

# Star

**Star**, any massive self-luminous celestial body of gas that shines by radiation derived from its internal energy sources. Of the tens of billions of trillions of stars composing the observable universe, only a very small percentage are visible to the naked eye. Many stars occur in pairs, multiple systems, or star clusters. The members of such stellar groups are physically related through common origin and are bound by mutual gravitational attraction. Somewhat related to star clusters are stellar associations, which consist of loose groups of physically similar stars that have insufficient mass as a group to remain together as an organization.

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**open cluster NGC 290**

Stars in the open cluster NGC 290, as seen by the Hubble Space Telescope.

*European Space Agency and NASA*

This article describes the properties and evolution of individual stars. Included in the discussion are the sizes, energetics, temperatures, masses, and chemical compositions of stars, as well as their distances and motions. The myriad other stars are compared with the Sun, strongly implying that “our” star is in no way special.

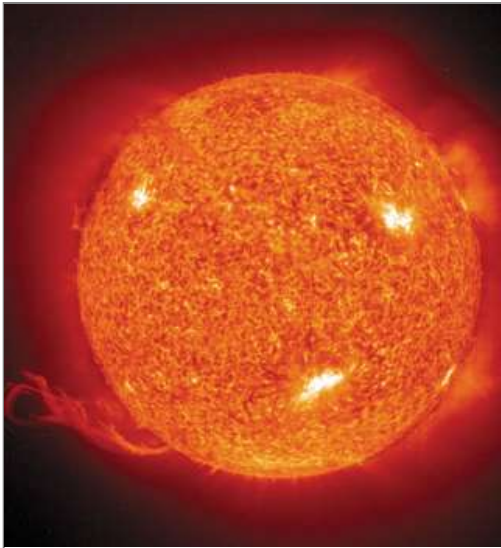
## General considerations

### The Sun as a point of comparison

#### Variations in stellar size

With regard to mass, size, and intrinsic brightness, the Sun is a typical star. Its approximate mass is  $2 \times 10^{30}$  kg (about 330,000 Earth masses), its approximate radius 700,000 km (430,000 miles), and its approximate luminosity  $4 \times 10^{33}$  ergs per second (or equivalently  $4 \times 10^{23}$  kilowatts of power). Other stars often have their respective quantities measured in terms of those of the Sun.

Many stars vary in the amount of light they radiate. Stars such as Altair, Alpha Centauri A and B, and Procyon A are called dwarf stars; their dimensions are roughly comparable to those of the Sun. Sirius A and Vega, though much brighter, also are dwarf stars; their higher temperatures yield a larger rate of emission per unit area. Aldebaran A, Arcturus, and Capella A are examples of giant stars, whose dimensions are much larger than those of the Sun. Observations with an interferometer (an instrument that measures the angle subtended by the diameter of a star at the observer’s position), combined with



The Sun as imaged in extreme ultraviolet light by the Earth-orbiting Solar and Heliospheric Observatory (SOHO) satellite. A massive loop-shaped eruptive prominence is visible at the lower left. Nearly white areas are the hottest; deeper reds indicate cooler temperatures.

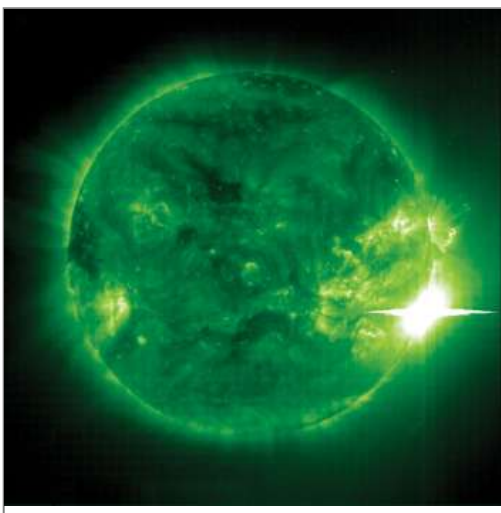
NASA

parallax measurements (which yield a star's distance; *see below* Determining stellar distances), give sizes of 12 and 22 solar radii for Arcturus and Aldebaran A. Betelgeuse and Antares A are examples of supergiant stars. The latter has a radius some 300 times that of the Sun, whereas the variable star Betelgeuse oscillates between roughly 300 and 600 solar radii. Several of the stellar class of white dwarf stars, which have low luminosities and high densities, also are among the brightest stars. Sirius B is a prime example, having a radius one-thousandth that of the Sun, which is comparable to the size of Earth. Also among the brightest stars are Rigel A, a young supergiant in the constellation Orion, and Canopus, a bright beacon in the Southern Hemisphere often used for spacecraft navigation.

## Stellar activity and mass loss

The Sun's activity is apparently not unique. It has been found that stars of many types are active and have stellar winds analogous to the solar wind. The importance and ubiquity of strong stellar winds became apparent only through advances in spaceborne ultraviolet and X-ray astronomy as well as in radio and infrared surface-based astronomy.

X-ray observations that were made during the early 1980s yielded some rather unexpected findings. They revealed that nearly all types of stars are surrounded by coronas having temperatures of one million kelvins (K) or more. Furthermore, all stars seemingly display active regions, including spots, flares, and prominences much like those of the Sun (*see* sunspot; solar flare; solar prominence). Some stars exhibit starspots so large that an entire face of the star is relatively dark, while others display flare activity thousands of times more intense than that on the Sun.



The highly luminous hot, blue stars have by far the strongest stellar winds. Observations of their ultraviolet spectra with telescopes on sounding rockets and spacecraft have shown that their wind speeds often reach 3,000 km (roughly 2,000 miles) per second, while losing mass at rates up to a billion times that of the solar wind. The corresponding mass-loss rates approach and sometimes exceed one hundred-thousandth of a solar mass per year, which means that one entire solar mass (perhaps a tenth of the total mass of the star) is carried away into space in a relatively short span of 100,000 years. Accordingly, the most

### **solar flare**

One of the strongest solar flares ever detected, in an extreme ultraviolet (false-colour) image of the Sun taken by the Solar and Heliospheric Observatory (SOHO) satellite, November 4, 2003. Such powerful flares, called X-class flares, release intense radiation that can temporarily cause blackouts in radio communications all over Earth.

SOHO/ESA/NASA

luminous stars are thought to lose substantial fractions of their mass during their lifetimes, which are calculated to be only a few million years.

Ultraviolet observations have proved that to produce such great winds the pressure of hot gases in a corona, which drives the solar wind, is not enough. Instead, the winds of the hot stars must be driven directly by the pressure of the energetic ultraviolet radiation emitted by these stars. Aside from the simple realization that copious quantities of ultraviolet radiation flow

from such hot stars, the details of the process are not well understood. Whatever is going on, it is surely complex, for the ultraviolet spectra of the stars tend to vary with time, implying that the wind is not steady. In an effort to understand better the variations in the rate of flow, theorists are investigating possible kinds of instabilities that might be peculiar to luminous hot stars.

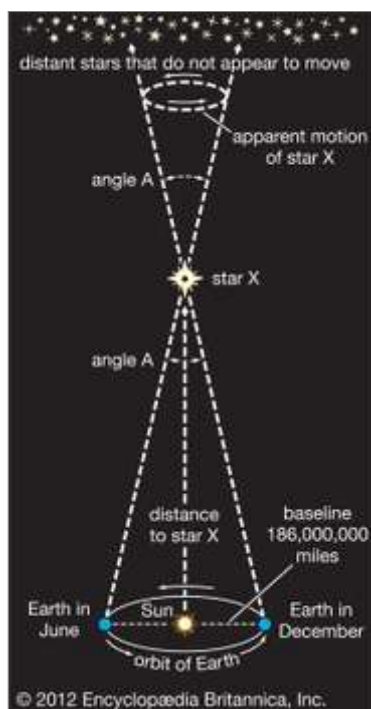
Observations made with radio and infrared telescopes as well as with optical instruments prove that luminous cool stars also have winds whose total mass-flow rates are comparable to those of the luminous hot stars, though their velocities are much lower—about 30 km (20 miles) per second. Because luminous red stars are inherently cool objects (having a surface temperature of about 3,000 K, or half that of the Sun), they emit very little detectable ultraviolet or X-ray radiation; thus, the mechanism driving the winds must differ from that in luminous hot stars. Winds from luminous cool stars, unlike those from hot stars, are rich in dust grains and molecules. Since nearly all stars more massive than the Sun eventually evolve into such cool stars, their winds, pouring into space from vast numbers of stars, provide a major source of new gas and dust in interstellar space, thereby furnishing a vital link in the cycle of star formation and galactic evolution. As in the case of the hot stars, the specific mechanism that drives the winds of the cool stars is not understood; at this time, investigators can only surmise that gas turbulence, magnetic fields, or both in the atmospheres of these stars are somehow responsible.

