

# Chapter 1

## Observations of Stars

The formation of stars and the formation of planets are intricately connected in monistic theories. The theory that I shall describe later, which forms the main topic of this book, is essentially a dualistic theory but one that is still dependent on the processes of star formation. However, before I give an account of how stars form, I shall first describe some of the properties of stars and how they are determined.

Looking up at the night sky, we see points of light that are individual stars and using telescopes, many more can be seen than with the naked eye. If we examine individual stars with optical instruments we find that the vast majority are indeed *point light sources* of no discernable size. Yet, for all that, by the use of optical instruments and a knowledge of physics, we can learn a great deal about these stars — their distances, their temperatures, how luminous they are, their masses, their radii and how fast they spin on their axes. How we achieve this miracle from just the evidence provided by points of light, I shall now explain.

### 1.1. Locations of Stars

In considering where stars are located, I shall limit myself to a very tiny part of the contents of the Universe, the Milky Way galaxy of which the Solar System is a member. It may seem a little strange to use the adjective ‘tiny’ in relation to the collection of about  $10^{11}$  stars that constitutes the Milky Way, but so it is, for there are of the order of  $10^{11}$  galaxies in the Universe, according to the latest estimates. The

other restriction I shall observe is mainly to concentrate on stars that, like the Sun, are generating energy by nuclear reactions that convert hydrogen to helium in their interiors. Stars in this state are said to be on the *main sequence*. The Sun has been a main-sequence star for about 5 billion years and will remain so for another 5 billion.

The stars in our galaxy are in a variety of environments. First, there are stars like the Sun that move through the galaxy in splendid isolation without any stellar companions. By contrast, many stars occur in large associations, *stellar clusters*, of which there are two main types. The first is the *galactic* or *open cluster* that usually consists of between 100 and 1,000 stars (Fig. 1.1) and is between 6 and 60 light years (ly)<sup>1</sup> across. The alternative names describe the structure of such clusters and where they are situated. They are ‘open’ in the sense that the stars are sufficiently separated for them to be seen individually and they are ‘galactic’ in the sense that they only occur in the galactic plane (Appendix G). The second type, the *globular cluster*, is much larger, containing as many as several tens of thousands to a million stars (Fig. 1.2) and with diameters of 60 to 200 ly. The name ‘globular’ describes the shape of these clusters. The



Fig. 1.1 The Pleiades open cluster (John Lanoue).

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<sup>1</sup>A light year (ly) is the distance that light will travel in one year.  $1 \text{ ly} = 9.46 \times 10^{12} \text{ km}$ .



Fig. 1.2 The globular cluster M80 (NASA/ESA).

number density of stars is so high in the central core of the cluster that individual stars cannot be easily resolved there, but stars in the outer regions can be seen individually. Globular clusters occur in all parts of the galaxy — the galactic plane, the nucleus and the halo (Appendix G).

Both within and outside clusters, many stars exist in pairs, known as *binary systems*, in which the two stars orbit around their centre of mass (Appendix H). For a small proportion of binary systems, the stars are sufficiently far apart for them to be seen individually; these are *visual binaries*. Greatly outnumbering visual binary systems are *spectroscopic binaries* in which the stars are so close together that they cannot be individually resolved, even with the most powerful telescopes. The fact that they consist of a pair of stars is determined by looking at the light that comes from them. As the two stars move around their orbits, the variation in their velocities relative to the Earth can be detected by Doppler shifts (Appendix I) in the wavelengths of spectral lines (Fig. 1.3) in the light emitted. There are about as many binary systems in the galaxy as there are individual stars, meaning that a minority of stars are isolated stars like the Sun. There are also some rare multiple-star close systems containing more than two, but very few, stars.



Fig. 1.3 Fraunhofer lines in the solar spectrum.

