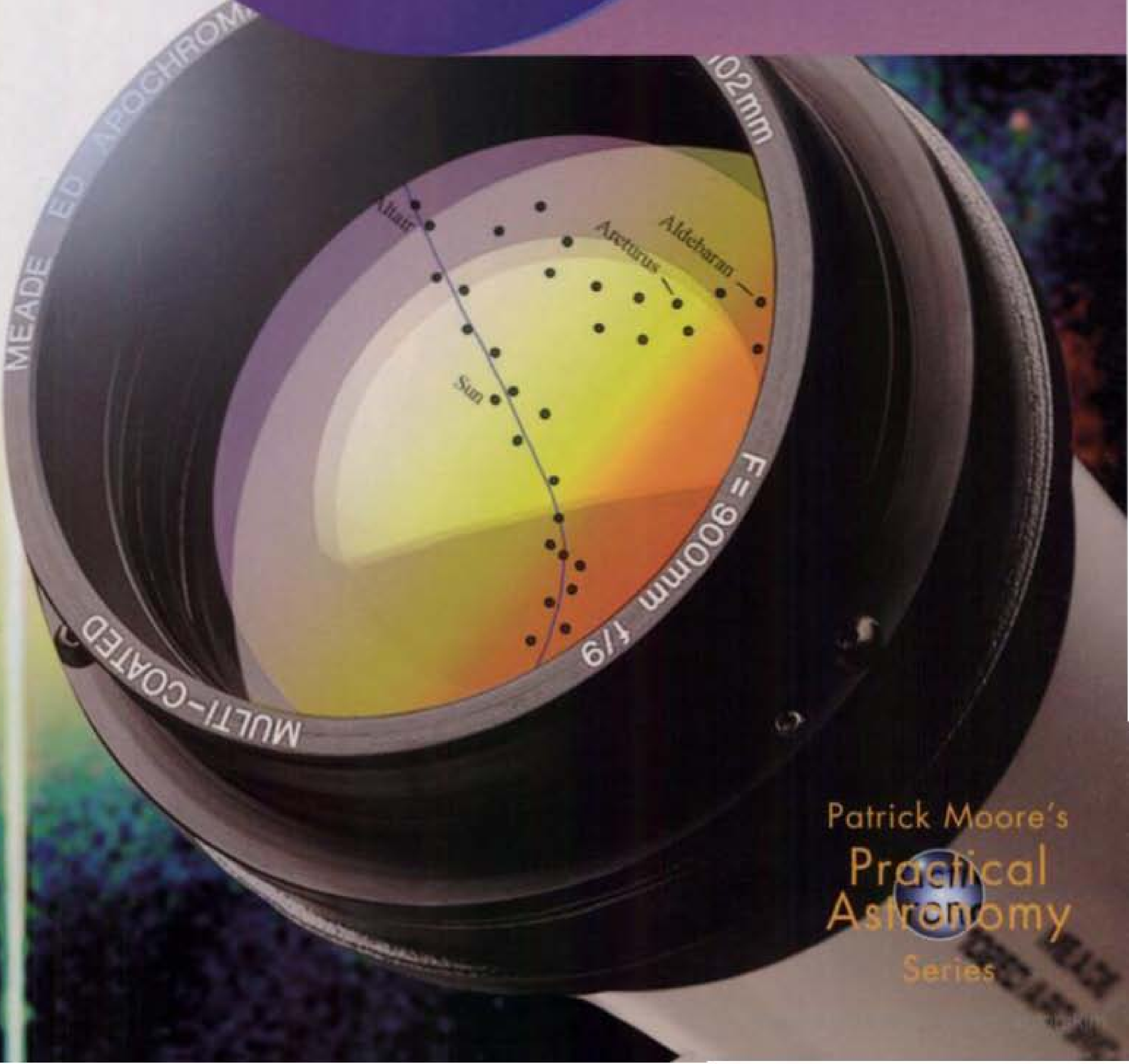
Mike Inglis

OBSERVER'S GUIDE TO STELLAR EVOLUTION



Patrick Moore's
Practical
Astronomy
Series

Contents

A Brief Introduction

To most people, stellar evolution, or the birth, life and death of stars, would seem to be a topic more suited to a university-level textbook, and so the idea of an observer's guide to stellar evolution may not, on first appearance, make any sense. However, let me assure you now, that anyone can understand how a star is born, lives its life, and dies - and what's more, there are numerous examples of each stage of a star's life that can be observed by anyone who steps out and looks up into a dark sky.

This is the reason behind the idea of the book. It will give a very understandable and accessible introduction to the various stages of a star's life cycle, and, at the same time, present many examples of the topics discussed that can be seen either with the naked eye or by using some sort of optical aid, such as binoculars and telescopes.

Learning about the mechanisms that give rise to star formation, fuel a star's life, and contribute to a star's death, can add another level of enjoyment and wonder to an observing session. Many amateur astronomers are familiar with, say, the star *Betelgeuse*, in the constellation *Orion*, but how many of you know that the star is a cool red giant star, which has left the "middle-age" of a star's life, and is now making a journey that will transform it from a giant star to perhaps an exploding star - a supernova! Or that the *Pleiades* star cluster, a familiar sight in the winter sky, is in fact a wonderful example of a group of young hot stars that were formed roughly all at the same time, and are now making their way through space, with the eventual result that they will disperse and spread out through their section of the *Milky Way*. Many such examples will be presented that will allow you to learn about stars and their lives, at your own pace, and thus give you a detailed panorama of the amazing objects which most of us observe whenever there is a clear night.

Each section of the book will cover a specific aspect of a star's life, starting with the formation of stars from dust and gas clouds, up to the final chapter of a star's life, which can end in the spectacular event known as a supernova, with the result that a neutron star is formed, and perhaps a black hole! At every point in the life cycle of the star, an observing section will describe those objects which best demonstrate the topics mentioned, with simple star maps. Most of the objects, whether it be a star, or nebulae, will be visible with modest optical instruments, many with the naked eye, but in some exceptional cases, a medium aperture telescope may be needed. Of course, not all of the objects that can be seen will be presented, but just a representative few, usually the brightest examples, will be mentioned. It is inevitable that a lot will be left out.

As is to be expected, the first section will deal with those concepts that will be needed, and indeed are vitally necessary, for a complete understanding of the remainder of the book, and as such will be divided into several topics such as the brightness, mass, and distance of stars, etc. Also covered will be the very important topic of stellar spectroscopy. It is true to say that nearly all of what we know about stars was and is determined from this important technique. In addition a section will be introduced on the Hertzsprung–Russell (H–R) diagram. If ever a single concept or diagram could fully epitomize a star's life (and even star clusters), then the H–R diagram, as it is known, is the one that can 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, then you understand how a star will evolve.

The second part of the book will deal with the formation of stars and discuss what we believe to be the processes of stellar birth. How and why stars form, what they are made out of and become what we see today. As an example of a star, a brief section will cover the nearest star to us – the Sun.

Following on from stellar birth is a section which deals with that part of a star's life when it settles down and shines for several million, or billion, years. The various means of producing and transporting energy in a star are looked at, and how the mass of a star determines how long it will live. This is normally a quiet time for a star and most of the stars we observe in the night sky are in this phase of their lives.

We then move on to the dramatic topic of star death! The way a star dies depends on several factors, but the most important one has to do with a star's mass. This is the time in star's life when it becomes a red giant star, and possibly a variable star. We look at how a low mass star, such as the Sun, will end its days, but also look at what happens to those high mass stars that may explode as supernovae.

For those of you who have a mathematical mind, then 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 there to highlight and further describe the mechanisms and principles of stellar evolution. However, if you are comfortable with the maths, then I recommend that you read these sections, as they will help you in your understanding of the various concepts, and will allow you to make your own determinations of such parameters as the ages and lifetimes of stars, their distances and masses, and brightnesses. All of the maths presented will be very simple, and of a level comparable to that of a 4th year school student, or 8th grader.

A final point I wish to emphasize here is that the book can be read in several ways. It makes sense, of course, to 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, then there is no reason why you shouldn't go straight to that section. Similarly, you may want to read about the middle-age of a star, so you could go to that section. Some of the nomenclature would of necessity be unfamiliar, but I hope that the book is written so that this shouldn't be a problem. Also, many of you, I have no doubt, will go straight to the observing lists. Read the book in a way that is comfortable to you.

So, without further ado, let us begin on a voyage of discovery...

Chapter 1

Stellar Evolution – The Basics

1.1 Distance to the Stars

In order to determine many of the basic parameters on stars, it is first necessary to be able to find out if a star is close, or distant. As we shall see later, this is vitally important if you want to know if, say, a star appears bright in the night sky because it is close to us, or is an inherently bright star. In the same vein, some stars may be faint because they are at immense distances from us, or just might be very faint stars in their own right.

Determining distances in astronomy has been, and still continues to this day, to be fraught with difficulty and error, and there is still no general consensus as to what is the best method, at least for distances to other galaxies and to the farthest edges of our own galaxy – the Milky Way. However, the oldest method still used is probably the one that remains the most accurate, especially for determining the distances to stars.

The technique used is called *Stellar Parallax,* and basically is the angular measurement when the star is observed from two different locations in the Earth's orbit. These are usually six months apart. 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 is 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*

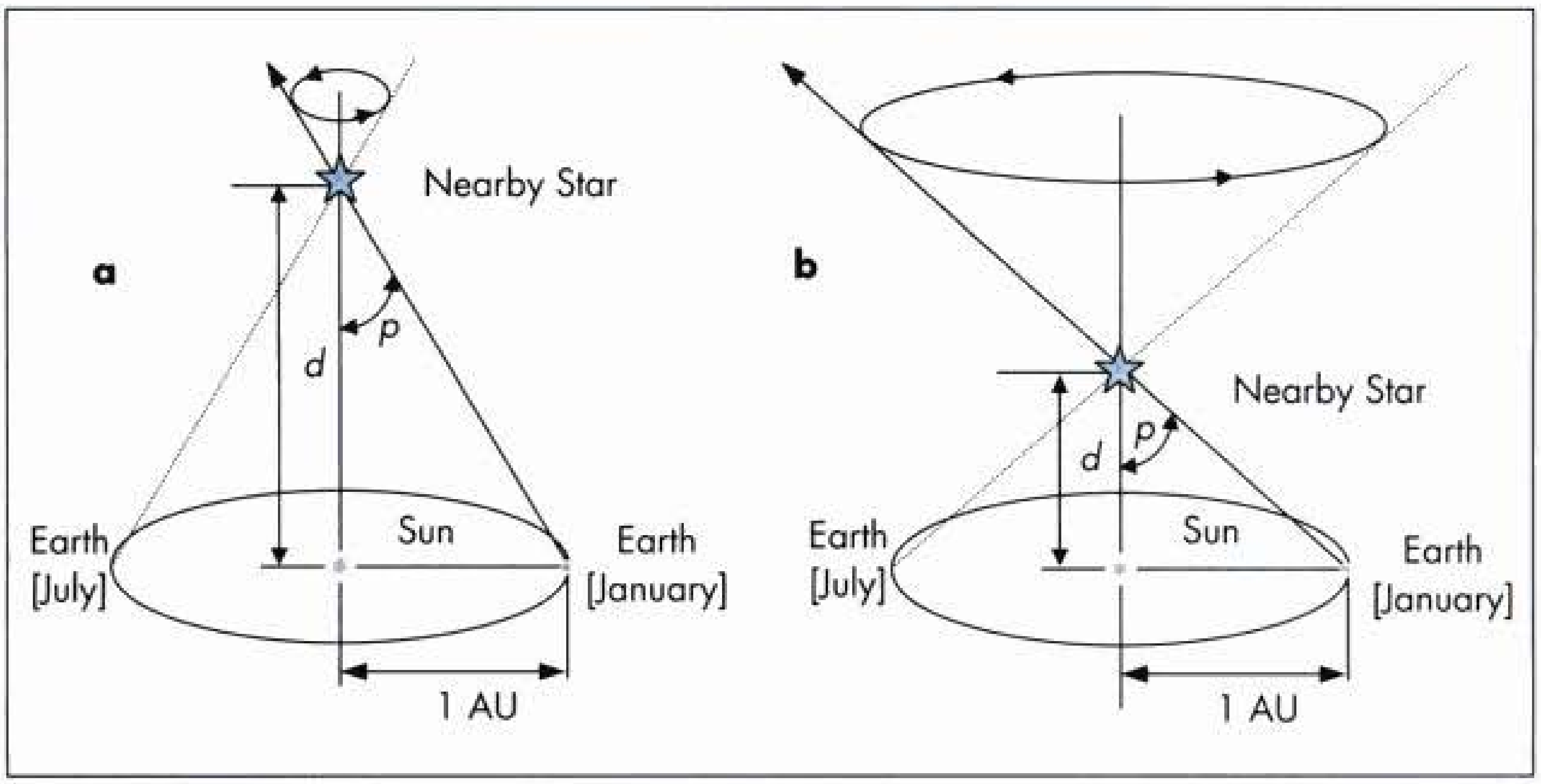


Figure 1.1. Stellar Parallax. **a** The Earth orbits the Sun, and a nearby star shifts its position with respect to the background stars. The parallax, *p*, of the star is the angular measurement of the Earth's orbit as seen from the star. **b** The closer the star, the greater the parallax angle.

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

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

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

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

It may surprise you to know that all known stars have a parallax angle smaller than 1 arcsecond, and angles smaller than about 0.01 arcsecs are very difficult to measure from Earth due to the effects of the atmosphere, and 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 even this great advance in distance determination is only useful for relatively close stars. Most of the

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[1] One parsec is equal to 3.26 light years, 3.09×10^{13} km, or 206,265 AU. 1 AU is 149,597,870 km.

[2] Nearly 200 previously unobserved stars were discovered, the nearest about 18 ly away. In addition, several hundred stars originally believed to be within 75 ly are in fact much farther away.

Relationship between parallax and the distance to a star

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

d = the distance to a star measured in parsecs
p = the parallax angle of the measured star, in arseconds

This simple relationship is a significant reason why most astronomical distances are given in parsecs, rather than light years. The nearest star to us (not counting the Sun!) is Proxima Centauri, which has a parallax of 0.772 arcseconds. Thus its distance from us is:

$$d = \frac{1}{p} = \frac{1}{0.772} = 1.30 \text{ pc}$$

However, 1 parsec is 3.26 light years, this distance can also be expressed as:

$$d = 1.30 \times \frac{3.26 \text{ ly}}{1 \text{ pc}} = 4.22 \text{ ly}$$

stars in the galaxy are too far for parallax measurements to be taken: another method has to be used.

Many stars actually alter in brightness, these are the variable stars, and several of them play an important part in distance determination. Although we will meet them again later, and discuss their properties in far greater detail, it is instructive to mention them now.

Two types of variable star in particular are 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

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[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 results show that the variability is decreasing, and the star may, at some time in the future, cease to pulsate. We discuss these important stars in detail in a later section.

[4] We will discuss the meaning of the term luminosity later. For the time being, think of it as the star's brightness.

are linked. The longer the time taken for the star to vary in brightness (the period), the greater the luminosity. This is the justifiably famous *Period-Luminosity relationship.*[5] It is relatively easy to measure the period of a star, and this is something that many amateur astronomers still do. Once this has been measured, you can determine the luminosity of the star. 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's, distances out to around 60 million ly 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 allow distances to about 2 million ly to be determined.

A further method of distance determination is that of spectroscopic parallax, whereby determining the star's spectral classification can lead to a measure of its intrinsic luminosity, and thus, by comparing this with its apparent brightness, its distance can be determined.

A final note on distance determination is in order. Do not be fooled into thinking that these various methods give exact measurements. They do not. A small amount of error is inevitable. Sometimes this can be about 10%, or 25%, but an error of 50% is not uncommon. Remember that a 25% error for a star estimated to be at a distance of 4000 ly means it could be anywhere from 3000 to 5000 ly away. Table 1.1 lists the 20 nearest stars.

1.2 The Nearest Stars

Let us now look at some of the nearest stars in the night sky. The list is by no means complete, but rather selects those stars which are most easily visible. Many of the nearest stars are very faint, and thus present an observing challenge.

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[5] The Period-Luminosity relationship was discovered by Henrietta Leavitt in 1908, whilst working at the Harvard College Observatory. She studied photographs of the Magellanic Clouds, and found over 1700 variable stars.

[6] The relationship between the apparent brightness of a star and its intrinsic brightness will be discussed in the next section.

Table 1.1. The 20 nearest stars in the sky

	Star	Distance, ly	Constellation
1	Sun	–	–
2	Proxima Centauri	4.22	Centaurus
3	Alpha Centauri A[a]	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[a]	8.60	Canis Major
8	UV Ceti A[a]	8.7	Cetus
9	Ross 154	9.69	Sagittarius
10	Ross 248	10.3	Andromeda
11	Epsilon Eridani	10.49	Eridanus
12	HD 217987	10.73	Piscis Austrinus
13	Ross 128	10.89	Virgo
14	L 789–6 A[a]	11.2	Aquarius
15	61 Cygni A	11.35	Cygnus
16	Procyon A[a]	11.42	Canis Minoris
17	61 Cygni B	11.43	Cygnus
18	HD 173740	11.47	Draco
19	HD 173739	11.64	Draco
20	GX Andromedae[a]	11.64	Andromeda

[a] This signifies that the star is in fact part of a double star system, and the distance quoted is for components A and B.

Throughout the book you will find some simple star maps, given at the end of each section of observable objects. In some cases, several objects will be on one map, so do not worry if you do not initially find the object you seek. For instance, the section on white dwarf stars lists four objects, but only one star map follows the list; the other three objects are found on star maps in earlier sections of the book. Every object mentioned will be on a map somewhere,[7] and so to aid identification, each object will reference which star map it can be found on on.

Throughout the book I will use the following nomenclature to list the stars; first is its common name, followed by its scientific designation. The next item will be its position in right ascension and declination. The final term shows those months when the star is best placed for observation. The month in bold type is the most favourable time of year, whilst plain type shows other months when it can also be seen.

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[7] The reason why there isn't a star map for each individual object is simple: it would double the size (and cost!) of this book.

The next line will present both standard data and information that is pertinent to the topic under discussion. Thus, its apparent magnitude, followed by its absolute magnitude, is given, then, specific data relating to the topic is given. The final item is the constellation in which the star resides.[8]

Proxima Centauri	V645 Cen	$14^h\ 29.7^m$	-62° 41′	Mar-**Apr**-May
11.01_vm[9]	15.45M	4.22 ly	0.772″	Centaurus

This is the second-closest star to the Earth, but is the closest star to the Solar System. It is a very faint red dwarf star and also a flare star, with frequent bursts having maximum amplitude of around one magnitude. Recent results 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. See Star Map 1.

Sirius A	α Canis Majoris	$06^h\ 29.7^m$	−16° 43′	Dec-**Jan**-Feb
−1.44m	1.45M	8.6 ly	0.379″	Canis Major

A lovely star to observe and the 6th closest. It is also the brightest star in the sky and known as the Dog Star. It is famous amongst amateurs for the exotic range of colours it exhibits. This is due to the effects of the atmosphere. It also has a dwarf star companion, the first to be discovered. Sirius is a dazzling sight in any optical device. See Star Map 2.

Procyon	α Canis Minoris	$07^h\ 39.3^m$	-56° 13′	Dec-**Jan**-Feb
0.40m	2.68M	11.41 ly	0.283″	Canis Minor

The fifteenth nearest star, and also the eighth brightest. It, like nearby *Sirius*, has a white dwarf companion star. However, it is not visible in amateur telescopes. See Star Map 1.

Barnard's Star	HD21185	$17^h\ 57.8^m$	+4° 38′	Apr-**May**-Jun
9.54m	13.24M	5.94 ly	0.549″	Ophiuchus

The third-closest star is a red dwarf. But what makes this star so famous is that it has the largest proper motion of any star[10] – 0.4 arcseconds per year. It has a velocity of 140 km per second so 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's also believed the star belongs to the Galaxy's *Halo Population*. Also known as *Barnard's Runaway Star*. See Star Map 3.

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[8] Most of the nearest stars are very faint, so only the brighter ones will be mentioned. 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* – lists in considerable detail much more information. Furthermore, there are many techniques that will enhance your observational skills, such as dark adaption, averted vision, etc. These are described in the aforementioned book.

[9] Denotes that the star, and thus the magnitude, is variable.

[10] The proper motion of a star is its apparent motion across the sky.

61 Cygni A	V 1803 Cyg	$21^h\ 06.9^m$	+38° 45′	Jul–**Aug**–Sep
5.20_vm	7.49M	11.35 ly	0.287″	Cygnus

This is a very nice double star, separation 30.3 arcseconds with a PA of 150°. Both stars are dwarfs and have a nice orange colour. It is famous as the first star to have its distance measured successfully by F.W. Bessel in 1838 using stellar parallax. See Star Map 4.

GX And	Grb 34	$00^h\ 18.2^m$	+44° 01′	Aug–**Sep**–Oct
8.09_vm	10.33M	11.65 ly	0.280″	Andromeda

This is half of a noted red dwarf binary system. The primary star is in itself a spectroscopic double star. Also known as *Groombridge 34 A*, it is located about $\frac{1}{4}$° north of 26 Andromedae. See Star Map 5.

Lacille	HD 217987[11]	$23^h\ 05.5^m$	–35° 52′	Aug–**Sep**–Oct
7.35m	9.76M	10.73 ly	0.304″	Piscis Austrinus

This is a red dwarf star, with the fourth-fastest proper motion of any known star. It traverses 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 half a degree. It is in the extreme southeast of the constellation, about 1° SSE of *π Pisces Austrinus*. See Star Map 6.

UV Ceti	L 726-8 A	$01^h\ 38.8^m$	–17° 57′	Sep–**Oct**–Nov
12.56_vm	15.42M	8.56 ly	0.381″	Cetus

The seventh closest star is a red dwarf system and is a very difficult, but not impossible, object to observe. The UV prefix indicates that the two components are flare stars, and the fainter is referred to in older texts as *Luyten's Flare Star*, after its discoverer, W.J. Luyten, who first observed it in 1949. See Star Map 7.

Epsilon Eridani	LHD 22049	$03^h\ 32.9^m$	–09° 77′	Oct–**Nov**–Dec
3.72m	6.18M	10.49 ly	0.311″	Eridanus

The tenth-closest star is a naked-eye object. Recent observations indicate there may be an unseen companion star with a very small mass, approximately 0.048 that of the Sun. See Star Map 8.

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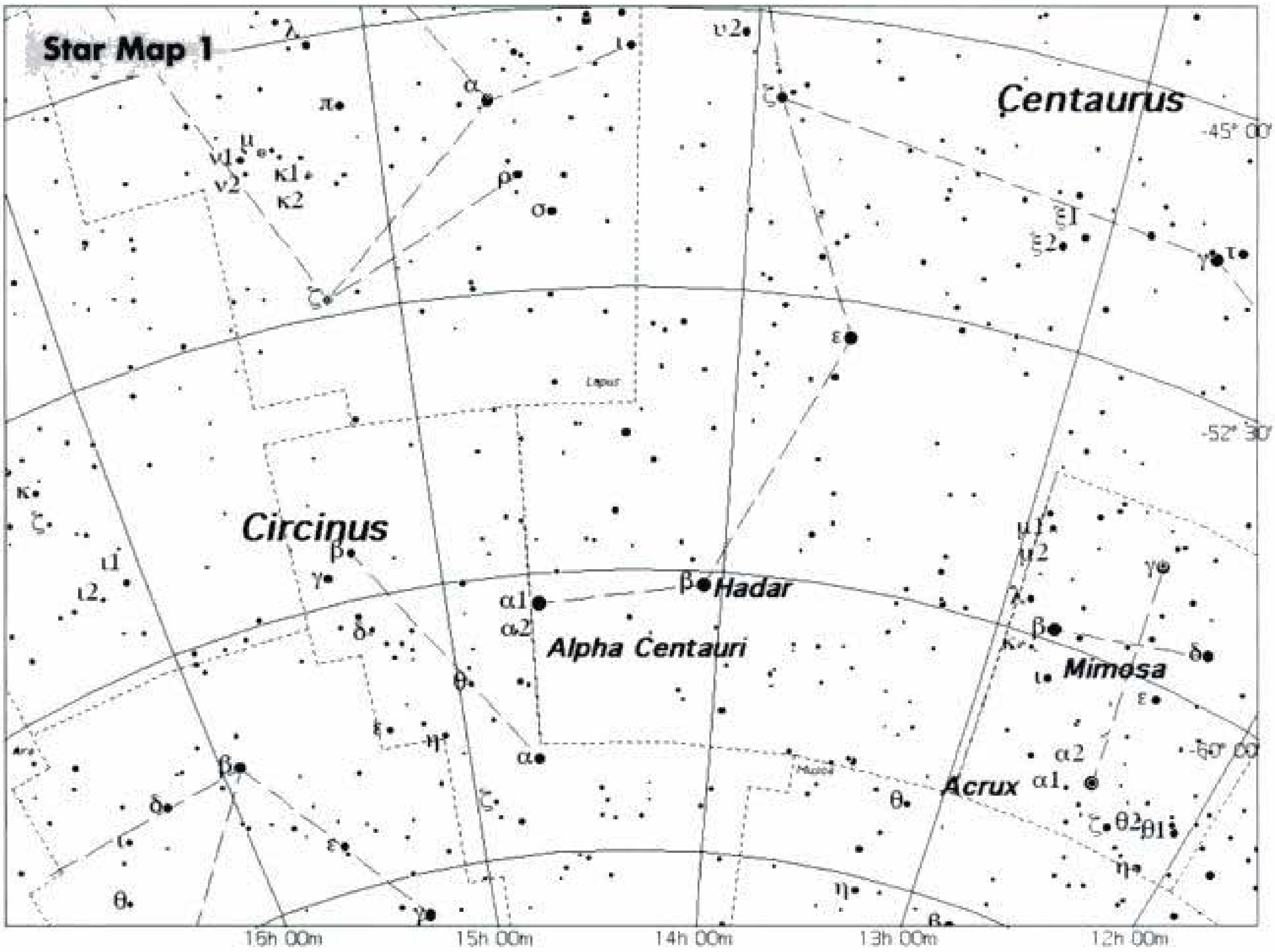
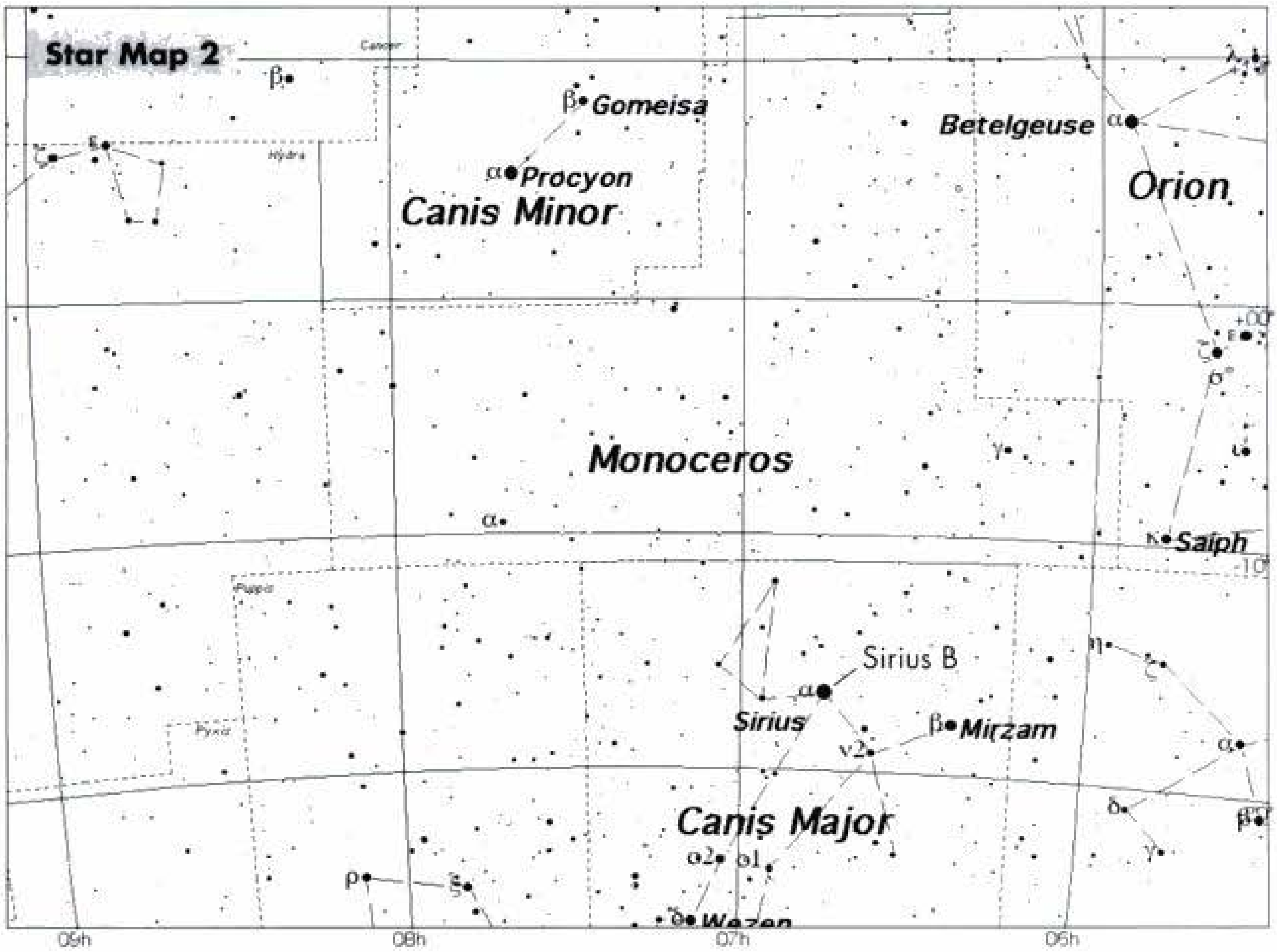
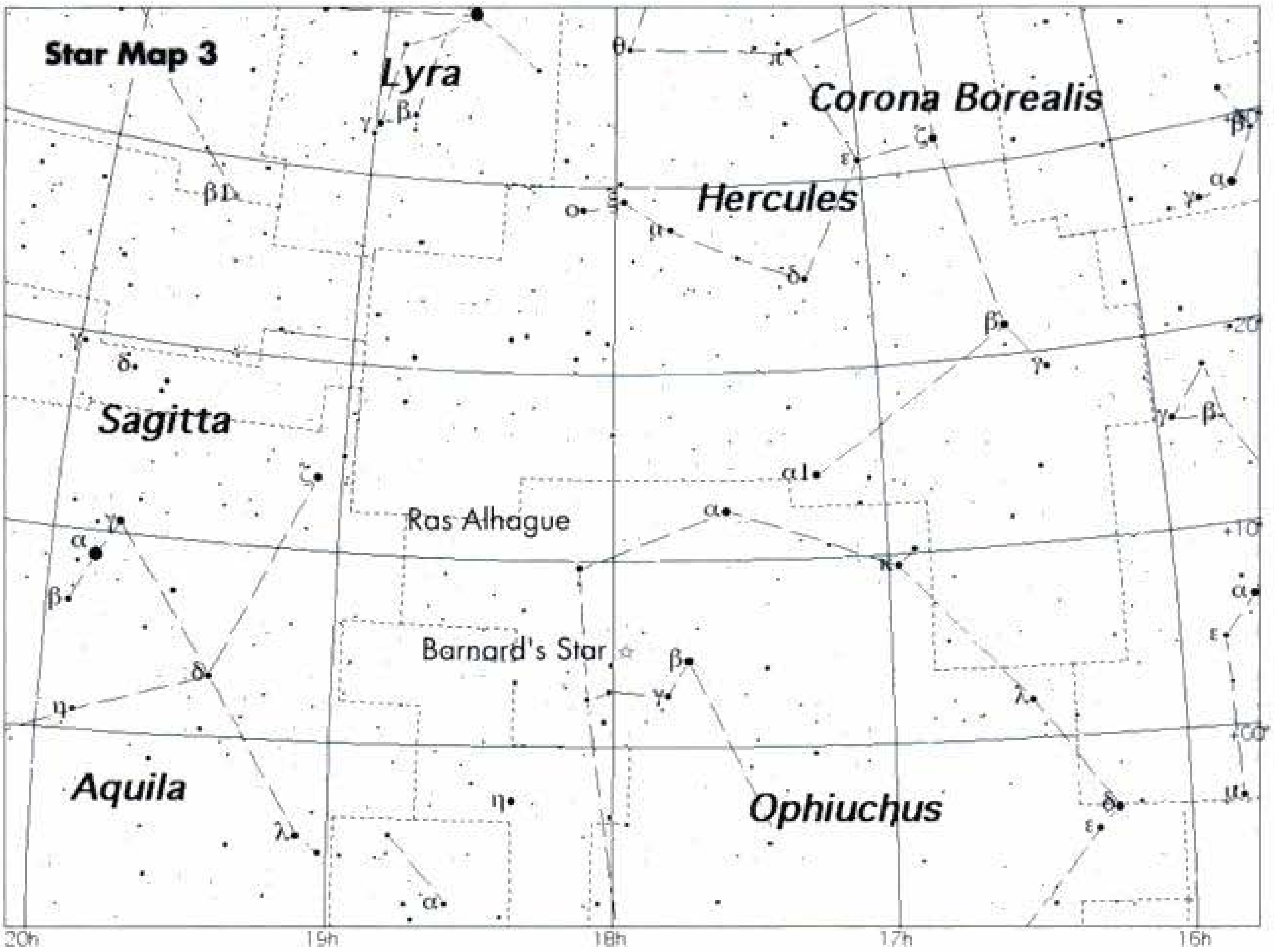
[11] The HD signifies it is the 217987th object in the Henry Draper catalogue.

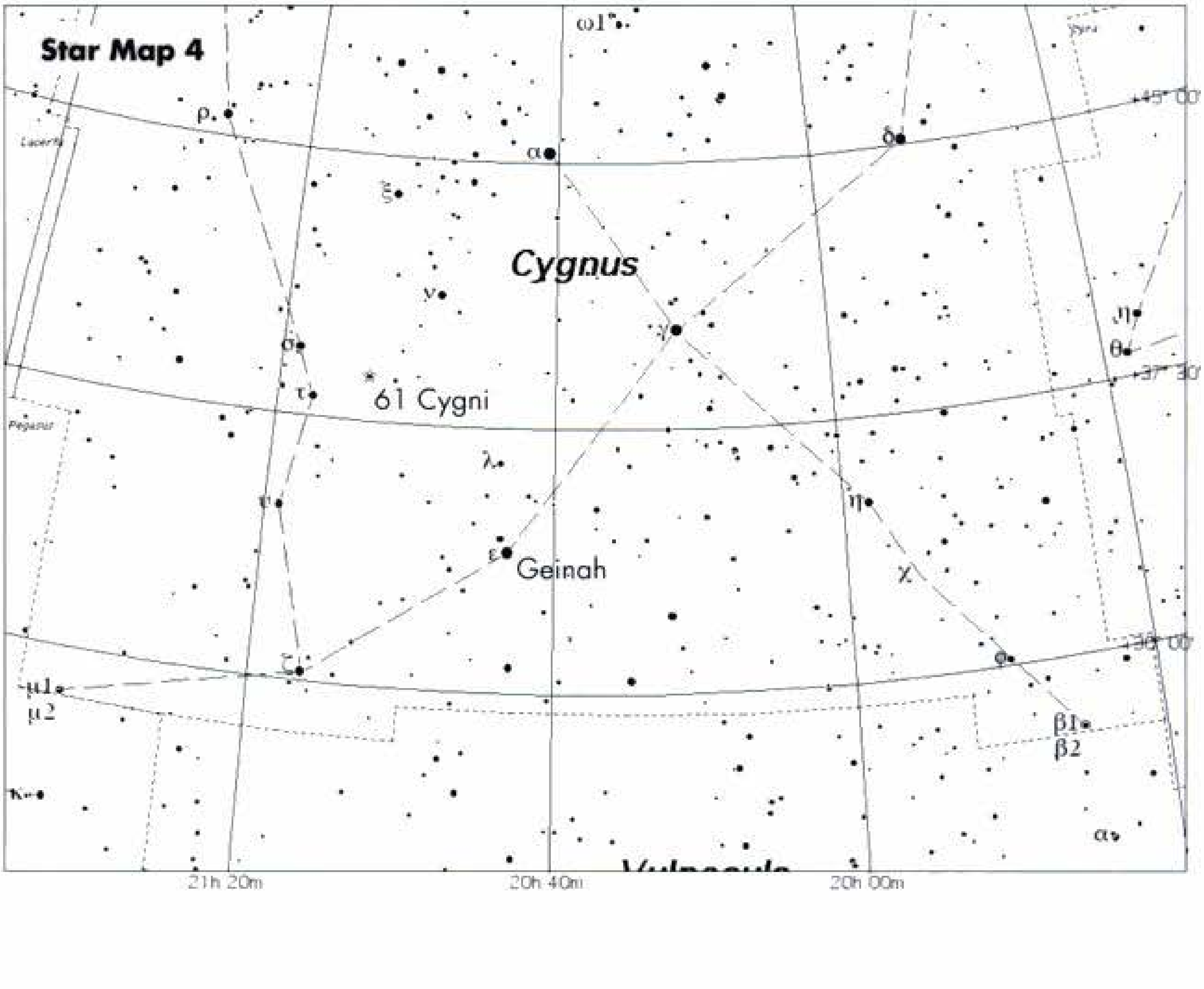


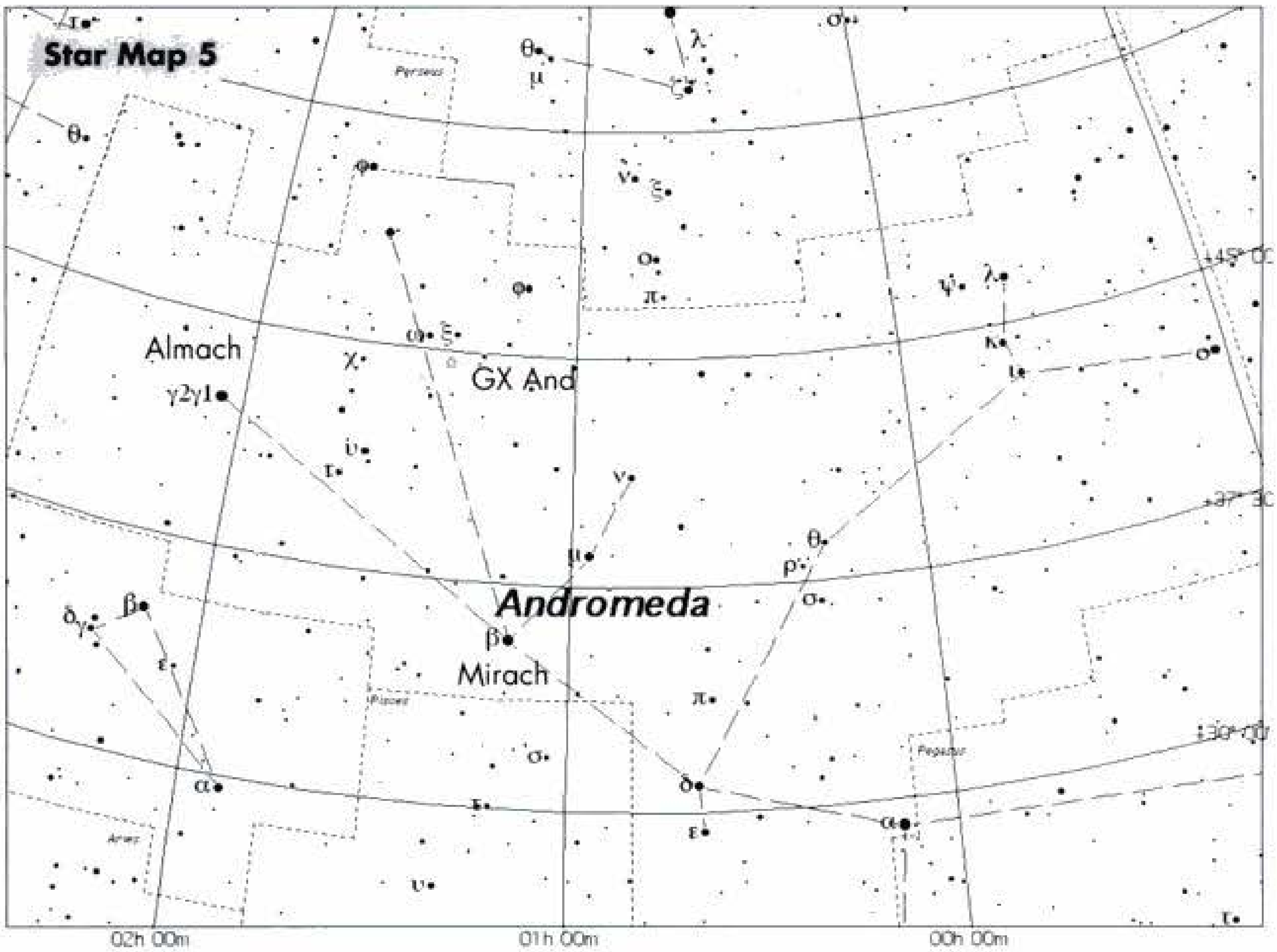
Star Map 1



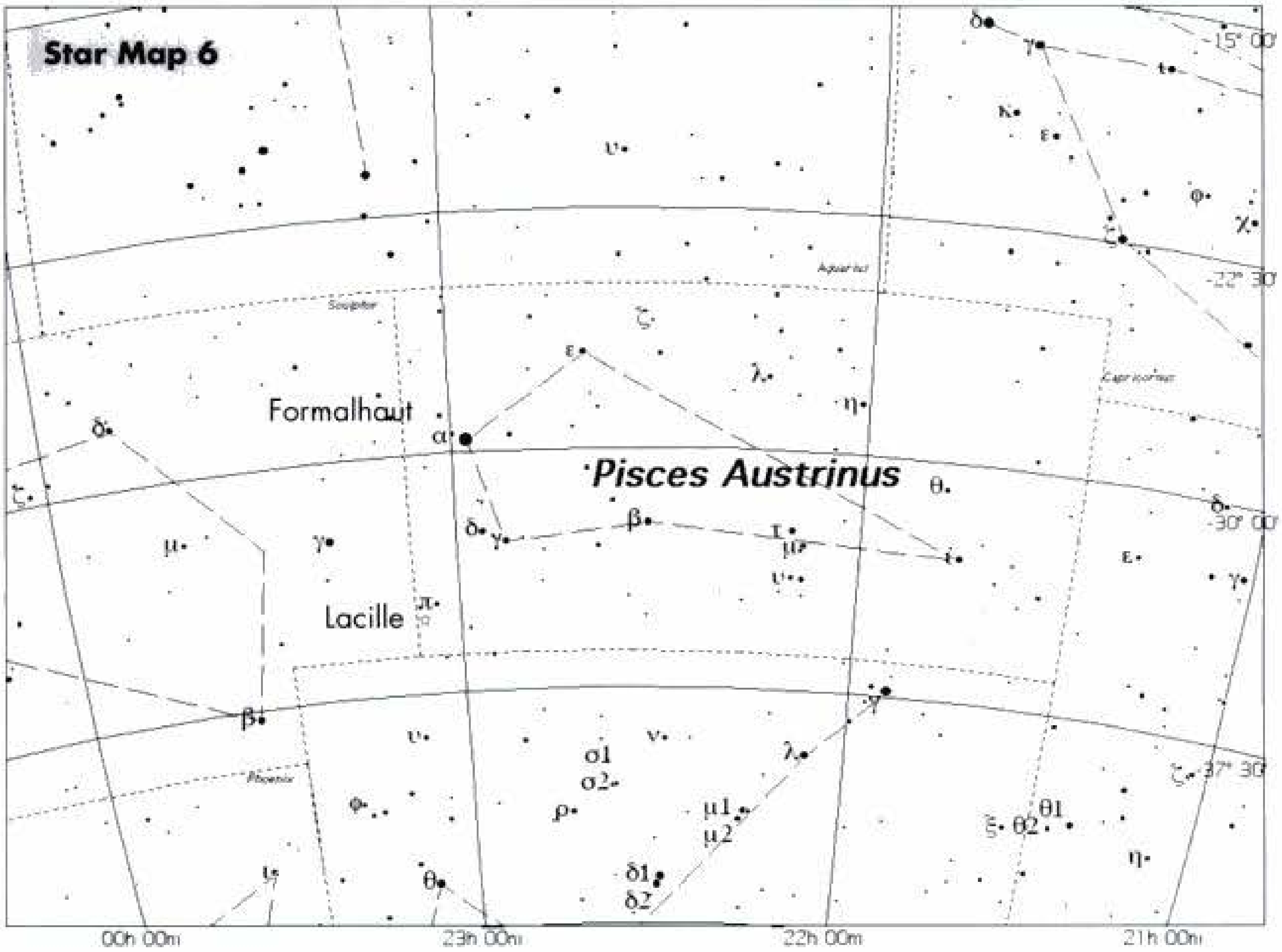
Star Map 2


Star Map 3
Lyra
Corona Borealis
Hercules
Sagitta
Ras Alhague
Barnard's Star
Aquila
Ophiuchus
+20°
+10°
+00°
20h
19h
18h
17h
16h

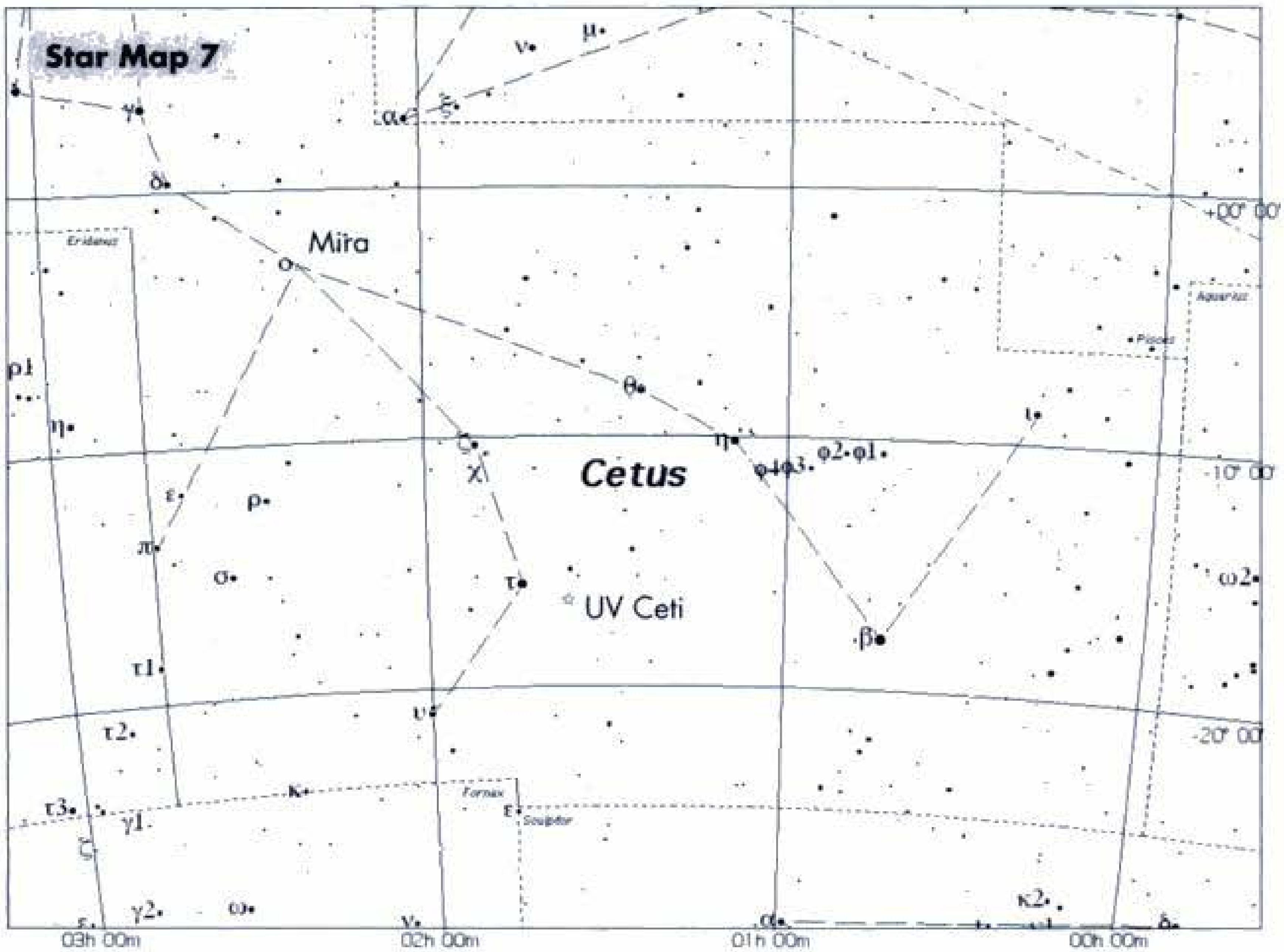

Star Map 4
Cygnus
61 Cygni
Geinah
Vulpecula
+45° 00'
+37° 30'
+30° 00'
21h 20m
20h 40m
20h 00m



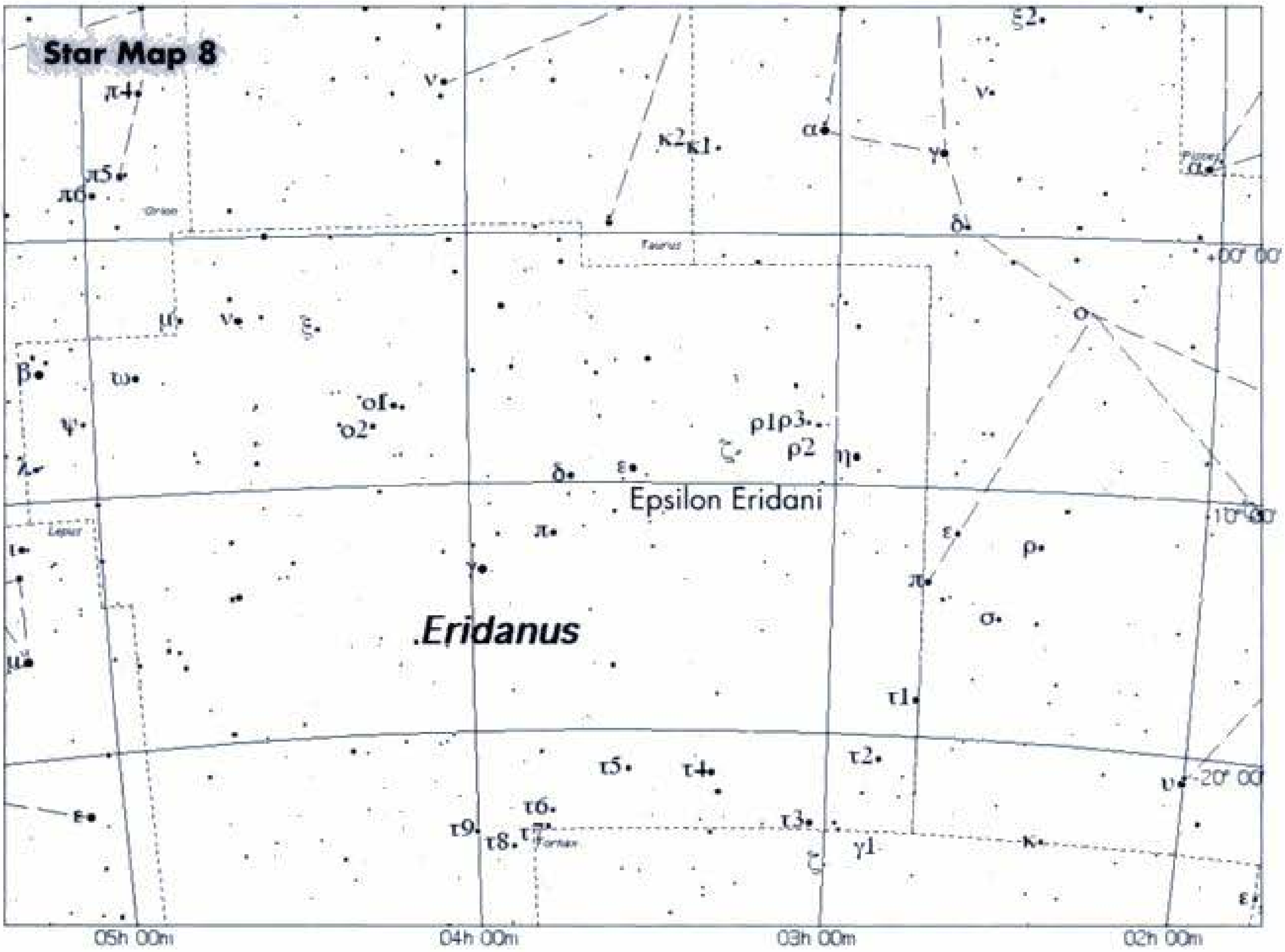
Star Map 5



Star Map 6



Star Map 7



Star Map 8

1.3 The Brightness and Luminosity of Stars

There is an immense number of stars in the sky and, for the most part, they are all powered by the same process that fuels the Sun. But this does not mean that they are all alike. Stars differ in many respects, such as mass, size, etc. One of the most important characteristics is their *luminosity, L*. It 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.

In order to determine the true luminosity of a star we need to know its *apparent brightness*, and we define this to be 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, and obeys what is termed an *inverse square law*. If the Sun were viewed at a distance twice that of the Earth's, then it would appear fainter by a factor of $2^2 = 4$. If we now viewed it from a distance 10 times that of the Earth's, it would appear 10^2 times fainter. If we observed the Sun from the same location as *α Centauri A*, it would be dimmed by $270{,}000^2$, or about 70 billion times!

The inverse square law describes the amount of energy that enters, say, your eye, or a detector. Try to imagine an enormous sphere of radius *d*, centred on a star. The amount of light that will pass through a square metre 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 simple formula $4\pi d^2$, then you can see that as the sphere increases, *d* increases, and so the amount of luminosity will decrease. You can see why the amount of luminosity that arrives at the Earth from a star is determined by the star's distance.

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[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] A more correct term for apparent brightness is *flux*.

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

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

1.4 The Magnitudes of Stars

Probably the first thing anyone notices when they glance up into the night sky is that the stars have different brightnesses. A small handful are bright, a few more are fairly bright, but the majority are faint. This characteristic – the brightness of a star – is called the *magnitude* of a star (or any astronomical object that is observed using the naked eye). It is one of the oldest scientific classifications used today, and was invented by the Greek astronomer Hipparchus. He classified the brightest stars as first-magnitude stars, stars that were about half as bright as first-magnitude were called

The luminosity–distance formula

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

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

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

Example:
We can apply this to the Sun that is at a distance of 1.50×10^{11} m.

$$\mathrm{b}_{\odot} = \frac{3.86 \times 10^{26}\,W}{4\pi(1.50 \times 10^{11}\,\mathrm{m})^2}$$

$\mathrm{b}_{\odot} = 1370\ \mathrm{W/m^3}$

This means that, say, a detector with an area of 1 square metre (possibly a reflecting telescope) will receive 1370 watts of power from the Sun.

Distance, luminosity and brightness

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

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

Now, using this equation as applied to the Sun, where the luminosity is given by $L_{\odot}$, and the distance is $d_{\odot}$, which is equal to 1 AU, then the Sun's apparent brightness, $b_{\odot}$ is:

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

Now, let's take the ratio of the two formulae:

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

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 away it is compared to the Earth–Sun distance, given by $d/d_{\odot}$, and how bright it is compared to that of the Sun, given by $b/b_{\odot}$.

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

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

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

second magnitude, and so on, down to sixth-magnitude, which were the faintest he could see.[14] Today, we can see much fainter stars, and so the magnitude range is even greater, down to thirtieth-magnitude. Because the scale relates to how bright the stars appear to an observer on Earth, the term is more correctly called *apparent magnitude*, and is denoted by *m*.

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[14] Observers have reported that under excellent conditions, and with very dark skies, objects down to magnitude 8 can be seen.

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

A difference in magnitude of 1 thus corresponds to a factor of 2.512 in brightness. This is easily shown by the following:

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

Apparent magnitude and brightness ratio

Both the apparent magnitude, m, and the 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:

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

What this means is that the *ratio* of their apparent brightnesses (b_1/b_2) corresponds to a *difference* in their apparent magnitudes ($m_1 - m_2$).

m_1, m_2 are a apparent magnitudes of stars s_1 and s_2
b_1, b_2 are the apparent brightnesses of stars s_1 and s_2

Example
A variable star changes in brightness by a factor of 4. The change in magnitude can be calculated thus:

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

$$m_1 - m_2 = 2.5 \ \log(4) = 1.5$$

Therefore, the change is ≈ 1.5 magnitudes.

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

Using this modern scale, several objects now have negative magnitude values. *Sirius*, the brightest star in the sky, has a value of -1.44 m, *Venus* (at brightest) is

Relationship between absolute magnitude and apparent magnitude

The *apparent magnitude* of a star and the *absolute magnitude* can be used to determine the distance to the star, and the formula for this is given by:

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

where m = the star's apparent magnitude
M = the star's absolute magnitude
and d = the distance to the star (in parsecs).

The term $m - M$ is referred to as the *distance modulus*, and this is a very important equation.

Example
A star has an absolute magnitude of +6.0, and apparent magnitude of +16.0. Its distance can be determined thus:

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

$$16 - 6 = 5 \log d - 5$$

$$\left(\frac{16 - 6 + 5}{5}\right) = 3 = \log d$$

$d = 10^3$ pc = 1000 pc.

Table 1.3. The 20 brightest stars in the sky

	Star	Apparent magnitude, m	Constellation
1	Sirius	-1.44_v^a	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	Orion
8	Procyon	0.40	Canis Minor
9	Achernar	0.45_v	Eridanus
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	Formalhaut	1.16	Piscis Austrinus
19	Becrux	1.25_v	Crux
20	Deneb	1.25	Cygnus

[a] Many stars are variable, so the value for the apparent magnitude will change. A variable star will have the suffix 'v' and the value given will be the mean value.

-4.4 m, the full *Moon* is -12.6 m, and the *Sun* is -26.7 m. Table 1.3 shows the 20 brightest stars.

The apparent magnitude scale doesn't tell us whether a star is bright because it is close to us, or faint because it's small or distant. All that this classification tells us is the apparent brightness of the star – that is, the brightness of the star as observed visually, with the naked eye or telescope. A more precise definition is the *absolute magnitude, M*, of a star. This is defined to be the brightness an object would have at a distance of 10 parsecs. It is an arbitrary distance, derived from the technique mentioned earlier – stellar parallax. Nevertheless, it does quantify the brightness of stars in a more rigorous way.[15] As an example, *Deneb*, a lovely star of the summer sky, in the constellation *Cygnus*, has an absolute magnitude of -8.73, while *Van Biesbroeck's* star, has a value of +18.6, making it one of the faintest stars known.

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[15] It shouldn't come as any surprise to you to learn that there are several other magnitude definitions that rely on the brightness of a star 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 from an object.

1.5 The Brightest Stars

Below is a list of some of the brightest stars. It is by no means complete, and for those interested in observing more bright stars, then I recommend the accompanying volume to this book. Several of the brightest stars will have already been mentioned in Section 1.2, "The Nearest Stars". For the sake of clarity and space, they will not be repeated here.

Pollux	β Gem	$07^h 45.3^m$	+28° 02′	Dec–**Jan**–Feb
1.16m	1.09M	33.72 ly		Gemini

This is the brighter star of the two famous stars in *Gemini*, the other being of course, *Castor*. It is the seventeenth-brightest in the sky. It is, however, the less interesting from an astronomical viewpoint. See Star Map 9.

Becrux	β Crucis	$12^h 47.7^m$	–59° 41′	Mar–**Apr**–May
1.25_vm	–3.92M	352.1 ly		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. It is the nineteenth-brightest star in the sky. Alas, it is too far south for northern observers. See Star Map 10.

Spica	α Virginis	13*h* 25.2*m*	–11° 10′	Mar–**Apr**–May
0.98_vm	–03.55M	262 ly		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 the pulsations are not visible with amateur equipment. See Star Map 11.

Hadar	β Centauri	$14^h 03.8^m$	–60° 22′	Mar–**Apr**–May
0.58_vm	–5.45M	525 ly		Centaurus

The eleventh-brightest star in the sky, and unknown to northern observers because of its low latitude, lying as it does only 4½° from *Alpha* (*α*) *Centauri*. It has a luminosity that is an astonishing 10,000 times that of the Sun. A definitely white star, it has a companion of magnitude 4.1, but is a difficult double to split as the companion is only 1.28 arcseconds from the primary. See Star Map 1.

Arcturus	α Boötis	$14^h 15.6^m$	+19° 11′	Mar–**Apr**–May
-0.16_vm	–0.10M	36.7 ly		Boötes

The fourth-brightest star in the sky, and the brightest star north of the celestial equator. It has a lovely orange colour. Notable for its peculiar motion through space, *Arcturus*, unlike most stars, is not travelling in the plane of the *Milky Way*, but is instead circling the Galactic centre in an orbit which is highly inclined. Calculations predict that it will swoop past the Solar System in several thousand years' time, moving towards the constellation *Virgo*. Some astronomers believe that in as little as half a million years Arcturus will have disappeared from naked-eye visibility. At present it is about 100 times more luminous than the Sun. See Star Map 12.

Rigel Kentaurus	α Centauri	14^h 39.6^m	–60° 50′	Apr–**May**–Jun
–0.20m	4.07M	4.39 ly		Centaurus

The third-brightest star in the sky, this is in fact 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). Unfortunately, it is too far south to be seen by any northern observer. See Star Map 1.

Antares	α Scorpii	16^h 29.4^m	–26° 26′	Apr–**May**–Jun
1.06$_v$m	-5.28M	604 ly		Scorpius

This is a red giant star, with a luminosity 6000 times that of the Sun and a diameter hundreds of times bigger than the Sun's. But what makes this star especially worthy is the vivid colour contrast that is seen 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, with a PA of 273°, lying 2.6" away. See Star Map 13.

Vega	α Lyrae	18^h 36.9^m	+38° 47′	Jun–**Jul**–Aug
0.03$_v$m	0.58M	25.3 ly		Lyra

The fifth-brightest star, familiar to northern observers, located high in the summer sky. Although similar to *Sirius* in composition and size, it is three times as distant, and thus appears fainter. Often described as having a steely-blue colour, 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 a further 12,000 years. See Star Map 14.

Altair	α Aquilae	19^h 50.8^m	+08° 52′	Jun–**Jul**–Aug
0.76vm	2.20M	16.77 ly		Aquila

The twelfth-brightest star, this has the honour of being the fastest-spinning of the bright stars, completing one revolution in approximately $6\frac{1}{2}$ 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 colour has been reported as completely white, although some observers see a hint of yellow. See Star Map 14.

Formalhaut	α Piscis Austrini	22^h 57.6^m	–29° 37′	Aug–**Sep**–Oct
1.17m	1.74M	25.07 ly		Piscis Austrinus

The eighteenth-brightest star is a white one, which often appears reddish to northern observers owing to the effect of the atmosphere. It lies in a barren area of the sky, and is remarkable only for the fact that a star close to it, which is not bound gravitationally yet lies at the same distance from Earth, is moving through space in a manner and direction similar to *Formalhaut's*. It has been suggested that the two stars are remnants of a star cluster or star association which has long since dispersed. The star is an orange 6.5-magnitude object about 2° south of *Formalhaut*. See Star Map 6.

Achernar	α Eridani	$01^h\ 37.7^m$	–57° 14′	Sep–**Oct**–Nov
0.45_vm	–2.77M	144 ly		Eridanus

The ninth-brightest star in the sky lies too far south for northern observers, at the southernmost end of the constellation. Among the bright stars it is one of the very few which has the designation "p" in its stellar classification, indicating that it is a "peculiar" star. See Star Map 15.

Aldebaran	α Tauri	$04^h\ 35.9^m$	+16° 31′	Oct–**Nov**–Dec
0.87m	–0.63M	65.11 ly		Taurus

The fourteenth-brightest star is apparently located in the star cluster the *Hyades.* However, it is not physically in the cluster at all, lying as it does twice as close as the cluster members. This pale-orange star is around 120 times more luminous than the Sun. It is also a double star, but a very difficult one to separate owing to the extreme faintness of the companion. The companion star, a red dwarf star, magnitude 13.4, lies at a PA of 34° at a distance of 121.7″. See Star Map 16.

Rigel	β Orionis	$05^h\ 14.5^m$	–08° 12′	Nov–**Dec**–Jan
-0.18_vm	–6.69M	773 ly		Orion

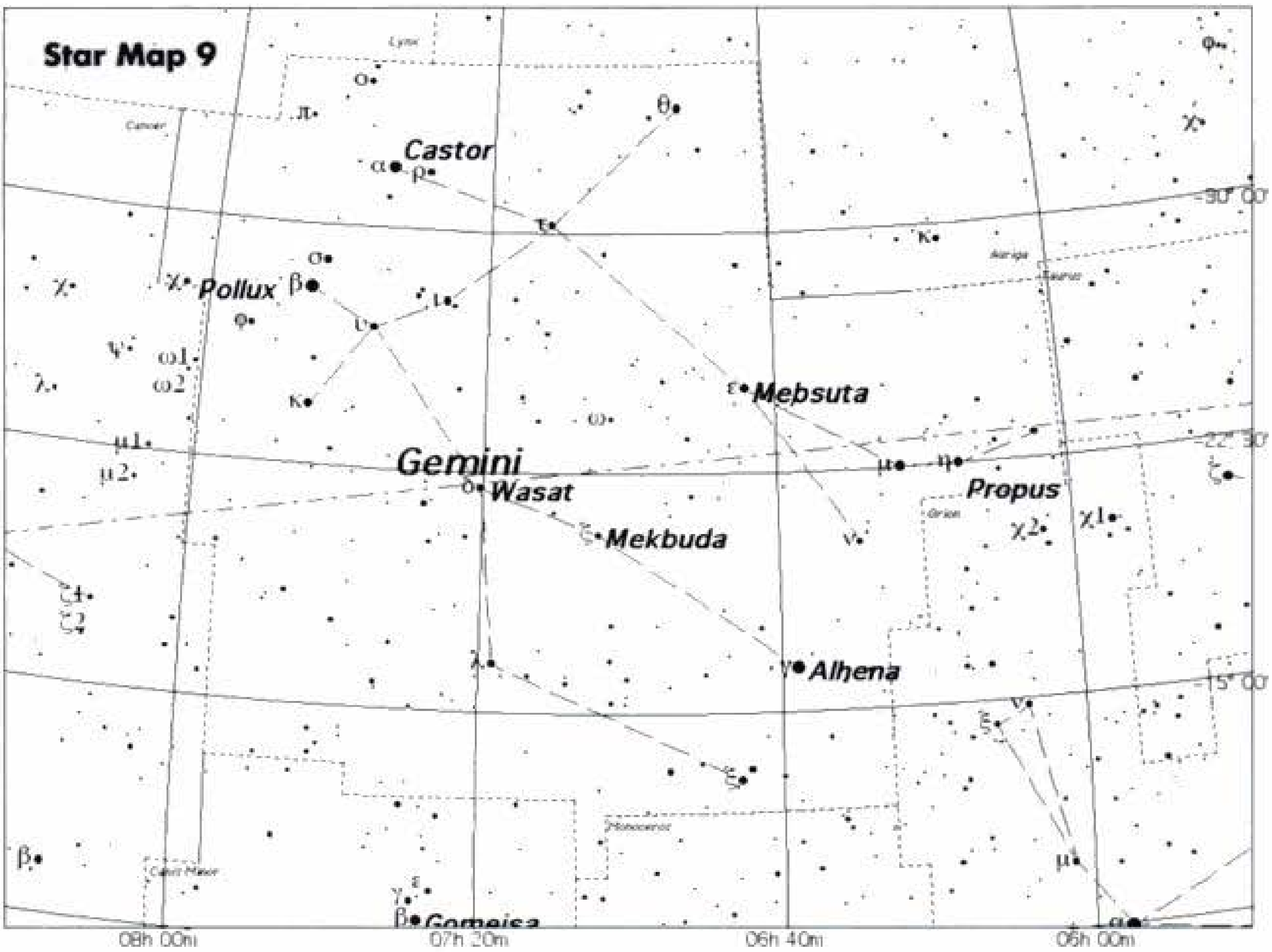
The seventh-brightest star in the sky, *Rigel* is in fact brighter than Alpha (α) *Orionis.* This supergiant star is one of the most luminous stars in our part of the galaxy, almost 560,000 times more luminous than our Sun but at a greater distance than any other nearby bright star. Often described as a bluish star, it is a truly tremendous star, with about 50 times the mass of the Sun, and around 50 times the diameter. It has a close bluish companion at a PA of 202°, apparent magnitude 6.8, at a distance of 9 arcseconds, which should be visible with a 15cm telescope, or one even smaller under excellent observing conditions. See Star Map 17.

Capella	α Aurigae	$05^h\ 16.7^m$	+46° 00′	Nov–**Dec**–Jan
0.08_vm	–0.48M	42 ly		Auriga

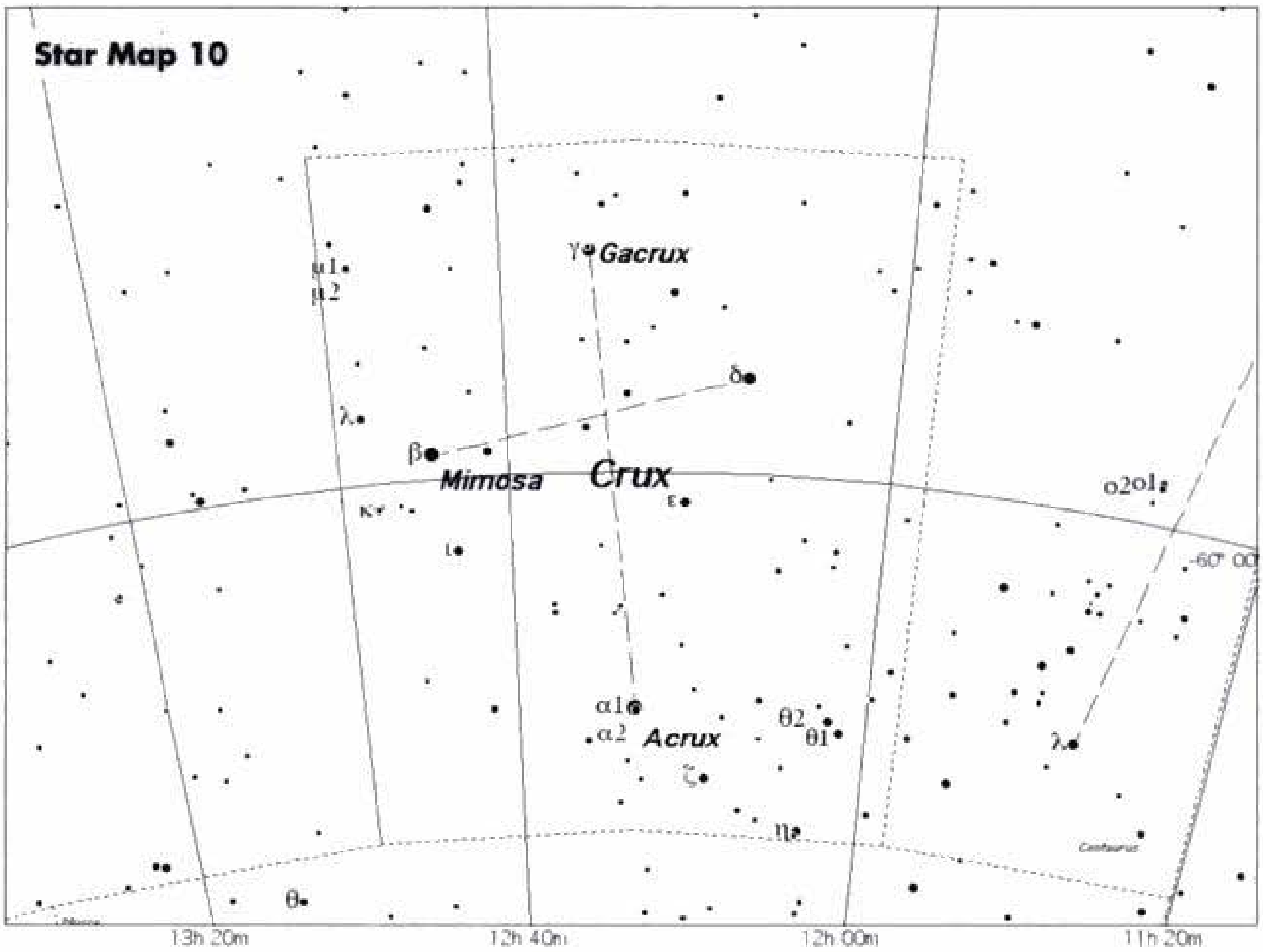
The sixth-brightest star in the sky is in fact a spectroscopic double, and is not split in a telescope; however, it has a fainter 10th-magnitude star about 12 arcseconds to the southeast, at a PA of 137°. This is a red dwarf star, which in turn is itself a double (only visible in larger telescopes). So *Capella* is in fact a quadruple system. See Star Map 18.

Betelgeuse	α Orionis	$05^h\ 55.2^m$	+07° 24′	Nov–**Dec**–Jan
0.45_vm	–5.14M	427 ly		Orion

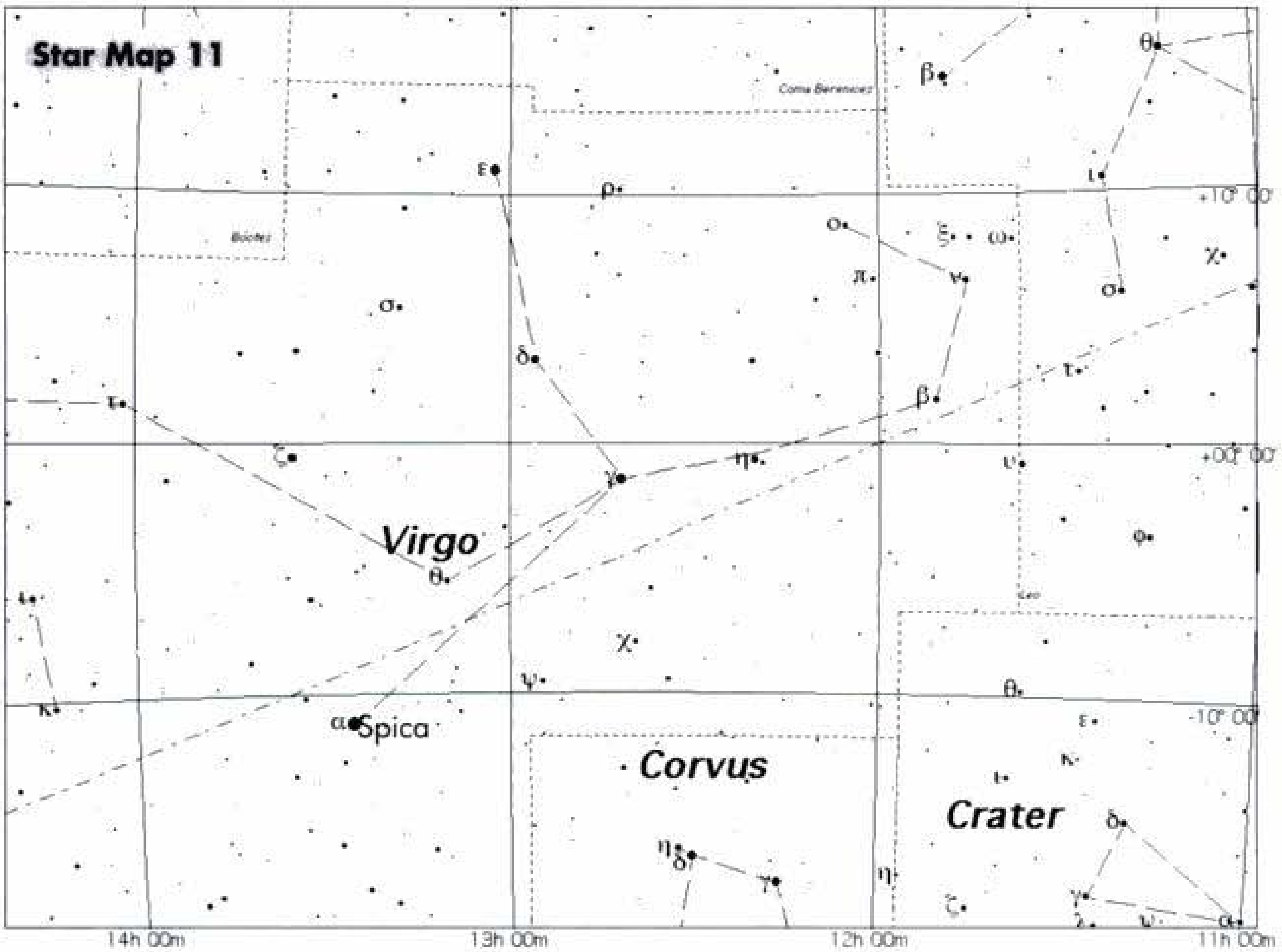
The tenth-brightest star in the sky, and a favourite among observers, this orange-red star is a giant variable, with an irregular period. Recent observations by the Hubble Space Telescope have shown that it has features on its surface that are similar to sunspots, but much larger, covering perhaps a 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 only 20 times greater than the Sun's, which together mean that the density is in fact about 0.000000005 that of the Sun. A lovely sight in a telescope of any aperture; subtle colour changes have been reported as the star goes through its variability cycle. See Star Map 18.

