars*. It is one of the brightest active galaxies visible even to amateur astronomers.

Caldwell 67	**NGC 1097**	**02^h 46.3^m**	**−30°16′**	**November 2**
9.5m [*13.6 m*]	**9.3′|6.6′**		**SB(s)b**	**easy**

This is a nice galaxy whose bar can be seen easily. With a 20 cm-aperture telescope, the core can be resolved, and a faint elongated glow is easy to see, which in fact is the bar. Larger apertures will resolve this feature quite well, along with the spiral arms that emanate from the bar's end. It is an active galaxy, and classified as a Seyfert galaxy of type 1. This means that gas close to the nucleus is moving at extremely fast speeds, maybe in excess of 1000 kilometers per second. The most likely cause of this motion is the influence of a *supermassive black hole*. A Seyfert 1 galaxy has both broad and narrow emission lines, the width of the line being a measure of the velocity of the gas that produced the emission line.

Messier 87	**NGC 4486**	**12^h 30.8^m**	**+12°24′**	**March 30**
8.6m [*12.7 m*]	**8.3′|6.6′**		**E0.5P**	**easy**

A very special galaxy, M87 is bright and easily seen with binoculars, and with telescopes a little more can be resolved. But its rather bland appearance is deceiving. This is a monster galaxy with a mass estimated to be that of 800 billion Suns. This makes it one of the most massive galaxies known in the entire universe. But that is not all. It is an active galaxy, and lurking at its core is a supermassive black hole with a mass of 3 billion Suns. Another feature that some observers report seeing with telescopes of aperture 50 cm is the famous "jet" that streams out from M87. It would be a challenge indeed, and a triumph, if it were ever observed from the light-polluted skies of the UK. The jet is a stream of plasma (hot ionized gas), several thousand light years in length, which is believed to be due to some sort of interaction between the black hole and its surroundings. It is, however, very easy to photograph and image with a CCD camera. M87 lies at the heart of the *Virgo Cluster*, and most of the surrounding galaxies are influenced by its tremendous gravitational attraction. The cluster has about 300 large galaxies and perhaps as many as two thousand smaller ones. It is the closest large cluster, lying at a distance of around 55 million l.y. It spans over 100 square degrees in both Virgo and Coma Berenices. Such is its influence that the Milky Way is actually gravitationally attracted to it.

Messier 82	**NGC 3034**	**09^h 55.8^m**	**+69°41′**	**February 19**
8.4m [*12.8 m*]	**11.2′|4.3′**		**IOsp**	**easy**

It is a very strange galaxy that becomes readily apparent when seen through a telescope. It can also be glimpsed with binoculars, where it would appear as an elongated pale glow. Large binoculars will hint at some more detail, and with averted vision the dark dust lane may be seen. With even a small telescope of 10 cm aperture, it becomes evident that something strange has happened to M82. The western part is obviously brighter than the eastern part. The core region appears jagged and angular. Throughout the length of the galaxy, the starlight appears to stream through the gaps in the dark dust lanes. It is a galaxy that will reward long and detailed study, especially with large aperture and high magnification. The galaxy is an active galaxy of the *starburst* type, and is undergoing an immense amount of star formation. This may have been caused by the close passage of its companion M81. Nearly 40 million years ago, the gravitational effect of M81 may have caused the interstellar material within M82 to collapse and form new stars. Subsequently, the material that was dragged from M82 is now believed to be falling back onto it, which gives rise to both its appearance and the new era of star formation. Both M81 and M82 can be seen in the same field of view and are a stunning sight.

Caldwell 77	**NGC 5128**	**13^h 25.5^m**	**−43°01′**	**April 13**
6.8m [*12.9 m*]	**18.2′|14.5′**		**SOpec**	**easy**

It is also known as *Centaurus A*. Although this galaxy is too far south to be visible to UK observers, it nevertheless is spectacular. Photographs show it as nearly a circular object bisected by a very prominent dark dust lane. It is visible with binoculars as a hazy star; larger binoculars just give a glimpse of the famous dark lane. With small telescopes of aperture 15 cm, the dark lane can be easily seen. Larger apertures will of course give a more detailed view, with the dark lane showing some structure. It is intriguing, especially because of its status as the nearest active galaxy. Note that this object has a compact core that probably houses a supermassive black hole, although it cannot be seen directly with the naked eye. This makes Centaurus A, for me, one of the most exciting objects in the sky.