## 1.2. Stellar Material

The Sun is a typical main-sequence star, although its mass is somewhat above the average for such stars. The light emitted from the Sun comes from a very thin layer, called the *photosphere*, which defines its visible surface. Light that comes from material below the photosphere is absorbed by material above it before it can escape and so does not add to the emitted light. The material above the photosphere is so diffuse that, although it is at a very high temperature, it emits very little light. However, the material above the photosphere does have an important effect on the emitted light; it contains different kinds of atoms in different states of ionization<sup>2</sup> and these absorb some of the light coming from the photosphere. The absorbed light is at many well-defined wavelengths, characteristic of particular atoms and their states of ionization, and produces in the solar spectrum a set of dark lines, known as Fraunhofer lines (Fig. 1.3). These absorption lines also occur in the spectra of the light from distant stars, and from the presence and strength of these lines it is possible to determine which elements are present in the star and to what extent.

The stars in the two types of cluster are distinguished by their chemical compositions. The vast majority of material in the Universe is either hydrogen or helium that together account for 98% of the total by mass. These are the elements, together with tiny amounts of lithium and beryllium, two other light elements, which were produced in the *Big Bang*, the cataclysmic event that is thought to have produced time, space and all matter.<sup>3</sup> The extent to which a star

<sup>2</sup>Ionized atoms are those that have lost one or more of their electrons.

<sup>3</sup>A description of the Big Bang can be found in the author's book, *Material, Matter and Particles: A Brief History*, 2009 (London: Imperial College Press).

contains heavier elements — those from carbon with atomic number six and heavier — is described as the *metallicity* of its material, although most of the heavier elements are not actually metals. Stars in open clusters, similar in type to the Sun, have high metallicity with typically 1–2% of their mass in the form of heavier elements. These open-cluster stars, and field stars of similar composition, are called *Population I stars*. Stars in globular clusters have much lower metallicities with typically 0.01% by mass of heavier elements. Such stars are called *Population II stars*. It is theorized that there may be *Population III stars* consisting of pure Big Bang material with no heavier element content whatsoever, but such stars have never been observed.

### 1.3. Determining the Distances of Stars

Starting with finding the distances of some nearer stars by a technique similar to that used in military rangefinders, astronomers have found ways of finding the distances of stars out to the limit at which individual stars can be seen. I shall now describe two techniques that enable us to determine the distances of stars within our galaxy — my self-imposed limited region of interest.

#### 1.3.1. *The distances of nearby stars*

The principle of measuring the distance of nearer stars is easily demonstrated. If you observe a vertical finger held at arm's length, first with one eye and then with the other, it will be seen to move relative to distant objects. In the same way, if a nearby star is observed at times six months apart, during which period the Earth has moved from one point of its orbit to the diametrically opposite point, then it will appear to have moved relative to those stars very much further away. This situation is illustrated in Fig. 1.4.

The best arrangement for making the observations is when the line joining the viewing positions is perpendicular to the direction of the star. The figure is completely out of scale and the angle  $\alpha$  is very

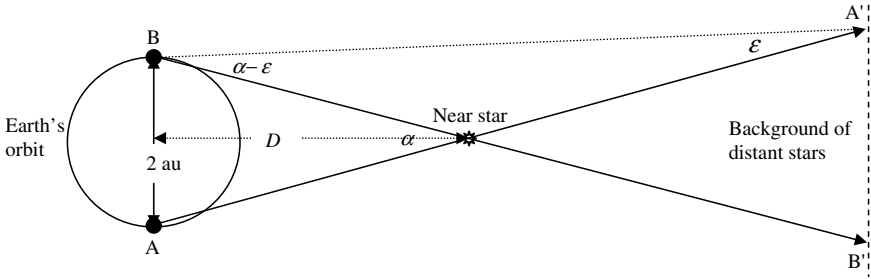


Fig. 1.4 Finding the distance of a nearby star by the parallax method.

small, of the order of one second of arc.<sup>4</sup> For the calculation of the star's distance we need to express the angle in radians (Appendix A) and then the distance of the star is given by

$$D = \frac{2}{\alpha} au. \quad (1.1)$$

The question then arises of how  $\alpha$  is measured since we cannot travel to the star and measure the angle between the viewing positions A and B. The answer is that we measure the angle from either of the viewing points between the positions A' and B' on the distant star field. As shown in Fig. 1.4, that angle is actually  $\alpha - \epsilon$  but since the background is so distant,  $\epsilon$  is extremely small — very much smaller than  $\alpha$ .

