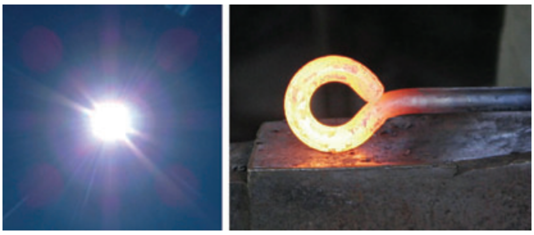
Stars

1 Why do stars shine?



Just as a piece of iron glows red or white hot when heated in a forge, stars shine because they are hot, very hot: millions of degrees at the core and thousands of degrees at the surface. Early on, this was thought to be the result of combustion, that the stars were burning in the same way that coal burns, but if that were the case, they would have lifetimes of only a few thousand years, whereas most stars live for billions of years.

The formidable amount of energy necessary for such long lifetimes comes from two sources: gravity while the star is forming, then nuclear fusion during the rest of its life.

Stars are formed from interstellar clouds of dust and gases, mostly hydrogen, that become progressively concentrated. In the first stage of a star's life, the force of gravity pulls the cloud into a spherical shape (Q. 3). This contraction – think of it as a falling inward – releases energy, just as an object falling on our foot transmits energy to us that we perceive as pain and bruising. As the gas and dust heat up, they start to glow, emitting light weakly in the infrared. Eventually, as the temperature of the gas continues to rise, it begins emitting visible light. The cloud has now become a young star.

As the interior of the collapsing sphere grows hotter and denser, the gas molecules break up into atoms, then the atoms lose their electrons and become ions. At that point the gas has become an electrically charged hot plasma composed of an equal number of freely moving, positively charged ions and negatively charged electrons. Finally, the core of the sphere becomes so dense and hot (15 million K) that the hydrogen nuclei begin to collide and fuse into helium.

Stars being formed inside a cloud of gas and dust (NGC 604). Each red dot is a new star – about 200 are visible. Their light, rich in ultraviolet radiation, excites the atoms in the cloud of gas, making it glow. Credit: NASA/ESA.

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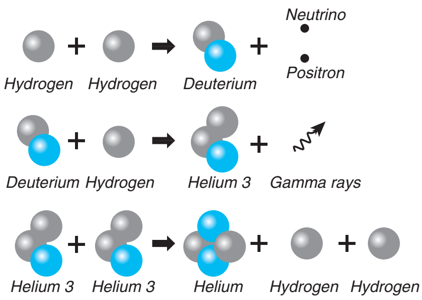


The three steps of hydrogen fusion into helium (the protons are shown in red, the neutrons in blue). Ultimately, four atoms of hydrogen have combined to form one atom of helium. The same result is also obtained via a chain of reactions with carbon, nitrogen, and oxygen acting as catalysts to convert hydrogen into helium.

Nuclear fusion† liberates enormous amounts of energy. Since the mass of a helium atom is 0.7% smaller than the mass of the four hydrogen atoms that formed it, a tiny amount of mass is "lost" for every helium atom produced. What happens to that mass? It is transformed into energy as per Einstein's famous equation, $E = mc^2$, which describes the equivalence of mass and energy. The mass that is transformed, m, may be minute but the speed of light, c, is very great (300 000 km/s), and its square is naturally much greater still. Thus, the product of the two terms, E, the equivalent energy, turns out to be enormous: the conversion of 1 kg of hydrogen into helium produces as much energy as burning 20 000 tons of coal. And the amount of hydrogen consumed in the stars is enormous, too: the Sun, for example, consumes 600 million tons of hydrogen every second! The total amount of energy produced is huge.

This energy produced in the core is propagated by radiation and convection towards the exterior layers of the star, and finally reaches the surface. The plasma at the surface then begins to radiate: the star shines.

The energy liberated in the interior of the star creates a pressure that combats and eventually counterbalances the force of gravity, so that the star ceases to collapse. At that point it stabilizes: it is an adult star.

