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*

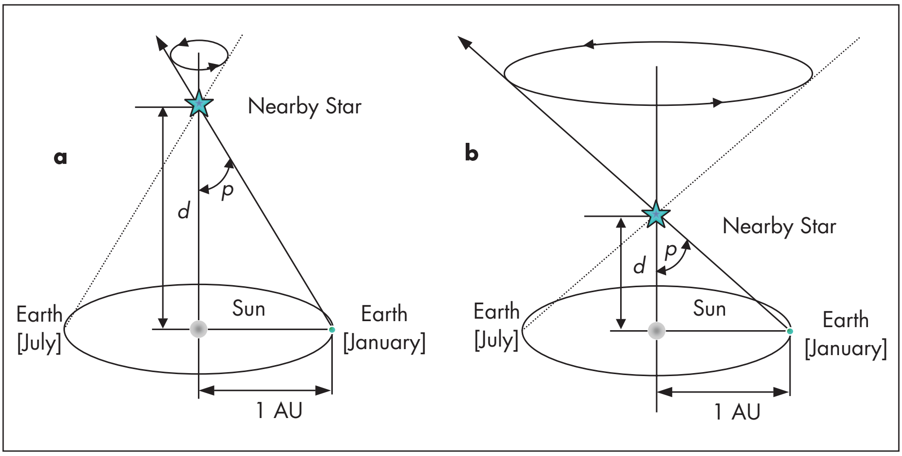

Figure 1.1. Stellar Parallax. **a** The Earth orbits the Sun, and a nearby star shifts its position with respect to the background stars. The parallax, *p*, of the star is the angular measurement of the Earth's orbit as seen from the star. **b** The closer the star, the greater the parallax angle.

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]

<table>
<tr><th>Proxima Centauri</th><th>V645 Cen</th><th>$14^h 29.7^m$</th><th>–62° 41′</th><th>Mar–**Apr**–May</th></tr>
<tr><td>11.01$_v$m[9]</td><td>15.45M</td><td>4.22 ly</td><td>0.772″</td><td>Centaurus</td></tr>
<tr><td colspan="5">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.</td></tr>
</table>

<table>
<tr><th>Sirius A</th><th>α Canis Majoris</th><th>$06^h 29.7^m$</th><th>–16° 43′</th><th>Dec–**Jan**–Feb</th></tr>
<tr><td>–1.44m</td><td>1.45M</td><td>8.6 ly</td><td>0.379″</td><td>Canis Major</td></tr>
<tr><td colspan="5">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.</td></tr>
</table>

<table>
<tr><th>Procyon</th><th>α Canis Minoris</th><th>$07^h 39.3^m$</th><th>–56° 13′</th><th>Dec–**Jan**–Feb</th></tr>
<tr><td>0.40m</td><td>2.68M</td><td>11.41 ly</td><td>0.283″</td><td>Canis Minor</td></tr>
<tr><td colspan="5">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.</td></tr>
</table>

<table>
<tr><th>Barnard's Star</th><th>HD21185</th><th>$17^h 57.8^m$</th><th>+4° 38′</th><th>Apr–**May**–Jun</th></tr>
<tr><td>9.54m</td><td>13.24M</td><td>5.94 ly</td><td>0.549″</td><td>Ophiuchus</td></tr>
<tr><td colspan="5">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.</td></tr>
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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 $\frac{1}{4}^\circ$ 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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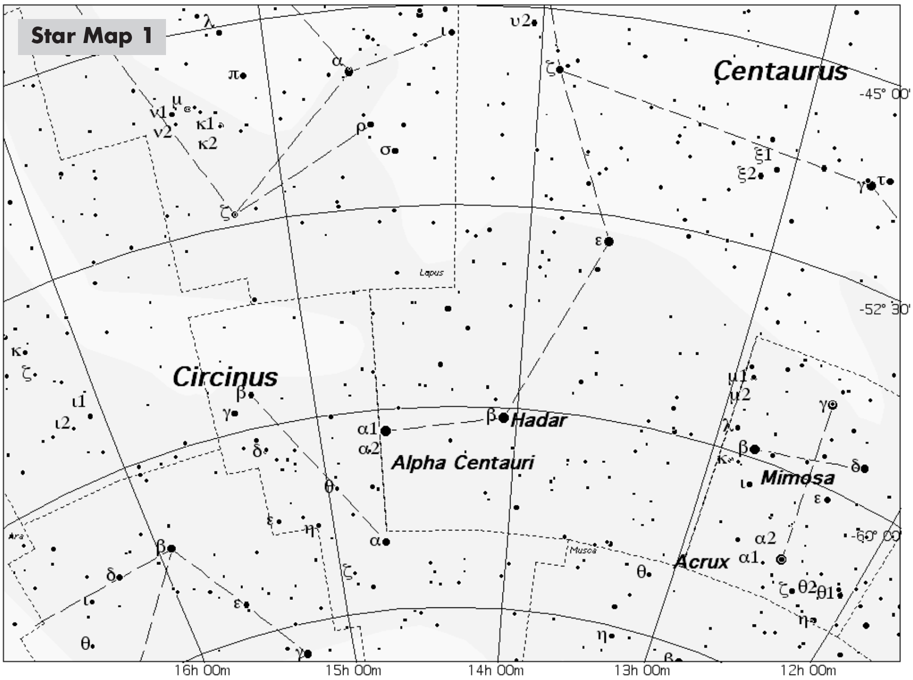
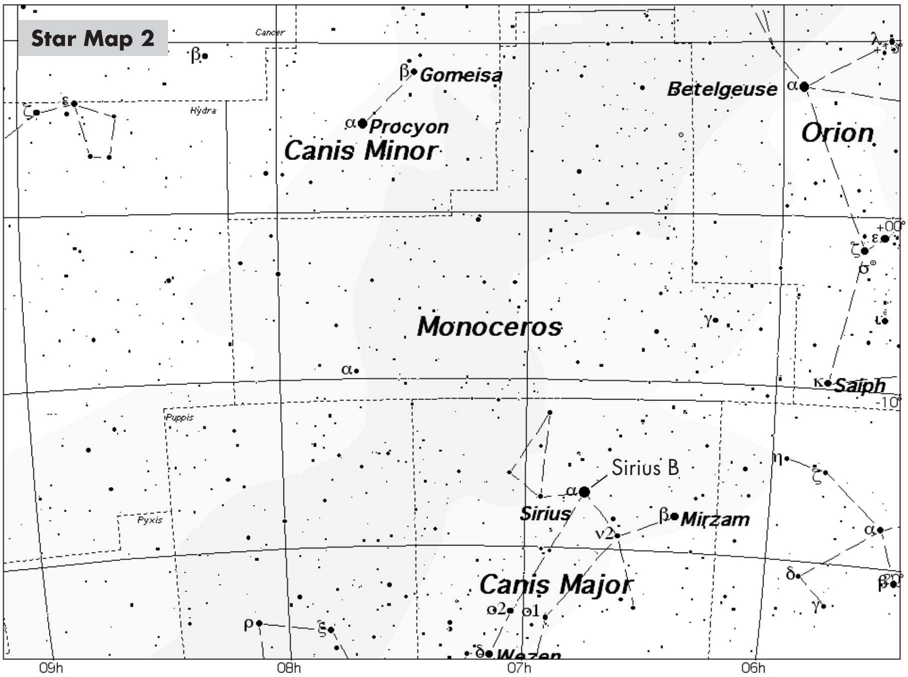
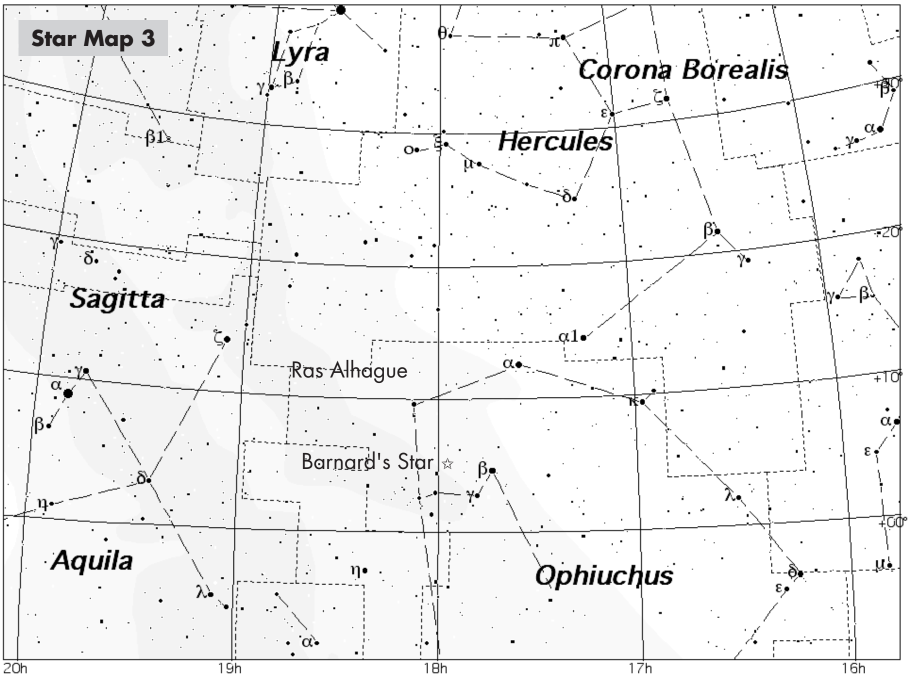
[11] The HD signifies it is the 217987th object in the Henry Draper catalogue.