By this method, called the *parallax method*, the distances of stars can be estimated out to about 100 ly by ground observations and up to about 600 ly by measurements from Hipparcos, a satellite launched by the European Space Agency in 1989. The distances of one million of the nearest stars have been measured by the parallax method. These measurements provide the launching pad for the measurement of stars at ever increasing distances.

You may have noticed that there was an assumption made in the above account, which is that the star did not move during the six-month interval between the observations. If it did move, Eq. (1.1) would not be valid. What is done in practice is to make

<sup>4</sup>60 seconds of arc equals one minute of arc and 60 minutes of arc equals one degree.

three measurements — from positions A, B and then A again. This not only gives the distance of the star but also its transverse component of velocity, the component at right angles to the direction of view.

There is a unit of distance, commonly used by astronomers, that is derived from the parallax method. The unit, the *parsec* (pc), is the distance at which 1 au subtends an angle of one second of arc and is equivalent to 3.26 light years. In Fig. 1.4, if the star were at a distance of 1 pc, then the angle  $\alpha$  would be two seconds of arc. If it were at a distance of 2 pc, then  $\alpha$  would be one second of arc. It will be seen that measuring the angle  $\alpha$  directly gives the distance in parsecs — hence its attraction.

### 1.3.2. Distance measurements using variable stars

In the 18th century, in the city of York, there lived a very interesting English astronomer, John Goodricke (1764–1786; Fig. 1.5(a)). He was a deaf mute at a time when society looked down on people with such impediments but he came from a distinguished family and so was able to overcome this disadvantage. His first education was at a special school in Edinburgh run by Thomas Braidwood, who had developed effective techniques for teaching deaf pupils. Later, Goodricke was able to attend a normal school, Warrington Academy,



(a)



(b)

Fig. 1.5 Personalities connected with Cepheid variables: (a) John Goodricke (b) Henrietta Leavitt.

where he acquired a deep interest in astronomy. When he returned to his home, the Treasurer's House immediately next to York Minster, he started a programme of stellar observations. He specialized in observing variable stars, those that vary in intensity, and one such star was  $\delta$ -Cephei. It is believed that exposure while observing this star led to his untimely death at the age of 21.

This star,  $\delta$ -Cephei, is a prototype of a whole class of stars, *Cepheid variables*, which vary in brightness in a periodic way. The observed brightness of a star depends on its distance; car headlights at a close distance are dazzling but may be seen quite comfortably if far away. The intrinsic brightness of a star, a measure independent of its distance, is its *luminosity*, the rate at which it emits electromagnetic energy. The luminosity of the Sun is approximately  $3.8 \times 10^{26}$  W.<sup>5</sup>

The observed brightness of a star depends on the energy per unit area per unit time received from the star by a detector (the eye, for example) on Earth. This decreases as the square of the distance to the star, so the observed brightness of a star of known distance enables its luminosity to be determined. Conversely, if the luminosity of the star were known, then its observed brightness would enable its distance to be estimated.

In 1908 a Harvard astronomer, Henrietta Leavitt (1868–1921; Fig. 1.5(b)), from a study of Cepheid variables within the range of parallax distance measurement, found that there was a relationship between the maximum luminosity of a Cepheid variable and its period (Fig. 1.6). Some Cepheid variables are extremely bright, with luminosities up to 30,000 times that of the Sun, so they can be seen at great distances. They occur, and can be seen, in the outer regions of some distant galaxies. From their periods, their maximum luminosities are known, as shown in Fig. 1.6. Then from their observed maximum observed brightness, their distances can be found. In this way the distances of galaxies can be estimated out to

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<sup>5</sup>The joule (symbol J) is the Standard International Unit of energy and the watt (symbol W) is  $1 \text{ J s}^{-1}$ .