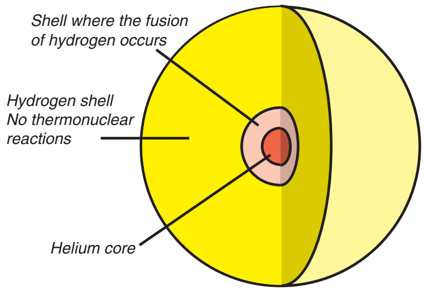
The amount of energy transported to the surface – and therefore the star's temperature and color – is primarily dependent on the mass of the star (Q. 13). A star's lifetime also depends on its mass: the greater the mass, the shorter the lifetime. Large mass stars (10 or more solar masses) can sustain fusion for only a few million years; stars such as the Sun, for several billion years; small mass stars (7–10% of the mass of the Sun), for trillions of years. Objects of even lower masses cannot sustain fusion for very long and rapidly become warm cinders called brown dwarfs (Q. 50). These objects do glow in the infrared, however, due to energy released by their contraction.

2 What are stars made of?

Stars are huge balls of gas, primarily made up of hydrogen and helium. Hydrogen represents about 90% of the atoms in a star, helium slightly less than 10%. Both elements were produced in the Big Bang at the birth of the Universe, but nuclear fusion

† Nuclear fusion must not be confused with nuclear *fission*, in which a large atom, uranium for example, is split into two lighter atoms (Q. 32).

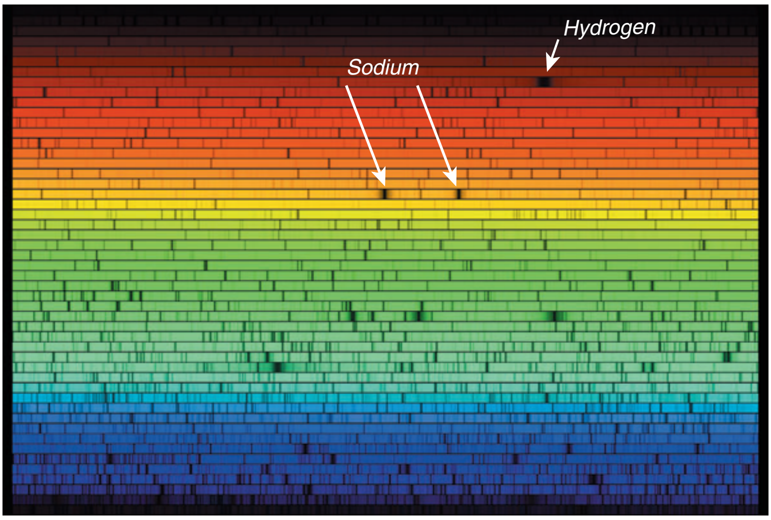
Schematic view of the interior of a star in which a helium core is forming. The core which is the size of Earth is actually much smaller than shown here.



in stellar cores is constantly transforming hydrogen into more helium (Q. 1), changing the relative proportions of the two elements in stars over time.

The other elements found in stars, representing no more than 1% of the total, are oxygen and carbon, together with very small amounts of nitrogen, silicon, iron, copper, gold, silver, nickel, plutonium, and uranium. These elements may have been present in the original cloud out of which the star formed, or have been created later in its core.

Indeed, the very high temperature (from 10 million to several billion kelvins) and pressure in the interior of a star make it an alchemist's delight, where heavy elements such as carbon and oxygen and even silicon and iron are formed. If a core in which



Spectrum of a typical star: the Sun. The bands, representing the wavelength ranges of visible light from purple to red, have been stacked on top of each other for compactness. Black areas are caused by the absorption by chemical elements present in the Sun's atmosphere, the darkness of their shade being a measure of their concentrations. One of the black areas in the red regions, for example, is due to the presence of hydrogen, the most abundant element in the atmosphere. The two black bands in the yellow region indicate the presence of sodium. Credit: Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF.