Caldwell 24	**NGC 1275**	**03^h 19.8^m**	**+41°30′**	**November 10**
11.9m [*13.2 m*]	**3.5′|2.5′**		**P**	**difficult**

The last galaxy in our list is a very important galaxy, even though it is not visually impressive. It should be observed for several reasons. It is the main member of the *Perseus Galaxy Cluster*, also known as *Abell 426*. Several observers have stated that it can be seen through telescopes as small as 15 cm aperture, while larger apertures will make it easier to locate. If you look at it through a telescope of aperture 40 cm or larger, this galaxy will appear to be surrounded by several fainter ones, which are all part of the cluster. In many respects, it is the most concentrated field of galaxies in the winter sky for northern observers. *Caldwell 24* is a strong *Radio Galaxy* and is believed to be the remnant of a merger between two older galaxies. It is one of more than 500 members of the *Perseus Cluster*. The cluster itself is part of an even larger supercluster, the *Pisces–Perseus Supercluster*.

3C 273	**12^h 29.1^m**	**02°03′**	**March 29**
12.8m	**Redshift (z) 0.158**		**2,000,000,000 l.y.**

This quasar is the brightest in the sky and within the reach of medium- and large-aperture telescopes. There are reports that this quasar has been glimpsed with telescopes of 20 cm, and thus is well within the reach of amateurs. Averted vision will also help locate this distant object. To locate the quasar, the following directions should help:

It is situated about 3.5° northeast of Eta Virginis.

Locate the galaxy NGC 4536 (magnitude 10.6, surface brightness 13.2, at position R.A. $12^h 34.5^m$ Dec. 02°11′). At about 1.25° east of this galaxy is the quasar.

In its immediate vicinity is a double star, arranged east–west with 3 arcsecs separation. The double system has magnitudes 12.8 and 13, and the quasar is a bright, blue-tinted stellar object east of the double system.

PKS 405−123	**MSH 04−12**	**04^h 07.8^m**	**−12°11′**	**November 22**
14.8m	**Redshift (z) 0.57**			**6,000,000,000 l.y.**

This is another quasar that should be within the reach of amateur astronomers, and it can be glimpsed with a telescope of 20 cm. It is located in the constellation Eridanus. The quasar lies about 3° to the northeast of Zaurak (Gamma Eri). When seen through an eyepiece, you may spot a tiny green dot to the left. This is the planetary nebula NGC 1535 (Cleopatra's Eye). If you managed to see the quasar, and you will need detailed star maps to confirm your observations, then you are a member of a very small and elite group of observers. It is also incredible to note that the light that enters your eye from this quasar started its journey some 1.5 billion years *before* the Solar System was formed!

4.8 Gravitational Lensing

Before I leave the topic of quasars, I should mention that it is possible, under the right conditions, to see one of the most fascinating consequences of Einstein's general theory of relativity—*gravitational lensing*.

The general theory of relativity is far beyond the scope of this book, but a simple outline of it is fairly sufficient. Gravity has the ability to "bend" light, if the gravitational force is strong enough. The first experimental justification of Einstein's theory was in fact a measure of this light bending. On May 29, 1919, the British astronomer Arthur S. Eddington measured the amount of starlight was deflected by the Sun. He used a total eclipse of the Sun so that any faint stars would not be rendered invisible by the glare of the Sun. The accuracy of the measurements was about 20%, but it was enough to vindicate the theory. Subsequent measurements using radio waves have managed to confirm the predictions made by Einstein to within 1%.

The Sun is not the only object that can bend a ray of light. Any object that has sufficient mass can deflect light waves. Calculations show that when light rays from a distant object pass close to a compact but massive galaxy, the bending of the light can result in the appearance of multiple or twisted images. It is as if the galaxy were acting like a lens, and so any object emitting light from *behind* the galaxy has its light bent as it passes close to the galaxy. This bizarre effect is called *gravitational lensing*.

In 1979, some astronomers noticed that a pair of quasars known as QSO 0957 + 561 had identical spectra and redshifts, and it was suggested that these two quasars may in fact be one, and that the two images were produced by an intervening object. This was subsequently proven to be the correct explanation, whereby the light from distant quasars was being lensed by an intervening cluster of galaxies.

You may have seen images of such objects in various books and magazines, and may have thought that it would be nearly impossible to see these through a telescope. The examples given are usually of quasars that are so distant that the Hubble Space Telescope or at least the world's largest ground-based telescopes are needed to image them.