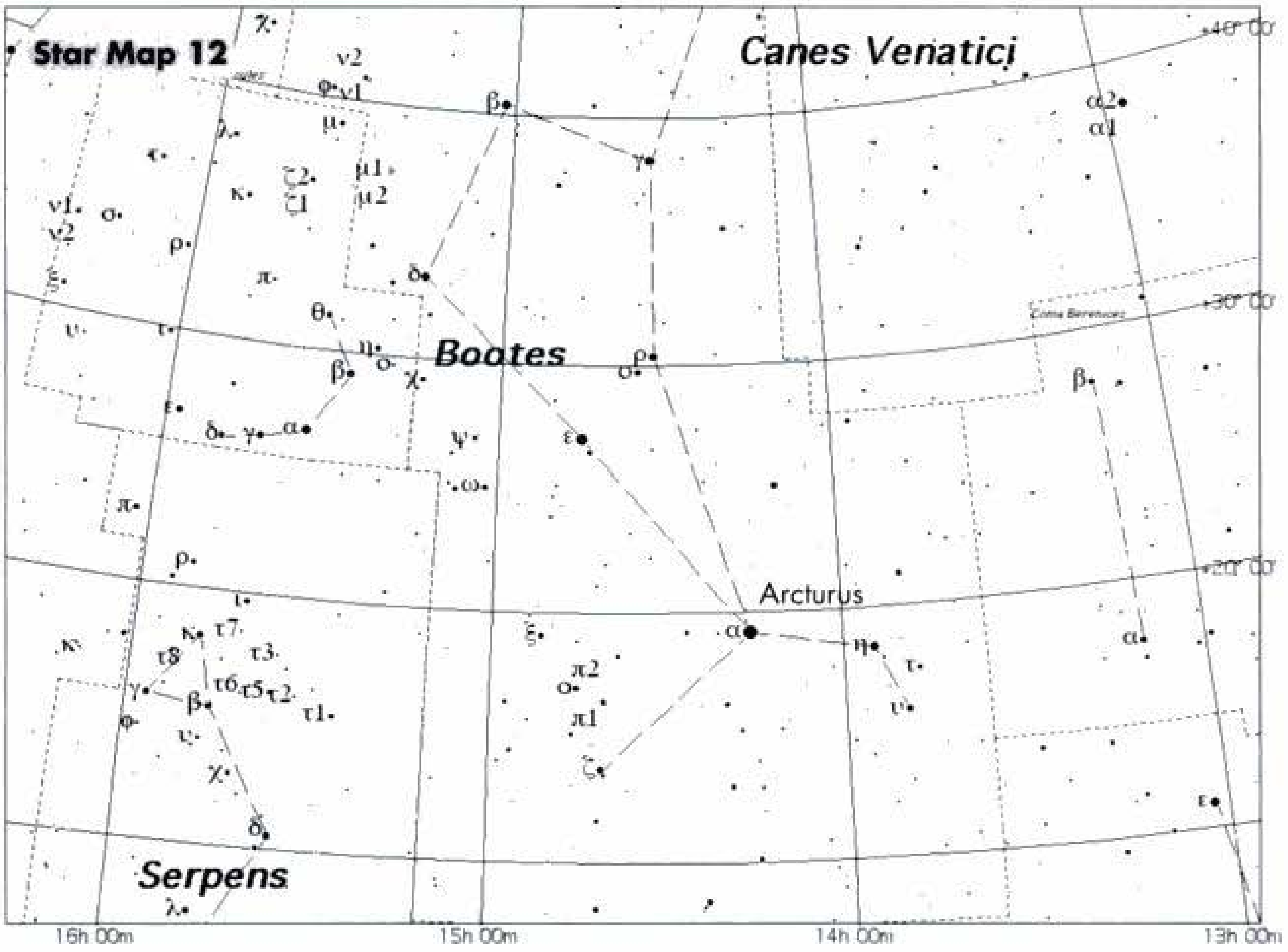


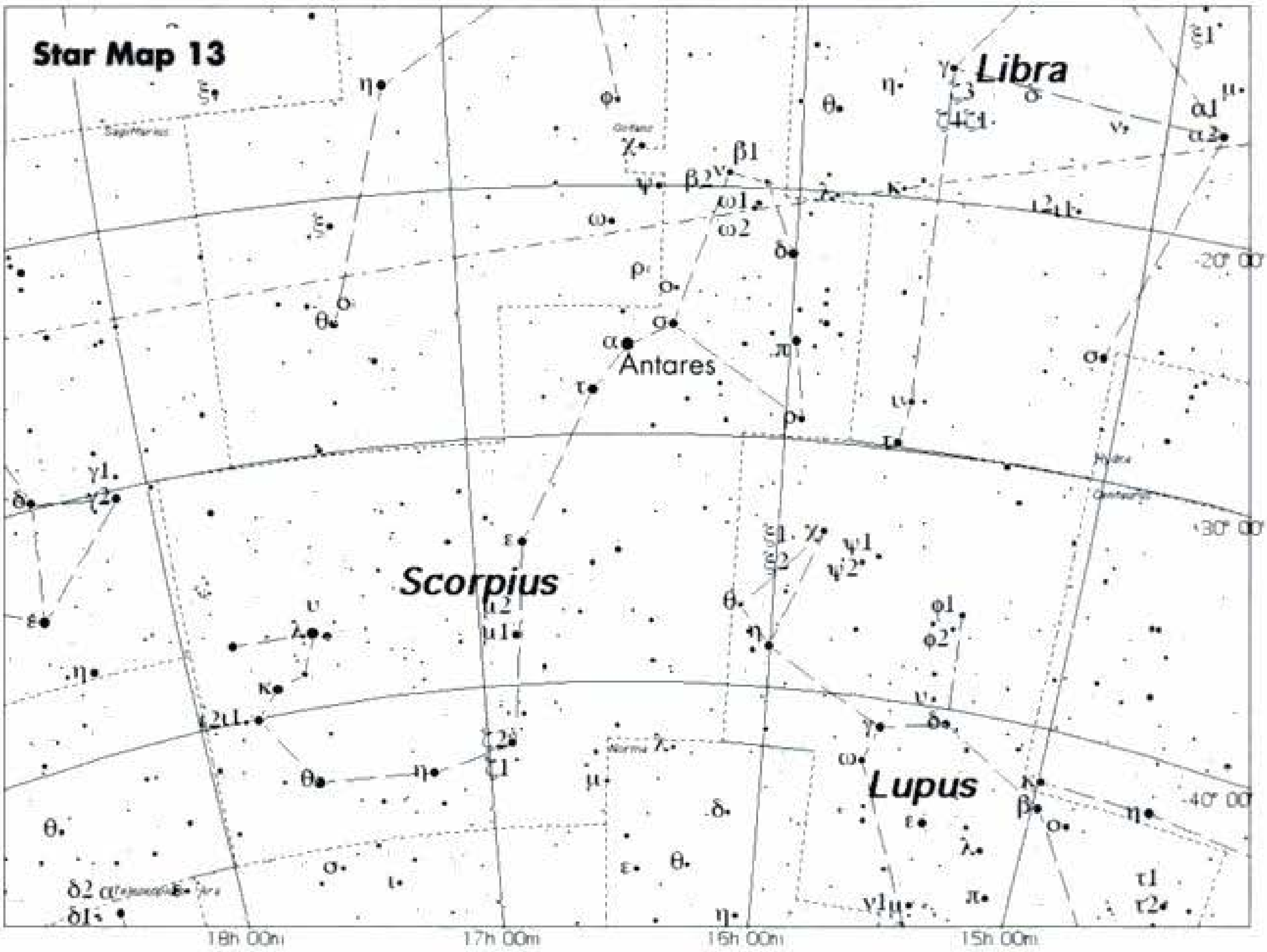
Star Map 9

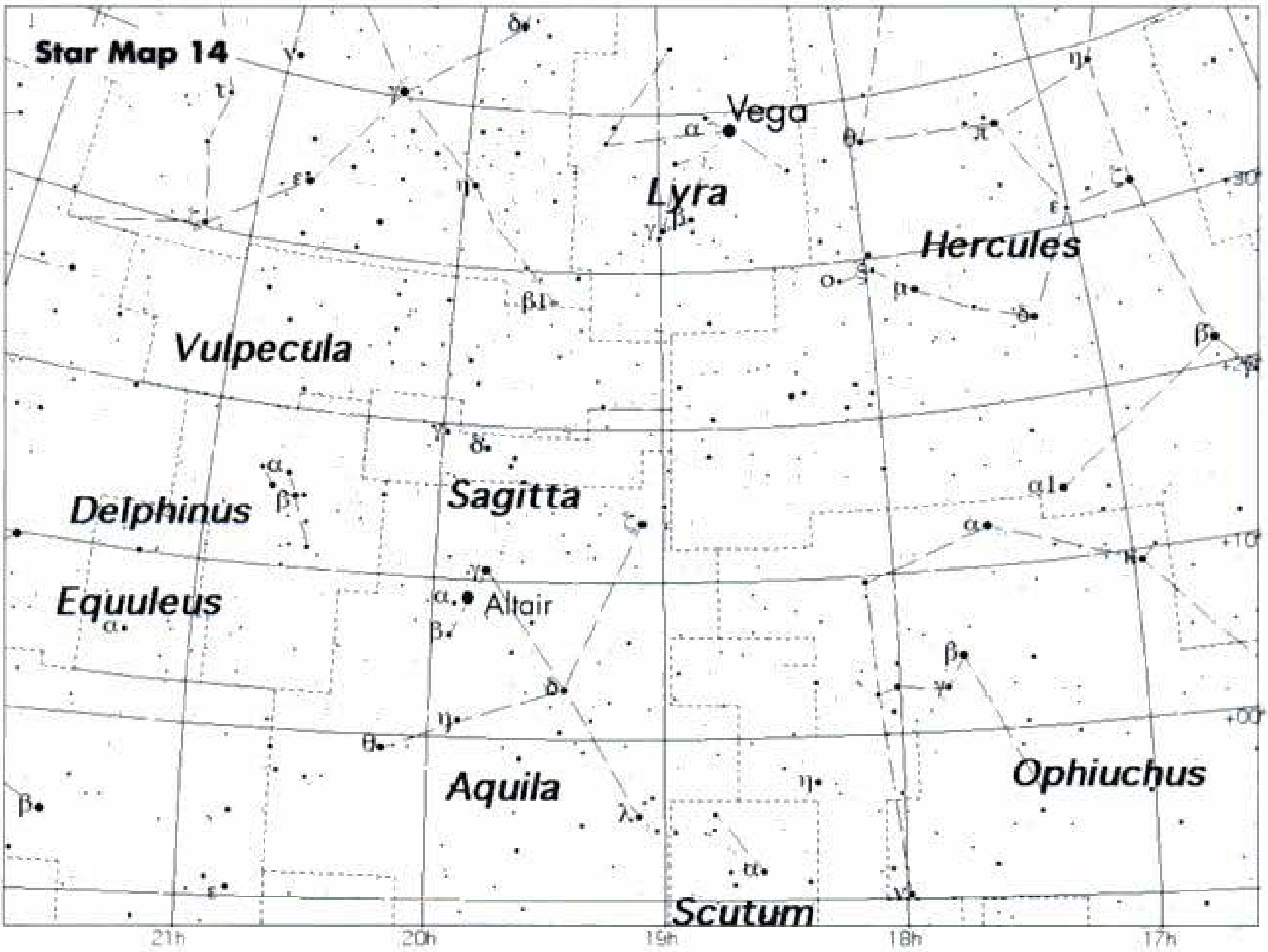


Star Map 10


Star Map 11


Star Map 12


Star Map 13
Libra
Scorpius
Antares
Lupus
-20° 00'
-30° 00'
-40° 00'
18h 00m
17h 00m
16h 00m
15h 00m


Star Map 14
Vega
Lyra
Hercules
Vulpecula
Sagitta
Delphinus
Equuleus
Altair
Aquila
Ophiuchus
Scutum
+30°
+20°
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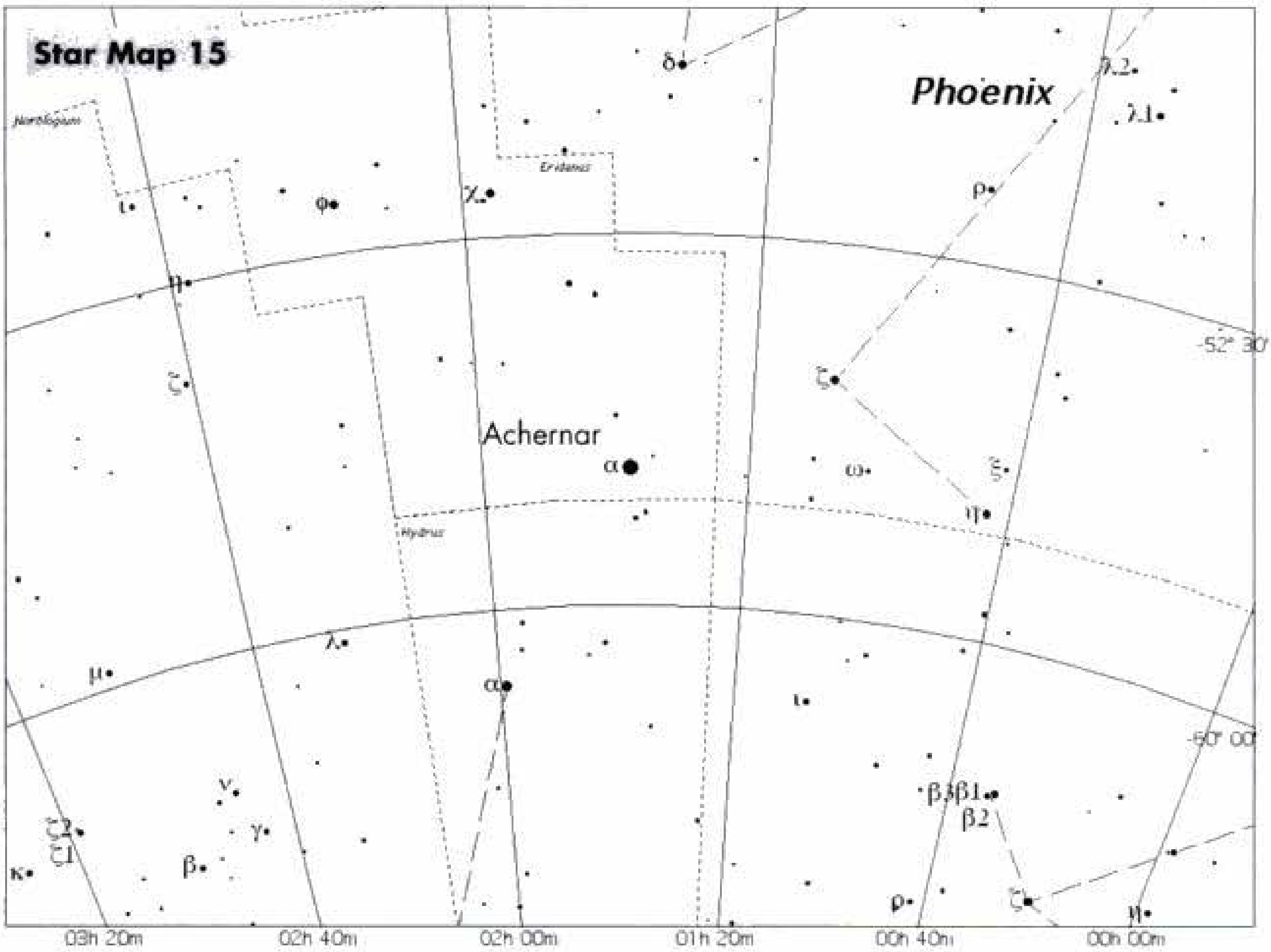
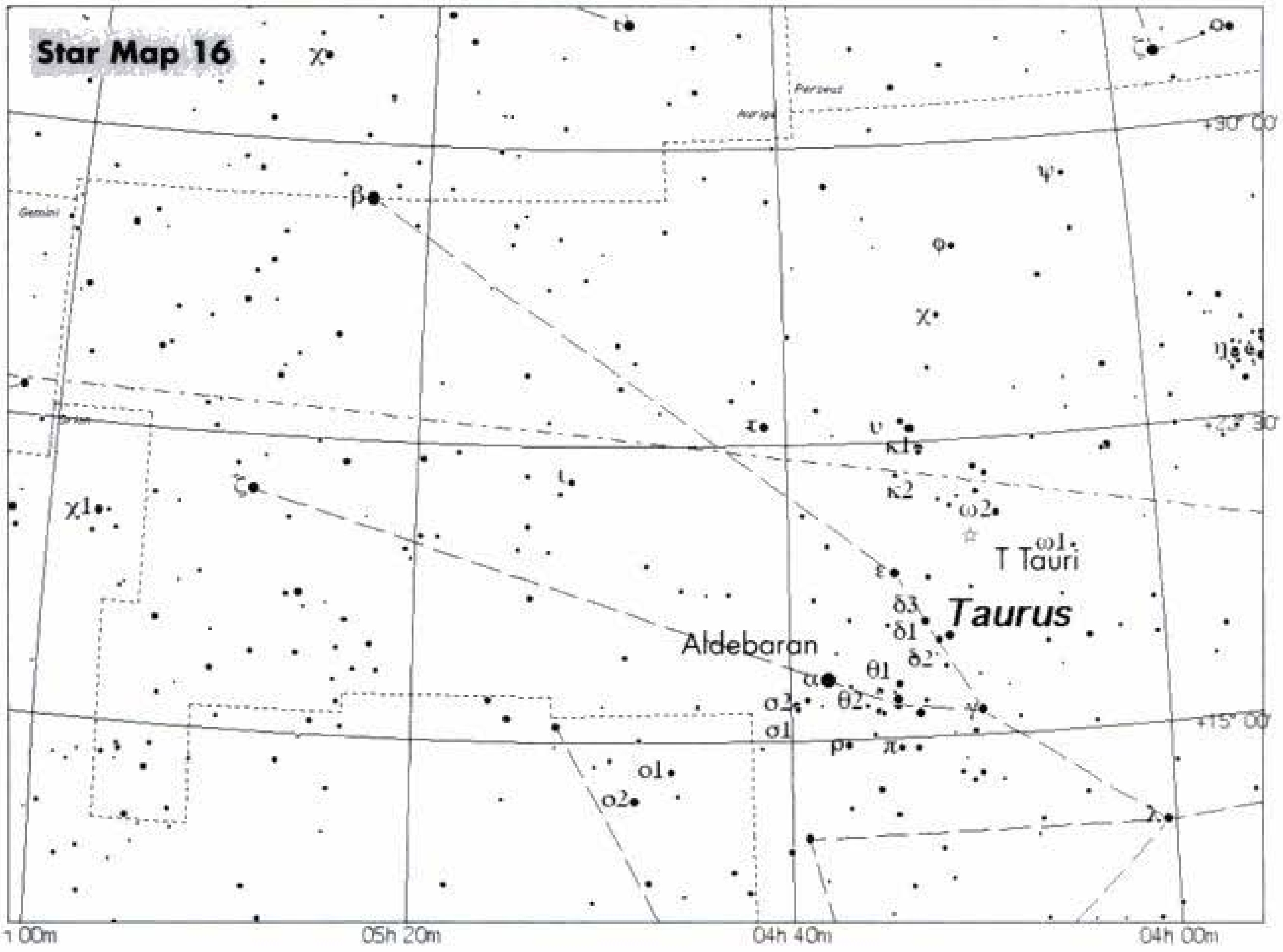
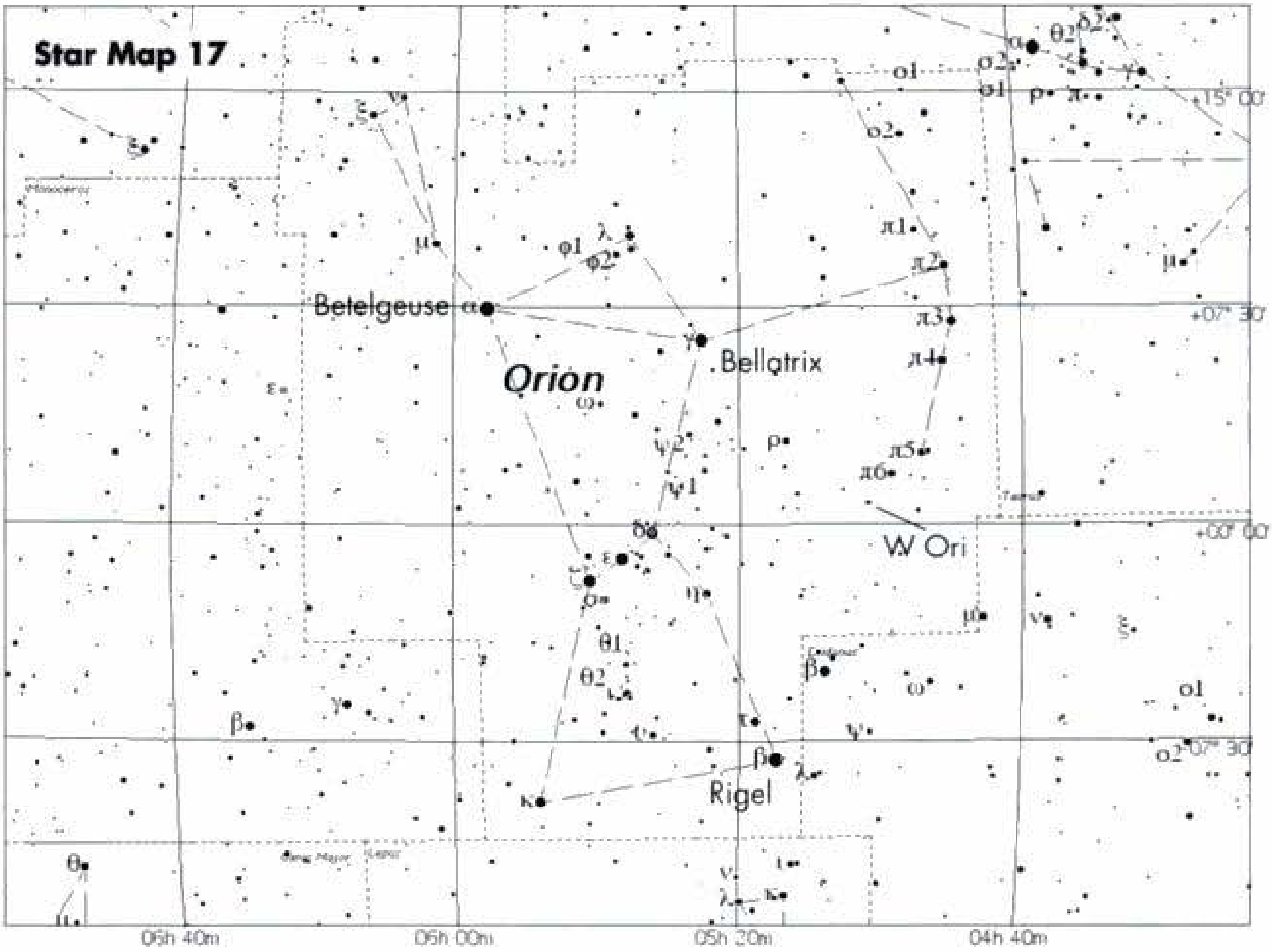
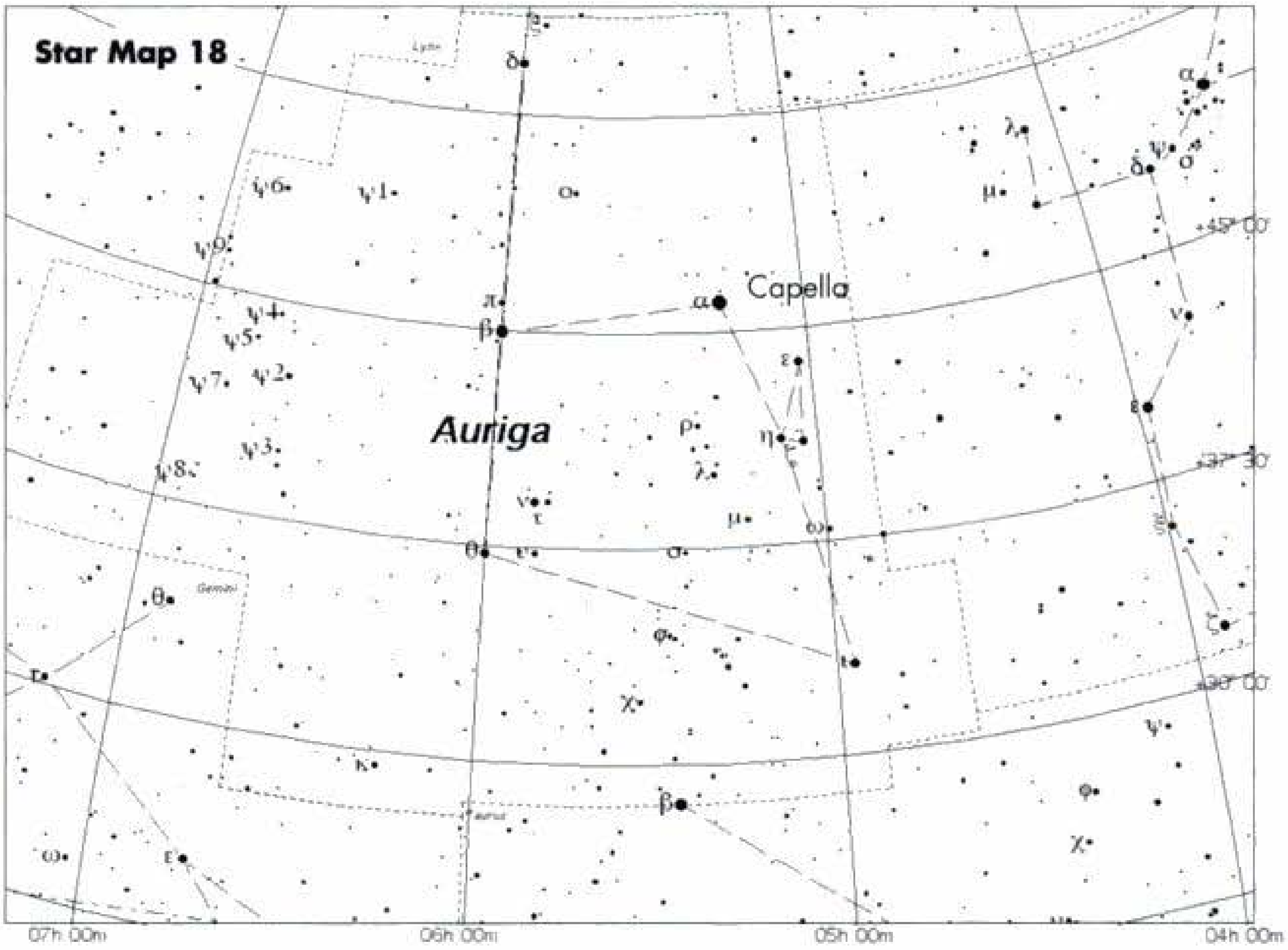
+00°
21h
20h
19h
18h
17h


Star Map 15


Star Map 16



Star Map 17



Star Map 18

1.6 The Colour of Stars

When we look up into the sky, we see many stars, all of the same general colour, usually white. There are, of course, a few which exhibit a distinct colour - *Betelgeuse* (*α Orionis*) is most definitely red as is *Antares* (*α Scorpi*), *Capella* (*α Aurigae*) is yellow, and *Vega* (*α Lyrae*) is steely blue. But for the most part, there does not seem to be any great variation in colour. Look through binoculars or a telescope, however, and the situation changes dramatically.[16] Variations in colour and hue abound![17]

The colour of a star is determined by its *surface temperature*. A red star has a lower temperature than a yellow star, which in turn has a lower temperature than a blue star. This is an example of what is called the *Wien Law* (see Box opposite). The law shows how low temperature stars emit most of their energy in the red to infrared part of the spectrum, whilst 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, so in fact we only see a fraction of the light they emit. Furthermore, many stars emit nearly all of their light in the infrared, so we do not see them at all. Surprisingly these low mass, low temperature stars make up abut 70% of the stars in our galaxy, but you would never know this by going out and observing on a clear night; we just cannot see them.

An important point to notice here is how 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 show how the light from three different stars is distributed, depending on the stars temperature. The coloured block represents the visible part of the spectrum. The first plot shows the light that would be measured from a coloured star of

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[16] The eye does not respond well to colour at low light levels. This is why, at night with the naked eye, we see only shades of grey, white and black.

[17] The most important factor which determines what the colour of a star you see is, is you - the observer! It is purely a matter of both 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, whilst another observes the same star as being yellow. It may even be that you will observe a star to have different colour when using different telescopes or magnifications, and atmospheric conditions will certainly have a role to play.

The Wien Law

This can be stated as:

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

Example
Two stars, γ^2 Vel and o Ceti, have a temperature of 50,000 K and 1900 K, respectively. What are their peak wavelengths?

$$\lambda_{\max} = \frac{2,900,000}{50,000(\mathrm{Kelvin})}\,\mathrm{nm} = 58\mathrm{nm};$$

i.e., in the far ultraviolet[a]

and

$$\lambda_{\max} = \frac{2,900,000}{1900(\mathrm{Kelvin})}\,\mathrm{nm} = 1526\ \mathrm{nm};$$

i.e., in the infrared.[b]

[a] This star is the brightest and nearest *Wolf–Rayet* star.
[b] This is the famous irregular variable star, *Mira*.

about 3000 K. Note that the curved line peaks at about 900 nm, which would make the star look red. The second plot shows a star at about 5500 K (similar to the Sun), and peaks in the middle of the visible spectrum, thus looking yellowish. The final plot is for a very hot star, at 25,000 K. This peaks at about 400 nm, so will appear blue. Thus, a star's colour, from an astronomical viewpoint, depends on where the peak of the curve is; short wavelengths (to the left part of the plot) indicate a hot, blue-white star, longer wavelengths (the right part of the plot) a cool reddish-orange star. The Sun actually peaks in the green part of the spectrum, but because 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 observation is that a few stars are so hot, possibly in millions of degrees, that they emit their energy at very short wavelengths. In fact they radiate X-rays. These are neutron stars!

Note, however, than when we speak of a star's temperature, we are referring to its surface temperature. The internal temperature cannot be measured

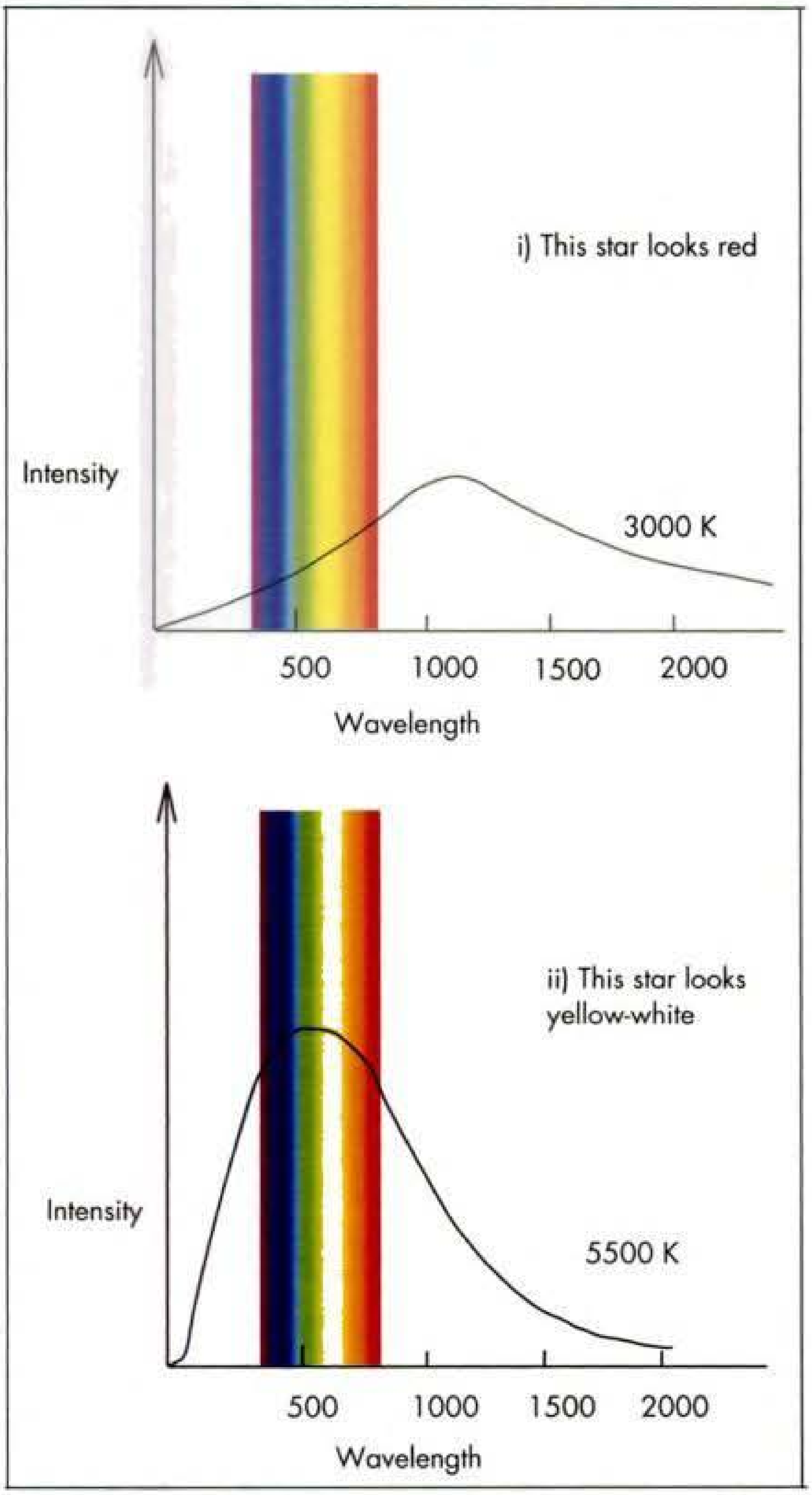

Figure 1.2. Colour and Temperature.

directly, and is usually determined from theoretical temperatures. So when you read that a star's temperature is "25,000 Kelvin", it refers to the surface temperature.[18]

Knowing the temperature allows us to determine many characteristics of the star. A scientific description of

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[18] From now on, when I mention temperature, I am referring to the surface temperature, unless indicated otherwise.

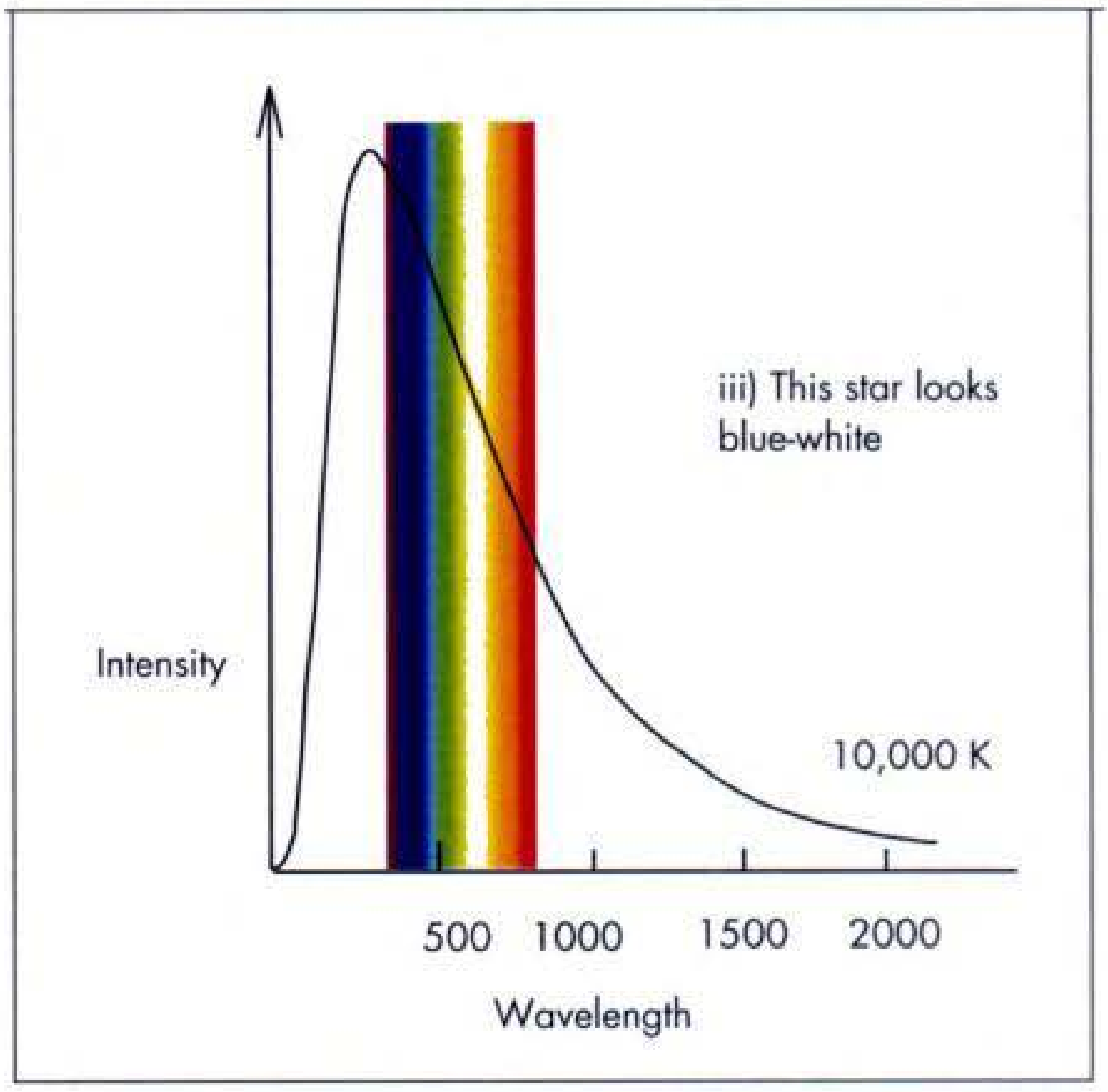

Figure 1.2. *(continued)*

a star's colour is one that is based on the stellar classification, which in turn is dependent upon the chemical composition and temperature of a star. A term commonly used by astronomers is the *colour index*. This is determined by observing a star through two filters, the *B* and the *V* filters, which correspond to wavelengths of 440 nm and 550 nm respectively, and measuring its brightness. Subtracting the two values obtained gives *B* – *V*, the colour index. Usually, a blue star will have a colour index that is negative; i.e., –0.3; orange-red stars could have a value greater than 0.0, and upwards to about 3.00 and greater for very red stars (M6 and greater).

Having discussed the colours of stars, lets now look at some examples. I have chosen only the representatively bright stars. There are, of course, literally thousands of other coloured stars that are visible. Also, the stars listed earlier (Section 1.5: "The Brightest Stars"), contains many examples of stars exhibiting distinct colours. In addition, many double stars (not mentioned here) show very distinct coloured hues and tints. The nomenclature is the same as previous, with the addition of the stars temperature and colour.[19]

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[19] Remember that a star's colour is observer-dependent! What one person sees as yellow, another sees as white. Do not be surprised if you see a different colour to that mentioned.

Bellatrix	γ Ori	$05^h\ 26.2^m$	+06° 21′	Nov–**Dec**–Jan
1.64m	–2.72M	21,450 K	Blue	Orion

Also known as the *Amazon Star*, this is a very steely-blue colour. Some observers report a faint nebulosity associated with the star, but this may be just part of the general nebulosity that envelopes much of *Orion*. See Star Map 17.

Merope	23 Tau	$03^h\ 46.3^m$	+23° 57′	Oct–**Nov**–Dec
4.14m	–1.07M	10,600 K	Blue	Taurus

Located within the *Pleiades* star cluster. A breathtaking and spectacular view when seen through binoculars, the cluster is a highlight of the night sky. Almost any of the stars in this cluster are worth looking at as they are all a lovely steely-blue colour (see also *Taygeta* (*19 Tau*) and *Electra* (*17 Tau*) in the *Pleiades* cluster).

Regulus	α Leo	$10^h\ 08.3^m$	+11° 58′	Jan–**Feb**–Mar
1.36m	–0.52M	12,000 K	Blue-white	Leo

Alpha (a) Leonis, is the handle of the Lion's sickle. It is an easy double star, the companion, an 8th-magnitude, orange-red colour, about 3' away. See Star Map 19.

Acrux	α Crucis	$12^h 26.6^m$	–63° 06′	Feb–**Mar**–Apr
0.72m	–4.19M	28,000/26,000 K	White	Crux

This is a double star, components about $4\frac{1}{2}$" apart. Both stars are around the same magnitude, 1.4 for α^1 and 1.9 for α^2. The colours of the stars are white and blue-white respectively. See Star Map 10.

Zubeneschamali	β Lib	$15^h 17.0^m$	–09° 23′	Apr–**May**–Jun
2.61m	–0.84M	11,000 K	Green!	Libra

A mysterious star for two reasons. Historical records state that it was much brighter than it is seen today, while observers of the past 100 years have declared that it is greenish or pale emerald in colour. Is it one of the rare green-coloured stars! See Star Map 20.

The Sun				Jan–Dec
–26.78m	4.82M	5800 K	Yellow	The Zodiac

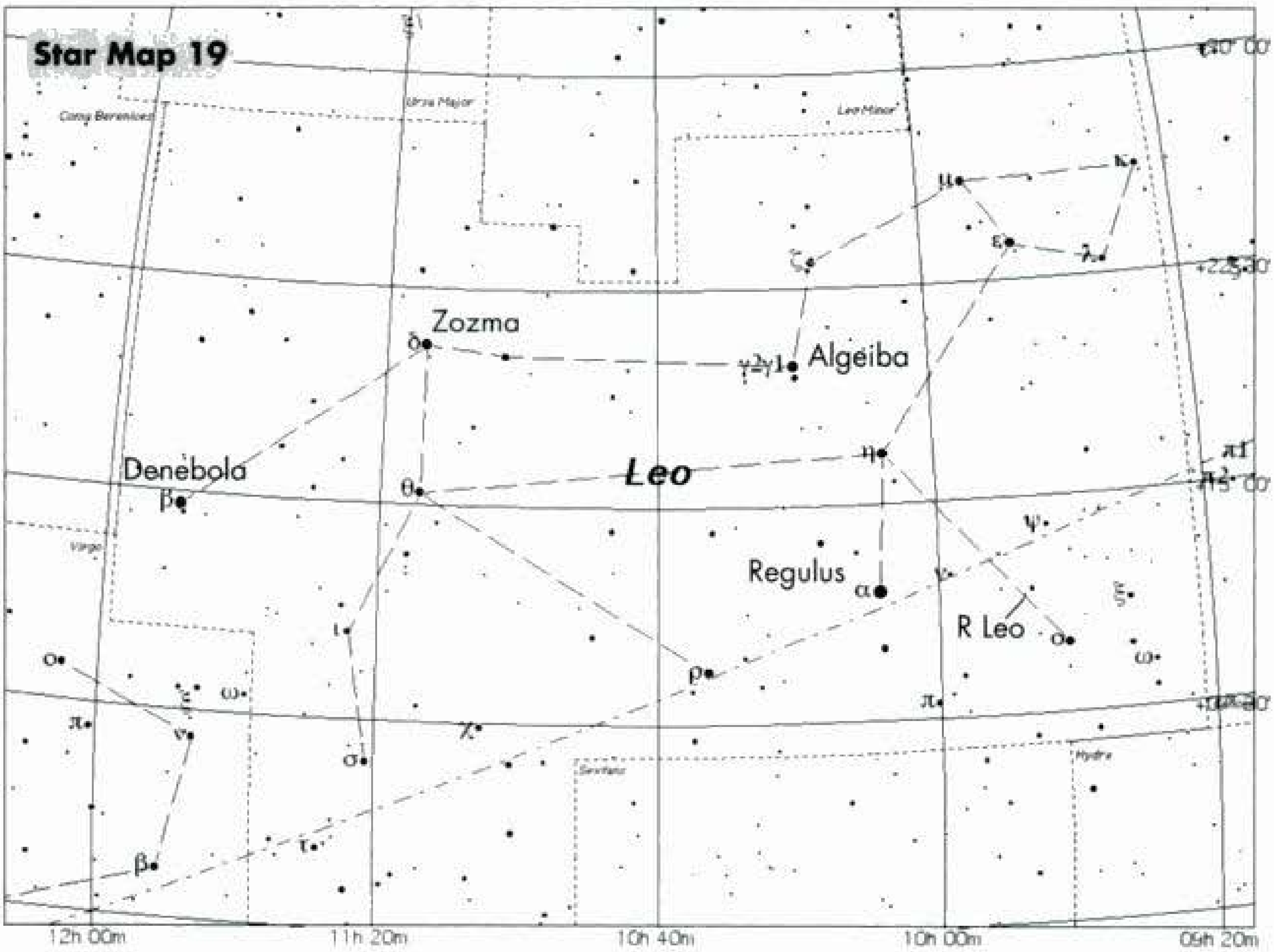
Our closest star, and the object without which no life would have evolved on Earth. Visible every day throughout the year, unless you happen to live in the UK. **DO NOT OBSERVE THROUGH ANY KIND OF OPTICAL EQUIPMENT.**

Garnet Star	μ Cep	$21^h43.5^m$	+58° 47′	Jul–**Aug**–Sep
4.08_vm	–7.3M	3500 K	Orange	Cepheus

Located on the north-eastern edge of the nebulosity IC1396, the *Garnet Star*, named by William Herschel, is one of the reddest stars in the entire sky. It has a deep orange or red colour seen against a backdrop of faint white stars. It is a pulsating red giant star, with a period of about 730 days, varying from 3.4 to 5.1m. Its distance and apparent brightness suggest an extraordinary luminosity a quarter million or more times that of the Sun, from which is derived a similar radius.[20] See Star Map 21.

Hind's Crimson Star	R Leporis	$04^h59.6^m$	–14° 48′	Nov–**Dec**–Jan
7.71_vm	1.08 M	3000 K[21]	Red	Lepus

The star, a classic long-period variable, period about 432 days, varies in brightness between 6.0 and 9.7m. At maximum brightness it displays the famous ruddy colour that gives it its name. Discovered in 1845 by J.R. Hind with a colour described as "intense smoky red". This may be the reddest star. It is also an AGB star (see Chapter 4 on Star Death). See Star Map 22.


Star Map 19

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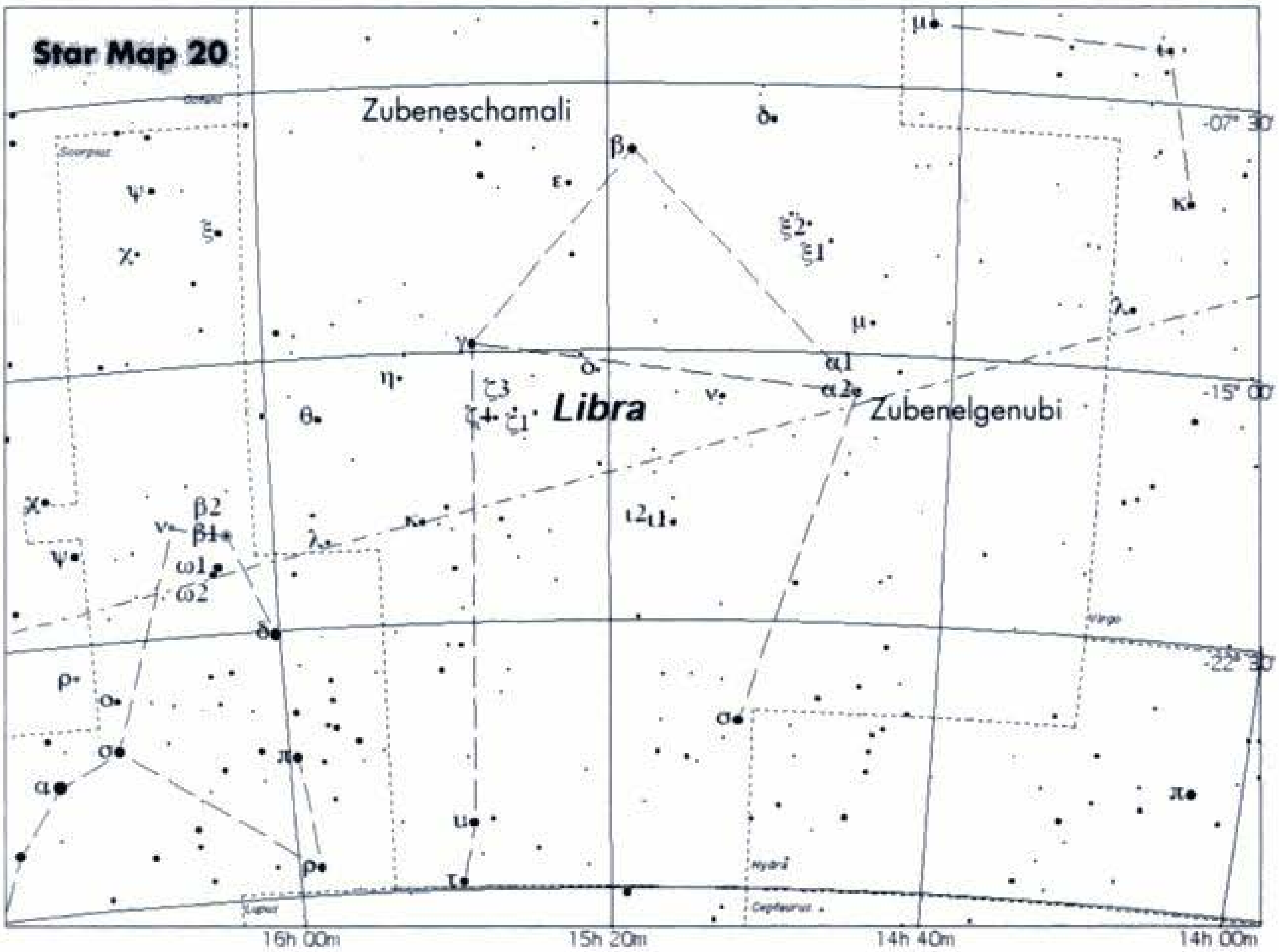
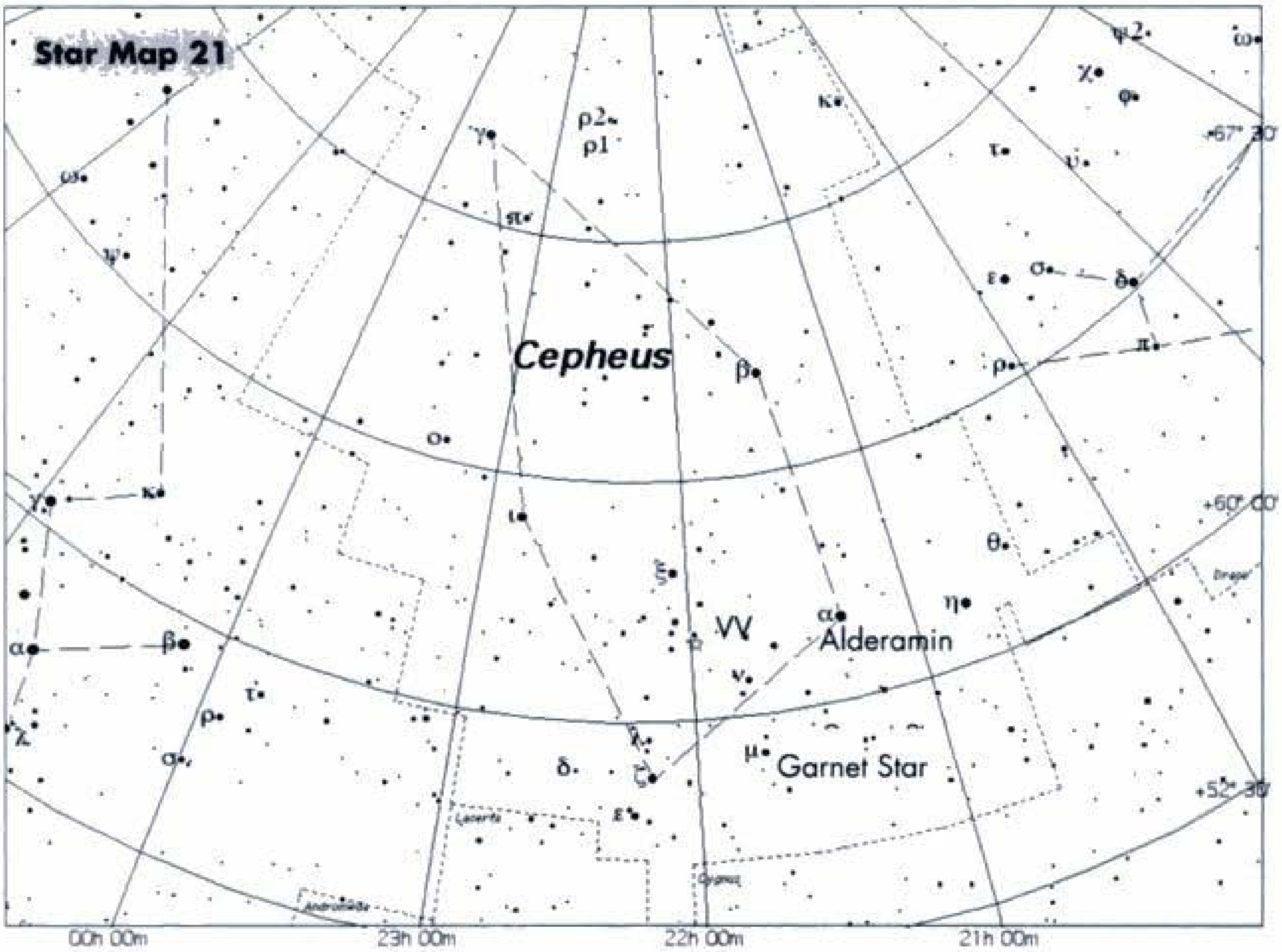
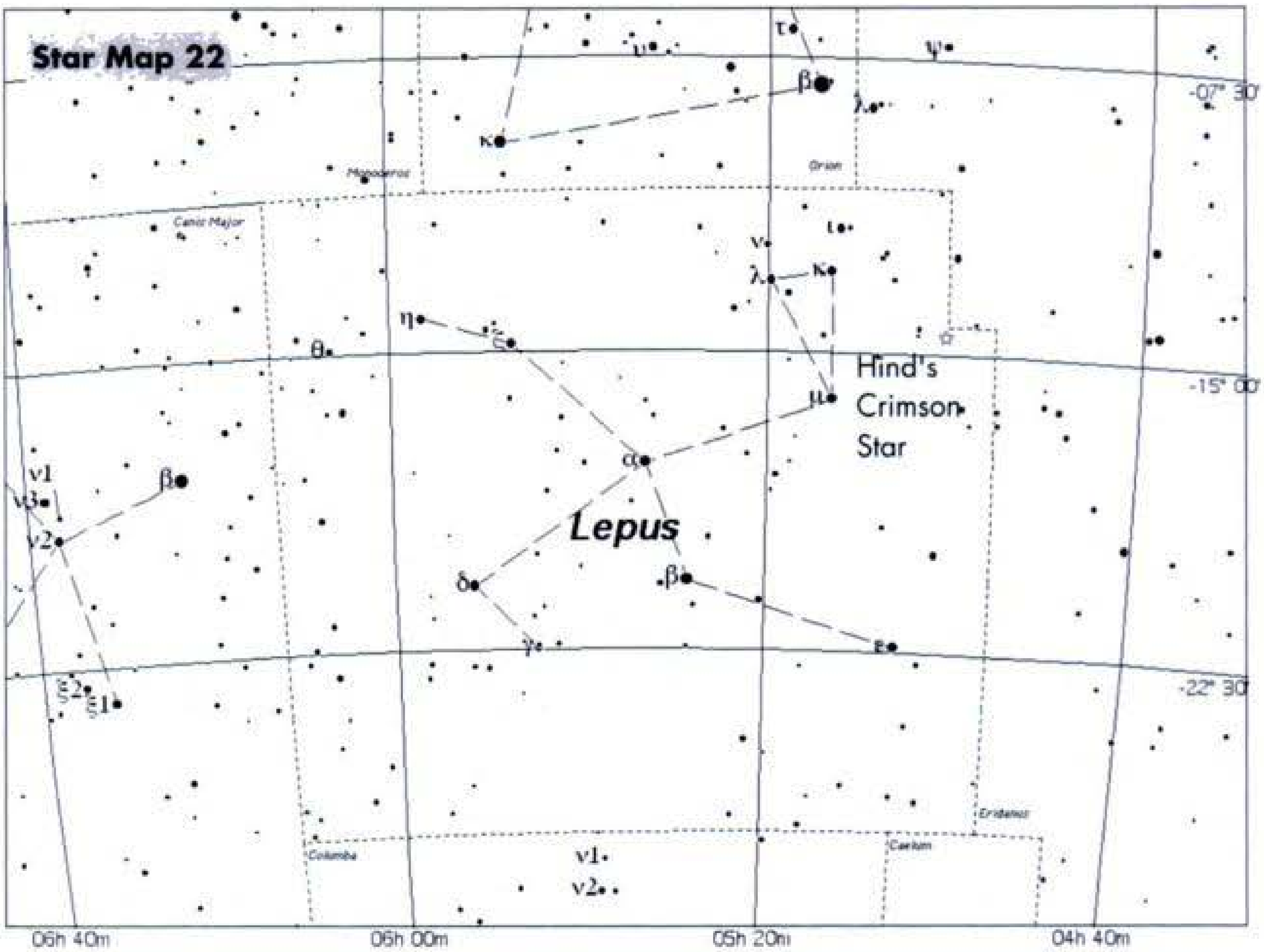
[20] There is considerable debate as to just how big this star is. Some sources believe it is about 5.7 AU, or just larger than Jupiter's orbit, to over 6 AU.

[21] The real temperature of the star is still undetermined.


Star Map 20
Zubeneschamali
Libra
Zubenelgenubi
β
γ
σ
α1
α2
Scorpius
Virgo
Hydra
Lupus
Centaurus
-07° 30'
-15° 00'
-22° 30'
16h 00m
15h 20m
14h 40m
14h 00m


Star Map 21
Cepheus
VV
Alderamin
Garnet Star
α
β
γ
δ
ζ
μ
Lacerta
Cygnus
Andromeda
Draco
+67° 30'
+60° 00'
+52° 30'
00h 00m
23h 00m
22h 00m
21h 00m



Star Map 22

1.7 The Size and Mass of Stars

Stars are at an immense distance from us, so no matter how much we magnify an image of a star, it will, in all but a handful of cases,[22] 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 star's luminosity (which is derived from its distance and brightness) and its surface temperature (determined from its spectral type), it is just a matter of manipulating the numbers with a few formulae. Astronomers using this technique have discovered that there are many stars much smaller than the Sun, while many more can be thousands of times larger.

In order to accurately determine the size of a star, a physical law, called the *Stefan–Boltzmann* law, is used. We won't bother looking at how this law came about,

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[22] A few stars, such as Betelgeuse, have had their radii determined by the technique known as interferometry. For the vast majority of stars the technique is not applicable, either due to distance or faintness.

but rather just quote it and show how it is used (see Box below). What the law tells us is that the amount of energy that a star radiates per second, from a square metre of its surface,[23] is proportional to the fourth power of the temperature, *T*, of the star's surface. Don't let the complexity of this statement distract you. It really just tells us the *energy flux* (*F*), is proportional to the temperature, which is makes sense when you think about it. A cool object has lower thermal energy than a hot object.

Now, think back and recall that we discussed how the luminosity from a star is a measure of the energy emitted from the surface every second. This luminosity is in fact, the flux *F*, multiplied by the *number of square metres that are on the star's surface.* If we now assume that most stars are spherical (which is not as silly as it sounds because a few stars are not spherical!), then the quantity which I highlighted in the previous sentence, is in fact the surface area of the star. This is given by a very simple formula which everyone knows: $4\pi R^2$, where *R* is the radius of the star (taken as the distance from the centre of the star to its surface).[24]

Flux, luminosity and radius of a star

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

$$F = \sigma T^4$$

The relationship between the 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 the star's radius in metres (m)
σ is the Stefan–Boltzmann constant: 5.67×10^{-8} W m^{-2} K^{-4}
and T is the star's temperature in Kelvin (K).

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[23] 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.

[24] No doubt some of you are already asking, "where is the surface of a star, if a star is made of gas". Fear not, all will be revealed in later chapters.

What the above equations tell us is that a coolish star, that is, one that has a low surface temperature, T, will have a low flux, but it may be quite luminous because it could have a very large radius, and thus a large surface area. In a similar vein, a hot star, with a high temperature, can have a low luminosity if the star has a small radius, which would mean a low surface area. Now you can see that knowing a stars temperature

More about flux, luminosity and radius of a star

We regard the Sun as a typical star. We can relate most of another star's parameters to those of the Sun. For instance:

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

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

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

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

You can see the constant, σ, has now gone, and we can also rearrange the formula to read:

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

where the $\frac{1}{2}$ factor 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's and $L/L_\odot$ is the ratio of the star's luminosity to that of the Sun.

Example
Betelgeuse has a temperature of about 3500 K, and has a luminosity of 60,000 $L_\odot$.

To determine its ratio:

$$R/R_\odot = \left(\frac{5800}{3500}\right)^2 \sqrt{60,000} = 670$$

Thus, its radius is about 670 times that of the Sun, which is on the order of 3 AU; i.e., greater than the orbit of Mars!

alone, is no indication of how luminous it will be - we also need its radius!

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 is easier to have an idea of a star if we say it is about 10 times as hotter than the Sun, than it would be by saying it is 54,000 K. and the same applies for *L*, and *R*.

1.8 The Biggest Stars

Let's now look at some examples of giant stars, particularly those that can be seen with the naked eye. See also *Betelgeuse*, *Antares*, *Rigel* and the *Garnet Star*.

α Herculis	ADS 10418	$17^h14.6^m$	+14° 23′	May–**Jun**–Jul
$3.5_v, 5.4_v$m	–1.9M	Radius: 2.0 AU		Hercules
A lovely colour-contrast double: orange and bluish green. The star lies at a distance of about 400 ly, and is a semi-regular, super-giant variable star. The primary star is itself variable, while the secondary is an unresolvable double. See Star Map 23.				

ψ^1 Aurigae	HD 44537	$06^h24.9^m$	+49° 17′	Nov–**Dec**–Jan
4.92_vm	–5.43M	Radius: 3.0 AU [25]		Auriga
This star has an incredible luminosity of over 11,000 $L_\odot$. It is an irregular variable star, the diameter of which is still not accurately known, but is believed to be about 4300 ly distant. See Star Map 18.				

η Persei	ADS 2157	$02^h50.7^m$	+55° 54′	Oct–**Nov**–Dec
3.8, 8.5m	–4M	Radius: 2.0 AU		Perseus
Lying at a distance of 1300 ly, this is a lovely double star – gold primary and blue secondary. The primary is the supergiant, with a luminosity of over 4000 $L_\odot$. See Star Map 24				

VV Cephei	HD 208816	$21^h56.6^m$	+63° 37′	Sep–**Oct**–Nov
5.11m	–6.93M	Radius: 8.8 AU		Cepheus
This star has a luminosity of over 46,00 $L_\odot$, and lies at a distance of 2000 ly. It is one of the famous *eclipsing binary* type variable stars, with a period of just over 20 years. The system consists of an O-type dwarf and a giant M-type supergiant. This giant star, if when was placed at the centre of our solar system, would have a radius to nearly Saturn! See Star Map 21.				

KQ Puppis	HD 60414	$07^h33.8^m$	–14° 31′	Sep–**Oct**–Nov
4.82m	–5.25M	Radius: 8.8 AU		Puppis
This star has a luminosity of over 9870 $L_\odot$, and lies at a distance of 3361 ly.[25] It is believed to be an irregular variable star. See Star Map 25.				

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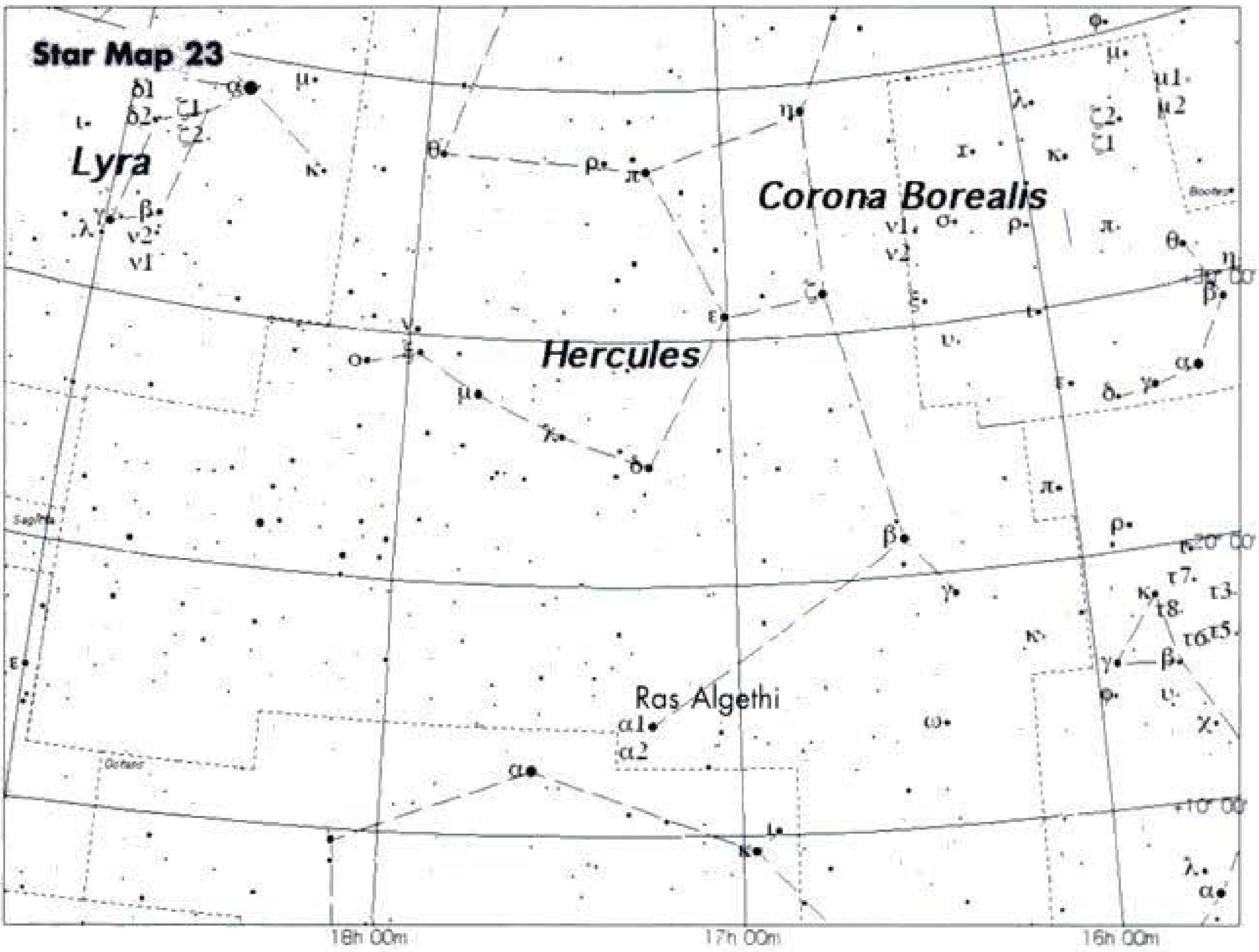
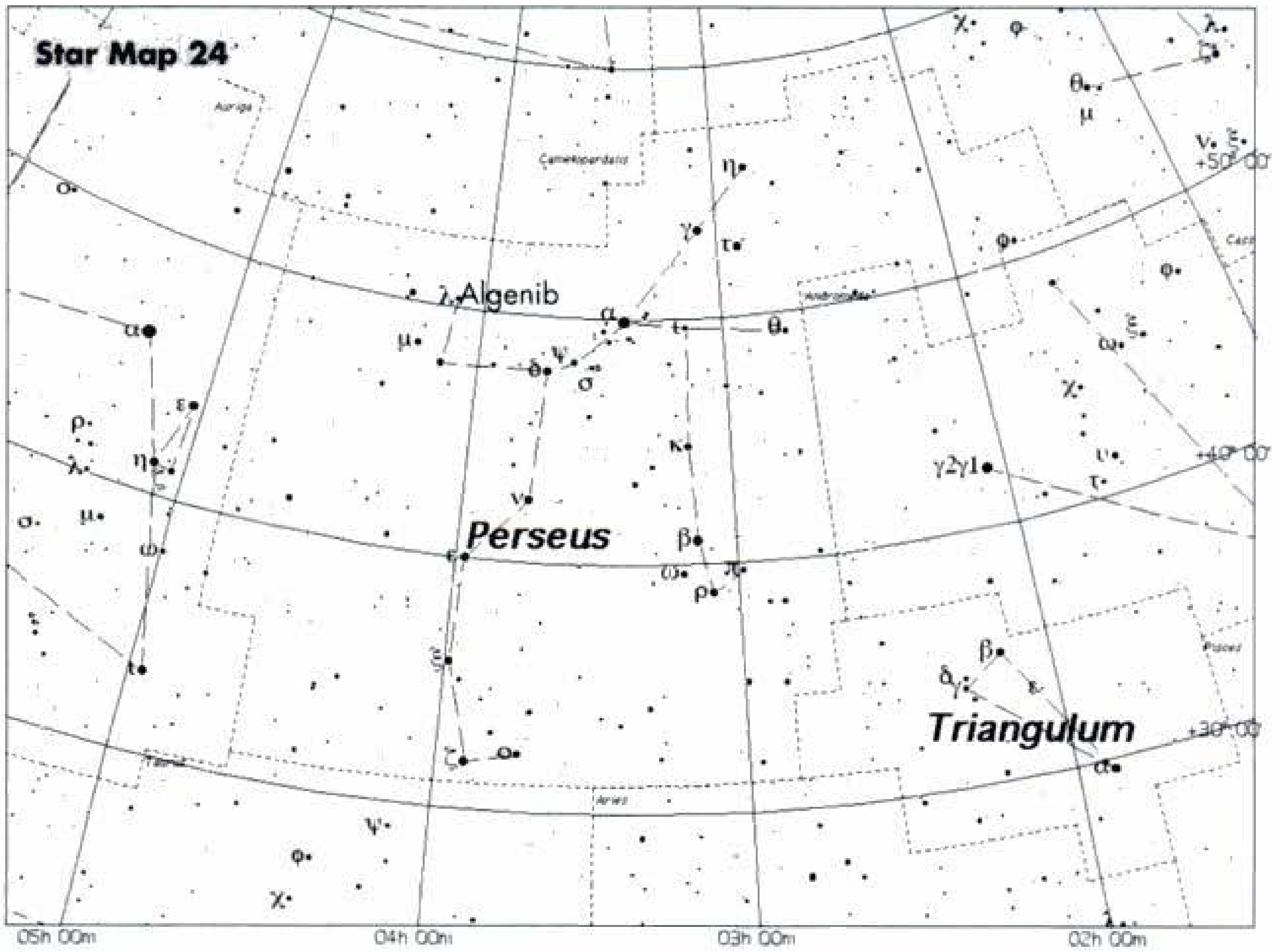
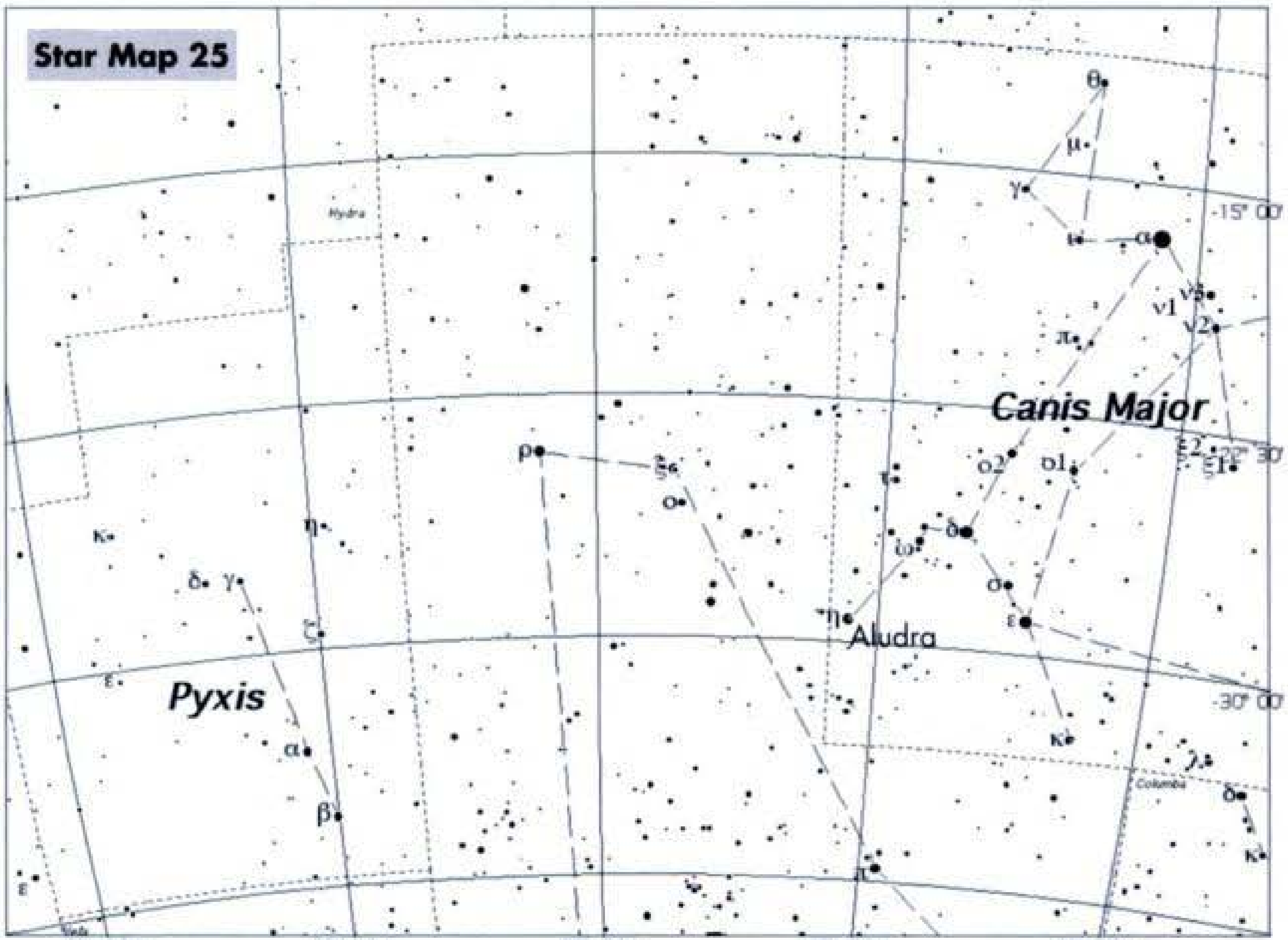
[25] There is some doubt about this value.