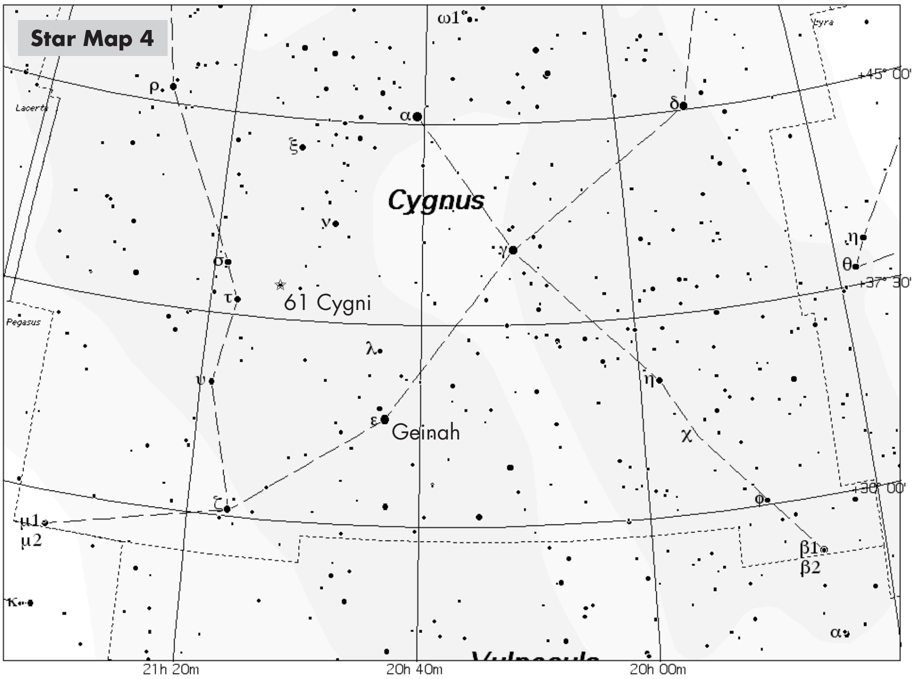


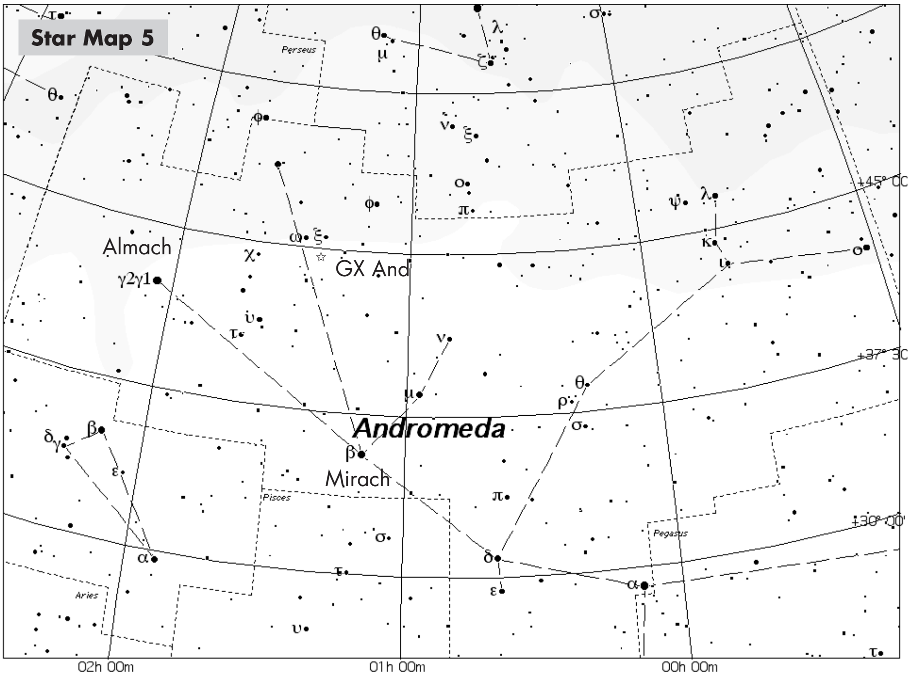
Star Map 1

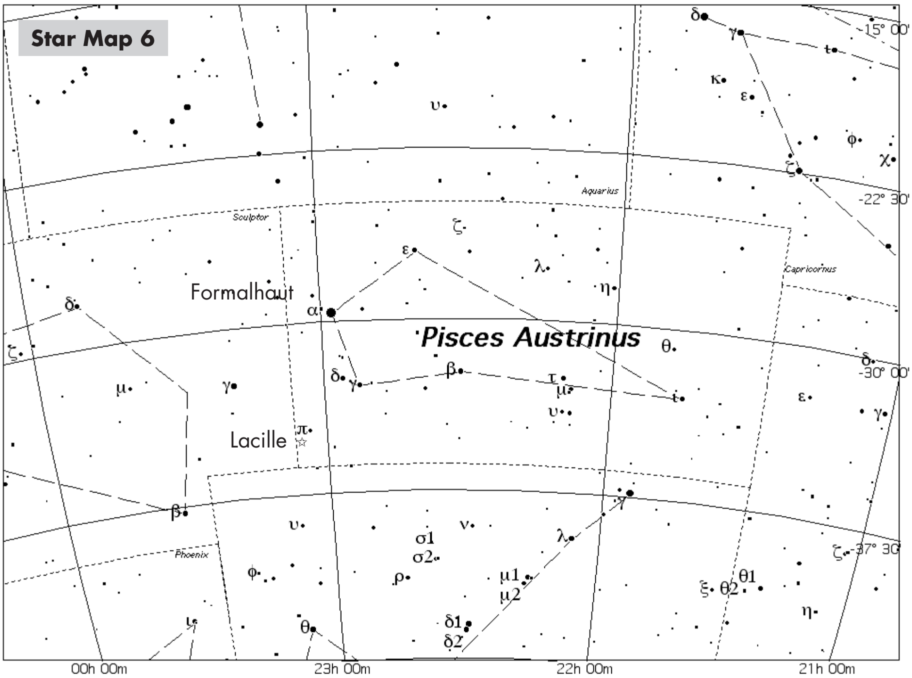


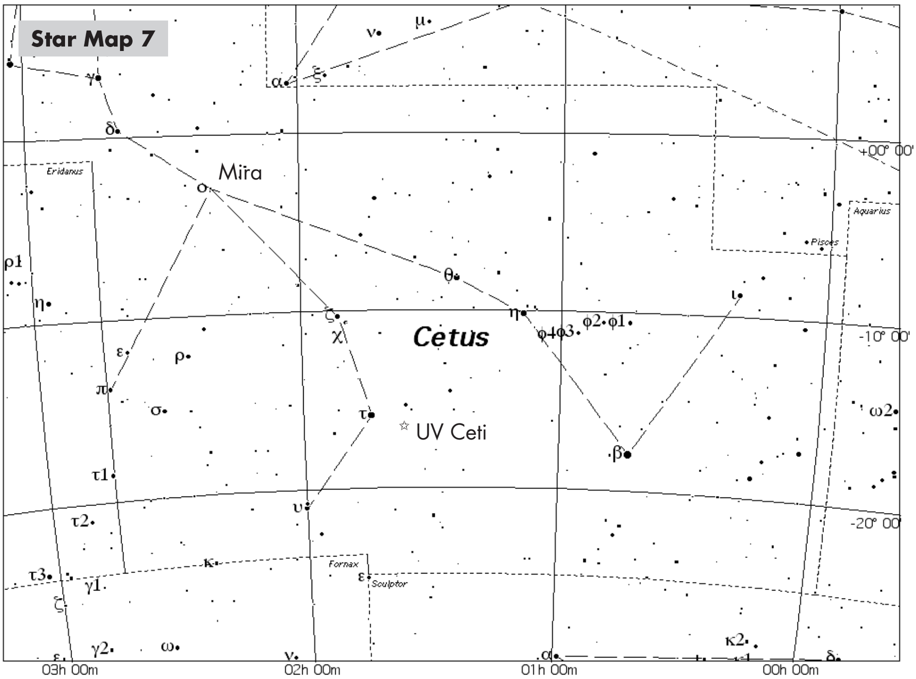
Star Map 2


Star Map 3
Lyra
Corona Borealis
Hercules
Sagitta
Ras Alhague
Barnard's Star
Aquila
Ophiuchus
+30°
+20°
+10°
+00°
20h
19h
18h
17h
16h

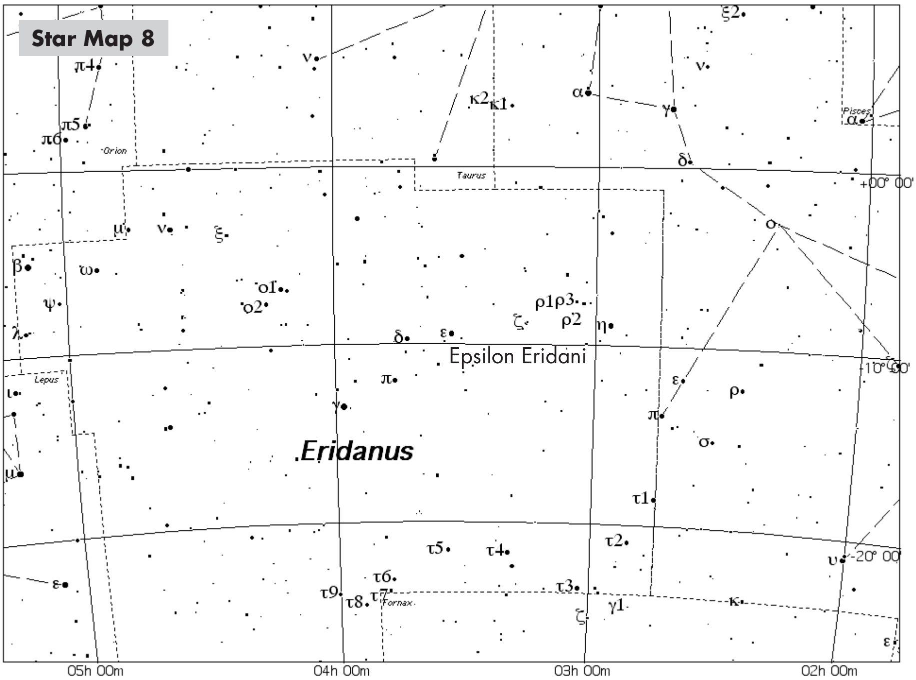

Star Map 4
Cygnus
61 Cygni
Gienah
Lacerta
Pegasus
Lyra
Vulpecula
+45° 00'
+37° 30'
+30° 00'
21h 20m
20h 40m
20h 00m


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.

<table>
<tr><th>Pollux</th><th>β Gem</th><th>07^h 45.3^m</th><th>+28° 02′</th><th>Dec–Jan–Feb</th></tr>
<tr><td>1.16m</td><td>1.09M</td><td>33.72 ly</td><td></td><td>Gemini</td></tr>
<tr><td colspan="5">This is the brighter star of the two famous stars in <i>Gemini</i>, the other being of course, <i>Castor</i>. It is the seventeenth-brightest in the sky. It is, however, the less interesting from an astronomical viewpoint. See Star Map 9.</td></tr>
</table>

<table>
<tr><th>Becrux</th><th>β Crucis</th><th>12^h 47.7^m</th><th>–59° 41′</th><th>Mar–Apr–May</th></tr>
<tr><td>1.25$_v$m</td><td>–3.92M</td><td>352.1 ly</td><td></td><td>Crux</td></tr>
<tr><td colspan="5">This star lies in the same field as the glorious <i>Jewel Box</i> 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.</td></tr>
</table>

<table>
<tr><th>Spica</th><th>α Virginis</th><th>13h 25.2m</th><th>–11° 10′</th><th>Mar–Apr–May</th></tr>
<tr><td>0.98$_v$m</td><td>–03.55M</td><td>262 ly</td><td></td><td>Virgo</td></tr>
<tr><td colspan="5">The fifteenth-brightest star is a large spectroscopic binary with the companion star lying very close to it and thus eclipsing it slightly. <i>Spica</i> is also a pulsating variable star, though the variability and the pulsations are not visible with amateur equipment. See Star Map 11.</td></tr>
</table>

<table>
<tr><th>Hadar</th><th>β Centauri</th><th>14^h 03.8^m</th><th>–60° 22′</th><th>Mar–Apr–May</th></tr>
<tr><td>0.58$_v$m</td><td>–5.45M</td><td>525 ly</td><td></td><td>Centaurus</td></tr>
<tr><td colspan="5">The eleventh-brightest star in the sky, and unknown to northern observers because of its low latitude, lying as it does only 4½° from <i>Alpha</i> (α) <i>Centauri</i>. 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.</td></tr>
</table>

<table>
<tr><th>Arcturus</th><th>α Boötis</th><th>14^h 15.6^m</th><th>+19° 11′</th><th>Mar–Apr–May</th></tr>
<tr><td>–0.16$_v$m</td><td>–0.10M</td><td>36.7 ly</td><td></td><td>Boötes</td></tr>
<tr><td colspan="5">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, <i>Arcturus</i>, unlike most stars, is not travelling in the plane of the <i>Milky Way</i>, 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 <i>Virgo</i>. 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.</td></tr>
</table>

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_vm	-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_vm	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
$0.45_v m$	–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
$-0.18_v m$	–6.69M	773 ly		Orion

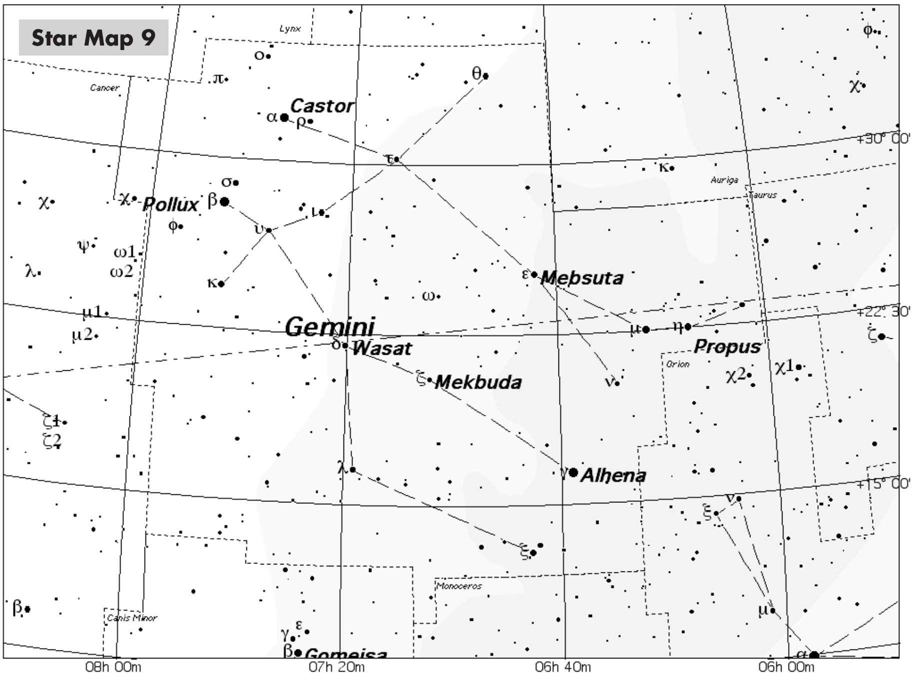
The seventh-brightest star in the sky, *Rigel* is in fact brighter than Alpha (α) *Orionis*. This supergiant star is one of the most luminous stars in our part of the galaxy, almost 560,000 times more luminous than our Sun but at a greater distance than any other nearby bright star. Often described as 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.

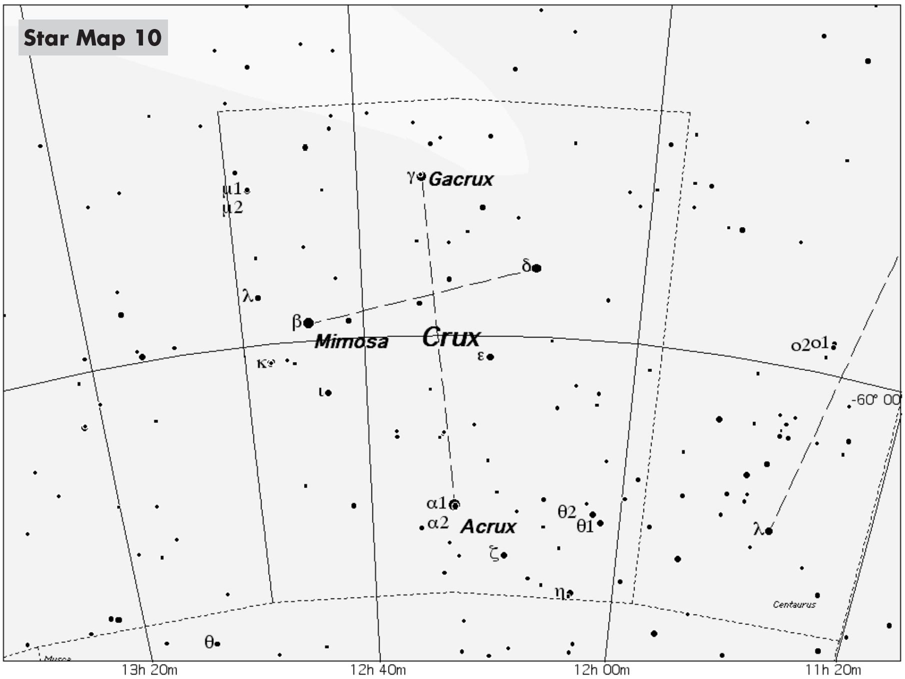
Capella	α Aurigae	$05^h\ 16.7^m$	+46° 00′	Nov–**Dec**–Jan
$0.08_v m$	–0.48M	42 ly		Auriga

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 south-east, 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.