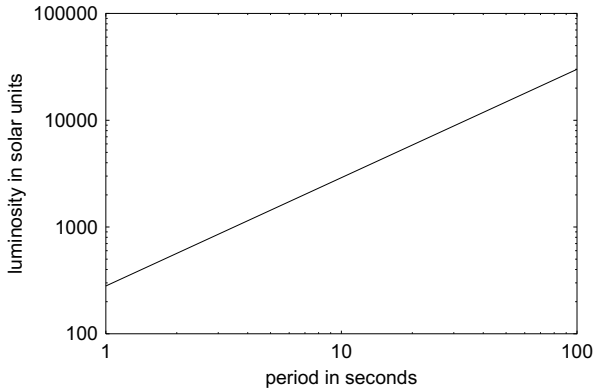


Fig. 1.6 Relationship between the luminosity of a Cepheid variable and its period.

80 million light years and also the distances of clusters of stars within our own galaxy if they happen to contain a Cepheid variable.

Astronomers have many more techniques available to extend estimates of distances to the limits of the observable Universe but we shall explore these no further — remember, I am only concerned with a tiny part of the Universe, our Milky Way galaxy.

## 1.4. The Temperature of Stars

In domestic situations we normally measure temperature with a thermometer in the form of a device that takes up the temperature of the object of interest and reveals it in some visual way — for example, by the expansion of mercury up a fine glass tube. Another way, which is used in metal foundries, is to measure the radiation coming from the hot metal and to use this to determine temperature. This, essentially, is how the surface temperatures of stars can be found. To understand how this can be done, we first need to know something about electromagnetic radiation, the form of energy that includes visible light, radio waves and x-rays. A representation of the full electromagnetic spectrum is shown in Fig. 1.7.

At the long wavelength end, there are radio waves of the type that are used to broadcast radio and television signals. Next, we

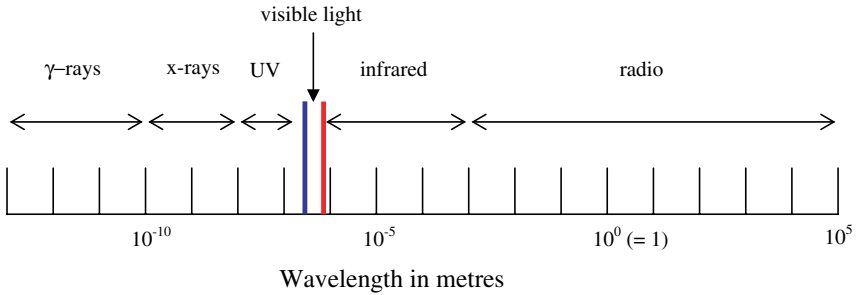


Fig. 1.7 The electromagnetic spectrum.

find the infrared region of the spectrum; wavelengths beyond the visible range but detectable by their heating effects. The visible part of the spectrum is a small region with wavelengths between  $4 \times 10^{-7}$  m (violet) and  $7 \times 10^{-7}$  m (red). It is surprising that we use so little of the spectrum in vision — infants can see a small distance into the ultraviolet region, as can some insects. After the ultraviolet region come x-rays, which are used in medical diagnosis and also in various ways by scientists as a tool for exploring the nature of matter. Finally we come to  $\gamma$ -rays, very high-energy electromagnetic radiation that is a component of the cosmic rays which permeate the whole Universe and also comes from some compact high-energy astronomical sources. Astronomers exploit the whole of this range of electromagnetic radiation in exploring the heavens, using devices that range from  $\gamma$ -ray telescopes to radio telescopes.

Figure 1.8 shows the intensity distribution against the wavelength of the radiation coming from sources with the same areas of emission at three different temperatures. Two properties of the curves shown in the figure are evident. The first is that the higher the temperature, the shorter the wavelength corresponding to the maximum. Theory shows that the product of the absolute temperature and peak wavelength is a constant (Wien's law). The second is that the total energy emitted per unit time, which is proportional to the area contained under the curve, increases with temperature; theory shows that it is proportional to  $T^4$  where  $T$  is the absolute temperature. I have already referred to this relationship in a non-quantitative way in describing how disks were detected around young stars. It is only