Star Map 23



Star Map 24



Star Map 25

1.9 The Constituents of Stars

Although we will be covering this topic in far greater detail later on in the book, it is important that we at least discuss briefly what stars are made of.

A star is an enormous sphere of hot gas. 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 to be expected, very, very complex!

The gases composing the star are for the most part hydrogen (H), the most common element in the universe, along with some helium (He) and then some other elements.[26] By and large, most stars are nearly all hydrogen, with just a few percent helium, and very small amounts of everything else. Usually this mix is about 75% hydrogen, 24% helium, and the remainder metals. This figure, however, changes when we discuss

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[26] Astronomers call every element other than hydrogen and helium, metals. It's odd, I agree, but don't worry about it – just accept it.

either very old stars, which are nearly all hydrogen and helium with a tiny amount of metals, or very new stars, which can have as much as 2–3% metals.

The energy needed to create and then maintain a star is formed by nuclear fusion; hydrogen is converted to helium due to the two immense forces at work, namely a very high temperature and very strong gravitational force. Owing to its very large mass, and its concomitant strong gravitational field, conditions in the centre of the ball of gas are such that the temperature can be about 10 *million* Kelvin. At such extremes of pressure and heat, nuclear fusion can occur, and 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 much, but when you consider that billions of these reactions take place every second, then the amount of energy liberated is quite substantial. Enough in fact to make a star shine!

As the 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. Thus, as time passes, the amount of hydrogen decreases and the helium increases. If conditions are right (these include a higher temperature and a large mass) then the helium itself will start to undergo nuclear fusion at the core of the star. After a long time, this in turn will produce, as a by-product of the reaction, the element carbon, and again, if conditions are suitable, this too will start to begin nuclear fusion and produce more energy. An important point to emphasise is that each step requires a higher temperature to begin the nuclear reactions, and if a star does not have the conditions necessary to provide this high temperature then further reactions will not occur. So you will realise that the "burning" of hydrogen and helium is the power source for nearly all the stars you can see, and that the mass of the star determines how the reaction will proceed.

1.10 The Spectra of Stars

We will now discuss a topic that is central to the topic of stars and stellar evolution – the spectra of stars. So important is this topic that, from this point on in the book, a star will be referred to by its spectral classification. Quoting a star's spectral classification, allows us to know roughly what type of star it is, its temperature, mass and age. It also places the star in its correct location within the context of stellar evolution.

To determine the classification of star is a theoretically easy task, although it can be difficult in practice. What is needed is a spectroscope. This is an instrument that looks at the light from a star in a special way by utilising either a prism or a diffraction grating to analyse the light. You'll be aware that white light is in fact a mixture of many different colours, or wavelengths, so it's safe to assume that the light from a star is also a mixture of colours. Indeed it is, but usually with an added component. Using a spectroscope mounted at the eyepiece end of the telescope,[27] light from the star can be collected and photographed (these days with a CCD camera). The end result is something called a spectrum. Many amateur astronomers are now making some very good observations of stars' spectra.

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

The electrons in the atoms located in the surface of a star can only have very specific energies, rather 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 back down to the lower level. The energy that the atom loses when the electron returns back to its original level must go somewhere,

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[27] 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 analysed simultaneously. This is called an *objective spectroscope*. The drawback is the considerable loss of detail (i.e., information about the stars) but does allow initial measurements to be made.

and often goes to emitting a photon of light. This emitted photon has a unique property – it has the exact same 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 I mentioned earlier that in addition to hydrogen and helium, there are also the other elements, or metals, present, although in minute quantities). Not only are photons emitted, but they can 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 necessary. To much, or too little, by even a minuscule amount, and the photon will not interact with the electron.

In hydrogen gas, an electron moving from level 2 to level 1 will emit a photon which 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 the wavelengths that occur for downward transitions. Also shown are the absorption and emission spectra.

Note that in Figure 1.3, the dark absorption lines and the bright emission lines occur at exactly the same wavelengths, regardless of whether the hydrogen is emitting or absorbing the light. Emission lines are simply the result of downward jumps, or transitions, of electrons between the energy levels, whilst absorption lines are upward transitions.

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

The factor that determines whether an absorption

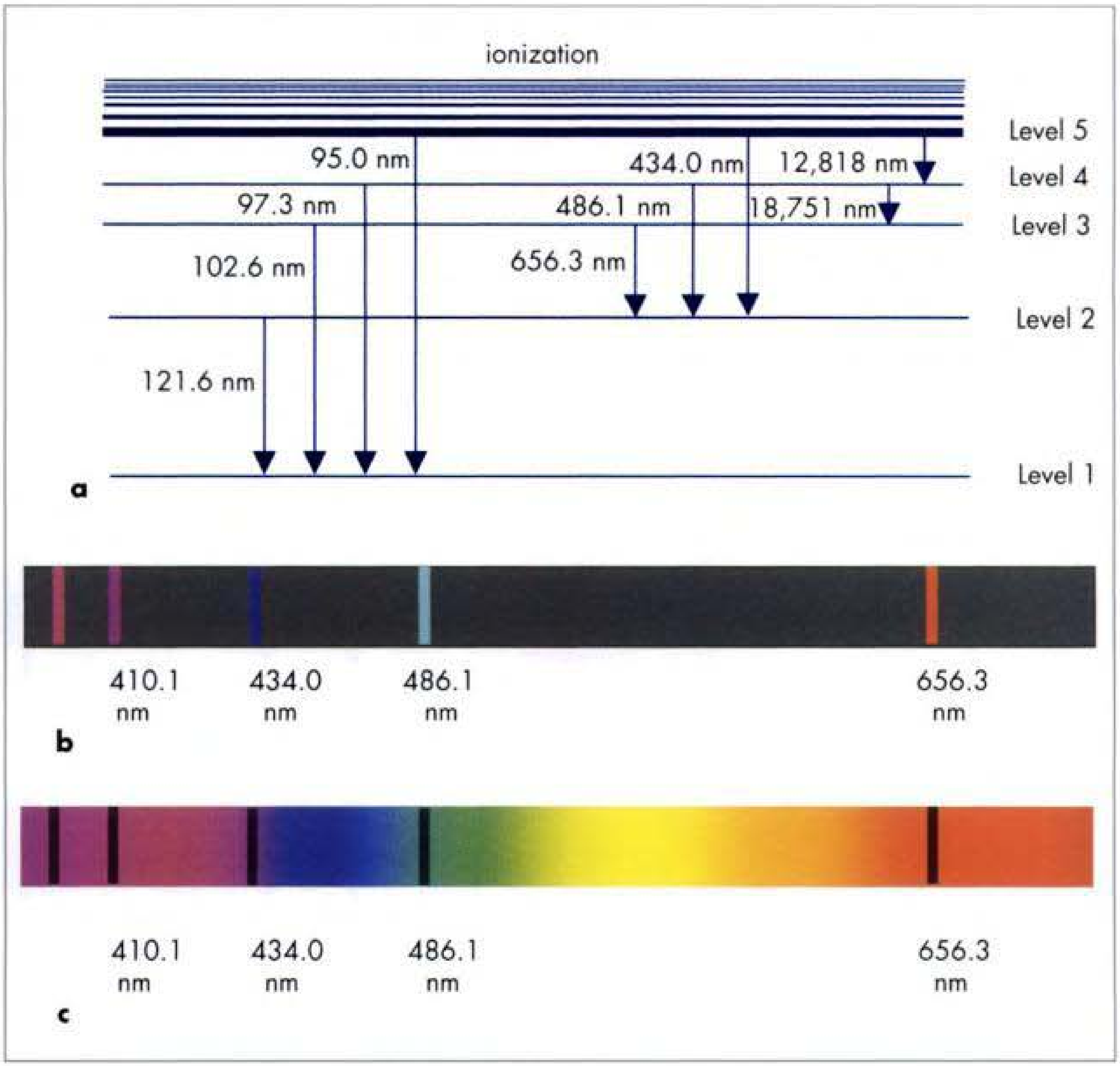

Figure 1.3. Hydrogen Transitions. **a** Shows the wavelengths of various energy level transitions in hydrogen, but only a few of the many transitions that occur are given. **b** Visible emission line spectrum, showing transitions that occur from high energy levels downward to level 2 for hydrogen. **c** Absorption line spectrum, showing transitions that arise from energy level 2 to higher levels. These absorption and emission lines of hydrogen are called the Balmer Lines.

line will arise is the temperature of the atmosphere of a star. Thus a hot star will have different absorption lines from 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 will emphasise is, 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 themselves can also be examined, and this gives further information on pressure, rotation and even whether a companion star is present.

1.11 Stellar Classification

We have seen how stars are distinguished by their spectra (and thus temperature); let's now think about the spectral type. For historical reasons a star's classification is designated by a capital letter; thus, in order of *decreasing* temperature:[28]

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 *K* and *M*. and *L*. In addition there are rare and hot stars called *Wolf–Rayet* stars, class *WC* and *WN*, exploding stars *Q*, and peculiar stars, *P*. The star types *R*, *N* and *S*, actually overlap class *M*, and so R and N have been reclassified as *C*-type stars, the C standing for Carbon stars. A new class has recently been introduced, the *L* class.[29] Furthermore, the spectral types themselves are divided into ten spectral classes beginning with 0, 1, 2, 3 and so on up to 9. A class A1 star is thus hotter than a class A8 star, which in turn is hotter than a class F0 star. Further 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
a variable spectrum	v
a star with a blue or shift in the line (for example P-Cygni stars)	q

And so forth. For historical reasons, the spectra of the hotter star 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*. Also, F and G stars are *intermediate-type* stars.

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[28] The reason why 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 ionised. Thus, without an electron to "jump" between energy levels, ionised 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.

[29] As we shall see later these are stars with very low temperatures – 1900 to 1500 K. Many astronomers believe these are brown dwarves.

Because the spectral type is so important, it is instructive to explain further how the appearance of a star's spectrum is affected by the star's surface temperature. We will consider the *Balmer* lines of hydrogen, mainly because these are by far the easiest o understand. Hydrogen gas makes up 75% of a star, yet the Balmer lines do not always show up 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 about 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 is the process of *ionisation.* Now that the hydrogen atom has lost its electron, it cannot produce absorption lines, and so the Balmer lines will be relatively weak in the spectra of such hot stars; for example, type O stars up to type B2.

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 few 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 M0 and M2 stars.

In order for the Balmer lines to be prominent, the 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 9000 K, then it will have the strongest hydrogen lines, for example, the A0 to A5 stars.

The Balmer lines of hydrogen become increasingly prominent as you go from Type B0 to A0. From A0 through to F and G class, the lines weaken and almost fade away. The Sun, a G2 star, has a spectrum dominated by lines of calcium and iron.

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

SuperGiants[30]	I
Bright giants	II

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[30] These can be further sub-classified into Ia and Ib, with Ia the brighter.

Giants	III
Subgiants	IV
Dwarfs	V
Subdwarfs	VI
White dwarfs	VII

It's 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 F9 should be reclassified as G0! Nevertheless, it is the system generally used, and so will be adhered to here. Examples of classification are:

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

I conclude my section on spectral classification by explaining what the spectral-type actually *refers* to.[31] You will recall that the classification was based on the detection of absorption lines, which in turn depend on the temperature of the 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 can be summarized best by Table 1.4.

It is interesting to point out that the distribution of stars throughout the Galaxy may not be what you assume. A casual glance at the stars you see 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 then think this is a fair picture of the type-distribution throughout the remainder of the galaxy. You would be wrong! As we shall see in later sections, the vast majority of stars in our Galaxy are the faint, cool and red M-type stars, over 72% of them. The bright and hot O-type stars number 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 of the spectral sequence.

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[31] It usual for only the classes O, A, B, F, G, K, M, to be listed. The other classes are used and defined as and when they are needed.

Table 1.4. Spectral classification

Spectral type	*Absorption lines*	*Temperature*	*Colour*	*Notes*	*Brightest wavelength (colour)*	*Examples*
O	ionised helium (HeII)	35 000 K +	blue–white	massive, short lived	< 97 nm (ultraviolet)	Stars Of Orion's Belt
B	neutral helium first appearance of hydrogen	20 000 K	blue–white	massive and luminous	97–290 nm (ultraviolet)	Rigel
A	hydrogen lines singly ionised metals	10 000 K	white	up to 100 times more luminous than Sun	290–390 nm (violet)	Sirius
F	ionised calcium (CaII), weak hydrogen	7000 K	yellow–white		390–480 nm (blue)	Polaris
G	CaII prominent, very weak hydrogen	6000 K	yellow	Sun is G–type	480–580 nm (yellow)	Alpha Centauri A, Sun
K	neutral metals, faint hydrogen, hydrocarbon bands	4000–4700 K	orange		580–830 nm (red)	Arcturus
M	molecular bands, titanium oxide (TiO)	2500–3000 K	red	most prolific stars in Galaxy	> 830 nm (infrared)	Proxima Centauri, Betelgeuse

-	HD 93129A	$10^h43.9^m$	–59° 33′	Jan–**Feb**–Mar
7.0m	–7.0M	O3 If		Carina

An extraordinary star! This supergiant star, lying at a distance of about 11,000 ly, shines around 5 million times as brightly as the Sun. It has a mass of 120 $M_\odot$ and is believed to be the most luminous star in the entire Galaxy. See Star Map 26.

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

A member of the famous Trapezium multiple star system in the Orion Nebula. Splitting the group is always a test for small telescopes. A fairly new star, maybe only several thousand years old, and as a consequence most of the star's light is emitted at ultraviolet wavelengths. It is at a temperature of 45,000 K, and has a diameter 10 times that of the Sun.

15 Monocerotis	HD47839	$06^h40.9^m$	+09° 54′	Nov–**Dec**–Jan
4.66$_v$m	–2.3M	O7		Monoceros

Both a visual binary and a variable star, it is located in the star cluster *NGC 2264*, which in turn is encased in a diffuse nebula. See Star Map 27.

Plaskett's Star	HD47129	$06^h37.4^m$	+06° 08′	Nov–**Dec**–Jan
6.05m	–3.54M	O8		Monoceros

This is actually composed of two stars, a spectroscopic binary system, with an estimated mass of around 110 Suns, making it one of the most massive known. See Star Map 27.

Gamma Cassiopeiae	γ Cas	$00^h56.7^m$	+60° 43′	Sep–**Oct**–Nov
2.15$_v$m	–4.22M	B0 IV		Cassiopeia

A peculiar star in that it has bright emission lines in its spectrum, indicating that it ejects material in periodic outbursts. The middle star of the familiar W-shape of *Cassiopeia*. See Star Map 28.

Murzim	β CMa	$06^h22.7^m$	–17° 57′	Nov–**Dec**–Jan
1.98$_v$m	–3.96M	B1 II		Canis Major

This is the prototype of a class of variable star now classified as *β Cepheid* stars, which are pulsating variables. The magnitude variation is too small to be observed visually. See Star Map 2.

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

A member of the type *β CMa* (Canis Majoris) variable star. It is the south-eastern corner star of the famed square of Pegasus. See Star Map 29.

Achernar	α Eri	$01^h37.7^m$	–57° 14′	Sep–**Oct**–Nov
0.45$_v$m	–2.77M	B3 V		Eridanus

A hot and blue star. It lies so far south that it can never be seen from the UK. See Star Map 15.

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

A highly luminous supergiant, with an estimated luminosity 50,000 times that of the Sun. See Star Map 25.

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

Located within the *Pleiades* star cluster. A breathtaking and spectacular view when seen through binoculars, the cluster is a highlight of the night sky. (See also *Taygeta* (19 Tau) and *Merope* (23 Tau) in the *Pleiades* cluster.)

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

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

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

Yet another lovely blue star in the *Pleiades* cluster. This one has a luminosity of around 8 times that of the Sun.

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

A brilliant orange star lying at a distance of 125 light years with a luminosity of 250 Suns. See Star Map 30.

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

A classic double star system visible in binoculars or small telescopes. Both stars are nearly identical in magnitude and stellar class, and have a lovely white colour. A true binary star system. See Star Map 31.

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

The star is relatively close at about 58 light years, with a luminosity of 160 Suns. See Star Map 9.

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

Part of the famous multiple star system, and fainter brother to *Pollux*. The visual magnitude stated is the result of combining the magnitudes of the two brighter components of the system, 1.9 and 2.9. See Star Map 9.

Deneb	α Cyg	20^{h}41.3^m	+45° 17′	Jul–**Aug**–Sep
1.25$_v$m	–8.73[32]M	A2 I		Cygnus

The faintest star of the *Summer Triangle* (the others being *Altair* and *Vega*). A supergiant star with a definite pale-blue colour. The prototype of a class of pulsating variable star. See Star Map 4.

Denebola	β Leo	11^{h}49.1^m	+14° 34′	Feb–**Mar**–Apr
2.14$_v$m	1.92M	A3 V		Leo

Several companion stars are visible in a variety of instruments. The star has only recently been designated a variable. See Star Map 19.

Delta Leonis	δ Leo	11^{h}14.1^m	+20° 31′	Feb–**Mar**–Apr
2.56m	1.32M	A4 V		Leo

Also called *Zozma*, it lies at a distance of 80 light years, with a luminosity of 50 Suns. See Star Map 19.

Ras Alhague	α Oph	17^{h}34.9^m	+12° 34′	May–**Jun**–Jul
2.08m	1.30M	A5 III		Ophiuchus

An interesting star for several reasons. It shows the same motions through space as several other stars called the *Ursa Major Group*. It also shows interstellar absorption lines in its spectrum. Finally, measurements show an oscillation, or wobble, in its proper motion, which would indicate an unseen companion star. (See also *β Triangulum*.) See Star Map 3.

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

The star lies at a distance of over 1900 light years, with a luminosity of 5000 Suns. See Star Map 27.

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

This is a rapidly rotating star which results in the spectral lines becoming broad and less clear. It also has the dubious distinction of becoming the Pole Star in AD 7500. (See also Altair.) See Star Map 21.

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

An optical double system, lying at a distance of 144 light years, and with a luminosity of 46 Suns. See Star Map 23.

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[32] This value is in question. The data is awaiting reassessment.

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

The second brightest star in the sky. Its colour is often reported as orange or yellow, as it is usually seen lying low down in the sky, and is thus apt to be affected by the atmosphere. Its true colour is white. See Star Map 32.

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

This star is unremarkable except that its luminosity has been calculated to be that of 180,000 Suns! See Star Map 33.

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

An easily resolvable double star, α^1 is also a spectroscopic binary. The colours are a nice faint yellow and pale blue. See Star Map 20.

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

The star lies within *Melotte 20*, a loosely bound stellar association, also known as the *Perseus OB-3*, or *Alpha Persei Association*. About 75 stars with magnitudes down to 10 are contained within the group. All are stellar infants, only 50 million years old, lying 550 light years away. The metallic lines now increase through the F class, especially the H and K lines of ionised calcium. See Star Map 24.

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

An interesting and famous star, even though it is only the 49th-brightest star in the sky. It is a *Cepheid Variable* type II (the *W Virginis* class); it will be closest to the celestial pole in AD 2102, and is a binary star (the companion reported as being pale bluish). See Star Map 34.

β Vir	HD 102870	11^{h}50.7^m	+01° 46′	Feb–**Mar**–Apr
3.59m	3.40M	F8 V		Virgo

A close star at 34 light years, only 3 times as luminous as the Sun. See Star Map 11.

Sadal Suud	β Aqr	21^{h}31.6^m	–05° 34′	Jul–**Aug**–Sep
2.90m	–3.47M	G0 I		Aquarius

A giant star, and a close twin to *α Aqr*. It lies at a distance of 990 light years, and is 5000 times more luminous than the Sun. See Star Map 35.

Sadal Melik	α Aqr	22^{h}05.8^m	–00° 19′	Jul–**Aug**–Sep
2.95m	–3.88M	G2 I		Aquarius

Although it has the same spectral class and surface temperature of the Sun, *α Aqr* is a giant star, whereas the Sun is a main sequence star. (See also Sun, *Alpha Centauri A*.) See Star Map 35.

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

As stated later, a beautiful double star, with colours of ruddy orange and blue-green. The spectral class refers to the primary of α^2 *Her*, which is a spectroscopic double, and thus visually inseparable with any telescope. See Star Map 23.

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

A famous double; most observers report orange-yellowish colours, but some see the G7 star as greenish. See Star Map 19.

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 there is no star given the classification α, *β LMi* has the misfortune of not even being the brightest star in the constellation; that honour goes to *46 LMi*. See Star Map 36.

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

The star lies at a distance of 60 light years with a luminosity of 42 Suns. See Star Map 7.

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*, the star is a spectroscopic binary. In the K-class stars the metallic lines are now becoming more prominent than the hydrogen lines. See Star Map 4.

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 light years with a luminosity 7 times that of the Sun. See Star Maps 2 and 25.

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

This star lies at a distance of 740 light years with a luminosity 7450 times that of the Sun. The two faint stars in the same field of view have been mistakenly classified as companions, but analysis has now shown them to be stars in the line of sight. See Star Map 29.

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

A famous binary star. The colours are gold and blue, although some observers see orange and greenish blue. Nevertheless, the fainter companion is hot enough to truly show a blue colour. It is also a binary in its own right, but not observable in amateur instruments. See Star Map 5.

ζ^2 Sco	HD 152334	$16^h54.6^m$	-42° 22′	May–**Jun**–Jul
3.62m	0.3M	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. See Star Map 13.

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

The star lies at a distance of 385 light years and has a luminosity of 104 Suns. (See also *Aldebaran*.) See Star Map 12.

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

With this stellar class, the bands of titanium oxide are strengthening. This red giant star is suspected of being slightly variable, like so many other stars of the same type. In the field of view is the galaxy *NGC 404*. See Star Map 5.

Antares	α Sco	$16^h29.4^m$	-26° 26′	Apr–**May**–Jun
1.06$_v$m	-5.28M	M1 I		Scorpius

A giant star measured to be some 600 times the diameter of our Sun, it is a gloriously coloured star of fiery red, which contrasts nicely with its fainter green companion. (See also *Betelgeuse*.) See Star Map 13.

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

Marking the north-western corner of the Square of Pegasus, this is a red irregular variable star. It is noted for having been one of the first stars to have its diameter measured by the technique of interferometry, at 0.021″. Being variable, its size oscillates, to a maximum diameter of 160 Suns. See Star Map 29.

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

The yellowish star in an easily resolved double star system. The colour contrasts nicely with its blue companion. See Star Map 24.

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

The top star of the *Southern Cross*, this is a giant star. γ^A and γ^B do not form a true binary as they are apparently moving in different directions. See Star Map 10.

Ras Algethi	α^1 Her	17^{h}14.6^m	+14° 23′	May–**Jun**–Jul
3.03$_v$m	–2.32M	M5 II		Hercules

A fine double-star system. The M5 semi-regular star is an orange supergiant, in contrast to its companion, a blue-green giant. However, it must be pointed out here that it can be resolved only with a telescope and not binoculars, as the two stars are less than 5″ apart. The changes in brightness are attributed to actual physical changes to the star, as it increases and then decreases in diameter. See Star Map 23.

Mira	o Cet	02^{h}19.3^m	02° 59′	Sep–**Oct**–Nov
2.00$_v$m	–3.54M	M5		Cetus

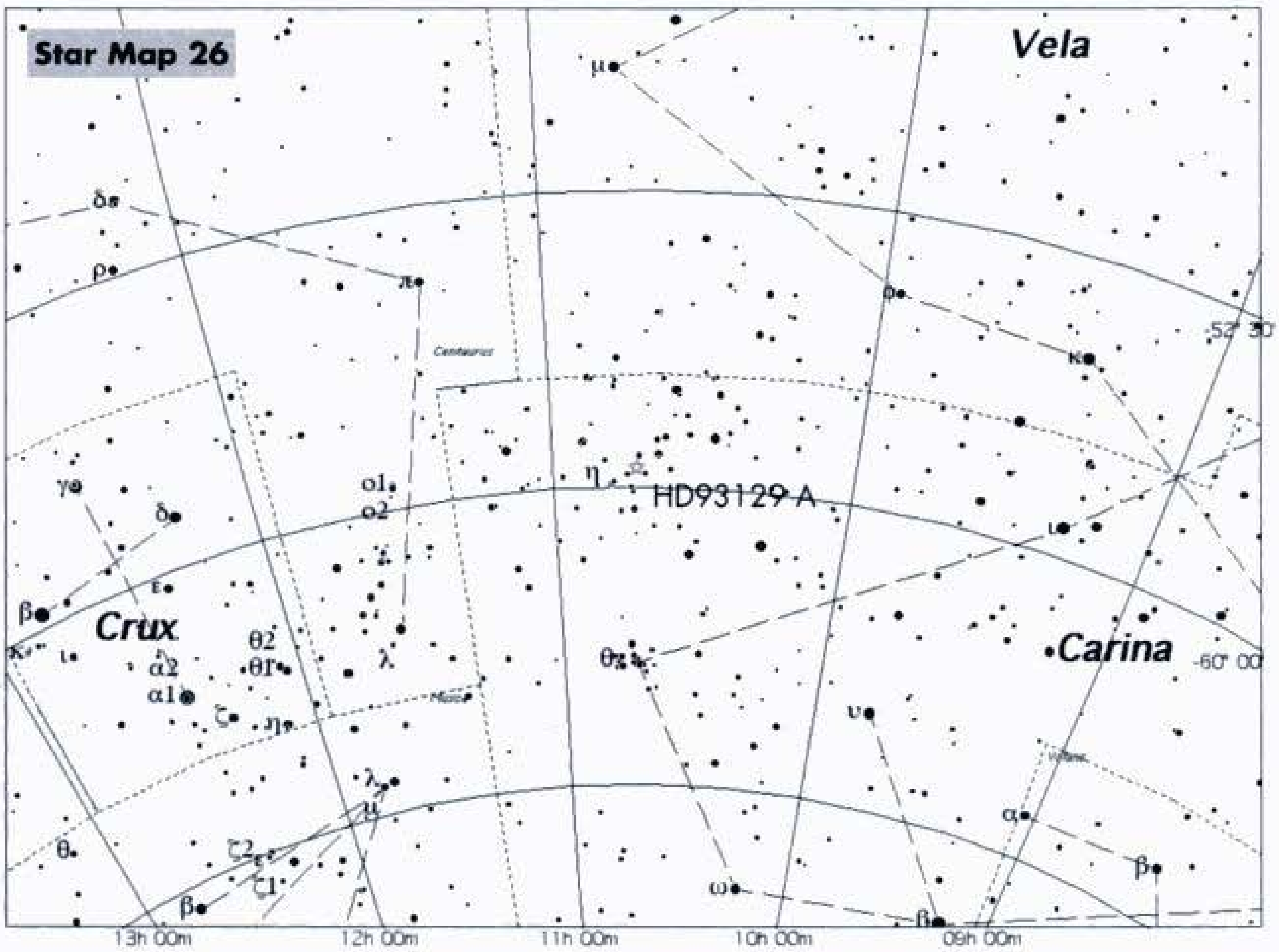
See the section on long period variables for full details on Mira. See Star Map 7.

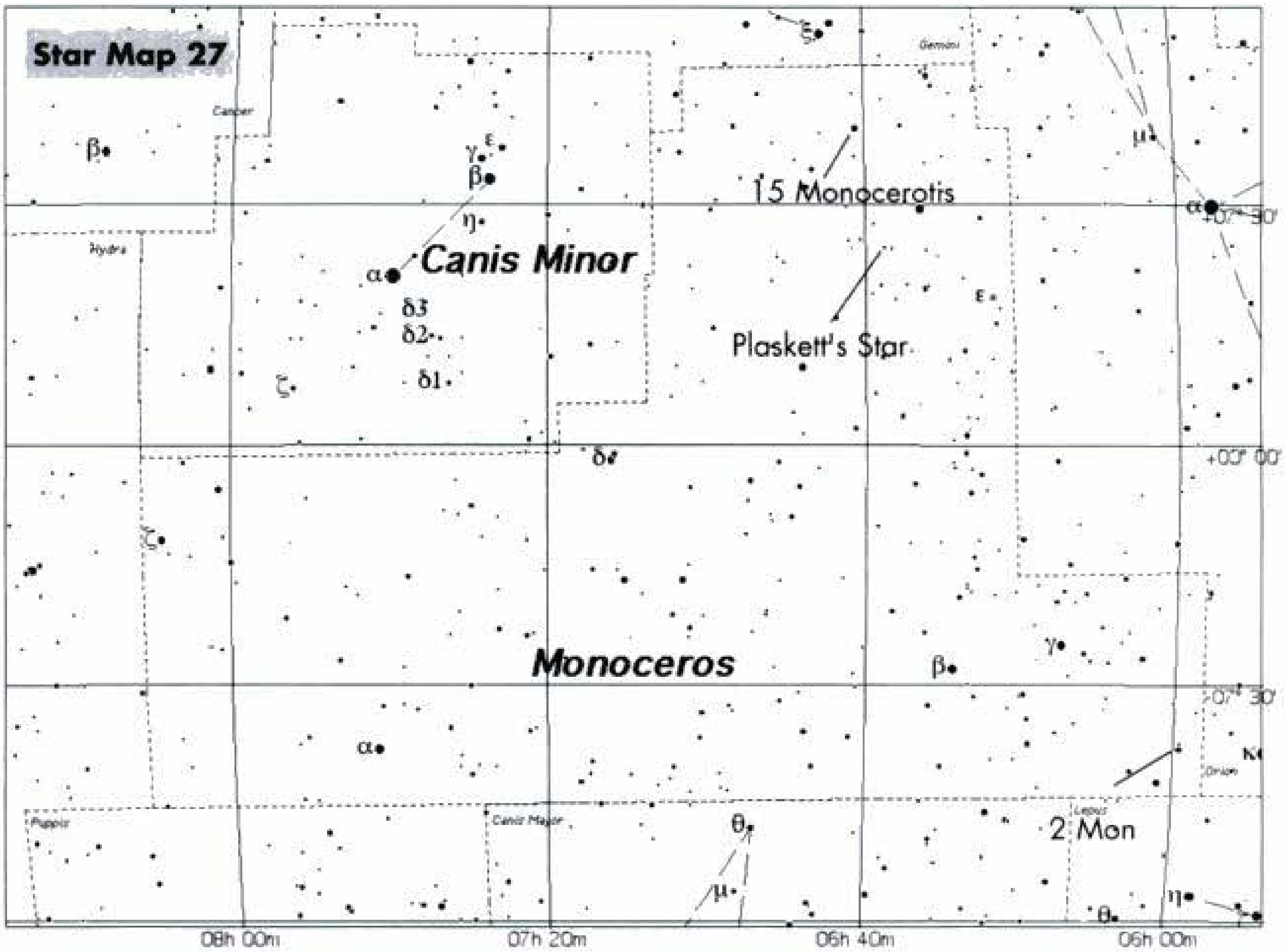
θ Apodis	HD 122250	14^{h}05.3^m	–76° 48′	Mar–**Apr**–May
5.69$_v$m	–0.67M	M6.5 III		Apus

This is a semi-regular variable with a period of 119 days and a range of 5th to nearly 8th magnitude. The titanium bands are now at their strongest. See Star Map 37.

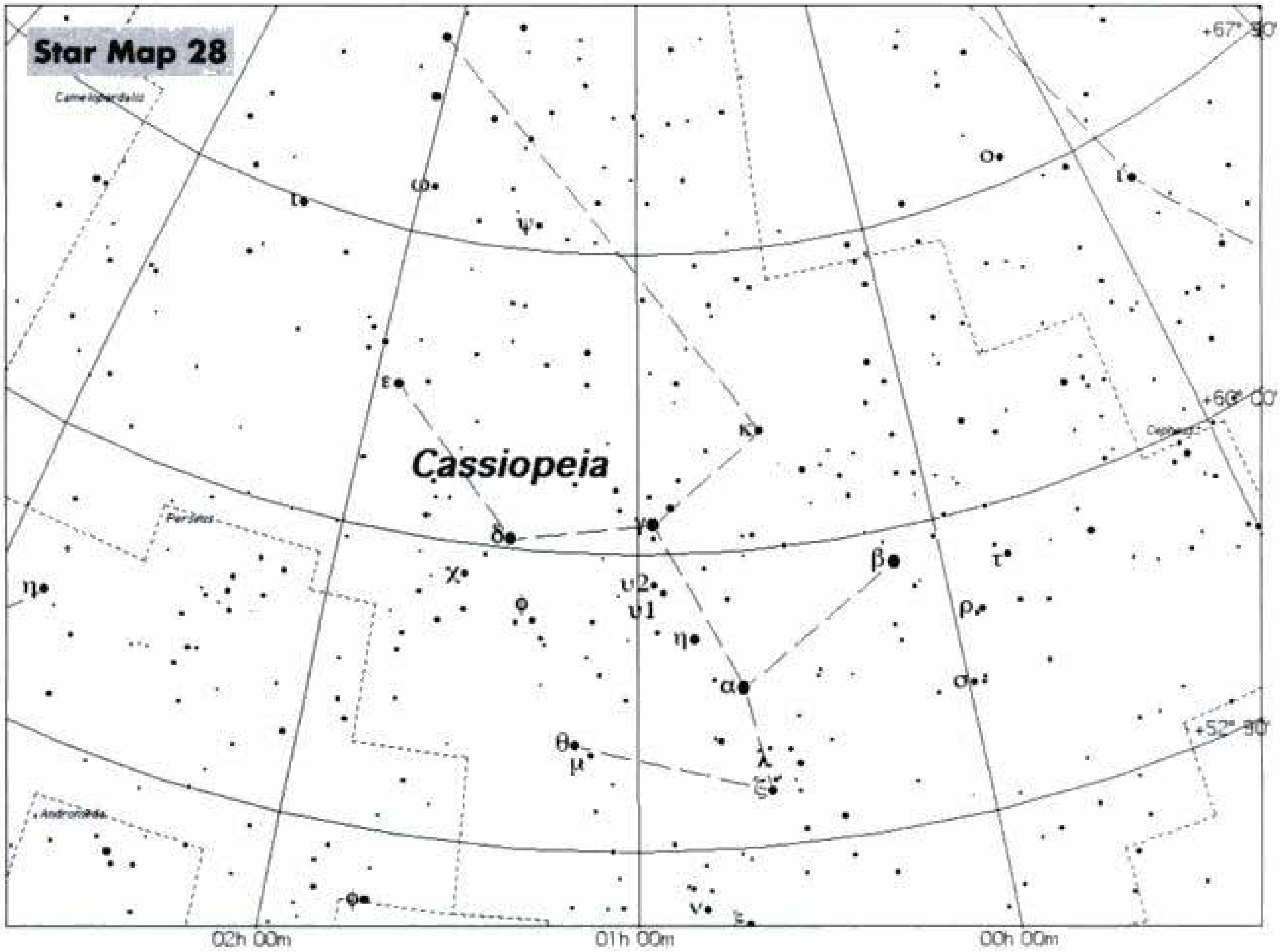
Mira at minimum	o Cet	02^{h}19.3^m	–02° 59′	Sep–**Oct**–Nov
10$_v$m	–0.5M	M9		Cetus

See the section on long period variables for full details on Mira. See Star Map 7.

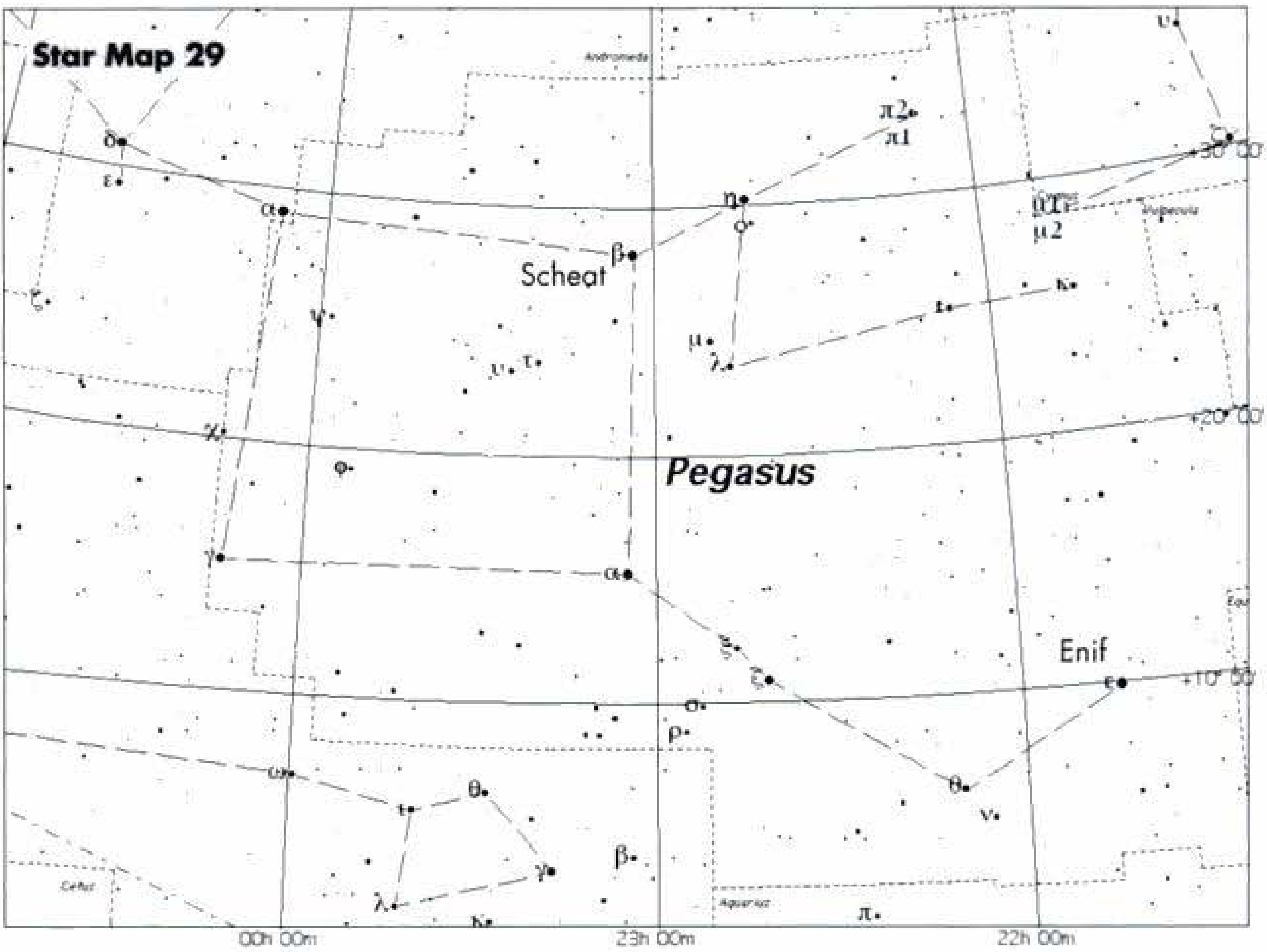




Star Map 27



Star Map 28


Star Map 29
Andromeda
Pegasus
Scheat
Enif
Aquarius
Cetus
Cygnus
Vulpecula
Equ
+30° 00'
+20° 00'
+10° 00'
00h 00m
23h 00m
22h 00m
α
β
γ
δ
ε
ζ
η
θ
ι
κ
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μ
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π
π1
π2
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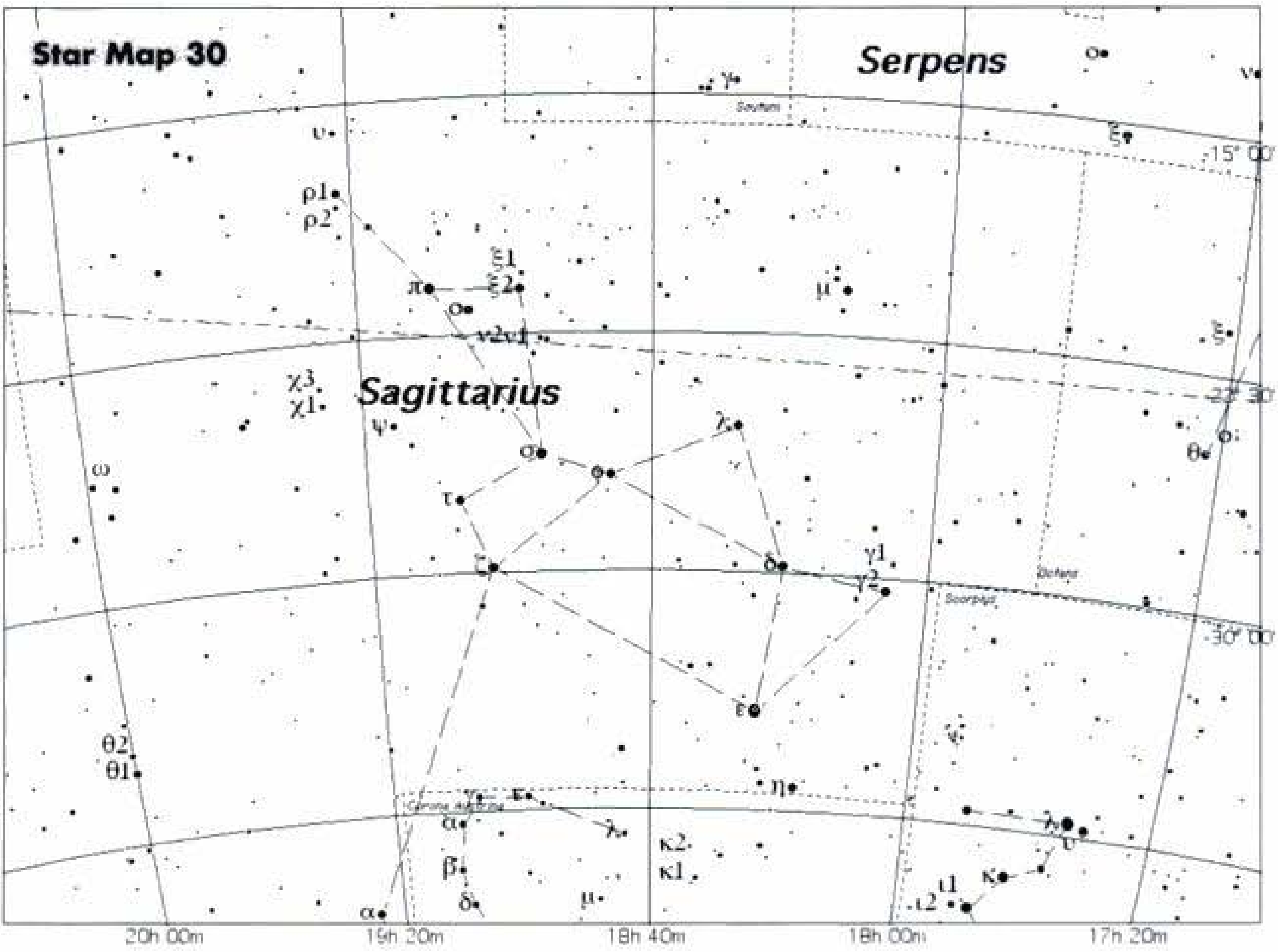
ω
μ1
μ2


Star Map 30
Serpens
Sagittarius
Scutum
Ophiuchus
Scorpius
Corona Australis
-15° 00'
-22° 30'
-30° 00'
20h 00m
19h 20m
18h 40m
18h 00m
17h 20m
α
β
γ
γ1
γ2
δ
ε
ζ
η
θ
θ1
θ2
ι1
ι2
κ
κ1
κ2
λ
μ
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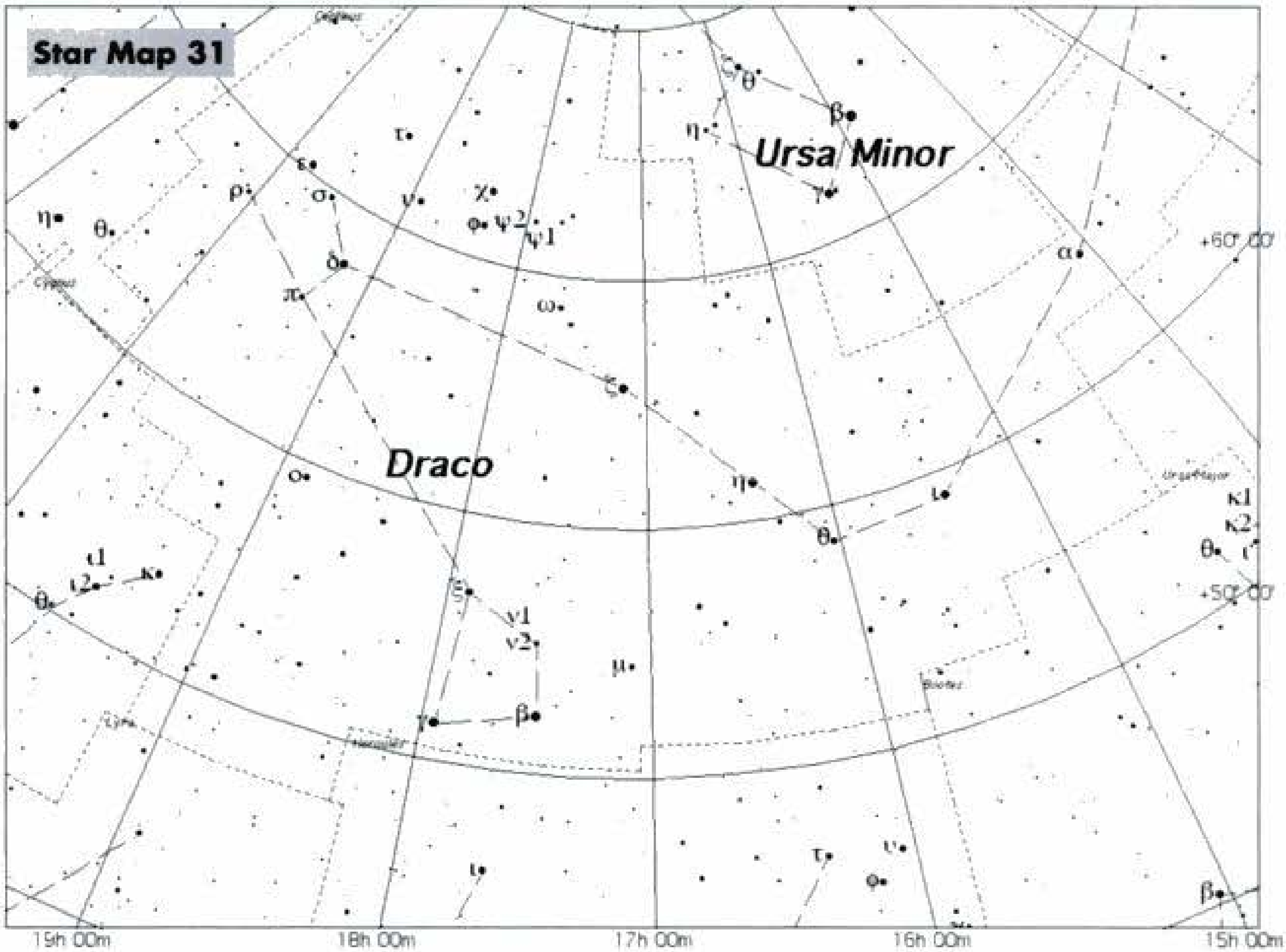
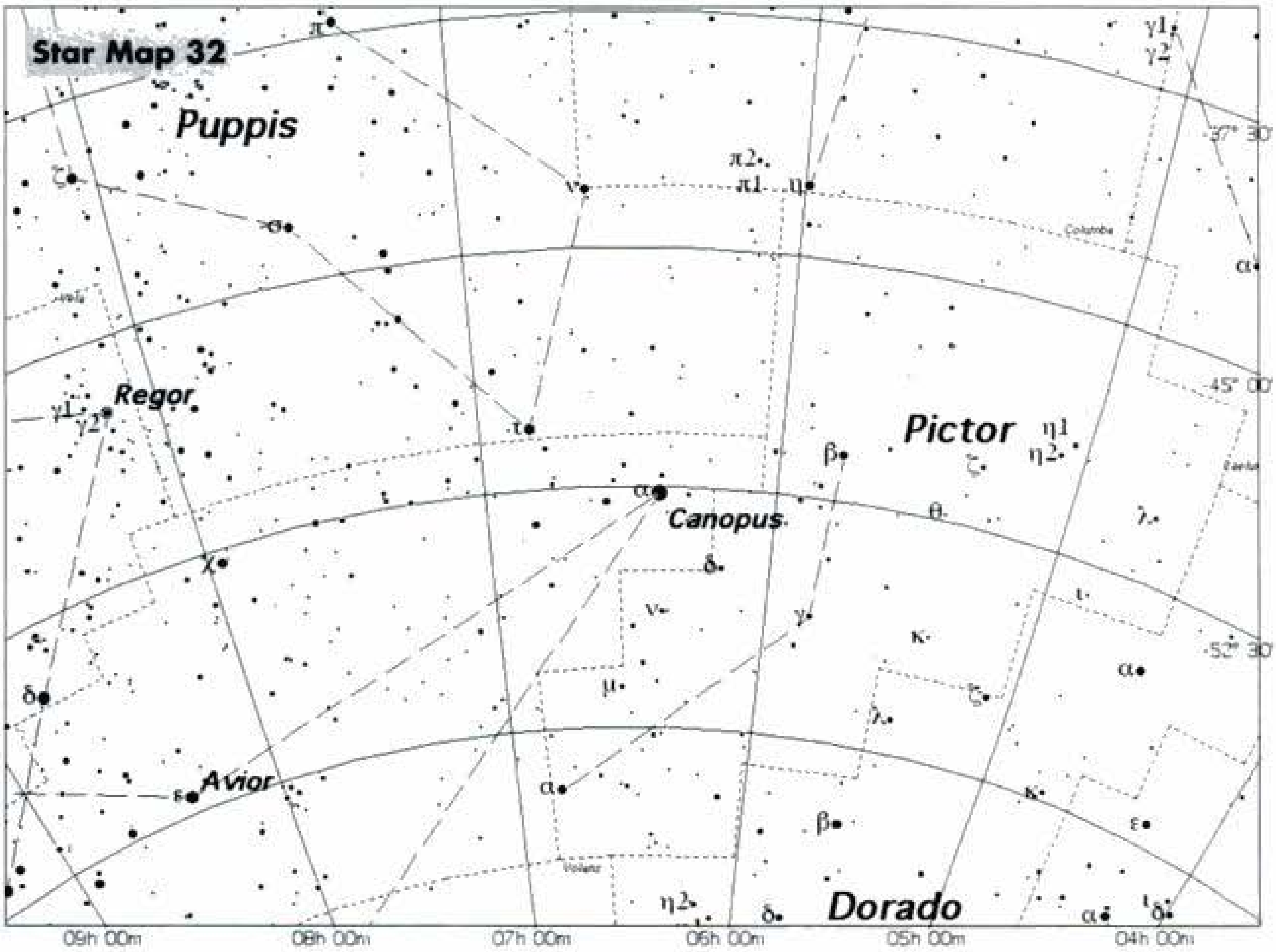
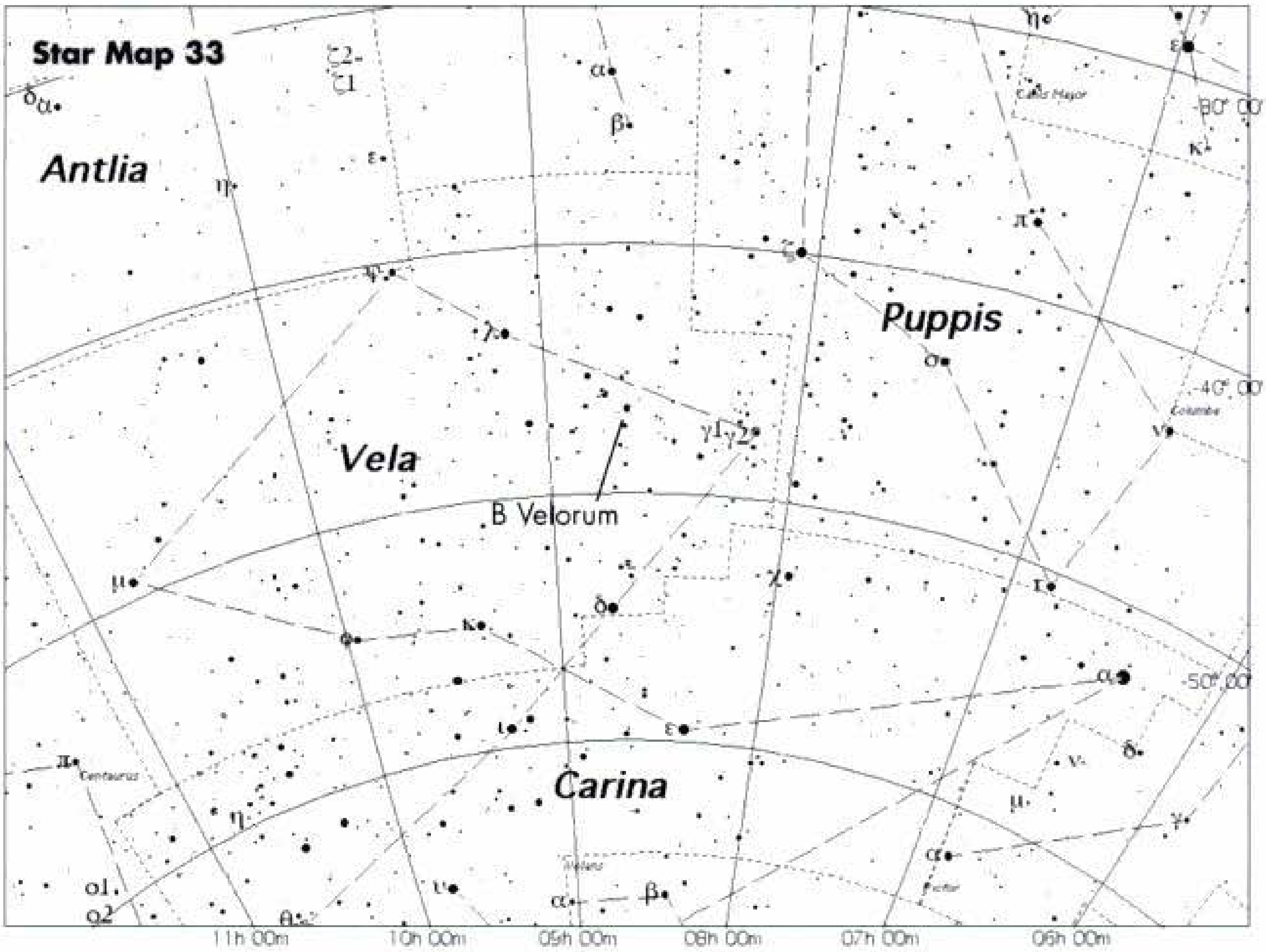


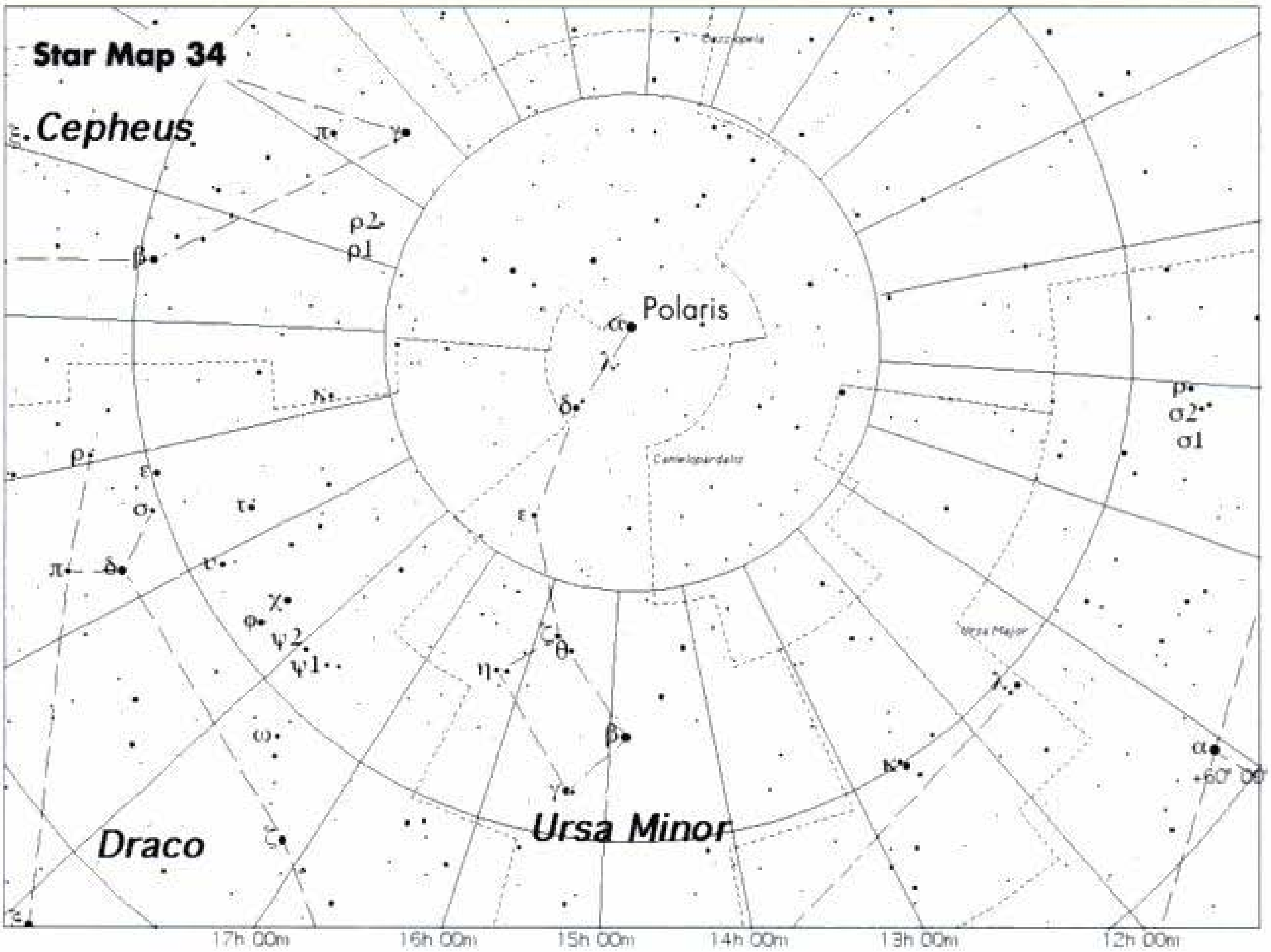
Star Map 31



Star Map 32

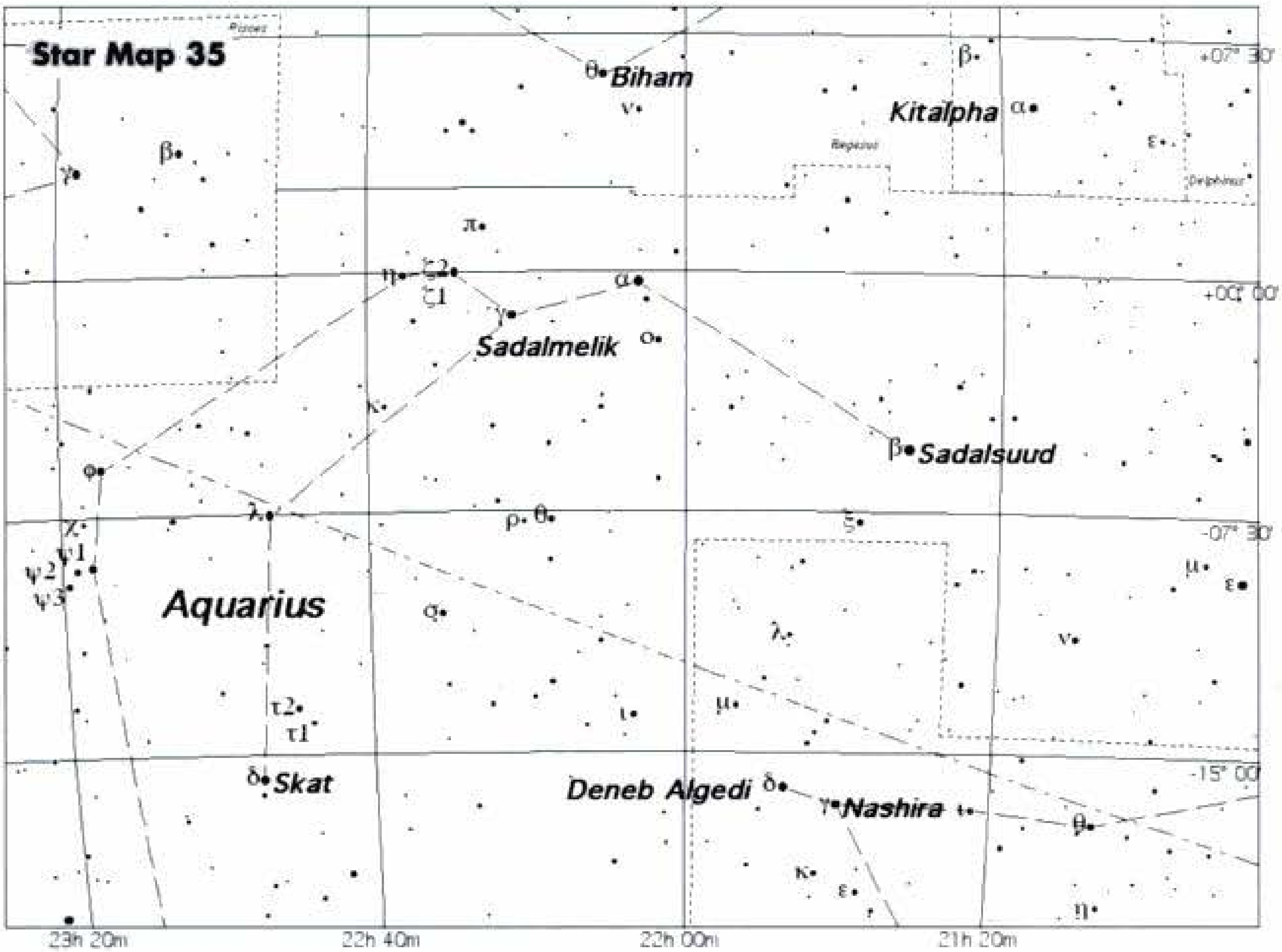


Star Map 33

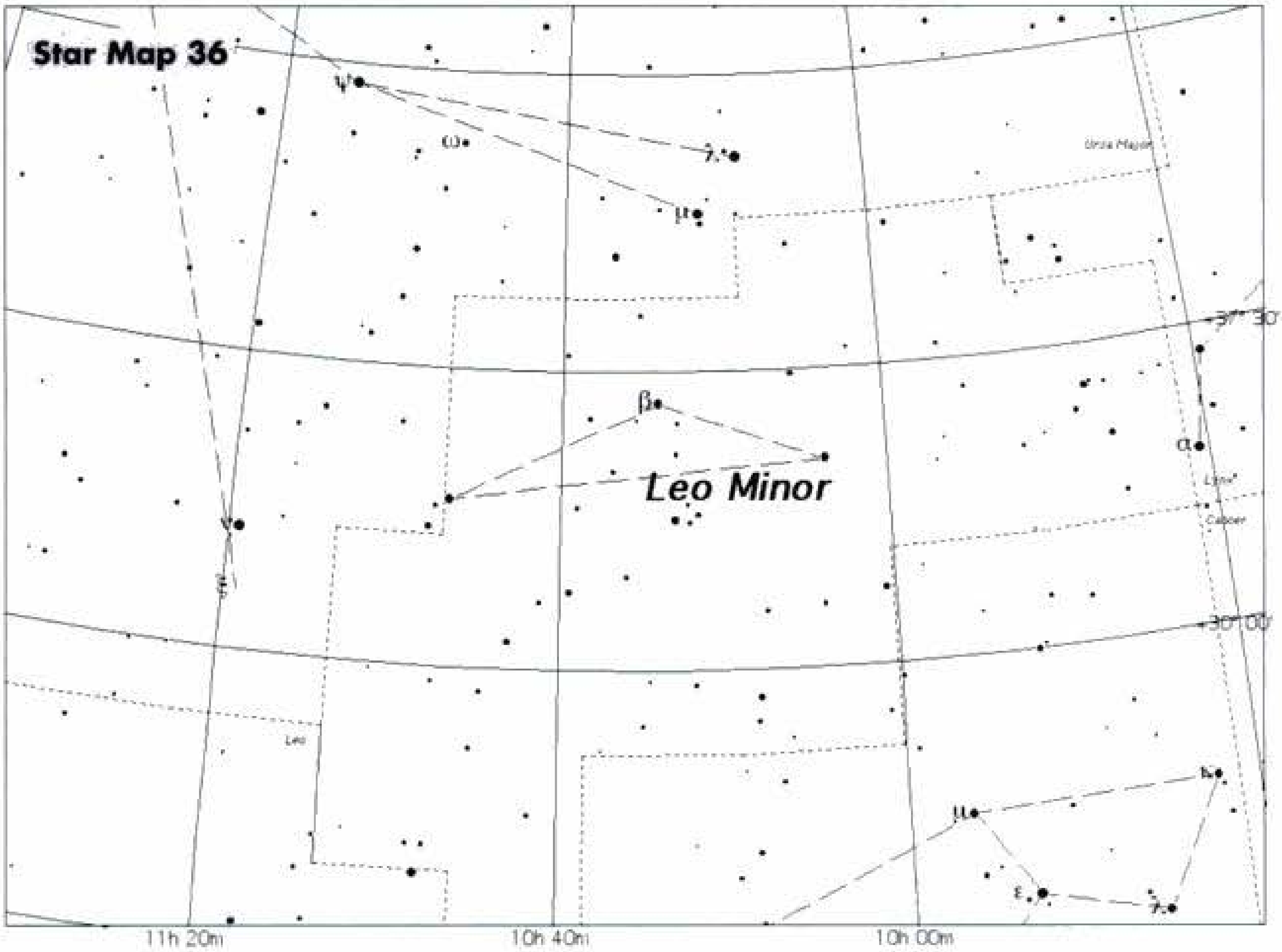


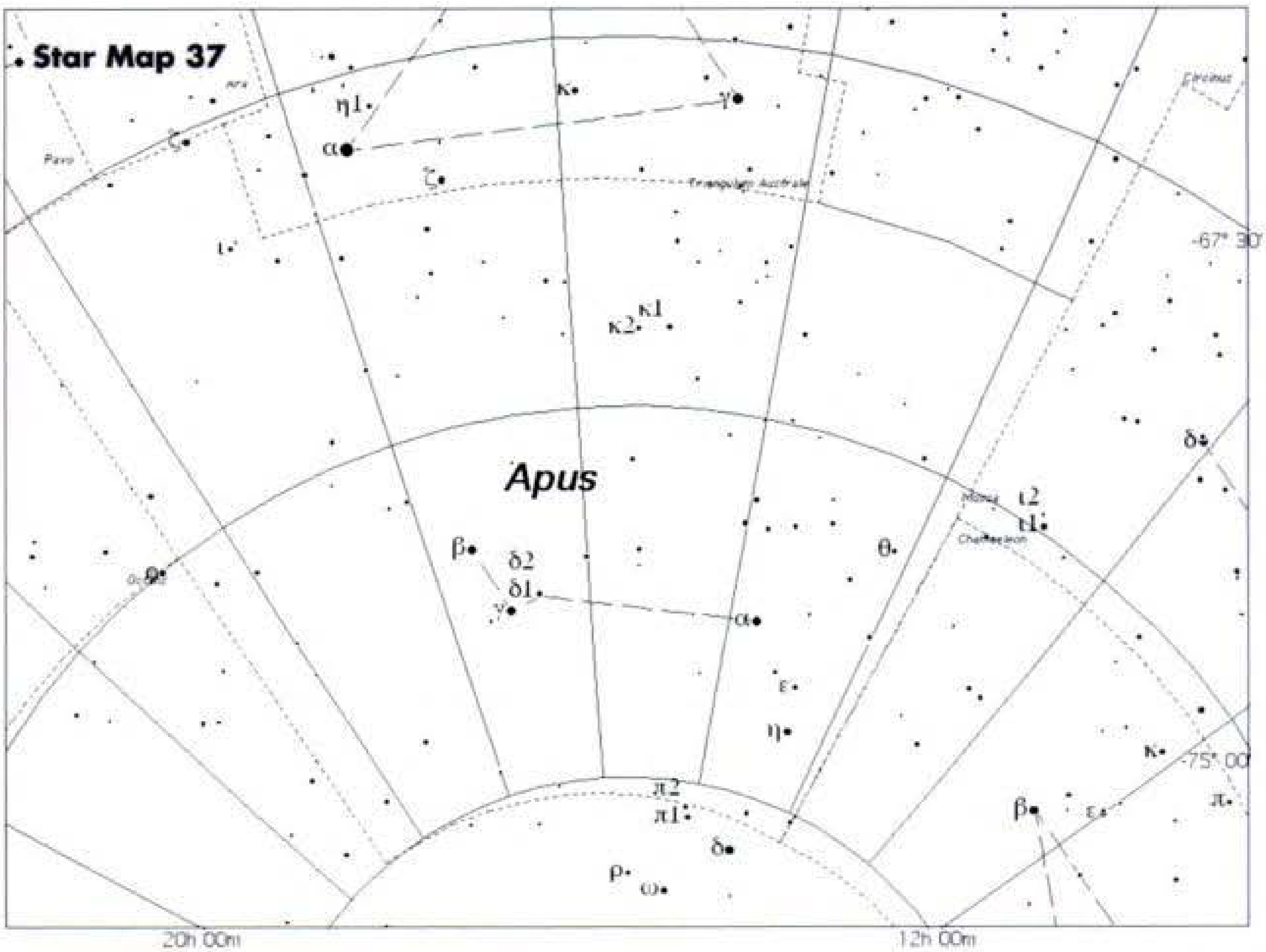
Star Map 34

Star Map 35



Star Map 36




Star Map 37

1.12 The Hertzsprung–Russell Diagram

We have covered several topics so far, in our description of the basic characteristics of star such as its mass, radius, spectral type and temperature. We can now put all these parameters together and get a picture of how a star evolves. It is often very useful in many sciences to represent the characteristic, or data, about a group of objects, in the form of a graph. We are probably familiar with graphs, having seen ones that display height as a function of age, or temperature as a function of the time of year. So a similar approach was pursued for the characteristics of stars. The graph that is used is called The *Hertzsprung–Russell Diagram*. It is, without a doubt, one of the most important and useful diagrams in the whole of astronomy.

In 1911, the Danish astronomer Ejnar Hertzsprung plotted the absolute magnitude of stars (which is a measure of their luminosities) against their colours (which is a measure of the temperature). Then, in 1913, the American astronomer, Henry Norris Russell independently plotted spectral types (which is another way to measure temperature) against the absolute magnitude. They both realised that certain previously unsuspected patterns began to emerge, and furthermore, an understanding of these patterns is of *crucial* importance to the study of stars. In recognition of the pioneering work that these two astronomers did, the graph is now known as the *Hertzsprung-Russell*, 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 Hertszprung 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, and is measured in units of the 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 tick mark.
- 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 the Sun's spectral type of G2, and a luminosity of $L_\odot = 1$.