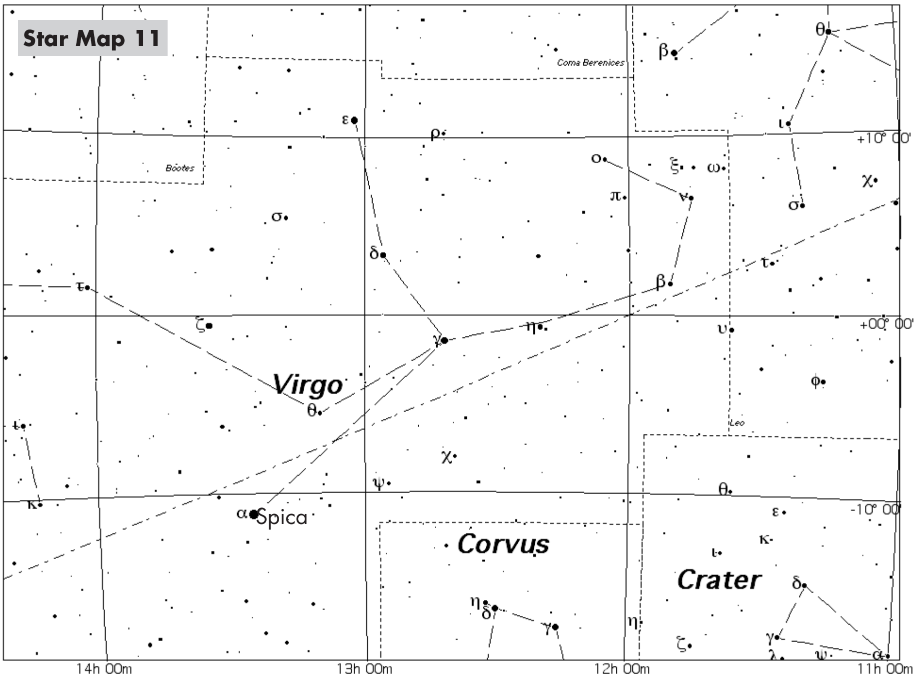
Betelgeuse	α Orionis	$05^h\ 55.2^m$	+07° 24′	Nov–**Dec**–Jan
$0.45_v m$	–5.14M	427 ly		Orion

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.

