CHAPTER 26

Variable and binary stars

The study of binary and variable stars reveals vital information about stars

26.1 Binary stars and their detection

■ *Describe binary stars in terms of the means of their detection: visual, eclipsing, spectroscopic and astrometric*

When viewing the stars on a clear night, it is apparent to the naked eye that some stars seem to be very close to each other. Almost all of these cases are simply due to the optical illusion of closeness caused by the observer's line of sight. One of the stars is closer than the other, and the two stars are most likely very far apart. These stars are known as optical binaries, and are not true double star systems. (The term 'optical illusion' can be thought of when referring to such stars.)

There are cases where stars are so close together that they have a common centre of gravity and revolve around one another. Such binary star systems are much more common than previously thought, as modern astronomical techniques unveil more stars as being double (or triple or even quadruple) star systems. Several methods are used by astronomers in identifying binary stars that to the naked eye appear as a single star.

Binary stars are especially important to astronomers. Calculations of their separation distance and observations of the period of the orbits of the two stars can yield the mass of the two stars. The mass of a star is an important quantity in astrophysics.

Figure 26.1 (a) Alpha Centauri (visible at left of photo)

Figure 26.1 (b) Alpha Centauri resolved into its two component stars

Visual binaries

As the name implies, visual binary stars can be resolved by a suitably large telescope. Successive observations over time show that the two stars do indeed revolve around each other. Alpha Centauri, the brighter of the two pointers to the Southern Cross, appears as a bright single star to the naked eye. However, with the resolving power of binoculars or a small telescope, two individual stars of spectral types G2 and K1 (yellow and orange) can be seen. The two stars are about as far apart as Uranus is from the Sun, or 24 times the distance of Earth from the Sun. They take 81 years to orbit their centre of mass. The third star that exists in this triple star system, Proxima Centauri, requires a modest size telescope to be seen.

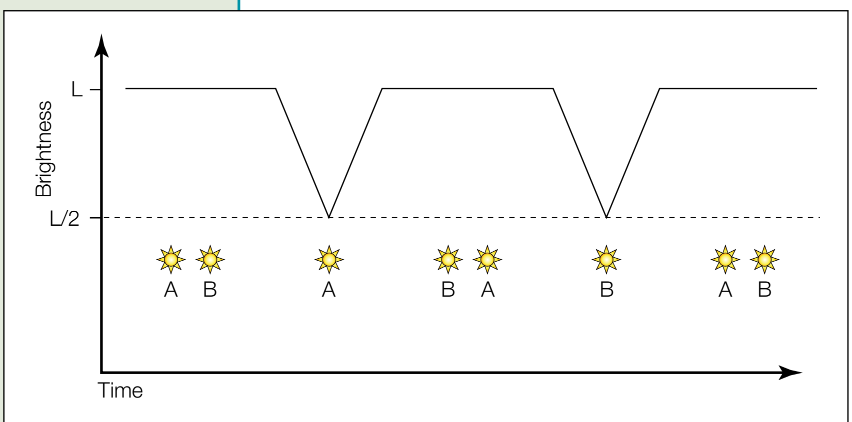
In many cases, the two stars cannot be resolved visually, as the angular separation is smaller than the resolution of even the largest telescopes available. In such cases, careful observation of the light being received from the star may reveal its binary nature.

Eclipsing binaries

As the name implies, eclipsing binary stars revolve about each other in a plane that brings one star in front of the other when viewed from Earth. This eclipsing, or occulting, of the light from the star behind, may result in a detectable dimming of the overall brightness of the light being observed from both stars. This variation in brightness may follow a regular pattern, and is repeated with each orbit.

Figure 26.2 shows how, if two identical stars are orbiting in a plane that results in the total eclipsing of one of the stars as one star passes in front of the other, then the brightness of the binary star will be observed to halve periodically. It is rare for the two stars in a binary system to be identical in size and luminosity. The light curves of most eclipsing binaries require careful analysis, taking in factors such as the size of each star, their spectral types (the factors which determine each star's luminosity) as well as the plane of the stars' orbits (which determines the extent to which the stars eclipse each other as viewed from Earth).