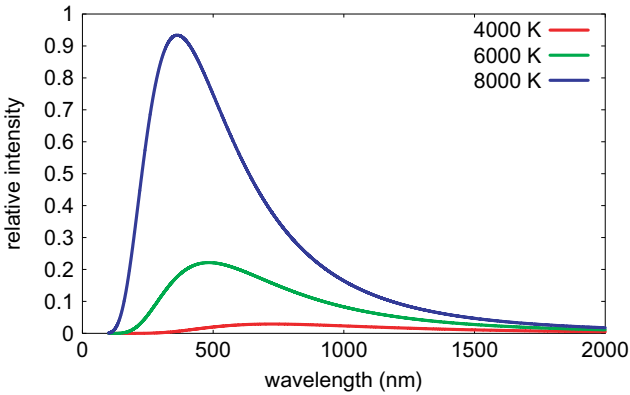


Fig. 1.8 The radiation intensity curves from sources at 4,000 K, 6,000 K and 8,000 K ( $1 \text{ nm} = 10^{-9} \text{ m}$ ).

possible to detect the radiation from a low temperature source when it has a large area.

In principle, by looking at the overall intensity distribution of the light coming from a star, or finding the wavelength of the maximum of the distribution, it should be possible to determine the temperature of the star. This is difficult in practice and only very approximate temperatures can be found in this way. Astronomers have found a much more accurate and subtler way of determining temperature based on the absorption lines shown in Fig. 1.3. The intensities of these lines are temperature-dependent (Appendix J) and the different lines vary in intensity with temperature in different ways. Figure 1.9 illustrates the variation of the intensities of various absorption lines for different temperatures.

If the spectra of many stars are available, they can be arranged in sequence such that each varies only slightly from its immediate neighbours. In the figure, three spectral lines produced by hydrogen —  $H\alpha$ ,  $H\beta$  and  $H\gamma$  — are shown and the gradual change from one spectrum to the next is evident. According to which spectral lines are most prominent, stars are assigned to *spectral classes* O, B, A, F, G, K or M; each class has ten subdivisions indicated as A0, A1, A2  $\dots$  A9, for example. Most astronomers remember the sequence of spectral-class letters by the mnemonic ‘Oh Be A Fine Girl — Kiss Me’. The spectral classifications for the illustrated spectra are

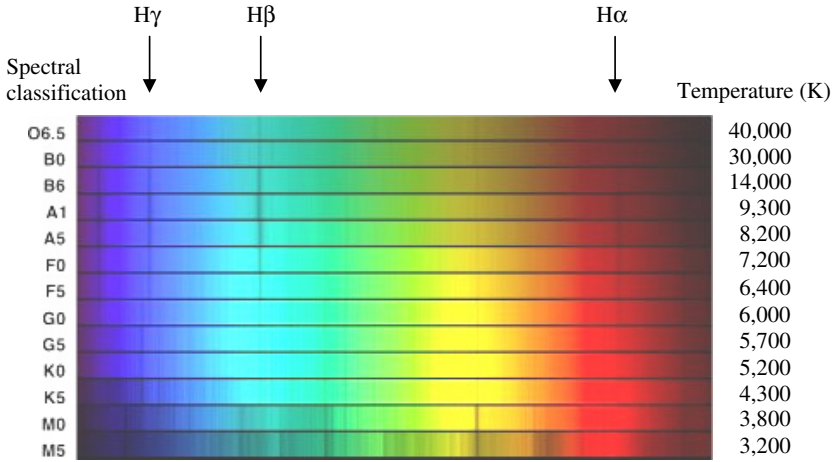


Fig. 1.9 The absorption spectra of stars at different temperatures.

shown on the left-hand margin in Fig. 1.9. By accurately comparing the relative intensities of a number of different absorption lines, it is possible to estimate stellar temperature with an accuracy of 10 K in the most favourable situations.

### 1.5. Stellar Radii

For about a dozen red giant stars, it is possible to produce an image of their disk and so estimate radii directly and, for a small number of other nearby stars, radii can be found by an optical technique known as stellar interferometry. However, the majority of stars are simple point sources of light and so estimates of their radii must be made by indirect means.