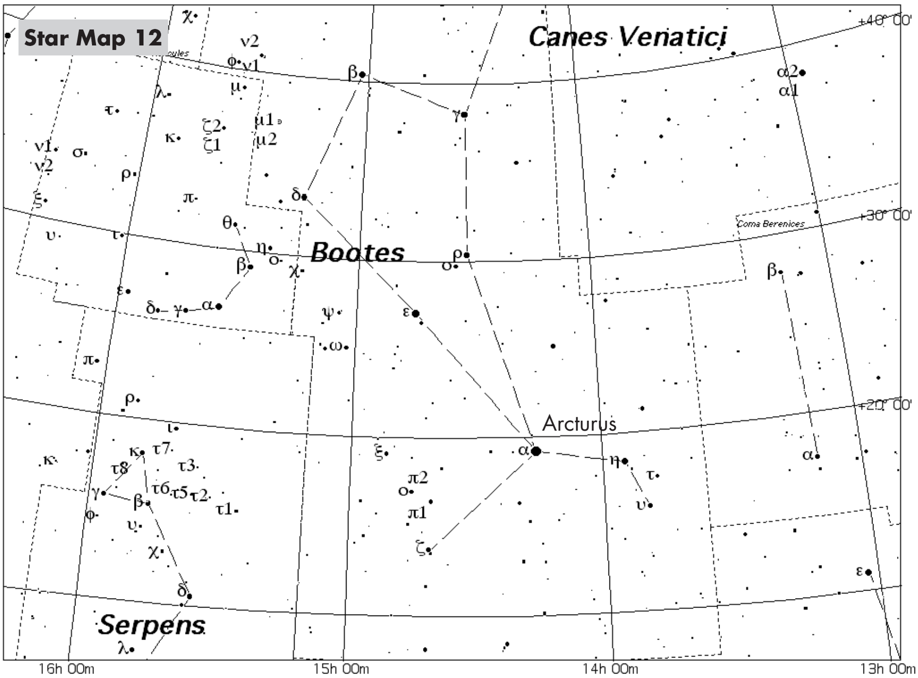

Star Map 9


Star Map 10

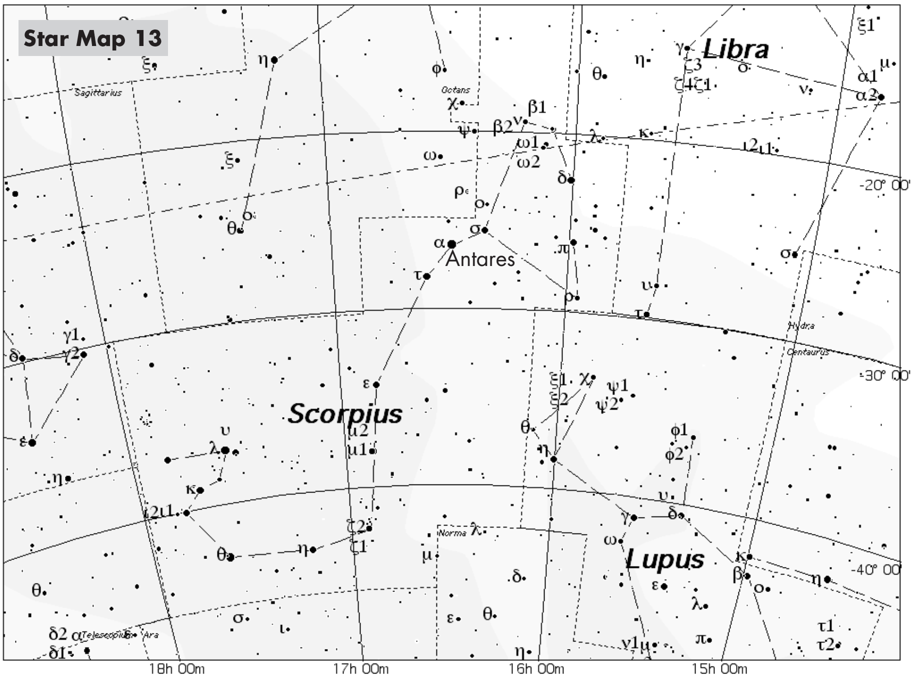
Star Map 11



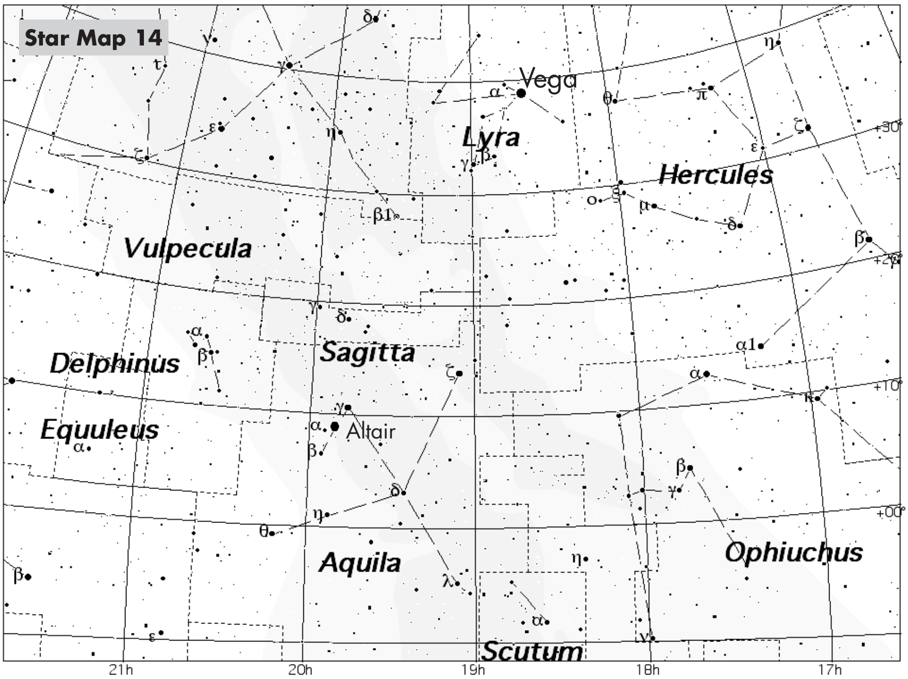
Star Map 12



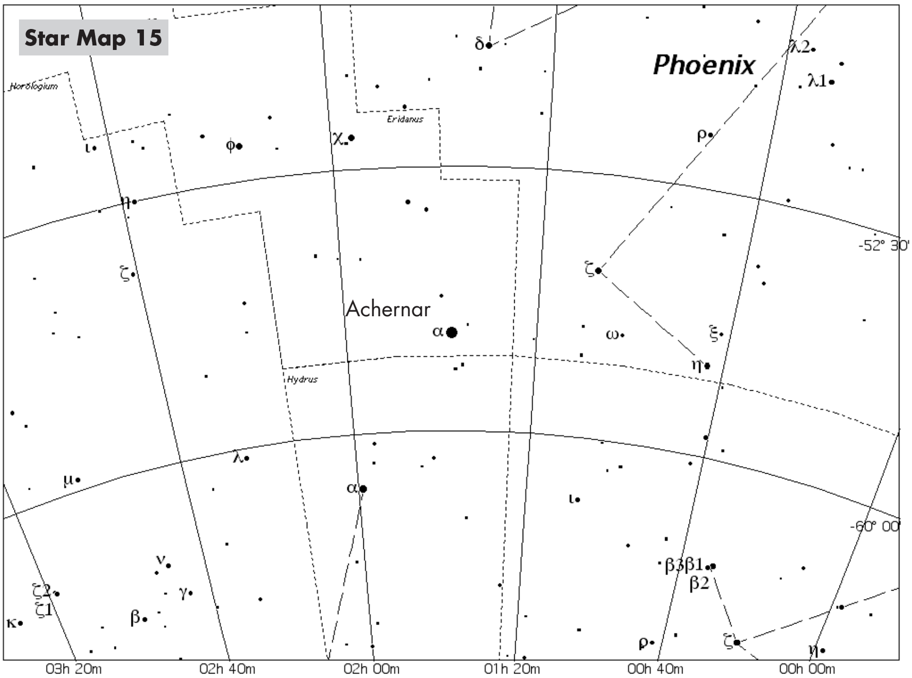
Star Map 13



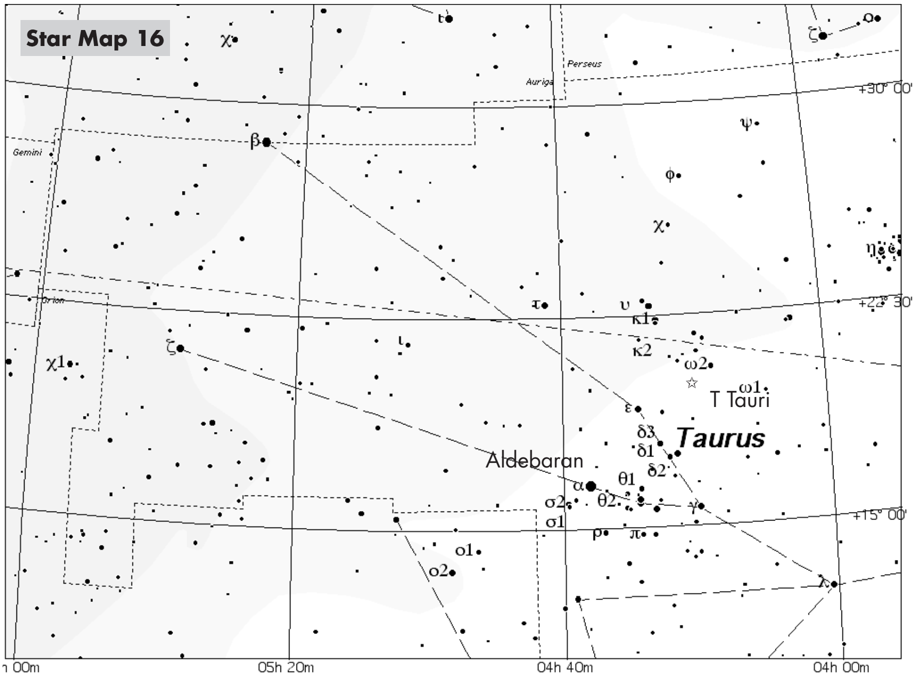
Star Map 14

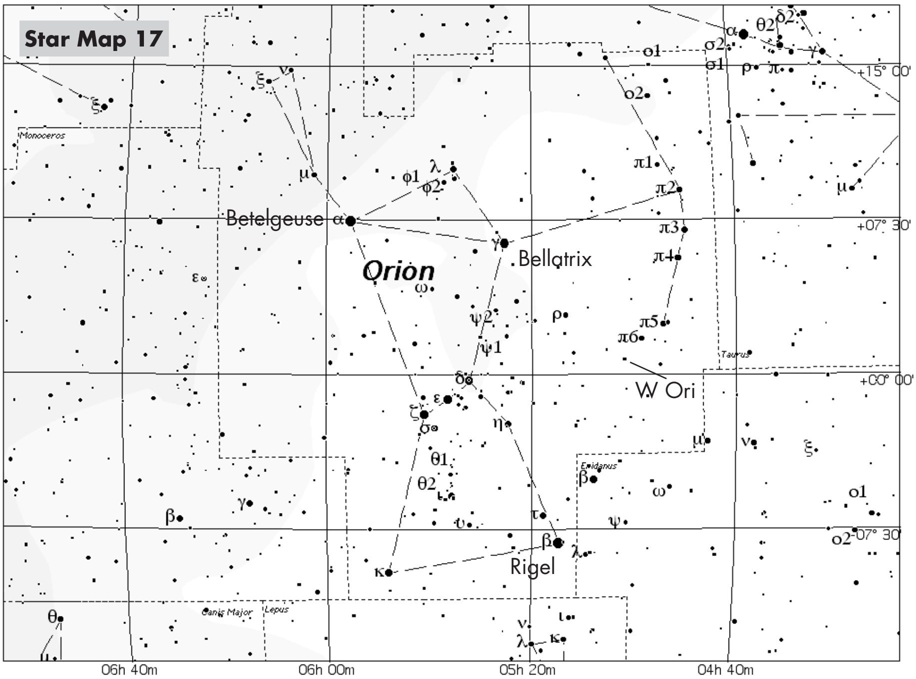


Star Map 15

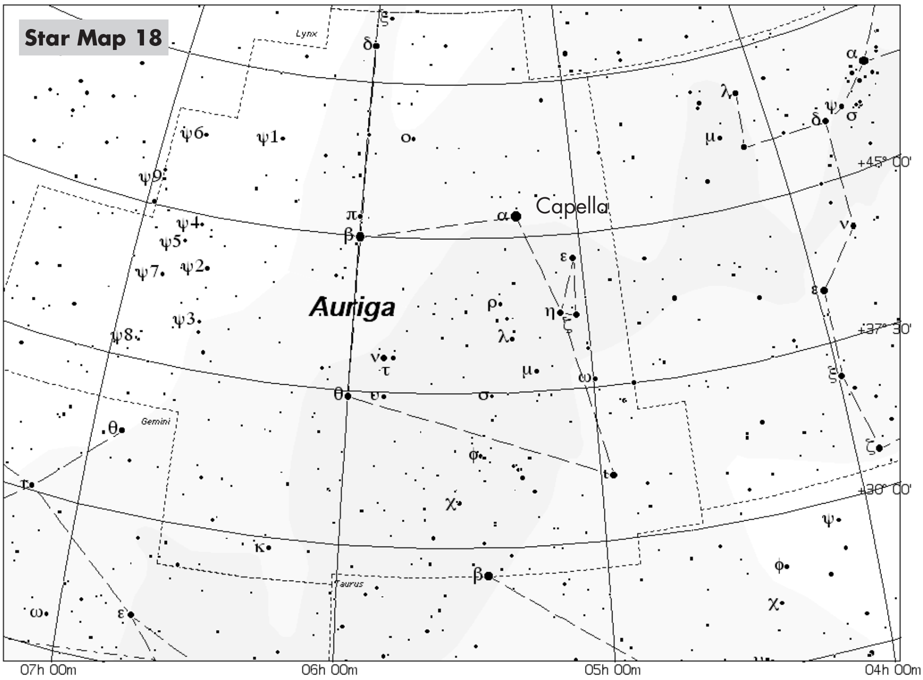


Star Map 16





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

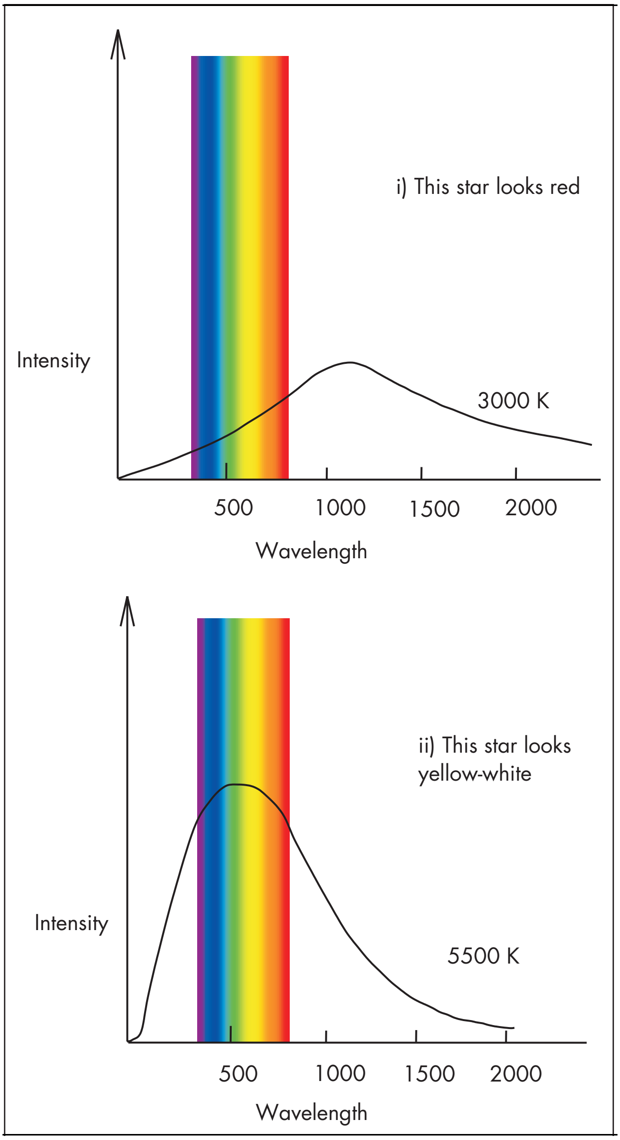

Figure 1.2. Colour and Temperature.

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.

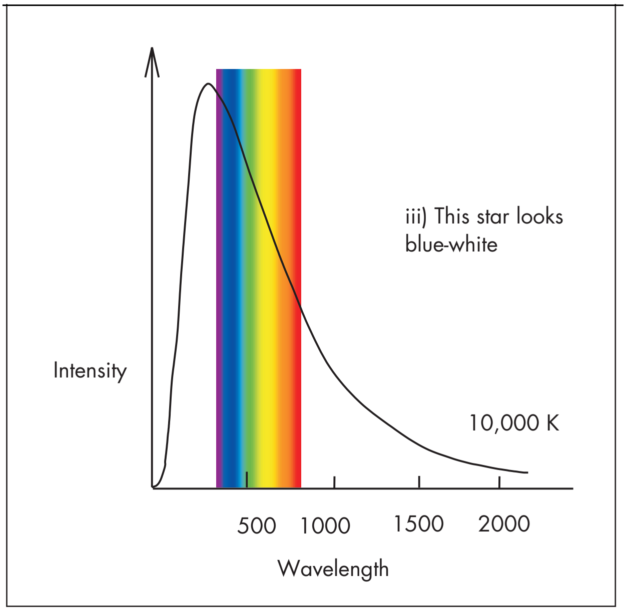

Figure 1.2. (*continued*)

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

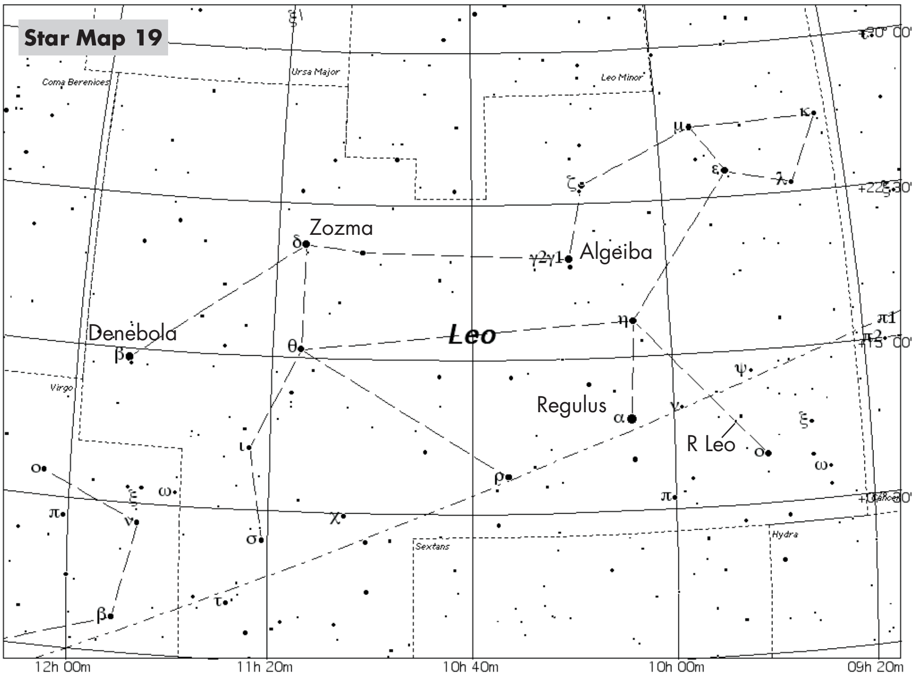
Our closest star, and the object without which no life would have evolved on Earth. Visible every day throughout the year, unless you happen to live in the UK. **DO NOT OBSERVE THROUGH ANY KIND OF OPTICAL EQUIPMENT.**

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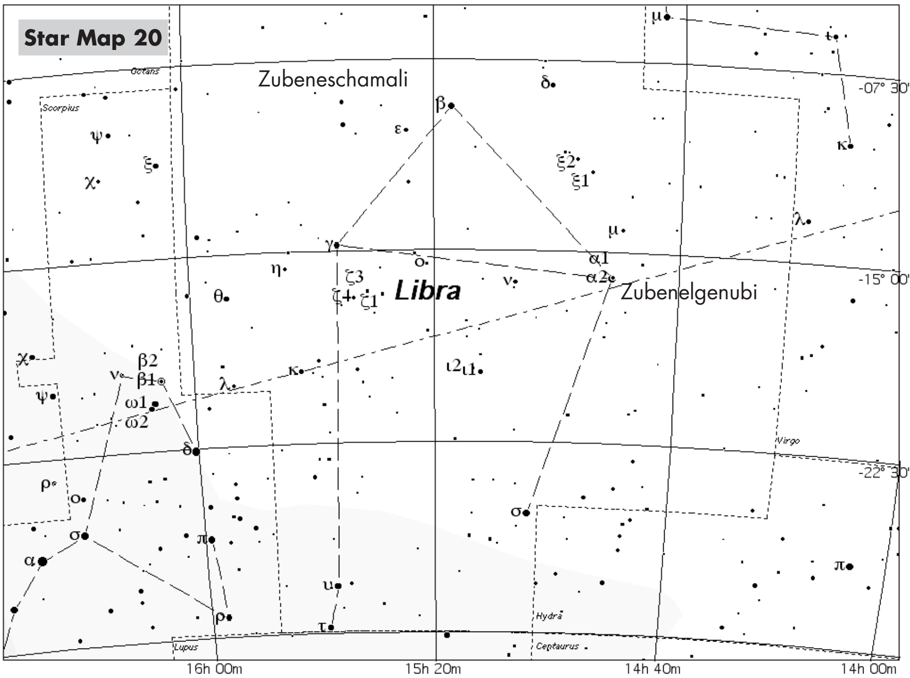
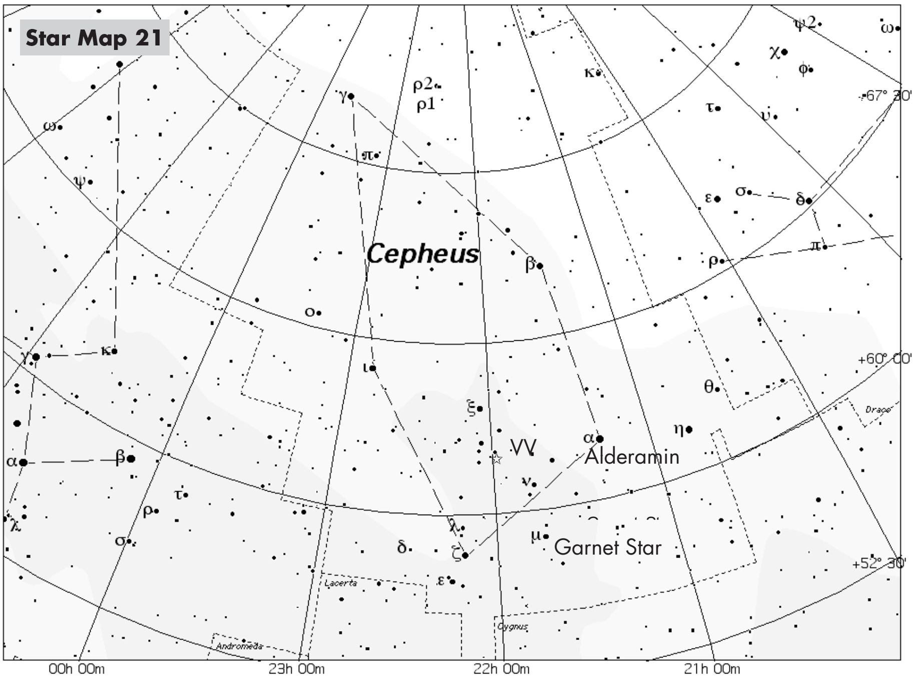
[20] There is considerable debate as to just how big this star is. Some sources believe it is about 5.7 AU, or just larger than Jupiter's orbit, to over 6 AU.