Figure 26.2 Brightness variation for a binary star system where the two stars happen to be identical, which is rare



Modelling light curves of eclipsing binaries

FIRST-HAND INVESTIGATION

PHYSICS SKILLS

H14.1B, C, F

- ***Perform an investigation to model the light curves of eclipsing binaries using computer simulation***

WWW→

USEFUL WEBSITE

This interactive website allows the user to choose these variables and observe a simulated light curve from a pair of eclipsing binary stars:
http://instruct1.cit.cornell.edu/courses/astro101/java/eclipse/eclipse.htm

Spectroscopic binaries

There are many examples where a binary star system cannot be identified by resolving the image of the two stars and that the binary stars do not orbit in a plane that causes eclipsing of either star. In these cases, further analysis of the star's spectrum reveals the slight Doppler shifting of the spectral lines as one star recedes from the observer and the other approaches. The simultaneous blue shifting and red shifting cause the spectral lines to split into two and then recombine when the star's motion is side-on, or translational, to the observer.

The majority of known binary systems have been discovered using this technique. Binary systems separated by less than one astronomical unit (the distance between the Earth and the Sun) have been identified where no telescope can resolve them visually.

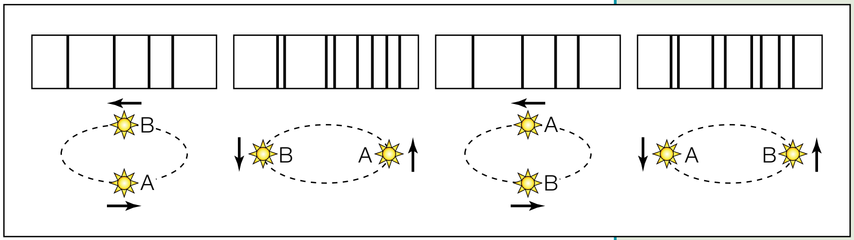


Figure 26.3 The periodic splitting of the spectral lines in a spectroscopic binary star system

WWW

USEFUL WEBSITE

A computer simulation similar to the one above is available at:
http://instruct1.cit.cornell.edu/courses/astro101/java/binary/binary.htm

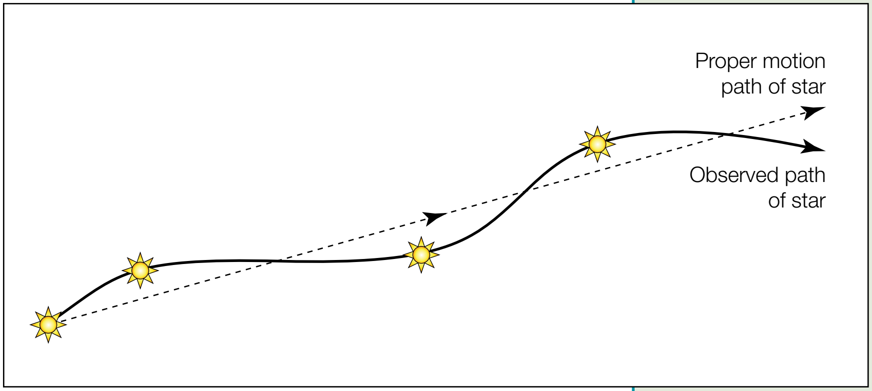
Astrometric binaries

The exact position of a star in the night sky can be measured very accurately. In the days when photography was the means of recording images, astronomers would compare glass plate 'negatives' taken some time apart and determine the 'proper' motion of stars. Stars are not fixed in their positions—most exhibit some degree of proper motion as they move through space. Proper motion of the stars causes the shape of constellations to change. Indeed, since the first maps of the night sky were produced by the Chinese and ancient Greeks, the constellations have changed slightly.

Astrometric binary star systems are detected by observing a star's very slight 'wobble' in its position along its path of proper motion.