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

1.13 The H-R Diagram and a Star's Radius

The H-R diagram can also provide important direct information about the radius of stars, because a star's luminosity depends both on its surface temperature and its surface area, or radius. You will recall that the surface temperature determines the amount of power emitted by

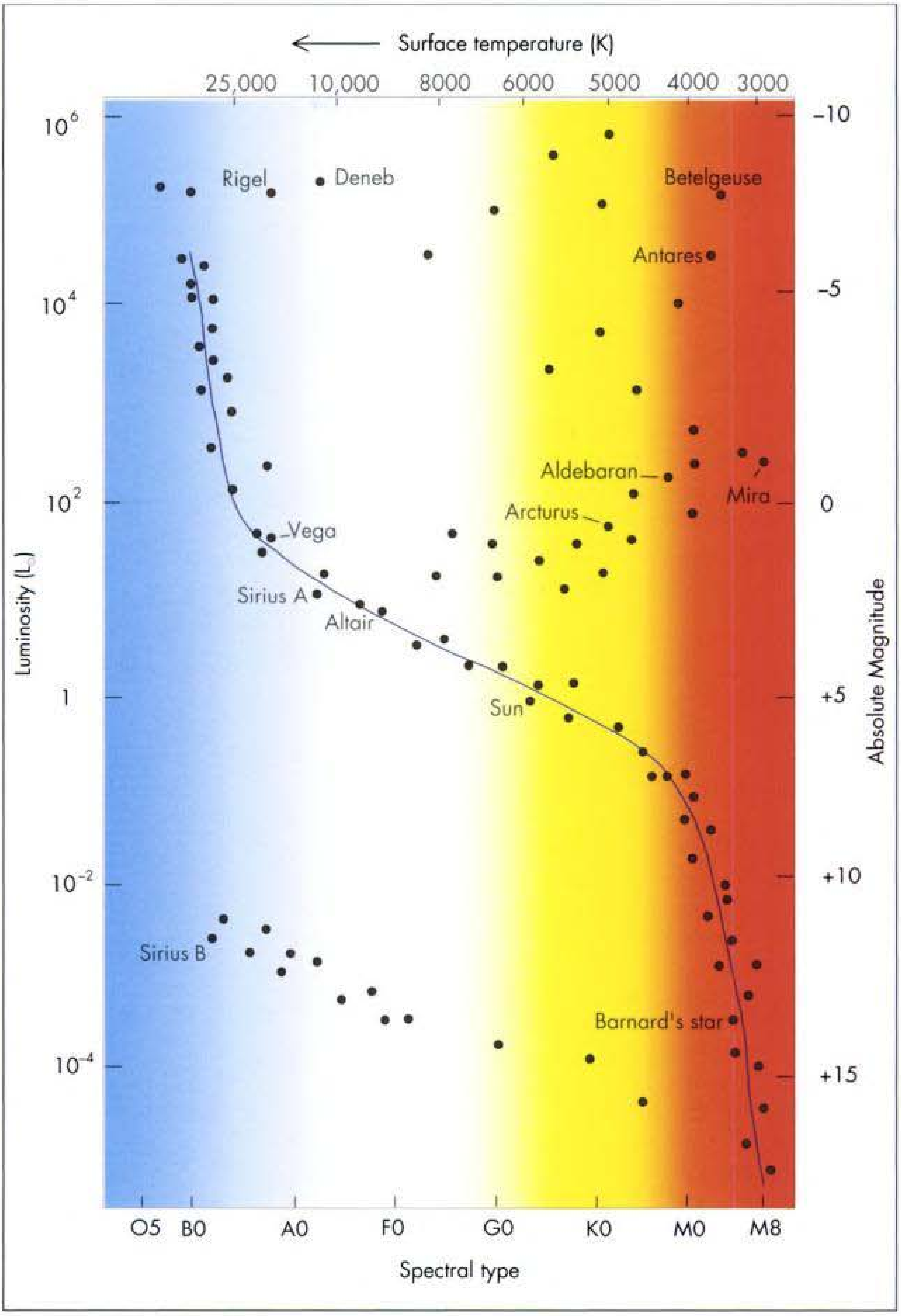


Figure 1.4. The Hertzsprung–Russell Diagram. Luminosity is plotted against spectral type for a selection of stars. Shown are some of the brighter stars. Each dot represents a star whose spectral type and luminosity has been determined. Note how the data are grouped in just a few regions indicating a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

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, one can be more luminous than the other by having a larger size. 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-hand corner. This is shown on 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 immediately implies that the surface temperature (or spectral type) and luminosities are related! The several groupings can be described thus:

- The band which stretches diagonally across the H–R diagram is called the *Main Sequence*, and represents about 90% of all the stars in the night sky. It extends from the hot and luminous blue stars in the upper left corner to the cool dim red stars in the bottom right. Any star that resides 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 will 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.
- The stars in the upper right are called *giants*. These stars are both cool and luminous. Recall that in an earlier section, we discussed the *Stefan–Boltzmann* law which told us that a cool stars will radiate much less energy per surface area, than a hot star. So for these stars to be as luminous as they appear, they must be immense, and are called supergiants. They can be anything 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. For the most part, most giant stars are about 100 to 1000 times more luminous than the Sun and can have temperatures of about 3000 to 6000 K. Many of the cooler members of this class are reddish in colour 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*.
- In the upper extreme right corner are a few stars that are even bigger than the giants. These are the *supergiants*, and have radii up to 1000 R. Giants and supergiants make up about 1% of all the stars in the night sky. *Antares* in *Scorpius* and *Betelgeuse* in *Orion* are two fine examples of supergiant stars.

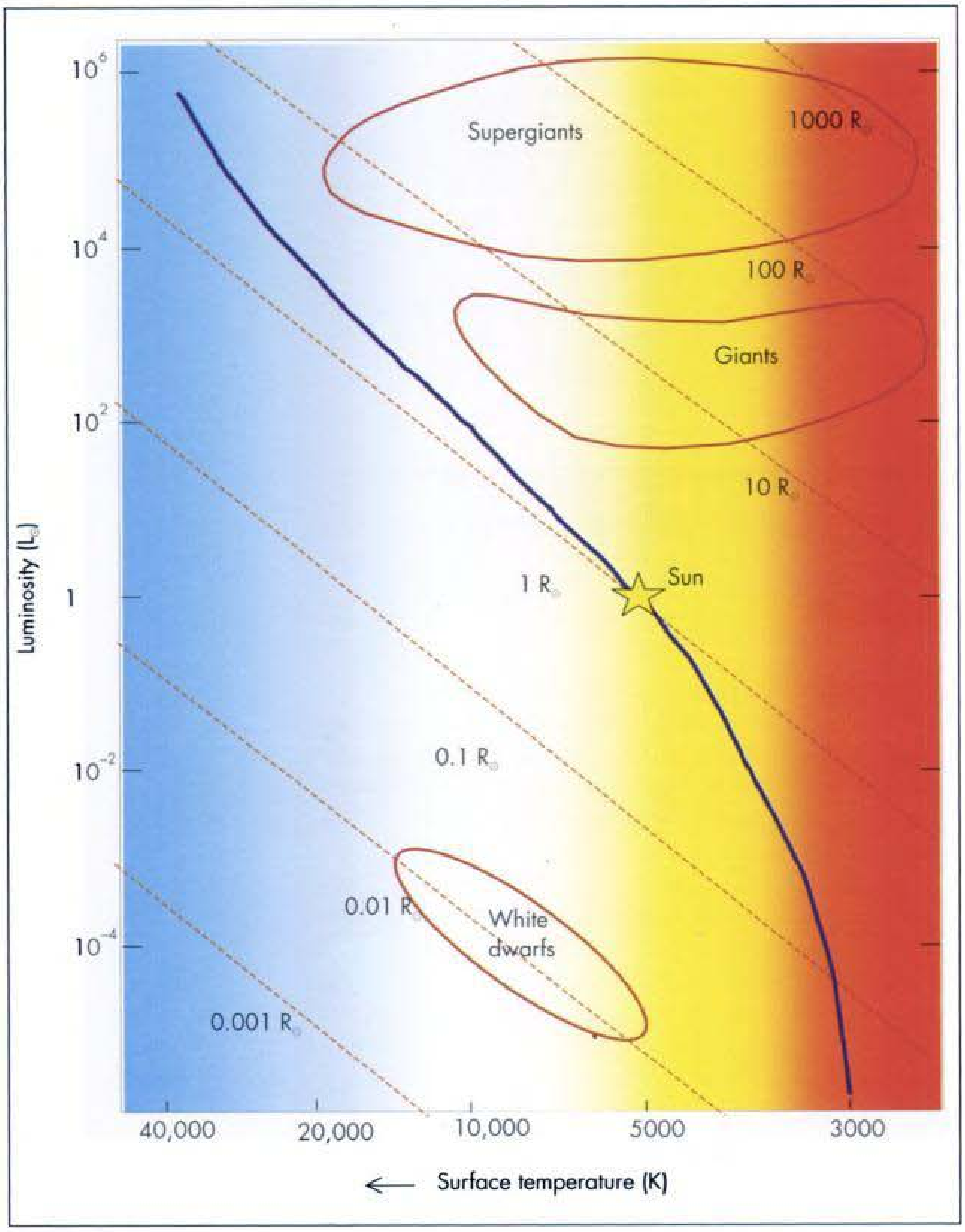


Figure 1.5. Size of Stars on a H–R Diagram. Stellar luminosity against surface temperature. The dashed diagonal lines indicate stars of different radius. At a given radius, the surface temperature increases (moving from right to left), and luminosity increases. Notice the main sequence and the Sun's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

Although nuclear fusion is taking place in these stars it is significantly different in both character and position, to the reactions taking place in the stars on the main sequence.

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

1.14 The H–R Diagram and a Star's Luminosity

The temperature of a star determines which spectral lines are most prominent in its spectrum. So classifying a star by its spectral type is essentially the same as by its temperature. But a quick glance at an H–R diagram will show that stars can have similar temperatures, but in fact very different luminosities.

Consider this example: a white dwarf star could have a temperature of 5700 K, but so could a main-sequence star, a giant, or a supergiant. It all depends on its luminosity. Therefore, by examining a star's spectral lines, one can determine to which category the star belongs. A general rule of thumb (for stars of spectral type B through F), is, the more luminous the star, the narrower the lines of hydrogen. The theory behind the phenomena is quite difficult, but suffice to say that these measurable differences in spectra are due to differences in stars' atmospheres, where the absorption lines are produced. The density and pressure of the hot gas in the atmosphere affect the lines, hydrogen in particular. If the pressure and density is high, the hydrogen atoms collide more frequently, and they interact with other atoms in the gas. The collisions cause the energy levels in the hydrogen atoms to shift with the result that the hydrogen spectral lines are broadened.

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

We saw in an earlier section describing stellar classification, that we can ascribe to a star a luminosity class. We can now use this to describe the region of the H–R diagram where a star of a particular luminosity will fall. This is shown on Figure 1.6.

Knowing both a star's spectral type and luminosity allows an astronomer to immediately know where on the main sequence it will lie. For instance, a G2 V star is a main-sequence star of about luminosity of 1 $L_\odot$, and a surface temperature of about 5700 K. In a similar vein, *Aldebaran* is a K5 III star which tell us immediately that it is a red giant star which has a luminosity of about 375 $L_\odot$ with an accompanying temperature of about 4000 K.

1.15 The H–R Diagram and a Star's Mass

The most common trait of main-sequence stars is that, just like our Sun, they undergo nuclear fusion in their cores to convert hydrogen to helium, and because most star spend most of their lives doing this, it naturally follows that the majority of stars spend their time somewhere on the main sequence. But even a cursory glance at the H–R diagrams will tell you that an enormous range of luminosities and temperatures are covered.

The question that must arise is: why such a large range?

Astronomers have determined the masses of stars by using binary star systems, and they found out that a star's mass increases as we move upward along the main sequence, Figure 1.7. The O-type stars at the upper part of the diagram, that is, hot and luminous stars, can have masses as high as 100 times that of the Sun – 100$M_\odot$. At the other end of the main sequence,

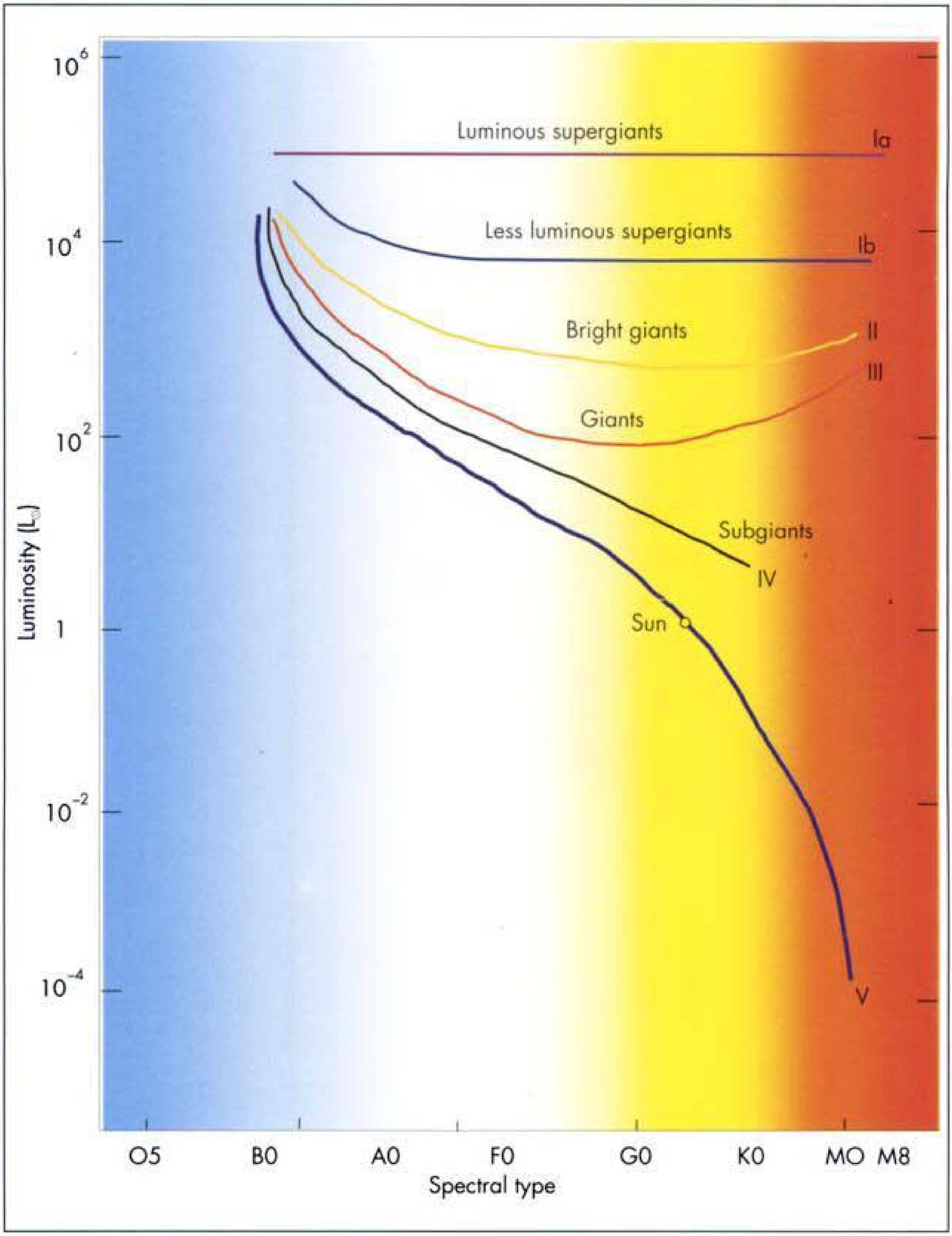


Figure 1.6. Luminosity Classes. Dividing the H–R diagram into luminosity classes allows distinctions to be made between giant and supergiant stars.

the cool and faint stars have masses as low as 0.1 times that of the Sun – 0.1 $M_\odot$.[33] This orderly distribution of stellar masses along the main sequence tells us it is a star's *mass*, that is the most important attribute of a hydrogen-burning star. The mass has a direct bearing

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[33] Over the past several years, astronomers have discovered that the low mass, faint M-type dwarf stars are far more numerous than other types. We have just not seen them!

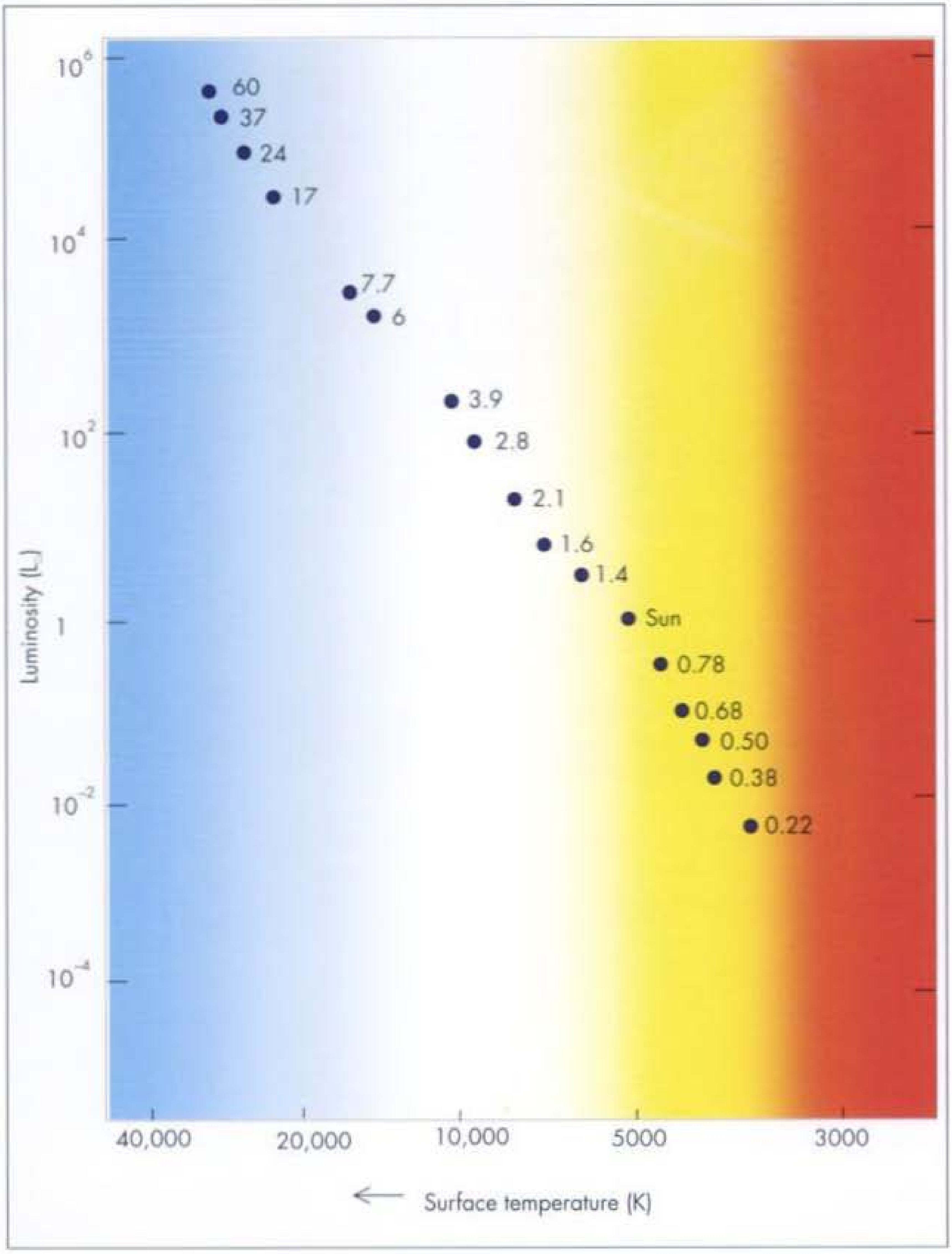

Figure 1.7. Mass and the Main Sequence. Each filled-in circle is a main-sequence star. The number is the mass of the star in solar masses ($M_\odot$). As you move up the main sequence from lower right to upper left, the mass, luminosity and temperature increase.

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 $10M_\odot$ star on the main sequence will be more than 1000 times more luminous than the Sun; i.e., 1000 $L_\odot$.

However, this mass–surface temperature relationship is just a little more subtle than the preceding paragraph would indicate. Generally, very luminous stars must be either very large or have a very high temperature, or even a combination of both. Those stars on the top left of the main sequence are some thousands of times more luminous than the Sun, but are only around 10 times larger than the Sun. Therefore, their surface temperatures must be significantly hotter than the Sun's in order to account for such high luminosities. Bearing this relationship in mind, we can now say that those main-sequence stars that are more massive than the Sun must have correspondingly higher temperatures, whilst those with lower masses must have lower surface temperatures. Thus, you can now see 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 all of astronomy. We will use it throughout the rest of the book, as it provide a means for us to determine and follow many of the paths that stars take during their lives from starbirth all the way to star death.

Now that we have covered the basic tools of stellar astronomy, let us being our journey into stellar evolution by looking at how a star is born.

Chapter 2

Beginnings – Star Birth

2.1 Introduction

The life of a star, from birth to death, may take several billion years - in some cases, tens of billions - so how can we say with any certainty that we know how stars evolve? After all, human beings have only been observing the universe for a few thousand years! Well, if you think about it for a while, it isn't difficult to work out. Take for instance a forest - full of oak trees of all sizes, saplings, young trees, old large trees, dead trees fallen over, and so on. A biologist cannot possibly live long enough to watch a tree grow from an acorn until it falls over and dies! But what he or she can do is to study each aspect of the tree's growth, from an acorn via a sapling to a full grown tree, and then put these all together to get a fair idea of how it develops and grows. An astronomer can take a similar approach. By observing different stars at different times in their evolution (and there is a rather lot of them to choose from), we can get a fair picture of how a star is born, lives, and dies.

The first thing we should look at is how stars are born.

2.2 The Interstellar Medium

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 doesn't 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 result 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).

As an astronomer, you will have already observed the interstellar medium, but perhaps without realizing it. As mentioned above, the ISM, as it is called, is composed of gas, mainly hydrogen,[1] and dust, so 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.*

2.3 Nebulae

Nebulae are actually very disparate in nature, even though many of them have a rather similar appearance. They are associated with the areas of star formation, 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 nebula: emission; reflecting; and dark, that are associated with the birth of a star. In addition, we are fortunate, from an observer's point of view, because these objects, associated with star birth, abound in the night sky and some of them are very spectacular objects!

2.3.1 Emission Nebulae

These clouds of gas are associated with very hot O- and B-type stars which produce immense amounts of ultraviolet radiation. They can have masses typically of about 100 to 10,000 solar masses. However, this huge mass is usually spread of a correspondingly large area

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[1] Recall that in fact the ISM is made up of about 74% hydrogen (by mass), 25% helium and the rest is metals.

possibly a few light years across, so that the actual density of the gas is extremely low, maybe only a few thousand hydrogen atoms per cubic centimetre. 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 (usually) hydrogen gas to undergo a process called *fluorescence*, and it is this which is responsible for the glow observed from the clouds of gas.

The energy provided by ultraviolet radiation from the young and hot stars ionises 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.[2] The electron, having gained extra energy, can leave the energy level it is in, and in some instances actually break free from the atom. This process when an atom loses an electron is called *ionisation*.

If electrons are broken free from their parent atoms, the hydrogen cloud will contain some hydrogen atoms without electrons – ionised hydrogen (also known as protons), and a corresponding number of free electrons. Eventually[3] the electrons recombine with the atoms, but an electron can't just settle down back to the state it originally had 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, you remember), an electron moving down from the third energy level to the second emits a photon of light at 656.3 nanometres (see Section 1.10 in Chapter 1).

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 colour and is

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[2] 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, electrons with less energy are closer to the nucleus. Not all orbits are allowed by quantum mechanics: in order to move up to higher energy levels, electrons need a very specific amount energy. Too much or too little and an electron will not move.

[3] The time spent before recombining is very short, millionths of seconds, but also depends on how much radiation is present and the density of the gas cloud.

responsible for all the pink and red glowing gas clouds seen in photographs of emission nebulae.[4]

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 ionise a gas, with electrons subsequently cascading down the energy levels of an atom, that is responsible for nearly all the light we see from emission nebulae. If a gas cloud is particularly dense, the oxygen gas in it may be ionised and the resulting recombination of the electron and atom produces the doubly ionised lines, at wavelengths of 495.9 nm and 500.7 nm.[5]

Emission nebulae are sometimes called *HII regions*, pronounced "aitch two". This astrophysical term refers to hydrogen that has lost one electron by ionisation. The term HI, or "aitch one", refers to hydrogen which is unaffected by any radiation, that is, neutral hydrogen. The *doubly ionised 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 ionisation.[6]

Physically, 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 ionisation. In the case where there is a significant amount of radiation, coupled with a small and low-density cloud, then most probably all of the cloud will be ionised, and thus the resulting HII region will be of an irregular shape - just the shape of the cloud itself. However, if the cloud of gas is large and dense, then the radiation can penetrate only a certain distance before it is used up - that is, there is only a fixed amount of radiation available for ionisation. In

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[4] Unfortunately, the red glow is usually too weak to be seen at the eyepiece.

[5] These lines are a rich blue-green colour, and under good seeing and with clean optics this colour can be glimpsed in the *Orion Nebula*, M42.

[6] In some astrophysical contexts, such as in the centre of quasars, conditions exist which can give rise to terms such as Fe23. The amount of radiation is so phenomenal that the atom of iron (Fe) has been ionised to such an extent that it has lost 22 of its electrons!

this case, the HII region will be a sphere,[7] 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*. Those that exhibit a circular shape, and thus are in fact spherical, are M20, the *Trifid Nebula*, and NGC 2237, the *Rosette Nebula*, to name only two.

After a suitable period of time, usually several million years, the group of young O- and B-type stars located at the centre of the nebula will be producing so much radiation that they can in affect 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 *M78*, which show the star cluster residing in a circular clear area within the larger emission nebula.

Let's 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 to 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 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 arc seconds and is indicated by the symbol ⊕. Where a value of ⊕ is given as $x \leftrightarrows y$, then the object is approximately x arc seconds long by y arc seconds wide. Simple finder charts are shown at the end of the list of objects.

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[7] This is often called the Stromgren sphere, named after the astronomer Bengt Stromgren, who did some pioneering work on HII regions.

Gum 4	NGC 2359	$07^h\ 18.6^m$	−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. Using an OIII filter will greatly improve the appearance of the emission nebula, showing the delicate filamentary nature. See Star Map 38.

Messier 20	NGC 6514	$18^h\ 02.3^m$	−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. The nebula is easy to see, along with its famous three dark lanes which give it its name, radiating 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 thus harder to observe. See Star Map 39.

Messier 8	NGC 6523	$18^h\ 03.8^m$	−24° 23′	May–**Jun**–Jul
❋ 1–5	⊕ 45 ⇆ 30″			Sagittarius

Also known as the *Lagoon Nebula.* 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. Telescopes of aperture 30 cm will show much 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 light years. See Star Map 39.

Messier 17	NGC 6618	$18^h\ 20.8^m$	−16° 11′	May–**Jun**–Jul
❋1–5	⊕ 20 ⇆ 16″			Sagittarius

Also known as the *Swan* or *Omega Nebula.* This is a magnificent object in binoculars, and is perhaps a rival to the Orion Nebula, M42, for the summer sky. Not often observed by amateurs, which is a pity as it offers much. 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 needs an OIII filter for the regions to be fully appreciated. See Star Map 39.

Messier 16	IC 4703	$18^h\ 18.6^m$	−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 is usual, the use of a filter enhances the 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, they can be spotted by an astute observer under near-perfect conditions. See Star Map 39.

Caldwell 27	NGC 6888	$20^h\,12.0^m$	+38° 21′	Jun–**Jul**–Aug
❋ 1–5	⊕ 20 ⇆ 10″			Cygnus

Also known as the *Crescent Nebula*. This difficult nebula is included 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 south-eastern side. The nebula is known as a *Stellar Wind Bubble*, and is the result of a fast-moving stellar wind from a *Wolf-Rayet* star which is sweeping up all the material that it had previously ejected during its red giant stage. See Star Map 38.

-	IC 5067–70	$20^h\,50.8^m$	+44° 21′	Jul–**Aug**–Sep
❋ 1–5	⊕ 60 ⇆ 50″			Cygnus

Also known as the *Pelican Nebula*. This nebula, close to the *North America Nebula* (see the entry below), has been reported to be visible to the naked eye. It is easily glimpsed in binoculars as a triangular faint hazy patch of light. It can be seen best with averted vision, and the use of light filters. See Star Map 38.

Caldwell 20	NGC 7000	$20^h\,58.8^m$	+44° 12′	Jul–**Aug**–Sep
❋ 1–5	⊕ 120 ⇆ 100″			Cygnus

Also known as the *North America Nebula*. Located just west of *Deneb*, it is magnificent in binoculars, melding as it does into the stunning star fields of *Cygnus*. Providing 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. See Star Map 38.

-	IC 1396	$21^h\,39.1^m$	+57° 30′	Jul–**Aug**–Sep
❋ 3–5	⊕ 170 ⇆ 40″			Cepheus/Cygnus ©

One of the few emission nebula visible to the naked eye (under perfect seeing 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*. Any telescope will lessen the impact of the nebula but the use of filters will help to locate knots and patches of brighter nebulosity and dark dust lanes. Dark adaption and averted vision will all enhance the observation of this giant emission nebula. See Star Map 38.

Caldwell 19	IC 5146	$21^h\,53.4^m$	+47° 16′	Jul–**Aug**–Sep
❋ 3–5	⊕ 12 ⇆ 12″			Cygnus

Also known as the *Cocoon Nebula*. It has a low surface brightness and appears as nothing more than a hazy amorphous glow surrounding a couple of 9th-magnitude stars. The dark nebula Barnard 168 (which the Cocoon lies at the end of) is surprisingly easy to find, and thus can 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 and protostars.

Caldwell 11	NGC 7635	$23^h\ 20.7^m$	+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 in its detection owing to their combined glare. Research suggests that a strong stellar wind from a star pushes material out – the "Bubble" – and also heats up a nearby *Molecular Cloud*, which in turn ionises the "Bubble". See Star Map 38.

-	NGC 604	$01^h\ 33.9^m$	+30° 39′	Sep-**Oct**-Nov
❋ 3–5	⊕ 60 ⇆ 35″			Triangulum

This may come as quite a surprise to many observers, but this is possibly the brightest emission nebula that can be glimpsed which is actually in another galaxy. It resides in M33, in Triangulum. It appears as a faint hazy glow some 10' northeast of M33's core. Owing to M33's low surface brightness (which often makes it a difficult object to find), the emission nebula may be visible while the galaxy isn't! It is estimated to be about 1000 times bigger than the Orion Nebula. See Star Map 38.

Caldwell 49	NGC 2237–39	$06^h\ 32.3^m$	+05° 03′	Nov-**Dec**-Jan
❋ 1–5	⊕ 80 ⇆ 60″			Monoceros

Also known as the *Rosette Nebula*. This giant emission nebula has the dubious reputation of being very difficult to observe. But this is wrong – on clear nights it can be seen with binoculars. It is over 1° in diameter, and thus 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*). See Star Map 38.

-	NGC 2024	$05^h\ 40.7^m$	+02° 27′	Nov-**Dec**-Jan
❋ 2–5	⊕ 30 ⇆ 30″			Orion

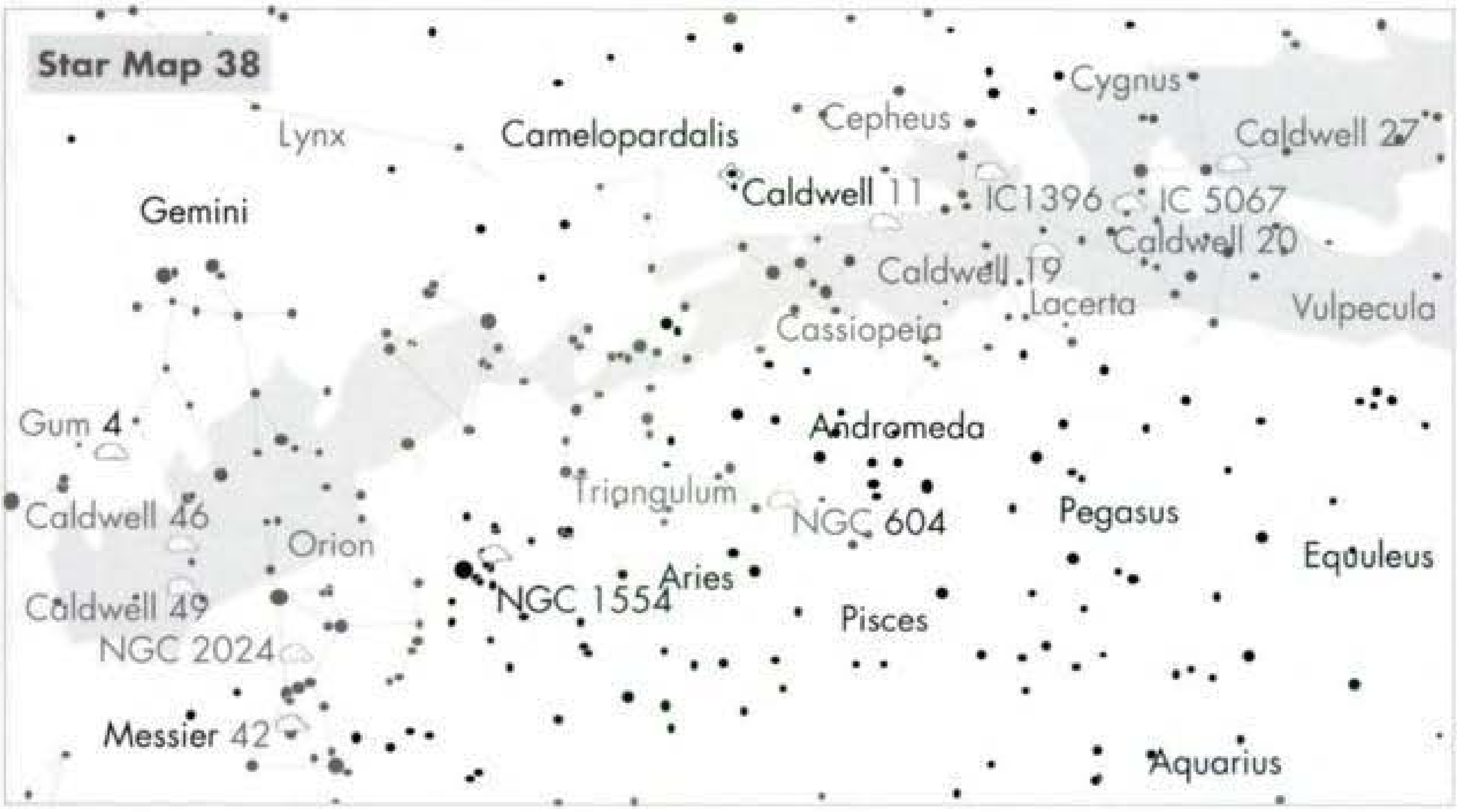
This difficult nebula lies next to the famous star *Zeta Orionis*, which is unfortunate as the glare from the star makes observation difficult. It can, however, be glimpsed in binoculars as an unevenly shaped hazy and faint patch to the east of the star, providing the star is placed out of the field of view. With large telescopes and filters the emission nebula is a striking object, and has a shape reminiscent of a maple leaf. See Star Map 38.

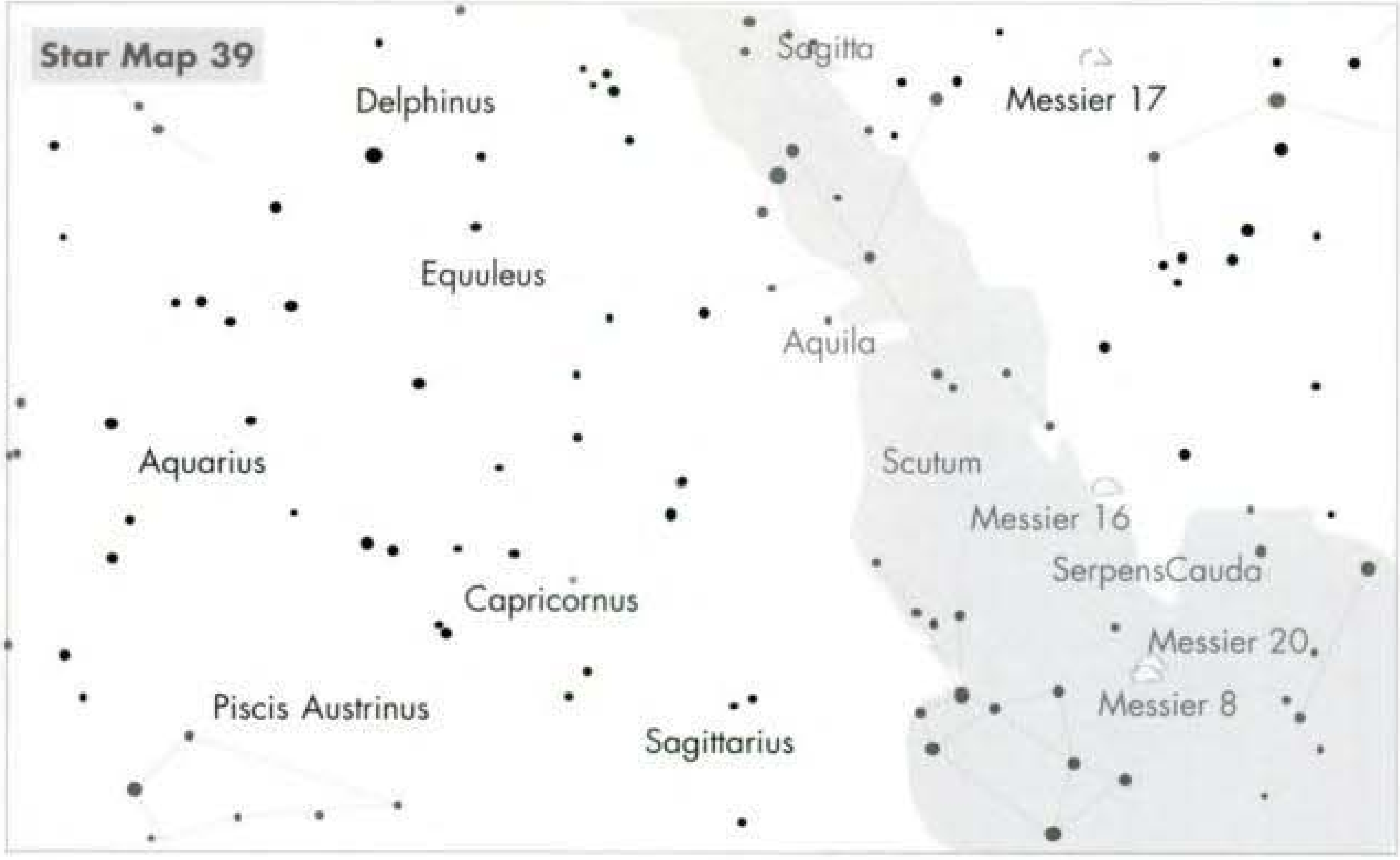
Caldwell 46	NGC 2261	$06^h\ 39.2^m$	+08° 44′	Nov-**Dec**-Jan
❋ 1–5	⊕ 3.5 ⇆ 1.5″			Monoceros

Also known as *Hubble's Variable Nebula*. Easily seen in small telescopes of 10 cm as a small, comet-like nebula that can be seen from the suburbs. Larger apertures just amplify what is seen with little detail visible. What we are observing 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 by Edwin Hubble in 1916, 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. See Star Map 38.

-	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 have included this object even though it is a very difficult nebula 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 has been much brighter in the past, but now is an exceedingly difficult object to locate. With 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 is well worth looking for in the hope that it makes an unexpected reappearance. See Star Map 16 and 38.





2.3.2 Dark Nebulae

Dark nebula, by their very nature, are different in one major respect from all the others. 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 *dust grains*. These grains, however, bear no resemblance at all to dust that we see on Earth. They are microscopic in size, believed to be in the region of 20 to 30 nm in size. 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. The shape of a dust grain is like a long spindle, and in some cases, they may rotate. The actual composition of the grains is a topic of vigorous debate, but are believed to be made from, in various unknown amounts, 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 be 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 anything from 10^4 to 10^9 particles made up of atoms, various molecules and dust grains.

The nebulae appear dark due to their vast size, and so are very effective of scattering all of the light with the result that hardly any reaches the naked eye. The process of scattering the light is so effective that, for instance, visible light emitted for the centre of our Galaxy is extinguished nearly 100% by the dust clouds between us and its centre. This is the reason why it is still a mystery as to what the central region looks like in *visible light*. Don't be confused, however, 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 dust grains 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* which shows dust clouds containing dense regions, or globules, which are resisting the radiation pressure from close, hot young stars, with the result that many of the globules have long tails of material trailing from them. 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 ionised and streaming from the surface of the cloud.

Most dark clouds have vastly different shapes, and this is due to several reasons. It may be that the cloud would have originally been spherical in shape, and thus present a circular image to us, but hot stars in its environment will have 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 will all have a role to play in determining the shape of the cloud. It is also thought that magnetic fields may also have some limited affect. As many of theses dark clouds are part of a much larger star forming region, then the new stars will themselves influence and alter its shape.

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 nebulae would indicate that it only very slightly attenuates the starlight from the background Milky Way, to a value of 6, which would mean that the cloud is nearly black, it is given the symbol ✦. Observing dark nebulae can be a very frustrating pastime. The best advice is to always use the lowest magnification possible. This will enhance the contrast between the dark nebulae and that of 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, and not the nebula itself. Dark skies are a must with these objects, as even a hint of light pollution will make their detection an impossible task. Simple finder charts are given at the end of the list.

Barnard 228		$15^h\ 45.5^m$	–34° 24′	Apr–**May**–Jun
✦ 6	⊕ 240 ⇆ 20″			Lupus
This is a long band of dark nebula, easily spotted in binoculars. It lies halfway between *Psi* (ψ) and *Chi* (χ) *Lupi*. Best seen in low-power, large-aperture binoculars, as it stands out well against the rich background star field. See Star Map 40.				

Barnard 59, 65-7	LDN 1773	$17^h\,21.0^m$	-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. 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. See Star Map 40.

Barnard 78	LDN 42	$17^h\,33.0^m$	-26° 30′	May-**Jun**-Jul
✦ 5	⊕ 200 ⇆ 150″			Ophiuchus

Also known as the *Pipe Nebula* (*Bowl*). 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 a part of the same complex as that which encompasses *Rho* (ρ) *Ophiuchi* and *Antares*, which are over 700 light years away from it. See Star Map 40.

Barnard 86	LDN 93	$18^h\,03.0^m$	-27° 53′	May-**Jun**-Jul
✦ 5	⊕ 6″			Sagittarius

Also known as the *Ink Spot.* Located within the *Great Sagittarius Star Cloud*, this is a near-perfect example of a dark nebula, appearing as a completely opaque blot against the background stars. See Star Map 40.

Barnard 87, 65-7	LDN 1771	$18^h\,04.3^m$	-32° 30′	May-**Jun**-Jul
✦ 4	⊕ 12″			Sagittarius/ Ophiuchus

Also known as the *Parrot Nebula.* Not a distinct nebula, but stands out because of its location within a stunning background of stars. Visible in binoculars as a small circular dark patch, it's best seen in small telescope of around 10 to 15 cm. See Star Map 40.

Barnard 103	LDN 497	$18^h\,39.4^m$	-06° 41′	Jun-**Jul**-Aug
✦ 6	⊕ 40 ⇆ 15″			Scutum

Easily seen at the north-east edge of the famous *Scutum Star Cloud.* It is a curved dark line. Can be glimpsed in binoculars. See Star Map 40.

Barnard 110-1		$18^h\,50.1^m$	-04° 48′	Jun-**Jul**-Aug
✦ 6	⊕ 11″			Scutum

An easily seen complex of dark nebulae that can be seen in binoculars. The contrast between the background star clouds and the darkness of the nebulae is immediately seen. See Star Map 40.

Barnard 142-3		$19^h\,41.0^m$	+10° 31′	Jun-**Jul**-Aug
✦ 6	⊕ 45″			Aquila

This is an easily seen pair of dark nebulae, visible in binoculars. It appears as a cloud with two "horns" extending towards the west. The nebula contrasts very easily with the background Milky Way and so is a fine object. See Star Map 40.

Barnard 145		$20^h\ 02.8^m$	+37° 40′	Jun–**Jul**–Aug
✦ 4	⊕ 35 ⇆ 8″			Cygnus

Visible in binoculars, it is a triangular dust cloud that stands out well against the impressive star field. As it is not completely opaque to starlight, several faint stars can be seen shining through it. See Star Map 40.

Barnard 343		$20^h\ 13.5^m$	+40° 16′	Jun–**Jul**–Aug
✦ 5	⊕ 13 ⇆ 6″			Cygnus

Easily seen as a "hole" in the background Milky Way, this is an oval dark nebula, which although glimpsed in binoculars is at its best in telescopes. See Star Map 40.

Lynds 906		$20^h\ 40.0^m$	+42° 00′	Jul–**Aug**–Sep
✦ 5	⊕ – –			Cygnus

Also known as the *Northern Coalsack.* This is probably the largest dark nebulosity of the northern sky. It is an immense region, easily visible on clear moonless nights just south of *Deneb.* It lies just at the northern boundary of the *Great Rift,* a collection of several dark nebulae which bisects the *Milky Way.* The Rift is of course part of a spiral arm of the Galaxy, so features prominent on photographs of other galaxies such as *NGC 891* in *Andromeda.* See Star Map 40.

Barnard 352		$20^h\ 57.1^m$	+45° 54′	Jul–**Aug**–Sep
✦ 5	⊕ 20 ⇆ 10″			Cygnus

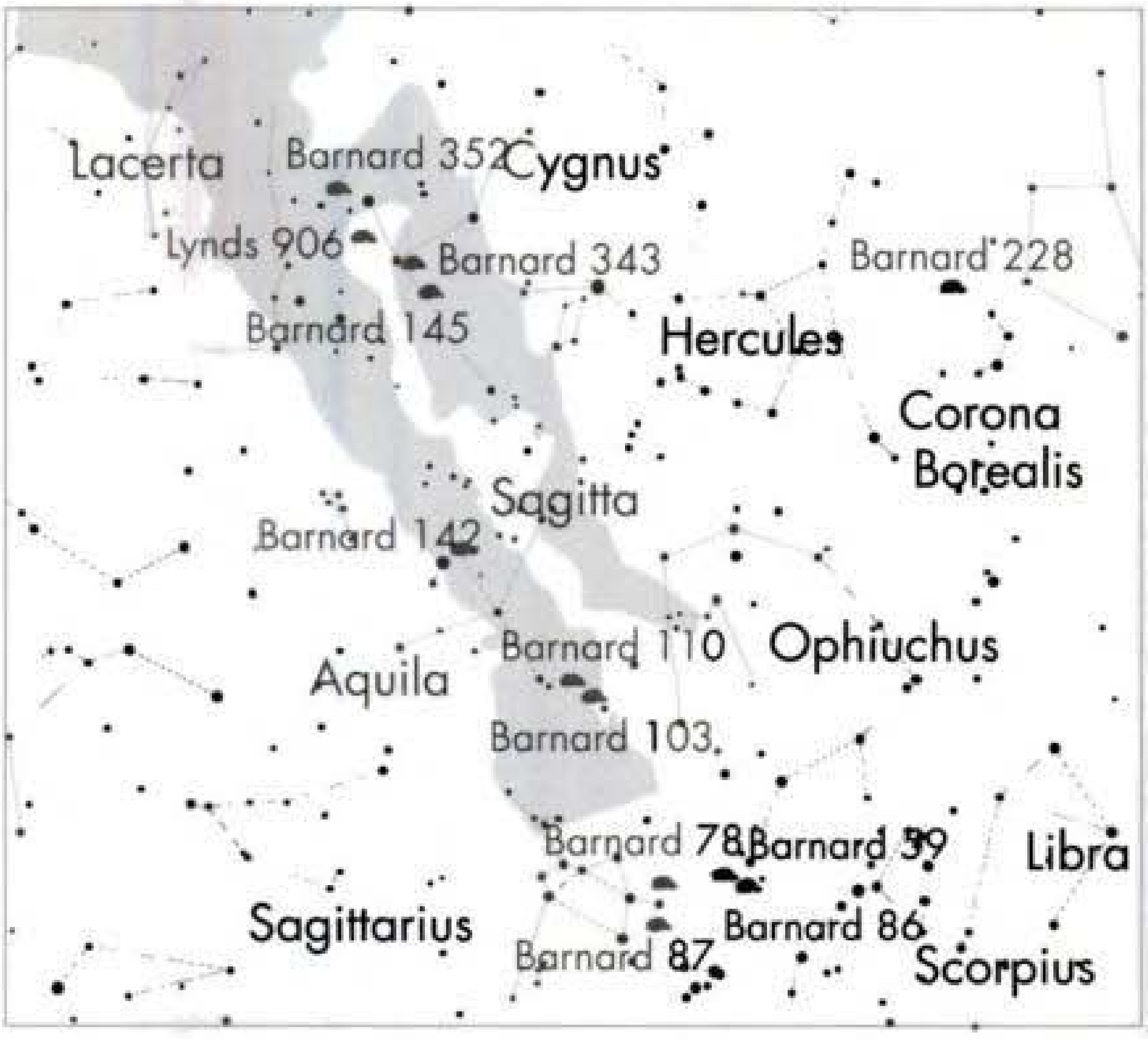
Visible in binoculars, this is part of the much more famous North America Nebula, though this dark part is located to the north. It is a well-defined triangular dark nebula. See Star Map 40.

Barnard 33		$05^h\ 40.9^m$	-02° 28′	Nov–**Dec**–Jan
✦ 4	⊕ 6 ⇆ 4″			Orion

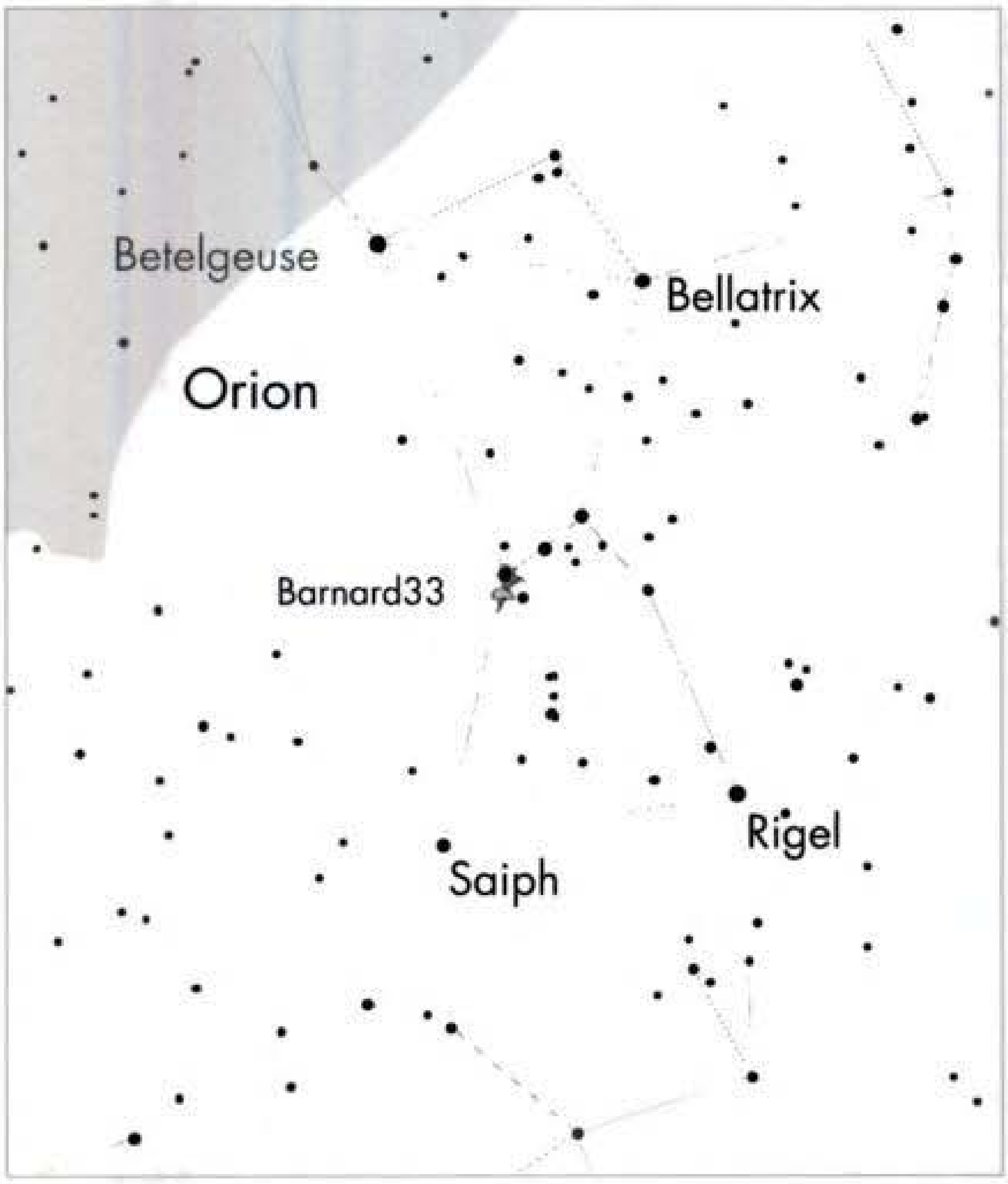
Also known as the *Horsehead Nebula.* Often photographed, but rarely observed, this famous nebula is very difficult to see. It is a small dark nebula which is seen in silhouette against the dim glow of the emission nebula *IC 434.* Both are very faint and will need perfect seeing conditions. Such is 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, but have a go! See Star Map 41.

2.3.3 Reflection Nebulae

The final classification of nebulae that we mention are *reflection nebulae.* As the name suggests, these nebulae shine by the light reflected from stars within the nebula, or perhaps close-by. 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,



Star Map 40



Star Map 41

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, hence its colour blue. This is one reason why reflection nebulae appear so blue on photographs, it is just the blue wavelengths of the light from (usually) hot blue stars nearby. To be scientifically correct, the nebulae should be called scattering nebulae instead of reflection nebulae, but the name has stuck. This property is often called interstellar reddening. An interesting property of the scattered light is that the scattering process itself polarises the light, useful in the studies of grain composition and structure.

Another phenomenon associated with dust grains that should be mentioned, as it affects ALL observations, is *interstellar extinction*. 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 has to 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 the tell-tale pink colour, indicative of the ionisation process responsible for the emission, whereas further out from the centre, the edge material is definitely blue, thus signposting the scattering nature of the nebula. Visually, reflection nebulae are very faint objects having a low surface brightness, thus they are not easy targets. Most require large aperture telescopes with moderate magnification in order to be seen, but there are a few visible in binoculars and small telescopes. Note that excellent seeing conditions are necessary and very dark skies.

<table>
<tr><td>Caldwell 4</td><td>NGC 7023</td><td>$21^h 00.5^m$</td><td>+68° 10′</td><td>Jul–Aug–Sep</td></tr>
<tr><td>• 1–5</td><td>⊕ 18 ⇆ 18″</td><td></td><td></td><td>Cepheus ©</td></tr>
<tr><td colspan="5">Though small, this is a very nice, easy to observe reflection nebula. It has a star cluster at its centre which can hinder observation. However, what makes the reflection nebula easy to detect is its location. It is surrounded by a larger area of dark nebulosity, probably part of the same nebula complex. The contrast between the background stars, the dark nebula and the reflection nebula makes for a very interesting region. See Star Map 42.</td></tr>
</table>

<table>
<tr><td>–</td><td>NGC 1333</td><td>$03^h 29.3^m$</td><td>+31° 25′</td><td>Oct–Nov–Dec</td></tr>
<tr><td>• 3–5</td><td>⊕ 6 ⇆ 3′</td><td></td><td></td><td>Perseus</td></tr>
<tr><td colspan="5">This is a nice, easily seen reflection nebula, and appears as an elongated hazy patch. Larger aperture telescopes will show some detail along with two fainter dark nebulae <i>Barnard 1</i> and <i>2</i>, lying toward that north and south of the reflection nebula. See Star Map 42.</td></tr>
</table>

-	NGC 1435	$03^h 46.1^m$	+23° 47′	Oct–**Nov**–Dec
• 2–5	⊕ 30 ⇆ 30″			Taurus

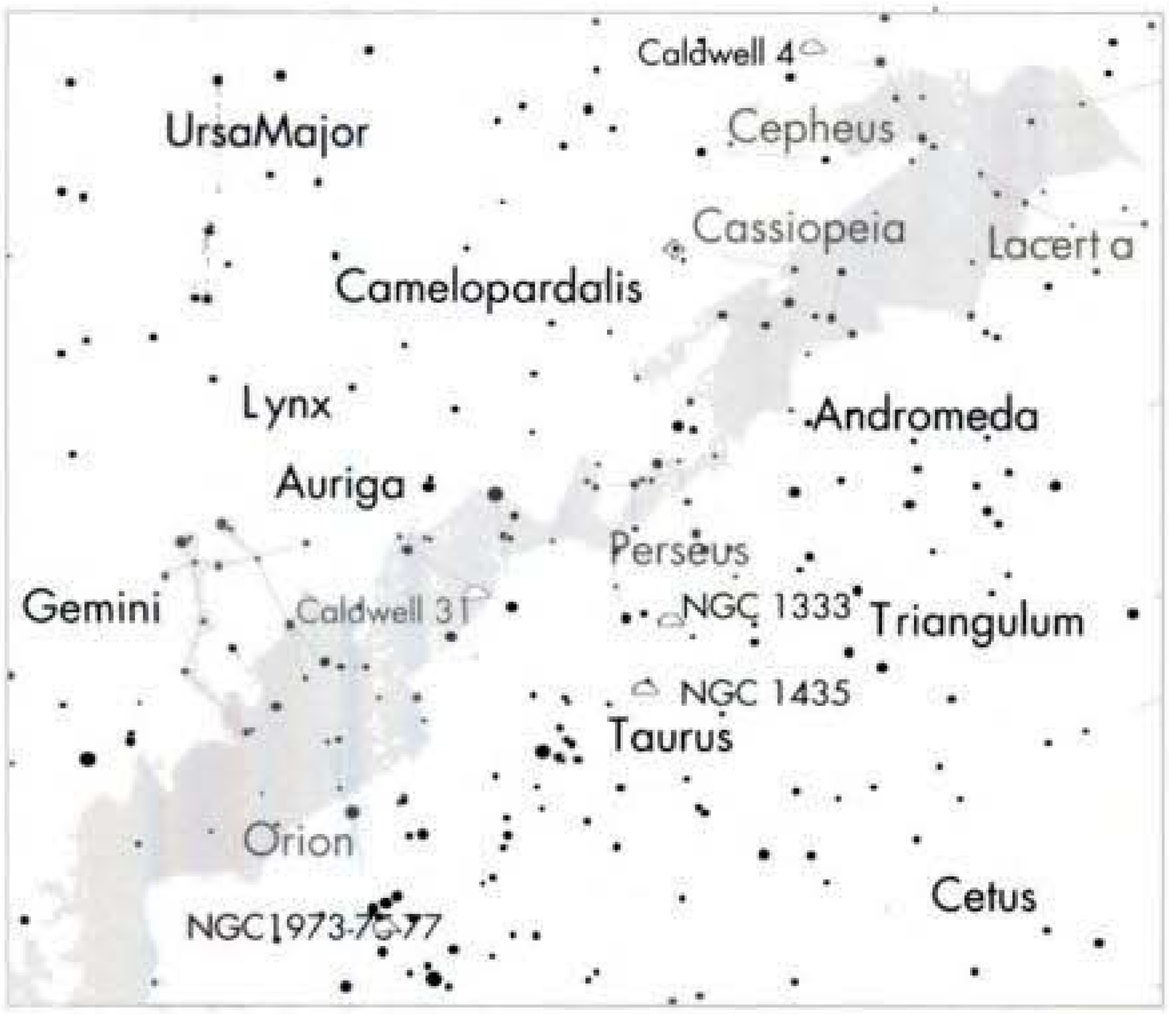
Also known as *Tempel's Nebula*. This faint patch of reflection nebula is located within the most famous star cluster in the sky. The nebula surrounds the star *Merope*, one of the brighter members of the *Pleiades*, and under perfect conditions can be glimpsed with binoculars. Several other members 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. See Star Map 42.

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*. A very hard reflection nebula to observe. It is actually several nebulae including *IC 405, 410* and *417*, plus the variable star *AE Aurigae*. Narrow-band filters are justified with this reflection nebula, as they will highlight the various components. A challenge to the observer. See Star Map 42.

-	NGC 1973–75–77	$05^h 35.1^m$	–04° 44′	Nov–**Dec**–Jan
• 1–5	⊕ 5 ⇆ 5″			Orion

The location of these reflection nebulae so close to M42 has meant that they are often neglected. They lie between M42 on their south and the cluster *NGC 1198* to their north. They are also difficult to see because the glare from the star *42 Orionis* tends to make observation difficult. See Star Map 42.



Star Map 42

2.4 Molecular Clouds

We have seen that interstellar space is filed with gas and dust, and that in certain locations, concentrations of this material gives rise to nebulae. But the locations of these nebulae are not, as one may 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 that, due to the conditions within them, allow the formation of several molecules, for example, carbon monoxide (CO), water (H_2O), and hydrogen molecules (H_2).[8] Molecular hydrogen, although being the most abundant molecule in a cloud, 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 at 10–30 K above absolute zero. It is these molecules that allowed the 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.

These 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 have diameters anywhere from 12 to 120 pc, or about 40 to 350 ly. The total mass of molecular clouds in our Galaxy is thought to be around 5 billion solar masses.[9] 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 can't see a metre in front of your own eyes. 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,

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[8] Other molecules such as ammonia (NH_3) and methanol (CH_3OH) have also been detected.

[9] In areas where the average density exceeds, say, a million solar masses, clouds referred to as *Giant Molecular Clouds* can form.

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 which have star formation in them, outline the spiral arms of the Galaxy, and lie about 1000 pc apart, strung out along the arms rather like pearls on a necklace.[10] However, spiral arms of galaxies are not the only place that star formation can occur. There are several other mechanisms which can give rise to stars as we shall see in a later section.

2.5 Protostars

Let's now turn our gaze on the mechanisms by which stars are believed to form. We discussed how space is full of gas and dust, and that local concentrations of this material gives 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 is particularly dense and thus will allow gravity to attract the particles. A further factor which will assist in formation is that the temperature of the cloud should be as cold as possible. A cold cloud will mean that the pressure of the interstellar medium is low. This is also a prerequisite as, if a cloud has a high pressure, it will tend to overcome any gravitational collapse. It is a delicate balancing act between gravity and pressure, whereby if gravity dominates, stars form.

From our discussion earlier in the book, you should by now have realised that there is only one place where conditions like those just mentioned arise; the dark nebulae. As a cloud contracts, pressure and gravity permitting, the dust and gas cloud becomes very opaque, and are the precursor regions to star formation. They are often called *Barnard objects*, after the astronomer who first catalogued them, Edward Barnard.[11] There are also even smaller objects, sometimes located with a Barnard object. These resemble small,

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[10] 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.

[11] See the section on Dark Nebulae for observable examples of Barnard objects.

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 these objects indicate the 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 centimetre, 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, with anything from between 1 to 1000 $M_{\odot}$. On the other hand, the larger Barnard object can have a mass of about 10,000 $M_{\odot}$, with a volume 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, then the densest areas within these objects and globules, will contract further under gravitational attraction. A consequence of this contraction is a heating up of the blob of material. However, the cloud can radiate this thermal energy away, and in doing so prevents 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 form the warmer interior to the outer 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. A consequence of this is that the central regions of the cloud become opaque, which traps nearly all of the thermal energy produced by the gravitational collapse. The result of trapping the energy is 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 look star like, but is not really a star, as no nuclear reactions occur in its core.

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

2.6 Pre-Main Sequence Evolution

A newly born star can be thought of a 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.*[12] This moment, when ignition of the fusion process occurs, will halt any further gravitational collapse of the protostar. The interior structure of the star stabilises, with the thermal energy created by nuclear fusion maintaining a balance between gravity and pressure. This important balancing act is called *gravitational equilibrium.*[13] 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 emphasise: 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 protostars luminosity and surface temperature, can be shown on a special H–R diagram. This is known as an *evolutionary track*, or *lifetrack*, for a star.[14] Each point along the star's track represents its luminosity and temperature at some point during its life, and so shows us how the protostars appearance changes due to changes in its interior. Figure 2.1 shows the evolutionary tracks for several protostars of different masses, from $0.5\ M_\odot$ to

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[12] We will discuss the proton-proton chain in much greater detail in the following sections on the Sun, and the main sequence.

[13] See the section on the Sun for a full discussion on gravitational equilibrium.

[14] When astronomers refers to a star following a specific evolutionary track, or moving on a H–R diagram, what they really mean is the star's luminosity and/or temperature change. Thus the point on the H–R diagram will change its position.

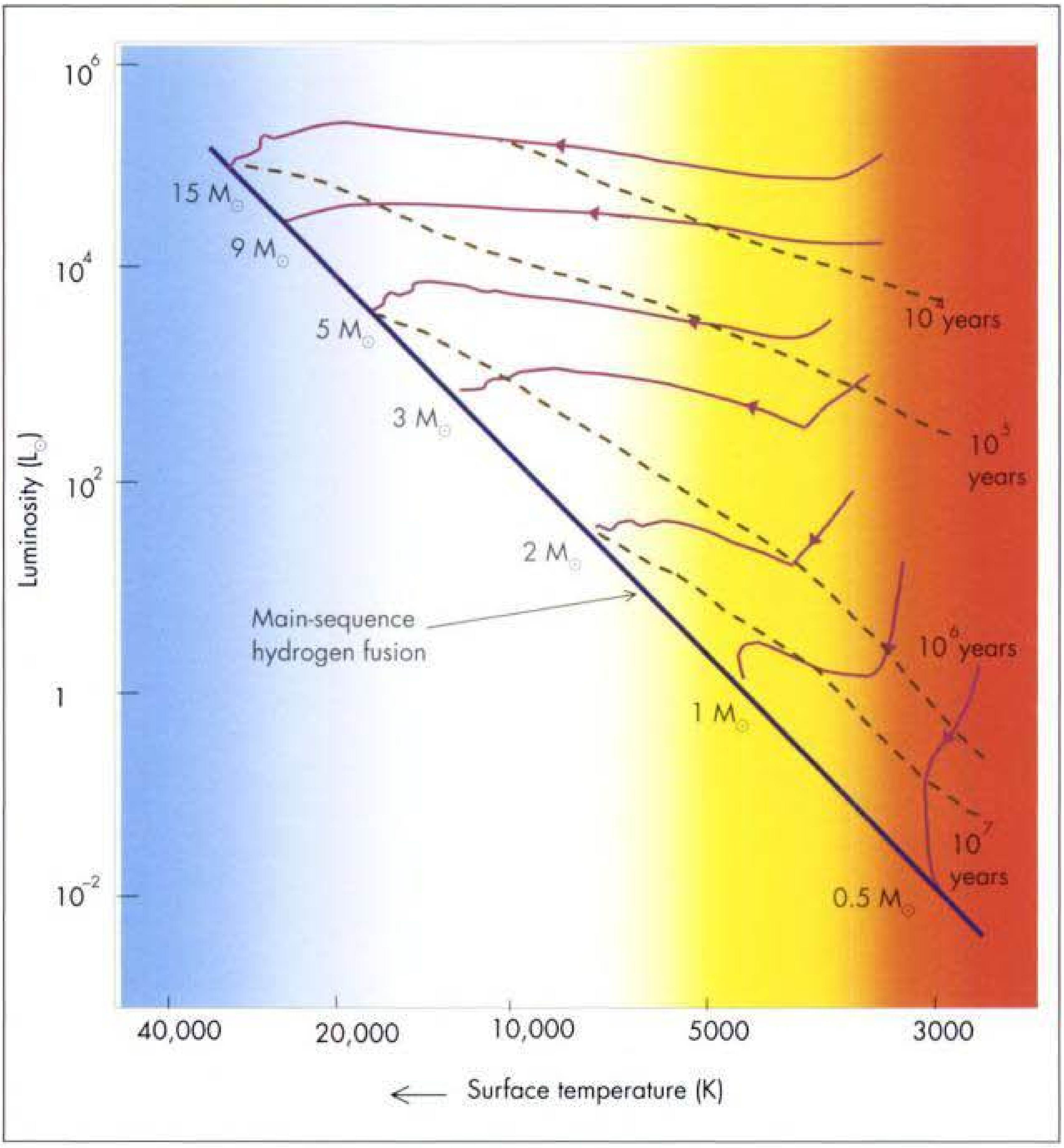

Figure 2.1. Pre-Main Sequence Lifetracks. The evolutionary lifetracks of seven protostars are shown. Also indicated are the stages reached after an indicated number of years of evolution (dashed lines). The mass shown for each protostar is the final mass it has when it becomes a main-sequence star. Note that the greater the mass, the higher the temperature and luminosity.

15 $M_\odot$ (it is important to realise that these evolutionary tracks are theoretical models, and the predictions are only as good as the theory;[15] 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

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[15] 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*.

at the right hand side of the H–R diagram. However, subsequent evolution is very different for stars of differing mass.

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 four very distinct phases:

1. The protostar forms from a cloud of cold gas, and thus is on the far right of the H–R diagram, but its surface area is enormous, with the result that its luminosity can be very large. This may be a hundred-times the luminosity it will have when it becomes a star.
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. However, its diminishing size reduces the luminosity. The evolutionary track now progresses almost vertically downward on the H–R diagram.
3. Now that the core temperate has reached 10 million K, hydrogen nuclei fuse into helium. The rate of nuclear fusion is not, however, sufficient to halt the collapse of the star, although it is slowed down considerably. As the star shrinks, its surface temperature increases. The result of shrinking and heating is 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.
4. Both the rate of nuclear fusion and 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 the star settles onto the hydrogen-burning main sequence.

Figure 2.2 shows the evolutionary track of just such an object.

From the viewpoint of an observer, however, this stage of stellar evolution doesn't present itself with many objects that can be seen. Even though the luminosity of such objects is very high, we will never see one. The reason is obvious. They are enshrouded within vast clouds of interstellar dust, and if you recall, these are very efficient at blocking out the light. The dust in the vicinity of a protostar, often called a *cocoon nebula*, absorbs the light, and so they are very difficult

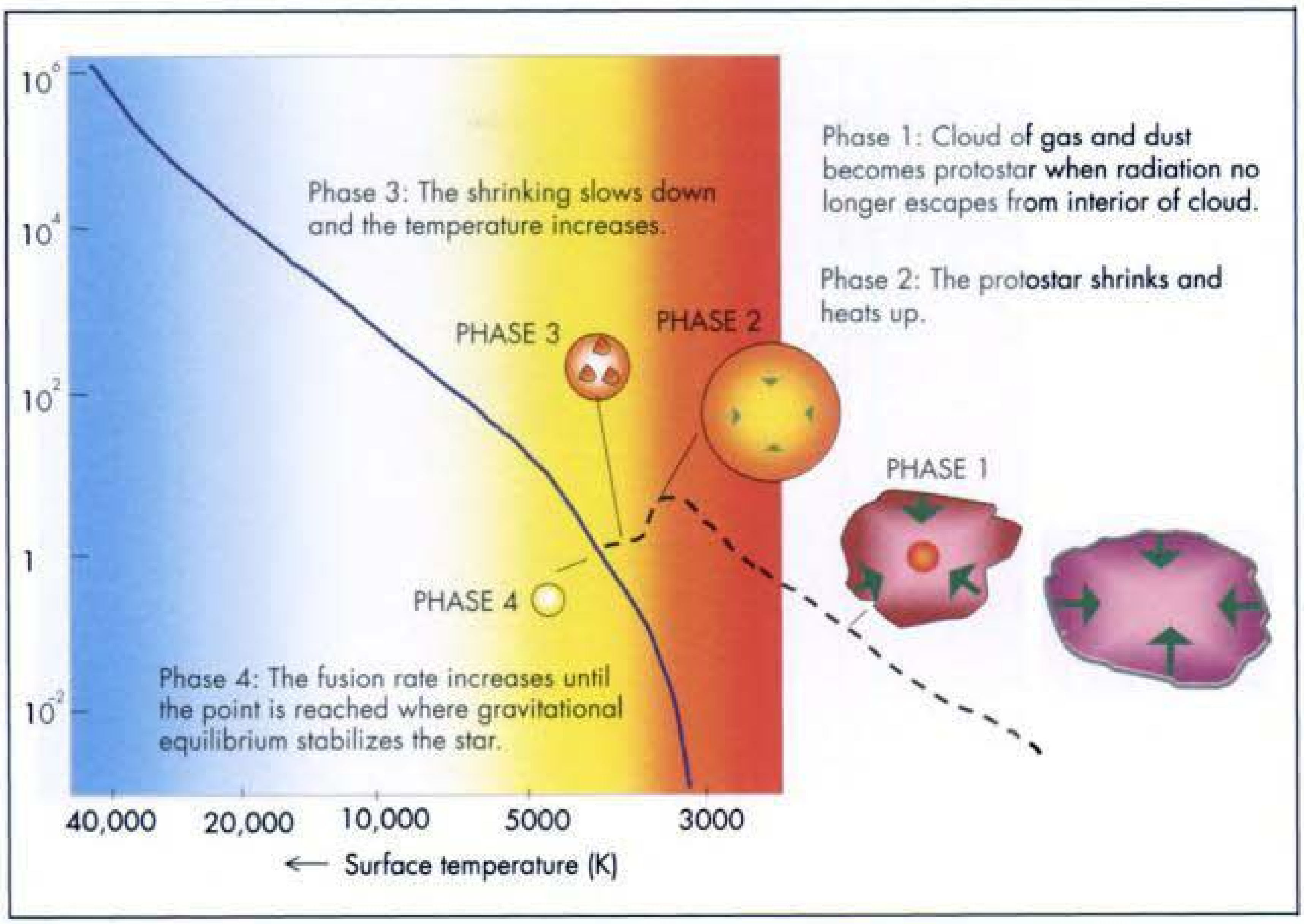

Figure 2.2. The Four Phases of Protostar Evolution. Evolutionary track of a one solar mass star as it approaches the main sequence.

to observe at visible wavelengths.[16] On the other hand, they can be seen at infrared wavelengths. But this doesn't really help us, as visual observational astronomers on the Earth.

2.6.1 The Effect of Mass on Pre-Main Sequence Evolution

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 slight problem with this scenario; at the time of writing this book, there is no satisfactory explanation of how protostars of differing masses are actually formed within the same cloud. Just what are the processes that govern the clumping and fragmentation of the cloud into protostars of widely differing masses?

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[16] 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.

Even though we cannot explain the process, we can at least observe the results of such a process.

Let's begin this section by looking at how protostars of differing mass are believed to form, and we'll start with a star of 1 $M_\odot$ - a star just like our Sun. The outer layers of such a protostar are cool and opaque,[17] which means that any 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 has to 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 at the same time the luminosity decreases because the radius decreases,[18] and the evolutionary track moves downward on the H–R diagram. This is exactly what is shown on Figure 2.1.

I said above that the surface temperature remains roughly constant during this phase, but conditions inside the protostar are far from unchanging. The internal temperature will start to increase during this time, and the interior becomes ionised. This reduces the opacity within the protostar and allows the transfer of energy to be 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 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 which have 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 will stabilise at approximately its final value, but the surface

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[17] We shall see why the Sun is opaque in a later section.

[18] 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.

temperature will continue 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 so 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 the 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 interior regions of the star. In contrast to this, 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 which have a mass greater than about 4 $M_\odot$, will have convective interiors and radiative outer layers, whilst 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, those 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 ionise the inner region and so is 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 2.3.

A very important point to make here is that all the evolutionary tracks shown on Figure 2.1 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 end point on the main sequence can be represented by a *Mass–Luminosity Relationship,* which is shown in Figure 2.4. What this diagram implies is that the hot bright blue stars are the most massive, whilst the faint dim cool stars are the least massive.[19] Thus, the H–R diagram is a progression not only in

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[19] There is no mass–luminosity relationship for white dwarfs, giant, and supergiant stars. The reasons for which will be explained in Chapter 3.