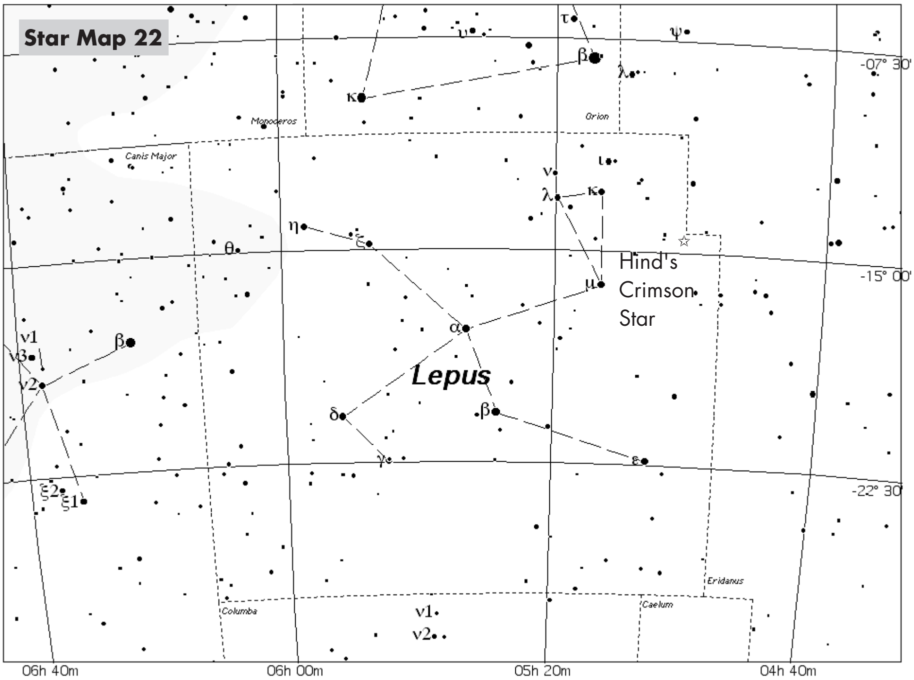
[21] The real temperature of the star is still undetermined.

Star Map 20



Star Map 21





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:

$$\mathrm{L}_\odot = 4\pi \mathrm{R}_\odot{}^2 \sigma T_\odot{}^4$$

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:

$$\mathrm{L}/L_\odot = (R/\mathrm{R}_\odot{}^2 (T/\mathrm{T}_\odot)^2$$

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

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

where the $\frac{1}{2}$ factor indicates a square root.

Now, $R/\mathrm{R}_\odot$ is the ratio of the star's radius to that of the Sun, $\mathrm{T}_\odot/T$ is the ratio of the Sun's temperature to that of the star's and $L/\mathrm{L}_\odot$ 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:

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

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*.

<table>
<tr><th>α Herculis</th><th>ADS 10418</th><th>$17^h14.6^m$</th><th>+14° 23′</th><th>May–**Jun**–Jul</th></tr>
<tr><td>3.5_v, 5.4_vm</td><td>–1.9M</td><td>Radius: 2.0 AU</td><td></td><td>Hercules</td></tr>
<tr><td colspan="5">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.</td></tr>
</table>

<table>
<tr><th>ψ^1 Aurigae</th><th>HD 44537</th><th>$06^h24.9^m$</th><th>+49° 17′</th><th>Nov–**Dec**–Jan</th></tr>
<tr><td>4.92_vm</td><td>–5.43M</td><td>Radius: 3.0 AU [25]</td><td></td><td>Auriga</td></tr>
<tr><td colspan="5">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.</td></tr>
</table>

<table>
<tr><th>η Persei</th><th>ADS 2157</th><th>$02^h50.7^m$</th><th>+55° 54′</th><th>Oct–**Nov**–Dec</th></tr>
<tr><td>3.8, 8.5m</td><td>–4M</td><td>Radius: 2.0 AU</td><td></td><td>Perseus</td></tr>
<tr><td colspan="5">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</td></tr>
</table>

<table>
<tr><th>VV Cephei</th><th>HD 208816</th><th>$21^h56.6^m$</th><th>+63° 37′</th><th>Sep–**Oct**–Nov</th></tr>
<tr><td>5.11m</td><td>–6.93M</td><td>Radius: 8.8 AU</td><td></td><td>Cepheus</td></tr>
<tr><td colspan="5">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.</td></tr>
</table>

<table>
<tr><th>KQ Puppis</th><th>HD 60414</th><th>$07^h33.8^m$</th><th>–14° 31′</th><th>Sep–**Oct**–Nov</th></tr>
<tr><td>4.82m</td><td>–5.25M</td><td>Radius: 8.8 AU</td><td></td><td>Puppis</td></tr>
<tr><td colspan="5">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.</td></tr>
</table>

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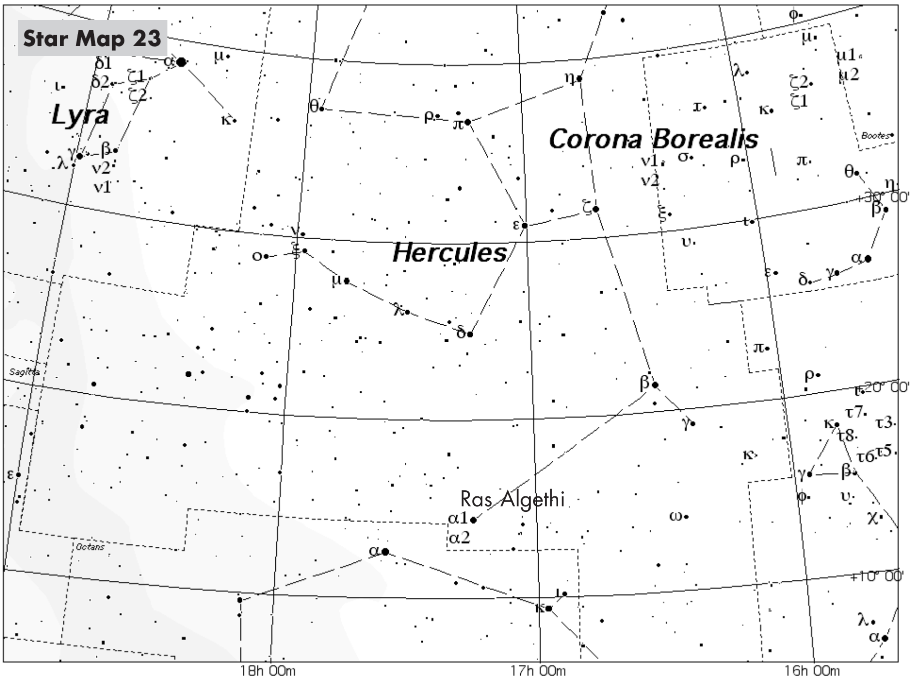
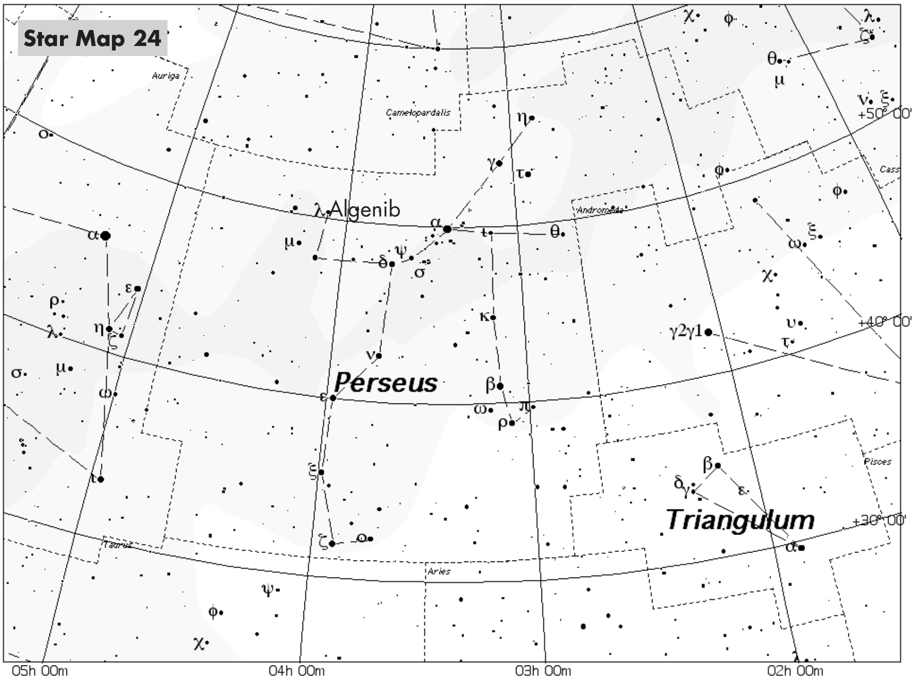
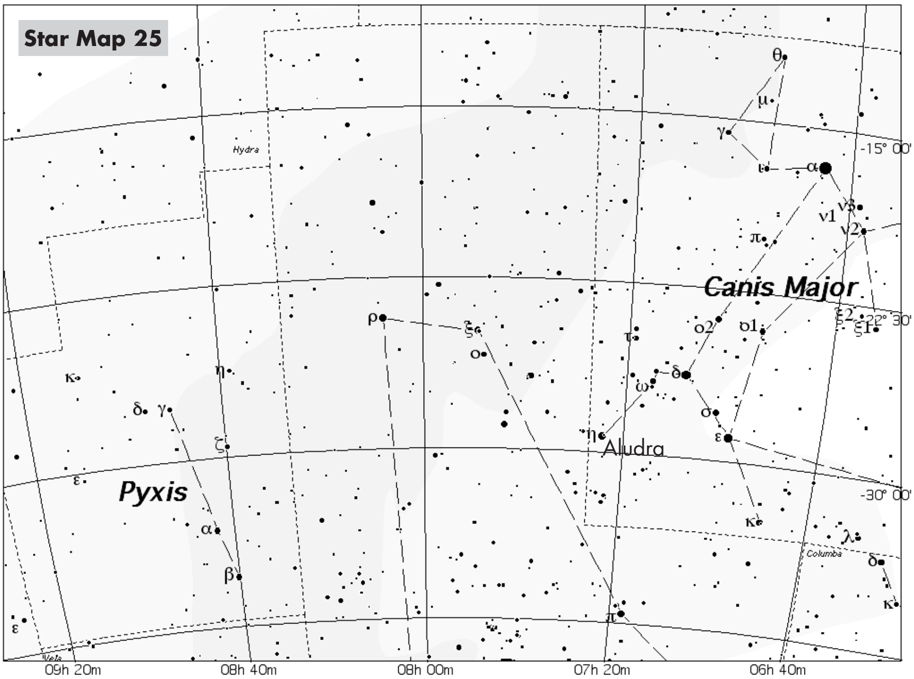
[25] There is some doubt about this value.



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

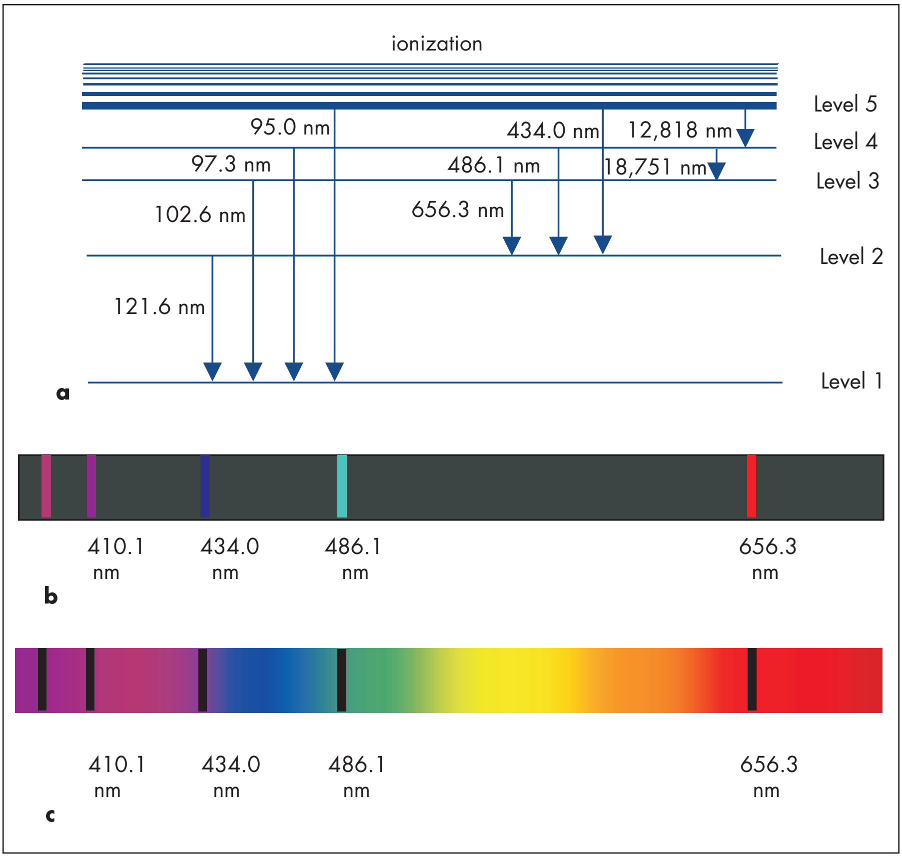

Figure 1.3. Hydrogen Transitions. **a** Shows the wavelengths of various energy level transitions in hydrogen, but only a few of the many transitions that occur are given.
b Visible emission line spectrum, showing transitions that occur from high energy levels downward to level 2 for hydrogen. **c** 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_vm	–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_vm	–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_vm	–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_vm	–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_vm	–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	$20^h41.3^m$	+45° 17′	Jul–**Aug**–Sep
1.25_vm	–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	$11^h49.1^m$	+14° 34′	Feb–**Mar**–Apr
2.14_vm	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	$11^h14.1^m$	+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	$17^h34.9^m$	+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	$05^h59.1^m$	–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	$21^h18.6^m$	+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	$16^h21.8^m$	+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	$06^h23.9^m$	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	$08^h40.6^m$	–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	$14^h50.7^m$	–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	$03^h24.3^m$	+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	$02^h31.8^m$	+89° 16′	Sep–**Oct**–Nov
1.97_vm	–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	$11^h50.7^m$	+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	$21^h31.6^m$	–05° 34′	Jul–**Aug**–Sep
2.90m	–3.47M	G0 I		Aquarius

A giant star, and a close twin to α *Aqr*. 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	$22^h05.8^m$	–00° 19′	Jul–**Aug**–Sep
2.95m	–3.88M	G2 I		Aquarius

Although it has the same spectral class and surface temperature 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.