The only force known that could cause a star to deviate in such a way is gravity from a nearby, invisible companion star that must be orbiting the visible star. In recent years, as measurements have become more accurate, many more astrometric binary star systems have been found. There are also now known to be hundreds of planets orbiting stars, causing them to exhibit such motion. The mass and separating distance of the companion star (or planet) can be calculated from the motion of the visible star. Other than the mass of the companion star, little else about its nature can be found out as its spectrum is not detectable from Earth. However, there are cases where the two stars are so close that matter is being dragged off the surface of one onto the other, causing the emission of X-rays, which can be detected from satellite-based observatories.

Figure 26.4 The 'wobbling' of the position of a star as it undergoes proper motion



WWW

USEFUL WEBSITE

Another downloadable program for eclipsing binary simulation for PCs is available here:
http://www.cosmion.net/software/ebs/

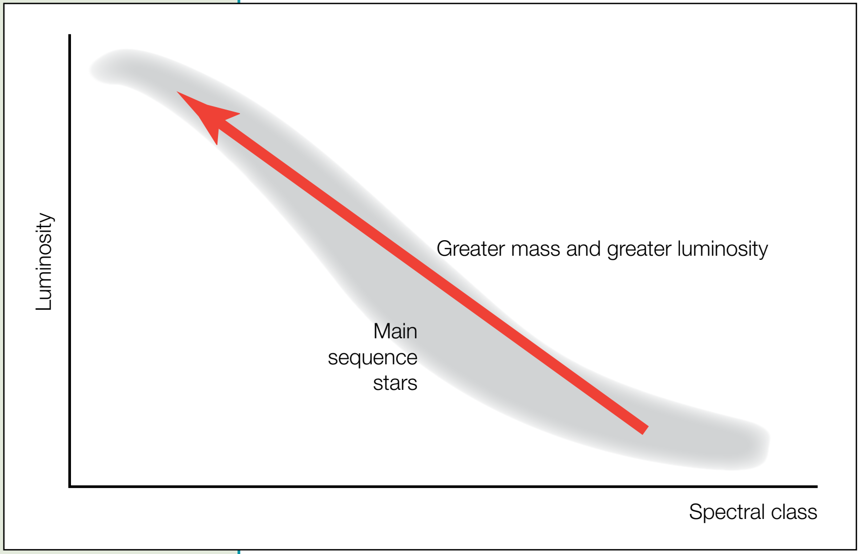
26.2 Important information from binary stars

■ *Explain the importance of binary stars in determining stellar masses*

The previous section has outlined various methods by which binary star systems are detected. Astronomers are particularly interested in binary star systems as they are the only way in which the mass of stars can be measured. Finding the distance separating the two stars (r) and their orbital period (T) can yield the combined mass of the system using a derivation of Kepler's laws. The mass of a star not only determines its position on the main sequence of a Hertzsprung-Russell (HR) diagram (more about these in Chapter 27) but also its luminosity. A more massive star will be larger and hotter, and therefore more luminous. This is known as the 'mass-luminosity' relationship. It is a very useful tool in being able to find the distance to the star using spectroscopic parallax (see Chapter 25). The luminosity of a star gives its absolute magnitude, M.

Once the period and the separation of a binary system is determined, the formula $m_1 + m_2 = \frac{4\pi^2 r^3}{GT^2}$ can be applied to find the mass of the two stars.

Figure 26.5 The mass-luminosity relationship for stars on the main sequence on an HR diagram



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Worked examples 23, 24

■ *Solve problems and analyse information by applying:*

$$m_1 + m_2 = \frac{4\pi^2 r^3}{GT^2}$$

This equation can be modified and used with non-SI units of solar masses (for $m_1 + m_2$), astronomical units (for separation distance r) and Earth years (for time T). If these units were used, the equation is simplified to:

$$m_1 + m_2 = \frac{r^3}{T^2}$$

The following examples show the equation used in both formats.

Example 1

A binary star system is observed to have a period of 28 years. The two stars are separated by a distance of 2.5×10^9 km. What is the total mass of the two stars in the binary system?

Solution

Since the units for distance are given in km, the full equation will be used.