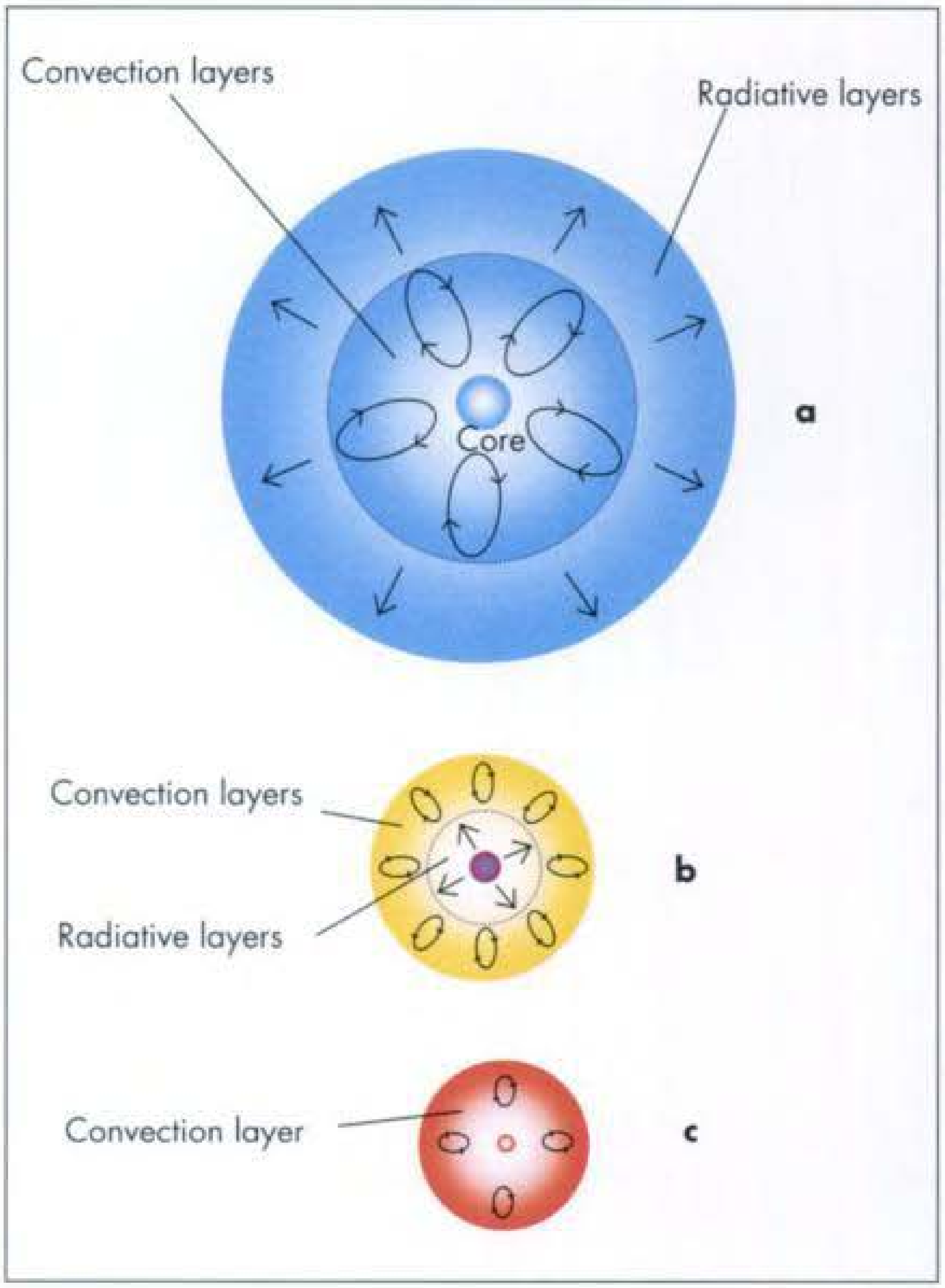

Figure 2.3. Mass of Main-Sequence Stars. **a** Energy flows from the core by convection in the inner regions, and radiation in the outer layers in stars of mass greater than 4 $M_{\odot}$. **b** Energy flows outward from the core by radiative means in inner regions, and by convection in outer layers, where the star's mass is less than 4 $M_{\odot}$ and greater than 0.8 $M_{\odot}$. **c** Energy flows outward by convection throughout the interior of stars of mass less than 0.8 $M_{\odot}$.

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 $L_{\odot}$; similarly, 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 described by the H–R diagram, it is important that I emphasise two factors that can cause confusion. Firstly, 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 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

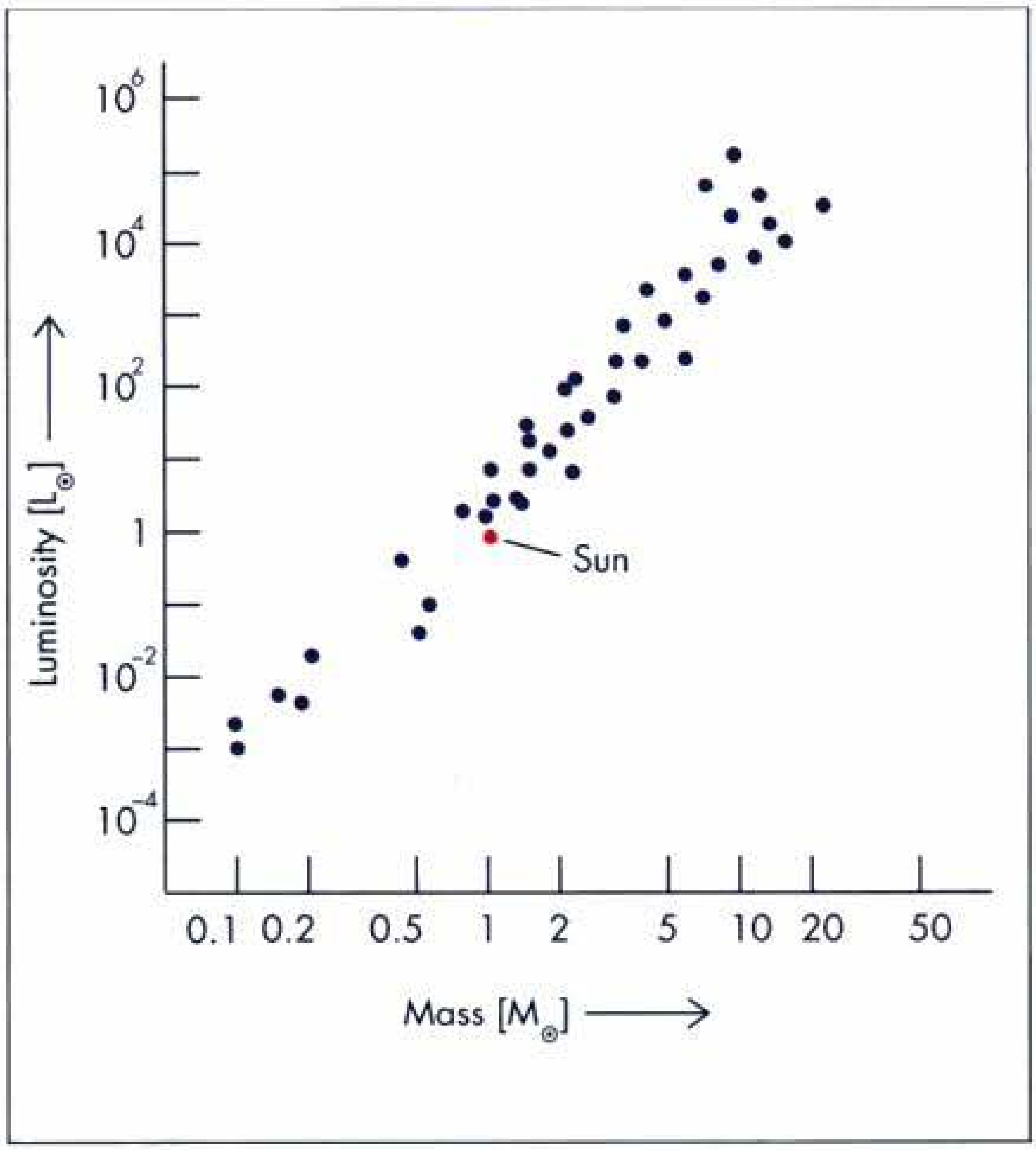

Figure 2.4. Mass–Luminosity Relationship.

takes about 20 million years to become a main-sequence star, whilst 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 $\approx$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 $M_\odot$[20] 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" that will slowly radiate away all 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 the infrared, so making them very difficult to detect. The first known detection was in 1995 of *Gliese 229B*, a 0.05 $M_\odot$ object.

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[20] This figure of 0.08 $M_\odot$ is around 80 times the mass of Jupiter.

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[21] 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 looking 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 and think that hidden deep in these clouds are stars in the process of being formed. Such an object is of course the *Orion Nebula.*

<table>
<tr><td>Messier 42</td><td>NGC 1976</td><td>$05^h\ 35.4^m$</td><td>−05° 27′</td><td>Nov–Dec–Jan</td></tr>
<tr><td>✺ 1–5</td><td>⊕ 65 ⇆ 60′</td><td></td><td></td><td>Orion</td></tr>
<tr><td colspan="5">Also known as the <i>Orion Nebula</i>. The premier emission nebula and one of the most magnificent objects in the entire 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 structure and detail, and in telescopes of aperture 10 cm the whole field will be filled. The entire nebulosity is glowing owing to the light (and thus energy) provided by the famous <i>Trapezium</i> stars located within it. These stars are stellar power houses, pouring forth vast amounts of energy, and are fairly new stars. What are 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 shows definite colour. Many observers report seeing a greenish glow, along with pale grey and blue, but to observe any colour besides gray will need 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 <i>Kleinmann–Low Sources</i> and the <i>Becklin–Neugebauer Object</i>, 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 light years, and about 40 light years 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. See Star Maps 17, 38, 41 and 42.</td></tr>
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[21] By "ordinary" I mean matter composed of atoms, to distinguish it from "dark matter" - whatever that may be!

2.7 Mass Loss and Mass Gain

2.7.1 T Tauri Stars

Having read the previous sections you may have gained 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 any stars at all. This ejected material can help sweep away the gas and dust that's surrounding the young stars and make them visible to us. Several examples of such a process can be seen in the *Rosette Nebula*, the *Trifid 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 well as 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 a H–R diagram, they would be on the right-hand side of the main sequence. By analysing 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 speeds 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 the 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 to the Sun, which looses 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 stared 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 which have 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 are called *Ae* or *Be* stars. Stars which are greater than 10 $M_\odot$ will reach the main sequence before the surrounding dust and gas from which they formed will have had a chance to disperse, and so these stars are often detected as highly luminous infrared objects located within molecular clouds.

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

T-Tauri		04^h 22.0^m	+19° 32′	Oct–**Nov**–Dec
8.5–13.6$_v$m		dGe – K1e		Taurus
This star is about 1.8° west and slightly north of ϵ *(epsilon) Tauri*, the northern-most 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, the spectrum varying from G4 to G8. Oddly enough, the variation in spectral type does not necessarily correlate with variability with 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*[22]). See Star Map 16.				

2.7.2 Discs and Winds

One aspect of protostar formation that came as a surprise to astronomers in the late twentieth century, was a curious phenomenon that was observed in many young stars, including the T Tauri stars mentioned above. It involves a loss of mass, once again, but the mass 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 jet outflowing

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[22] 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 on an accompanying star. Many astronomers believe that all T Tauri stars probably go through FU Orionis-type behaviour one or more times in their development.

is referred to as a *bipolar outflow*. The material is moving with a velocity that can reach several hundred kilometres per second, and 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 which 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 infalling gas and dust due to gravity. As this cloud of denser material clumps together, the protostar nebula will begin to rotate. This is just a consequence of physics, and 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 onto the ever-faster rotating disc is called the *circumstellar accretion disc*.

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

Since the 1990s, the discovery of accretion disks round 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.

2.8 Star Clusters

Stars do not form in isolation. You don't get one star forming here, and perhaps another forming over there! A dark nebula can contain the material that could form hundreds of stars, and so stars tend to form in groups, or clusters.

However, 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 differing times. As I mentioned earlier, high-mass stars will 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 with the their dusty mantles. A consequence of this is that 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, in relation to stars of mass about equal to that of the Sun, that where there may be several thousand of the 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 conclusion is that the most dense or closely packed clusters, which 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 anything from maybe a dozen members to hundreds. A few of them, for example, *Messier 11* in Scutum, contains an impressive number of stars, equaling 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 appreciated 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 which consist of only a few bright members accompanied by several fainter companions, as is the case of *Messier 29* in Cygnus. The stars which make up an open cluster are called *Population I* stars, which are metal-rich and usually to be found in or near the spiral arms of the Galaxy.

The size of a cluster can vary from a few dozen light years across, as in the case of *NGC 255* in Cassiopeia, to about 70 light years across, 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 which 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 it allows us to study in detail the process of star formation and interaction between low- and high-mass stars. As an example, look at Figure 2.5 which shows the H–R diagram for the cluster *NGC 2264*, located in *Monoceros*. Note how all the high-mass stars, which are the hottest stars with temperature of about 20,000 K, have already reached the main sequence, whilst those with temperatures at about 10,000 K or cooler 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 have deduced that this particular cluster is very young at only two million years old.

By comparison, we can look at the H–R diagram for a very famous cluster – the *Pleiades* star cluster, Figure 2.6. We can see straight 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 the cluster to be about 50 million years old. Also look at the area on the H–R diagram, which has 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 isn't because they are still in the process of being formed. On the contrary, these massive stars have left the main sequence. They were amongst the first to be formed, and thus are the oldest, and are now evolving into a different kind of star. As we shall see later, all the hydrogen at the centre of

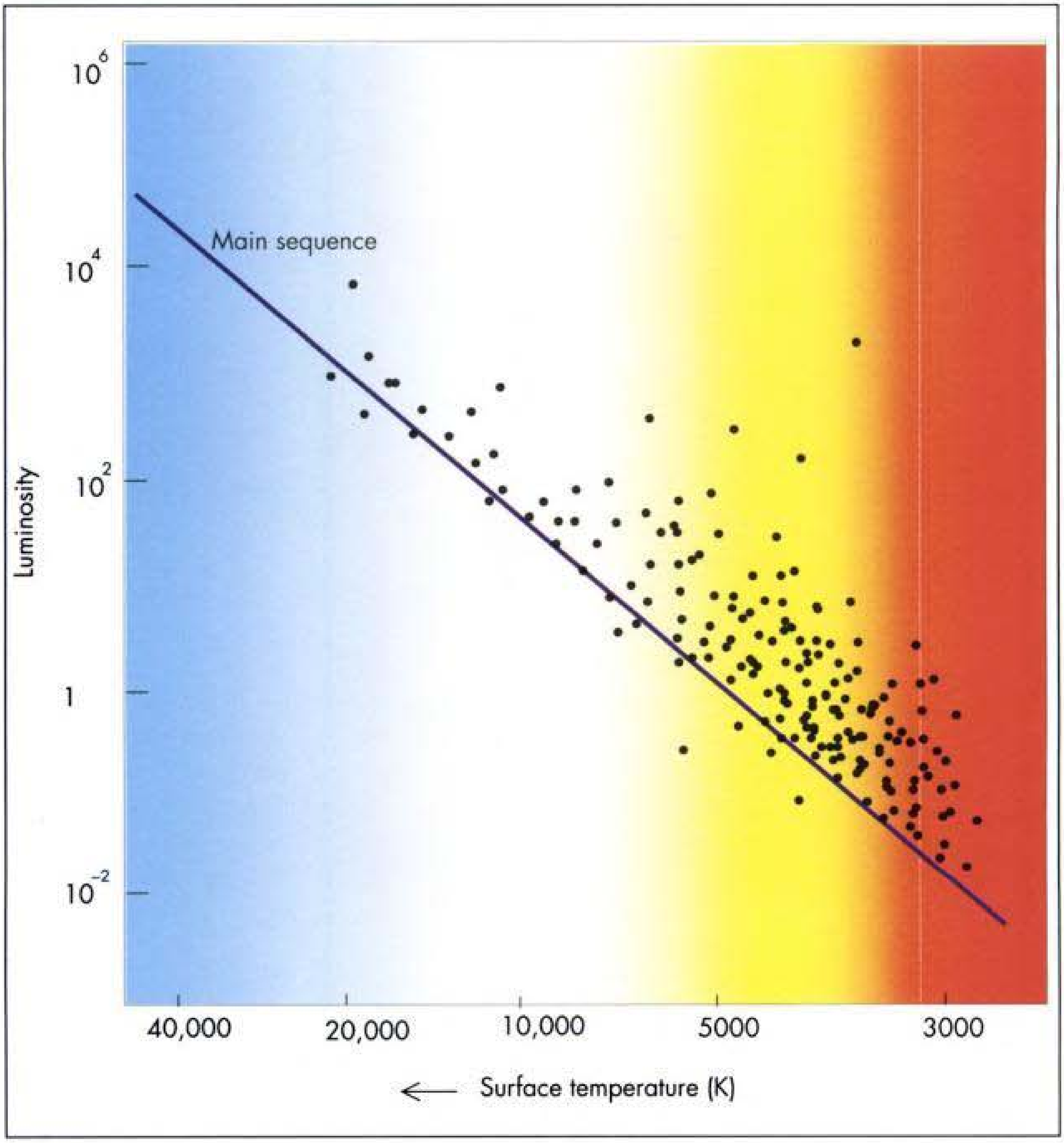

Figure 2.5. NGC 2264. This young star cluster is about 800 pc from Earth, and contains many T Tauri stars. Each dot is a star whose temperature and luminosity has been measured.

these stars has been used up,[23] and helium burning is now proceeding.

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 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 – *Cassiopeia*, and *Puppis* – and this is due to the absence of dust lying along these lines of

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[23] Remember that hydrogen burning is a characteristic for stars on the main sequence.

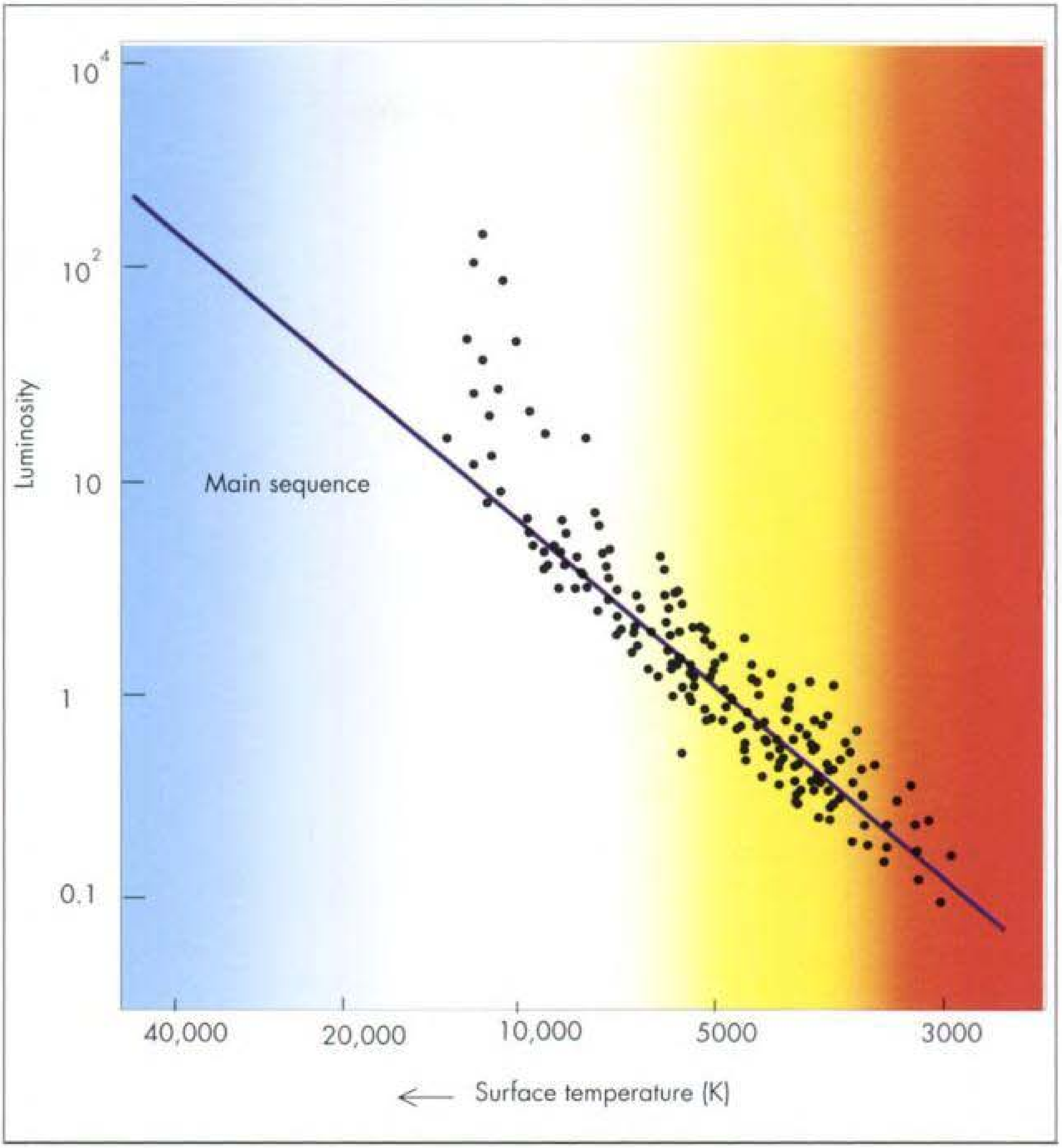

Figure 2.6. The Pleiades Star Cluster. This is a much older cluster at 50 million years. Most, if not all, of the low-mass cool stars have reached the main sequence, which implies that hydrogen burning has started in their cores. Note the different scales on this H–R diagram to those of Figure 2.5.

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, neither are they born simultaneously. Recall that the more massive a star the faster it contracts and becomes stable, thus joining the main sequence, and 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 centre of the *Lagoon Nebula*. In a few cases, the star production in a cluster is at a very early stage, with only a few stars visible, the majority 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 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 with 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, then 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 a 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 doesn't 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 which pervades everywhere – the Galaxy's gravitational field. As time passes, the cluster will be affected by the influence of other clusters and the interstellar matter itself, as well as the tidal force of the Galaxy. The cumulative affect of all these encounters will result in some of the less massive members of the cluster acquiring enough velocity to escape from the cluster. Thus, given enough time, a cluster will fade and disperse. (Take heart, as this isn't 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. Happily, many of them are best viewed by 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 of interest to be seen.

From the preceding chapter you will know that colour in observed stars is best seen when contrasted with a companion or companions. Thus an open cluster presents a perfect opportunity for observing star colours. Many clusters, such as the ever and rightly popular *Pleiades*, are all a lovely steely blue colour. 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 *Messier 41* in Canis Major.

Because open clusters display such a wealth of characteristics, different parameters are assigned to a cluster which 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 (less than 50 stars) to rich (more than 100). The full classification is:

Trumpler Classification for Star Clusters

Concentration

I Detached – strong concentration of stars towards the centre.
II Detached – weak concentration of stars towards the centre.
III Detached – no concentration of stars towards the centre.
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 less than 50 stars).
m Moderate (with 50–100 stars).
r Rich (with more than 100 stars).
n Cluster within nebulosity.

Two further and final points need to be mentioned which can often cause problems: 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 the visual magnitude (this is the combined magnitude of all stars in cluster), 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).

Messier 41	NGC 2287	$06^h\ 47.0^m$	−20° 44′	Dec–**Jan**–Feb
4.5m	⊕ 38′	70	II 3 m	Canis Major

Easily visible to the naked eye on very 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 light years in diameter. See Star Map 45.

Caldwell 58	NGC 2360	$07^h\ 17.8^m$	−15° 37′	Dec–**Jan**–Feb
7.2m	⊕ 12′	80	II 2 m	Canis Major

A beautiful open cluster, irregularly shaped and very rich. There are many faint stars, however, so the cluster needs moderate-aperture telescopes for these to be resolved, although it will appear as a faint blur in binoculars. This is believed to be an old cluster with an estimated age of around 1.3 billion years. See Star Map 45.

Caldwell 64	NGC 2362	$07^h 18.8^m$	–24° 57′	Dec–**Jan**–Feb
4.1m	⊕ 8′	60	I 3 p n	Canis Major

A very nice cluster, tightly packed and easily seen. With small binoculars the glare from *τ CMa* 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. See Star Map 45.

Messier 48	NGC 2548	$08^h 13.8^m$	–05° 48′	Dec–**Jan**–Feb
5.8m	⊕ 55′	80	I 3 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 in both binoculars and small telescopes. In the former, about a dozen stars are seen, with a pleasing triangular asterism at its centre, 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. See Star Map 48.

Messier 44	NGC 2632	$08^h 40.1^m$	+19° 59′	Dec–**Jan**–Feb
3.1m	⊕ 95′	60	II 2 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 light years, 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 centre. A unique Messier object in that it is brighter than the stars of the constellation within which it resides. Owing to its large angular size in the sky, it is best seen through binoculars or a low-power eyepiece. See Star Maps 43 (page 112) and 49 (page 119).

Caldwell 54	NGC 2506	$08^h 00.2^m$	–10° 47′	Dec–**Jan**–Feb
7.6m	⊕ 7′	100	I 2 r	Monoceros

A nice, rich and concentrated cluster, best seen with a telescope, but one that is often overlooked owing to its faintness even though it is just visible in binoculars. Includes many 11th- and 12th-magnitude stars. It is a very old cluster, around 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. See Star Map 45.

Messier 67	NGC 2682	$08^h 50.4^m$	+11° 49′	Jan–**Feb**–Mar
6.9m	⊕ 30′	200	II 2 m	Cancer

Often overlooked owing to its proximity to M44, it is nevertheless very pleasing. However, the stars it is composed of are faint ones, so in binoculars it will be unresolved, and seen as a faint misty glow. At a distance of 2500 light years, 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 light years off the plane. See Star Maps 45 (page 113) and 49 (page 119).

Caldwell 76	NGC 6231	$16^h 54.0^m$	−41° 48′	May–**Jun**–Jul
2.6m	⊕ 14′	100	I 3 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[24] *Sco OB1*, with an estimated age of 3 million years. A wonderful object 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. See Star Map 48.

Trumpler 24	Harvard 12	$16^h 57.0^m$	−40° 40′	May–**Jun**–Jul
8.6m	⊕ 60′	100	IV 2 p n	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. See Star Map 48.

Messier 7	NGC 6475	$17^h 53.9^m$	−34° 49′	May–**Jun**–Jul
3.3m	⊕ 80′	80	I 3 r	Scorpius

An enormous and spectacular cluster. It presents a fine spectacle in binoculars and telescopes, containing over 80 blue-white and pale yellow stars. It is only just over 800 light years away, but 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. See Star Map 48.

Messier 24[25]	–	$18^h 16.5^m$	−18° 50′	May–**Jun**–Jul
2.5m	⊕ 95′–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 light years 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. See Star Map 48.

Messier 16	NGC 6611	$18^h 18.8^m$	−13° 47′	May–**Jun**–Jul
6.0m	⊕ 22′	50	II 3 m n	Serpens Cauda

A fine large cluster easily seen with binoculars. It is about 7000 light years 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. A very young cluster of only 800,000 years, with a few at 50,000 years old. See Star Map 48.

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[24] See next section.

[25] Located within Sagittarius are numerous open clusters. Only the brightest are listed here.

Messier 25	IC 4725	$18^h 31.6^m$	–19° 15′	May–**Jun**–Jul
4.6m	⊕ 32′	40	I 3 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. See Star Map 48.

Messier 29	NGC 6913	$20^h 23.9^m$	+38° 32′	Jun–**Jul**–Aug
6.6m	⊕ 7′	80	I 2 m n	Cygnus

A very small cluster and one of only two Messier objects in Cygnus. It contains only about a dozen stars visible with small instruments, and even then benefits from a low magnification. However, studies show that it contains many more bright B0-type giant stars, which are obscured by dust. Without this, the cluster would be a very spectacular object. See Star Map 47.

Messier 11	NGC 6705	$18^h 51.1^m$	–06° 16′	Jun–**Jul**–Aug
5.8m	⊕ 13′	200	I 2 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, however, its full majesty becomes apparent. Containing many hundreds of stars, it is a very impressive cluster. It takes high magnification well, where many more of its 700 members become visible. At the top of the cluster is a glorious pale yellow tinted star. See Star Map 48.

–	IC 1396	$21^h 39.1^m$	+57° 30′	Jul–**Aug**–Sep
3.7m	⊕ 50′	40	II m n	Cepheus

Although a telescope of at least 20 cm is needed to really appreciate this cluster, it is nevertheless worth searching out. 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. See Star Map 46.

Caldwell 13	NGC 457	$01^h 19.1^m$	+58° 20	Sep–**Oct**–Nov
6.4m	⊕ 13′	80	I 3 r	Cassiopeia

This is a wonderful cluster, and can be considered 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 light years, this young cluster is located within the *Perseus Spiral Arm* of our Galaxy. See Star Map 46.

Collinder 33	NGC 752	$01^h 57.8^m$	+37° 41′	Sep–**Oct**–Nov
5.7m	⊕ 45′	77	III 1 m	Andromeda

Best seen in binoculars, or even at low powers in a telescope, this is a large, loosely structured group of stars containing many chains and double stars. Lies about 5° south-south-west of *γ Andromedae*. Often underrated by observing guides, it is worth seeking out. It is a cluster of intermediate age. See Star Map 46.

Caldwell 14	NGC 869	$02^h 19.0^m$	+57° 09′	Sep–**Oct**–Nov
5.3m	⊕ 29′	200	I 3 r	Perseus
	NGC 884	$02^h 22.4^m$	+57° 07′	
6.1m	⊕ 29′	150	II 2 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 marvelous. *NGC 869* has around 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 light years), whereas NGC 884 is younger at 3.2 million (at a distance of 7500 light years). But be advised that in astrophysics, especially distance and age determination, there are very large errors! Also, it was found that nearly half the stars are variables of the type Be, indicating that they are young stars with possible circumstellar discs of dust. Both are part of the *Perseus OB1 Association*[26] from which the *Perseus Spiral Arm* of the Galaxy has been named. Don't rush these clusters, but spend a long time observing both of them and the background star fields. See Star Map 46.

Messier 45	Melotte 22	$03^h 47.0^m$	+24° 07′	Oct–**Nov**–Dec
1.2m	⊕ 110′	100	I 3 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 over 100 stars, spanning an area four times that of the full Moon, it will never cease to amaze. 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 light years, is about 20 million years old (although some report it as 70 million) and is the 4th-nearest cluster. It 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 kilometres 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. See Star Map 44.

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[26] See section three in this chapter for a discussion on stellar associations.

Caldwell 41	Melotte 25	$04^h 27.0^m$	+16° 00′	Oct-**Nov**-Dec
0.5m	⊕ 330′	40	II 3 m	Taurus

Also known as the *Hyades*. The nearest cluster after the *Ursa Major Moving Stream*, lying at a distance of 151 light years, 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 the centre of the cluster. Best seen with binoculars owing to the large extent of the cluster – over $5\frac{1}{2}^\circ$. 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 is a foreground star only 70 light years away. Visible even from light-polluted urban areas – a rarity! See Star Map 45.

Messier 38	NGC 1912	$05^h 28.7^m$	+35° 50′	Nov-**Dec**-Jan
6.4m	⊕ 21′	75	III 2 m	Auriga

One of the three Messier clusters in Auriga, and visible to the naked eye. It contains many A-type main sequence and G-type giant stars, with a G0 giant being the brightest, magnitude 7.9. Is elongated in shape with several double stars and voids within it. It is an old galactic cluster with a star density calculated to be about 8 stars per cubic parsec. See Star Map 46.

Collinder 69	–	$05^h 35.1^m$	+09° 56′	Nov-**Dec**-Jan
2.8m	⊕ 65′	20	II 3 p n	Orion

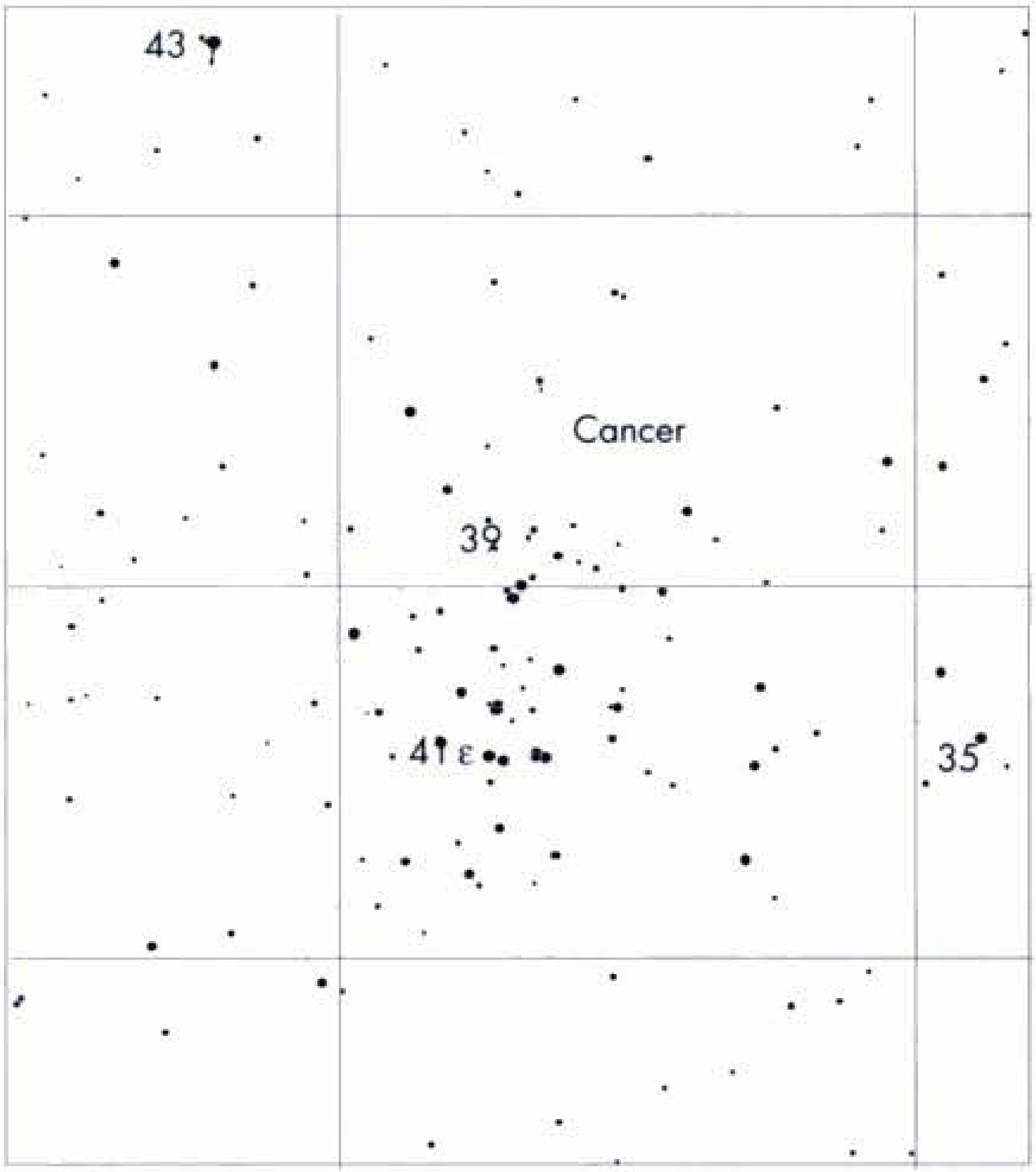
This cluster surrounds the 3rd-magnitude stars λ *Orionis*, and includes φ^{-1} and φ^{-2} *Orionis*, both 4th-magnitude. Encircling the cluster is the very faint emission nebula *Sharpless 2-264*, only visible using averted vision and an OIII filter with extremely dark skies. Perfect for binoculars. See Star Map 45.

Messier 37	NGC 2099	$05^h 52.4^m$	+32° 33′	Nov-**Dec**-Jan
5.6m	⊕ 20′	150	II 1 r	Auriga

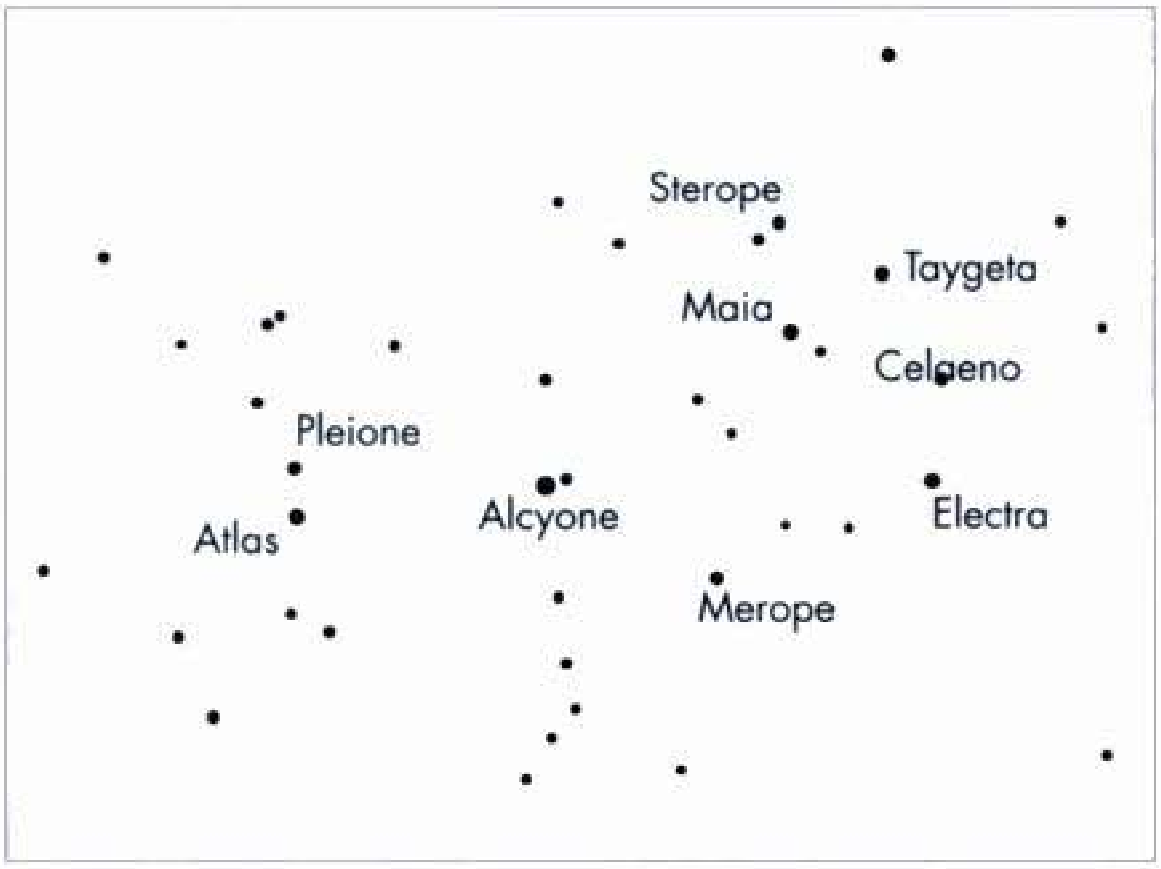
The finest cluster in Auriga. Contains many A-type stars and several red giants. Visible at all apertures, from a soft glow with a few stars in binoculars to a fine, star-studded field in medium-aperture telescopes. In small telescopes using a low magnification it can appear as a globular cluster. The central star is coloured 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. See Star Map 45.

Collinder 81	NGC 2158	$06^h 07.5^m$	+24° 06′	Nov-**Dec**-Jan
8.6m	⊕ 5′	70	II 3 r	Gemini

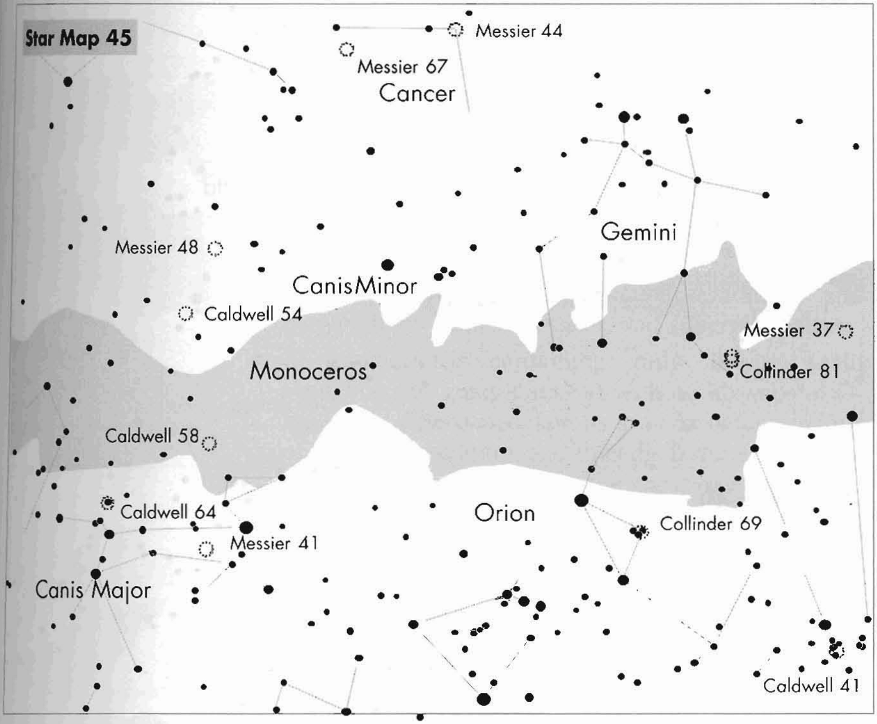
Lying at a distance of 160,00 light years, this is one of the most distant clusters visible using small telescopes, and lies at the edge of the Galaxy. It needs a 20 cm telescope to be resolved, and even then only a few stars will be visible against a background glow. It is a very tight, compact grouping 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. See Star Map 45.



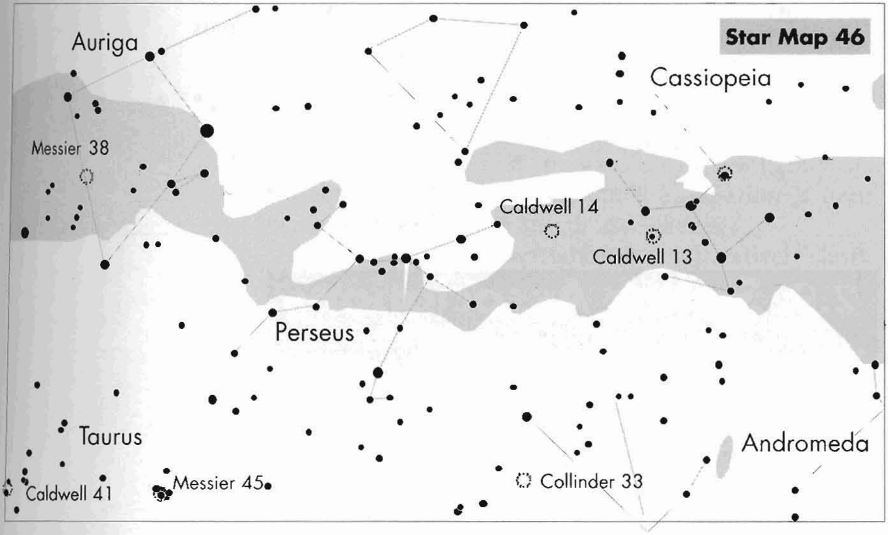
Star Map 43



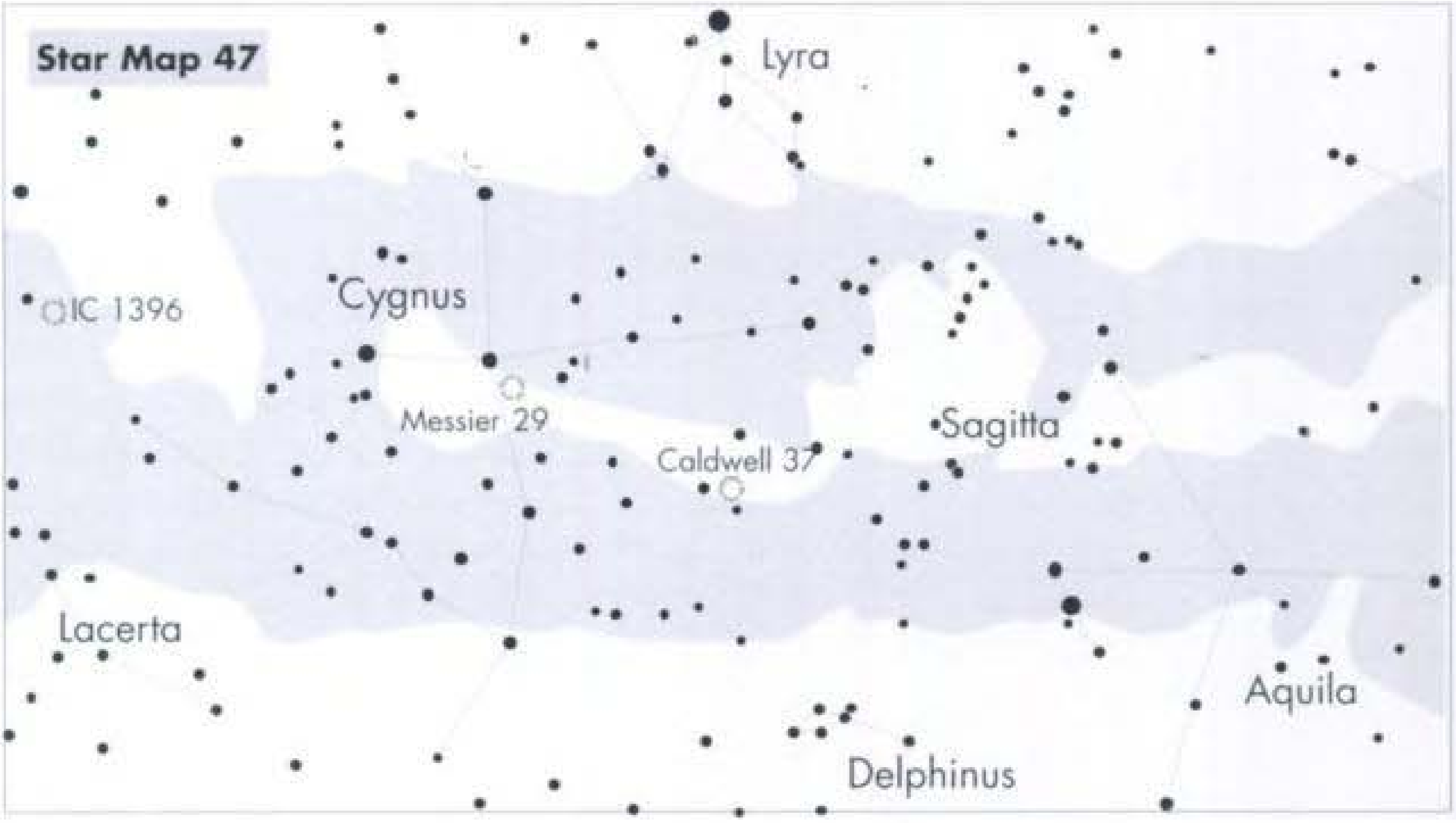
Star Map 44



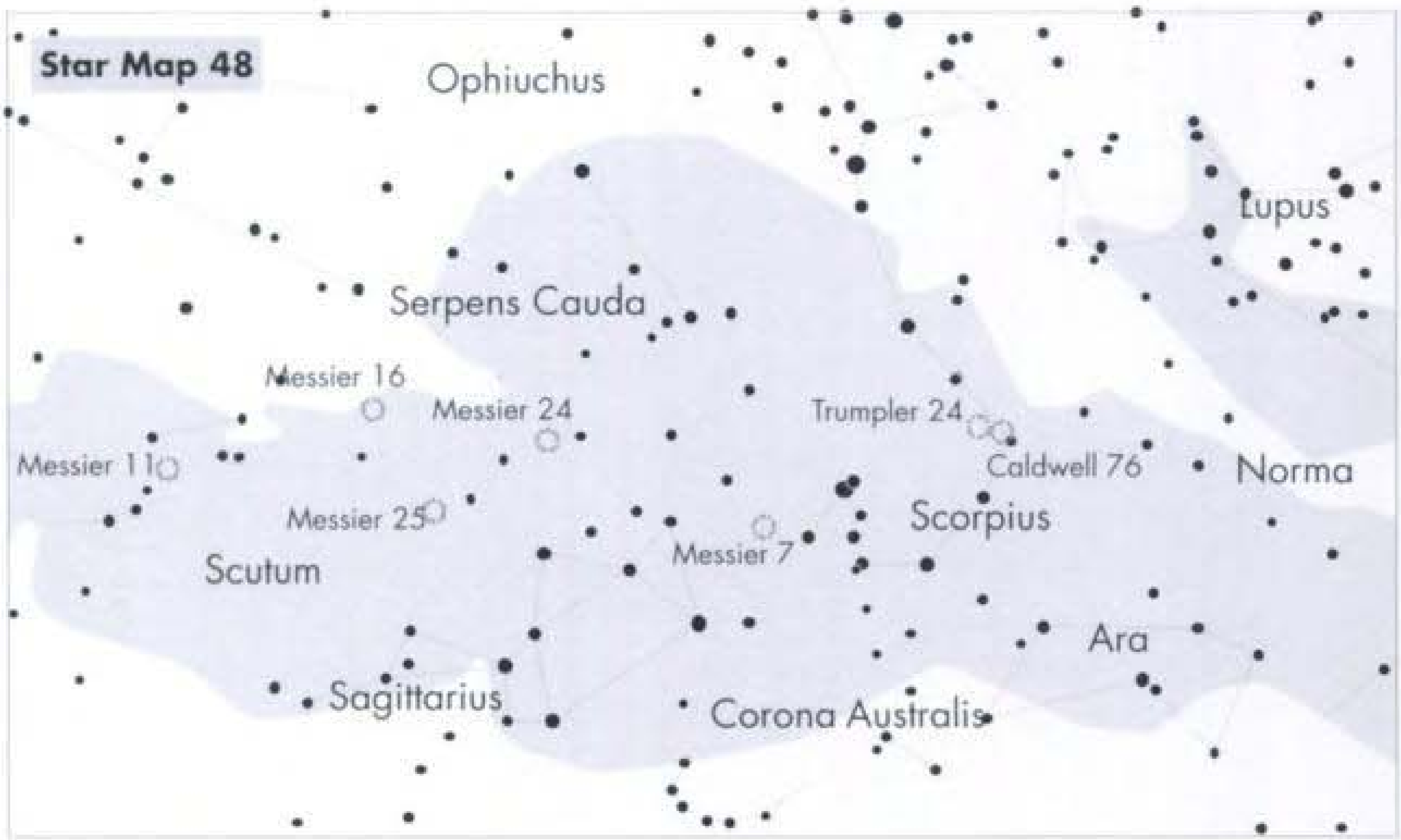
Star Map 45



Star Map 46



Star Map 47



Star Map 48

2.9 Stellar Associations and Streams

There exists another type of grouping of stars, that is much more ephemeral and spread over a very large region of the sky, and although not strictly associated with star formation, they are, however, an integral part of star evolution. Furthermore, as this is book which deals 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 they formed within and star formation will still be occurring within the cloud. Where they differ from open clusters is in the fact that they are enormous, covering both a sizable angular area of the night sky, and at the same time encompass a comparably large volume in space. As an illustration of this huge size, the *Scorpius–Centaurus Association* is around 700 by 760 light years in extent, and covers about 80°.

There are three types of stellar association:

- *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*: 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 light years. This is a consequence of the fact that massive O- and B-type stars can only be formed within the huge giant molecular clouds which are themselves hundreds of light years across. On the other hand, the T associations are much smaller affairs, perhaps only a few light years 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 amongst them will be their motion through space. The association is now called a *stellar stream*. An example of such a stream and one which often surprises the amateur (it did me!) is the *Ursa Major Stream*. This is an enormous group of stars, with the five central stars of Ursa Major (The Plough) being its most concentrated and brightest members. Furthermore, 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).

The Orion Association

1600 ly

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 ly across and 1000 ly 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 ly

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 around 80°. It is estimated to be 750 × 300 ly in size, and 400 ly deep, with the centre 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 centre. Bright stars in this association include *θ Ophiuchi*, *β*, *ν*, *δ* and *σ Scorpii*, *α*, *γ* Lupi, *ϵ*, *δ*, *μ* and *ϵ Centauri*, and *β Crucis*.

The Zeta Persei Association

1300 ly

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 ly

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 the sky, approximately 24°, and is around 20 × 30 ly in extent. It includes as members, *Sirius* (*α Canis Majoris*), *α Coronae Borea*lis, *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*, *δ Cassiopeiae* and *λ Ursae Majoris*. The stream extends to over 200 light years beyond the Hyades star cluster, and 300 light years behind the Sun. Thus, the Sun is believed to lie within this stream.

The Alpha Persei Stream	540 ly
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 amongst 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 light years in length; the distance between *29* to *ψ Persei*.	

2.10 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 star will depend on the initial mass of the protostar, and so determine where it will arrive on the main sequence. But the one thing we have not mentioned is *what causes* a protostar to form in the first place! This is the topic of the final part in this section.

The mechanisms by which provides 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 chapter 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 centre of a galaxy.[27] 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 emit immense amounts of radiation, usually in the ultraviolet part of the spectrum. This in turn causes the surrounding gas to ionise 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

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[27] We are talking about spiral galaxies here, and not elliptical. Elliptical galaxies are believed to be the results of mergers between spiral galaxies where the rate of star formation is very low.

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 which result from this induce further star formation, but at the same time, the precursor O- and B-type stars which originally started the procedure, may well have dispersed by now. In this manner an OB association "devours" a molecular cloud, leaving older stars in its wake.

The Orion nebula is one such 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 a later chapter, 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, maybe several thousand kilometres per second! This shock wave, which will be an expanding shell of material, will be moving at supersonic velocities, and in a similar manner as mentioned above, will impact on 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 forming stars, 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 don't! 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 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 traditional from other hot stars that are close by. However, in a nearby galaxy – *The Large Magellanic Cloud*[28] (LMC) – it's been

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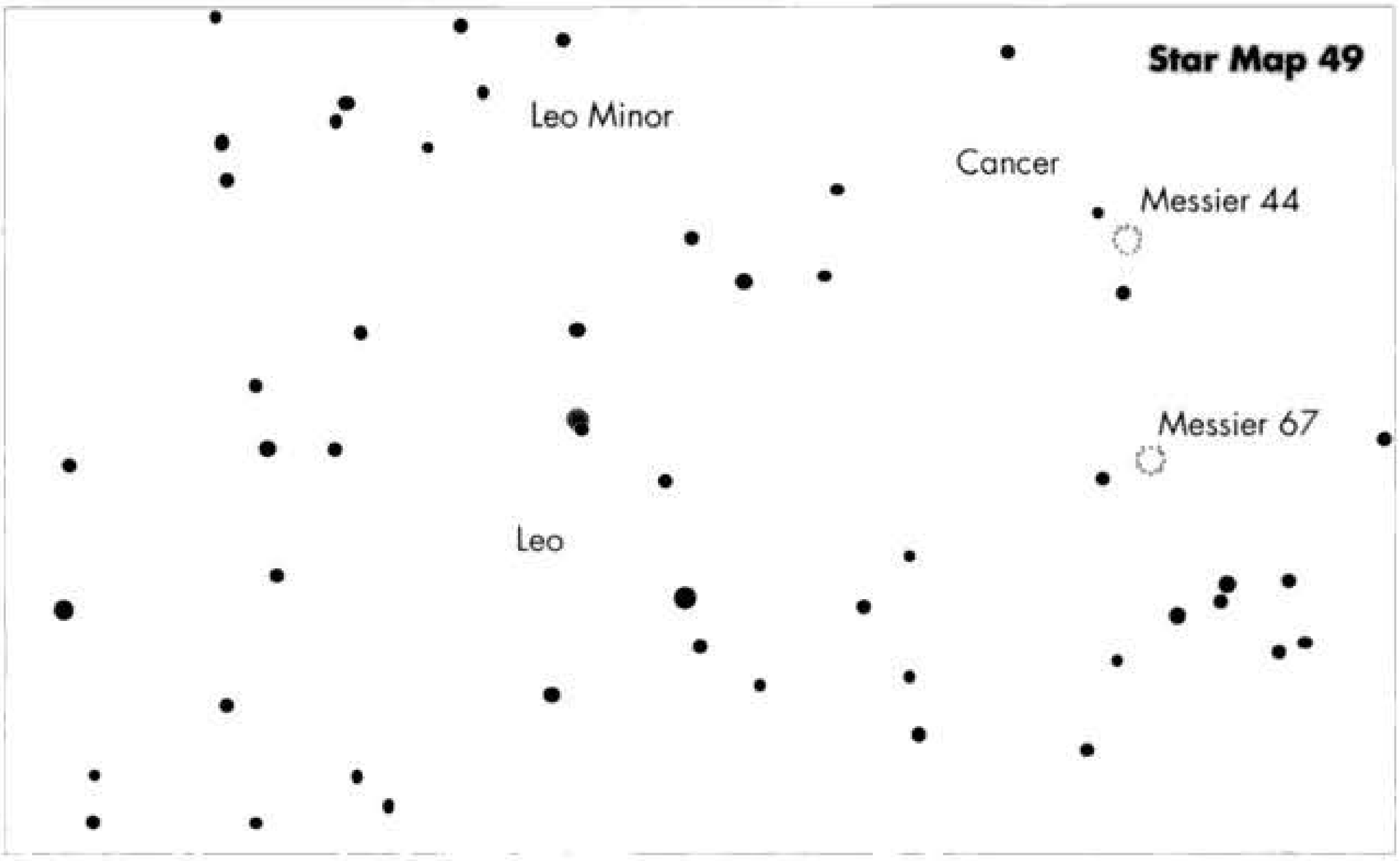
[28] It isn't a cloud at all, this is just the name ancient astronomers gave the galaxy before they knew what it really was!



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.

The next section looks in detail at the steady and stable middle ages of a star whilst it remains on the main sequence.

Chapter 3

The Main Sequence and Beyond

3.1 Introduction

Most of the stars that we observe in the night sky have all got 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 centre of its core has stopped, and now helium is burning by fusion processes; while *Sirius B* has evolved far from the main sequence and has become a white dwarf star, with no nuclear fusion occurring at all 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. This chapter then will look at these periods in a star's life, whether it is a small, low-mass and cool star, or a bright, hot and high-mass star.

Before we start to look at the many types of star 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's going on.[1] In looking at the Sun in

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[1] This is of course an exaggeration as only in the last ten years have astronomers solved (possibly!) the problem of the solar neutrino, as we shall see in a later section.

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.

3.2 Our Nearest Star – The Sun

In this section we shall look at the Sun bearing in mind it is a star on the main sequence. So I shall not discuss in any depth topics such as sunspots, the sunspot cycle, etc.,[2] but concentrate instead on the internal structure, 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 we can compare to stars that are smaller, or bigger, than the Sun.

Due to the advances not only in astronomy, but in computing as well, astronomers have been able to describe the conditions inside the Sun by solving several equations that describe how the temperature, mass, luminosity and pressure change with distance from the centre of the Sun. In order to solve them, we need to know the mechanisms by which energy is transported throughout the Sun, either with radiation or convection, the chemical composition of the Sun, and the rate of energy production at any specific distance from its centre. 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.

Now let's take a look at the structure of the Sun, and in doing so, throw in some mind-blowing statistics as well!

3.3 From the Surface to the Core

The Sun's internal structure is shown in Figure 3.1. The visible surface of the Sun, called the photosphere, has a

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[2] There are many excellent books available which are totally devoted to the Sun. See appendices for a list of suitable texts.

temperature 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 smoothly 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 there can be far greater than that of water, but remember that we are still talking about a gas, albeit one in a very strange state. It is usual to call a gas under these extreme conditions of temperature, and/or pressure, *plasma*.[3] 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 centre, the very turbulent convection zone will gave 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 into helium. The pressure in this region is nearly 200 billion times that surface pressure found on the Earth. The central temperature

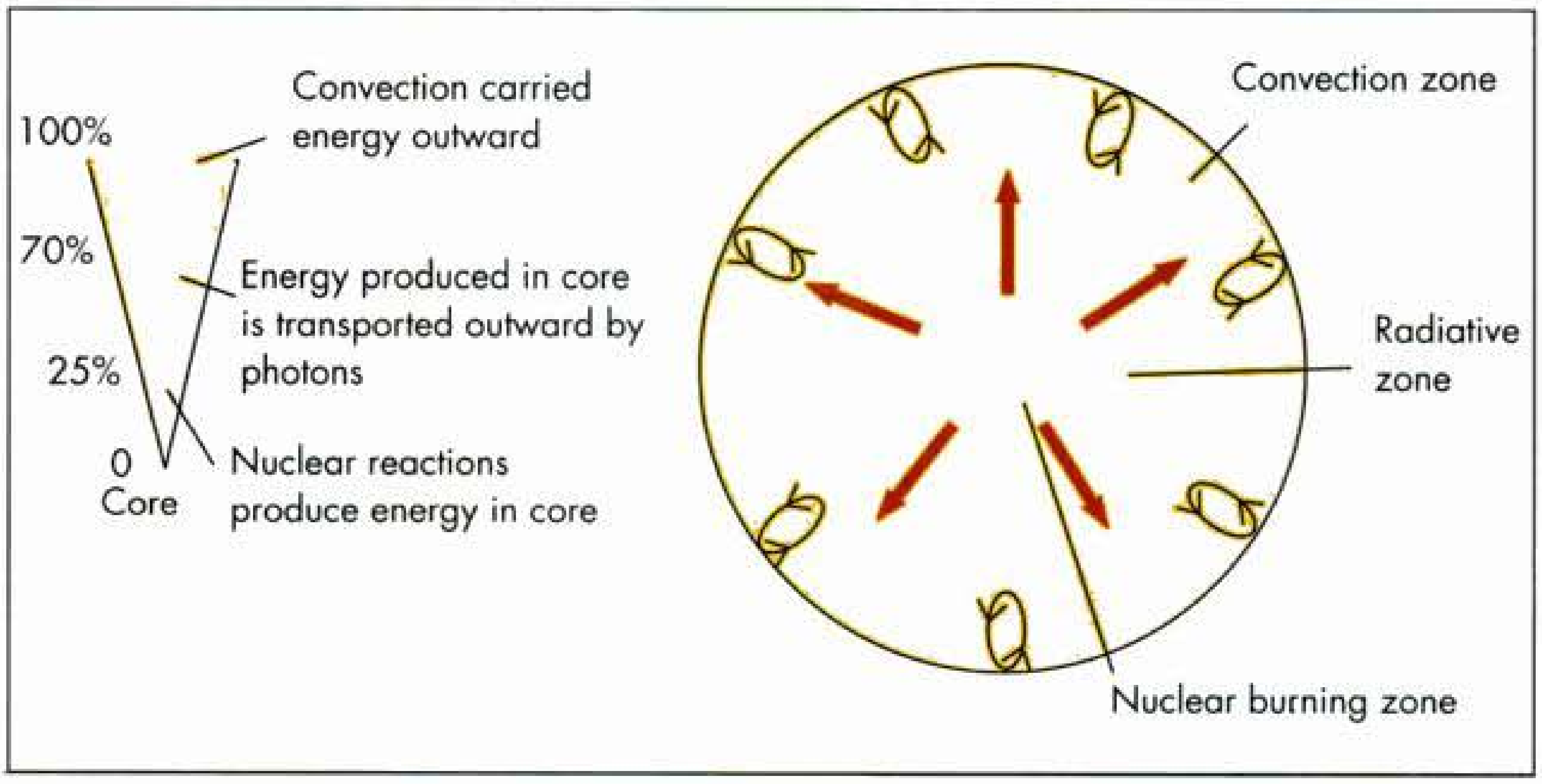

Figure 3.1. The Internal Structure of the Sun.

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[3] A plasma is a collection of positively charged ions and free electrons.

and pressure are both impressive; with the core compressed to a density of about 150,000 kg cm^{-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 the Sun's 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 one-quarter of the distance from the centre of the Sun to its core, the temperature would have fallen to about 8,000,000 K, and at this lower temperature nuclear fusion energy production will 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 has about 71% of hydrogen in it, 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 this energy, even if for only one second, then 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 of energy. 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, and 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 will increase with the depth. This makes the Sun extremely hot and dense in its core.

The efficiency by 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 distances between emission and re-absorption, than when the opacity is high (a foggy, hazy day). If opacity is low, the transport 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.

3.4 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.

The hydrogen nucleus, which is the lightest of all elements, consists 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 together and instantly make a helium nucleus. This is so unlikely to happen that it has probably never happened before, not even once, in the entire 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*.[4] The reactions begin with an interaction between two protons which must come to within 10^{-15} metres of each other in order for a nuclear reaction to occur. There is a slight problem, however, as the protons are positively charged and so, just like magnets, they will repel each other. The result of this mutual repulsion is that most collisions between protons do not result in any reaction. Instead, the

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[4] 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.

two protons deflect each other and move apart. At room temperature there is no possibility at all that two protons would collide with enough energy to get close enough to instigate a reaction.

So, for any reactions to be able to occur, we need something that will allow protons to move at very high velocities. Such a place is the centre of the Sun (and, of course, other stars). At the core of the Sun the temperature is 15 million K, and a typical proton will be travelling at about 1 million kilometres per hour. But even at this fantastic speed, the likelihood of a reaction occurring is still 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 about 5 billion years! The important point here is that there are so many protons in the Sun's core that, every second, 10^{34} of them can undergo a reaction.

The sequence of steps in the proton–proton chain is shown in Figure 3.2.

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

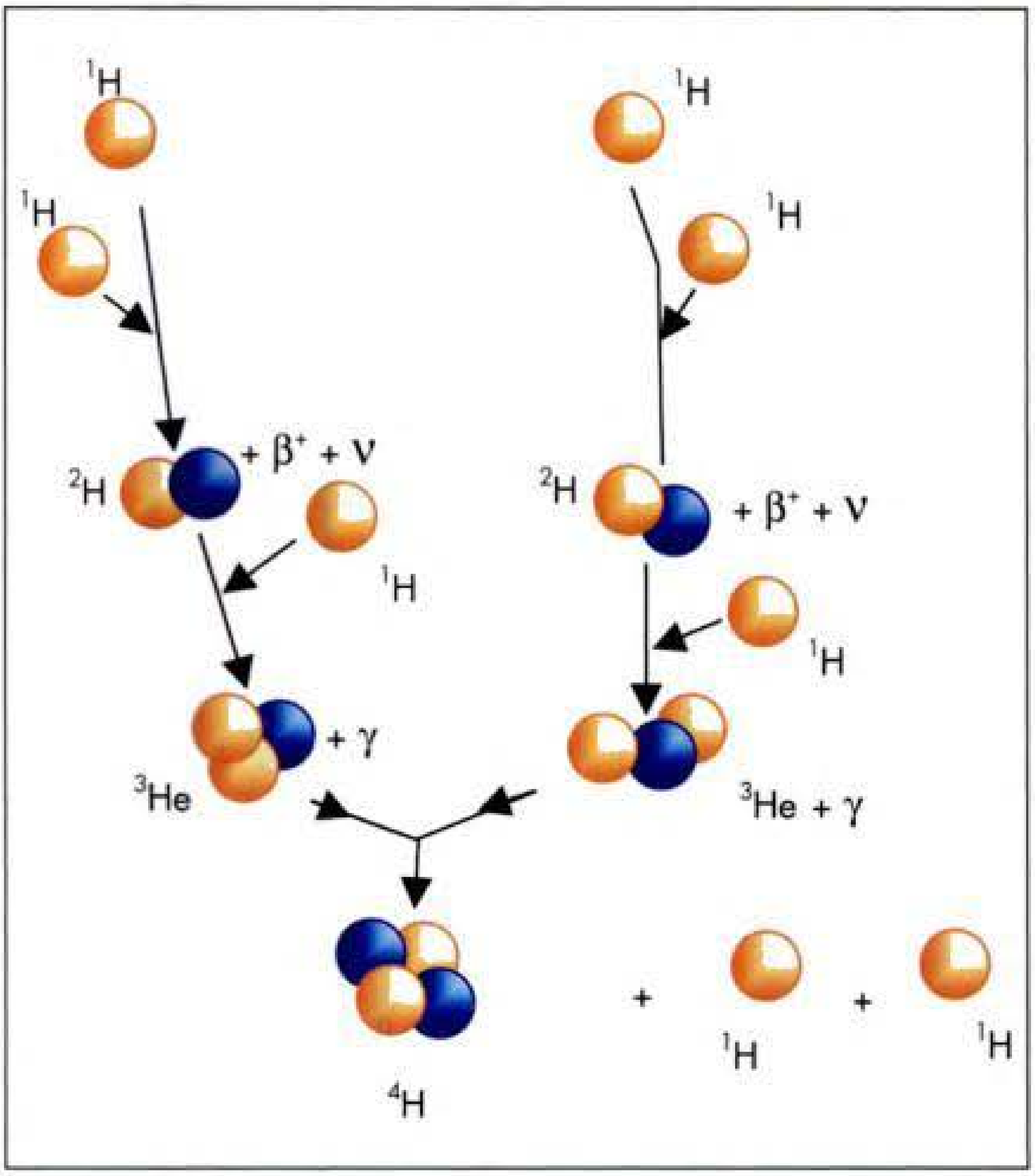

Figure 3.2. The Reactions of the Proton–Proton Chain. The symbol ν indicates a neutrino, β^+ indicates positrons, and γ indicates photons. The orange spheres represent protons, and blue spheres indicate neutrons.

other products formed are a positively charged electron, called a *positron* (β^+), and a *neutrino* (v), a minuscule particle with a tiny mass. The positron doesn't last long, however. It soon meets up with an ordinary electron and the result is the creation of two gamma rays, which are rapidly absorbed by the surrounding gas, heating up as a result. What happens to the neutrino? We shall discuss that later.

Step 2: The deuterium now fuses with a proton, producing a helium nucleus (^{3}He) and *gamma rays*. The ^{3}He nucleus consists of two protons and one neutron, whereas an ordinary helium nucleus has two protons and two neutrons. This step, of producing ^{3}He from a deuteron, takes place 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 ^{3}He nuclei, thereby making normal ^{4}He. This final step can proceed in several ways, with the most common involving a collision of two ^{3}He nuclei. Each of these ^{3}He nuclei resulted from a prior, separate occurrence of step 2 somewhere else in the core. The final result is a normal ^{4}He nucleus and two protons. On average, a ^{3}He nucleus has to wait for 4 million years before it participates in this reaction.

The net result of the chain of reaction is:

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

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 ^{4}He nucleus has a mass that is slightly less than the combined mass of the four protons that created it (by around 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. This, as you can see, 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 accord with the famous equation formulated by Einstein: $E = mc^2$. The neutrinos carry off about 2% of this energy. Since neutrinos rarely interact with matter, this energy passes straight out into space. The remaining energy emerges as kinetic energy of the nuclei, and as the radiative energy of the gamma rays.

3.5 The Flow of Energy from the Core to the Surface

Energy produced in the central region of the Sun flows outward towards 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} metres before it is absorbed again. In being absorbed, it heats up the surrounding gases, and these gases 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 reemissions occur before energy reaches the surface. This slow, outward migration of photons is often called a *random walk*.

The above process means that there is a considerable time delay before energy produced at the core reaches the surface. On average, about 170,000 years will pass before energy created at the core, eventually reaches the surface.[5] Furthermore, the energy produced in one second does not all 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, and some 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. Firstly, when we observe the light emitted by the Sun, we learn

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[5] 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.

Mass and Energy Conversion in the Sun

It is easy to calculate how much mass the Sun loses through nuclear fusion. First let's 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 6.90×10^{-27} kg.

A single ^{4}He nucleus has a mass of only 6.643×10^{-27} kg, which is slightly less than the mass of four protons; i.e.:

$$6.90 \times 10^{-27}\ \text{kg} - 1.6726 \times 10^{-27}\ \text{kg} = 4.7 \times 10^{-29}\ \text{kg}$$

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. In order to calculate the total amount of energy, let's use Einstein's famous equation: $E = mc^2$.

The total amount of energy that the Sun produces each second is 3.8×10^{26} joules, so the total mass converted to energy is given by:

$$E = mc^2 \Rightarrow m = \frac{E}{c^2} = \frac{3.8 \times 10^{26}\ \text{joules}}{(3.0 \times 10^8\ \text{ms}^{-1})} = 4.2 \times 10^9\ \text{kg}$$

Thus, the Sun loses about 4 billion kg of mass every second, which is about the same as the mass of 100 million people.

Let's now see how much hydrogen is converted to helium every second. We know that the Sun loses 4.2×10^9 kg of mass every second, and this is only 0.07% of the mass of hydrogen that is fused:

$$4.2 \times 10^9\ \text{kg} = 0.007 \times [\text{mass of hydrogen fused}]$$

$$\begin{aligned} \text{mass of hydrogen fused} &= \frac{4.2 \times 10^9\ \text{kg}}{0.007} \\ &= 6.0 \times 10^{11}\ \text{kg} \\ &\qquad \times \frac{1\ \text{metric tonne}}{10^3\ \text{kg}} \\ &= 6 \times 10^8\ \text{metric tonnes} \end{aligned}$$

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

nothing about what is going on in the core *at this moment*. All we can say is that energy was created in the core many 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 with amateur astronomers. But let me say: **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. Don't do it. Instead, project the Sun onto a card. There are several excellent books on solar observing and a very recent one is by Chris Kitchin and called *Observing the Sun*, which I thoroughly recommend.

3.6 Main Sequence Lifetimes

We have covered topics that describe how a star forms, and how long it takes to become a star, but 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 billion years, the core has a much greater mass of helium than 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 appearance of the star. 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 will increase its density and temperature. This has the effect of causing the hydrogen nuclei to collide with each much more often, which increases the rate of hydrogen burning. The resulting increase of core pressure causes the star 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 increase of luminosity. In addition, the surface temperature will increase as well. In the case of the Sun, astronomers have calculated that the Sun has increased its luminosity by 40%, its radius by 6%, and its surface temperature by 300 K, all during the past 4.6 billion years.

As the 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 the mass of the star. Basically it can be summed up in a few words – "*low-mass stars have much longer lifetimes than high-mass stars*". Figure 3.3 illustrates this nicely.

High-mass stars are extremely bright, and their lifetimes are also 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 contains more hydrogen than, say, a less massive M-type star, it will use up its hydrogen much sooner than the M-type star. It may only take a few million years for O- or B- type stars to

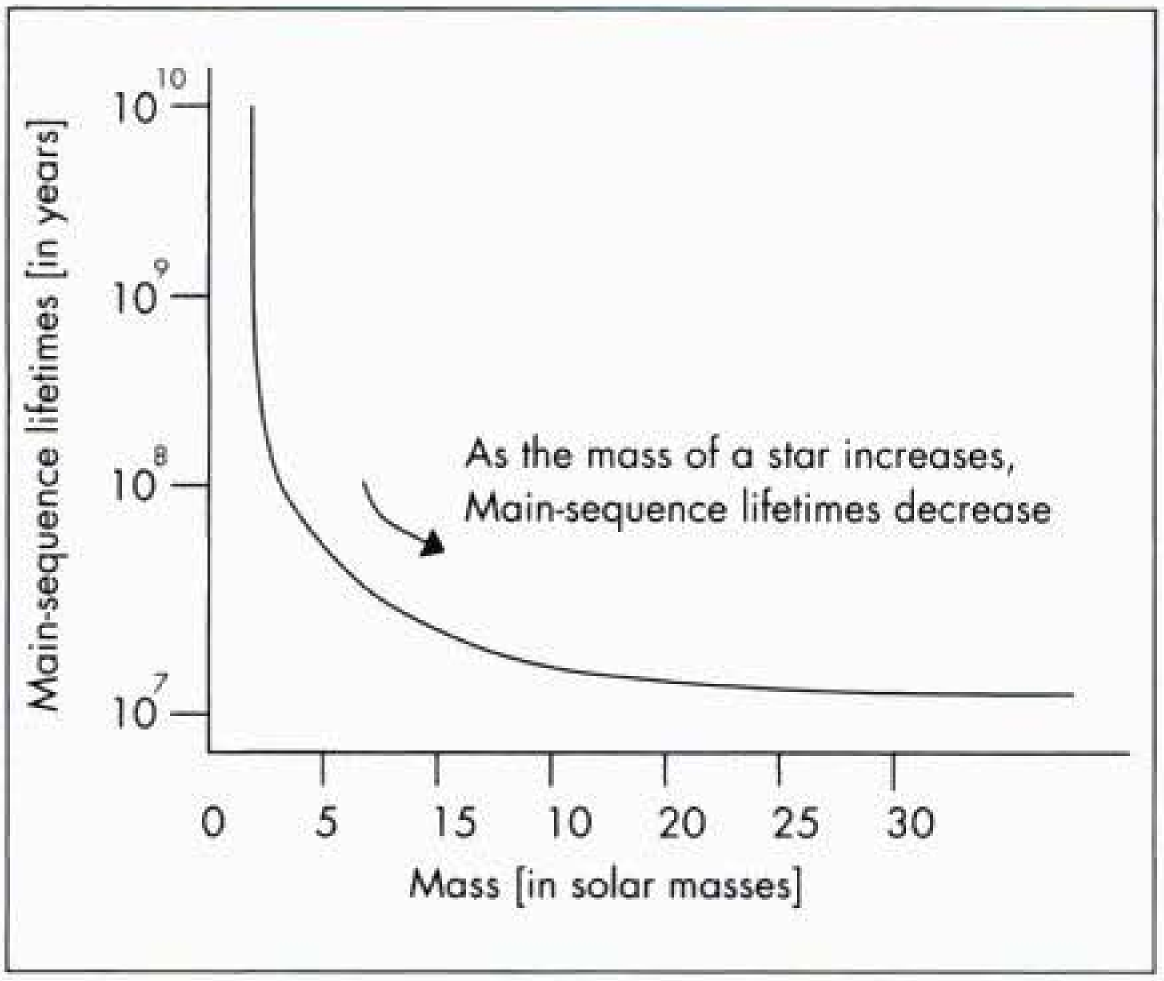

Figure 3.3. Main Sequence Lifetimes for Stars of Different Mass.

use up their supply of hydrogen, whereas for a low-mass M-type star, 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*![6] Table 3.1 shows the mass of a star relates to temperature and spectral class.