Strong winds also are found to be associated with objects called protostars, which are huge gas balls that have not yet become full-fledged stars in which energy is provided by nuclear reactions (*see below* Star formation and evolution). Radio and infrared observations of deuterium (heavy hydrogen) and carbon monoxide (CO) molecules in the Orion Nebula have revealed clouds of gas expanding outward at velocities approaching 100 km (60 miles) per second. Furthermore, high-resolution, very-long-baseline interferometry observations have disclosed expanding knots of natural maser (coherent microwave) emission of water vapour near the star-forming regions in Orion, thus linking the strong winds to the protostars themselves. The specific causes of these winds remain unknown, but if they generally accompany star formation, astronomers will have to consider the implications for the early solar system. After all, the Sun was presumably once a protostar too.

# Distances to the stars

## Determining stellar distances

Distances to stars were first determined by the technique of trigonometric parallax, a method still used for nearby stars. When the position of a nearby star is measured from two points on opposite sides of Earth's orbit (i.e., six months apart), a small angular (artificial) displacement is observed relative to a background of very remote (essentially fixed) stars. Using the radius of Earth's orbit as the baseline, the distance of the star can be found from the parallactic angle,  $p$ . If  $p = 1''$  (one second of arc), the distance of the star is 206,265 times Earth's distance from the Sun—namely, 3.26 light-years. This unit of distance is termed the parsec, defined as the distance of an object whose parallax equals one arc second. Therefore, one parsec equals 3.26 light-years. Since parallax is inversely proportional to distance, a star at 10 parsecs would have a parallax of  $0.1''$ . The nearest star to Earth, Proxima Centauri (a member of the triple system of Alpha Centauri), has a parallax of  $0.76813''$ , meaning that its distance is  $1/0.76813$ , or 1.302, parsecs, which equals 4.24 light-years. The parallax of Barnard's star, the next closest after the Alpha Centauri system, is  $0.54831''$ , so that its distance is nearly 6 light-years. Errors of such parallaxes are now typically  $0.001''$ . Thus, measurements of trigonometric parallaxes are useful for only the nearby stars within a few thousand light-years. In fact, of the approximately 100 billion stars in the Milky Way Galaxy (also simply called the Galaxy), the Hipparcos satellite has measured only about 100,000 to an accuracy of  $0.001''$ . For more distant stars, indirect methods are used; most of them depend on comparing the intrinsic brightness of a star (found, for example, from its spectrum or other observable property) with its apparent brightness.

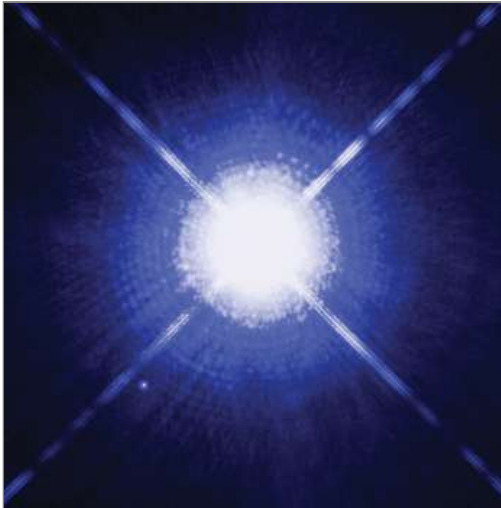


stellar distances

## Nearest stars

Only three stars, Alpha Centauri, Procyon, and Sirius, are both among the 20 nearest and among the 20 brightest stars. Ironically, most of the relatively nearby stars are dimmer than the Sun and are invisible without the aid of a telescope. By contrast, some of the well-known bright stars outlining the constellations have parallaxes as small as the limiting value of  $0.001''$  and are therefore well beyond several hundred light-years' distance from the Sun. The most luminous stars can be seen at great distances, whereas the intrinsically faint stars can be observed only if they are relatively close to Earth.

Although the lists of the brightest and the nearest stars pertain to only a very small number of stars, they nonetheless serve to illustrate some important points. The stars listed fall roughly into three categories: (1) giant stars and supergiant stars having sizes of tens or even hundreds of solar



### Sirius

Sirius A and B (lower left) photographed by the Hubble Space Telescope.

*NASA, ESA, H. Bond (STScI), and M. Barstow  
(University of Leicester)*

radii and extremely low average densities—in fact, several orders of magnitude less than that of water (one gram per cubic centimetre); (2) dwarf stars having sizes ranging from 0.1 to 5 solar radii and masses from 0.1 to about 10 solar masses; and (3) white dwarf stars having masses comparable to that of the Sun but dimensions appropriate to planets, meaning that their average densities are hundreds of thousands of times greater than that of water.

These rough groupings of stars correspond to stages in their life histories (*see below* Later stages of evolution). The second category is identified with what is called the main sequence (*see below* Hertzsprung-Russell diagram) and includes stars that emit energy mainly by converting hydrogen into helium in their cores. The first category comprises stars that have exhausted the hydrogen in their cores and are burning hydrogen within a shell surrounding the core. The white dwarfs represent the final stage in the life of a typical star, when most available sources of energy have been exhausted and the star has become relatively dim.

The large number of binary stars and even multiple systems is notable. These star systems exhibit scales comparable in size to that of the solar system. Some, and perhaps many, of the nearby single stars have invisible (or very dim) companions detectable by their gravitational effects on the primary star; this orbital motion of the unseen member causes the visible star to “wobble” in its motion through space. Some of the invisible companions have been found to have masses on the order of 0.001 solar mass or less, which is in the range of planetary rather than stellar dimensions. Current observations suggest that they are genuine planets, though some are merely extremely dim stars (sometimes called brown dwarfs). Nonetheless, a reasonable inference that can be drawn from these data is that double stars and planetary systems are formed by similar evolutionary processes.

## Stellar positions

### Basic measurements

Accurate observations of stellar positions are essential to many problems of astronomy. Positions of the brighter stars can be measured very accurately in the equatorial system (the coordinates of which are called right ascension [ $\alpha$ , or RA] and declination [ $\delta$ , or DEC] and are given for some epoch—for example, 1950.0 or, currently, 2000.0). Positions of fainter stars are measured by using electronic imaging devices (e.g., a charge-coupled device, or CCD) with respect to the brighter stars, and, finally, the entire group is

referred to the positions of known external galaxies. These distant galaxies are far enough away to define an essentially fixed, or immovable, system, whereas in the Milky Way the positions of both bright and faint stars are affected over relatively short periods of time by galactic rotation and by their own motions through the Galaxy.

## Stellar motions

Accurate measurements of position make it possible to determine the movement of a star across the line of sight (i.e., perpendicular to the observer)—its proper motion. The amount of proper motion, denoted by  $\mu$  (in arc seconds per year), divided by the parallax of the star and multiplied by a factor of 4.74 equals the tangential velocity,  $V_T$ , in kilometres per second in the plane of the celestial sphere.