This is (only) more or less true, but one or two quasars can be and have been seen by amateur astronomers. It is not easy. I must stress that good seeing conditions are essential to observe these faint objects, and that a detailed star atlas is required to confirm the observations.

Twin quasar Q0957+0561A/B 10^h01^m 55°53′ February 20
16.8m (17.1 17.4 A/B) Separation 6″ 8,000,000,000 light years

The quasar is in the constellation Ursa Major, and so it is a fine target for observers from the northern hemisphere. The starting point for the quasar is the bright edge-on galaxy *NGC 3079* (8.1′× 1.4′, magnitude 11.5, within the reach of a 20 cm telescope; several fainter galaxies lie nearby). The galaxy points to the quasar to the southeast, about two galaxy lengths away near a parallelogram of 13th- and 14th-magnitude stars. The quasar lies off the southeast corner. The two components are 17.1 and 17.4 magnitude, separated by 6″. Observers with very large instruments of aperture 50 cm have reported seeing the two objects cleanly split. Like most quasars, *Q0957+0561* is slightly variable in brightness. With small telescopes, the two images will appear as one, but slightly elongated. In this case, the lensing is done by a cluster of galaxies, which lie 3.5 billion l.y. away, and is splitting the light of the more distant *Q0957+0561* into multiple images. Two of these images are much brighter than the others, and this is what was observed. It may be wise to try as high a magnification as possible. This is a good observing challenge for CCD users. The quasar lies at a distance of almost 8 billion l.y. and may well be the most distant object visible to the amateur astronomer.

Leo Double Quasar QSO 1120+019 11^h 23.3^m 01°37′ March 13
15.7 20.1m (A/B) Redshift (z) 1.477

This is an extremely difficult quasar to resolve. The brighter A component can be easily seen with large telescopes, but the fainter B component is very difficult.

Cloverleaf Quasar H 1413+117 14^h 15.8^m 11°29′ April 25
17m(A/B/C/D) Redshift (z) 2.558

It is an exceedingly difficult object to observe, except under perfect conditions and with very large-aperture telescopes. The greatest separation among the four is about 1.36″. To my knowledge, it has never been observed from the UK, but US observers report seeing just an asymmetric, faint hazy, and tiny blob of light, although it has been imaged by CCD.

4.9 Redshift, Distance, and the Hubble Law

During the early part of the 20th century, astronomers, notably Edwin Hubble, were beginning to take accurate measurements of the spectra of galaxies. What soon became apparent was that many of them exhibited a redshift, that is, the spectral lines were shifted to the red end of the spectrum, indicating that the galaxy was moving away from the Earth. Furthermore, as astronomers such as Milton Humason, who refined the distance determination measurements, observed, galaxies that were farthest away seemed to have the greatest redshifts. This phenomenon was observed not in just a few galaxies but in thousands, and as more and more measurements were taken, and as techniques improved, it became apparent that throughout the observed universe galaxies were moving away from us, and those that were far away moved faster toward the most distant galaxies with the greatest velocity.

What had been discovered was the expansion of the universe and the *Hubble Law*.

Although a rigorous treatment of this topic is beyond the scope of this book, it is very easy [within limits] to determine both the redshift and *recessional velocity* of a galaxy. As an aside, it is important to mention that to be completely accurate it is really galaxy clusters, and thus the galaxies contained therein, that are moving away from each other. Galaxies, say within the Local Group, actually have random motions. Understand the fact that we are moving *toward* M31 and that the Large Magellanic Cloud is moving *toward* us!

The Hubble Law is one of the most important concepts in astrophysics, as not only does it relate to distance and velocity but it has more profound implications. It deals with the subject of cosmology and begins to set the scene for the greatest of all concepts—the Big Bang.

Box 4.1: Redshift

The *redshift* of an object is the difference between the observed wavelength of a spectral line and its rest wavelength.

$$\text{Redshift} = z = \frac{\lambda_{observed} - \lambda_{rest}}{\lambda_{rest}}$$

Example:
A galaxy has an observed Hα line at 662.9 nm. The rest wavelength of Hα is 656.3 nm. Calculate the redshift of the galaxy and its velocity of recession.

$$z = \frac{662.9 - 656.3}{656.3} = 0.010$$

The redshift of the galaxy is 0.010
For nearby galaxies, when z is much less than 1, its velocity can be calculated by

$$v = c \times z$$

where c = speed of light, 3.0×10^8 m/s. Thus

$$v = c \times z = (3.0 \times 10^8\,\text{m/s}) \times 0.01 = 3,000\,\text{km/s}$$

The galaxy's velocity of recession is 3,000 km/s.