The differing lifetimes of stars can be easily demonstrated 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 star in 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 3.4 shows this erosion of main-sequence stars by comparing the H–R diagrams of several different star clusters. In every case, some

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	15
3	11,000	A	60	500
1.5	7000	F	5	3000
1	6000	G	1	10,000
0.75	5000	K	0.5	15,000
0.5	4000	M	0.03	200,000

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[6] We shall discuss this remarkable fact in later sections.

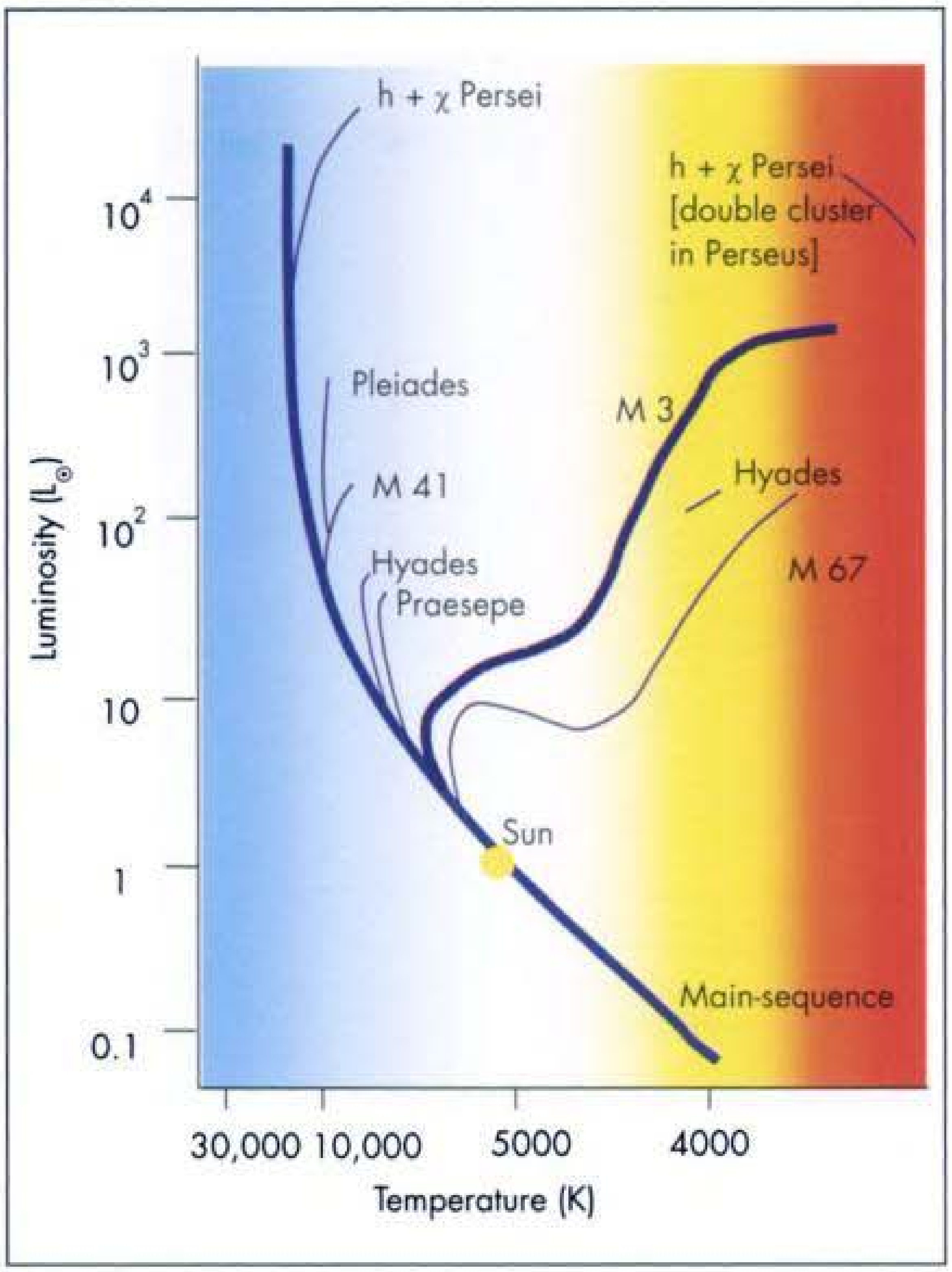

Figure 3.4. H–R Diagrams for Several Star Clusters of Different Ages.

stars will have left the main sequence to become red giants,[7] or are already red giants.

The temperature and the 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 that is 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 on it for such a long time. It is also very easy to estimate the lifetime of a star if we know its mass.

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[7] See the next section for a discussion on red giant stars.

Main Sequence Lifetimes

The length of time 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:

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

and 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 9 $M_\odot$ star will be:

$$\frac{1}{9^{2.5}} = \frac{1}{9^2\sqrt{9}} = \frac{1}{243} \text{ solar lifetimes}$$

So a 9 $M_\odot$ star will burn hydrogen in its core for about 1/243 10^{10} years, or about 40 million 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.

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: *Regulus, Vega, Sirius A, Procyon A, the Sun,* and *Barnard's Star,* to name but a few.

3.7 Towards the Red Giant

Although the amount of hydrogen in the core of a star 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 is due 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 3.5.

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 centre of the star, where, along with the helium already there, heats up as the core continues to contract and

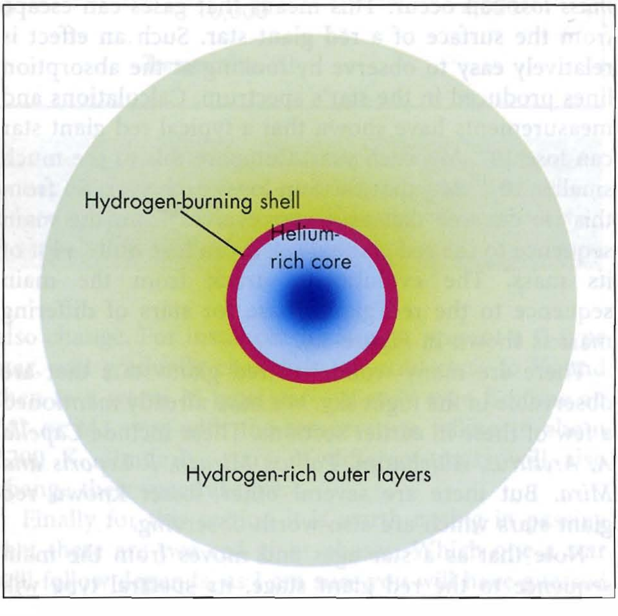


Figure 3.5. Star with Shell Hydrogen Burning. The core will consist of helium but the outer layers are hydrogen rich. The shell where energy production occurs is realtively thin (not to scale).

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 of 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 been inside it, and so invisible to our eyes. Nevertheless, it does have effects on the structure of a star, which drastically alters its appearance. The star's outer layers expand as the core contracts. What with the increasing 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 that we 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 to the much smaller 10^{-17} $M_\odot$ that the Sun loses each year. So 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 3.6.

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

Note that as a star ages and moves from the main sequence to the red giant stage, its spectral type will

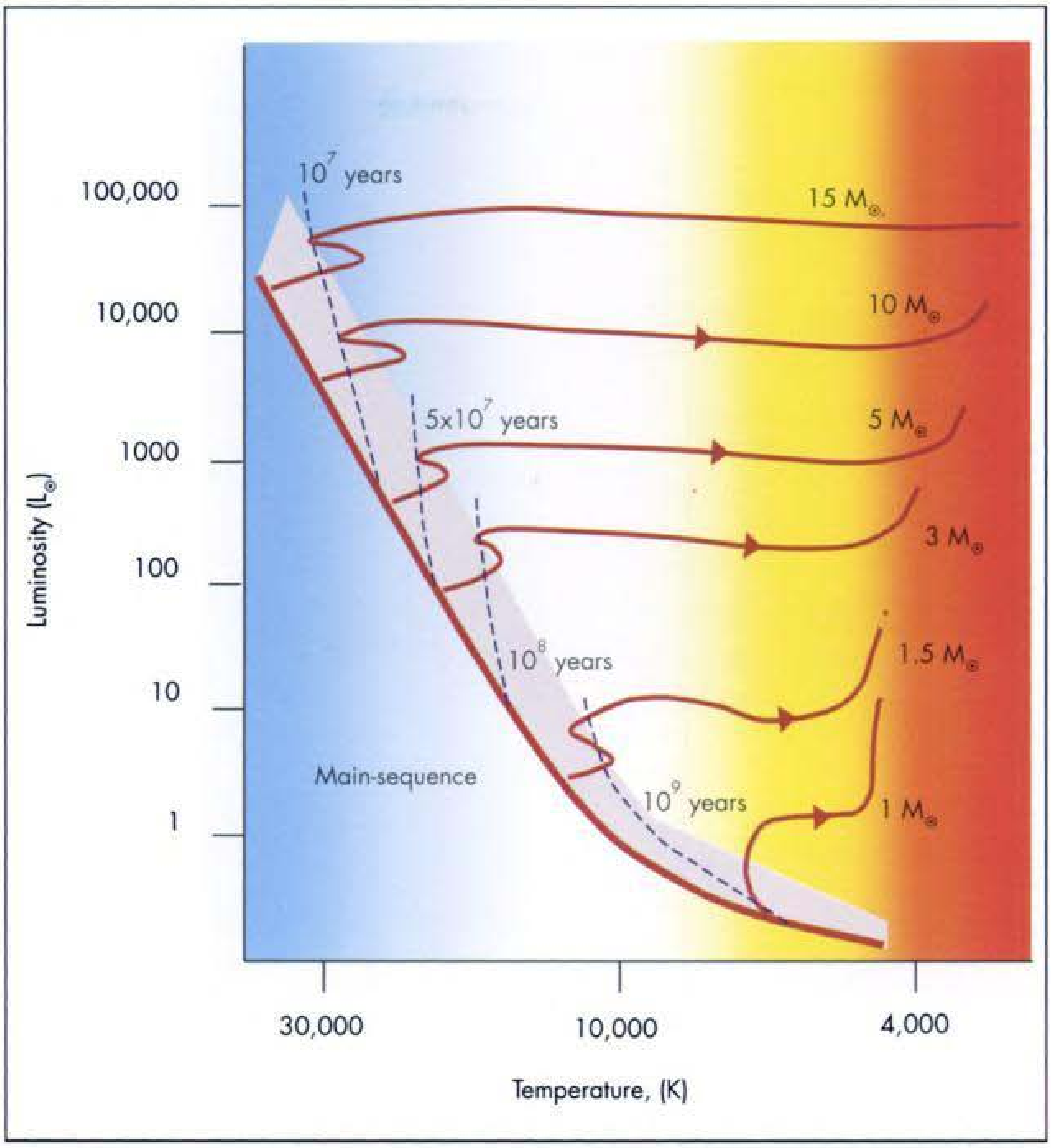


Figure 3.6. Evolutionary Tracks from the Main Sequence to the Red Giant Phase for Stars of Different Mass. The dotted blue lines indicate time scales of 10 million, 50 million, 100 million and 1 billion years. You can see that a star of about 15 solar masses leaves the main sequence (the shaded area) around 100 times earlier than a star of 1.5 solar masses.

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 mass 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 the star's mass and can lead to the formation of *supergiant* stars. We will discuss these in a later and more appropriate section.

RS Cyg	HD 192443	20^h 13.3^m	+38° 44′	Jun-**Jun**-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 9.5m. A strange star where the light curve can vary appreciably, with the maxima sometimes doubling. A deep red-coloured star. See Star Map 50.

19 Piscium	TX Psc	23^h 46.4^m	+03° 29′	Aug-**Sep**-Oct
4.95_vm	B-V:2.5	C5 II	3500 K	Pisces

A slow, irregular-period variable star. Classification LB, with a magnitude range of 4.8 to 5.2m. The colour is an orange-red, best seen in small instruments. It lies at a distance of 750 ly. See Star Map 51.

R Aqr	HD 222800	23^h 43.8^m	-15° 17′	Jul-**Aug**-Sep
5.8_vm	B-V:1.5	M4 pe	2500 K	Aquarius

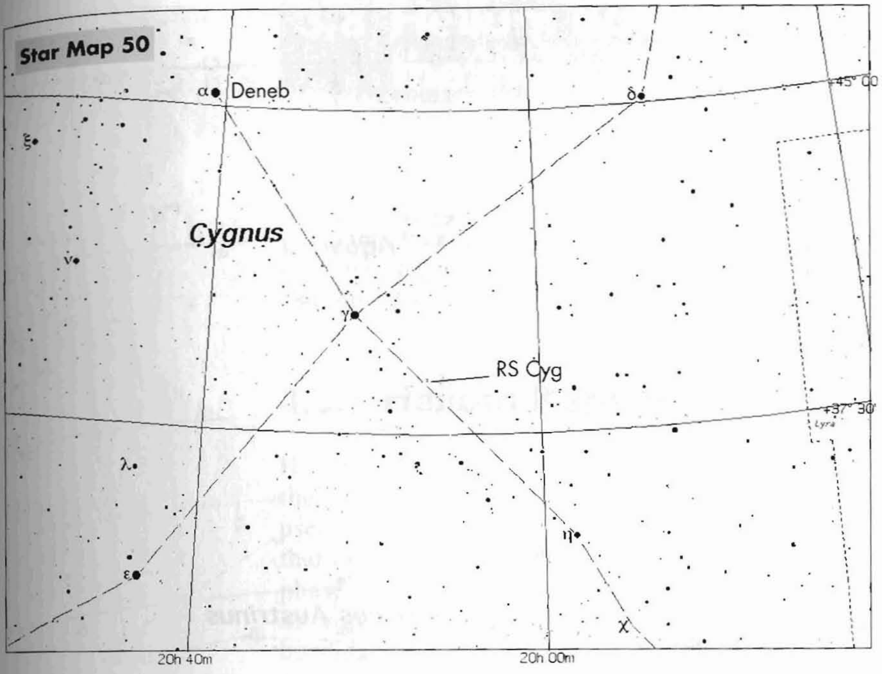
This is a symbiotic double star and is classed as a *Z Andromedae* type star. *R Aqr* is a nice red giant, which incidentally has a small, blue - thus, very hot - companion star. Due to its variable nature, its magnitude can fall to 11.5, and so be somewhat difficult to locate. It is believed to lie at a distance of about 640 ly. It is also an AGB star (see the section on Star Death). See Star Map 52.

R Cas	HD 224490	23^h 58.4^m	+51° 23′	Sep-**Oct**-Nov
5.5_vm	B-V:1.5	M7 IIIe	2000 K	Cassiopeia

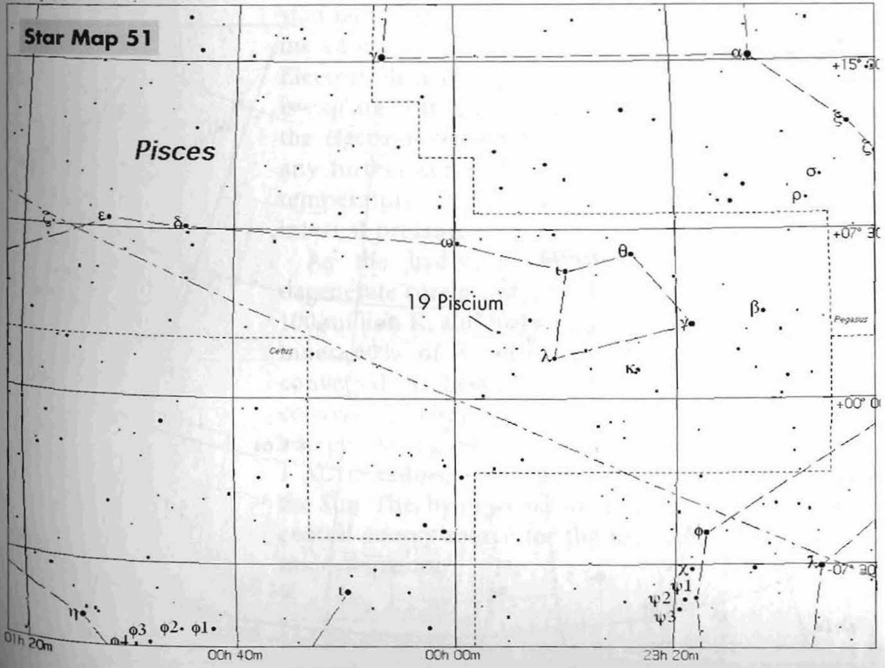
This is a Mira-type variable star with quite a large magnitude range, 5.5–13.0m. It is estimated to lie at a distance of 350 ly. Its surface temperature of only 2000 K is still a matter of speculation. It is also an AGB star (see the section on Star Death). See Star Map 19.

R Leo	HD 84748	09^h 47.6^m	+11° 26′	Jan-**Feb**-Mar
6.02_vm	B-V:1.5	M8 IIIe	2000 K	Leo

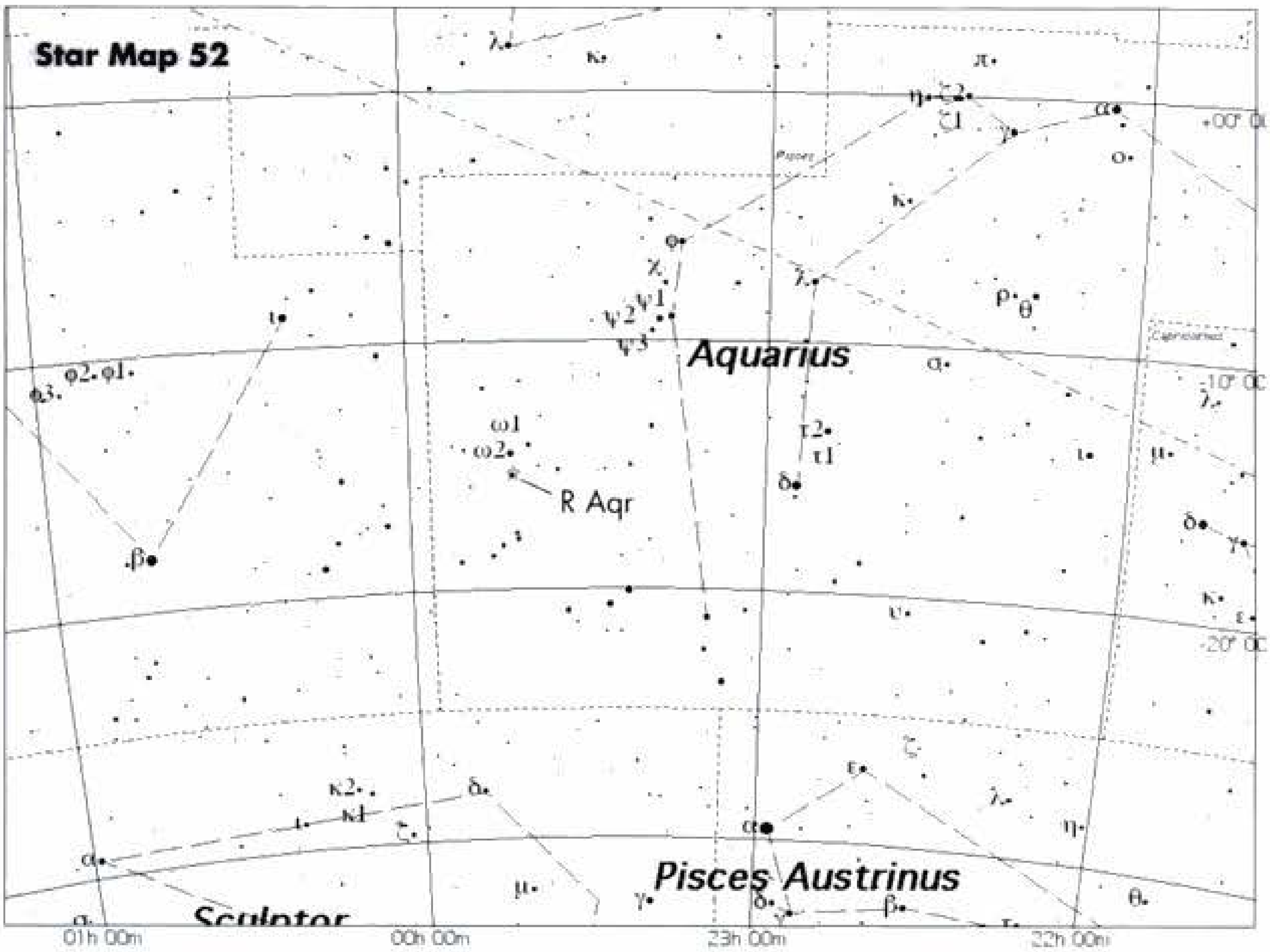
A very bright Mira-type variable star and a favourite with amateur astronomers. Again, like so many other red giants, its low temperature of 2000 K is in some doubt. It is a very deep red colour. This star is often cited as being a perfect introductory star for those who wish to observe a variable star. It is also an AGB star (see the section on Star Death). See Star Map 19.



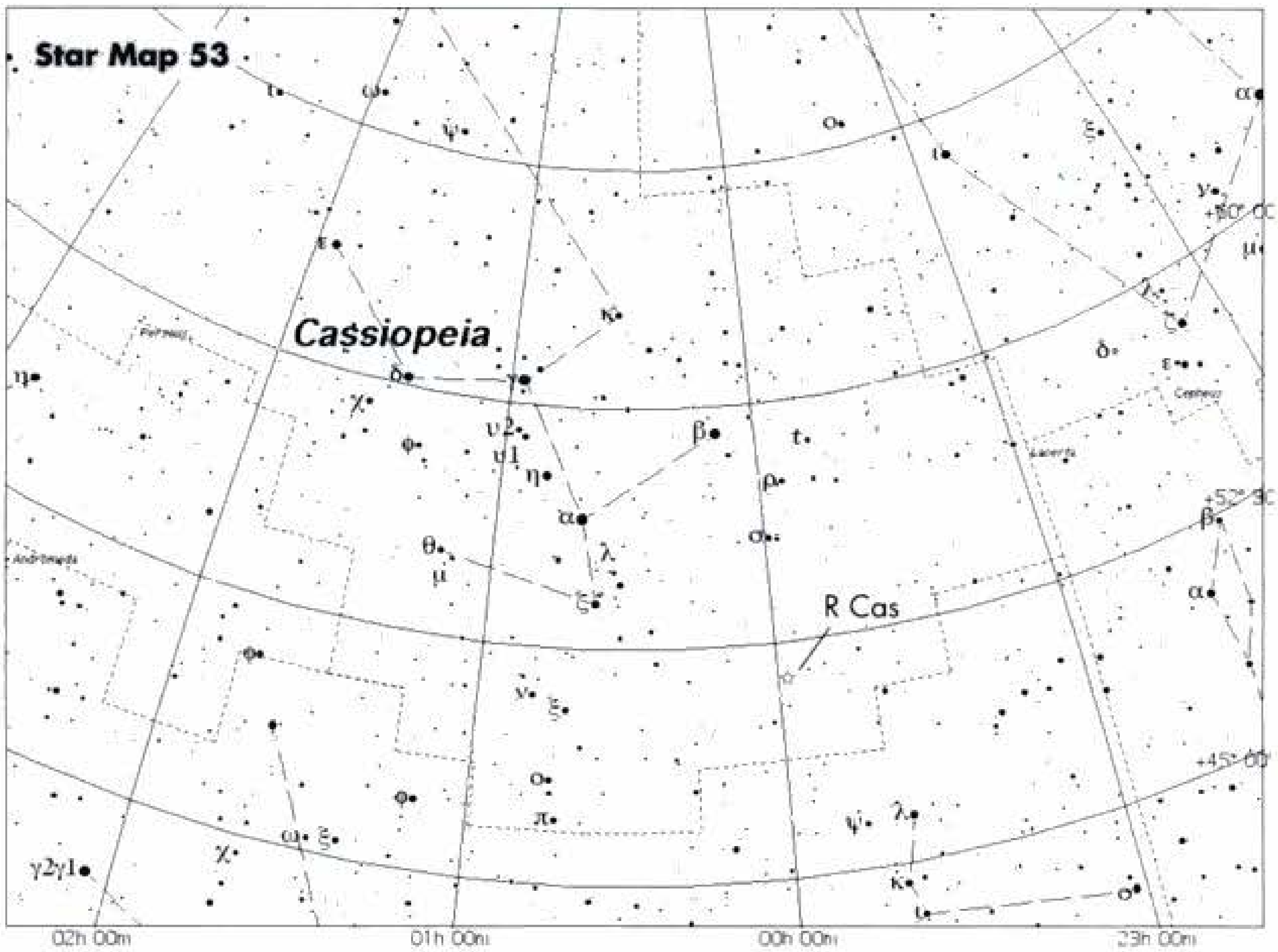
Star Map 50



Star Map 51



Star Map 52



Star Map 53

3.8 Helium Burning and the Helium Flash

All the stars that have 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.

3.8.1 Helium Burning

Helium can be though 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, that 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 which surrounds the dormant helium core, adds mass to the core, with the result that it contracts further, becomes denser and the temperature increases substantially.[8] 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. The, by now, old star has once again obtained a central energy source for the first time since it left the main sequence.

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[8] 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.

The helium burning in the core fuses three helium nuclei to form a carbon nucleus, 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 is 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 origin of the phrase "triple α" comes about because helium nuclei are also called alpha particles.[9] 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 these isotopes of oxygen and carbon are the most abundant forms, and in fact make up the majority of carbon atoms in our bodies, and the oxygen which we breathe. We will explore this fascinating piece of information in greater depth later in the 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 length 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.

3.8.2 The Helium Flash

As I mentioned earlier, the mass of the star will decide on 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

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[9] If you are a particle physicist!

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 of less than 2–3 $M_{\odot}$, the helium burning stage can begin very 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 do, however, is 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 the solar luminosity. This converts to a rate of energy outut 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 no matter whether the helium flash occurs or doesn't occur, the start of helium burning actually reduces the luminosity of the star. 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 also allows its outer layers to contract from their peak size during the red giant phase. As the outer layers contract, so 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.

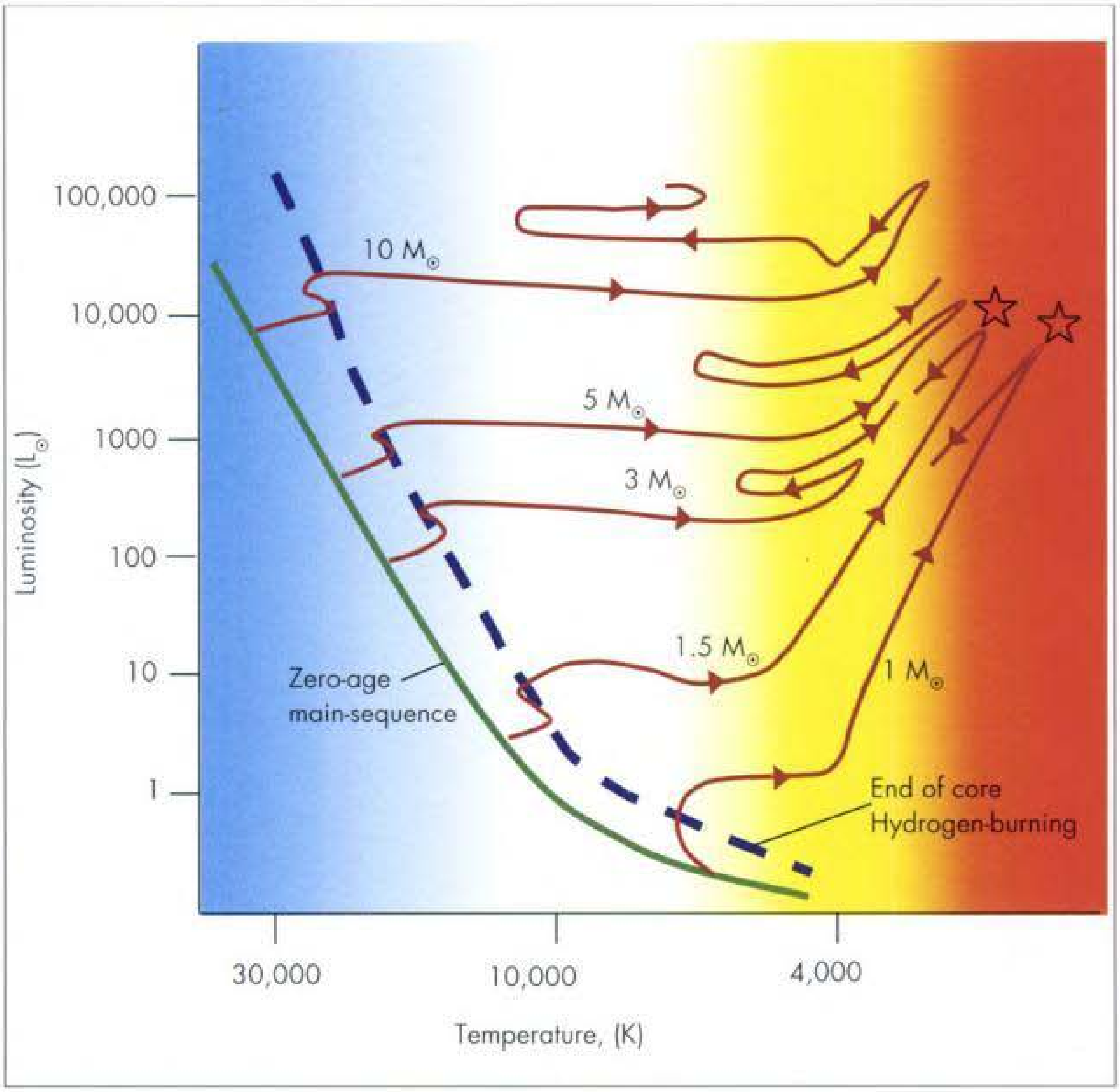
3.9 Red Giants, Star Clusters and the H–R Diagram

At this point on our story of stellar evolution, it is a good idea if we take stock of what we have learned so far. We have discussed how stars are formed before moving on to 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 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 this 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 3.7 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 blue-dashed line in Figure 3.7 represents those stars where 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 the phase, the core is contracting and outer layers expanding as energy flows from the hydrogen-burning shell.

Figure 3.7. Post-Main Sequence Evolutionary Track for Several Different Mass Stars. 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 of the H–R diagram. This occurs just before the onset of core helium-burning. After the start of helium-burning, the core then expands, the outer layers contract, and the evolutionary track of the star falls from these high, albeit temporary, luminosities. Notice how the tracks then just wander back and forth on the H–R diagram. This represents the stars readjusting 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 rise. This occurs because the reduction in luminosity is proportionally less than the reduction in size. So now 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 then 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.

3.10 Post-Main Sequence Star Clusters: The Globular Clusters

In the night sky are many compact and spherically shaped collections of stars. These star clusters are called *globular clusters*. These are metal-poor stars and are usually to be found in a spherical distribution around the galactic centre at a radius of about 200 light years. Furthermore, the number of globular clusters increases significantly the closer one gets to the galactic centre. This means that particular constellations which are located in a direction towards 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 to 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 the oldest structures in our Galaxy. In fact, the youngest of the globular clusters is still far older than the oldest open cluster. The origin of the globular clusters is a scene of fierce debate and research with the current models predicting that the globular clusters may have been formed within the proto-galaxy clouds which went to make up our Galaxy.

As mentioned above, the 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 *colour–magnitude diagram.* On a colour–magnitude diagram, the apparent brightness is plotted against the colour ratio for many of the stars in a cluster, as in Figure 3.8. The colour 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 brightnesses can tell us their relative luminosities.

Even a cursory glance at such a colour–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 all the high-mass stars in a globular cluster have evolved into red giants a long time ago. What are left 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 towards the centre-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 around 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.

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 this time can be used to determine

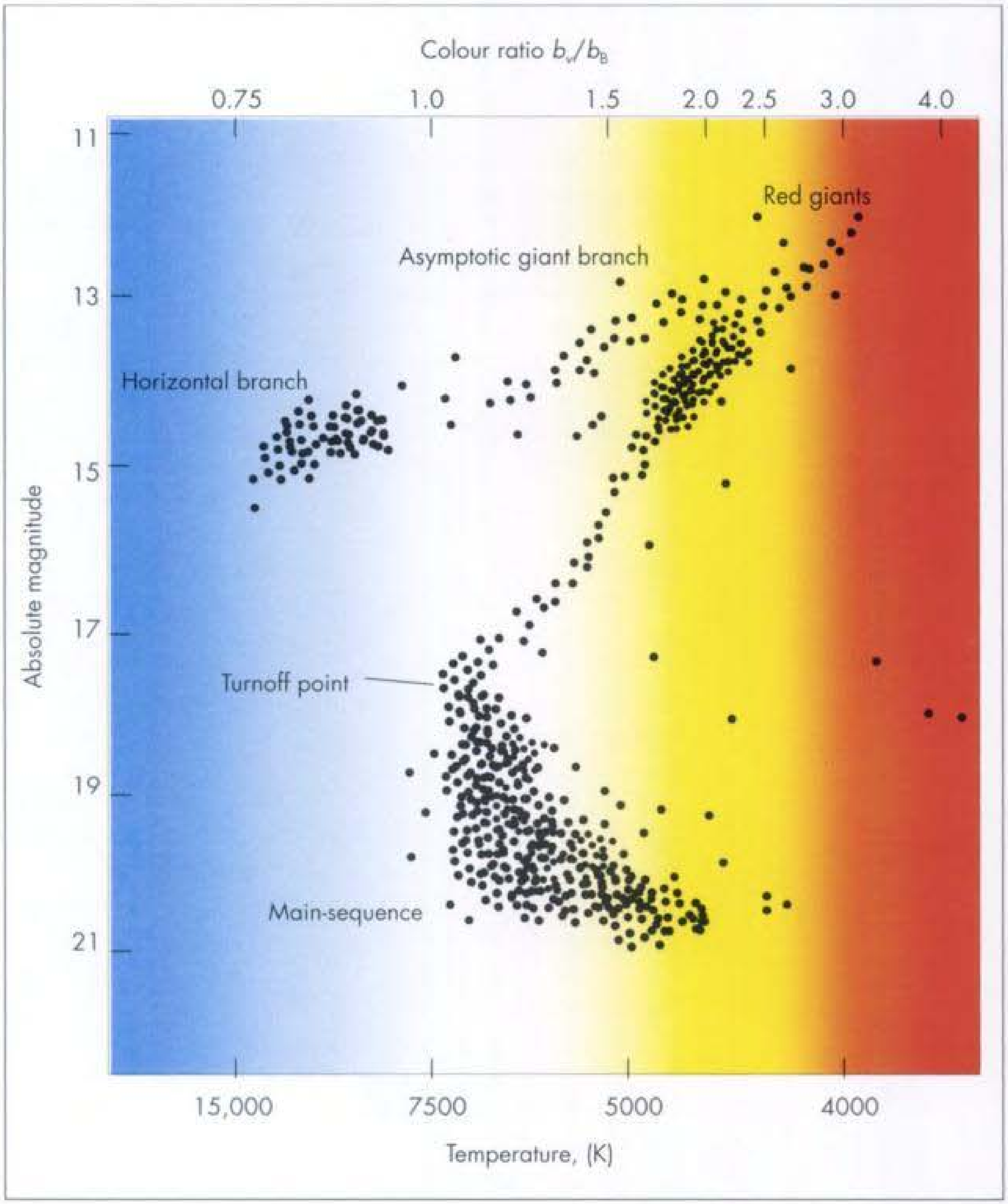


Figure 3.8. Colour–Magnitude Diagram for the Globular Cluster M3. A star that has had its surface temperature and visual magnitude determined is represented by a black dot. All the stars in M3 lie at approximately the same distance from us (32,000 ly), so their magnitudes are a direct measurement of their luminosities. The asymptotic giant branch is described in Section 4.1.

the clusters 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 3.9.

From an observational point of view, globular clusters are ideal, if not a challenge. Many are visible in optical instruments, from binoculars to telescopes, and a few are even visible to the naked eye. There are about 150 globular clusters ranging in size from 60 to 150 light years in diameter. They all lie at vast distances from the Sun, and are about 60,000 light years from the *Galactic plane.* The nearest globular clusters, for example *Caldwell 86* in *Ara* lies at a distance of over 6000 light years, and thus the clusters are difficult objects for small telescopes. That is not to say they can't be seen, rather, it means that any structure within the cluster will be difficult to observe. Even the brightest and biggest globular will need apertures of at least

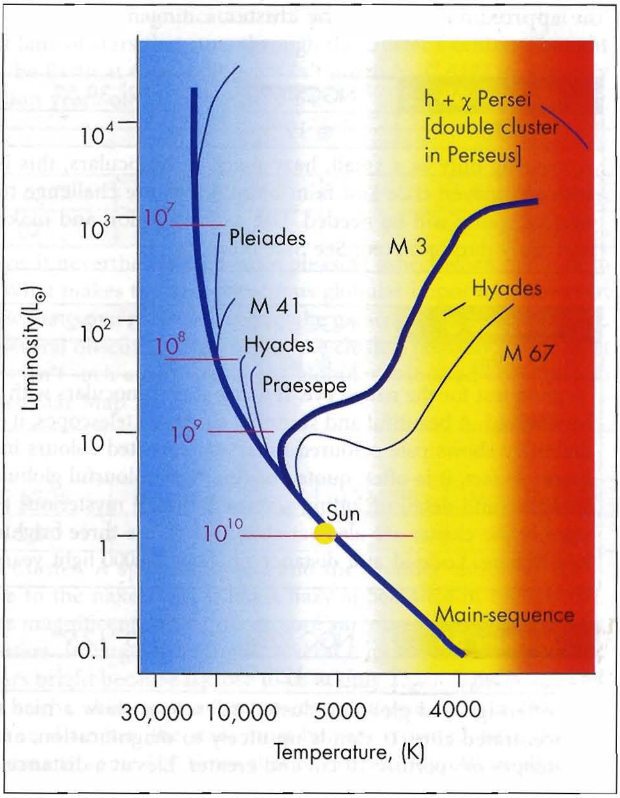


Figure 3.9. H–R Diagram for Star Clusters Showing the Turnoff Point. The time for the turnoff point is shown as a purple line. For example, the cluster M41 has a turnoff point near the 10^8 year point, so the cluster is about 100,000,000 years old.

15 cm for individual stars to be resolved. However, if large aperture telescopes are used, then these objects are magnificent. Some globular clusters have dense concentrations towards their centre whilst 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.

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, while Class XII is the least star-dense. The ability of an amateur to resolve the stars in a globular actually depends on how condensed the cluster actually is, and so the scheme will be used in the descriptions, but it is only really useful for those amateurs who have large aperture instruments. Nevertheless, the observation of these clusters which are amongst 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.

Messier 68	NGC 4590	$12^h\ 39.5^m$	−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 will be needed. Use averted vision and make sure that your eyes are well and truly dark-adapted. See Star Map 55.				

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, some stars may be resolved. A beautiful and stunning cluster in telescopes, it easily rivals *M13* in *Hercules*. It definitely shows pale coloured tints, and reported colours include yellow, blue and even green; in fact, it is often quoted as the most colourful globular in the northern sky. Full of structure and detail including several dark and mysterious tiny dark patches. Many of the stars in the cluster are also variable. One of the three brightest clusters in the northern hemisphere. Located at a distance of about 35,000 light years. See Star Map 55.				

Messier 53	NGC 5024	$13^h\ 12.9^m$	+18° 10′	Mar–**Apr**–May
7.5m	⊕ 12″		V	Coma Berenices
An often-ignored globular cluster, telescopes show a nice symmetrical glow with a concentrated core. It stands up nicely to magnification, and indeed is lovely sight in telescopes of aperture 10 cm and greater. Lies at a distance of around 330,000 light years. See Star Map 55.				

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 coloured globulars, with a faint, pale yellow outer region surrounding a blue-tinted interior. It gets even better with higher magnification, as more detail and stars become 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. See Star Map 55.

Messier 80	NGC 6093	$16^h\ 17.0^m$	−22° 59′	Apr–**May**–Jun
7.3m	⊕ 8.9″		II	Scorpius

Telescopes will be needed to resolve its 14th-magnitude stellar core. One of the few globulars to have been the origin of a nova, *T Scorpii*, when it flared to prominence in 1860, then disappeared back into obscurity within 3 months. See Star Map 54.

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 that the glare of the latter may prove a problem in the 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 centre. Thought to be the closest globular to the Earth at 6500 light years (although *NGC 6397* in *Ara* may be closer), and about 10 billion years old. See Star Map 54.

Messier 107	NGC 6171	$16^h\ 32.5^m$	−13° 03′	Apr–**May**–Jun
8.1m	⊕ 10″		X	Ophiuchus

Not visible with the naked eye, it nevertheless presents a pleasing aspect when medium to high magnification is used. What makes this inconspicuous globular important, however, is that it is one of the very few that seem to be affected by the presence of interstellar dust. Deep imaging has revealed several obscured areas within the cluster, possibly due to dust grains lying between us. This isn't such a surprise, as the globular is located over the hub of the Galaxy in *Scorpius*. See Star Map 54.

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 is close to us at only 23,000 light years, and also because it is inherently bright, shining at a luminosity equivalent to over 250,000 Suns. At only 140 light years in diameter, the stars must be very crowded, with several stars per cubic light year, a density some 500 times that of our vicinity. All in all a magnificent cluster. See Star Map 54.

Messier 12	NGC 6218	$16^h 47.2^m$	–01° 57′	May–**Jun**–Jul
6.8m	⊕ 14.5″		IX	Ophiuchus

In telescopes of aperture 20 cm and more, this cluster is very impressive, with many stars being resolved against the fainter background of unresolved members. It is nearly the twin of Messier 10, which is within 3° south-east. See Star Map 54.

Messier 10	NGC 6254	$16^h 57.1^m$	–04° 06′	May–**Jun**–Jul
6.6m	⊕ 15″		VII	Ophiuchus

Similar to M12, it is, however, 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 coloured components have been reported: a pale blue tinted outer region surrounding a very faint pink area, with a yellow star at the cluster's centre. See Star Map 54.

Messier 19	NGC 6273	$17^h 02.6^m$	–26° 16′	May–**Jun**–Jul
6.7m	⊕ 13.5″		VIII	Ophiuchus

A splendid, albeit faint, cluster when viewed through a telescope. Although a challenge to resolve, it is nevertheless a colourful object, reported as having both faint orange and blue stars, while the overall colour of the cluster is a creamy white. See Star Map 54.

Messier 9	NGC 6333	$17^h 19.2^m$	–18° 31′	May–**Jun**–Jul
7.6m	⊕ 9.3″		VII	Ophiuchus

Visible in binoculars, this is a small cluster, with a brighter core. The cluster is one of the nearest to the centre 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 light years away. See Star Map 54.

Messier 22	NGC 6656	$18^h 36.4^m$	–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 owing to its low declination. Only 10,000 light years away, nearly twice as close as *M13*. See Star Map 54.

Messier 92	NGC 6341	$17^h 17.1^m$	+43° 08′	May-**Jun**-Jul
6.4m	⊕ 11″		IV	Hercules

A beautiful cluster, often overshadowed by its more illustrious neighbour, M13. In binoculars it will appear as a hazy small patch, but in 20cm 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 light years distant. See Star Map 54.

Messier 14	NGC 6402	$17^h 37.6^m$	-03° 15′	May-**Jun**-Jul
7.6m	⊕ 11.7″		VIII	Ophiuchus

Located in an empty part of the sky, it is brighter and larger than is usual for a globular. Though visible only in binoculars as a small patch of light, and not resolved even in a small telescope (<15 cm), it is nevertheless worth searching for. It shows a delicate structure with a lot of detail, much of which will be obscured if seen from an urban location. It has a pale yellow tint, and some observers report seeing a definite stellar core, which has a striking orange colour. But this feature is seen only with telescopes of aperture 15 cm and greater and using a high magnification. See Star Map 54.

Messier 54	NGC 6715	$18^h 55.1^m$	-30° 29′	Jun-**Jul**-Aug
7.6m	⊕ 9.1″		III	Sagittarius

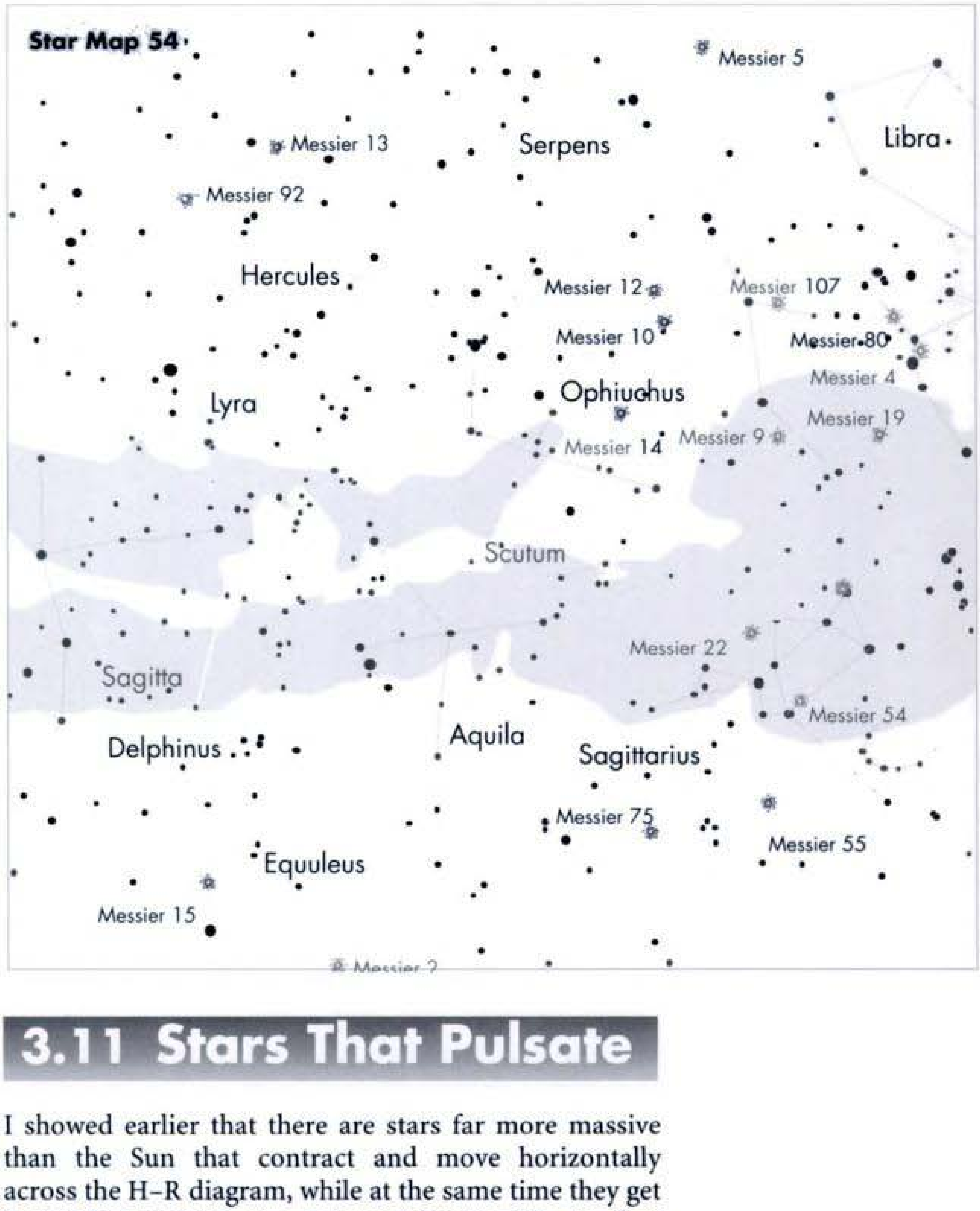
It has a colourful aspect - a pale blue outer region and pale yellow inner core. Recent research has found that the cluster was originally related to the *Sagittarius Dwarf Galaxy*, but that the gravitational attraction of our Galaxy has pulled the cluster from its parent. Among the globular clusters in the Messier catalogue it is one of the densest as well as being the most distant. See Star Map 54.

Messier 15	NGC 7078	$21^h 30.0^m$	+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. See Star Map 54.

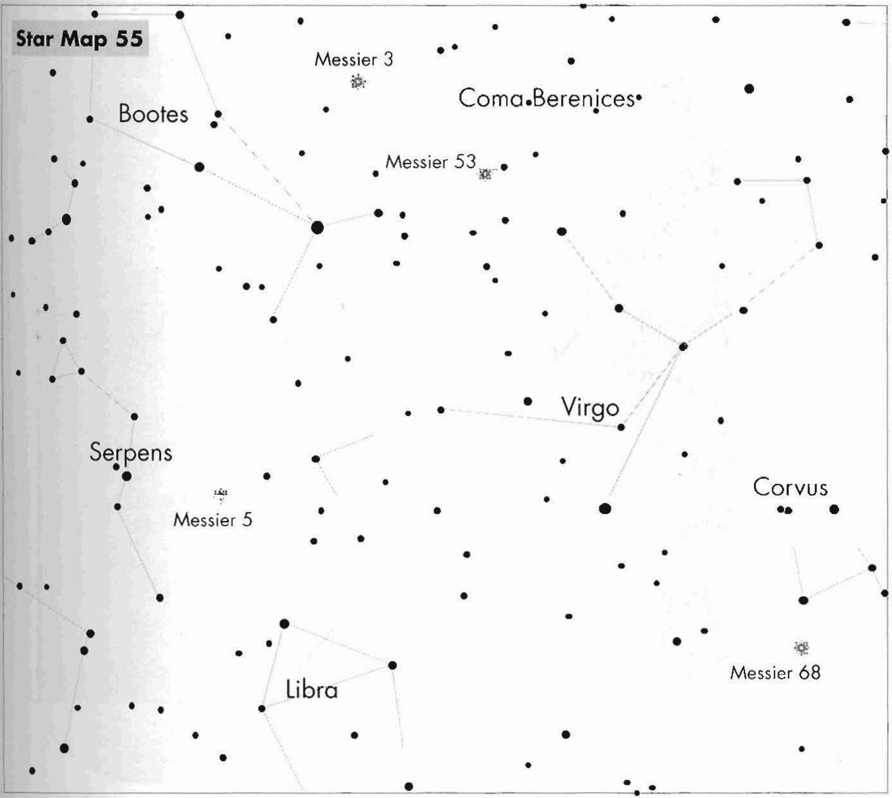
Messier 2	NGC 7089	$21^h 33.5^m$	-00° 49′	Jul-**Aug**-Sep
6.4m	⊕ 13″		II	Aquarius

This is a very impressive non-stellar object. It can be seen with the naked eye, although averted vision will be necessary. However, as it is located in a barren area of the sky it can prove difficult to locate. But when found it is a rewarding object, and even in large binoculars its oval shape is apparent. Believed to be about 37,000 light years away and to contain over 100,000 stars. See Star Map 54.


Star Map 54

3.11 Stars That Pulsate

I showed 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, however, change their size quite considerably, alternately shrinking and expanding, as their surface moves in and out. As the stars very in size, so does their brightness. These stars are the *pulsating variable stars*. There exist several classes of pulsating variable star, but we will just discuss the main types; the *long-period variables*, the *Cepheid variables*, and the *RR Lyrae* stars. Figure 3.10 shows where on the H–R diagram these pulsating stars reside.



3.11.1 Why Do Stars Pulsate?

You may think that the pulsations are caused by variations in the rate of energy production deep in the core of a star. You would be wrong, however, as the rate of nuclear fusion remains constant in a pulsating star. Astronomers have realised 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 in downward-pushing 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 3.11 for a schematic of this process. As the star expands, its gravity will naturally fall, but the pressure force would fall at a faster rate. A

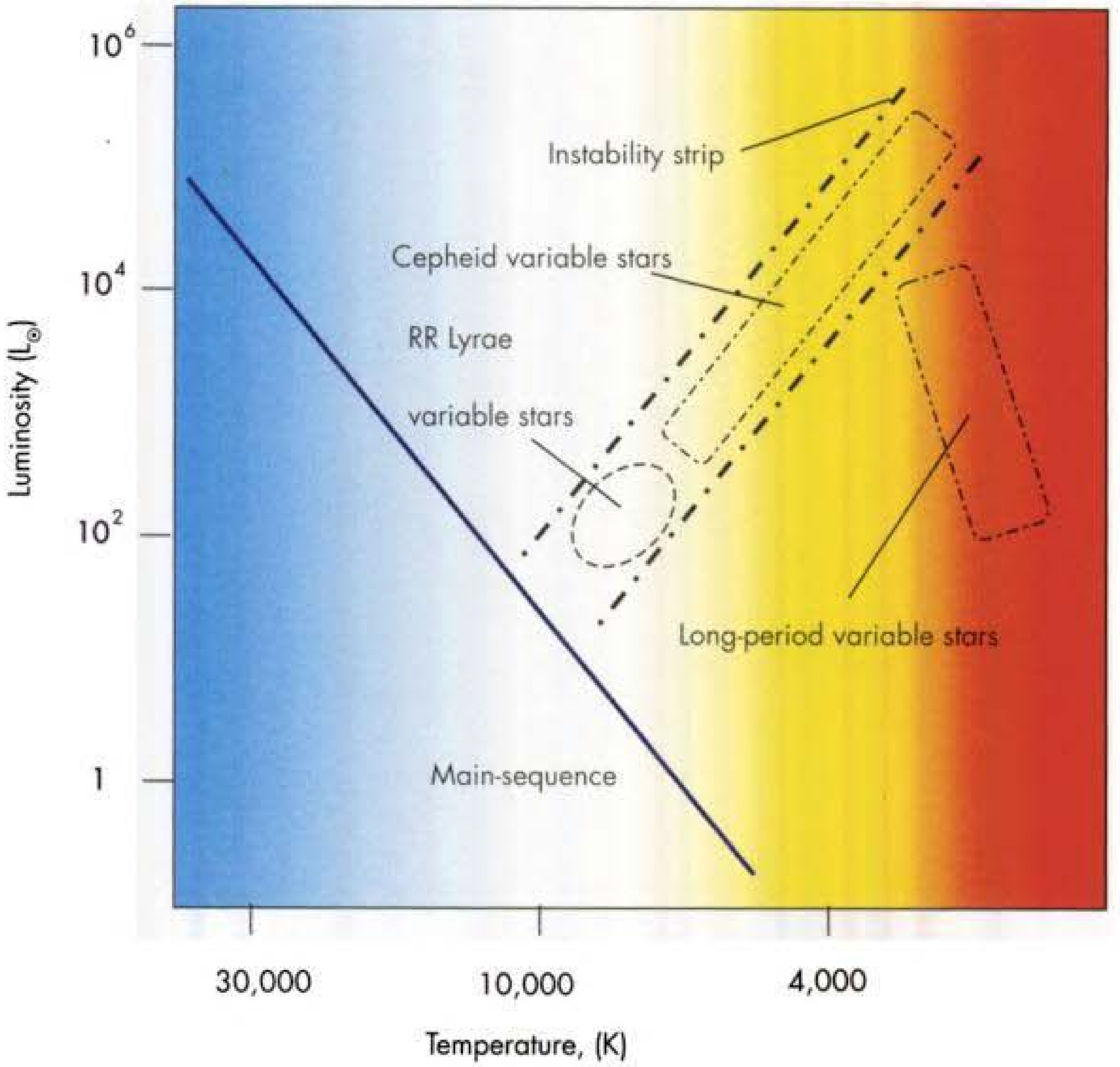
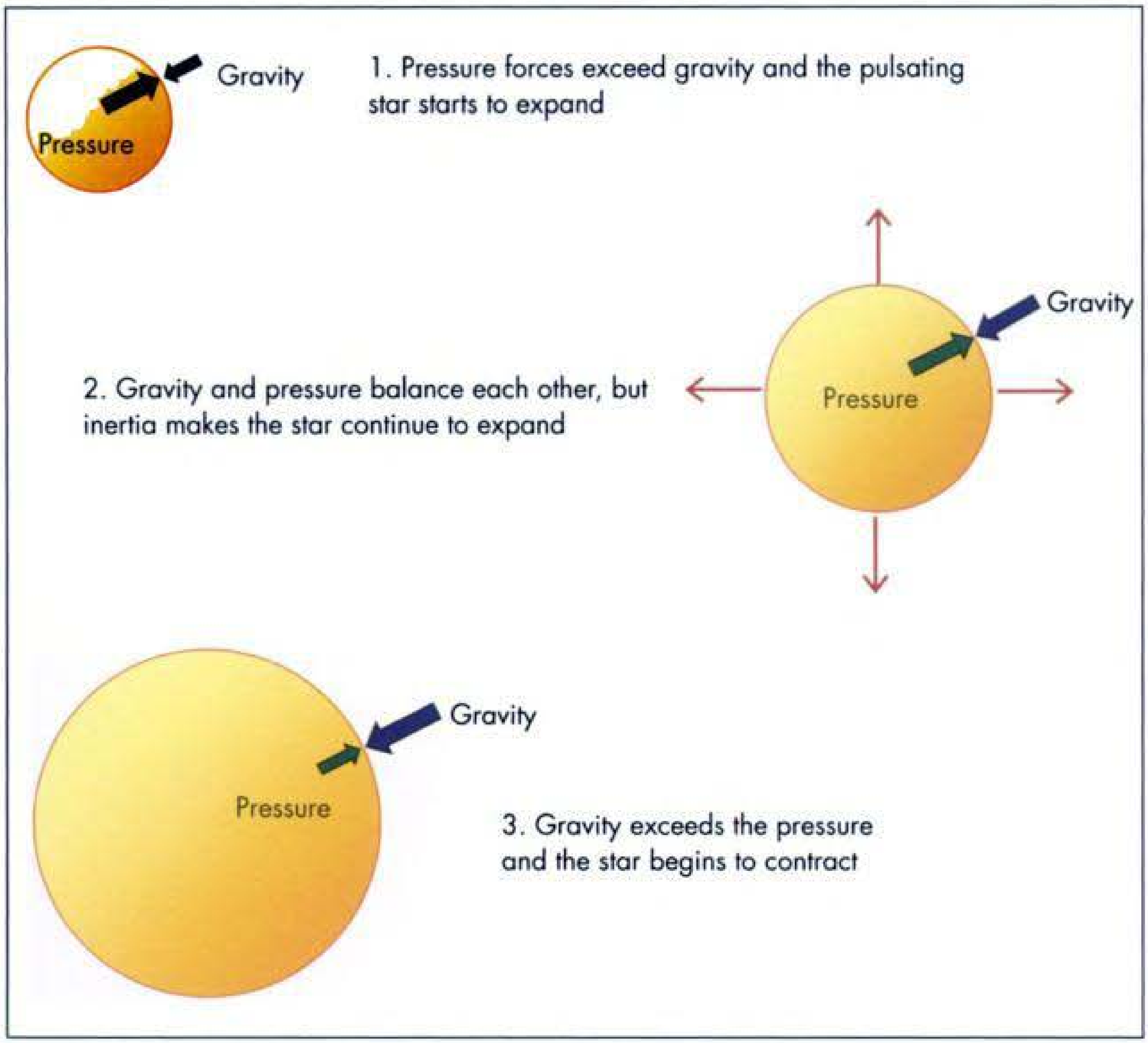


Figure 3.10. Variable Stars on the H–R Diagram.

time would then come when the star will have expanded to a larger size where, once again, hydrostatic equilibrium would reign. But this doesn't 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 that gravity will have brought everything to a stop, the pressure would now be to 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. 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 stop. And here 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



1. Pressure forces exceed gravity and the pulsating star starts to expand

2. Gravity and pressure balance each other, but inertia makes the star continue to expand

3. Gravity exceeds the pressure and the star begins to contract

Figure 3.11. Gravity and Pressure During the Pulsation Cycle of a Pulsating Star.

spring, and the force of gravity, are in balance. After a while, however, friction in the spring will dampen down 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 die out, the star also needs an outward push each time it contracts to its minimum size. Discovering what caused 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.

Then, in 1960, the American astronomer John Cox further developed the idea, and proved that it was helium that is the key to a Cepheid's pulsations. When a star contracts, the gas beneath its surface gets hotter, but the extra heat doesn't raise the temperature, but instead ionises the helium. This ionised helium is very good at absorbing radiation, in other words, it becomes more opaque and absorbs the radiant energy flowing outward through it, towards the surface. This trapped heat makes the star expand. This, then, provides the "push" that propels the surface layers of the star back outward again. 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.

In order for a star to be susceptible to pulsations, it must have a layer beneath its surface in which the helium is partially ionised. 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 a region exists, and is the location of the pulsating stars. It is called the *instability strip*. In this region are found the Cepheid variable and RR Lyre stars.

3.12 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.[10] Figure 3.12 shows the approximate variations of *δ Cephei* in luminosity, size and temperature.

You will immediately notice that its luminosity and temperature have a near maximum value when its size has a minimum value. And vice-versa; its size is at near maximum when its luminosity and temperature are at their minima. Cepheids are very important to

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[10] The time for a star to complete one cycle of its brightness variation is called its period. Thus, for ä Cephei, its period is 5.5 days

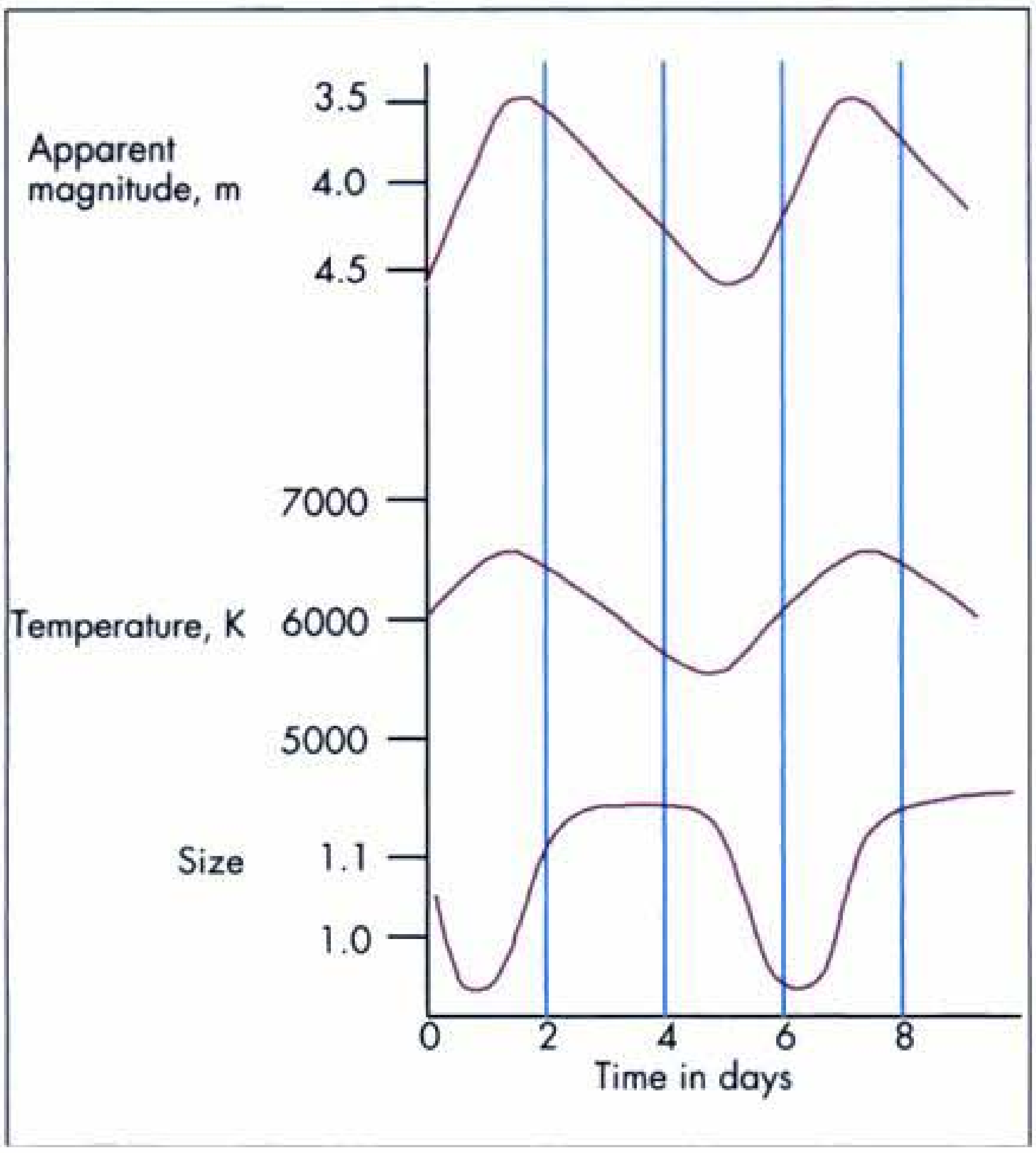

Figure 3.12. The size, temperature and magnitude of δ Cephei during one period.

astronomers for two reasons. They can be seen at extreme distances, perhaps as great as a few millions of parsecs. 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 $L_\odot$. Secondly, 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, whilst the brightest (as much as 30,000 times brighter than the Sun) have a much slower period or about 100 days. The correlation between the pulsation period and luminosity is called the *period-luminosity relation*. 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 affect on the opacity of the gas. This means they can be classified according to their metal content. If a Cepheid is a metal-rich, *Population I* star,[11] 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 3.13 shows a period–luminosity diagram for the two types of Cepheid. So, an astronomer must first determine what type of Cepheid he or she is observing before the period–luminosity relationship can be applied.

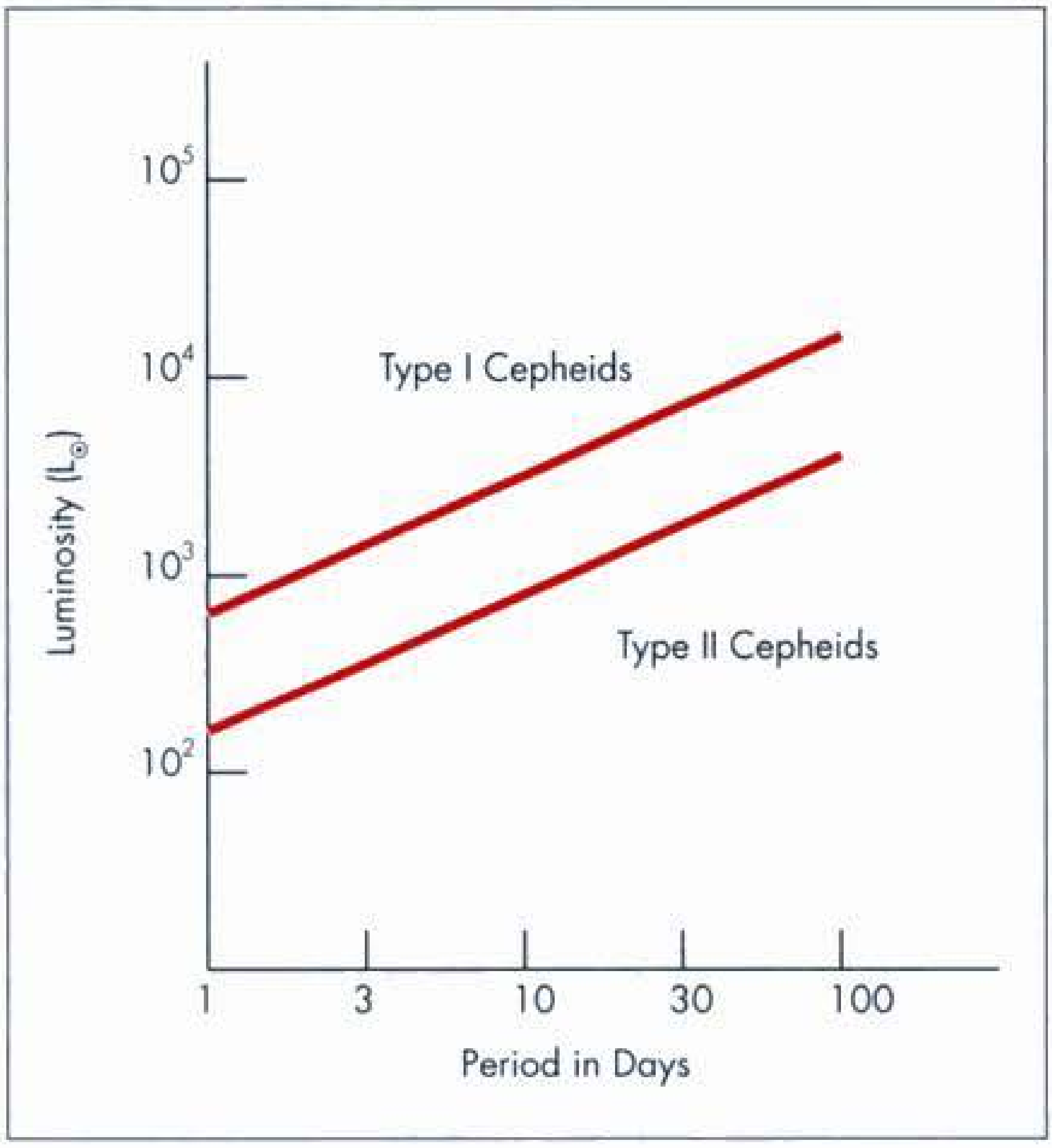

Figure 3.13. Period–Luminosity Relationship for the Two Types of Cepheid Variable Star.

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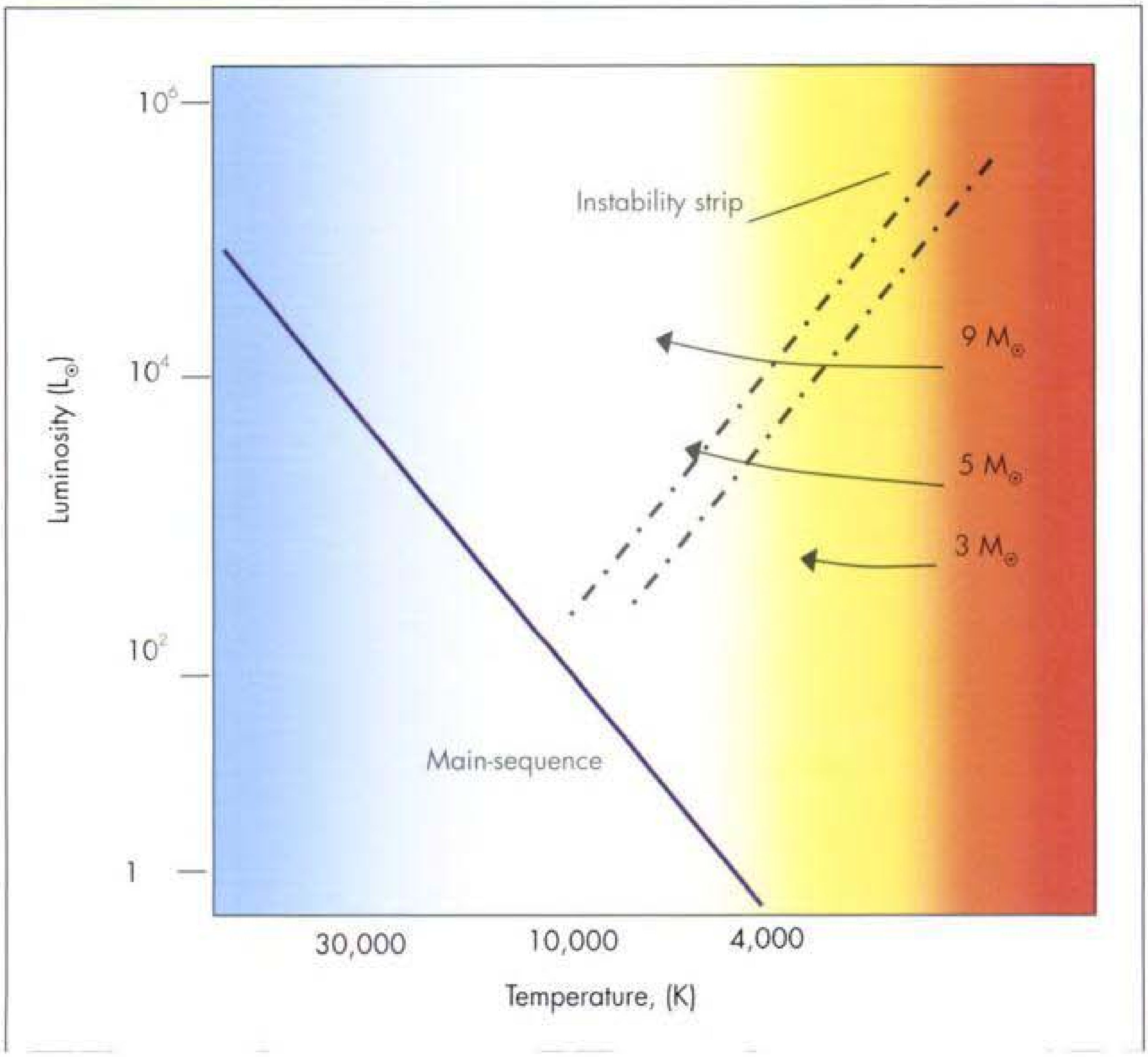
[11] *Population I* stars are bright supergiant main-sequence stars with high luminosity, such as O- and B-type stars and members of young open star clusters. Molecular clouds are often found in the same location as Population I stars. They are usually located in the disc of a galaxy and concentrated in the spiral arms, following nearly, but not always, circular orbits. Population I stars are stars with a range of ages, maybe 10 billion years, or one year, old. *Population II* stars, however, 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 that were formed very early in the history of the Galaxy.

3.13 Cepheid Variables: 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 that the massive pulsating stars have the greater luminosities and the longest periods. This is shown in Figure 3.14.