ν^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_vm	–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_vm	–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	$17^h14.6^m$	+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	$02^h19.3^m$	02° 59′	Sep–**Oct**–Nov
$2.00_{v}m$	–3.54M	M5		Cetus

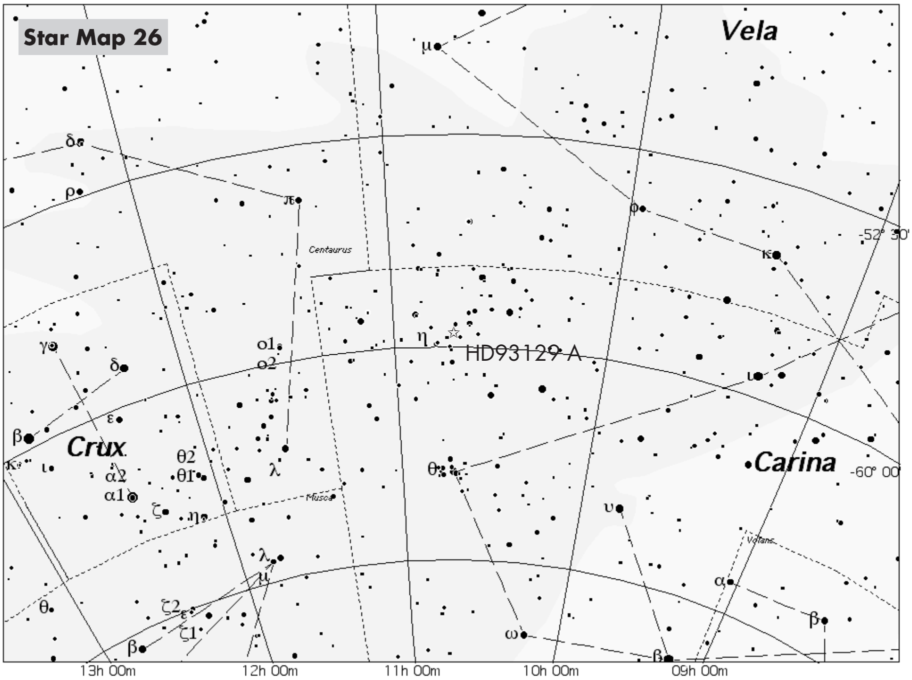
See the section on long period variables for full details on Mira. See Star Map 7.

θ **Apodis**	HD 122250	$14^h05.3^m$	–76° 48′	Mar–**Apr**–May
$5.69_{v}m$	–0.67M	M6.5 III		Apus

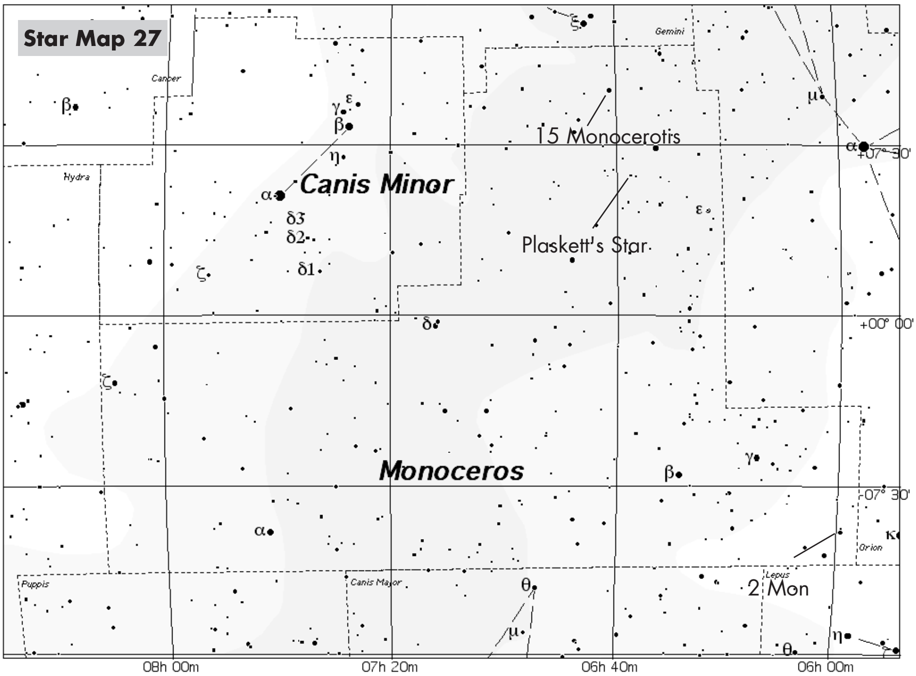
This is a semi-regular variable with a period of 119 days and a range of 5th to nearly 8th magnitude. The titanium bands are now at their strongest. See Star Map 37.

Mira at minimum	o Cet	$02^h19.3^m$	–02° 59′	Sep–**Oct**–Nov
$10_{v}m$	–0.5M	M9		Cetus

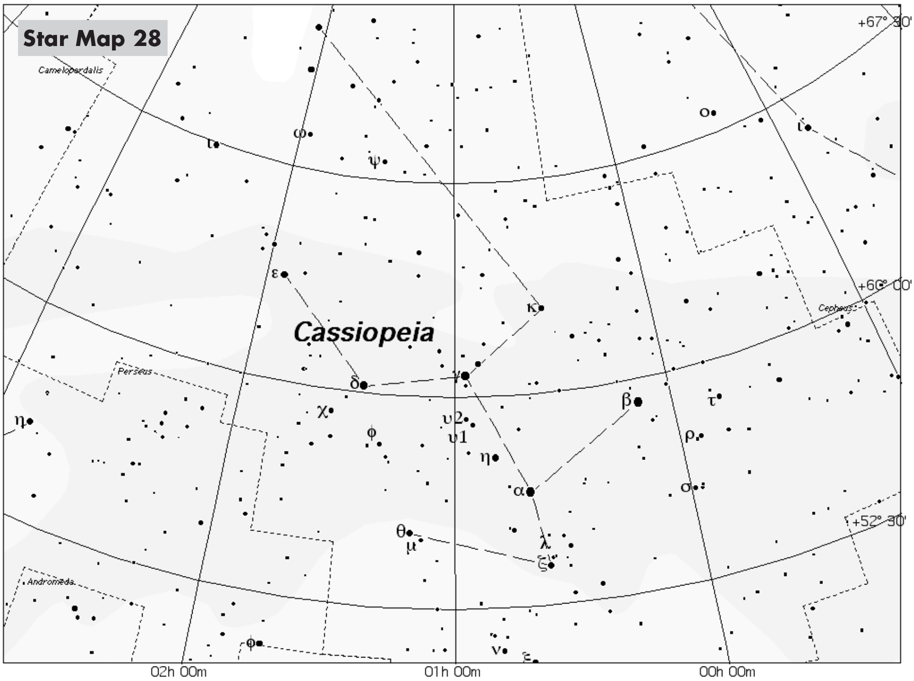
See the section on long period variables for full details on Mira. See Star Map 7.