Hubble's Law

Using Hubble's Law, we can determine the distance to a galaxy if we know how fast it is moving away from us. This velocity is called the *recessional velocity*.

$$v = H_0 \times d$$

H_0 is called the Hubble constant, and it is generally quoted in kilometers per second per megaparsec (km/s/Mpc). The value [currently!] appears to be about 70 km/s/Mpc.
Example:
Estimate the distance to the galaxy used above.

$$d = \frac{v}{H_0}$$

$$d = \frac{v}{H_0} = \frac{3,000}{70} \approx 43\,\text{Mpc}$$

The galaxy is approximately 43 Mpc away. As 1 Mpc = 3.26 million l.y., this is equivalent to 140 million l.y.

4.10 Clusters of Galaxies

Surprisingly, single galaxies are a rare breed. Most galaxies live in clusters, which may contain just a few; some are giant clusters, which may have thousands of members. In addition, small clusters occupy only a relatively small region of space, say 1 Mpc, while the largest clusters cover an immense 10 Mpc. The Milky Way is a member of a small cluster called the *Local Group*, with more than three dozen[15] other galaxies.

One can consider two types of clusters: *Rich Clusters* and *Poor Clusters*. The former may consist of more than 1000 galaxies, lots of ellipticals, and cover an area of over 3 Mpc in diameter. In this type of cluster, the galaxies are more often concentrated towards the cluster center. At the center itself, there may be one or two giant elliptical galaxies. A fine example is the Virgo cluster, with the giant elliptical M87 at its center.

Poor clusters, as the name suggests, contain fewer than a thousand members that cover an area as big as that of a rich cluster, thus making the galaxies more spread out.

It seems that rich clusters contain about 80–90% E-type and S0-type galaxies, with a few spirals, whereas poor clusters have a larger proportion of spiral galaxies. Furthermore, for galaxies that are in isolation (i.e., those not in clusters), it appears that 80–90% of these are spirals. There is a large amount of evidence suggest that large elliptical galaxies have been involved in to many galaxy collisions, whereas spirals have not. In fact, it may well be that ellipticals are formed by the merger of spirals. The dwarf elliptical, on the other hand, seems to have followed a different evolutionary path. These are small galaxies that have lost their gas and dust due to interactions with several larger galaxies.

Although the evolution of galaxies is still not fully understood, it is obvious that interactions between them is very important. Collisions, mergers, and close encounters can all cause bursts of rapid star formation and very dramatic and spectacular tidal disruption. In fact, our own Milky Way, I think, is cannibalizing the Magellanic Clouds.

Amazing!

4.10.1 Groups and Clusters of Galaxies

Hickson Group 68	**NGC 5353**	**13^h 53.4^m**	**+40°47′**	**April 20**
11.1m	**→ 11.2′ ←**	**5**		**moderate**

This is a very nice group of stars for amateur instruments. The brightest member can be seen with a telescope as small as 6 cm, and with a 15 cm aperture, it will show a slight brightening at its center. The other galaxies will appear as faint patches of light; to see the faintest member would most certainly require an aperture of about 25 cm.

Copelands Septet	**NGC 3753**	**11^h 37.9^m**	**+21°59′**	**March 16**
13.4m	**→ 7.0′ ←**	**7**		**difficult**

Also known as the *Hickson Galaxy Group 57*, this is a very small group of galaxies. It is situated in the constellation *Leo*, all within about 7 arcsecs of each other. Even telescopes of 25 cm aperture will not spot the fainter members of the group, but just the four brighter galaxies. Larger apertures should, of course, help spot them. Nevertheless, seeing conditions will determine what you observe. The group is a mix of barred spirals, ordinary spirals, and lenticular galaxies.

Coma Cluster	**NGC 4889**	**12^h 57.7^m**	**+28°15′**	**April 6**
11.4m	**→120+′←**	**10+**		**difficult**

This is a large cluster of galaxies. Many of its members are within the reach of amateur telescopes of aperture 25 cm or larger. It is fairly well spread out, and so the field of view will be dotted with many indistinct faint patches of light. It contains many elliptical, spiral, barred spiral, and lenticular galaxies.