The areas under the curves in Fig. 1.8 are proportional to the energy emitted per unit area per unit time, a quantity that we have already indicated as proportional to  $T^4$ . The luminosity of a star is the total energy per unit time emitted by its surface, which has area  $4\pi R^2$ , where  $R$  is the radius of the star. Putting these two statements together, we may express the luminosity as

$$L = \sigma 4\pi R^2 T^4 \tag{1.2}$$

where  $\sigma$  is Stefan's constant, equal to  $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ . From this, if both  $L$  and  $T$  have been estimated from astronomical observations, the radius of the star may be found from

$$R = \sqrt{\frac{L}{4\pi\sigma T^4}}. \quad (1.3)$$

For the Sun, a G2 star with a surface temperature of 5,770 K and a luminosity of  $3.8 \times 10^{26} \text{ W}$ , this formula gives a radius of  $6.94 \times 10^5 \text{ km}$  which compares well with the accepted value of  $6.96 \times 10^5 \text{ km}$ .

## 1.6. Estimating Stellar Masses

If all stars existed as single isolated stars, it would be virtually impossible to know anything about their masses, except for that of the Sun. The mass of a star manifests itself through its gravitational influence and the characteristics of the planetary orbits enable the mass of the Sun to be found. The existence of binary-star systems, in which the actions of gravitational forces also manifest themselves through the motions of the two stars, detected by Doppler shifts of spectral lines, enables the masses of the individual stars to be estimated (Appendix K).

Very massive stars are comparatively rare and stars are ever more common with decreasing mass. To put this into a quantitative form, the mass frequency function,  $f(M)$ , is used to describe the relative numbers of stars per unit mass range: the proportion of stars with mass between  $M$  and  $M + dM$ , for small  $dM$ , is  $f(M)dM$ . From observation it is found that  $f(M)$  is proportional to  $M^{-\mu}$  where  $\mu$  is in the range 2.3 to 2.6 for stars between one-tenth and ten times a solar mass. To give some feel of what this means for stars with masses in this given range, just one star in 30 has the mass of the Sun or more and one star in 100 has twice the mass of the Sun or more. Figure 1.10 shows, for  $\mu = 2.4$ , the proportion of main-sequence stars in the range from 0.1 to 10 solar masses that have a mass less than that indicated by the  $x$ -coordinate. This shows that very few stars have mass greater than a solar mass.

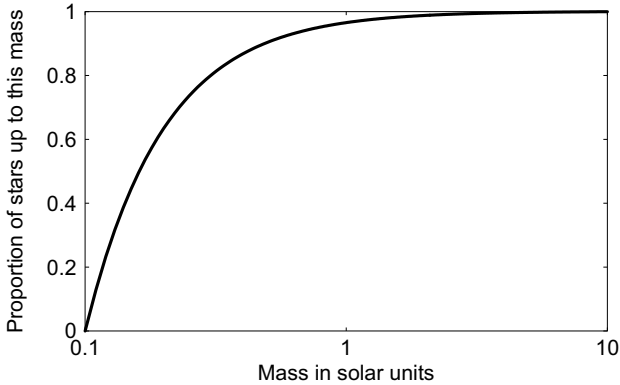


Fig. 1.10 The proportion of stars with mass less than the  $x$ -coordinate mass.

## 1.7. The Physical Properties of Main-Sequence Stars

The only property of a star that can always be measured is its temperature, as judged by its spectral class. If it is an individual, isolated star outside the range of parallax measurements, then neither its luminosity nor its mass can be directly estimated.

Fortunately, the masses, luminosities and radii of main-sequence stars are related to their spectral class so the general physical properties may be inferred for any main-sequence star for which the spectral class has been determined. Table 1.1 gives the properties of main-sequence stars for a sample of spectral classes.

Table 1.1 Properties of main-sequence stars related to spectral class.