We have seen how old, high-mass stars have evolutionary tracks that cross back and forth on the H–R diagram, and thus they will intercept the upper end of the instability strip. Such stars become Cepheids when the helium ionises at just the right depth to drive the

Figure 3.14. Instability Strip and Evolutionary Tracks for Stars of Different Mass.



pulsations. Those stars on the left (high-temperature) of the instability strip will have helium ionisation happening 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.

3.14 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 Lyrae variables, named after the prototype in the constellation *Lyra,* all have periods shorter than Cepheids of around 1.5 hours to 1 day. They are small and dense stars compared to 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 which 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.* After all that has been written above, 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 organisations exist throughout the world that cater specifically for this pastime.[12] 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 the list is the same as before, with a few changes. The apparent magnitude range of the variable is given, along with its period in days.

δ Cephei	HD 213306	$22^h 29.1^m$	+58° 25′	Jul–**Aug**–Sep
3.48–4.37m	−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 John Goodricke. It is an easy favourite with amateurs as two 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 behaviour of the star is as follows: the star will brighten for about 1½ 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) a nice white colour, which contrasts nicely with the yellowish tint of the primary. See Star Map 56.

η Aquilae	HD 187929	$19^h 52.5^m$	+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 two days, with the remainder of the time in a slow fading. 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! See Star Map 57.

RT Aurigae	HD 45412	$06^h 28.6^m$	+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 variable by T. Astbury in 1905, whilst a member of the British Astronomical Association. The rise to maximum takes $1\frac{1}{2}$ days, with a diminishing over $2\frac{1}{2}$ days. Easy to observe in binoculars, it lies midway between *Epsilon(ϵ) Geminorum* (3.06m) and *Theta (θ) Aurigae* (2.65 m). The period has been measured with an astounding accuracy to be 3.728261 days! See Star Map 58.

α Ursae Minoris	ADS 1477	$02^h 31.8^m$	+89° 16′	Sep–**Oct**–Nov
1.92–2.07m	−3.64M	3.97 days	F7:Iib–Iiv	Ursa Minor

Possibly the most famous star in the entire sky. *Polaris,* or the *Pole Star,* is located less than a degree from the celestial pole. It is a Type II Cepheid, which are also known as *W Virginis* variable stars. The magnitude changes are very small and therefore not really detectable with the naked eye. It is also a nice double consisting of a yellowish primary and a faint whitish blue secondary at a magnitude of 8.2. The primary is also 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 AD. See Star Map 67.

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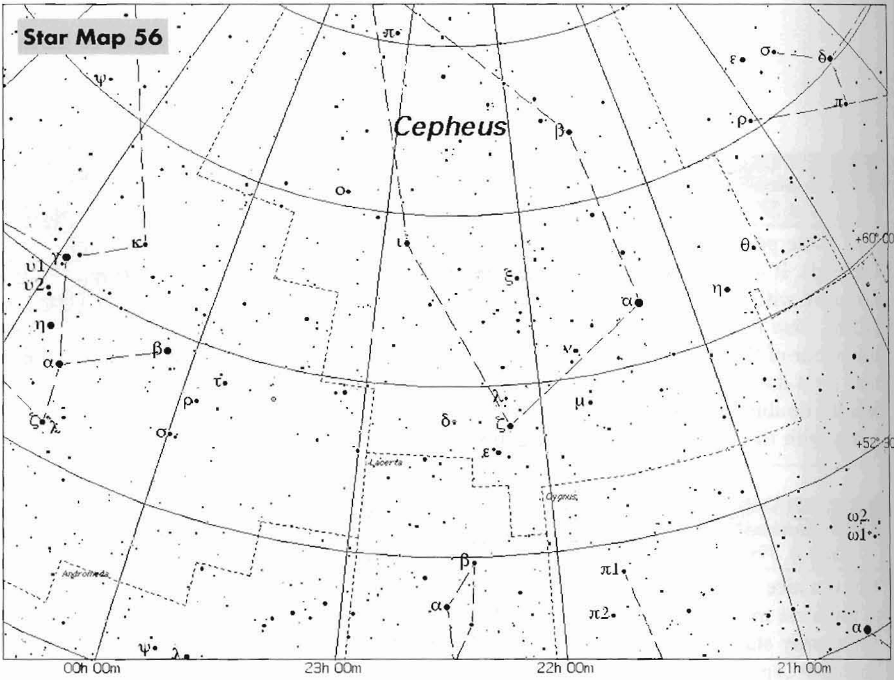
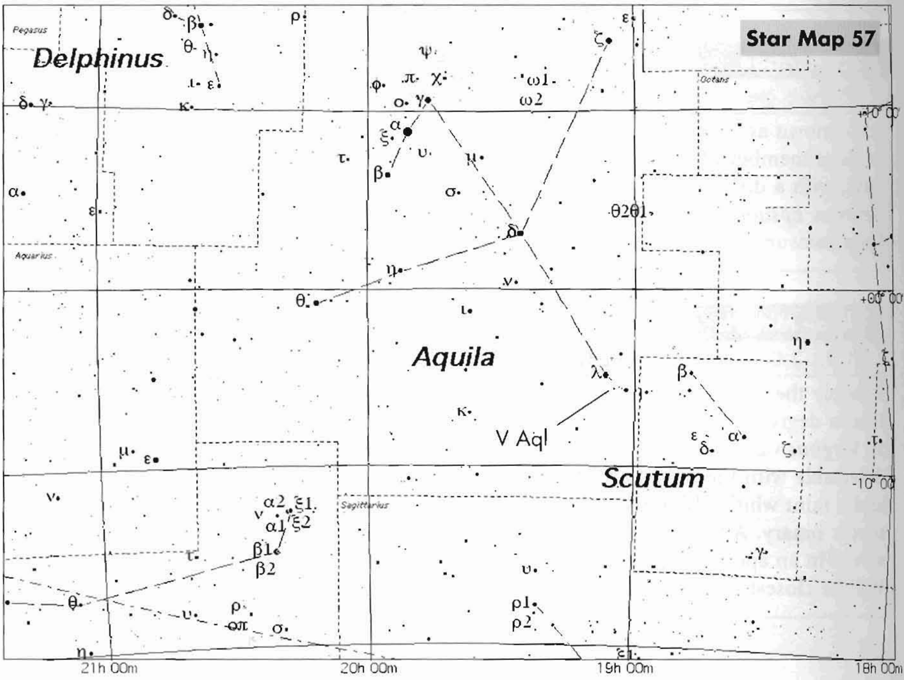
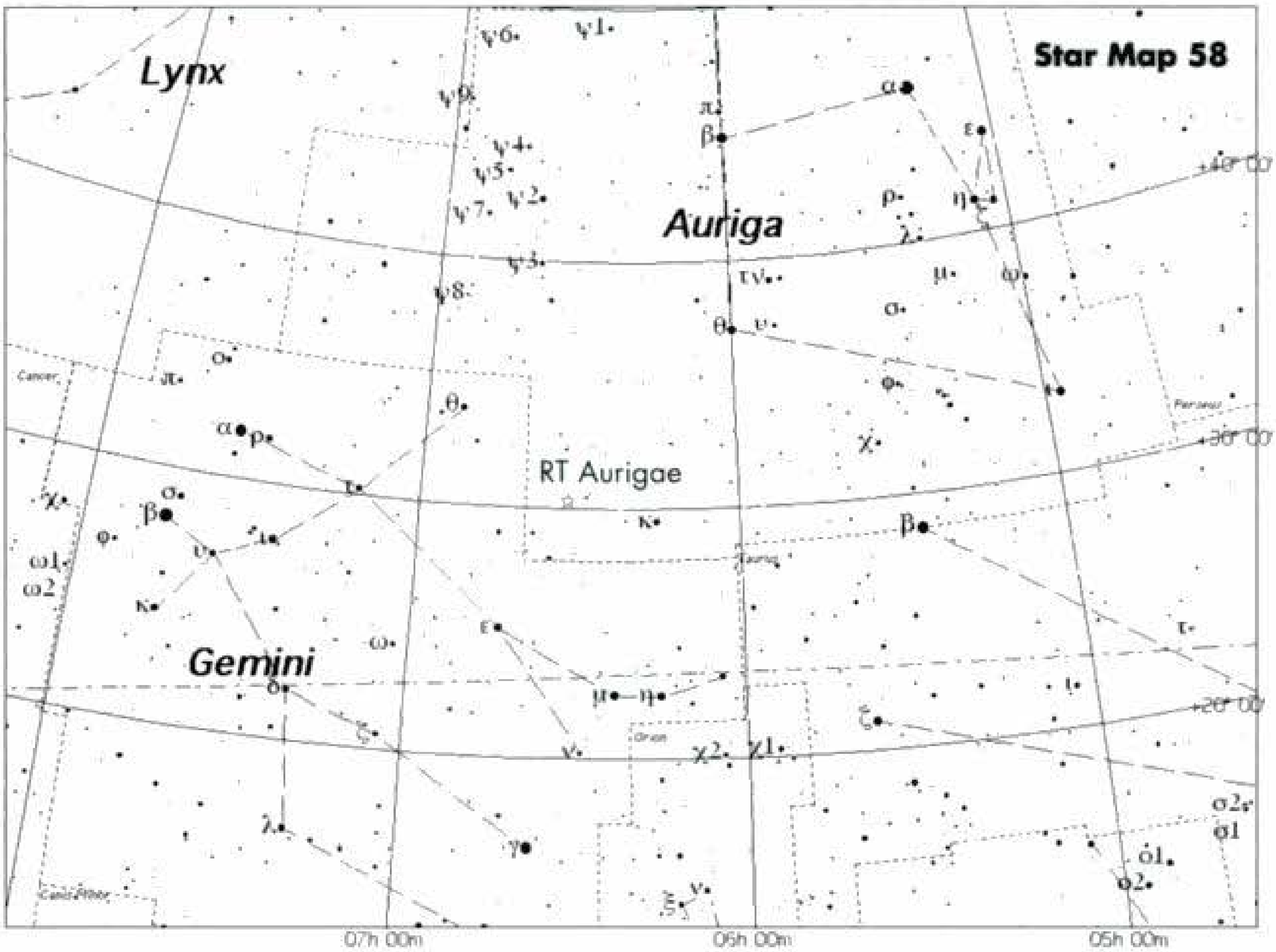
[12] A list of organisations

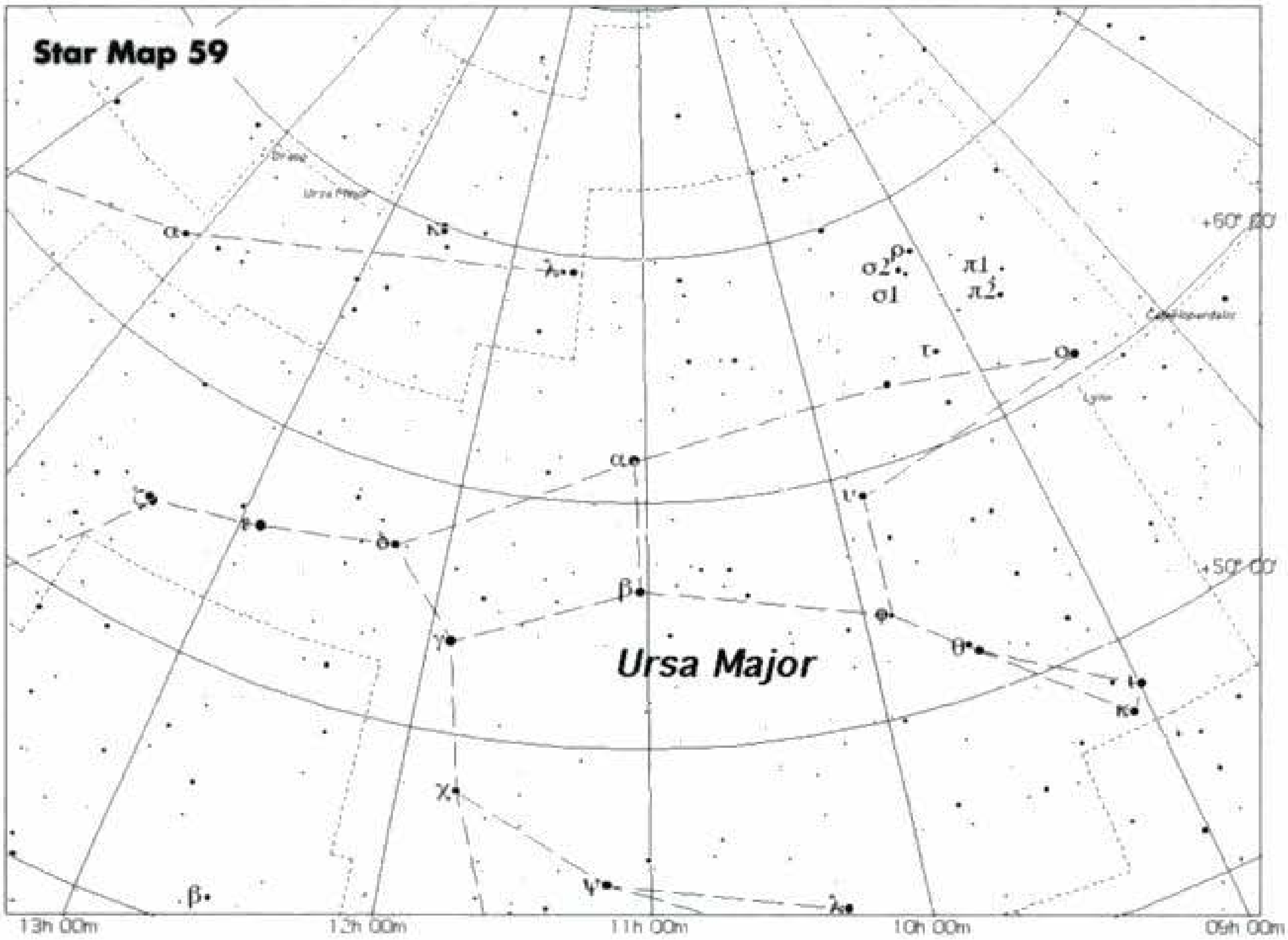
Other stars that are Cepheid variables and can be observed with amateur equipment are: *U Aquilae, Y Ophiuchi, W Sagittae, SU Cassiopeiae, T Monocerotis, T Vulpeculae.*







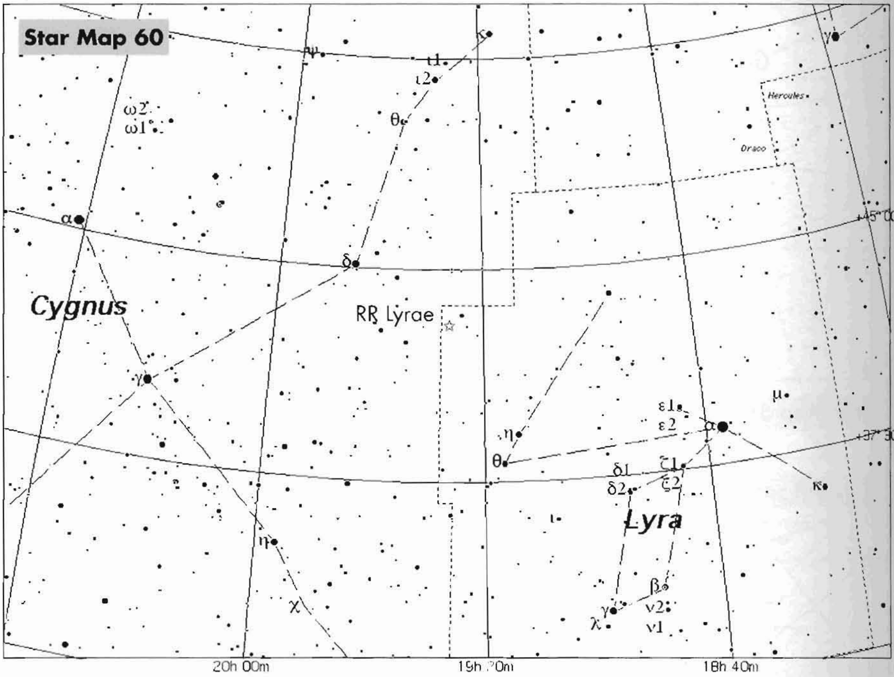
Star Map 58



Star Map 59

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*	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 bluer 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 another A2–F1 – take your pick. There is also some indications that there is another variability period along with the shorter one, which has a period of about 41 days. See Star Map 60.



Star Map 60

Other RR Lyrae variable stars are: *RV Arietis, RW Arietis,* and *V467 Sagittarii.* However, all these stars are faint, and so will present a considerable challenge to observers.

Other Mira-type stars are *R Leonis* and *R Leporis,* both of which have been described in earlier sections.

We have now seen how stars evolve during the middle age of their life, and how a star behaves on the main sequence depends on the mass of the star. Small mass stars will evolve in a different manner to those which

<table>
<tr><td>Mira</td><td>o Cet</td><td>$02^h\ 19.3^m$</td><td>−02° 59′</td><td>Sep–Oct–Nov</td></tr>
<tr><td>2.00–10m</td><td>−3.54M</td><td>331.96 days</td><td>M9–M6e</td><td>Cetus</td></tr>
<tr><td colspan="5">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 is an ideal star for the first-time variable star observer. At minimum, the star is a deeper red colour, 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 <i>Aldebaran</i>! 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 <i>Mira</i> is at its faintest, it apparently is also at its largest, when you would think that the opposite would be true. A reason for this has been put forward recently in that the star produces titanium oxide in its atmosphere, as it cools and expands. The compound then acts like a filter, blocking out the light. The name <i>Mira</i> is Arabic for "wonderful star". See Star Map 7.</td></tr>
</table>

have a high mass. As you may have already guessed, the same criteria will also decide how a star proceeds into old age. This then is the topic for the next section – Star Death!

Chapter 4

The End Point – Star Death

4.1 Introduction

Stars live for millions, billions, and even hundreds of billions of years,[1] 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 been studying astronomy for about 10,000 years. Well, fortunately for us, it is 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 very 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 then proceeding to a small and ever-cooling white dwarf star. 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.

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[1] Current theories predict that low-mass M-type stars will stay on the main sequence for trillions of years!!!

4.2 The Asymptotic Giant Branch

Let's recap briefly how low-mass stars (and by this I mean stars that have a mass of around 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 is 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 the luminosity. The outer layers of the star also contract a little, heating them 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.

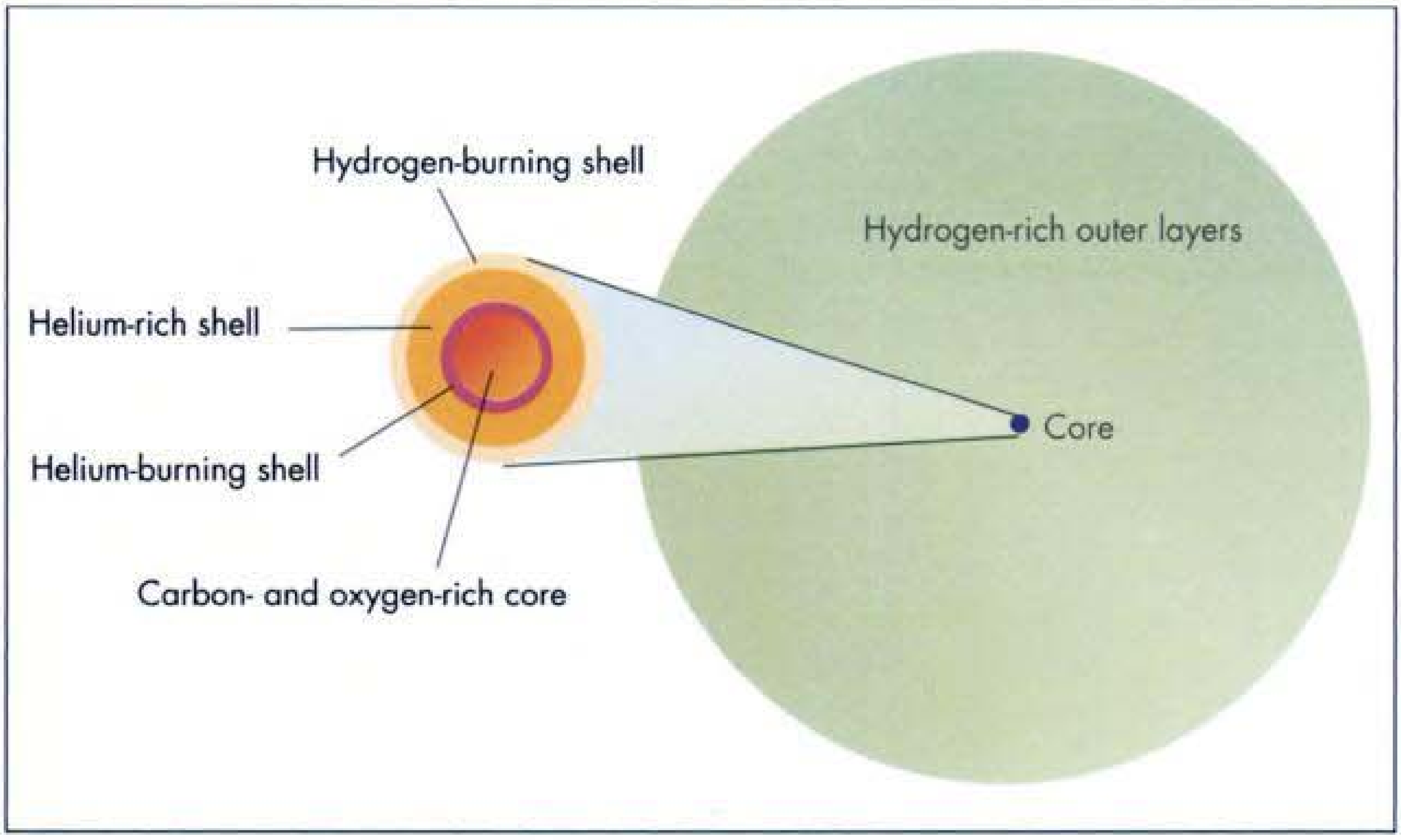
We can now look at the next stage of a star's life. Recall from Chapter 3 that by-products of the triple α process are the elements carbon and oxygen. So after a suitably long period of time, maybe 100 million years, we could expect all the helium in the core to have been converted into carbon and oxygen. This would mean that core helium-burning would then stop. A similar process to that which was explained in Chapter 3 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 which is surrounding the core, and so helium burning begins in a thin shell around the carbon–oxygen core. This is, aptly enough, 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. Its position on the main sequence is shown on Figure 3.8.

The structure of an AGB star is shown in Figure 4.1. 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 this, however, is further encompassed by a hydrogen-rich outer layer. What is truly remarkable is the size of these objects. The core region is around 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,

Figure 4.1. The Structure of an AGB Star.



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 to the luminosity of only 1000 $L_\odot$ it achieved when it reached the helium flash phase and a poor 1 $L_\odot$ when it resided 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 *R Cassiopea*. In addition there are also a few others, albeit somewhat fainter. These include; *χ Cygni*, *W Hydrae*, *S Pegasi* and *TT Monocerotis*.

4.3 Dredge-Ups

We have seen how 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 upwards towards the surface, and then a 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 has left 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 surface of the star 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[2] cycle of hydrogen are transported to the

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[2] In stars which are hotter than the Sun, and also have a higher mass, 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.

surface because the convective zone now reaches deeply down into the core regions. A *second dredge-up* starts 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*.

4.4 Mass Loss and Stellar Winds

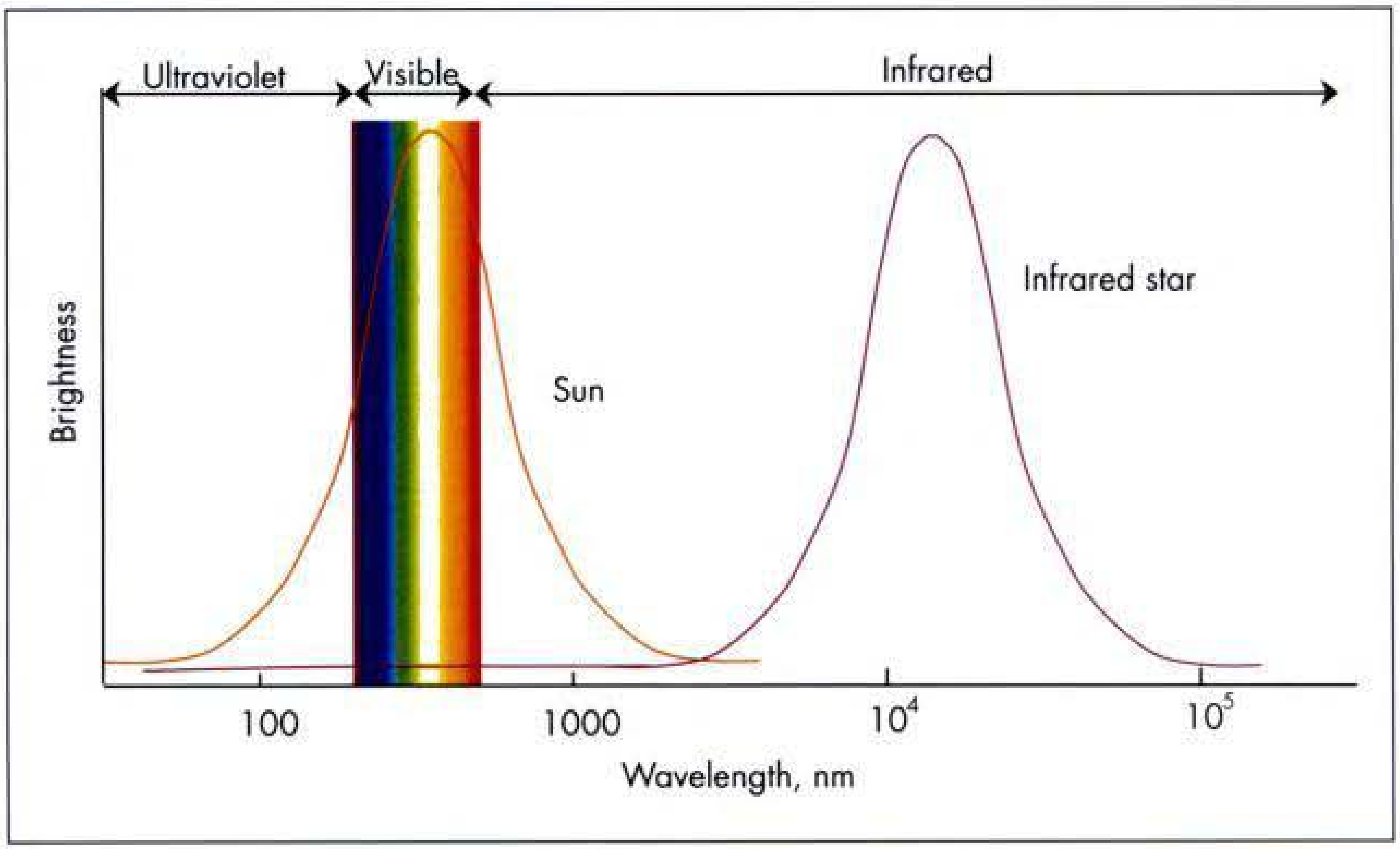
As the star continues to rise up the AGB it increases in both brightness and size, and one of the consequences of this is that the star develops a very strong stellar wind. This blows the star's outer layers into interstellar space. Thus the star undergoes a substantial mass loss during this phase, maybe 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. It 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.

4.5 Infrared Stars

It may come as a surprise to know that AGB stars, which can have luminosities that are 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 has only been explored in detail in the past 30 years. This is shown in Figure 4.2. These stars 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 a 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 some 10 times the size of the Solar System. These outer layers of the star are extremely tenuous and hold only a fraction of the total mass of the star. 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 stars 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 the energy radiated from the dust surrounded an infrared star is invisible to the naked eye.

Figure 4.2. The Spectrum of an Infrared Star Compared to the Sun.



4.6 The End of an AGB Star's Life

As it ages, the 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 less that 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 those stars that are greater than 8 $M_\odot$, the end of the AGB phase arrives in a much more spectacular event a – supernova. But we leave that discussion for a later section.

I want to end this section on the AGB part of a star's life with a sobering and amazing thought. Recall that carbon stars enrich the interstellar medium with not only carbon, but 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 which 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 then expelled into space. Later on, by some means it formed the precursor to the Solar System, 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 there are many of the rare carbon stars visible in the night sky that can be seen 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 these below. The one aspect of these stars that will be immediately apparent to you is their colour. All of them are strongly coloured red. They are, in fact, the reddest stars visible to the amateur astronomer.

X Cnc	HD 76221	$08^h 55.4^m$	+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. See Star Map 61.

V Hydrae	Lalande 16	$10^h 51.6^m$	−21° 15′	Feb–**Mar**–Apr
7.0_vm	B-V:4.5	C9		Hydra

The star, another classic long-period variable, period about 533 days, varies in brightness between 6 and 12m. It also has a second periodicity of 18 years. It has been described as coloured a "magnificent copper red". It is, however, difficult to observe owing to its large magnitude range. See Star Map 62.

La Superba	Y CVn	$12^h 45.1^m$	+45° 26′	Mar–**Apr**–May
5.4_vm	B-V:2.9	C7		Canes Venatici

The colour of this star is best seen through binoculars or a small telescope. With a period of 159 days, and varying in magnitude between 4.9 and 6.0m, this red giant has a diameter of 400 million kilometres. See Star Map 63.

RY Dra	GD 112559	$12^h 56.3^m$	+66° 00′	Mar–**Apr**–May
6.4_vm	B-V:3.3	C7		Draco

A red giant variable with poorly understood periodicity, class SRB, with a period believed to be 200 days, and a magnitude range of 6.0–8.0m, this star has a lovely red colour. See Star Map 64.

V Pav	HD 160435	$17^h 43.3^m$	−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 8.2m, over a period of 225.4 days. It also has a secondary period of about 3735 days. A glorious deep-red colour. See Star Map 65.

T Lyr		$18^h 32.3^m$	+37° 00′	May–**Jun**–Jul
8.5_vm	B-V:	C8		Lyra

An extremely red-coloured star, this is another with an irregular period; magnitude range 7.5 to 9.3. See Star Map 66.

V Aql	HD 177336	$19^h 04.4^m$	−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 8.1m. A very deep red in colour. See Star Map 57.

S Cephei	HD 206362	$21^h 35.2^m$	+78° 37′	Jul–**Aug**–Sep
7.9_vm	B-V:2.7	C6		Cepheus ©

A moderately difficult star to observe, owing to its magnitude range of between 7 and 12 magnitudes, it nevertheless has a very high colour index, making it one of the reddest stars in the sky if not *the* reddest. Its red colour immediately strikes you, and once seen, never forgotten. See Star Map 67.

R Scl	HD 8879	$01^h 26.9^m$	−32° 33′	Sep–**Oct**–Nov
5.79_vm	B-V:1.4	C6		Sculptor

A semi-regular-period variable star, with a period of between 140 and 146 days, it varies in brightness from 5.0 to 6.5. See Star Map 68.

U Cam		$03^h 41.8^m$	+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 9.5m. It has a very deep-red colour. See Star Map 69.

W Ori	HD 32736	$05^h 0.4^m$	+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. See Star Map 17.

R Corona Borealis	HD 141527	$15^h 48.6^m$	+28° 09′	Apr–**May**–Jun
5.89_vm	B-V: 0.608	G0Iab: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 several weeks, or months, or even as long as a year.[3] Then just as suddenly, it can brighten back again to its normal brightness. The reason for this strange behaviour 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 once again with the grains building up over time. Other stars which show a similar behaviour are *RY Sagittarii* (6.5 m), *SU Tauri* (10 m) and *S Apodis* (10 m). See Star Map 70.

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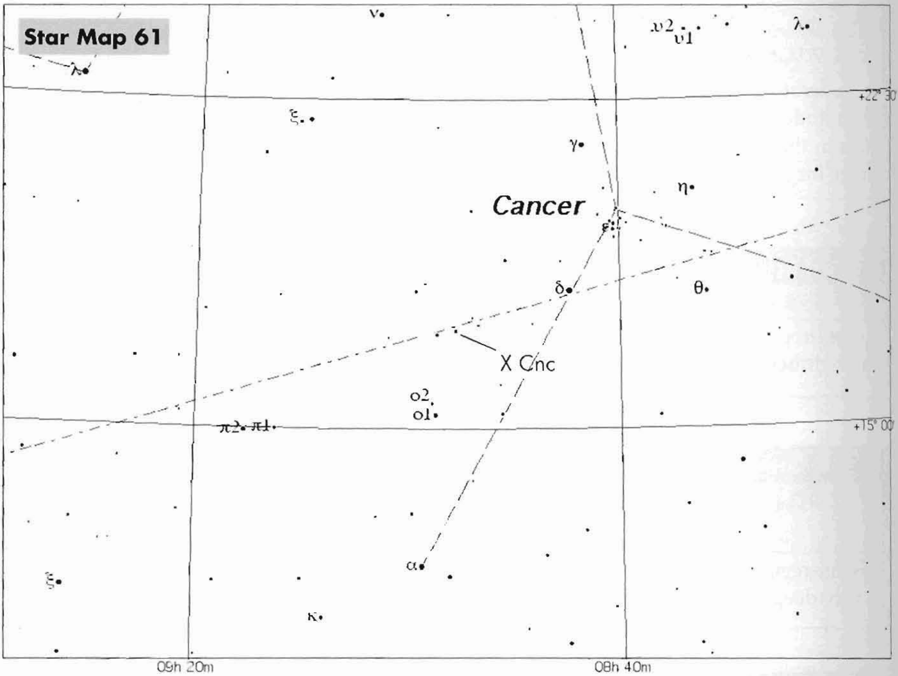
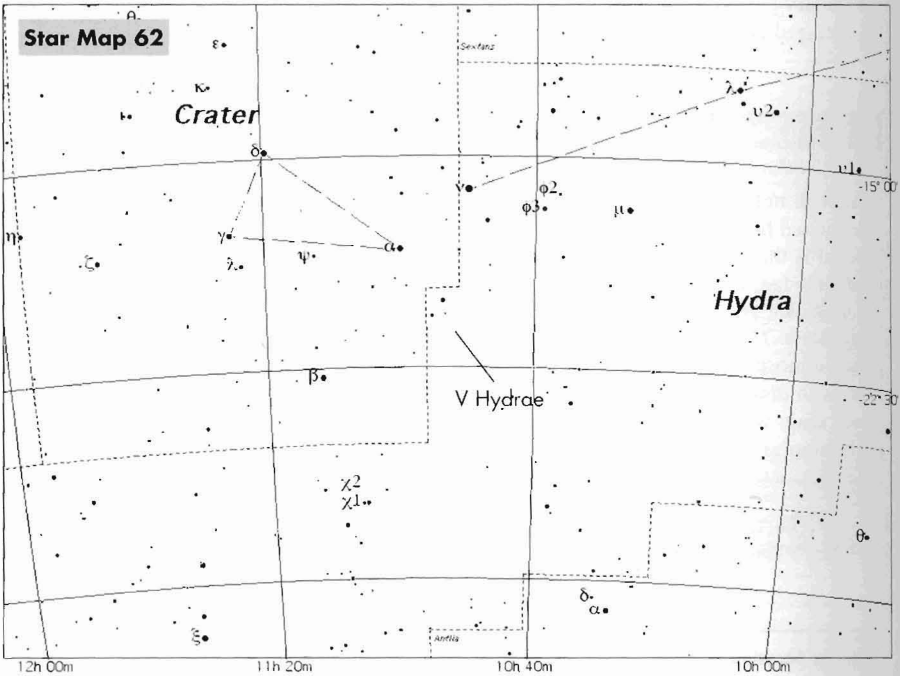
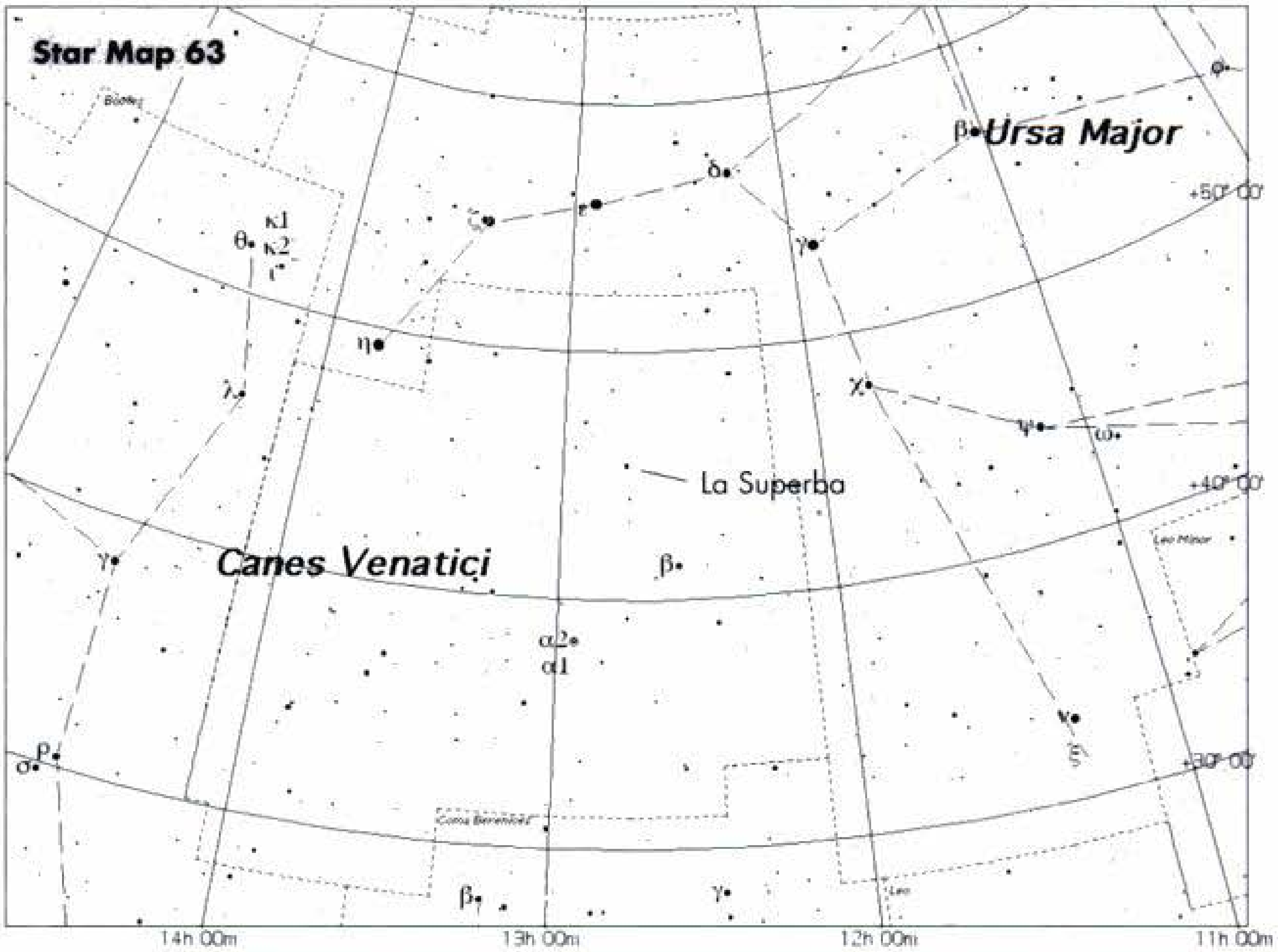
[3] On one occasion it remained at minimum magnitude for 10 years!

Star Map 61

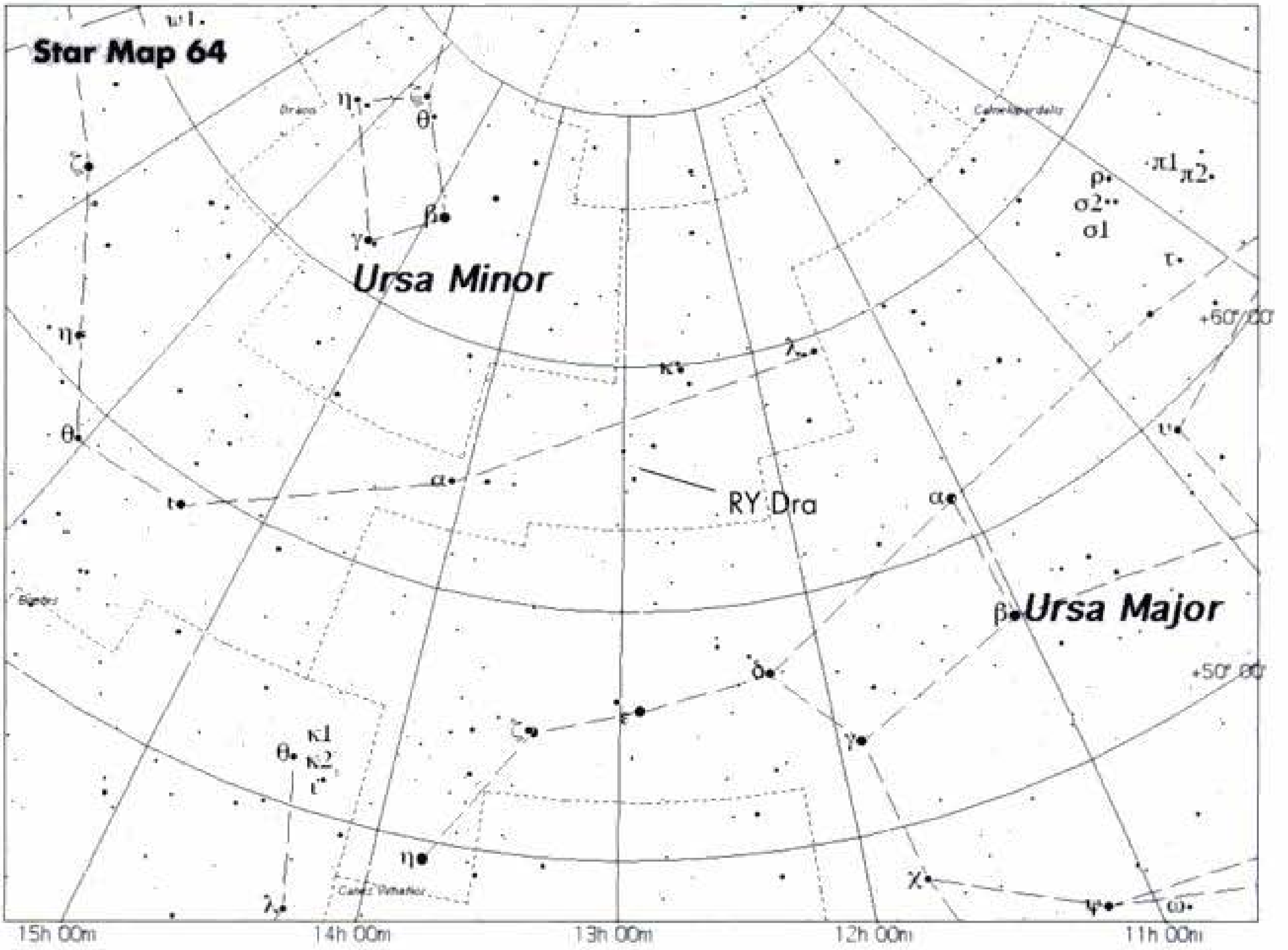


Star Map 62



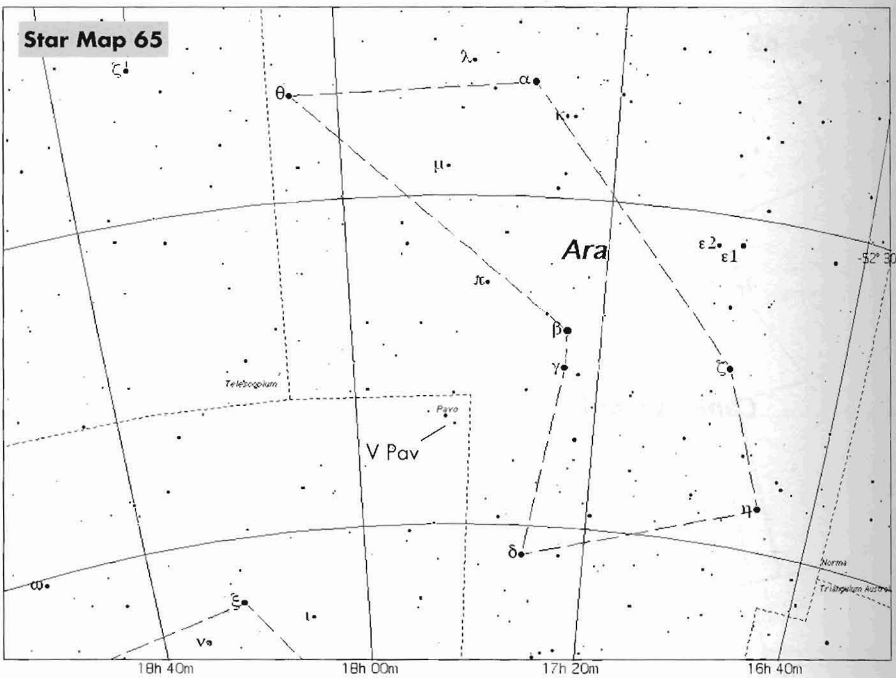


Star Map 63

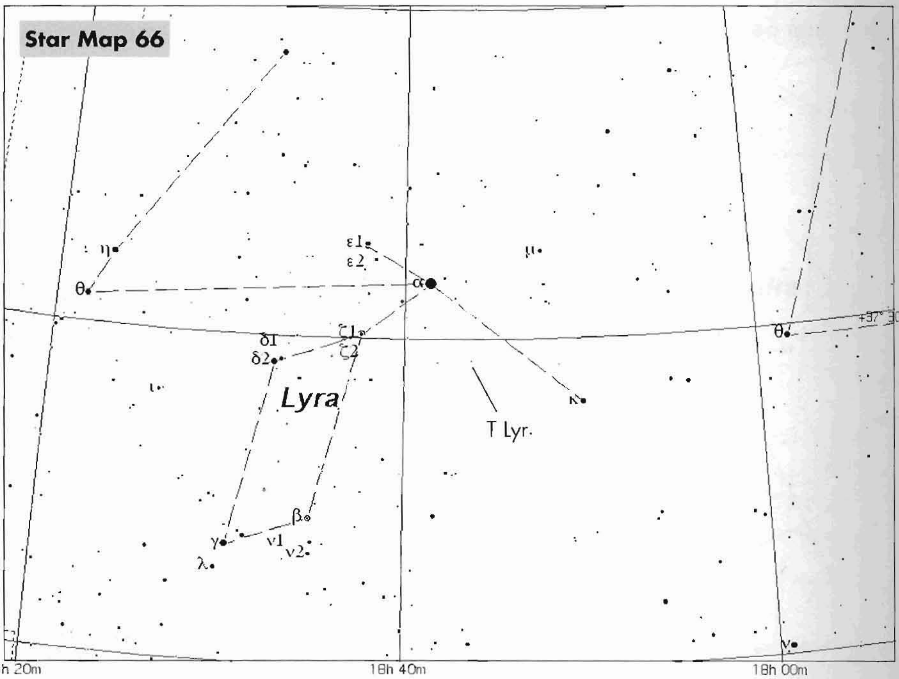


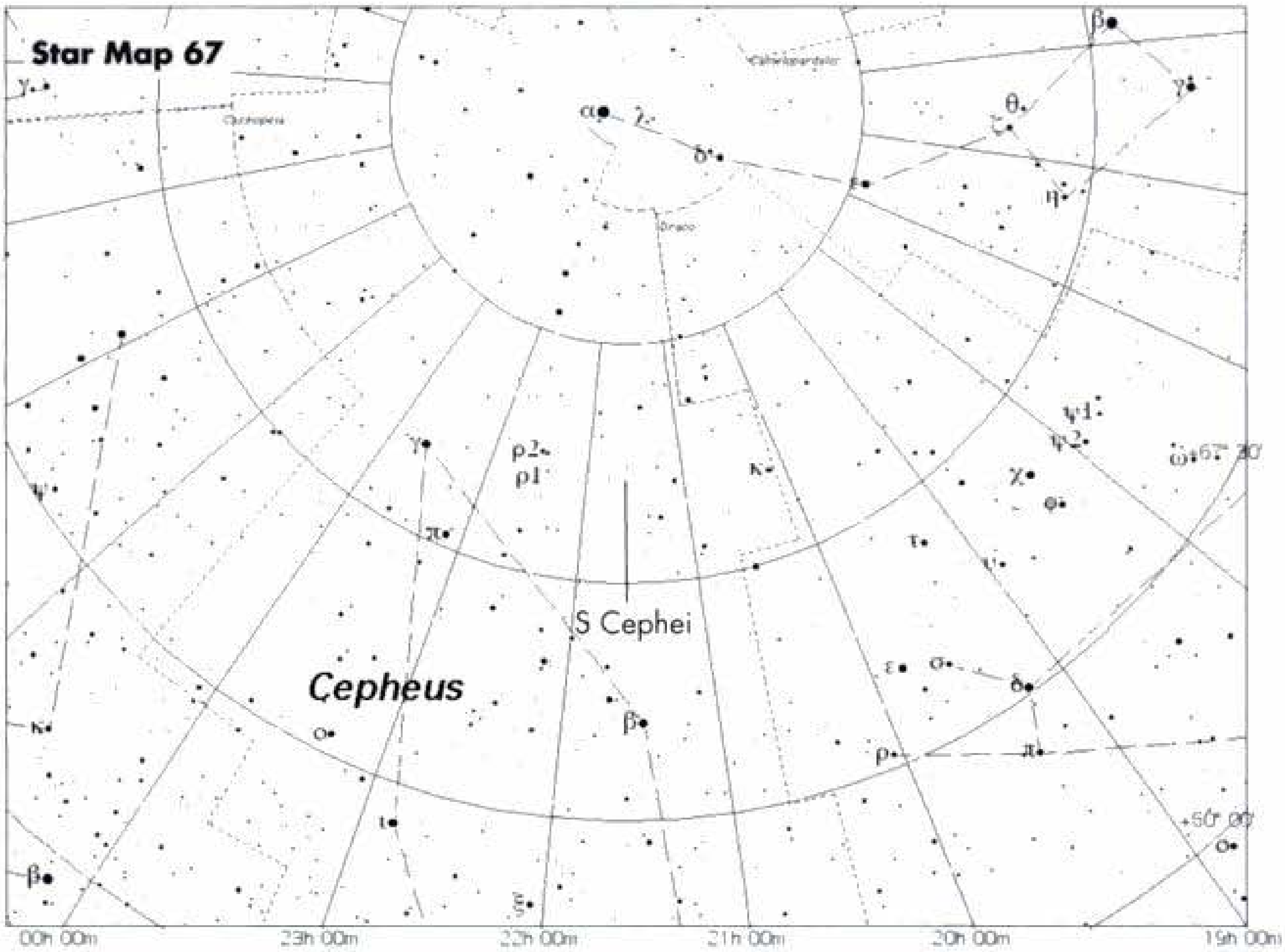
Star Map 64

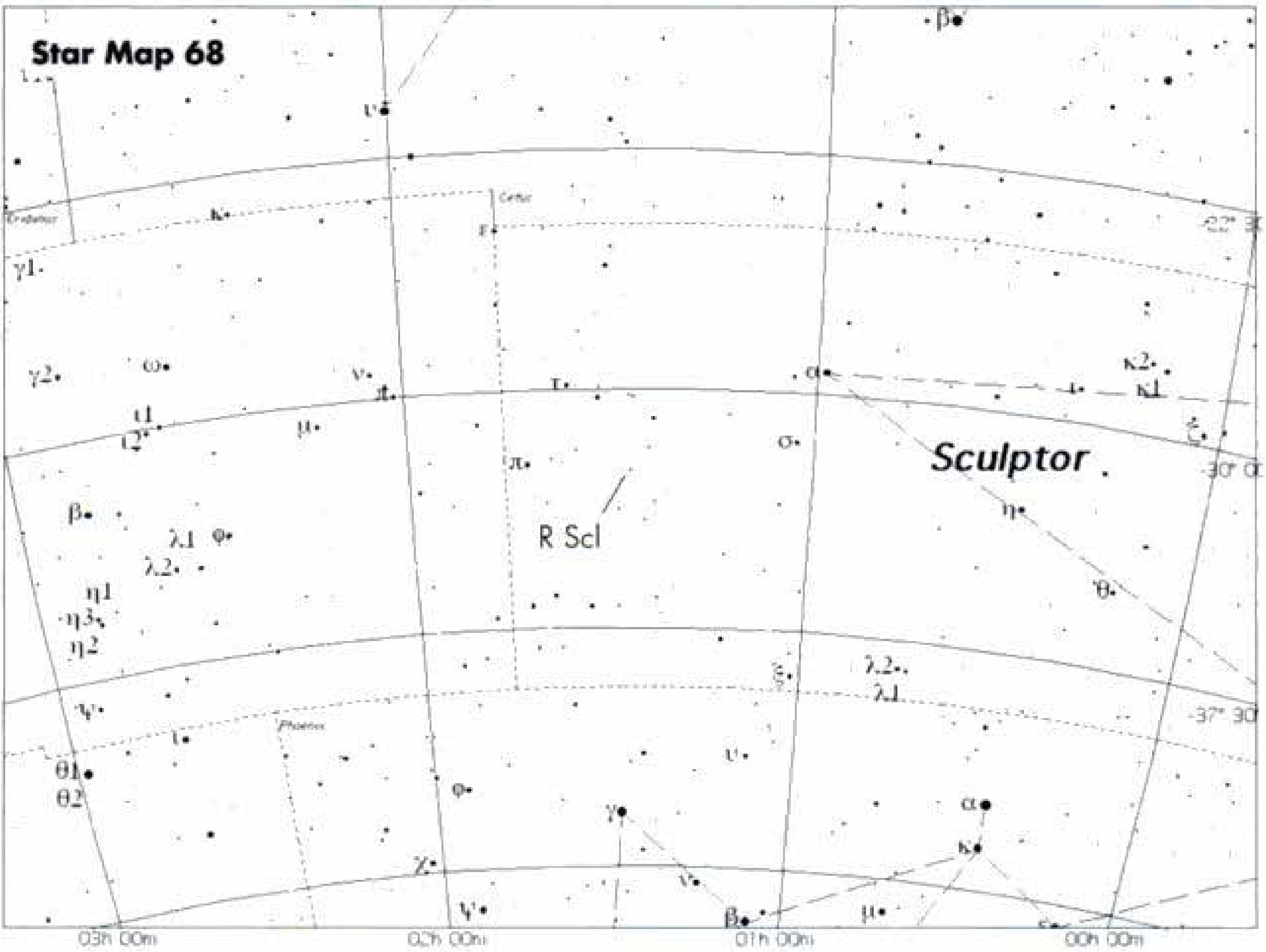
Star Map 65

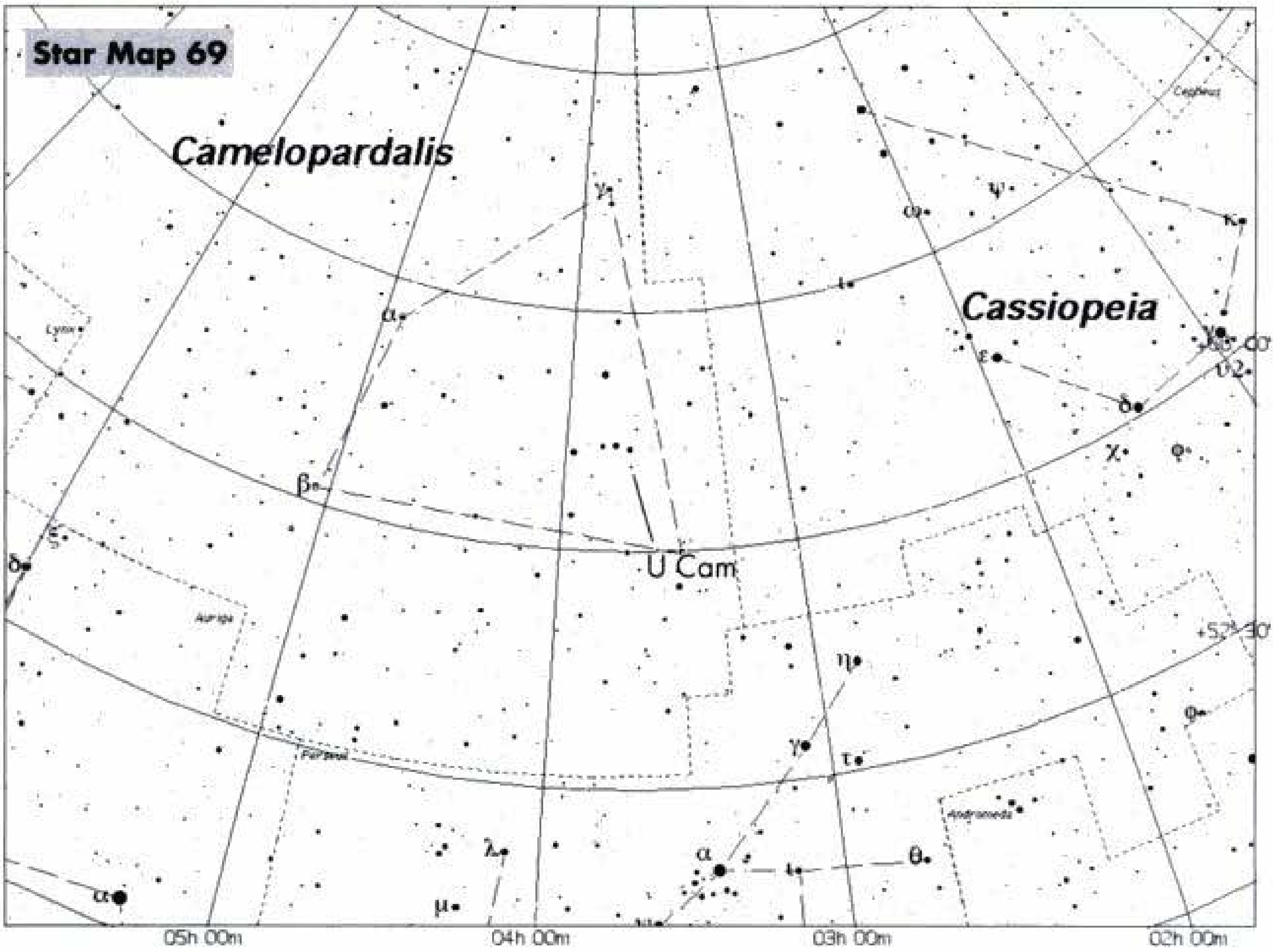


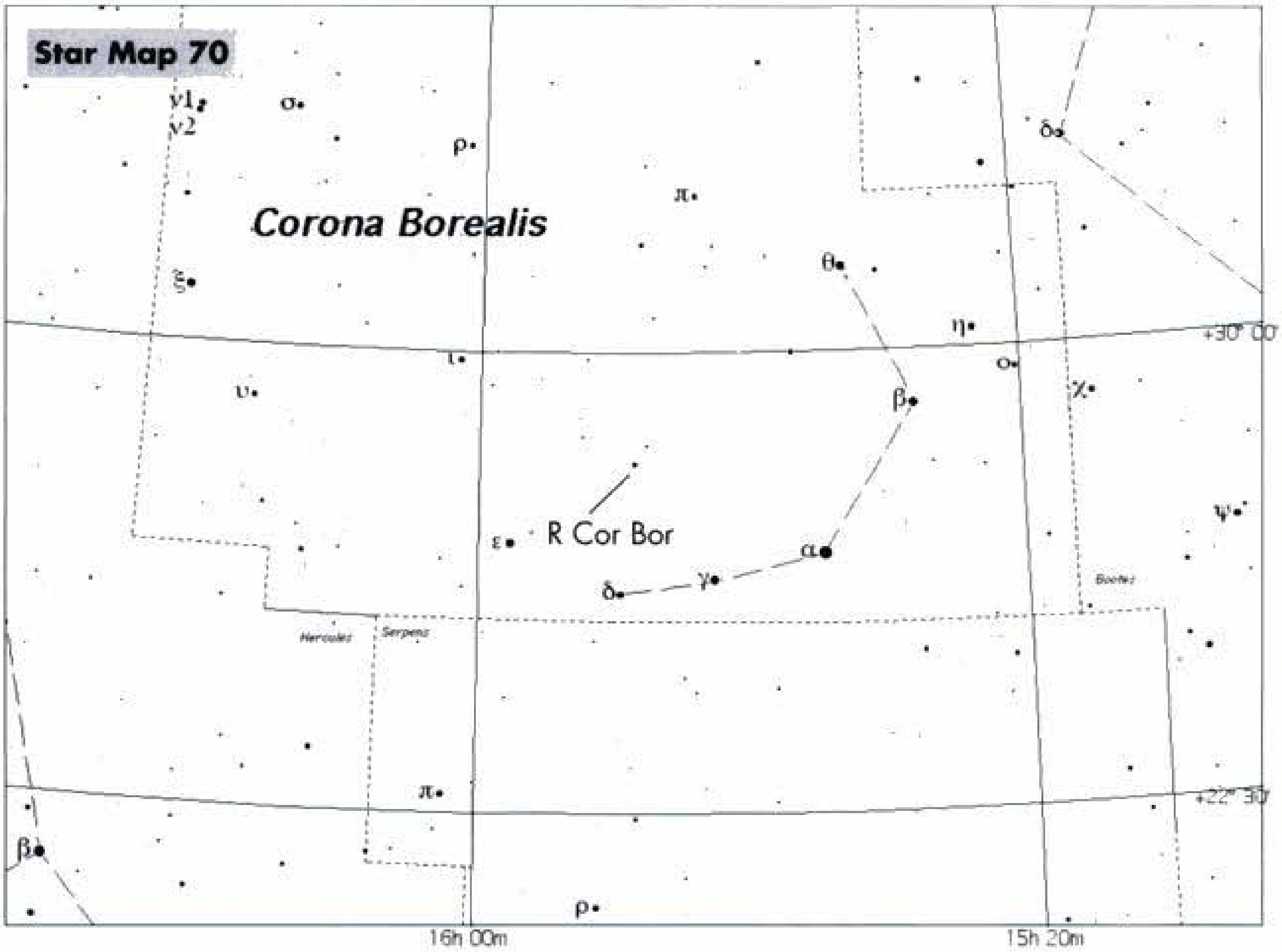
Star Map 66




Star Map 67


Star Map 68


Star Map 69
Camelopardalis
Cassiopeia
Cepheus
Lynx
Auriga
Perseus
Andromeda
γ1
α
β
ξ
δ
U Cam
ω
ψ
κ
ι
ε
δ
υ2
χ
φ
+60° 00'
+52° 30'
η
γ
τ
φ
λ
μ
α
ι
θ
α
05h 00m
04h 00m
03h 00m
02h 00m


Star Map 70
ν1
ν2
σ
ρ
Corona Borealis
π
θ
ξ
η
+30° 00'
ι
ο
υ
β
χ
ψ1
R Cor Bor
ε
α
γ
δ
Boötes
Hercules
Serpens
π
+22° 30'
β
ρ
16h 00m
15h 20m

4.7 Planetary Nebulae

At the end of the AGB phase, all that will remain of the 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 kilometres per second. As the debris moves away, the hot, dense and small core of the star will become visible. The ageing star will also undergo a series of bursts in luminosity, and in each burst, eject a shell of material into interstellar space. The star now begins to move rapidly towards the left of the H–R diagram, at an approximately constant luminosity, but getting increasingly hotter. It will only take, say, a few thousand years for the surface temperature to get to 30,000 K. Some stars achieve temperatures of 100,000 K. The exposed core of the star will, at these high temperatures, emit prodigious amounts of ultraviolet radiation that can excite and ionise the expanding shell of gas. The shell of ionised and heated gas will begin to glow, and produce what is called a *planetary nebula*.

To appreciate fully what is happening here, let's look a little deeper into what's going on. 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 re-ignites in what is called the *helium-shell flash,* similar to (but less intense than) the helium flash that occurs in the evolution of the 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, whilst the luminosity of the star during this time would slowly increase overall.

Significant mass loss can also occur during the thermal pulses. The 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 further 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 illuminates the surrounding dust and gas cloud.

The evolution of the remaining core is itself of interest as it progress rapidly to its final state. There are two factors that can influence the rate at which the core evolves. Firstly, 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. Secondly, 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 luminosities that can decrease by as much as 90% in as little as 100 years, whereas others may require a little longer, perhaps a few thousand years. As the source of ionising photons decreases over time, the planetary nebula grows darker, and eventually fades away.

Planetary nebulae[4] are some of the most interesting and beautiful objects in the sky and have a lot to offer the amateur. They range across the whole of the

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[4] The name "planetary nebula" was first applied to these objects by Herschel who thought that the nebula looked like Jupiter when seen in a telescope.

observational spectrum: some are easy to find in binoculars, whilst others will require large aperture, patience, and even maybe specialised filters in order for them to be distinguished from the background star fields. These small shells of gas, once the atmosphere of stars, come in a variety of shapes, sizes and brightness. 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 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 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, the nebula 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 old. However, this aspect of a star's evolution is apparently very common, and there are over 1400 planetary nebulae in our part of the Galaxy alone!

Visually, the nebulae are one of the few deep sky objects that actually appear coloured. Around 90% of its light comes from the doubly-ionised oxygen line, OIII, at wavelengths 495.9 nm and 500.7 nm. This is a very characteristic blue-green colour, and, it so happens, the colour at which the dark adapted eye is at its most sensitive. The specialised light filters are also extremely useful for observing planetaries as they isolate the OIII light in particular, increasing the contrast between the nebula and the sky background, thus markedly improving the nebula's visibility.

Such is the variety of shapes and sizes that there is something to offer all types of observer. Some planetaries are so tiny that even at high magnification, using large aperture telescopes, the nebula 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 exhibit a bi-polar shape, such as the *Dumbbell Nebula*, M27, in *Vulpecula*. Whilst others show ring shapes, such as the ever-popular *Ring Nebula, M57*, in *Lyra*.

An interesting aside 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 type O and B, but, as they are running down their nuclear reactions, or in some cases, no longer producing energy by nuclear reactions, 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. A smooth disclike appearance
    a. bright towards centre
    b. uniform brightness
    c. possible, faint ring structure
3. Irregular disclike 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;
    i.e., 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 point source. 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.

Caldwell 39	NGC 2392	$07^h\ 29.2^m$	+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 beginnings 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 in doubt, with values ranging from 1600 to 7500 light years. See Star Map 71.				

Caldwell 59	NGC 3242	$10^h\,24.8^m$	−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 nebula, and 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 colour 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. See Star Map 72.

Messier 97	NGC 3587	$11^h\,14.8^m$	+55° 01′	Feb–**Mar**–Apr
9.9m	⊕ 194″	◉ 3a	✸ 16	Ursa Major ©

Also known as the *Owl Nebula*. Not visible in binoculars owing 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 colour in regard to this particular planetary nebula is in question. See Star Map 71.

Caldwell 6	NGC 6543	$17^h\,58.6^m$	+66° 38′	May–**Jun**–Jul
8.3m	⊕ 18″	◉ 3a + 2	✸ 11	Draco ©

Also known as the *Cat's Eye Nebula*. Seen as a bright oval planetary nebula with a fine blue-green colour, this 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 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. See Star Map 71.

Messier 57	NGC 6720	$18^h\,53.6^m$	+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 nebula, and, surprisingly – and pleasantly – visible in binoculars. However, it will not be resolved into the famous "smoke-ring" shape seen so often in colour 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 large aperture and perfect conditions will be needed to see the central star. See Star Map 71.

Caldwell 15	NGC 6826	$19^h\,44.8^m$	+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 due solely 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, and 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*, and a halo which is delicate in structure with a bright shell. See Star Map 71.

Messier 27	NGC 6853	$19^h 59.6^m$	+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 rate this as 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 which spread out to the north and south of the planetary nebula's centre, and central star may be glimpsed. See Star Map 71.

Herschel 16	NGC 6905	$20^h 22.4^m$	+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 colour is seen. The central star can be seen only under good seeing conditions. See Star Map 71.

Caldwell 55	NGC 7009	$21^h 04.2^m$	−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 aperture, a telescope of at least 25 cm is needed to see the striking morphology of the planetary nebula which 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. 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. See Star Map 71.

Caldwell 63	NGC 7293	$22^h 29.6^m$	−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 light years, it has an angular size of over $\frac{1}{4}^\circ$ – 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 in order to glimpse the central star. The use of an OIII filter will drastically improve the image. See Star Map 71.

Caldwell 22	NGC 7662	$23^h 25.9^m$	+42° 33′	Aug-**Sep**-Oct
8.6m	⊕ 12″	◉ 4 + 3	✸ 13.2	Andromeda

Also known as the *Blue Snowball*. This nice planetary nebula is visible in binoculars owing to its striking blue colour, but 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-Ionisation Emission Regions* (Fliers). These are clumps of above-average-density gas ejected from the central star before it formed the planetary nebula. See Star Map 71.

Caldwell 56	NGC 246	$00^h 47.0^m$	−11° 53′	Sep-**Oct**-Nov
8.5m	⊕ 225″	◉ 3b	✸ 11	Cetus

A nice planetary nebula that is large and bright and shows a distinct circular appearance. An aperture of at least 20 cm is needed for its true nature to become apparent. With larger apertures the mottling appearance is easily seen, with bright and dark areas making up the characteristic shape of this planetary nebula. Its central star is very strange, believed to be one of the hottest stars known, with a temperature of at least 135,000 K. It is also thought to be a binary star, which may account for its peculiar shape. See Star Map 71.

Messier 76	NGC 6501	$01^h 42.4^m$	+51° 34′	Sep-**Oct**-Nov
10.1m	⊕ 65″	◉ 3 + 6	✸ 15.9	Perseus ©

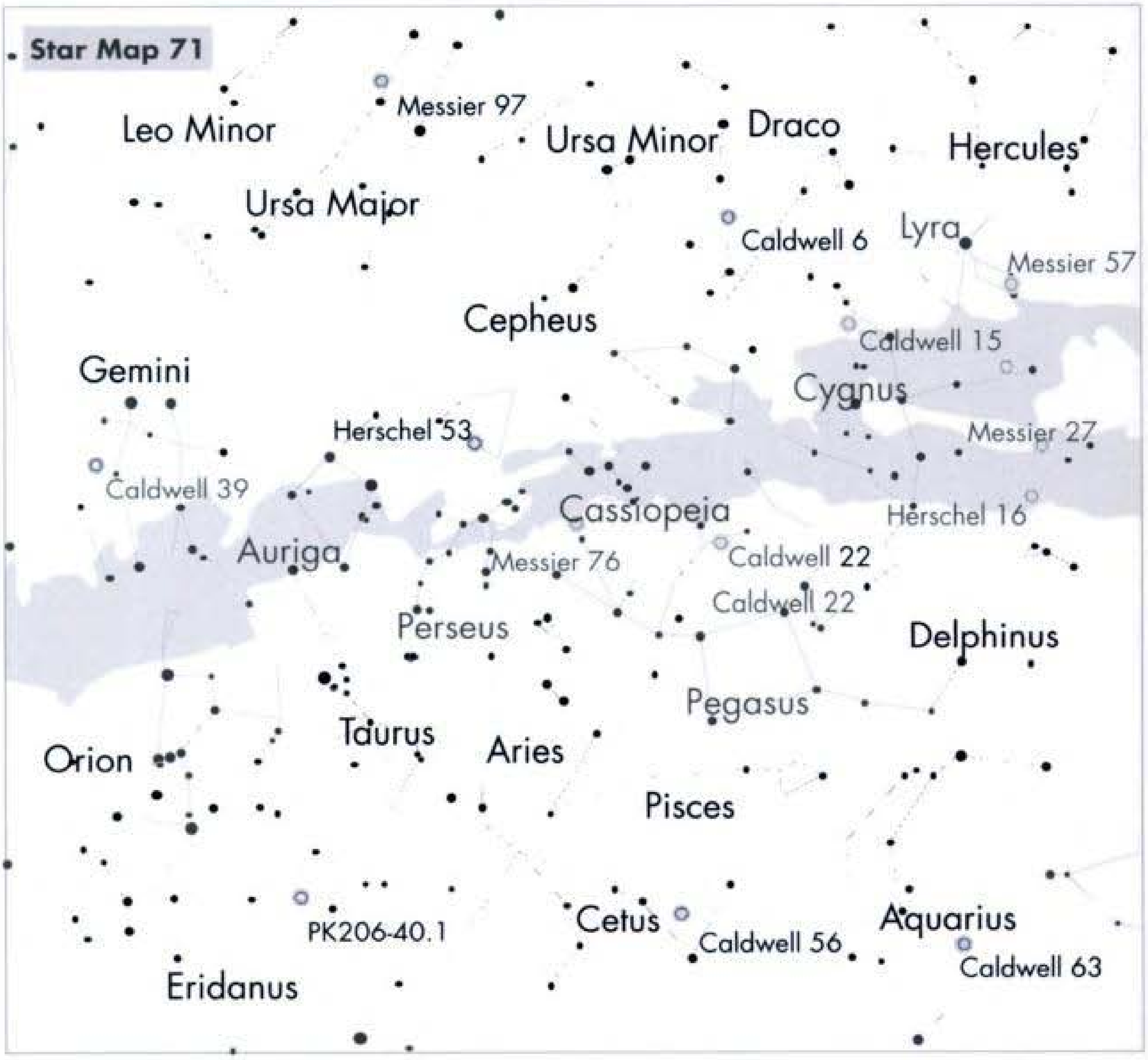
Also known as the *Little Dumbbell Nebula*. This is a small planetary nebula that shows a definite non-symmetrical shape. In small telescopes of aperture 10 cm, and using averted vision, two distinct "nodes" or protuberances can be seen. With apertures of around 30 cm, the planetary nebula will appear as two bright but small discs which are in contact. Even larger telescopes will show considerably more detail. See Star Map 71.

PK206-40.1	NGC 1535	$04^h 14.2^m$	12° 44′	Oct-**Nov**-Dec
9.6m	⊕ 18″	◉ 4 + 2c	✸ 12	Eridanus

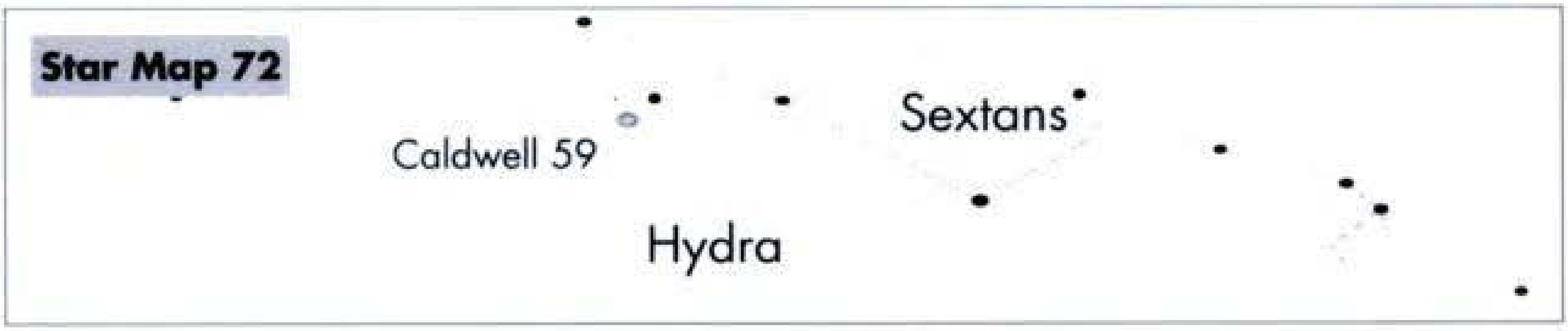
One of the few planetary nebulae that show a distinct circular appearance in small telescopes. With an aperture of 5 cm and magnification of at least 100%, a small hazy glow will be seen. Under higher apertures, the disc is resolved along with the nice blue colour. Telescopes of 20 cm will easily resolve the subtle hazy outer ring structure, and the bright bluish-green disc, and central star is easily seen. See Star Map 71.