Star Map 26

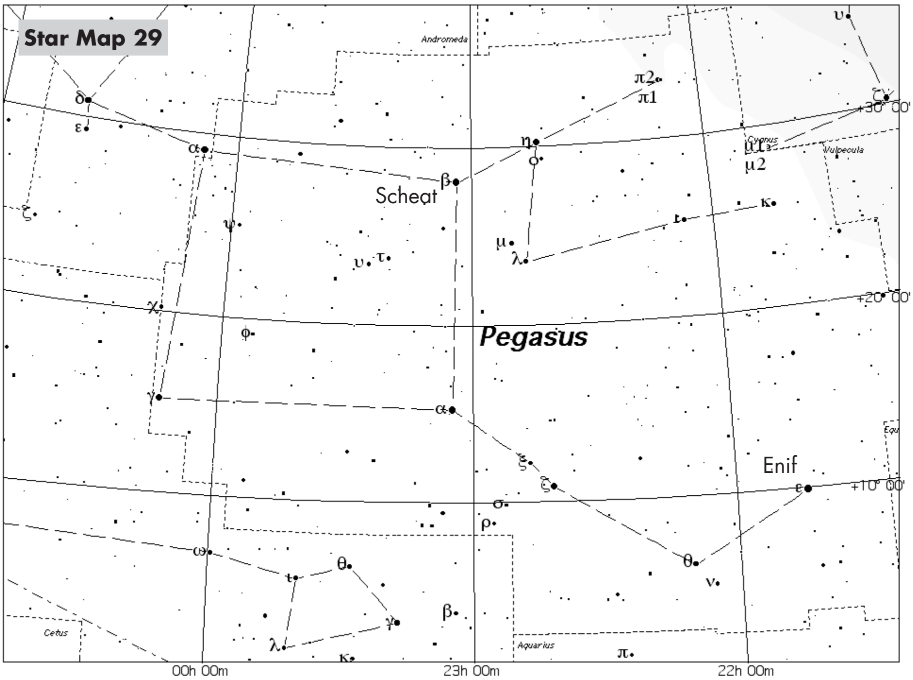
Star Map 27



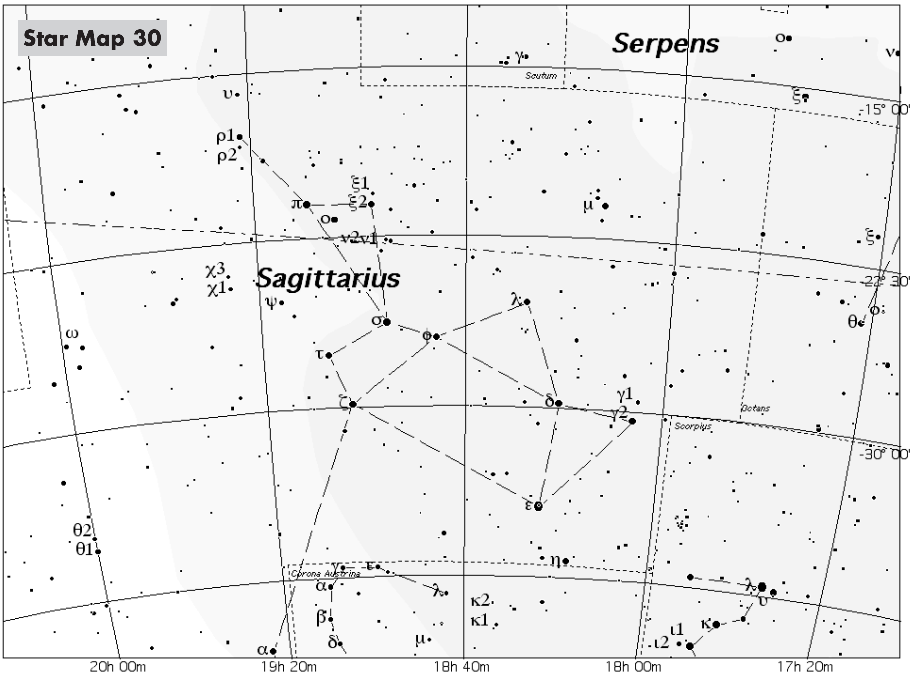
Star Map 28



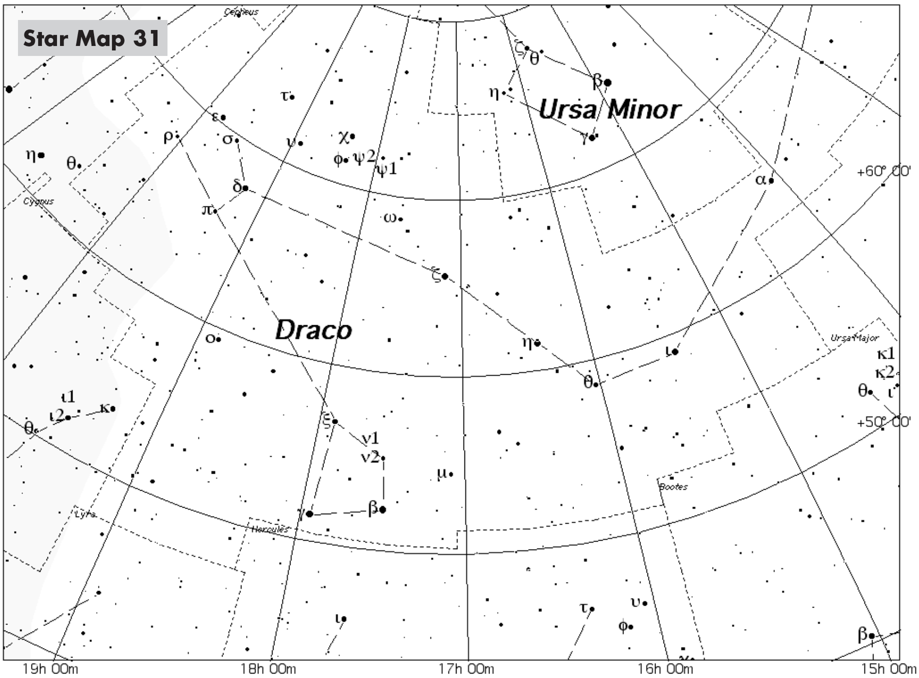
Star Map 29



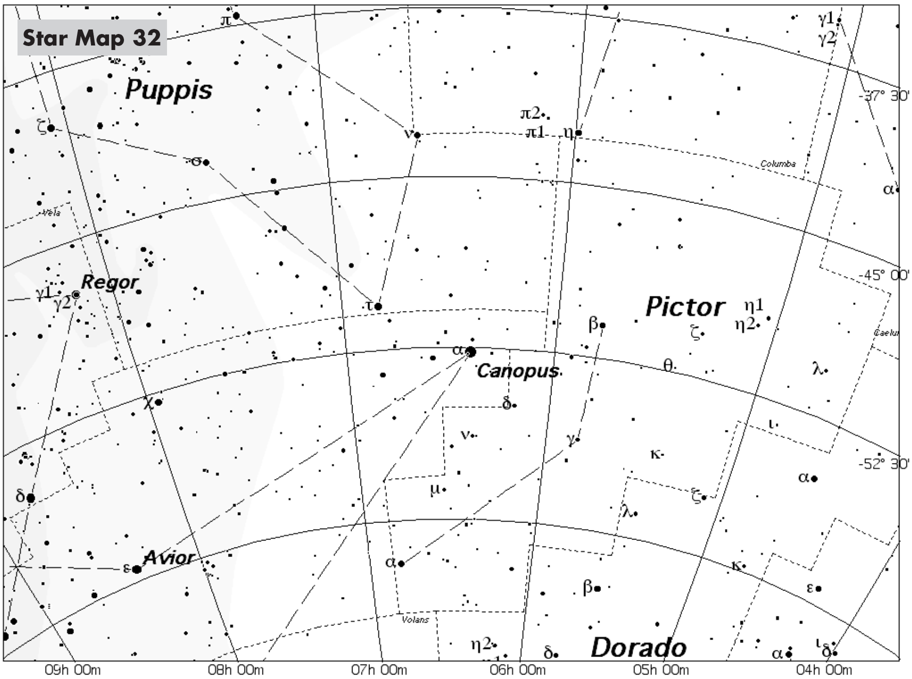
Star Map 30

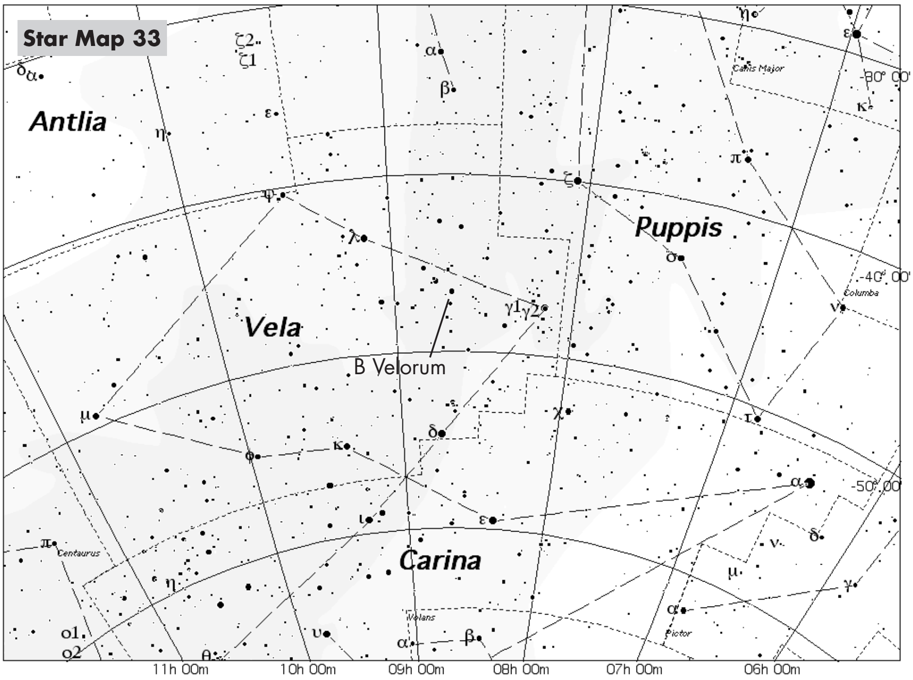


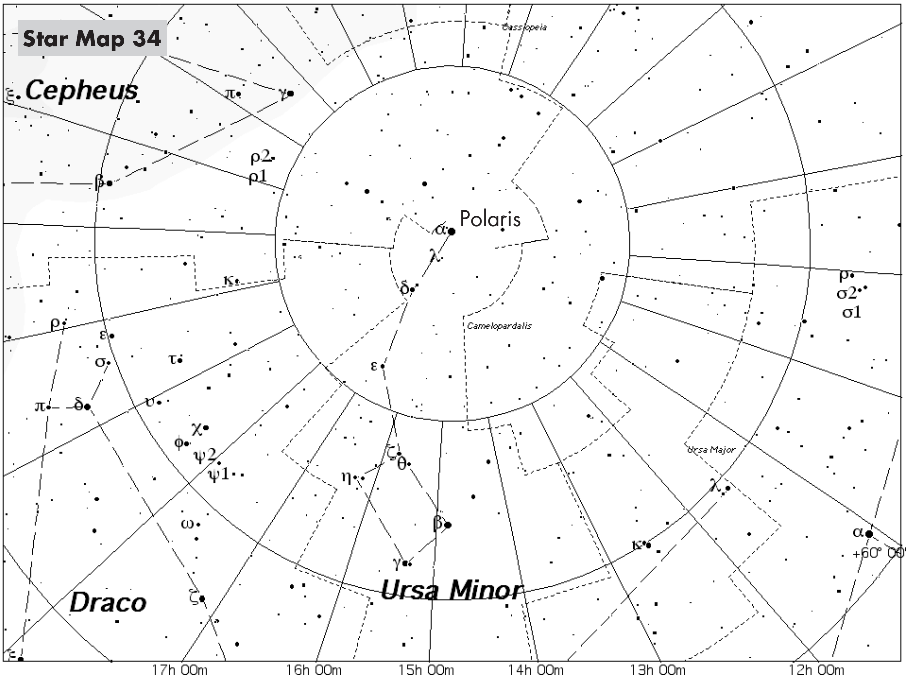
Star Map 31



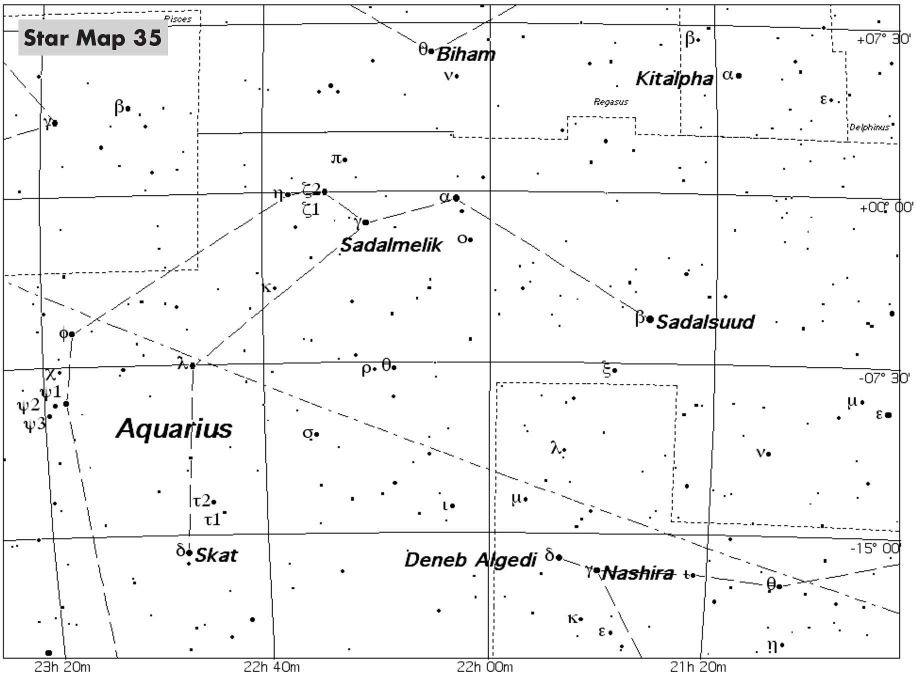
Star Map 32



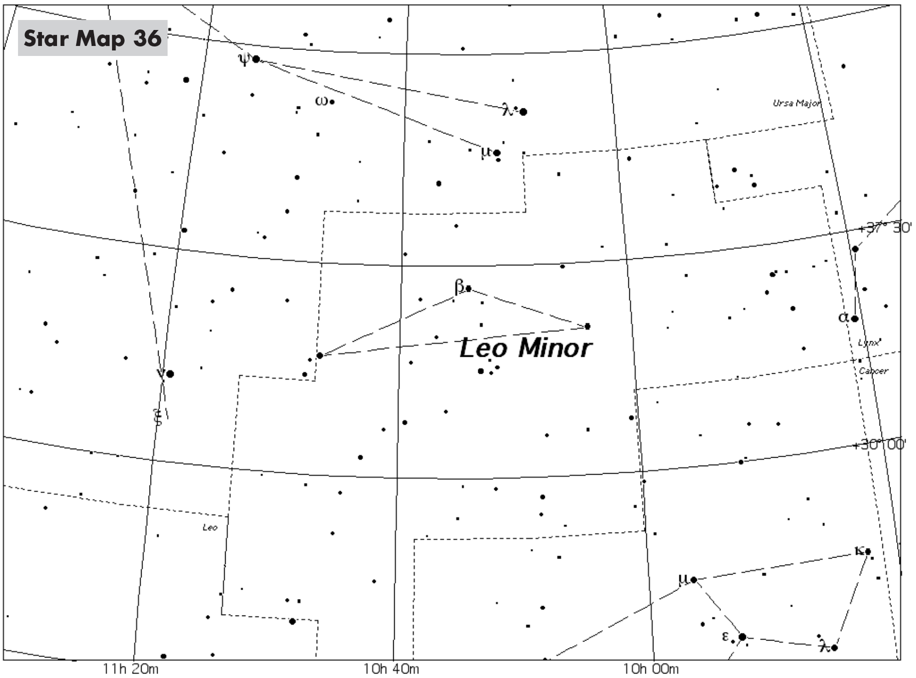

Star Map 33
Antlia
Vela
Puppis
Carina
B Velorum
Canis Major
Columba
Centaurus
Volans
Pictor
-30° 00'
-40° 00'
-50° 00'
11h 00m
10h 00m
09h 00m
08h 00m
07h 00m
06h 00m

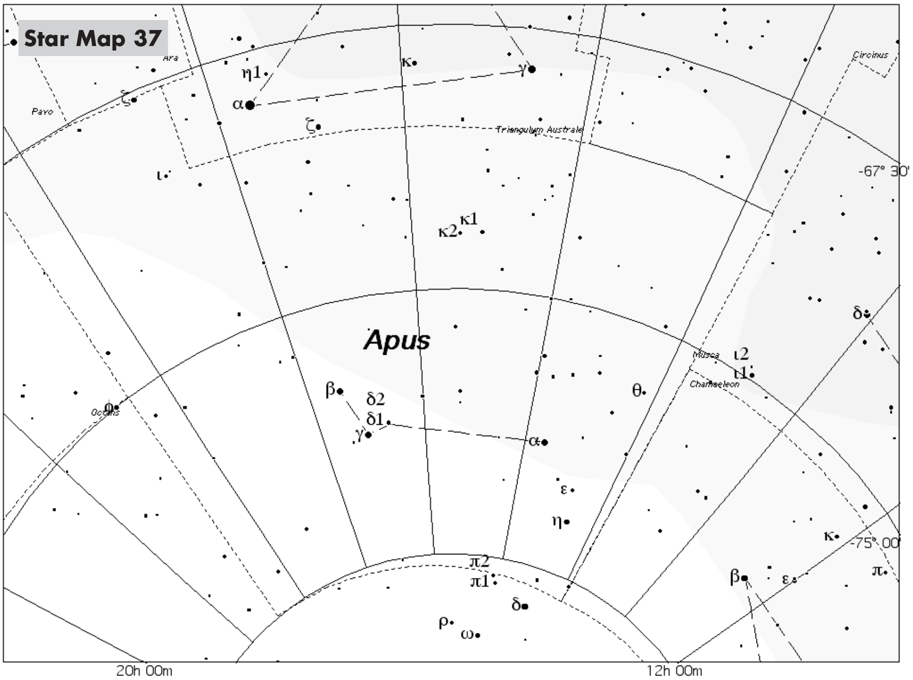

Star Map 34
Cepheus
Polaris
Camelopardalis
Cassiopeia
Ursa Major
Draco
Ursa Minor
+60° 00'
17h 00m
16h 00m
15h 00m
14h 00m
13h 00m
12h 00m