Stephen's Quintet	**NGC 7320**	**22^h 36.1^m**	**+33°57′**	**April 6**
12.6m	**→4′←**	**5**		**difficult**

It is a very famous group of galaxies located in Pegasus, but one that was proved strangely difficult for amateurs in the past. Under perfect seeing conditions, the group is visible with a 20 cm telescope. However, I stress the word *perfect*! The largest member of the quintet is only 2.2 × 1.2 arcsecs in size, and so it is very small but the brightest. To observe the group as a distinct unit, and not a faint smudge of light, you will need a telescope of aperture 25 cm. This will show at least four of the group, but the fifth one would require an aperture of at least 30 cm. With high magnification and a larger aperture, the structure can be seen within the brighter members. It is believed that the four in the group are interacting with each other. There has been debate as to whether the fifth is in fact a line-of-sight galaxy. Finally, it is a definite observing challenge from an urban locality.

Seyfert's Sextet	**NGC 6027**	**15^h 59.2^m**	**+20°46′**	**May 22**
13.3m	**→ 1.5′←**	**6**		**very difficult**

This is a real challenge! Except with the largest telescopes, it is doubtful that you can see anything at all, and even with apertures around 40 cm, the galaxies will barely be resolved. Nevertheless, it would be interesting to find out what would be the smallest aperture required to spot these faint galaxies.

Fornax Cluster	**NGC 1316**	**03^h 20.9^m**	**−37°17′**	**November 10**
11.4m	**→+12′←**	**10+**		**difficult**

This is another large cluster of galaxies. Amateur telescopes should be able to pick out the brightest members with no difficulty. What makes this cluster spectacular, however, is that, with a modest aperture (say 25 cm) and clear dark skies, there are so many galaxies visible that identifying it will be very difficult. The brightest member is visible even with an 8 cm telescope! A galaxy of note in the cluster is *NGC 1365*, which is a nice barred spiral 8 arcsecs in length and visible as a faint blur in an 8 cm aperture telescope. The cluster also contains a galaxy known as the *Fornax System*. It is a dwarf spheroidal galaxy, a very small and faint class of galaxy.

4.11 Endnote

We have now come to the end of our spectacular journey, and I hope you have enjoyed the trip as well as being amazed and sometimes astounded by what you have read and hopefully observed. But this is not the end—it is just the beginning because you have only seen a handful of the plethora of celestial delights that await you.

The next time you observe the night sky, just think: you will have an inkling of what those objects are, how they formed, how they could die, what they are made of, and whether they are stars, clusters, nebulae, or galaxies.

Incredible!

Happy observing!

Notes

1. The Milky Way galaxy is often referred to as the “Galaxy,” with a capital letter, whereas any other is simply a “galaxy.”
2. Although a few stars may, after an immense amount of time, break free of a galaxy’s grip and become intergalactic wanderers.
3. Or, at times, a rugby ball (for those of us in the UK).
4. See Chapter 2 for a description of HII regions.
5. Recent research has shown that the Large Magellanic Cloud, often classified as irregular, is in fact a spiral galaxy, even though it bears little resemblance to the classic spiral shape.
6. Of course, I don’t really have to mention that if you have a medium-to-large-aperture telescope, then the number of galaxies visible to you is vast, and the detail you will be able to see will astound you!
7. The Local Group is a cluster of several galaxies, including the Milky Way. It consists of M31, M33, M110, and M32, the Large and Small Magellanic Clouds, and about 25 other dwarf galaxies, including Leo I and II, And I and II, the Draco, Carina, Sextans, and Phoenix dwarfs.
8. Cepheid variables are used as *standard candles*, which measure distances to other extra-galactic objects.
9. The galaxy M83 lies at the same distance and has reportedly been seen with the naked eye.
10. Sometimes the cluster is just referred to as the *Virgo Cluster*. For a description of the cluster, see the entry on M87.
11. A large HII region, NGC 604, is visible. See the entry under Emission Nebulae in Chapter 2.
12. Active galactic nuclei are usually classified by three parameters: optical variability, radio emission, and spectral line width. Seyfert galaxies are mostly radio-quiet and not so strongly variable as other types of AGN; Seyfert 1s have broad and narrow spectral lines, while Seyfert 2s only have narrow lines. In addition, some Seyfert 1s exhibit broadened lines that are relatively narrow and are designated “Narrow Line Seyfert 1s” (NLS1s).