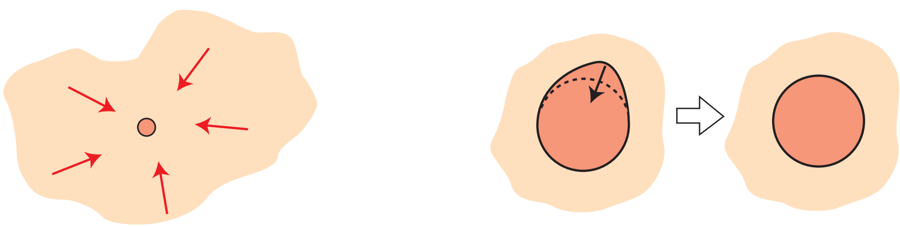
hydrogen fusion is taking place reaches a high enough temperature, nuclear fusion based on helium begins. Three helium (He^4) atoms combine to form carbon (C^{12}), for example, then a carbon atom can combine with helium to form an atom of oxygen (O^{16}). The process continues, with the number of different reactions increasing over time. In some stars, the hydrogen fusion that began in the core eventually becomes a shell of hydrogen fusion moving outward through the body of the star, while helium fusion continues to take place in the interior.

We cannot see the composition of a star's interior, but we can use spectroscopy to determine the chemical elements at its surface[†] and also their relative percentages, because the different gases absorb light at very particular wavelengths.

3 Why are stars round?

Stars form when clouds of gas and dust coalesce under the influence of gravity. While the original cloud can be of any shape, the coalescing gas will eventually take on a spherical shape because any protuberance in the outer layers will exert pressure on the inner ones and tend to sink inward.

In reality, however, stars are not usually perfectly spherical because most stars rotate, and centrifugal force causes them to bulge out at the equator and be slightly flattened at the poles, as has happened with Earth.

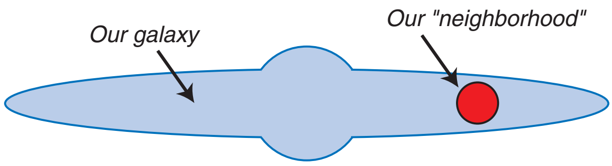


4 How many stars are there in the Galaxy?

Our galaxy, the Milky Way (Q. 153), contains literally billions of stars – far too many to be counted one by one. Even the latest computer programs for automated deep digital sky surveys cannot count all the stars in our galaxy. We cannot even see all of them with our most powerful telescopes because some are obscured by gas and dust and some are very faint. Besides that, our solar system is embedded in our galaxy, and trying to determine the total number of stars from inside it is like trying to count the buildings in a large city by looking out of a window in a downtown apartment: we can see the buildings on the other side of the street and make out the upper stories of others further away, but our view of most of the buildings is blocked by other structures or veiled by haze in the distance. We do not even accurately know the number of stars

[†] Spectroscopy is the analysis of the wavelengths that make up the light from an object. This is similar to using a prism to spread light from a lamp into its constituent colors. The distribution of light intensity across a range of wavelengths is called a *spectrum*.

in our own solar neighborhood, which only extends out about 330 light-years, whereas the diameter of the Galaxy is of the order of 100 000 light-years.

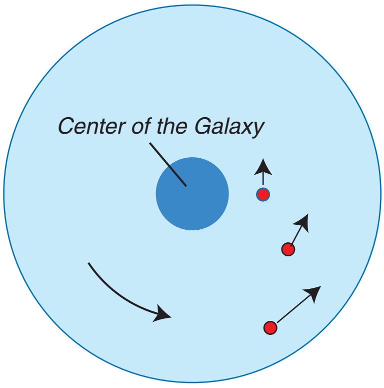


Our solar neighborhood is the region that we can see well enough to analyze. It represents only about 5% of the Galaxy.

Luckily, there are several ways to estimate the number of stars without having to count each one. One method involves first determining the overall brightness of our galaxy. Although things other than stars glow in the sky – luminescent gases and galaxies outside our own – their contribution to the brightness of the sky is small. We can then obtain the approximate number of stars by simply dividing the total brightness of the Galaxy by the average brightness of a star. How do we obtain the brightness of the Galaxy?