The motion along the line of sight (i.e., toward the observer), called radial velocity, is obtained directly from spectroscopic observations. If  $\lambda$  is the wavelength of a characteristic spectral line of some atom or ion present in the star and  $\lambda_L$  is the wavelength of the same line measured in the laboratory, then the difference  $\Delta\lambda$ , or  $\lambda - \lambda_L$ , divided by  $\lambda_L$  equals the radial velocity,  $V_R$ , divided by the velocity of light,  $c$ —namely,  $\Delta\lambda/\lambda_L = V_R/c$ . Shifts of a spectral line toward the red end of the electromagnetic spectrum (i.e., positive  $V_R$ ) indicate recession, and those toward the blue end (negative  $V_R$ ) indicate approach (see Doppler effect; redshift). If the parallax is known, measurements of  $\mu$  and  $V_R$  enable a determination of the space motion of the star. Normally, radial velocities are corrected for Earth's rotation and for its motion around the Sun, so that they refer to the line-of-sight motion of the star with respect to the Sun.

Consider a pertinent example. The proper motion of Alpha Centauri is about 3.5 arc seconds, which, at a distance of 4.4 light-years, means that this star moves 0.00007 light-year in one year. It thus has a projected velocity in the plane of the sky of 22 km per second. (One kilometre is about 0.62 mile.) As for motion along the line of sight, Alpha Centauri's spectral lines are slightly blueshifted, implying a velocity of approach of about 20 km per second. The true space motion, equal to  $(22^2 + 20^2)^{1/2}$  or about 30 km per second, suggests that this star will make its closest approach to the Sun (at three light-years' distance) some 280 centuries from now.

## Light from the stars

### Stellar magnitudes

### Measuring starlight intensity

Stellar brightnesses are usually expressed by means of their magnitudes, a usage inherited from classical times. A star of the first magnitude is about 2.5 times as bright as one of the second magnitude, which in

turn is some 2.5 times as bright as one of the third magnitude, and so on. A star of the first magnitude is therefore  $2.5^5$  or 100 times as bright as one of the sixth magnitude. The magnitude of Sirius, which appears to an observer on Earth as the brightest star in the sky (save the Sun), is  $-1.4$ . Canopus, the second brightest, has a magnitude of  $-0.7$ , while the faintest star normally seen without the aid of a telescope is of the sixth magnitude. Stars as faint as the 30th magnitude have been measured with modern telescopes, meaning that these instruments can detect stars about four billion times fainter than can the human eye alone.

The scale of magnitudes comprises a geometric progression of brightness. Magnitudes can be converted to light ratios by letting  $I_n$  and  $I_m$  be the brightnesses of stars of magnitudes  $n$  and  $m$ ; the logarithm of the ratio of the two brightnesses then equals 0.4 times the difference between them—i.e.,  $\log(I_n / I_m) = 0.4(n - m)$ . Magnitudes are actually defined in terms of observed brightness, a quantity that depends on the light-detecting device employed. Visual magnitudes were originally measured with the eye, which is most sensitive to yellow-green light, while photographic magnitudes were obtained from images on old photographic plates, which were most sensitive to blue light. Today, magnitudes are measured electronically, using detectors such as CCDs equipped with yellow-green or blue filters to create conditions that roughly correspond to those under which the original visual and photographic magnitudes were measured. Yellow-green magnitudes are still often designated  $V$  magnitudes, but blue magnitudes are now designated  $B$ . The scheme has been extended to other magnitudes, such as ultraviolet ( $U$ ), red ( $R$ ), and near-infrared ( $I$ ). Other systems vary the details of this scheme. All magnitude systems must have a reference, or zero, point. In practice, this is fixed arbitrarily by agreed-upon magnitudes measured for a variety of standard stars.

The actually measured brightnesses of stars give apparent magnitudes. These cannot be converted to intrinsic brightnesses until the distances of the objects concerned are known. The absolute magnitude of a star is defined as the magnitude it would have if it were viewed at a standard distance of 10 parsecs (32.6 light-years). Since the apparent visual magnitude of the Sun is  $-26.75$ , its absolute magnitude corresponds to a diminution in brightness by a factor of  $(2,062,650)^2$  and is, using logarithms,  $-26.75 + 2.5 \times \log(2,062,650)^2$ , or  $-26.75 + 31.57 = 4.82$ . This is the magnitude that the Sun would have if it were at a distance of 10 parsecs—an object still visible to the naked eye, though not a very conspicuous one and certainly not the brightest in the sky. Very luminous stars, such as Deneb, Rigel, and Betelgeuse, have absolute magnitudes of  $-7$  to  $-9$ , while one of the faintest known stars, the companion to the star with the catalog name BD + 4°4048, has an absolute visual magnitude of  $+19$ , which is about a million times fainter than the Sun. Many astronomers suspect that large numbers of such faint stars exist, but most of these objects have so far eluded detection.

## Stellar colours

Stars differ in colour. Most of the stars in the constellation Orion visible to the naked eye are blue-white, most notably Rigel (Beta Orionis), but Betelgeuse (Alpha Orionis) is a deep red. In the telescope, Albireo (Beta Cygni) is seen as two stars, one blue and the other orange. One quantitative means of measuring stellar colours involves a comparison of the yellow (visual) magnitude of the star with its magnitude measured through a blue filter. Hot, blue stars appear brighter through the blue filter, while the opposite is true for cooler, red stars. In all magnitude scales, one magnitude step corresponds to a brightness ratio of 2.512. The zero point is chosen so that white stars with surface temperatures of about 10,000 K have the same visual and blue magnitudes. The conventional colour index is defined as the blue magnitude,  $B$ , minus the visual magnitude,  $V$ ; the colour index,  $B - V$ , of the Sun is thus  $+5.47 - 4.82 = 0.65$ .



**Orion**

The constellation Orion is one of the easiest to recognize because of a group of three stars. The three stars form a straight line that is often called Orion's Belt. The Orion Nebula can be seen as a pink fuzzy light below the line of three stars. The red star Betelgeuse is in the upper left, and the bright star Rigel is in the lower right.

*iStockphoto/Thinkstock*

## Magnitude systems

Problems arise when only one colour index is observed. If, for instance, a star is found to have, say, a  $B - V$  colour index of 1.0 (i.e., a reddish colour), it is impossible without further information to decide whether the star is red because it is cool or whether it is really a hot star whose colour has been reddened by the passage of light through interstellar dust. Astronomers have overcome these difficulties by measuring the magnitudes of the same stars through three or more filters, often  $U$  (ultraviolet),  $B$ , and  $V$  (see  $UBV$  system).

Observations of stellar infrared light also have assumed considerable importance. In addition, photometric observations of individual stars from spacecraft and rockets have made possible the measurement of stellar colours over a large range of wavelengths. These data are important for hot stars and for assessing the effects of interstellar attenuation.

## Bolometric magnitudes

The measured total of all radiation at all wavelengths from a star is called a bolometric magnitude. The corrections required to reduce visual magnitudes to bolometric magnitudes are large for very cool stars and for very hot ones, but they are relatively small

for stars such as the Sun. A determination of the true total luminosity of a star affords a measure of its actual energy output. When the energy radiated by a star is observed from Earth's surface, only that portion to which the energy detector is sensitive and that can be transmitted through the atmosphere is recorded. Most of the energy of stars like the Sun is emitted in spectral regions that can be observed from



Earth's surface. On the other hand, a cool dwarf star with a surface temperature of 3,000 K has an energy maximum on a wavelength scale at 10000 angstroms ( $\text{\AA}$ ) in the far-infrared, and most of its energy cannot therefore be measured as visible light. (One angstrom equals  $10^{-10}$  metre, or 0.1 nanometre.) Bright, cool stars can be observed at infrared wavelengths, however, with special instruments that measure the amount of heat radiated by the star. Corrections for the heavy absorption of the infrared waves by water and other molecules in Earth's air must be made unless the measurements are made from above the atmosphere.