Quasars are broad-lined and some of them are variable; they can be further divided between radio-quiet and radio-loud quasars. Radio galaxies have strong radio emission and are not variable. Blazers are highly variable and some of them have strong radio emission; they can be divided between narrow-lined BL Lac objects (some of them show no lines of spectra at all; that's why redshift of many BL Lacs remains unknown) and broad-lined OVVs (Optically Violently Variable quasars).

13. And this is not a complete list, either!
14. By easily, I mean photographically.
15. Additional members of the Local Group are being found at regular intervals. These are small and indistinct, thus their difficulty in being observed!

APPENDIX ONE

Degeneracy

Degeneracy is a very complex topic but a very important one, especially when discussing the end stages of a star's life. It is, however, a topic that sends quivers of apprehension down the back of most people. It has to do with quantum mechanics, and that in itself is usually enough for most people to move on, and not learn about it. That said, it is actually quite easy to understand, providing that the information given is basic and not peppered throughout with mathematics. This is the approach I shall take.

In most stars, the gas of which they are made up will behave like an ideal gas, that is, one that has a simple relationship among its temperature, pressure, and density. To be specific, the pressure exerted by a gas is directly proportional to its temperature and density. We are all familiar with this. If a gas is compressed, it heats up; likewise, if it expands, it cools down. This also happens inside a star. As the temperature rises, the core regions expand and cool, and so it can be thought of as a safety valve.

However, in order for certain reactions to take place inside a star, the core is compressed to very high limits, which allows very high temperatures to be achieved. These high temperatures are necessary in order for, say, helium nuclear reactions to take place. At such high temperatures, the atoms are ionized so that it becomes a soup of atomic nuclei and electrons.

Inside stars, especially those whose density is approaching very high values, say, a white dwarf star or the core of a red giant, the electrons that make up the central regions of the star will resist any further compression and themselves set up a powerful pressure.[1] This is termed degeneracy, so that in a low-mass red giant star, for instance, the electrons are degenerate, and the core is supported by an electron-degenerate pressure. But a consequence of this degeneracy is that the behavior of the gas is not at all like an ideal gas. In a degenerate gas, the electron degenerate pressure is not affected by an increase in temperature, and in a red giant star, as the temperature increases, the pressure does not, and the core does not expand as it would if it were in an ideal gas. The temperature, therefore, continues to increase, and further nuclear reactions can take place.

There comes a point, however, when the temperatures are so high that the electrons in the central core regions are no longer degenerate, and the gas behaves once again like an ideal gas.

Neutrons can also become degenerate, but this occurs only in neutron stars.

For a fuller and more rigorous description of degeneracy, I recommend the books mentioned in the latter appendices. Be warned, however, that mathematics is used liberally.

Note

1. This is a consequence of the *Pauli exclusion principle*, which states that two electrons cannot occupy the same quantum state. Enough said, I think!

APPENDIX TWO

Books, Magazines, and Astronomical Organizations

Books, Magazines, and Organizations

There are many fine astronomy and astrophysics books in print, and to choose among them is a difficult task. Nevertheless, I have selected a few, which I believe are among the best on offer. I do not expect you to buy, or even read, them all, but it would be in your better interest to check at your local library to see if they have some of them.

Star Atlases and Observing Guides

Norton's Star Atlas and Reference Handbook, 20th edn, Ian Ridpath (ed.), Prentice Hall, 2003 USA.
Sky Atlas 2000.0, W. Tirion & R. Sinnott, Sky Publishing & Cambridge University Press, 1999, Massachusetts, USA.
Millennium Star Atlas, R. Sinnott & M. Perryman, Sky Publishing, 2006, Massachusetts, USA
Uranometria 2000.0, Vols. 1 & 2, Wil Tirion (ed.), Willmann-Bell, 2001, Virginia, USA.