Our solar system is located about halfway along the radius of the Galaxy, meaning that we actually see a good part of the light emitted by the whole of it. Now, one of the best all sky images that we have comes from the Two Micron All Sky Survey (2MASS) in the infrared (Q. 154). Infrared light is similar to visible light but is lower in energy and usually associated with thermal emission (heat). One of the great advantages of infrared light is that it penetrates dust, "sees" further, and so provides us with a more complete picture. The value for the total brightness of the Galaxy derived from these infrared images is comparable to that for other galaxies similar to ours, confirming the validity of that measurement. As for the average luminosity of stars, we can obtain it by measuring the luminosity of stars in our own solar neighborhood whose distances we can evaluate, and thence derive their intrinsic luminosities (Q. 5).

A second estimate of the number of stars can be made by determining the mass of the Milky Way and dividing it by the mass of an average star. The mass of a galaxy can be determined from the influence of gravity on the gas, dust, and stars it contains. All the celestial bodies that make up the Galaxy rotate around the galactic center; and just as Newton's law of gravitational attraction allows us to calculate the movement of one body around another if we know the mass of the central body, we can determine the mass of the central body if we know the speed of rotation of a body in orbit around it.†



By this method we arrive at the total mass of the Galaxy, not only stars, but also interstellar dust and the invisible "dark matter" (Q. 148), so the result is an upper limit for the total mass of all stars.

† The force of gravitational attraction between two bodies of mass M and m separated by distance r is: $F = GM\,m/r^2$, where G is the gravitational constant. If the body of mass m revolves around the (larger) mass M, the force is $F = mv^2/r$. This "centrifugal" force is balanced by the force of gravity. Combining the two equations, we find that $M = v^2 r/G$. Thus, if we know the velocity, v, of mass m, we can determine M.

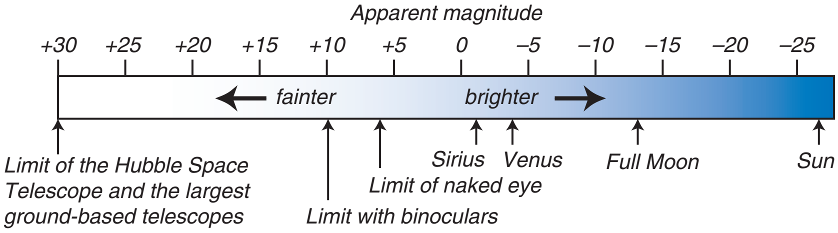
Both methods provide approximately the same result, namely that our galaxy contains about 100 billion stars (10^{11}).

5 How are the luminosities of stars measured?

Astronomy is a very old science, and in its earliest days the brightness of stars was estimated subjectively with the naked eye. It was the second century BC Greek astronomer Hipparchus who, as he was compiling the first star catalog in history (Q. 192),[†] devised the scale known as "magnitudes" to categorize stellar brightness. He established six categories, in which the stars in each category appear to be twice as bright as those in the previous one. The brightest stars were assigned a magnitude of 1, while magnitude 6 stars were barely visible to the naked eye.

With the advent of photographic plates and more recently, of electronic devices like those in digital cameras, we can now assess brightness objectively. For the sake of continuity, the magnitude scale has been retained, but it is now defined in physical instead of physiological terms. As it turns out, human perception of auditory and visual stimuli follows an approximately logarithmic law. For example, if we hear a series of sounds whose intensities actually vary as the progression 1, 2, 4, 8, 16, our brain interprets it as intensities progressing by 1, 2, 3, 4, 5. We judge the last sound to be five times louder when it is actually sixteen times louder.[‡] For this reason the decibel scale for sound intensity follows a logarithmic law.

Since the same type of perception also applies to the eye's reaction to light intensity, the magnitude system in use today defines the magnitude of a star as being proportional to the logarithm of its intensity, with the proportionality constant slightly adjusted so that the magnitude of visible stars roughly corresponds to the naked eye classification of Hipparchus.[§]



[†] An impressive feat for its time, his catalog contained relatively precise positions and apparent brightnesses for 850 stars.