The hotter stars pose more difficult problems, since Earth's atmosphere extinguishes all radiation at wavelengths shorter than 2900  $\text{\AA}$ . A star whose surface temperature is 20,000 K or higher radiates most of its energy in the inaccessible ultraviolet part of the electromagnetic spectrum. Measurements made with detectors flown in rockets or spacecraft extend the observable wavelength region down to 1000  $\text{\AA}$  or lower, though most radiation of distant stars is extinguished below 912  $\text{\AA}$ —a region in which absorption by neutral hydrogen atoms in intervening space becomes effective.

To compare the true luminosities of two stars, the appropriate bolometric corrections must first be added to each of their absolute magnitudes. The ratio of the luminosities can then be calculated.

## **Stellar spectra**

A star's spectrum contains information about its temperature, chemical composition, and intrinsic luminosity. Spectrograms secured with a slit spectrograph consist of a sequence of images of the slit in the light of the star at successive wavelengths. Adequate spectral resolution (or dispersion) might show the star to be a member of a close binary system, in rapid rotation, or to have an extended atmosphere. Quantitative determination of its chemical composition then becomes possible. Inspection of a high-resolution spectrum of the star may reveal evidence of a strong magnetic field.

## **Line spectrum**

Spectral lines are produced by transitions of electrons within atoms or ions. As the electrons move closer to or farther from the nucleus of an atom (or of an ion), energy in the form of light (or other radiation) is emitted or absorbed. The yellow D lines of sodium or the H and K lines of ionized calcium (seen as dark absorption lines) are produced by discrete quantum jumps from the lowest energy levels (ground states) of these atoms. The visible hydrogen lines (the so-called Balmer series; *see* spectral line series), however, are produced by electron transitions within atoms in the second energy level (or first excited state), which lies well above the ground level in energy. Only at high temperatures are sufficient numbers of atoms maintained in this state by collisions, radiations, and so forth to permit an appreciable number of absorptions to occur. At the low surface temperatures of a red dwarf star, few electrons populate the second level of hydrogen, and thus the hydrogen lines are dim. By contrast, at very high temperatures—

for instance, that of the surface of a blue giant star—the hydrogen atoms are nearly all ionized and therefore cannot absorb or emit any line radiation. Consequently, only faint dark hydrogen lines are observed. The characteristic features of ionized metals such as iron are often weak in such hotter stars because the appropriate electron transitions involve higher energy levels that tend to be more sparsely populated than the lower levels. Another factor is that the general “fogginess,” or opacity, of the atmospheres of these hotter stars is greatly increased, resulting in fewer atoms in the visible stellar layers capable of producing the observed lines.

The continuous (as distinct from the line) spectrum of the Sun is produced primarily by the photodissociation of negatively charged hydrogen ions ( $\text{H}^-$ )—i.e., atoms of hydrogen to which an extra electron is loosely attached. In the Sun’s atmosphere, when  $\text{H}^-$  is subsequently destroyed by photodissociation, it can absorb energy at any of a whole range of wavelengths and thus produce a continuous range of absorption of radiation. The main source of light absorption in the hotter stars is the photoionization of hydrogen atoms, both from ground level and from higher levels.

## **Spectral analysis**

The physical processes behind the formation of stellar spectra are well enough understood to permit determinations of temperatures, densities, and chemical compositions of stellar atmospheres. The star studied most extensively is, of course, the Sun, but many others also have been investigated in detail.

The general characteristics of the spectra of stars depend more on temperature variations among the stars than on their chemical differences. Spectral features also depend on the density of the absorbing atmospheric matter, and density in turn is related to a star’s surface gravity. Dwarf stars, with great surface gravities, tend to have high atmospheric densities; giants and supergiants, with low surface gravities, have relatively low densities. Hydrogen absorption lines provide a case in point. Normally, an undisturbed atom radiates a very narrow line. If its energy levels are perturbed by charged particles passing nearby, it radiates at a wavelength near its characteristic wavelength. In a hot gas, the range of disturbance of the hydrogen lines is very high, so that the spectral line radiated by the whole mass of gas is spread out considerably; the amount of blurring depends on the density of the gas in a known fashion. Dwarf stars such as Sirius show broad hydrogen features with extensive “wings” where the line fades slowly out into the background, while supergiant stars, with less-dense atmospheres, display relatively narrow hydrogen lines.

## **Classification of spectral types**

Most stars are grouped into a small number of spectral types. The *Henry Draper Catalogue* and the *Bright Star Catalogue* list spectral types from the hottest to the coolest stars (see stellar classification). These types are designated, in order of decreasing temperature, by the letters O, B, A, F, G, K, and M. This

group is supplemented by R- and N-type stars (today often referred to as carbon, or C-type, stars) and S-type stars. The R-, N-, and S-type stars differ from the others in chemical composition; also, they are invariably giant or supergiant stars. With the discovery of brown dwarfs—objects that form like stars but do not shine through thermonuclear fusion—the system of stellar classification has been expanded to include spectral types L, T, and Y.

The spectral sequence O through M represents stars of essentially the same chemical composition but of different temperatures and atmospheric pressures. This simple interpretation, put forward in the 1920s by the Indian astrophysicist Meghnad N. Saha, has provided the physical basis for all subsequent interpretations of stellar spectra. The spectral sequence is also a colour sequence: the O- and B-type stars are intrinsically the bluest and hottest; the M-, R-, N-, and S-type stars are the reddest and coolest.

In the case of cool stars of type M, the spectra indicate the presence of familiar metals, including iron, calcium, magnesium, and also titanium oxide molecules (TiO), particularly in the red and green parts of the spectrum. In the somewhat hotter K-type stars, the TiO features disappear, and the spectrum exhibits a wealth of metallic lines. A few especially stable fragments of molecules such as cyanogen (CN) and the hydroxyl radical (OH) persist in these stars and even in G-type stars such as the Sun. The spectra of G-type stars are dominated by the characteristic lines of metals, particularly those of iron, calcium, sodium, magnesium, and titanium.

The behaviour of calcium illustrates the phenomenon of thermal ionization. At low temperatures a calcium atom retains all of its electrons and radiates a spectrum characteristic of the neutral, or normal, atom; at higher temperatures collisions between atoms and electrons and the absorption of radiation both tend to detach electrons and to produce singly ionized calcium atoms. At the same time, these ions can recombine with electrons to produce neutral calcium atoms. At high temperatures or low electron pressures, or both, most of the atoms are ionized. At low temperatures and high densities, the equilibrium favours the neutral state. The concentrations of ions and neutral atoms can be computed from the temperature, the density, and the ionization potential (namely, the energy required to detach an electron from the atom).

The absorption line of neutral calcium at  $4227 \text{ \AA}$  is thus strong in cool M-type dwarf stars, in which the pressure is high and the temperature is low. In the hotter G-type stars, however, the lines of ionized calcium at  $3968$  and  $3933 \text{ \AA}$  (the H and K lines) become much stronger than any other feature in the spectrum.

In stars of spectral type F, the lines of neutral atoms are weak relative to those of ionized atoms. The hydrogen lines are stronger, attaining their maximum intensities in A-type stars, in which the surface temperature is about  $9,000 \text{ K}$ . Thereafter, these absorption lines gradually fade as the hydrogen becomes ionized.

The hot B-type stars, such as Epsilon Orionis, are characterized by lines of helium and of singly ionized oxygen, nitrogen, and neon. In very hot O-type stars, lines of ionized helium appear. Other prominent features include lines of doubly ionized nitrogen, oxygen, and carbon and of triply ionized silicon, all of which require more energy to produce.

In the more modern system of spectral classification, called the MK system (after the American astronomers William W. Morgan and Philip C. Keenan, who introduced it), luminosity class is assigned to the star along with the Draper spectral type. For example, the star Alpha Persei is classified as F5 Ib, which means that it falls about halfway between the beginning of type F (i.e., F0) and of type G (i.e., G0). The Ib suffix means that it is a moderately luminous supergiant. The star Pi Cephei, classified as G2 III, is a giant falling between G0 and K0 but much closer to G0. The Sun, a dwarf star of type G2, is classified as G2 V. A star of luminosity class II falls between giants and supergiants; one of class IV is called a subgiant.