T = 28 years

= 28 × 365 × 24 × 60 × 60 seconds (approximately)

= 8.8×10^8 s

$$r = 2.5 \times 10^{9}\text{ km}$$
$$= 2.5 \times 10^{12}\text{ m}$$

Substituting into the original equation:

$$m_1 + m_2 = \frac{4\pi^2 r^3}{GT^2}$$

$$= \frac{4\pi^2 \times (2.5 \times 10^{12})^3}{6.67 \times 10^{-11} \times (8.8 \times 10^{8})^2}$$

$$= 1.2 \times 10^{31}\text{ kg}$$

Example 2

Another binary star system has a period of 3.50 years and a separation of 2.70 a.u. The mass of the larger star is estimated as being 7.50×10^{30} kg. What is the mass of the smaller star? (The Sun's mass is 6.00×10^{30} kg.)

Solution

The combined mass of both stars in the system must be found first:

$$m_1 + m_2 = \frac{r^3}{T^2}$$

$$= \frac{2.70^3}{3.50^2}$$

$$= 1.61\text{ solar masses}$$

This gives the combined masses as $1.61 \times 6.0 \times 10^{30}\text{ kg} = 9.66 \times 10^{30}\text{ kg}$
The smaller star's mass $= 9.66 \times 10^{30}\text{ kg} - 7.50 \times 10^{30}\text{ kg}$
$= 2.16 \times 10^{30}\text{ kg}$

26.3 Classifying variable stars

■ ***Classify variable stars as either intrinsic or extrinsic and periodic or non-periodic***

Variable stars are ones that appear to vary in brightness. This may be due to the changing luminosity of the star itself, or it may be due to an external factor such as a companion star passing in between the observer (Earth) and the star, causing an apparent dimming of the star but not actually changing the star's luminosity.

The difference between intrinsic and extrinsic variables lies in the cause of the change in the brightness of the star. Intrinsic variables vary in luminosity, that is, the light output of the star changes. Extrinsic variables appear to change in brightness; however, their luminosity is not changing, but an external factor changes the light reaching the Earth.

Types of extrinsic variable stars

There are two known methods by which a star may be an extrinsic variable. The first, eclipsing binary systems, has been covered previously. An eclipsing binary system is thus classified as an extrinsic variable. It is also possible that the stars that make up a binary system are intrinsic variables as well.

Stars like our Sun have sunspots that are darker than the surrounding surface of the star. Sunspots are not dispersed symmetrically around the Sun. As the Sun rotates, an observer may notice a slight variation in its luminosity. A greater area of sunspots would result in an apparent reduction in the Sun's brightness. Such observations have been made in other stars, which are classified as intrinsic variables.

Types of intrinsic variable stars

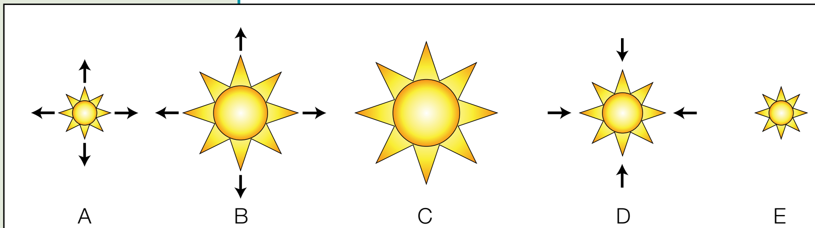
Many stars have been identified as being *pulsating* variables. These stars are periodically expanding and contracting, which changes their size, spectral type and luminosity. These stars appear to be otherwise stable, their pulsating nature being within certain limits, enabling them to continue to pulsate without exploding or disintegrating.

Occasionally, a star is observed to brighten by millions of times. Such occurrences have been recorded throughout history. When a star that was invisible to observers began to shine brightly in the night sky, it was said to be a new star, hence the name nova, or supernova. Modern astronomical research using spectroscopic techniques have led to theories on how such events occur.