Observing Handbook and Catalogue of Deep-Sky Objects, C. Luginbuhl & B. Skiff, Cambridge University Press, 1990, Cambridge, UK.
The Night Sky Observer's Guide, Vols. I & II, G. Kepple & G. Sanner, Willman-Bell, 1999, Richmond, USA.
Deep-Sky Companions: The Messier Objects, S. O'Meara, Cambridge University Press, 1999, Cambridge, UK.
Deep-Sky Companions: The Caldwell Objects, S. O'Meara, Cambridge University Press, 2004, Cambridge, UK.
Observing the Caldwell Objects, D. Ratledge, Springer-Verlag, 2000, London, UK.
Burnham's Celestial Handbook, R. Burnham, Dover Books, 1978, New York, USA.
Star Clusters and How To Observe Them, M. Allison, Springer, 2006, New York, USA.
Double & Multiple Stars and How To Observe Them, J. Mullaney, Springer, 2006, New York, USA.
Nebulae and How To Observe Them, S. Coe, Springer, 2006, New York, USA.
Galaxies and How To Observe Them, W. Steinicke & R. Jakiel, Springer, 2006, New York, USA.

Astronomy and Astrophysics Books

Astrophysical Techniques, 4th edn, C. Kitchin, Institute of Physics, 2003, Bristol, UK.
Discovering the Cosmos, R. Bless, University Science Books, 1996, Sausilito, USA.
The Cosmic Perspective, J. Bennett, M. Donahue, N. Schneider, M. Voit, Addison Wesley, 1999, Massachusetts, USA.
Voyages Through The Universe, A. Fraknoi, D. Morrison, S. Wolff, Saunders College Publishing, 2000, Philadelphia, USA.
Introductory Astronomy & Astrophysics, M. Zeilik, S. Gregory, E. Smith, Saunders College Publishing, 1999, Philadelphia, USA.
Pathways To Astronomy, Schneider & Arny, McGraw-Hill, 2006, USA.
An Introduction To The Sun & Stars, Green & Jones, Open University/Cambridge University Press, 2005, Cambridge, UK.
An Introduction To Galaxies & Cosmology, Jones & Lambourne, Open University/ Cambridge University Press, 2005, Cambridge, UK.
Introduction to Modern Astrophysics, 2nd edn, B. W. Carroll & D. A. Ostlie, Addison Wesley, 2006, USA.
Stars, J. B. Kaler, Scientific American Library, 1998, New York, USA.
Extreme Stars, J. B. Kaler, Cambridge University Press, 2001, Cambridge, UK.
The Physics of Stars, 2nd edn, A. Phillips, Wiley, 1999, Chichester, UK.
Stars, Nebulae and the Interstellar Medium, C. Kitchin, Adam Hilger, 1987, Bristol, UK.
100 Billion Stars, R. Kippenhahn, Princeton University Press, 1993, Princeton, USA.
Stellar Evolution, A. Harpaz, A. K. Peters, Ltd, 1994, Massachusetts, USA.
The Fullness of Space, G. Wynn-Williams, Cambridge University Press, 1992, Cambridge, UK.
Astrophysics Of Gaseous Nebulae And Active Galactic Nuclei, 2nd edn, D. E. Osterbrock & G. J. Ferland, University Science Books, 2005, Sausilito, USA.
The Dusty Universe, A. Evans, John Wiley, 1994, Chichester, UK.
Galaxies and Galactic Structure, D. Elmegreen, Prentice Hall, 1998, USA.

Exploring Black Holes, E. Taylor & J. A. Wheeler, Princeton University Press, 2001, Princeton, USA.

Magazines

Astronomy Now, UK

Sky & Telescope, USA

New Scientist, UK

Scientific American, USA

Science, USA

Nature, UK

The first three magazines are aimed at a general audience and so are applicable to everyone, while the last three are aimed at the well-informed lay person. In addition, there are many research-level journals that can be found in university libraries and observatories.

Organizations

The Federation of Astronomical Societies, 10 Glan y Llyn, North Cornelly, Bridgend County Borough, CF33 4EF, Wales
[http://www.fedastro.org.uk/]

Society for Popular Astronomy, The SPA Secretary, 36 Fairway, Keyworth, Nottingham, NG12 5DU, UK
[http://www.popastro.com/]

The American Association of Amateur Astronomers, P.O. Box 7981, Dallas, TX 75209-0981
[http://www.astromax.com/]

The Astronomical League
[http://www.astroleague.org/]

The British Astronomical Association, Burlington House, Piccadilly, London, W1V 9AG, UK
[http://www.britastro.org/baa/]

The Royal Astronomical Society, Burlington House, Piccadilly, London W1V 0NL
[http://www.ras.org.uk/membership.htm]

International Dark Sky Association
[http://www.darksky.org/]

Topic Index

Object Index