## Bulk stellar properties

### Stellar temperatures

Temperatures of stars can be defined in a number of ways. From the character of the spectrum and the various degrees of ionization and excitation found from its analysis, an ionization or excitation temperature can be determined.

A comparison of the  $V$  and  $B$  magnitudes (*see above* Stellar colours) yields a  $B - V$  colour index, which is related to the colour temperature of the star. The colour temperature is therefore a measure of the relative amounts of radiation in two more or less broad wavelength regions, while the ionization and excitation temperatures pertain to the temperatures of strata wherein spectral lines are formed.

Provided that the angular size of a star can be measured (*see below* Stellar radii) and that the total energy flux received at Earth (corrected for atmospheric extinction) is known, the so-called brightness temperature can be found.

The effective temperature,  $T_{eff}$ , of a star is defined in terms of its total energy output and radius. Thus, since  $\sigma T_{eff}^4$  is the rate of radiation per unit area for a perfectly radiating sphere and if  $L$  is the total radiation (i.e., luminosity) of a star considered to be a sphere of radius  $R$ , such a sphere (called a blackbody) would emit a total amount of energy equal to its surface area,  $4\pi R^2$ , multiplied by its energy per unit area. In symbols,  $L = 4\pi R^2 \sigma T_{eff}^4$ . This relation defines the star's equivalent blackbody, or effective, temperature.

Since the total energy radiated by a star cannot be directly observed (except in the case of the Sun), the effective temperature is a derived quantity rather than an observed one. Yet, theoretically, it is the fundamental temperature. If the bolometric corrections are known, the effective temperature can be found for any star whose absolute visual magnitude and radius are known. Effective temperatures are closely related to spectral type and range from about 40,000 K for hot O-type stars, through 5,800 K for stars like the Sun, to about 300 K for brown dwarfs.

## Stellar masses

Masses of stars can be found directly only from binary systems and only if the scale of the orbits of the stars around each other is known. Binary stars are divided into three categories, depending on the mode of observation employed: visual binaries, spectroscopic binaries, and eclipsing binaries.

### Visual binaries

Visual binaries can be seen as double stars with the telescope. True doubles, as distinguished from apparent doubles caused by line-of-sight effects, move through space together and display a common space motion. Sometimes a common orbital motion can be measured as well. Provided that the distance to the binary is known, such systems permit a determination of stellar masses,  $m_1$  and  $m_2$ , of the two members. The angular radius,  $a''$ , of the orbit (more accurately, its semimajor axis) can be measured directly, and, with the distance known, the true dimensions of the semimajor axis,  $a$ , can be found. If  $a$  is expressed in astronomical units, which is given by  $a$  (measured in seconds of arc) multiplied by the distance in parsecs, and the period,  $P$ , also measured directly, is expressed in years, then the sum of the masses of the two orbiting stars can be found from an application of Kepler's third law. (An astronomical unit is the average distance from Earth to the Sun, 149,597,870.7 km [92,955,807.3 miles].) In symbols,  $(m_1 + m_2) = a^3 / P^2$  in units of the Sun's mass. For example, for the binary system 70 Ophiuchi,  $P$  is 87.8 years, and the distance is 5.0 parsecs; thus,  $a$  is 22.8 astronomical units, and  $m_1 + m_2 = 1.56$  solar masses. From a measurement of the motions of the two members relative to the background stars, the orbit of each star has been determined with respect to their common centre of gravity. The mass ratio,  $m_2 / (m_1 + m_2)$ , is 0.42; the individual masses for  $m_1$  and  $m_2$ , respectively, are then 0.90 and 0.66 solar mass.

The star known as 61 Cygni was the first whose distance was measured (via parallax by the German astronomer Friedrich W. Bessel in the mid-19th century). Visually, 61 Cygni is a double star separated by 83.2 astronomical units. Its members move around one another with a period of 653 years. It was among the first stellar systems thought to contain a potential planet, although this has not been confirmed and is now considered unlikely. Nevertheless, since the 1990s a variety of discovery techniques have confirmed

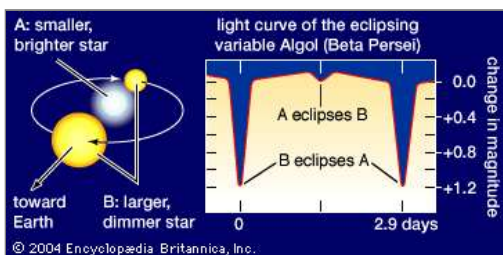
the existence of thousands of planets orbiting other stars (*see below* Binaries and extrasolar planetary systems).

## Spectroscopic binaries

Spectroscopic binary stars are found from observations of radial velocity. At least the brighter member of such a binary can be seen to have a continuously changing periodic velocity that alters the wavelengths of its spectral lines in a rhythmic way; the velocity curve repeats itself exactly from one cycle to the next, and the motion can be interpreted as orbital motion. In some cases, rhythmic changes in the lines of both members can be measured. Unlike visual binaries, the semimajor axes or the individual masses cannot be found for most spectroscopic binaries, since the angle between the orbit plane and the plane of the sky cannot be determined. If spectra from both members are observed, mass ratios can be found. If one spectrum alone is observed, only a quantity called the mass function can be derived, from which is calculated a lower limit to the stellar masses. If a spectroscopic binary is also observed to be an eclipsing system, the inclination of the orbit and often the values of the individual masses can be ascertained.

## Eclipsing binaries

An eclipsing binary consists of two close stars moving in an orbit so placed in space in relation to Earth that the light of one can at times be hidden behind the other. Depending on the orientation of the orbit and sizes of the stars, the eclipses can be total or annular (in the latter, a ring of one star shows behind the other at the maximum of the eclipse) or both eclipses can be partial. The best known example of an eclipsing binary is Algol (Beta Persei), which has a period (interval between eclipses) of 2.9 days. The brighter (B8-type) star contributes about 92 percent of the light of the system, and the eclipsed star provides less than 8 percent. The system contains a third star that is not eclipsed. Some 20 eclipsing binaries are visible to the naked eye.



Light curve of Algol (Beta Persei), an eclipsing variable, or eclipsing binary, star system. The relative brightness of the system is plotted against time. A sharp dip occurs every 2.9 days when the fainter component star eclipses the brighter one, a shallower dip when the brighter star eclipses the fainter one.

*Encyclopædia Britannica, Inc.*

The light curve for an eclipsing binary displays magnitude measurements for the system over a complete light cycle. The light of the variable star is usually compared with that of a nearby (comparison) star thought to be fixed in brightness. Often, a deep, or primary, minimum is produced when the component having the higher surface brightness is eclipsed. It represents the total eclipse and is characterized by a flat bottom. A shallower secondary eclipse occurs when the brighter component passes in front of the other; it corresponds to an annular eclipse (or transit). In a partial eclipse neither star is ever completely hidden, and the light changes continuously during an eclipse.

The shape of the light curve during an eclipse gives the ratio of the radii of the two stars and also one radius in terms of the size of the orbit, the ratio of luminosities, and the inclination of the orbital plane to the plane of the sky.

If radial-velocity curves are also available—i.e., if the binary is spectroscopic as well as eclipsing—additional information can be obtained. When both velocity curves are observable, the size of the orbit as well as the sizes, masses, and densities of the stars can be calculated. Furthermore, if the distance of the system is measurable, the brightness temperatures of the individual stars can be estimated from their luminosities and radii. All of these procedures have been carried out for the faint binary Castor C (two red-dwarf components of the six-member Castor multiple star system) and for the bright B-type star Mu Scorpii.

Close stars may reflect each other's light noticeably. If a small, high-temperature star is paired with a larger object of low surface brightness and if the distance between the stars is small, the part of the cool star facing the hotter one is substantially brightened by it. Just before (and just after) secondary eclipse, this illuminated hemisphere is pointed toward the observer, and the total light of the system is at a maximum.