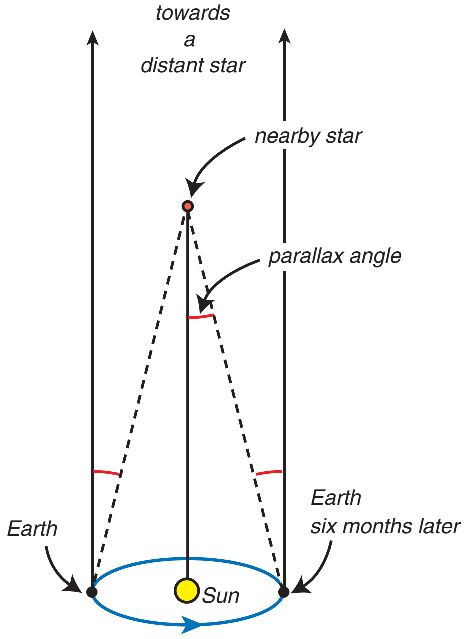
[‡] This sensory peculiarity evolved in man, and in mammals in general, because it is advantageous: senses can collect a much wider range of intensities if the response is logarithmic than if the perception is linear.

[§] In this system, two objects with apparent fluxes ϕ_1 and ϕ_2 measured in the same conditions (i.e. in the same wavelength), have the magnitudes m_1 and m_2 such that: $m_1 - m_2 = 2.5 \log \frac{\phi_2}{\phi_1}$. A difference of five magnitudes corresponds to a brightness ratio of 100, and a difference of 10 magnitudes to a brightness ratio of 10 000.

The above diagram provides some guidance. Note that Sirius, the brightest star in the sky, does not have a magnitude of 1, as per Hipparchus, but now has a negative magnitude (−1.4). The faintest objects we can observe with current large optical telescopes have a magnitude of 30, i.e. are 1000 billion times less luminous than the brightest stars. A telescope 10 m in diameter receives only a dozen photons per second from such objects and it requires hours of exposure to detect them accurately.

The magnitude system is counterintuitive because the fainter the star, the larger the magnitude number. Besides that, the magnitude of a star actually depends on the specific wavelength and bandwidth, i.e. the range of wavelengths, observed. So currently, the tendency is to use the more intuitive scale used in radio astronomy, the jansky, which is a measure of the energy received from a star (in watts) per unit of surface area (square meter) and of frequency observed (hertz).†

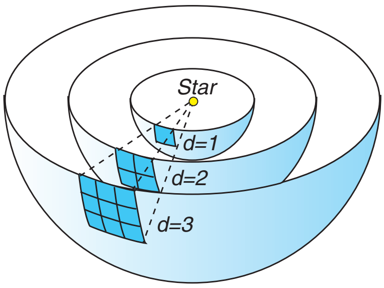
6 How are the distances to stars measured?



The nearest stars are so far away that we cannot hope to measure their distances by using radar, as we do for the Moon, but we can use the method that surveyors employ to determine the distance to a remote hilltop or church steeple. They measure the change in the direction of their landmark when viewed from two points separated by a known distance, called the base (Q. 79). With the two angles and the base length known, the triangle is completely determined and the distance to the object can be calculated. For stars, where the distances involved are so great, as long a base as possible must be used in order to obtain sufficient precision. And the longest base at our disposal is the diameter of the Earth's orbit.

The position of the target star is therefore observed relative to much more distant background stars at a certain time of year. Over the following six months, the Earth completes half an orbit around the Sun, creating a base line of approximately 300 million km. The star is then observed from this new vantage point, again relative to the background stars, and its apparent shift in position allows the determination of the star's distance as described above. The angle subtended by the radius of the Earth's orbit as seen from the star is called the *parallax*, and this stellar triangulation method bears the same name. If the parallax is 1 arcsecond (e.g. 1/3600 of a degree), the distance to the star is 3.26 light-years ($3 \cdot 10^{13}$km) which is called a *parsec* (Q. 7).

† A jansky, abbreviated Jy, is equal to 10^{-26} W m^{-2} Hz^{-1}.



A source of light such as a star illuminates an area that grows as the square of the distance, so the apparent luminosity of the star decreases as the inverse of the square of that distance.