Current theories suggest that most supernova are due to a white dwarf in a binary system 'accreting' matter from its nearby companion star until a cataclysmic explosion occurs due to a sudden, very energetic nuclear reaction. Such events are termed type 1 supernova. The less common type 2 supernova events are believed to be the result of the collapsing core of very massive stars at the end of their life cycle. Having consumed all of the available nuclear fuel, the core collapses and an extreme, sudden event blasts the outer layers of the star into space. Supernova 1987a (seen in the year 1987) was the first such event recorded with the original star having been previously identified.

Yet other types of intrinsically variable stars are known as 'eruptive'. These stellar events usually occur due to the presence of a binary star system. One such event is believed to be due to the way in which a white dwarf companion to a red giant is able to 'blow off' matter it has accumulated without destroying itself, repeating the action every 100 000 years or so. The result is that to observers, the star system suddenly brightens and gradually returns to normal over a number of days or weeks.

Figure 26.6
Pulsating variables



A: Expansion phase; as the star expands, its surface cools.
B: Expansion phase slows.
C: Expansion phase ends. Star has cooled and begins to shrink.
D: Shrinking phase continues.
E: Shrinkage phase ends. Star has heated and begins new expansion phase.

Periodic or non-periodic?

The cataclysmic and eruptive type of variable stars that do not repeat their brightness variation are considered non-periodic.

It is apparent from the previous section that stars can vary in brightness on a regular, repeating basis. Such variations are called periodic, as is a sine or cosine curve. The period can range from hours to years. RR Lyrae, a regular variable with a period of 13 hours, has given its name to a class of regular variables. The Hubble Space Telescope was able to measure the distance to this star in 2002 with reasonable accuracy, which is important as such stars are used as 'standard candles'. As their period is related to their absolute magnitude, they can be used as distance measuring objects in space. (See next section.)

A special class of regular periodic variables are Cepheids.

26.4 Distance and the period-luminosity relationship for Cepheid variables

■ *Explain the importance of the period-luminosity relationship for determining the distance of Cepheids*

Cepheid variables are named after the first such star to be identified, Delta Cephei. They are very luminous yellow giant stars. They are so luminous that some can be individually observed in neighbouring galaxies such as M31, Andromeda and in the Virgo cluster at a distance of some 60 million light-years. In the early 1900s, Henrietta Leavitt, an American astronomer, had catalogued over 1700 variable stars in the Small and Large Magellanic Clouds. She found that there was a good correlation between the periods of the 47 Cepheids observed and their luminosities. These clouds are two small galaxies neighbouring the Milky Way. The stars within them all have approximately the same distance from Earth, making it possible to correlate the period with the luminosity of the Cepheids. These were cross-referenced with a number of Cepheids of known distance. The Cepheids could now be used as 'standard candles,' stars which astronomers can use as distance measuring tools. Figure 26.7 shows a period-luminosity graph for Type I Cepheid variables. Type II Cepheids have a very similar graph, but are slightly less luminous. R R Lyrae stars are similar to Cepheids but have shorter periods and are less luminous. They too have a period-luminosity relationship. The time axis shown in the diagram is a log scale, not linear.