The properties of stars derived from eclipsing binary systems are not necessarily applicable to isolated single stars. Systems in which a smaller, hotter star is accompanied by a larger, cooler object are easier to detect than are systems that contain, for example, two main-sequence stars (*see below* Hertzsprung-Russell diagram). In such an unequal system, at least the cooler star has certainly been affected by evolutionary changes, and probably so has the brighter one. The evolutionary development of two stars near one another does not exactly parallel that of two well-separated or isolated ones.

Eclipsing binaries include combinations of a variety of stars ranging from white dwarfs to huge supergiants (e.g., VV Cephei), which would engulf Jupiter and all the inner planets of the solar system if placed at the position of the Sun.

Some members of eclipsing binaries are intrinsic variables, stars whose energy output fluctuates with time (*see below* Variable stars). In many such systems, large clouds of ionized gas swirl between the stellar members. In others, such as Castor C, at least one of the faint M-type dwarf components might be a flare star, one in which the brightness can unpredictably and suddenly increase to many times its normal value (*see below* Peculiar variables).

## **Binaries and extrasolar planetary systems**

Near the Sun, most stars are members of binaries, and many of the nearest single stars are suspected of having companions. Although some binary members are separated by hundreds of astronomical units

and others are contact binaries (stars close enough for material to pass between them), binary systems are most frequently built on the same scale as that of the solar system—namely, on the order of about 10 astronomical units. The division in mass between two components of a binary seems to be nearly random. A mass ratio as small as about 1:20 could occur about 5 percent of the time, and under these circumstances a planetary system comparable to the solar system is able to form.

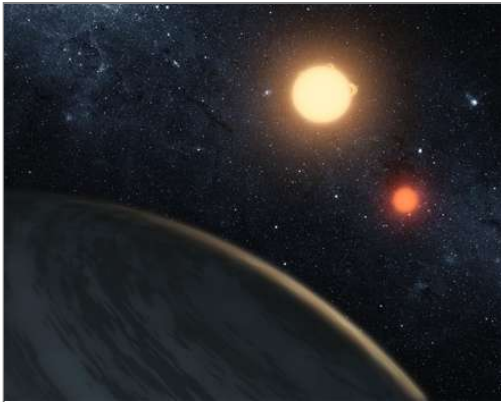
The formation of double and multiple stars on the one hand and that of planetary systems on the other seem to be different facets of the same process. Planets are probably produced as a natural by-product of star formation. Only a small fraction of the original nebula matter is likely to be retained in planets, since much of the mass and angular momentum is swept out of the system. Conceivably, as many as 100 million stars could have bona fide planets in the Milky Way Galaxy.

Individual planets around other stars—i.e., extrasolar planets—are very difficult to observe directly because a star is always much brighter than its attendant planet. Jupiter, for example, would be only one-billionth as bright as the Sun and appear so close to it as to be undetectable from even the nearest star. If candidate stars are treated as possible spectroscopic binaries, however, then one may look for a periodic change in the star's radial velocity caused by a planet swinging around it. The effect is very small: even Jupiter would cause a change in the apparent radial velocity of the Sun of only about 10 metres (33 feet) per second spread over Jupiter's orbital period of about 12 years at best. Current techniques using very large telescopes to study fairly bright stars can measure radial velocities with a precision of about a metre per second, provided that the star has very sharp spectral lines, such as is observed for Sun-like stars and stars of types K and M. This means that at present the radial-velocity method normally can detect planets like Earth around M-type stars. Moreover, the closer the planet is to its parent star, the greater and quicker the velocity swing, so that detection of giant planets close to a star is favoured over planets farther out. Finally, even when a planet is detected, the usual spectroscopic binary problem of not knowing the angle between the orbit plane and that of the sky allows only a minimum mass to be assigned to the planet.

One exception to this last problem is HD 209458, a seventh-magnitude G0 V star about 150 light-years away with a planetary object orbiting it every 3.5 days. Soon after the companion, HD 209458b, was discovered in 1999 by its effect on the star's radial velocity, it also was found to be eclipsing the star, meaning that its orbit is oriented almost edge-on toward Earth. This type of eclipse is called a transit, and this method has been used, most notably by the Kepler satellite, to find thousands of extrasolar planets. Some of these planets are roughly the size of Earth and can be found in their star's habitable zone, the distance from a star where liquid water, and thus possibly life, can survive on the surface.

This transit of HD 209458b, as well as observations of spectral lines in the planet's atmosphere, allowed determination of the planet's mass and radius—0.64 and 1.38 times those of Jupiter, respectively. These numbers imply that the planet is even more of a giant than Jupiter itself. What was unexpected is its





### extrasolar planet Kepler-16b

The first planet found to orbit two stars, Kepler-16b (artist's conception).

*T. Pyle—JPL-Caltech/NASA*

proximity to the parent star—more than 100 times closer than Jupiter is to the Sun, raising the question of how a giant gaseous planet that close can survive the star's radiation. The fact that many other extrasolar planets have been found to have orbital periods measured in days rather than years, and thus to be very close to their parent stars, suggests that the HD 209458 case is not unusual. There are also some confirmed cases of planets around supernova remnants called pulsars, although whether the planets preceded the supernova explosions that produced the pulsars or were acquired afterward remains to be determined.

The first extrasolar planets were discovered in 1992. Thousands of extrasolar planets are known, with more such discoveries being added regularly.

In addition to the growing evidence for existence of extrasolar planets, space-based observatories designed to detect infrared radiation have found many young stars (including Vega, Fomalhaut, and Beta Pictoris) to have disks of warm matter orbiting them. This matter is composed of myriad particles mostly about the size of sand grains and might be taking part in the first stage of planetary formation.



The infrared emission from the young star Fomalhaut and the dust belt surrounding it, as recorded with the European Space Agency's satellite observatory Herschel.

*ESA/Herschel/PACS/Bram Acke, KU Leuven, Belgium*

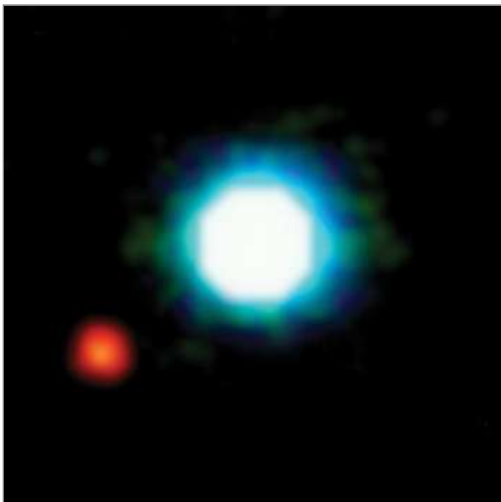
## Mass extremes

The mass of most stars lies within the range of 0.3 to 3 solar masses. The star with the largest mass determined to date is R136a1, a giant of about 265 solar masses that had as much as 320 solar masses when it was formed. There is a theoretical upper limit to the masses of nuclear-burning stars (the Eddington limit), which limits stars to no more than a few hundred solar masses. On the low mass side, most stars seem to have at least 0.1 solar mass. The theoretical lower mass limit for an ordinary star is about 0.075 solar mass, for below this value an object cannot attain a central temperature high enough to enable it to shine by nuclear energy. Instead, it may produce a much lower level of energy by gravitational shrinkage. If its mass is not much below the critical 0.075 solar mass value, it will appear as a very cool, dim star known as a brown dwarf. Its evolution is simply to continue cooling toward eventual extinction. At still somewhat

lower masses, the object would be a giant planet. Jupiter, with a mass roughly 0.001 that of the Sun, is

just such an object, emitting a very low level of energy (apart from reflected sunlight) that is derived from gravitational shrinkage.

Brown dwarfs were late to be discovered, the first unambiguous identification having been made in 1995. It is estimated, however, that hundreds must exist in the solar neighbourhood. An extension of the spectral sequence for objects cooler than M-type stars has been constructed, using L for warmer brown dwarfs, T for cooler ones, and Y for the coolest. The presence of methane in the T brown dwarfs and of ammonia in the Y brown dwarfs emphasizes their similarity to giant planets.