This method works for distances up to about 500 light-years. Beyond that, the parallax is too small to be measured with current instruments. The best measures have been obtained from space by the Hipparcos satellite, which was able to determine the distance of stars up to 650 light-years away with an accuracy of 5%.

For more distant stars, we must turn to indirect methods, the most common being estimating a star's distance from its apparent brightness. Stars come in many types and colors, but it turns out that, in general, stars of the same color shine with the same intrinsic luminosity (Q. 14).† Since the apparent brightness of a light source decreases as the square of its distance, the distance of a star can be calculated from a comparison of its apparent brightness to its intrinsic brightness as estimated for its type. For example, if we find a star similar to the Sun, we can estimate its distance from its apparent brightness, since we know the intrinsic brightness of the Sun.

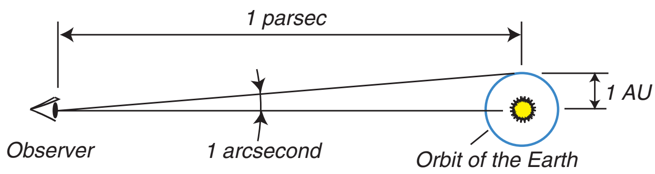
This method works best with a very special class of stars called "standard candles," whose intrinsic luminosity can be determined with great accuracy from characteristics other than color. A common example is the Cepheid variable, a class of stars whose intrinsic luminosities are related to their pulsation periods (Q. 18).

Unfortunately, measurements of stellar distances based on apparent brightness are affected by interstellar gas and dust that absorb some of the stars' light, thus making them appear dimmer than they actually are.

7 Parsecs? Light-years? Why not miles or kilometers?

The distance to the Moon, our closest neighbor in space, is 384 000 km, and to Alpha Centauri, the binary star nearest us, it is 41 500 000 000 000 km. Our minds can easily

† Astronomers make a subtle distinction between luminosity and brightness. The *luminosity* of a star is a measure of how bright it really is, while *apparent brightness* or just *brightness* is a measure of how bright it appears to us on Earth. More precisely, the luminosity of a star is the total amount of energy at all wavelengths and in all directions that it radiates per unit of time, and is expressed in watts, while apparent brightness is the amount of energy received per unit time and unit area and is expressed in W/m^2. To avoid possible confusion in this text, we generally qualify luminosity as *intrinsic luminosity*. Astronomers often express intrinsic luminosity in terms of magnitude, using the concept of *absolute magnitude*, which is by convention, the apparent magnitude a star would have if it were at a distance of 10 parsecs.



grasp the approximate magnitude of the first distance, but for the second, the long string of zeros baffles comprehension. We need something more compact and intuitive. We could always write such large numbers in scientific notation: $4.15 \cdot 10^{13}$ km, which is certainly more convenient for making calculations, but is still not very easy to grasp. This is why astronomers have adopted special units to describe cosmic distances.

Inside the solar system, the most convenient unit to use is the astronomical unit (AU), which is defined as the average distance from Earth to the Sun (Q. 43) and is about 150 million km. This unit works well in our home system: Neptune, for example, the most outlying planet, has an orbital diameter of 30 AU, and comets, in their vast orbits, travel to a maximum distance of 100 000 AU from the Sun.

For stars and galaxies, the most commonly used unit is the parsec (pc) and its multiples (kiloparsec and megaparsec). The parsec, which is an abbreviation for the words *parallax* and *arcsecond*, is the distance at which an object would be located if it had a parallax angle of 1 arcsecond, using a base distance equal to the radius of the Earth's orbit.