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

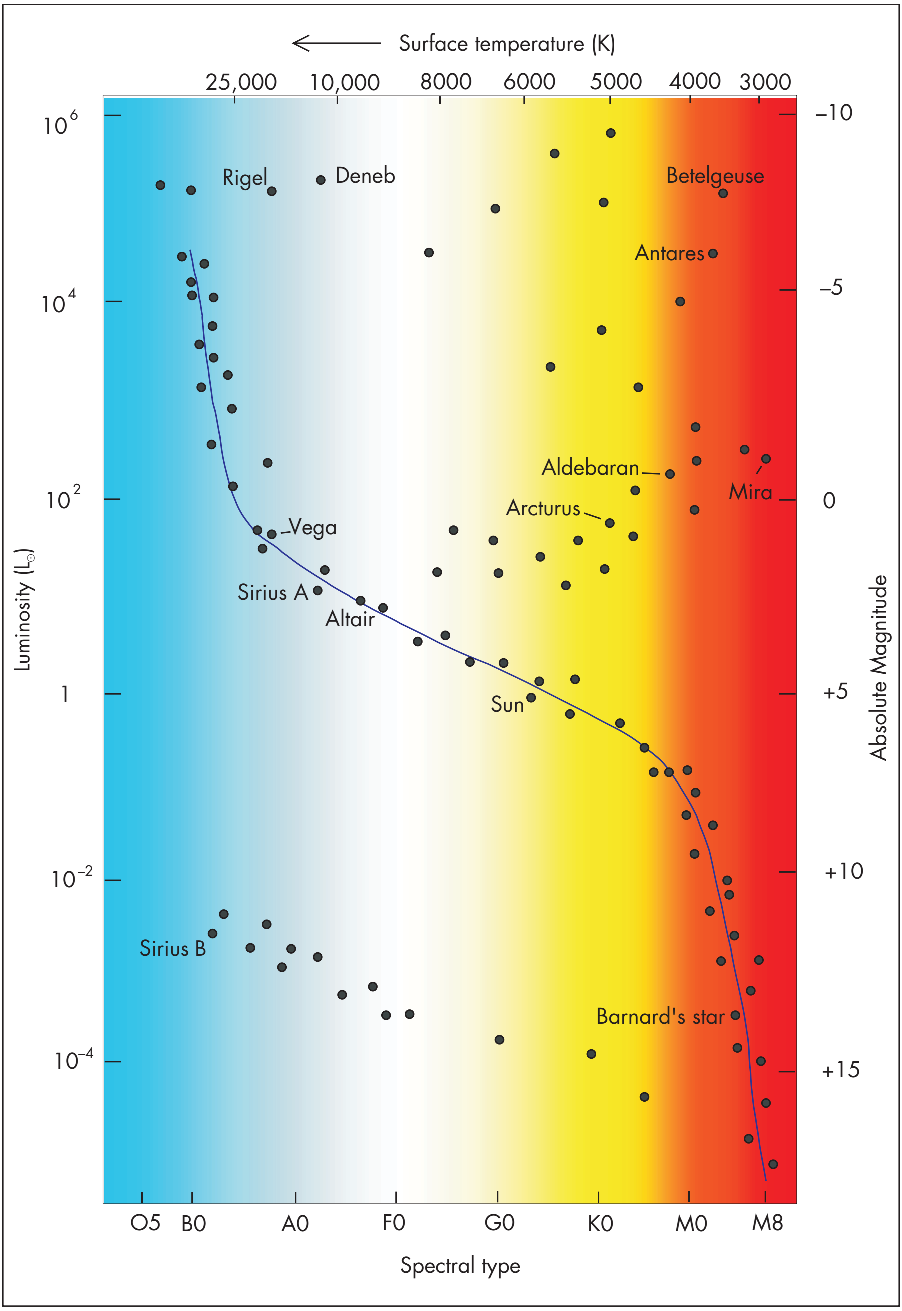


Figure 1.4. The Hertzsprung–Russell Diagram. Luminosity is plotted against spectral type for a selection of stars. Shown are some of the brighter stars. Each dot represents a star whose spectral type and luminosity has been determined. Note how the data are grouped in just a few regions indicating a 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 s*upergiants*, 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.

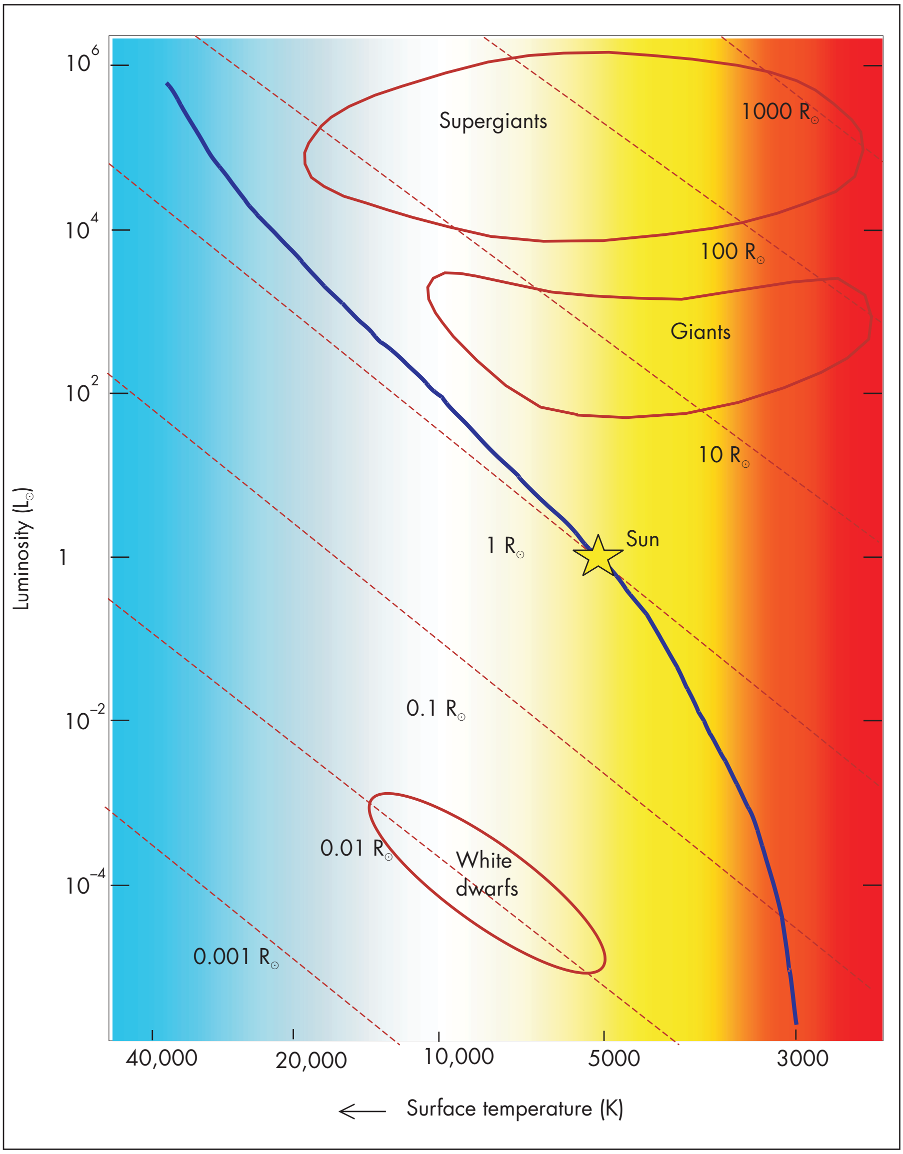


Figure 1.5. Size of Stars on a H–R Diagram. Stellar luminosity against surface temperature. The dashed diagonal lines indicate stars of different radius. At a given radius, the surface temperature increases (moving from right to left), and luminosity increases. Notice the main sequence and the Sun's 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 – $100M_\odot$. At the other end of the main sequence,

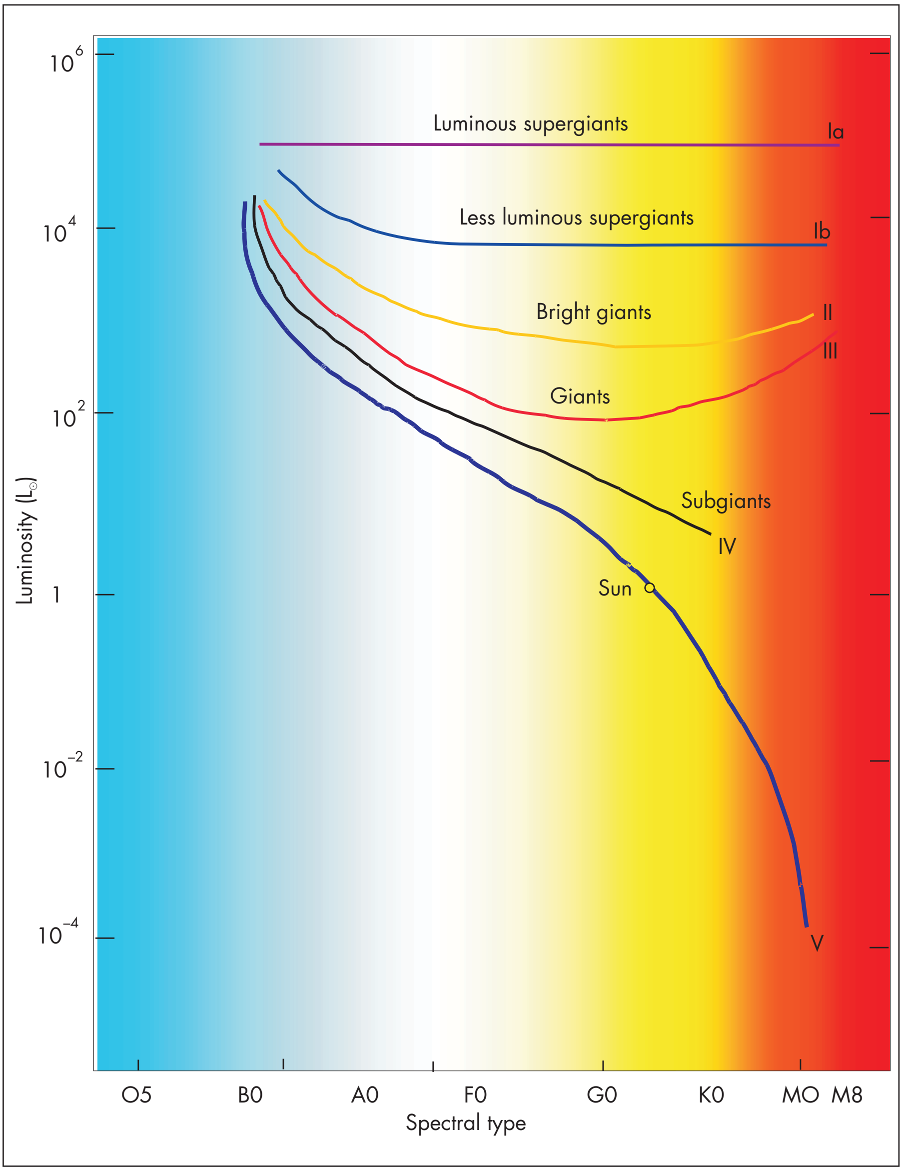


Figure 1.6. Luminosity Classes. Dividing the H–R diagram into luminosity classes allows distinctions to be made between giant and supergiant stars.

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!

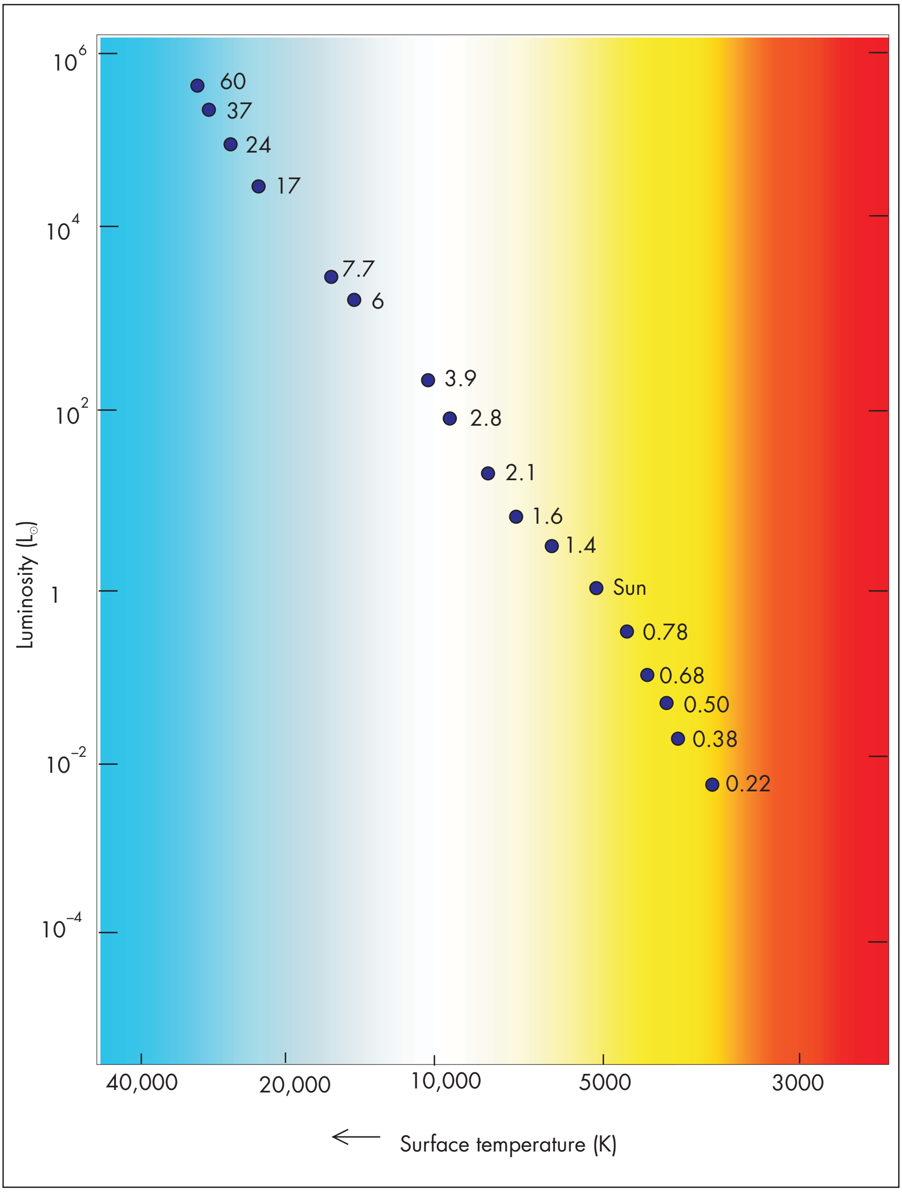

Figure 1.7. Mass and the Main Sequence. Each filled-in circle is a main–sequence star. The number is the mass of the star in solar masses ($M_\odot$). As you move up the main sequence from lower right to upper left, the mass, luminosity and temperature increase.

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.