Spectral class	Temperature (K)	Mass (solar units)	Radius (solar units)	Luminosity (solar units)
O5	45,000	60	12	790,000
B5	15,000	5.9	3.9	830
A5	8,200	2.0	1.7	14
F5	6,400	1.3	1.3	3.2
G5	5,700	0.92	0.92	0.79
K5	4,300	0.67	0.72	0.15
M5	3,200	0.21	0.27	0.011

This enables the distances of main-sequence field stars to be estimated well beyond the parallax range. The spectral class gives the luminosity and the measured brightness gives the distance of the star.

## 1.8. Stellar Spin Rates

I have explained why an explanation of the slow spin of the Sun has proved to be a difficulty for monistic theories of solar-system origin, so it is clearly interesting to know whether or not the Sun is typical in this respect. In general, due to their spins, when stars are observed, different parts of the star are moving either towards the Earth or away from it, relative to the motion of the star's centre. If the star's spin axis were perpendicular to the line of sight, then material at one edge of the equator would be moving with the greatest speed away from the observer while that from the opposite edge would be moving with the greatest speed towards the observer. Light from different parts of the star would have different Doppler shifts and the effect of this would be a broadening of the observed spectral lines. From the extent of the broadening, the equatorial speed can be estimated. In general, the tilt of the stellar axis relative to the observer is unknown but from observations of many stars of similar mass, and with the assumption that their axes are randomly tilted with respect to the observer, an average equatorial speed for that mass can be found. The average equatorial speed for stars of different masses is shown in Fig. 1.11. It is clear from the figure that stars of a solar mass or less typically have low equatorial speeds while more massive stars have higher ones. The equatorial speed for the Sun,  $2 \text{ km s}^{-1}$ , is on the low side when compared with that indicated for a solar mass in Fig. 1.11, but is within the normal range of variation for such stars.

## 1.9. Summary

In this chapter I have described some of the important features of main-sequence stars. They can occur within open clusters, outside a cluster, as an individual star or as a member of a binary pair.

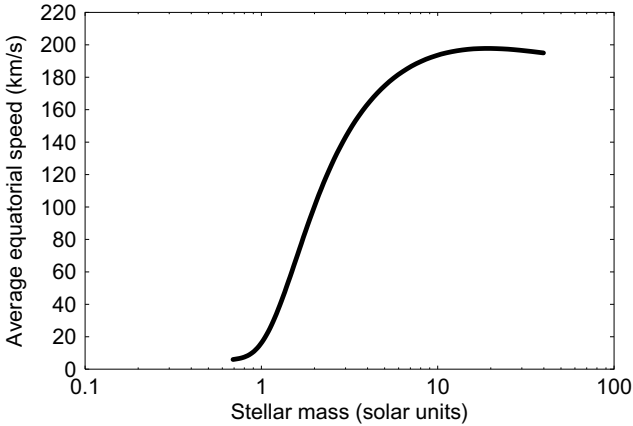


Fig. 1.11 The relationship between mean equatorial speed and stellar mass.

There are more stars existing within binary pairs than there are as individual stars and the majority of binaries are of the close spectroscopic type.

The Sun, and stars in open clusters, are Population I stars with 1–2% of their mass in the form of elements of atomic number equal to, or higher than, that of carbon. Stars in globular clusters are Population II stars with typically only 0.01% of their mass in the form of heavier elements.

The distances of about one million stars closest to the Sun have been determined by parallax measurements. By the use of Cepheid variables, distance measurements can reach out to all parts of the Milky Way galaxy and beyond.

Stellar masses can be deduced from observations of binary-star systems. The frequency of stellar masses decreases with increasing mass; only about 3% of main sequence stars have greater than a solar mass.

A combination of the apparent brightness of a star and its distance gives an estimate of its luminosity, while its spectral class gives an estimate of its temperature. From its temperature and luminosity, the radius of a star can then be found. For main-sequence stars, physical properties are linked to spectral class and thus these

properties can be inferred for isolated individual stars outside the parallax range for distance measurement.

Stellar equatorial speeds generally increase with stellar mass, except for a slight fall-off for the most massive stars. In terms of spin rate, the Sun is typical of stars of the same or lower mass.