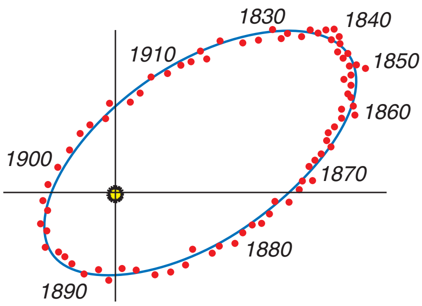
The advantage of using the parsec is that it is intrinsically connected to the method of measuring distances by parallax (Q. 6). If the parallax of a star is 1 arcsecond, its distance is 1 parsec (1 pc = $3.1 \cdot 10^{13}$ km). If the parallax is 10 times as small, or 0.1 arcsecond, the distance is 10 times greater, or 10 pc. For very great distances inside the Galaxy, we measure in thousands of parsecs, or kiloparsecs (kpc), and for distances to other galaxies, in millions of parsecs, or megaparsecs (Mpc). For example, the Sun is 8 kpc from the center of the Galaxy, and the Virgo cluster, the cluster of galaxies nearest us, is at 15 to 20 Mpc.

Another common unit is the light-year (LY), the distance traveled by light in one year (1 pc = 3.26 LY). It is a unit of distance, not of time as its name would suggest. It has the advantage of incorporating information on the age of distant objects. For example, if a galaxy is 1 billion LY away, we know that we are seeing the Galaxy as it was 1 billion years ago. The limit of the visible Universe is 13.7 billion LY (Q. 134). If we detected an object at this outer limit today, we would be seeing it as it was 13.7 billion years ago, i.e. almost at the birth of the Universe.

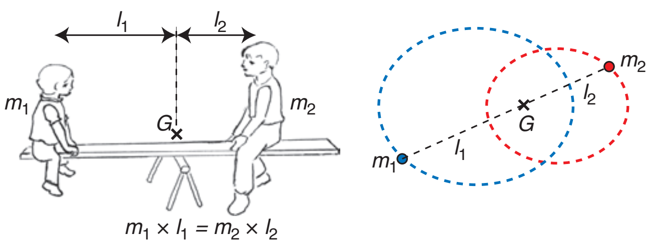
8 How are the masses of stars determined?

The light from a star brings us a great deal of information. From it we can infer the star's surface temperature, its diameter and chemical composition, but not its mass. The only way to determine the mass of a celestial body is to observe the effect of its gravitational pull on another object revolving around it. For example, observing the dance of satellites in orbit around a planet allows us to determine the planet's mass.

Since we cannot determine the mass of a star in isolation, it is fortunate for us that more than half of all stars are binaries. However, for a binary system to be useful to us, it must be a "visual binary" (Q. 17), that is to say that we must be able to *visually*



The orbit of the companion star of 70 Ophiuchi, with a period of 88 years.



distinguish the movements of both stars in order to map the orbit of one around the other.

The position of the stars in the sky are measured in terms of angles, so we must also determine the distance between Earth and the binary system in order to convert these angular measurements into actual distances between the two stars. This done, Kepler's third law then provides the sum of the two masses in the system (Q. 194).†

How do we obtain the mass of each of the two stars after determining the total mass of the system? In reality, one star does not revolve around the other; the two stars orbit around their common center of gravity (Q. 107). Their positions relative to the common center of gravity allows us to determine the ratio of their masses. For an analogy, imagine two children sitting on a seesaw. If they wish to stay in equilibrium, the heavier child must sit closer to the pivot. The distance of each child from the balance point is inversely proportional to the child's weight. Once we know the ratio of the masses of two stars and the sum of their masses, we can easily deduce the individual masses.

Unlike stellar diameters and luminosities which extend over a very wide range (one million and 10 billion times, respectively), the range of star masses is nowhere near that great, extending between about 1/15th and 150 times one solar mass. But even at the bottom of the scale a star has a lot of mass: the lightest stars are nearly 30 000 times more massive than Earth. True stars cannot exist with less than about 0.08 times the mass of the Sun because their gravity is insufficient to trigger nuclear fusion (Q. 1).

† Using the Sun/Earth system as reference, this law can be expressed as $m_1 + m_2 = a^3/P^2$ where m_1 and m_2 are the masses of two stars in Sun-mass units, a is the semi-major axis of the ellipse traveled by one of the stars around the other, expressed in astronomical units (the distance from Earth to the Sun – see Q. 43), and P is the period of revolution of the star in its orbit expressed in years.