The brown dwarf 2MASSWJ 1207334-393254 (centre) as seen in a photo taken by the Very Large Telescope at the European Southern Observatory, Cerro Paranal, Chile. The brown dwarf has a mass 25 times that of Jupiter and a surface temperature of 2,400 K. Orbiting the brown dwarf at a distance of 8.3 billion km (5.2 billion miles) is a planet (lower left) that has a mass five times that of Jupiter and a surface temperature of 1,250 K.

*ESO*

## Stellar radii

Angular sizes of bright red giant and supergiant stars were first measured directly during the 1920s, using the principle of interference of light. Only bright stars with large angular size can be measured by this method. Provided the distance to the star is known, the physical radius can be determined.

Eclipsing binaries also provide extensive data on stellar dimensions. The timing of eclipses provides the angular size of any occulting object, and so analyzing the light curves of eclipsing binaries can be a useful means of determining the dimensions of either dwarf or giant stars. Members of close binary systems, however, are sometimes subject to evolutionary effects, mass exchange, and other disturbances that change the details of their spectra.

A more recent method, called speckle interferometry, has been developed to reproduce the true disks of red supergiant stars and to resolve spectroscopic binaries such as Capella. The speckle phenomenon is a rapidly changing interference-diffraction effect seen in a highly magnified diffraction image of a

star observed with a large telescope.

If the absolute magnitude of a star and its temperature are known, its size can be computed. The temperature determines the rate at which energy is emitted by each unit of area, and the total luminosity gives the total power output. Thus, the surface area of the star and, from it, the radius of the object can be estimated. This is the only way available for estimating the dimensions of white dwarf stars. The chief uncertainty lies in choosing the temperature that represents the rate of energy emission.

## Average stellar values

Main-sequence stars range from very luminous objects to faint M-type dwarf stars, and they vary considerably in their surface temperatures, their bolometric (total) luminosities, and their radii. Moreover, for stars of a given mass, a fair spread in radius, luminosity, surface temperature, and spectral type may exist. This spread is produced by stellar evolutionary effects and tends to broaden the main sequence. Masses are obtained from visual and eclipsing binary systems observed spectroscopically. Radii are found from eclipsing binary systems, from direct measurements in a few favourable cases, by calculations, and from absolute visual magnitudes and temperatures.

Average values for radius, bolometric luminosity, and mass are meaningful only for dwarf stars. Giant and subgiant stars all show large ranges in radius for a given mass. Conversely, giant stars of very nearly the same radius, surface temperature, and luminosity can have appreciably different masses.

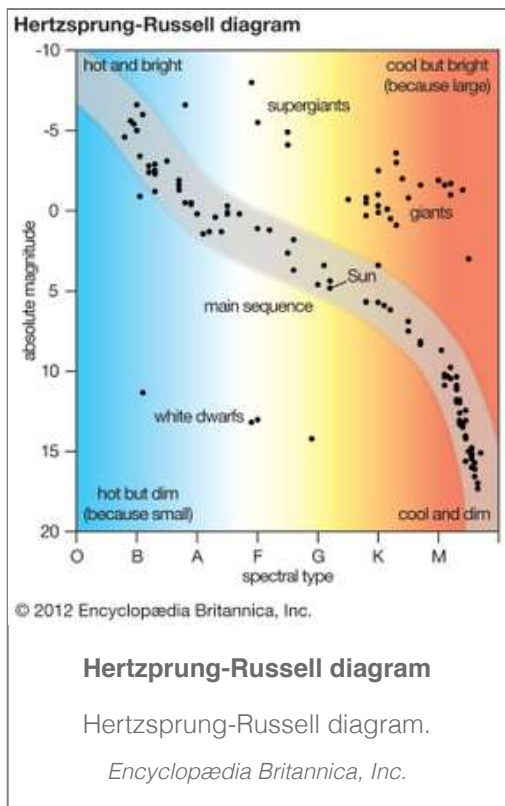
## Stellar statistics

Some of the most important generalizations concerning the nature and evolution of stars can be derived from correlations between observable properties and from certain statistical results. One of the most important of these correlations concerns temperature and luminosity—or, equivalently, colour and magnitude.

## Hertzsprung-Russell diagram

When the absolute magnitudes of stars, or their intrinsic luminosities on a logarithmic scale, are plotted in a diagram against temperature or, equivalently, against the spectral types, the stars do not fall at random on the diagram but tend to congregate in certain restricted domains. Such a plot is usually called a Hertzsprung-Russell diagram, named for the early 20th-century astronomers Ejnar Hertzsprung of Denmark and Henry Norris Russell of the United States, who independently discovered the relations shown in it. As is seen in the diagram, most of the congregated stars are dwarfs lying closely around a diagonal line called the main sequence. These stars range from hot, O- and B-type, blue objects at least 10,000 times brighter than the Sun down through white A-type stars such as Sirius to orange K-type stars such as Epsilon Eridani and finally to M-type red dwarfs thousands of times fainter than the Sun. The sequence is continuous; the luminosities fall off smoothly with decreasing surface temperature; the masses and radii decrease but at a much slower rate; and the stellar densities gradually increase.

The second group of stars to be recognized was a group of giants—such objects as Capella, Arcturus, and Aldebaran—which are yellow, orange, or red stars about 100 times as bright as the Sun and have radii on the order of 10–30 million km (about 6–20 million miles, or 15–40 times as large as the Sun). The giants lie above the main sequence in the upper right portion of the diagram. The category of supergiants includes stars of all spectral types; these stars show a large spread in intrinsic brightness, and some even



approach absolute magnitudes of  $-7$  or  $-8$ . A few red supergiants, such as the variable star VV Cephei, exceed in size the orbit of Jupiter or even that of Saturn, although most of them are smaller. Supergiants are short-lived and rare objects, but they can be seen at great distances because of their tremendous luminosity.

Subgiants are stars that are redder and larger than main-sequence stars of the same luminosity. Many of the best-known examples are found in close binary systems where conditions favour their detection.

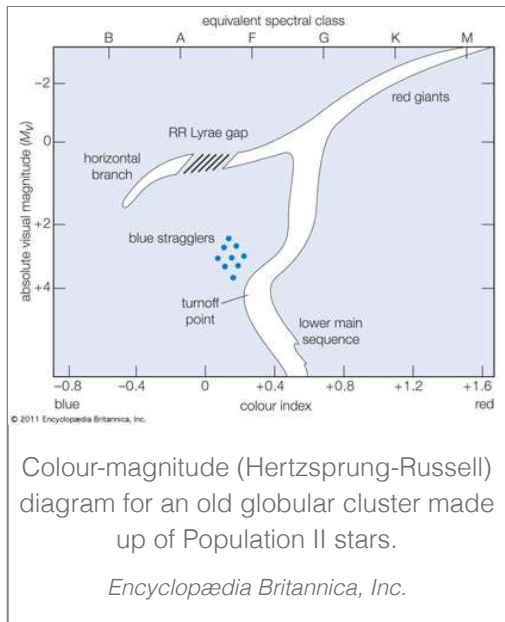
The white dwarf domain lies about 10 magnitudes below the main sequence. These stars are in the last stages of their evolution (*see below* End states of stars).

The spectrum-luminosity diagram has numerous gaps. Few stars exist above the white dwarfs and to the left of the main

sequence. The giants are separated from the main sequence by a gap named for Hertzsprung, who in 1911 became the first to recognize the difference between main-sequence and giant stars. The actual concentration of stars differs considerably in different parts of the diagram. Highly luminous stars are rare, whereas those of low luminosity are very numerous.

The spectrum-luminosity diagram applies to the stars in the galactic spiral arm in the neighbourhood of the Sun and represents what would be obtained if a composite Hertzsprung-Russell diagram were constructed combining data for a large number of the star groups called open (or galactic) star clusters, as, for example, the double cluster  $h$  and  $\chi$  Persei, the Pleiades, the Coma cluster, and the Hyades. It includes very young stars, a few million years old, as well as ancient stars perhaps as old as 10 billion years.