Herschel 53	NGC 1501	$04^h 07.0^m$	+60° 55′	Oct-**Nov**-Dec
11.5m	⊕ 52″	◉ 3	✸ 14.5	Camelopardalis ©

Has been called the *Oyster Nebula*. A very nice blue planetary nebula, easily seen in telescopes of 20 cm, and glimpsed in apertures of 10 cm. With larger aperture, some structure can be glimpsed, and many observers liken this planetary nebula to that of the *Eskimo nebula*. See Star Map 71.



Star Map 71



Star Map 72

4.8 White Dwarf Stars

We now look at the final end point for low mass stars, and it is a very strange end indeed. We have seen how stars which have a mass less than $4\,M_{\odot}$, never manage to produce the internal pressure and temperature that is 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.

4.9 Electron Degeneracy and White Dwarfs

Experience tells us that as the mass of an object increases, so does it 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 is, the smaller it becomes. The reason for this contrary behaviour is 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. 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. What this means is that 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 around 50% larger than the Earth. If the white dwarf is 1.3 $M_\odot$, then it is only 40% as large as the Earth.

4.10 The Chandrasekhar Limit

White dwarf stars have a very unusual mass–radius relationship that relates it mass to its radius, and this is shown in Figure 4.3. It shows that the more degenerate matter you put into a white dwarf star, the smaller it gets. However, you cannot do this ad infinitum, 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 behaviour of white dwarfs. It is the mass for which the 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 type 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 whilst 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.

A question that is often asked is "what is a white dwarf star made out of?", and the answer often surprises – it surprised me! The matter making up the white dwarf star consists for the most part of ionised oxygen and carbon atoms, that are floating in a sea of fast moving degenerate electrons. As the star continues to cool, the particles in this matter slow down which results in electric forces between the ions beginning to dominate over the random thermal motions that they originally had. These ions now no longer move freely

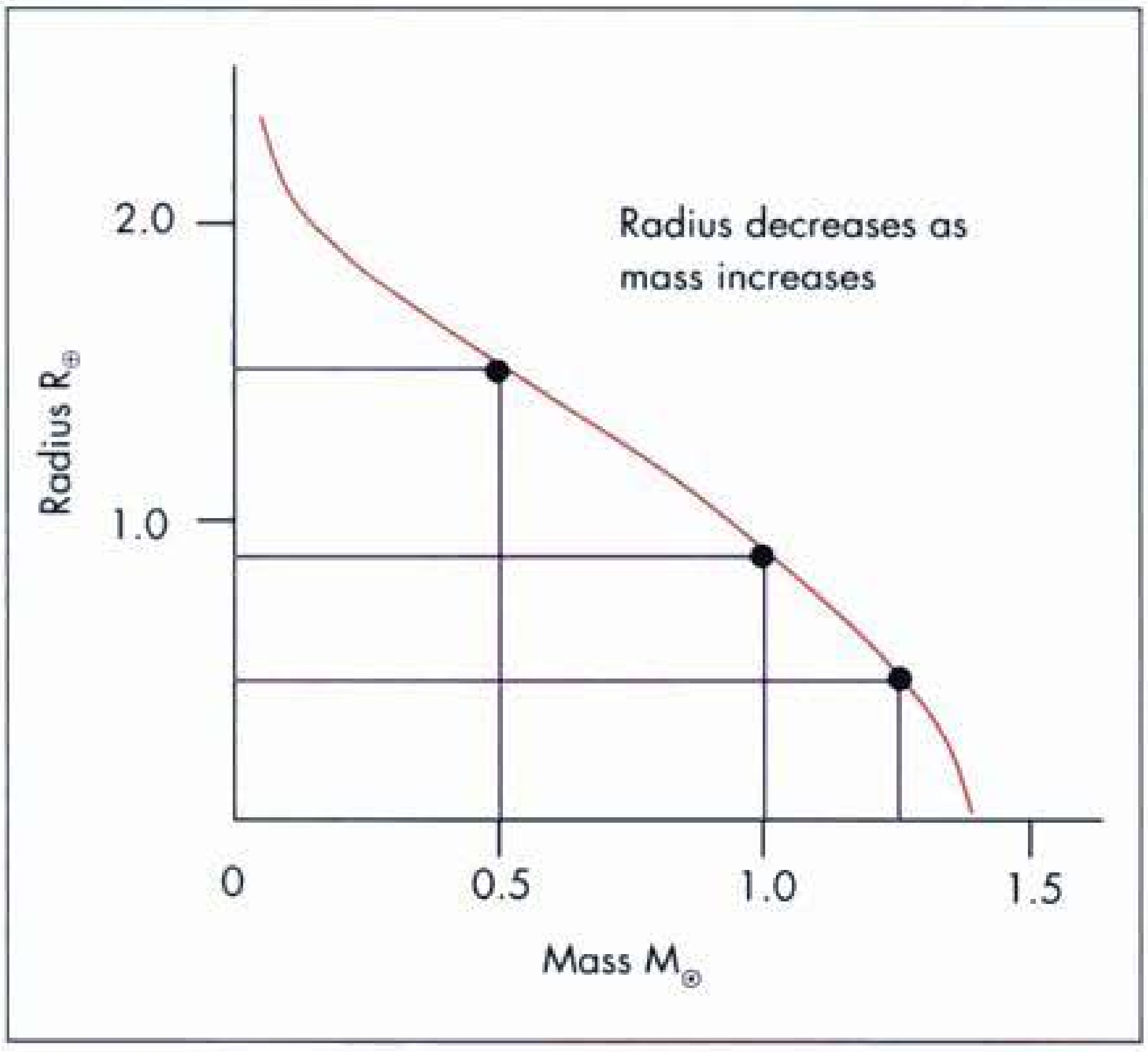


Figure 4.3. Mass–Radius Relationship for White Dwarf Stars. The radius is given in terms of the Earth's radius. The more massive a white dwarf, the smaller it will be. Note that on this graph, the size of a white dwarf will fall to zero if it has a mass of 1.4 $M_\odot$.

though the white dwarf, but instead 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 that 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 of you could get a teaspoon of the matter to the Earth in the first place.

4.11 White Dwarf Evolution

When the white dwarf shrinks down to its final size, it will no longer have any 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 is shown in Figure 4.4, where white dwarf stars of differing mass are plotted on a H–R diagram. The more massive a white dwarf star the smaller its surface area than those white dwarfs which are less massive. This means that massive white dwarfs are less luminous for a given temperature, so that their evolutionary tracks are below those of the less massive white dwarf stars.

Theoretical models have been constructed of the evolution of white dwarfs 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 falls in luminosity take progressively longer 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 reach a luminosity of 0.001 $L_\odot$. At this point the white dwarf will have the same temperature and colour of the Sun. it will be so faint, however, that unless it were within a few parsecs of the

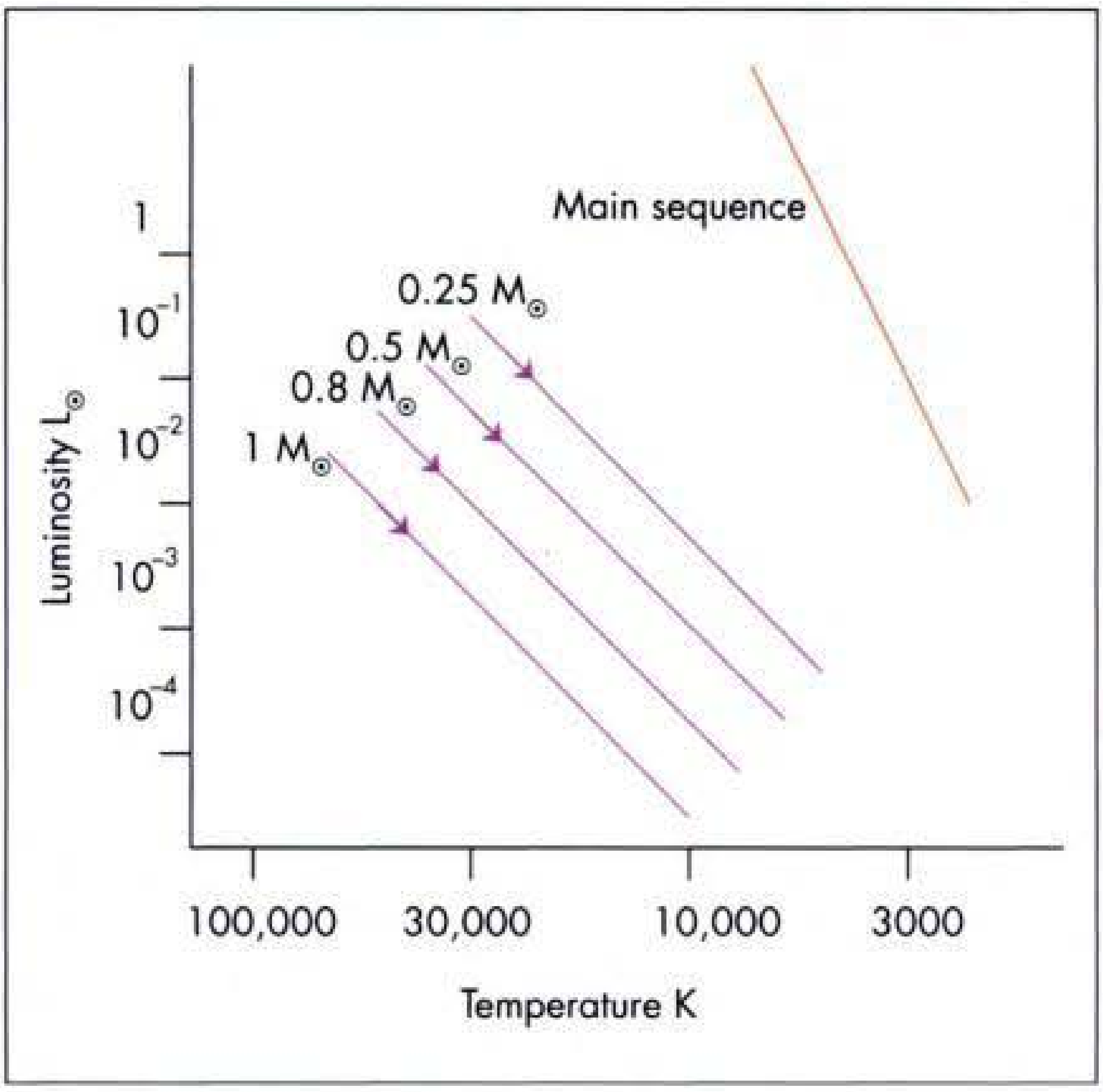


Figure 4.4. White Dwarf Evolutionary Tracks. A white dwarf will cool and grow fainter so it moves downwards and to the right on the H–R diagram. The more massive a white dwarf, the smaller and fainter it will be. Therefore track for a 1 $M_\odot$ white dwarf will lie below the track for less massive white dwarfs. Note that although a white dwarf may have the same temperature as a main-sequence star, it will be fainter because it has a smaller surface area.

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 even longer to cool down and grow faint.

In the case of the Sun, it will eject most of its mass into space, and will eventually end up about the same size as the Earth, but its luminosity will change dramatically, perhaps only achieving one tenth the brightness it has presently. As it ages even further it will continue to get even fainter. When around 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!

4.12 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 is now a planetary nebula, and at the moment nuclear fusion ends, a white dwarf is born.[5] But even though theory matches well with observations, there is still doubt as to what the mass of the star may originally have been and still 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 $M_{\odot}$ will produce white dwarfs of mass 0.6 to 07 $M_{\odot}$. If a white dwarf star has a mass less than 0.6 $M_{\odot}$, then 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, that 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 to 100,000 years.

Due to their faintness and small size, white dwarf stars present a challenge to observers. There are, of course, a lot 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 in locating and observing them. On the other hand, there are a handful that can, given the right conditions, 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 to the Earth, thus $0.5_{\oplus}$ would mean that it is half the size of the Earth.

Sirius B		$06^h\ 45.1^m$	−16° 43′	Dec–**Jan**–Feb
8.4m	11.2M	0.92 ⊕	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. Firstly, 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* was not a companion to Sirius, it would be easily visible in binoculars. Secondly, its orbit changes over a period of 50 years. This means that at certain times it will be too close to Sirius for it to be detected with amateur instruments. The next time when it will be at maximum separation will be in 2025. See Star Map 2.

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[5] 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, and grew to red-giant size once again, and is now ejecting more gas. Another star which has showed a similar behaviour is V605 Aquilae.

Procyon B	α Canis Minoris	$07^h 39.3^m$	+05° 13′	Dec–**Jan**–Feb
10.9m	13.2M	1.05 ⊕	8700 K	Canis Minoris

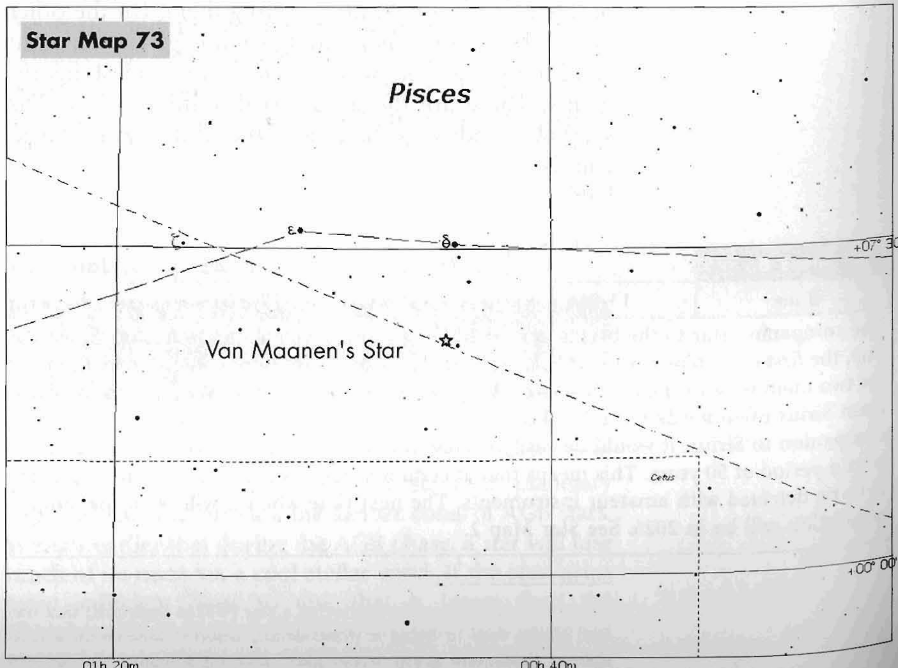
This dwarf star is not easily visible in small amateur telescopes, having a magnitude of 10.8 and a mean separation of 5 arcseconds. Note that it has a low temperature as compared to other white dwarfs. It is the second closest white dwarf to the Earth. A challenge to observers. See Star Map 2.

o² Eradini	40 Eridani B	$04^h 15.2^m$	−07° 39′	Oct–**Nov**–Dec
9.5m	11.0M	1.48 ⊕	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 2nd 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. See Star Map 8.

van Maanen's Star	Wolf 28	$00^h 49.1^m$	+05° 25′	Aug–**Sep**–Oct
12.3m	14.1M	0.9(?) ⊕	6000 K	Pisces

One of the few stars visible to amateurs, it is a close white dwarf, at only 13.8 light years 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 arcseconds per year. See Star Map 73.



4.13 High-Mass Stars: Nuclear Burning and an Onion

We have seen what happens to those stars that have a low mass, and how they age and fade away gracefully. We now turn our attention to the high-mass stars. And as you have probably surmised by now, the death throes of these stars are very different from those of low-mass stars, and very spectacular.

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 $M_\odot$, also 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.[6] The core continues to collapse with an accompanying rise in temperature to about 600 million Kelvin. 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 Kelvin, and *neon*

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[6] Some helium nuclei do remain in the star's core, but these are not in sufficient number to initiate helium burning in any great amount.

burning begins. In this manner the neon produced by the earlier carbon burning reaction, is used up, but at the same time, increases 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 temperature reaches 1.5 billion Kelvin, with the production of sulphur. *Silicon burning* can also occur if the core temperature reaches the staggering temperature of 2.7 billion Kelvin. 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 zig-zagging across the top of the H–R diagram.

Some of the reactions that occur also release neutrons, which are particles similar to a proton, except that they do not have an electric charge. This neutrality means that they can, and do, collide with positively charged nuclei and also 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 stars life helps to initiate the next succeeding phase. As each phase ends due to the star 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 as 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 increasingly rapid rate. One calculation has been made in detail for a 20–25 $M_\odot$ zero-age stars, and the results are very surprising. The carbon burning stage can last for about 600 years, whilst the neon burning stage can be as short as 1 year. Then things start to speed up! The oxygen burning last only 6 months, and the silicon burning only 1 day!

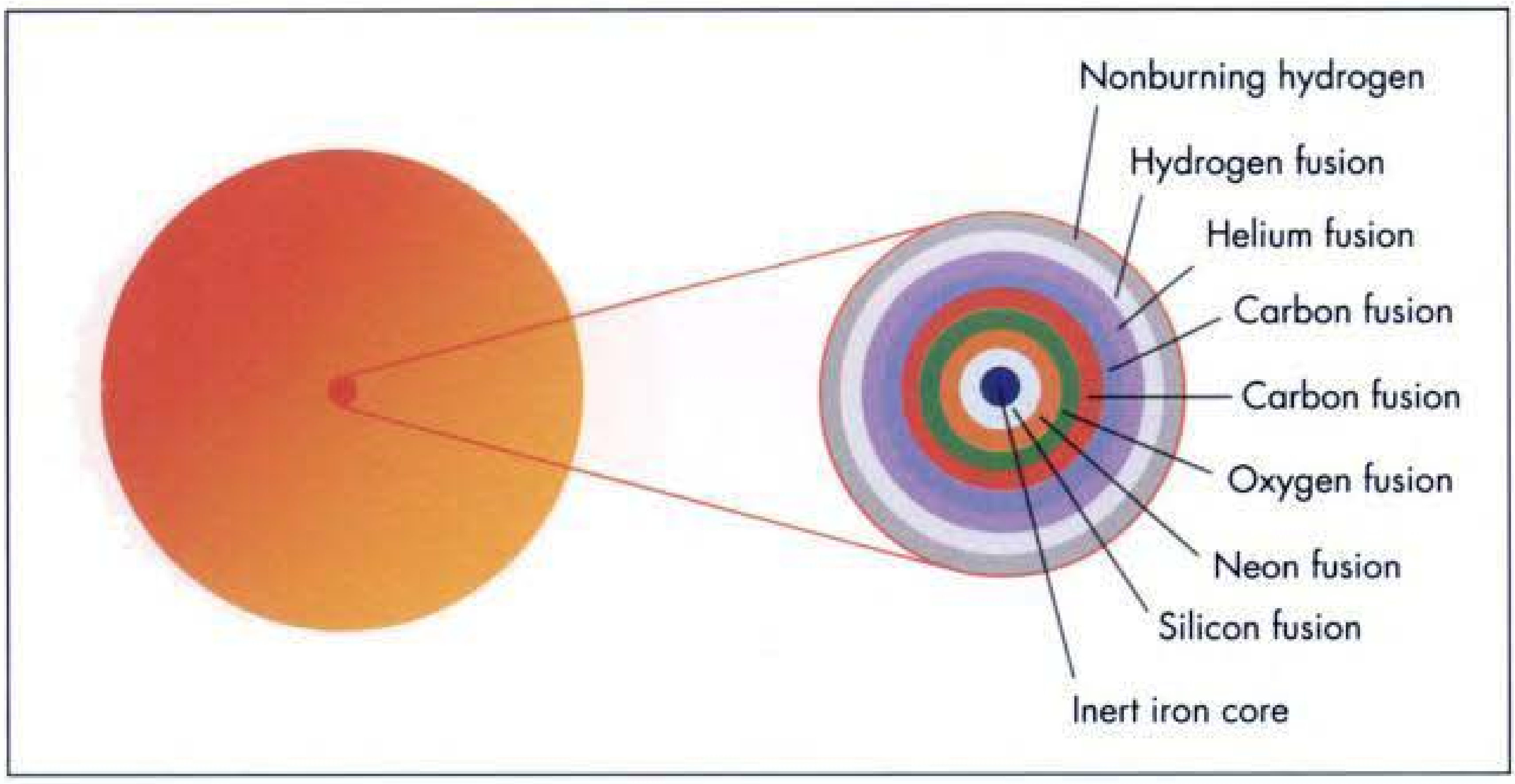
At each phase of core burning, a new shell of material is formed around the core of the high-mass star, and after several such stages, in say, a very massive star of mass 20–25 $M_{\odot}$, the internal structure of the star can resemble an onion, shown in Figure 4.5.

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.

Many of the brightest stars in the night sky are supergiants. Including several we have met earlier in the book. These include *Rigel* and *Betelgeuse* in *Orion*, and *Arcturus* in *Scorpius*. Rigel has a temperature of 11,000 Kelvin, while Betelgeuse is only 3700 Kelvin (or even cooler), and is an example of a "red supergiant'. Thus, although Betelgeuse is cooler, it must be correspondingly larger in order 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 around 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 by thinking of it this way; if it were placed in the Solar System, it would

Figure 4.5. The Multiple-Layer Structure of an Old High-Mass Star.

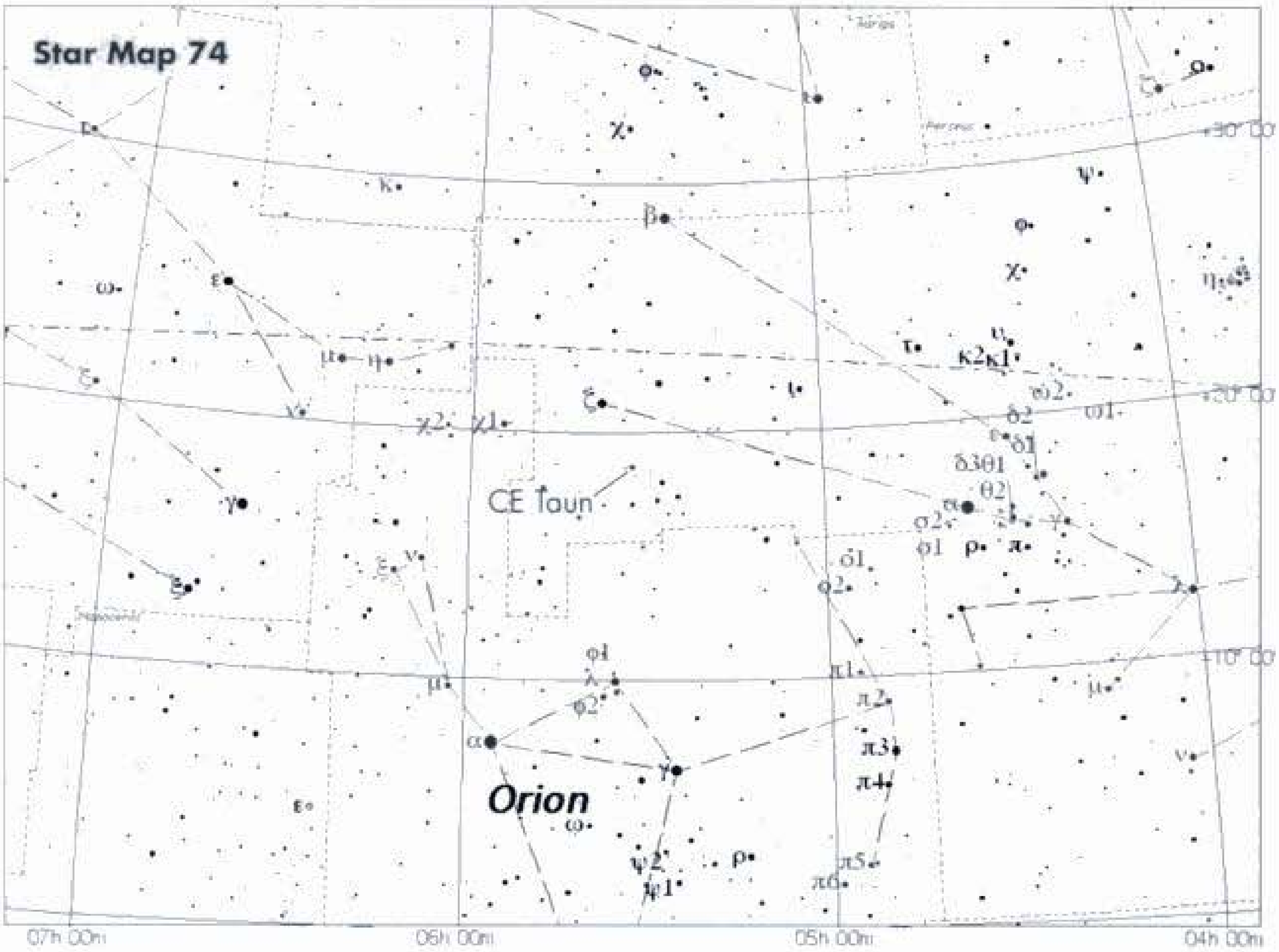


extend past the asteroid belt to about half-way between the orbits of Mars and Jupiter. *Antares* would extend nearly to Jupiter! *Alpha Herculis* is only a mere 2 astronomical units in radius. The record however must go to *VV Cephei*, which is an eclipsing binary star. Its radius is a staggering 1900 times that of the Sun, or 8.8 astronomical units. This means that it would extend nearly all the way to Saturn.

As I mentioned above, supergiant stars are quite rare, but fortunately for us as observers, there are several we can see with the naked eye, and these are listed below.

CE Tauri	HD36389	$05^h\ 32.2^m$	+18° 35′	Nov–**Dec**–Jan
4.38m	–6M	M2 Iab		Taurus
Also known as *119 Tauri*, this star has a radius of 2.9 astronomical units, and lies about 2000 light years 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. See Star Map 74.				

Mu Geminorum	HD44478	$06^h\ 12.3^m$	+22° 54′	Nov–**Dec**–Jan
6.51m	–4.09M	M2 Iab		Gemini
Part of the *Gem OB1* stellar association, this is at the limit of naked eye visibility as observed from an urban location. It lies at a distance of 4900 light years. See Star Map 9.				



Other stars that are supergiants, but have been mentioned in earlier sections are: *Rigel, Betelgeuse, Antares, Mu Cephei, Eta Persei,* ψ^{-1}*Aurigae, VV Cephei, Alpha Herculis.*

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 the O-type stars, but have very strange spectra that show only emission lines and, strangely enough, no hydrogen lines. They are few and far between, with perhaps only 1000 in our Galaxy. They have, however, a terrific mass loss, and images from large telescopes show these stars surrounded by rich clouds of material that has been ejected. Fortunately for us, there is a very bright example which can be easily observed.

γ^2 Vel	HD 68273	$08^h\ 09.5^m$	–47° 20′	Dec–**Jan**–Feb
$1.99_v m$	0.05M	WC 8		Vela
The brightest and closest of all *Wolf–Rayet* stars. Believed to be precursors to the formation of planetary nebulae. Extremely luminous stars, they have luminosities that may reach 100,000 times that of the Sun, and temperatures in excess of 50,000 K. γ^2 *Vel* is an easy double, of colours white and greenish-white. See Star Map 33.				

This aspect of a supergiant's life, whereby several layers of nuclear burning occur, resembling the layers of an onion, cannot go on for ever, 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 very spectacular manner – a *supernova.*

4.14 Iron, Supernovae and the Formation of the Elements

When nuclei collide in the core 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 that makes up the 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 an 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 and including 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 talking place within it.

Of course, surrounding this inert core of iron will be the various shells of nuclear burning.[7] However, this is a state of affairs that cannot go on for much longer.

Astronomers use a variety of techniques in order 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 come from very 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 which 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.[8]

During these final days of the 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. But recall 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 so it collapses.

A consequence of the core contraction is an increase in the density, and this in turn gives rise to a process

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[7] 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.

[8] Don't think that astronomers know all there is to know about what gives rise to a supernova. Prior to the famous supernova in 1987, "SN 1987A", astronomers believed that only red supergiants could form supernovae. They were thrown into some confusion when it was discovered that the progenitor star of SN1987 was a blue supergiant!

called *neutronisation*. This is a process where electrons react with the protons in the iron nuclei to form neutrons. This shown below.

$$e^- + p^+ \rightarrow n + \nu$$

Each neutronisation 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 better be termed a collapse of the core. It only takes about a second for the core to collapse from a radius of thousands of kilometres, to about 50 kilometres. Then in only a few more seconds, it shrinks down to a 5-kilometre radius. The core temperature also increases during this time to about 500 million Kelvin. The gravitational energy released as a result of the *core collapse* is equal to the Sun's luminosity for several billions of 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 of a second, the central 0.6 to 0.8 $M_\odot$ of the collapsing core will reach a density equal to the density 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 metres in diameter. The core of the star, for all intents and purposes 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 illustrated in Figure 4.6. This is called the *core bounce*.

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 so 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

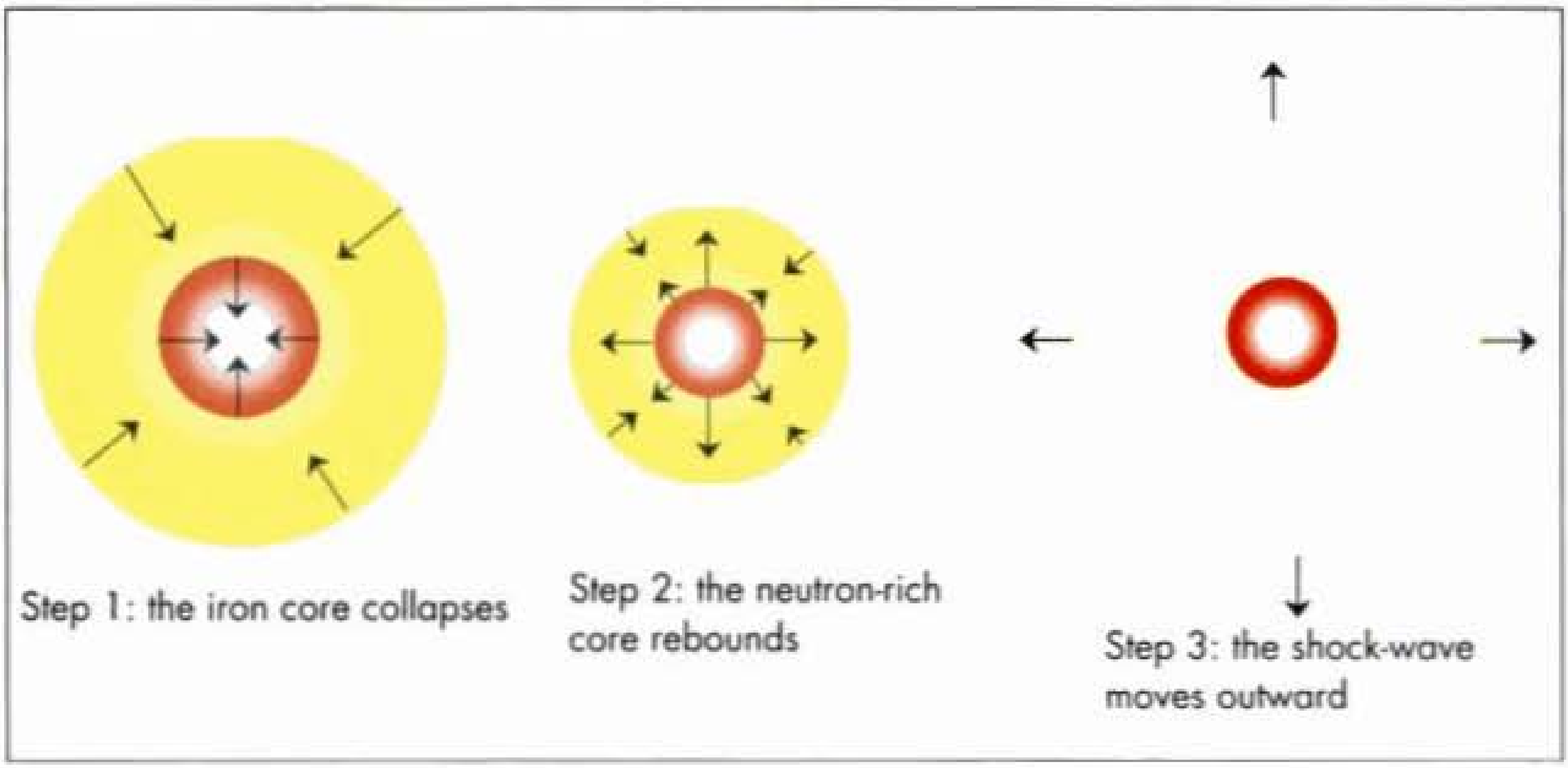


Figure 4.6. Evolution of a Supernova Explosion.

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 towards the surface of the star.

Surprisingly enough, this wave of pressure would soon die out long before it reached the surface of the star if it wasn't for the fact that helping it along is the immense amount 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 that of the speed of sound in the star's outer regions. The pressure wave now behaves like a shockwave.

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 kilometres per second. The energy released during this event is a staggering 10^{46} joules, 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 but a few, are produced, and this has profound implications because it means that the stuff which 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 supernova event. These decaying nuclei are able to keep the supernova shining for many years.

As an observer, it would be delightful if, on a few nights a year, you could go out and just pick a supernova that you wish to look at. Life isn't 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. But think again. 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 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 which blocks out the light from any supernova that may be happening. That isn't 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 which we should keep an eye on, *Betelgeuse* and *Eta Carinae* to name but two.

We can, however, see the remains of a supernova, the *supernova remnant.*

4.15 The Supernova Remnant

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 which 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 centre that provides a replenishing source of energy to the far-flung material. The classic archetypal SNR which 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, whilst others emit radiation as a consequence of the tremendous kinetic energies of the exploding star material.

Caldwell 34	NGC 6960	$20^h\ 45.7^m$	+30° 43′	Jul–**Aug**–Sep
• 3–5	⊕ 7016″			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 impacting on the much denser interstellar medium. The actual remains of the star have not been detected. See Star Map 75.

Caldwell 33	NGC 69925	$20^h\ 56.4^m$	+31° 43′	Jul–**Aug**–Sep
• 2–5	⊕ 6018″			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 been described as looking like a fish-hook. Using a telescope, it becomes apparent why the nebula has been the named the *Filamentary Nebula,* as lacy and delicate strands will be seen. However, there is a down side: 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). See Star Map 75.

	IC 2118	$05^h\ 06.9^m$	–07° 13′	Nov–**Dec**–Jan
• 3–5	⊕ 180|60″			Orion

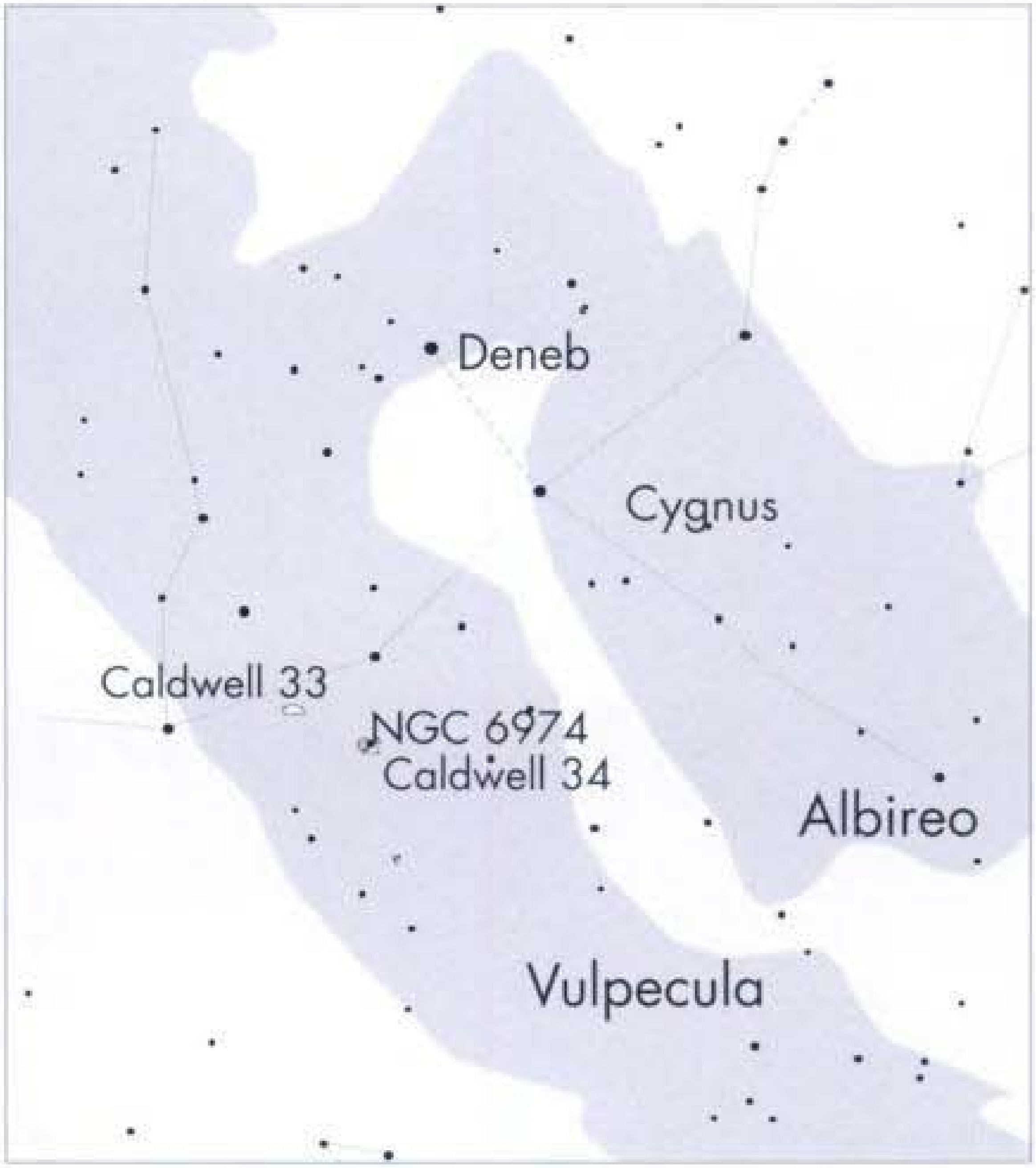
Also known as the *Witch Head Nebula*. This is a very faint patch of nebulosity which apparently is the last of a very old supernova remnant. It resembles a long ribbon of material, which can be glimpsed with binoculars. It is glowing by reflecting the light of nearby *Rigel*. Very rarely mentioned in observing guides. See Star Map 77.

Messier 1	NGC 1952	$05^h\ 34.5^m$	+22° 01′	Nov–**Dec**–Jan
• 1–5	⊕ 614″			Taurus

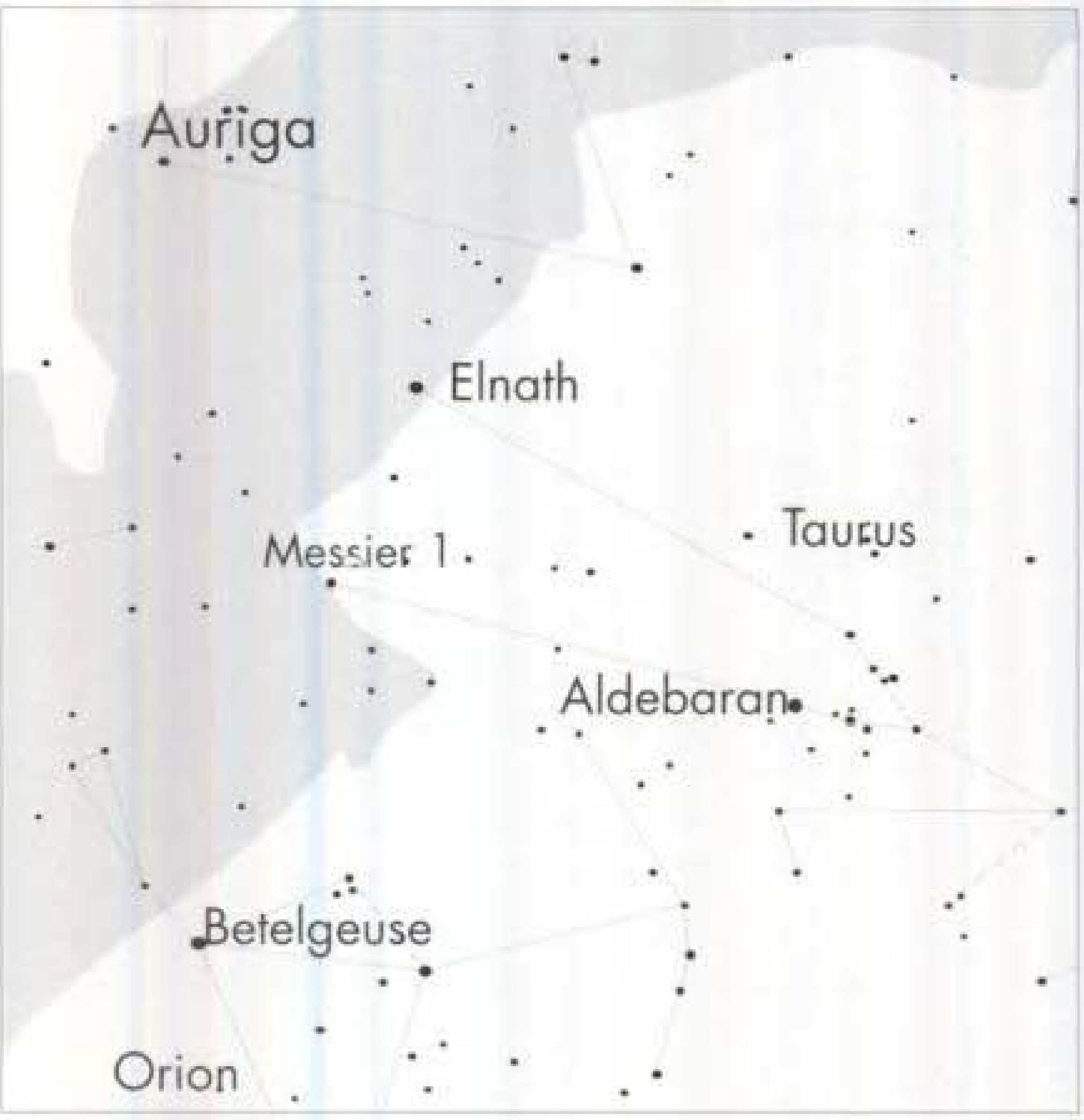
Also known as the *Crab Nebula*. The most famous supernova remnant in the sky, it can be glimpsed in binoculars as an oval light of plain appearance. With telescopes of aperture 20 cm it becomes a ghostly patch of grey light. In 1968, in its centre was discovered the *Crab Pulsar*, the source of the energy responsible for the pearly glow observed: a rapidly rotating neutron star which 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. See Star Map 76.

Sharpless 2-276		$05^h\ 56.0^m$	−02° 00′	Nov–**Dec**–Jan
• 6.5 ?	⊕ 600″			Orion

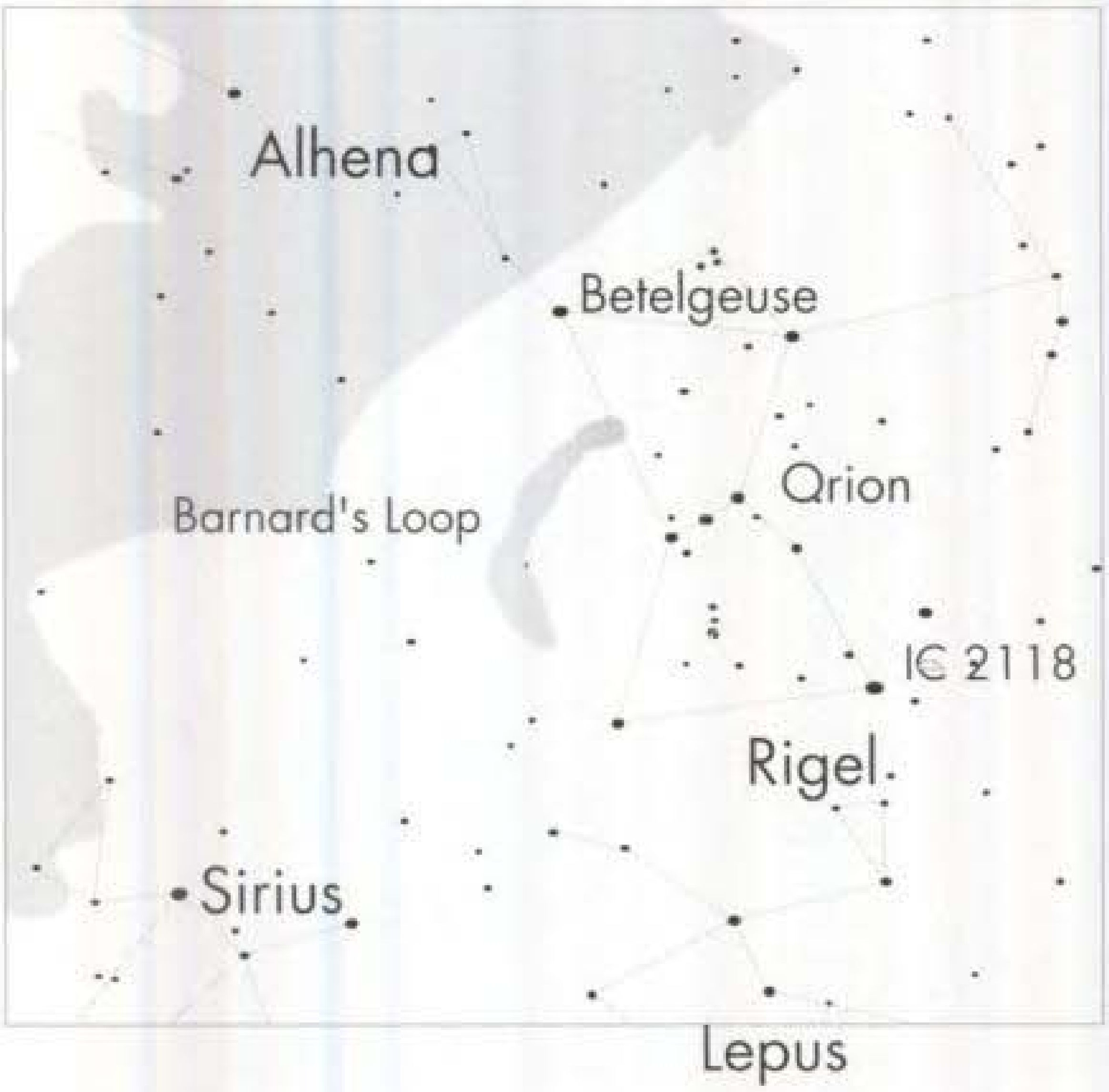
Also known as *Barnard's Loop*. It seems to be the remains of a very old supernova. Often mentioned in books, but very rarely observed, this is a huge arcing loop of gas located to the east of the constellation Orion. It encloses both the sword and belt of Orion, and if it were a complete circle it would 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 it being seen. See Star Map 77.



Star Map 75



Star Map 76



Star Map 77

4.16 A Final Note on Supernovae

Before we say a fond farewell to supernovae, and 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 between 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* supernova do not have these lines, whereas *Type II* do have them. The supernova we have discussed above is a Type II supernova. This class of supernova involves the final death throes of a very evolved and 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. On the other hand, Type I do not have hydrogen emission lines and can be further sub-divided into Type Ia, Ib and Ic. Type Ia has absorption lines of ionised silicon, and Type Ib and Ic do not. Furthermore, 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 the story that has to be mentioned. Types Ib, Ic and Type 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 close-by 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.

However, Type Ia supernovae are a different beast altogether. They are found usually, but not always, in galaxies where star formation may be minimal or 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, we have discussed, in an earlier section, stars that are the originators of Type Ia supernovae. These are white dwarf stars which 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 can "flow" or be transferred to a companion star.[9] This material then falls onto the white dwarf star. A consequence of this extra material is that the Chadrasekhar 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 cooling down, and the carbon burning ceasing. However, as we have seen, white dwarfs are not normal. They are made of degenerate matter and this means that the increase in temperature just 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 to be 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,[10] whereas Type II involve gravitational energy and emit an enormous number of neutrinos.

All this of course has no bearing on the amateur astronomer who wishes to observe a supernova, as this will not help or hinder you in the observation of any supernova. Nevertheless, it is important on know, when and if you read about it in magazines or on the WWW, that the latest supernova 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.

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[9] 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.

[10] As there is no core collapse in a Type I supernova, there will be comparatively little neutrino emission.

4.17 Neutron Stars, Pulsars and Black Holes

The final end point 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 to all intents and purposes are not observable with amateur equipment.[11] 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 how in a Type II supernova the central 0.6 $M_\odot$ of the collapsing core has a density that equals 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 this 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 of those of white dwarf stars. For instance, an increase in 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 what calculation is being used at the time. Nevertheless, they give a good picture of the star.

Two properties of neutron stars that we can describe with confidence are its rotation and magnetic field. A neutron star rotates at a very rapid rate, as many as a hundreds and even thousand 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 visualise. Just picture an

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[11] 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!

ice skater spinning around, as she/he pulls in her/his arms, she/he 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 into 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 shrank 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 perhaps at nearly half the speed of light. The material literally crashed onto the star and results in hot spots. The temperature of these "hot spots" are 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 a bit 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, which is nearly 100,000 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 will last 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 in Cambridge, Jocelyn Bell, discovered a source of extremely 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 to be 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 civilisation. Not surprisingly, this last idea was discounted. Another model was that of a rotating white dwarf star. All 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 is the pulse that we detect. 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 which have periods of say, 5 seconds or longer. This would imply that the pulse mechanism must stop 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 above 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 centre of supernova remnants, or SNRs. We do, but so far there are only three known SNRs with associated pulsars. There are two reasons for this. In order to detect a pulsar, the beams have to sweep past the Earth, and if they don't we will not detect them. Secondly, the supernova remnant will only last a relatively short time, perhaps 100,000 years before it merges into the interstellar medium, and disappear 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 centre 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 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 on a white dwarf's mass, the Chandrasekhar limit, beyond which the star cannot support the weight of the material making up the star. 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 the famous equation of *Einstein*, $E = mc^2$, 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*.[12] We have reached the end of a star's life.

4.18 From Beginning to End

We have travelled a path through space and time, following the birth of stars from clouds of dust and gas, deep in the cold of interstellar space. We have seen how the star ages and grows, and how it behaves depending on its mass. Then we watched as it aged and died, perhaps a slow process as in a white dwarf star, or perhaps in a vast brilliant explosion that sends the building blocks of stars, planets, and life itself, into space. It is a fascinating and at times amazing story. But perhaps the most incredible aspect of this whole process is that, not only have we the ability to comprehend and begin to understand what we see in the night sky, but that we ourselves are made from the very material that we observe. We are starstuff.

Read this book - and then go outside and see for yourselves what wonderful things the stars are.

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[12] I have chosen to end here even though black holes are fascinating objects. They play no further role in stellar evolution. A list of books covering the topic can be found in the appendices.

Appendix 1

Degeneracy

The topic of degeneracy is a very important one, especially in the later part of a star's life. It is, however, a topic that sends quivers of apprehension down the backs 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 a star is made up will behave like an *ideal gas*; i.e., one that has a simple relationship between 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. 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 ionised so that they become a soup of atomic nuclei and electrons.

Inside stars, especially those where the 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.*

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[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!

But a consequence of this degeneracy is that the behaviour 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, then I recommend some of the books mentioned in the latter appendices. Be warned, however, that mathematics is used liberally.

Appendix 2

Books, Magazines and Organizations

There are many fine astronomy and astrophysics books in print, and to choose amongst them is a difficult task. Nevertheless, I have selected a few which I believe are amongst the best on offer. I do not expect you to buy, or even read them all, but it would be in your better interests 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, I. Ridpath (ed.), Longmans, 1999, Harlow, UK.

Sky Atlas 2000.0, W. Tirion and R. Sinnott, Sky Publishing and Cambridge University Press, 1999, Massachusetts, USA.

Millennium Star Atlas, R. Sinnott and M. Perryman, Sky Publishing, 1999, Massachusetts, USA.

Uranometria 2000.0: Volumes 1 and 2, Wil Tirion (ed.), Willmann-Bell; Virginia, 2001, USA.

Observing Handbook and Catalogue of Deep-Sky Objects, C. Luginbuhl and B. Skiff, Cambridge University Press, 1990, USA.

The Night Sky Observer's Guide: Vols. I and II, G. Kepple and G. Sanner, Willman-Bell, 1999, Richmond, USA.

Deep-Sky Companions: The Messier Objects, S. O'Meara, Cambridge University Press, 1999, 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.

Astronomy and Astrophysics Books

Astrophysical Techniques, C. Kitchin, Institute of Physics, 1998, Bristol, UK.

Discovering the Cosmos, R. Bless, University Science Books, 1996, Sausolito, USA.

The Cosmic Perspective, J. Bennett, M. Donahue, N. Schneider and M. Voit, Addison Wesley, 1999, Massachusetts, USA.

Voyages Through The Universe, A. Fraknoi, D. Morrison and S. Wolff, Saunders College Publishing, 2000, Philadelphia, USA.

Introductory Astronomy and Astrophysics, M. Zeilik, S. Gregory and E. Smith, Saunders College Publishing, 1999, Philadelphia, USA.

Stars, J. B. Kaler, Scientific American Library, 1998, New York, USA.

Extreme Stars, J.B. Kaler, Cambridge University Press, 2001, UK.

The Physics of Stars, 2nd Edition, 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, UK.

The Dusty Universe, A. Evans, John Wiley, Chichester, 1994, UK.

Exploring Black Holes, E. Taylor and J.A. Wheeler, Princeton University Press, 2001, Princeton, USA.

Magazines

Astronomy Now, UK
Sky and 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, 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.demon.co.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.corvus.com]

The Astronomical League. [http://www.astroleague.org/]

The British Astronomical Association, Burlington House, Piccadilly, London, W1V 9AG, UK. [http://www.ast.cam.ac.uk/~baa/]

The Royal Astronomical Society, Burlington House, Piccadilly, London, W1V 0NL, UK. [http://www.ras.org.uk/membership.htm]

Campaign for Dark Skies, 38 The Vineries, Colehill, Wimborne, Dorset, BH21 2PX, UK. [http://www.dark-skies.freeserve.co.uk/]

Appendix 3

The Greek Alphabet

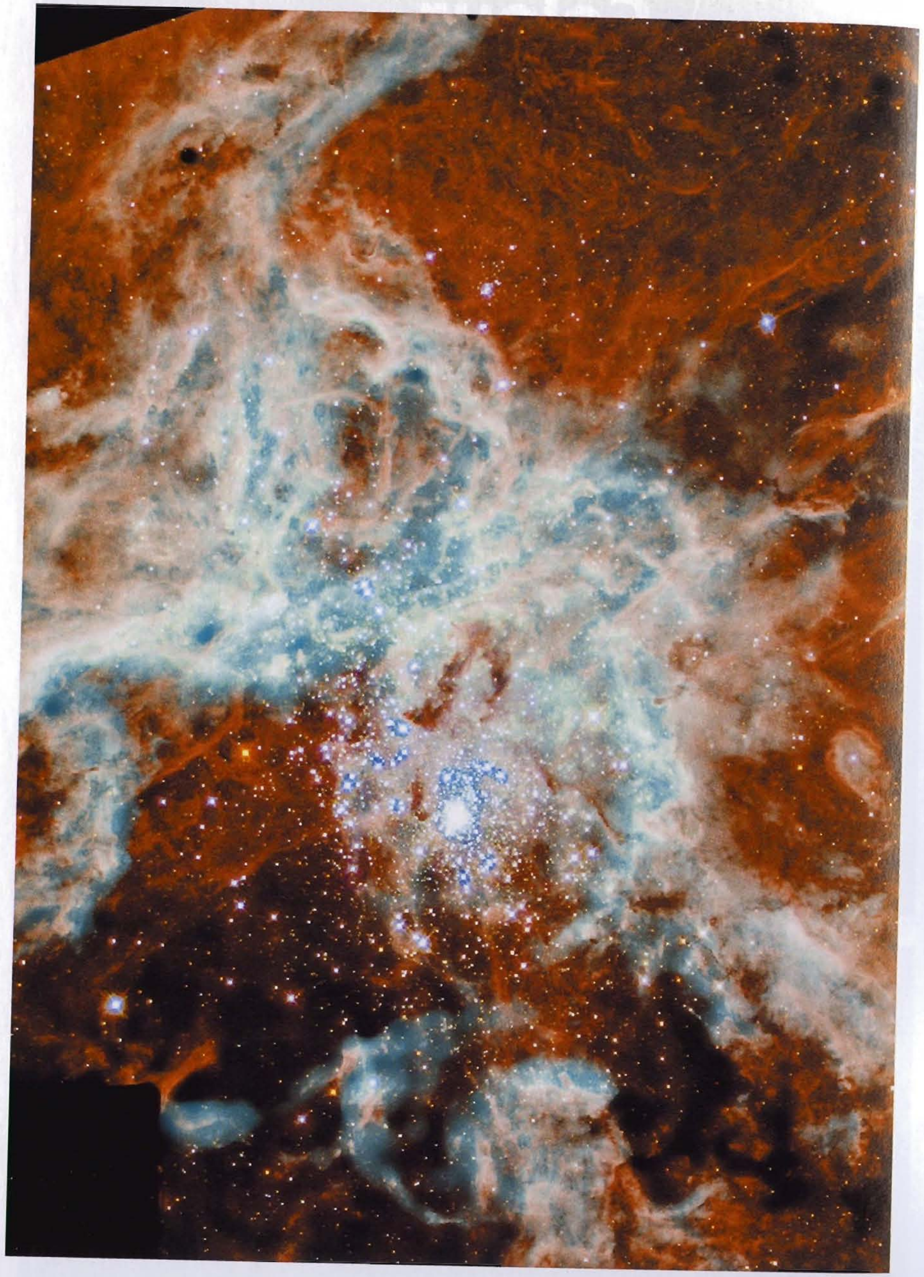
The following is a quick reference guide to the Greek letters, used in the Bayer classification system. Each entry shows the uppercase letter, the lowercase letter, and the pronunciation.

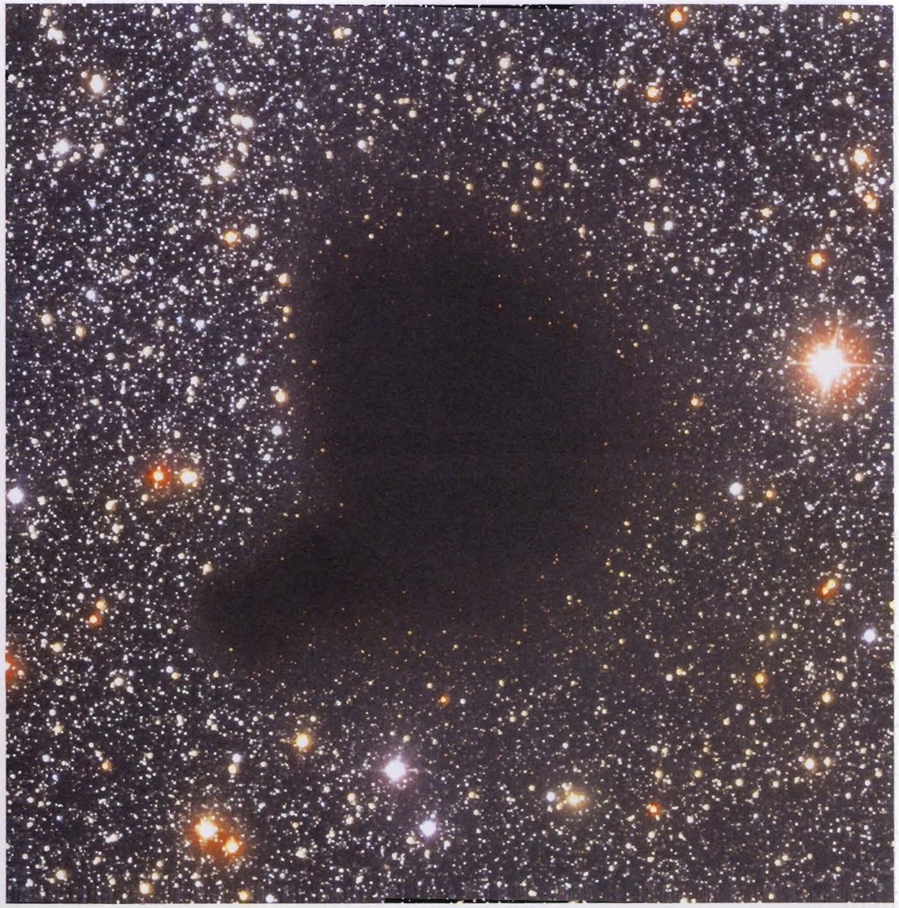
Α	α	Alpha	Ν	ν	Nu
Β	β	Beta	Ν	ξ	Xi
Γ	γ	Gamma	Ο	ο	Omicron
Δ	δ	Delta	Π	π	Pi
Ε	ϵ	Epsilon	Ρ	ρ	Rho
Ζ	ζ	Zeta	Σ	σ	Sigma
Η	η	Eta	Τ	τ	Tau
Θ	θ	Theta	Υ	υ	Upsilon
Ι	ι	Iota	Φ	ϕ	Phi
Κ	κ	Kappa	Χ	χ	Chi
Λ	λ	Lambda	Ψ	ψ	Psi
Μ	μ	Mu	Ω	ω	Omega

Appendix 4

Colour Photographs

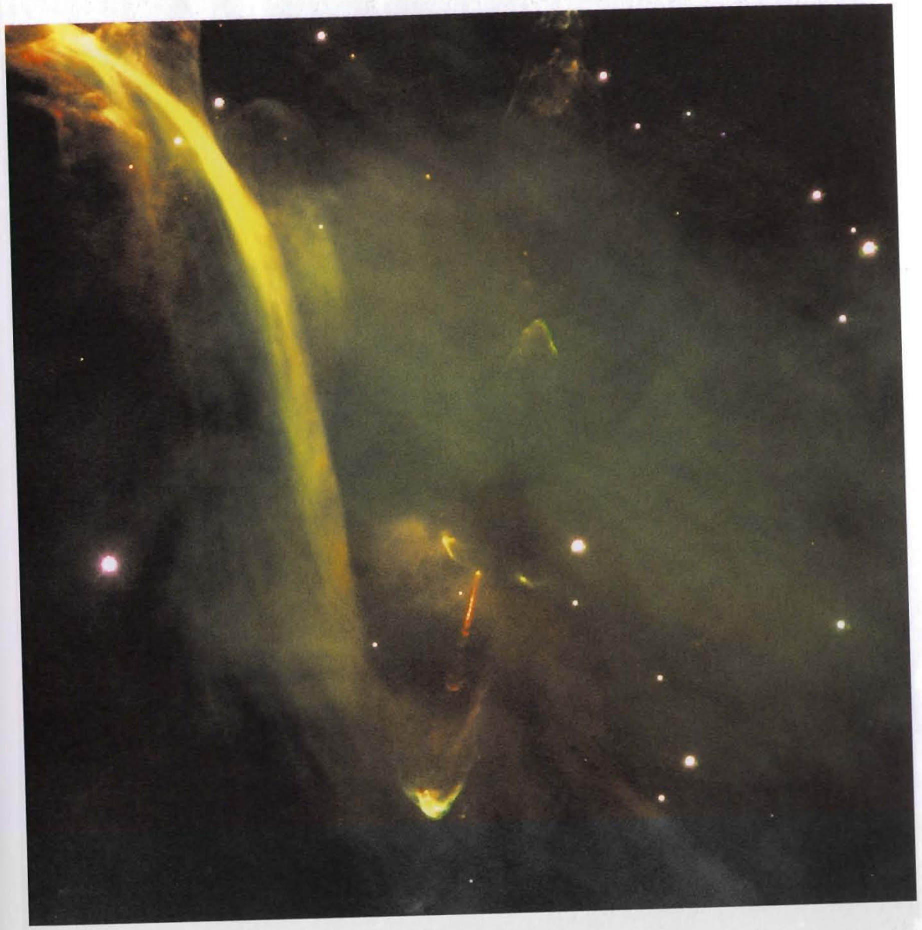
NGC 1850. The double cluster NGC 1850, found in one of our neighbouring galaxies, the Large Magellanic Cloud, is an eye-catching object. It is a young, "globular-like" star cluster – a type of object unknown in our own Milky Way Galaxy. Moreover, NGC 1850 is surrounded by a filigree pattern of diffuse gas, which scientists believe was created by the explosion of massive stars. NGC 1850, imaged here with the NASA Hubble Space Telescope, is an unusual double cluster that lies in the bar of the Large Magellanic Cloud, a satellite galaxy of our own Milky Way. After the 30 Doradus complex, NGC 1850 is the brightest star cluster in the Large Magellanic Cloud. It is representative of a special class of objects – young, globular-like star clusters – that have no counterpart in our galaxy. The two components of the cluster are both relatively young and consist of a main, globular-like cluster in the centre and an even younger, smaller cluster, seen below and to the right, composed of extremely hot, blue stars and, fainter red T-Tauri stars. The main cluster is about 50 million years old; the smaller cluster is only 4 million years old. Images courtesy of: NASA, ESA, and Martino Romaniello (European Southern Observatory, Germany). Acknowledgments: Martino Romaniello, Richard Hook, Bob Fosbury and the Hubble European Space Agency Information Centre.





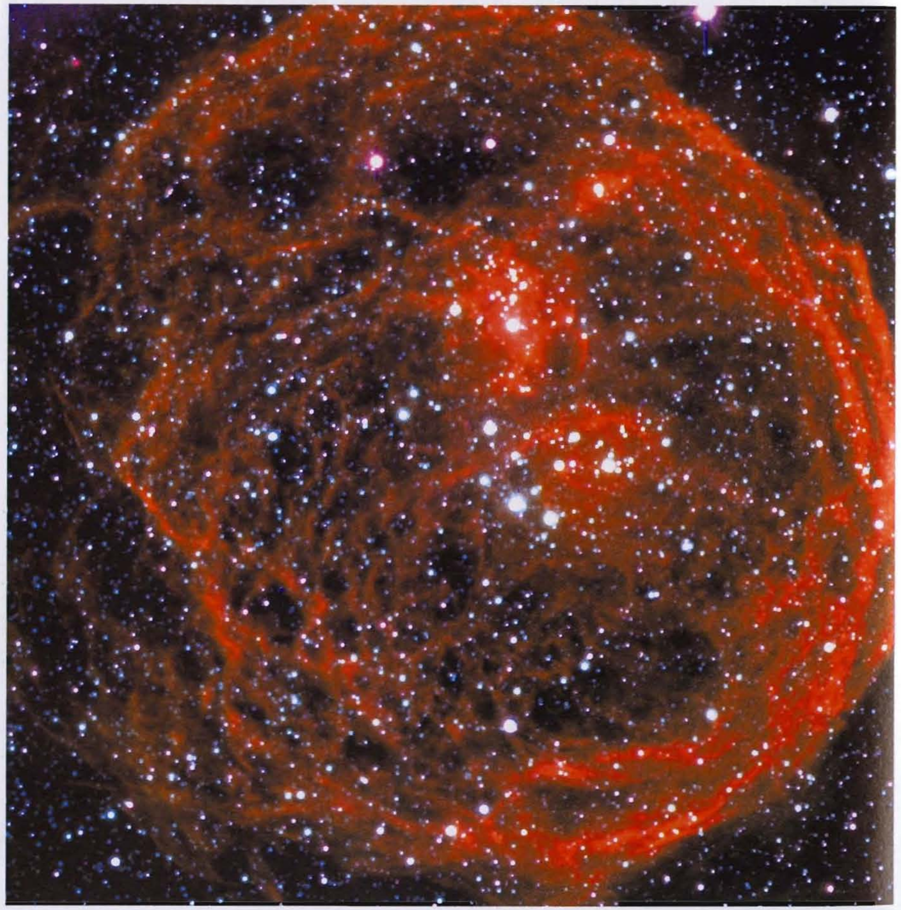
Barnard 68 *(above)*. At a distance of only 410 light-years, Barnard 68 is one of the nearest dark clouds. Its size is about 12,500 AU (= 2 million million km; 1 Astronomical Unit [AU] = 150 million km), or just about the same as the so-called "Oort Cloud" of long-period comets that surrounds the solar system. The temperature of Barnard 68 is 16 Kelvin (-257 C) and the pressure at its boundary is 0.0025 nPa, or about 10 times higher than in the interstellar medium (but still 40,000 million million times less than the atmospheric pressure at the Earth's surface!). The total mass of the cloud is about twice that of the Sun. Image courtesy of the European Southern Observatory.

◄ **Star Forming Region: 30 Doradus** *(opposite)*. NASA's Hubble Space Telescope has snapped a panoramic portrait of a vast, sculpted landscape of gas and dust where thousands of stars are being born. This fertile star-forming region, called the 30 Doradus Nebula, has a sparkling stellar centrepiece: the most spectacular cluster of massive stars in our cosmic neighbourhood of about 25 galaxies. The mosaic picture shows that ultraviolet radiation and high-speed material unleashed by the stars in the cluster, called R136 [the large blue blob below centre], are weaving a tapestry of creation and destruction, triggering the collapse of looming gas and dust clouds and forming pillar-like structures that are incubators for nascent stars. Images courtesy of: NASA, N. Walborn and J. Maíz-Apellániz (Space Telescope Science Institute, Baltimore, MD), R. Barbá (La Plata Observatory, La Plata, Argentina).

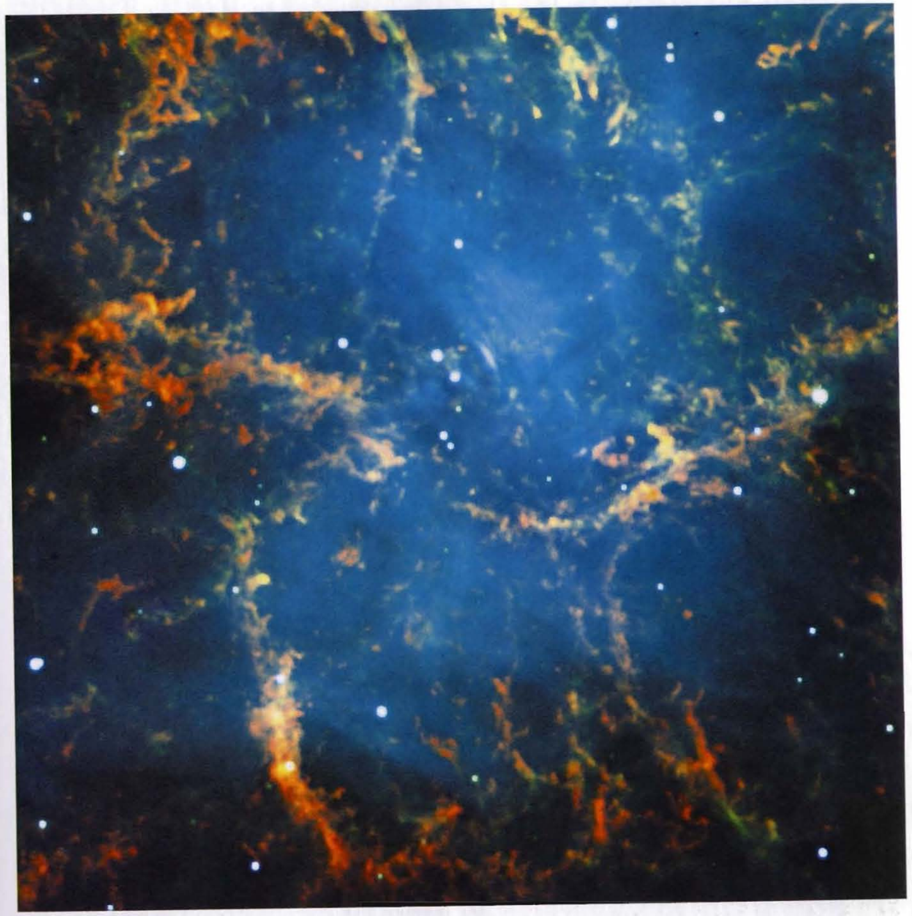


HH 34 *(above)*. This is an image of the young object Herbig-Haro 34 (HH-34), now in the protostar stage of evolution. It is based on CCD frames obtained with the FORS2 instrument in imaging mode, on November 2 and 6, 1999. This object has a remarkable, very complicated appearance that includes two opposite jets that ram into the surrounding interstellar matter. This structure is produced by a machine-gun-like blast of "bullets" of dense gas ejected from the star at high velocities (approaching 250 km/sec). This seems to indicate that the star experiences episodic "outbursts" when large chunks of material fall onto it from a surrounding disk. HH-34 is located at a distance of approx. 1,500 light-years, near the famous Orion Nebula, one of the most productive star birth regions. Note also the enigmatic "waterfall" to the upper left, a feature that is still unexplained. Image courtesy of the European Southern Observatory.

◀ **CH1** *(opposite)*. This image displays a sky area near the Chamaeleon I complex of bright nebulae and hot stars in the constellation of the same name, close to the southern celestial pole. Image courtesy of the European Southern Observatory.



N70. N70 is a "Super Bubble" in the Large Magellanic Cloud (LMC), a satellite galaxy to the Milky Way system, located in the southern sky at a distance of about 160,000 light-years. This photo is based on CCD frames obtained with the FORS2 instrument in imaging mode in the morning of November 5, 1999. N 70 is a luminous bubble of interstellar gas, measuring about 300 light-years in diameter. It was created by winds from hot, massive stars and supernova explosions and the interior is filled with tenuous, hot expanding gas. An object like N70 provides astronomers with an excellent opportunity to explore the connection between the lifecycles of stars and the evolution of galaxies. Very massive stars profoundly affect their environment. They stir and mix the interstellar clouds of gas and dust, and they leave their mark in the compositions and locations of future generations of stars and star systems. Image courtesy of the European Southern Observatory.



Crab Nebula. This is the well-known Crab Nebula (also known as "Messier 1"), as observed with the FORS2 instrument in imaging mode on the morning of November 10, 1999. It is the remnant of a supernova explosion at a distance of about 6,000 light-years, observed almost 1000 years ago, in the year 1054. It contains a neutron star near its centre that spins 30 times per second around its axis (see below). The green light is predominantly produced by hydrogen emission from material ejected by the star that exploded. The blue light is predominantly emitted by very high-energy ("relativistic") electrons that spiral in a large-scale magnetic field (so-called synchrotron emission). It is believed that these electrons are continuously accelerated and ejected by the rapidly spinning neutron star at the centre of the nebula and which is the remnant core of the exploded star. This pulsar has been identified with the lower-right of the two close stars near the geometric centre of the nebula, immediately left of the small arc-like feature. Image courtesy of the European Southern Observatory.

Object Index

This list references the main entry of the object in the book. It may actually be mentioned in other sections.

Subject Index

This list references the main entry of the topic in the book. It may actually be mentioned in other sections.

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