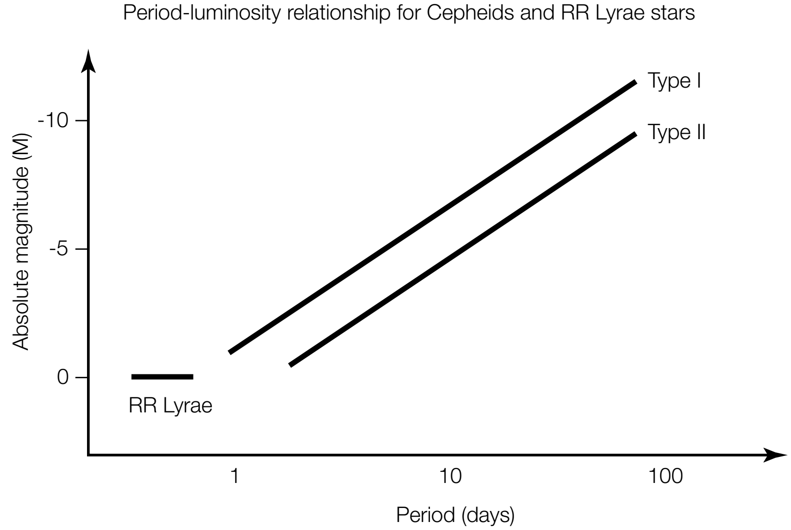


Figure 26.7 A period versus luminosity graph for Cepheid and R R Lyrae variables

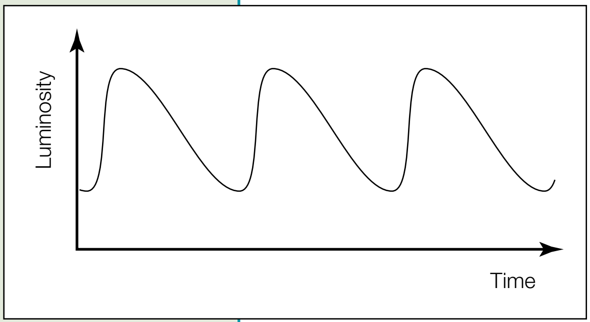


Figure 26.8
Typical light output curve of a Cepheid variable star: note the characteristic rapid brightening and more gradual dimming phases

Cepheid variables also exhibit light output curves characterised by a more rapid brightening phase and a more gradual dimming phase. See Figure 26.8. The shape of the curve is indicative of a Cepheid, and is due to the mechanisms within the star that cause the pulsating.

The importance of this period-luminosity relationship is illustrated in the following example.

Example

A Cepheid variable, classified as a Type I by its spectral characteristics, is observed in a globular cluster. It has a period of 10 days and an average apparent magnitude of +9.4. (It is an average apparent magnitude as the actual magnitude varies with time.)

Using a period-luminosity relationship graph (see Fig. 26.7), calculate the distance to this globular cluster.

Solution

Moving along the *x*-axis of Figure 26.7 to 10 days, and then moving vertically upwards gives the absolute magnitude for this Cepheid variable as −7.0.

The distance modulus equation used for spectroscopic parallax, $M = m - 5\log\left(\frac{d}{10}\right)$ (see Chapter 25), is now used:

$$M = m - 5\log\left(\frac{d}{10}\right)$$

$$-7 = 9.4 - 5\log\left(\frac{d}{10}\right)$$

$$-16.4 = -5\log\left(\frac{d}{10}\right)$$

$$\frac{-16.4}{-5} = \log\left(\frac{d}{10}\right)$$

$$\frac{d}{10} = 10^{3.28}$$

$$\frac{d}{10} = 1905$$

$$d = 1.9 \times 10^4 \text{ pc}$$

The use of Cepheid variables in this way enabled astronomers at the start of the 1900s to estimate the size of the then known Universe. An early recalibration of the period-luminosity relationship caused a near doubling in the estimated size of the Universe! More recently, observations of the red shift of distant galaxies has allowed a more accurate measurement of the Hubble constant, H, and therefore a more accurate estimation of the age of the Universe itself. The use of Cepheid variables as standard candles, or distance measuring stars has helped this estimation.

CHAPTER REVISION QUESTIONS

1. How can binary star systems give astronomers information about the mass of the binary system?
2. Describe the difference in the means of detection of a spectroscopic binary system and an astrometric binary system.
3. Which type of binary system can be seen as separate stars through a telescope?
4. A star is observed to have a regular dip in its apparent brightness, after which its normal brightness is resumed. No other changes are observed in the star's spectrum. Give a possible explanation for this.
5. What is the difference between extrinsic and intrinsic variable stars?
6. What is meant by 'the period-luminosity relationship' for Cepheid variable stars?
7. A Cepheid variable with a period of 10 days has an apparent magnitude of +21. Use Figure 26.7 to determine the distance to this star.
8. Calculate the combined mass of a binary system that has a period of 6.0 Earth years and a separation of 3.0×10^{12} m.
9. What would be the effect on the period of a binary system if the two stars' separation was somehow halved?
10. Why is it important to astronomers to find a star's mass?

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Answers to chapter revision questions