By contrast, another Hertzsprung-Russell diagram exhibits the type of temperature-luminosity, or colour-magnitude, relation characteristic of stars in globular clusters, in the central bulge of the Galaxy, and in elliptical external galaxies—namely, of the so-called stellar Population II. (In addition to these oldest objects, Population II includes other very old stars that occur between the spiral arms of the Galaxy and at some distance above and below the galactic plane.) Because these systems are very remote from the observer, the stars are faint, and their spectra can be observed only with difficulty. As a consequence, their colours rather than their spectra must be measured. Since the colours are closely related to surface temperature and therefore to spectral types, equivalent spectral types may be used, but it is stellar colours, not spectral types, that are observed in this instance (*see colour-magnitude diagram*).



The differences between the two Hertzsprung-Russell diagrams are striking. In the second there are no supergiants, and, instead of a domain at an absolute magnitude of about 0, the giant stars form a branch that starts high and to the right at about  $-3.5$  for very red stars and flows in a continuous sequence until it reaches an absolute magnitude of about 0. At that point the giant branch splits: a main band of stars, all about the same colour, proceeds downward (i.e., to fainter stars) to a magnitude of about  $+3$  and then connects to the main sequence at about  $+4$  by way of a narrow band. The main sequence of Population II stars extends downward to fainter, redder stars in much the same way as in the spiral-arm Population I stars. (Population I is the name given to the stars found within the spiral arms of the

Milky Way system and other galaxies of the same type. Containing stars of all ages, from those in the process of formation to defunct white dwarfs, Population I is nonetheless always associated with the gas and dust of the interstellar medium.) The main sequence ends at about spectral type G, however, and does not extend up through the A, B, and O spectral types, though occasionally a few such stars, blue stragglers, are found in the region normally occupied by the main sequence. The blue stragglers are likely red stars that have gained mass from another star through stellar collision or mass transfer.

The other band of stars formed from the split of the giant branch is the “horizontal branch,” which falls near magnitude  $+0.6$  and fills the aforementioned Hertzsprung gap, extending to increasingly blue stars beyond the RR Lyrae stars (*see below* Variable stars), which are indicated by the crosshatched area in the diagram. Among these blue hot stars are found novae and the nuclei of planetary nebulas, the latter so called because their photographic image resembles that of a distant planet. Not all globular clusters show identical colour-magnitude diagrams, which may be due to differences in the cluster ages or other factors. (For a discussion of other aspects of colour-magnitude diagrams for star clusters, *see* star cluster: Globular cluster.)

## Estimates of stellar ages

The shapes of the colour-magnitude diagrams permit estimates of globular-cluster ages. The point at which stars move away from the main sequence is called the turnoff point, For example, in a cluster where stars more massive than about 1.3 solar masses have evolved away from the main sequence at a point just above the position occupied by the Sun, the time required for such a star to exhaust the hydrogen in its core is about 5–6 billion years, and the cluster must be at least as old. More ancient clusters have been identified. In the Galaxy, globular clusters are all very ancient objects, having ages within a few billion years of the average of 11 billion years. In the Magellanic Clouds, however, clusters

exist that resemble globular ones, but they contain numerous blue stars and therefore must be relatively young.



### Small Magellanic Cloud

Infant stars in the Small Magellanic Cloud.

*A. Nota-ESA/NASA*

Open clusters in the spiral arms of the Galaxy—extreme Population I—tell a somewhat different story. A colour-magnitude diagram can be plotted for a number of different open clusters—for example, the double cluster  $h$  and  $\chi$  Persei, the Pleiades, Praesepe, and M67—with the main feature distinguishing the clusters being their ages. The young cluster  $h$  and  $\chi$  Persei, which is a few million years old, contains stars ranging widely in luminosity. Some stars have already evolved into the supergiant stage (in such a diagram the top of the main sequence is bent over). The stars of luminosity 10,000 times greater than that of the Sun have already largely depleted the hydrogen in their cores and are leaving the main sequence.

The brightest stars of the Pleiades cluster, aged about 100 million years, have begun to leave the main sequence and are approaching the critical phase when they will have exhausted all the hydrogen in their cores. There are no giants in the Pleiades. Presumably, the cluster contained no stars as massive as some of those found in  $h$  and  $\chi$  Persei.



### Pleiades

Bright nebulosity in the Pleiades (M45, NGC 1432), distance 490 light-years.

Cluster stars provide the light, and surrounding clouds of dust reflect and scatter the rays from the stars.

*Courtesy of Palomar Observatory/California Institute of Technology*

The cluster known as Praesepe, or the Beehive, at an age of 790 million years, is older than the Pleiades. All stars much more luminous than the first magnitude have begun to leave the main sequence; there are some giants. The Hyades, about 620 million years old, displays a similar colour-magnitude array. These clusters contain a number of white dwarfs, indicating that the initially most luminous stars have already run the gamut of evolution. In a very old cluster such as M67, which is 4.5 billion years old, all of the bright main-sequence stars have disappeared.

The colour-magnitude diagrams for globular and open clusters differ quantitatively because the latter show a wider range of ages and differ in chemical composition. Most globular clusters have smaller metal-to-hydrogen ratios than do open clusters or the Sun. The gaps between the red giants and the blue main-sequence stars of the open clusters (Population I) often contain

unstable stars such as variables. The Cepheid variable stars, for instance, fall in these gaps (*see below* Variable stars).



### Cepheid variables

Cepheid variables, as seen by the Hubble Space Telescope.

NASA-HQ-GRIN

The giant stars of the Praesepe cluster are comparable to the brightest stars in M67. The M67 giants have evolved from the main sequence near an absolute magnitude of +3.5, whereas the Praesepe giants must have masses about twice as great as those of the M67 giants. Giant stars of the same luminosity may therefore have appreciably different masses.

## Numbers of stars versus luminosity

Of great statistical interest is the relationship between the luminosities of the stars and their frequency of occurrence. The naked-eye stars are nearly all intrinsically brighter than the Sun, but the opposite is true for the known stars within 20 light-years of the Sun. The bright stars are easily seen at great distances; the faint ones can be detected only if they are close.

The luminosity function (the number of stars with a specific luminosity) depends on population type. The luminosity function for pure Population II differs substantially from that for pure Population I. There is a small peak near absolute magnitude +0.6, corresponding to the horizontal branch for Population II, and no stars as bright as absolute magnitude  $-5$ . The luminosity function for pure Population I is evaluated best from open star clusters, the stars in such a cluster being at about the same distance. The neighbourhood of the Sun includes examples of both Populations I and II.

## Mass-luminosity correlations

A plot of mass against bolometric luminosity for visual binaries for which good parallaxes and masses are available shows that for stars with masses comparable to that of the Sun the luminosity,  $L$ , varies as a power,  $3 + \beta$ , of the mass  $M$ . This relation can be expressed as  $L = (M)^{3+\beta}$ . The power differs for substantially fainter or much brighter stars.

This mass-luminosity correlation applies only to unevolved main-sequence stars. It fails for giants and supergiants and for the subgiant (dimmer) components of eclipsing binaries, all of which have changed considerably during their lifetimes. It does not apply to any stars in a globular cluster not on the main sequence, or to white dwarfs that are abnormally faint for their masses.

The mass-luminosity correlation, predicted theoretically in the early 20th century by the English astronomer Arthur Eddington, is a general relationship that holds for all stars having essentially the same internal density and temperature distributions—i.e., for what are termed the same stellar models.

## Variable stars

Many stars are variable. Some are geometric variables, as in the eclipsing binaries considered earlier. Others are intrinsically variable—i.e., their total energy output fluctuates with time. Such intrinsic variable stars are dealt with in this section.

A fair number of stars are intrinsically variable. Some objects of this type were found by accident, but many were detected as a result of carefully planned searches. Variable stars are important in astronomy for several reasons. They usually appear to be stars at critical or short-lived phases of their evolution, and detailed studies of their light and spectral characteristics, spatial distribution, and association with other types of stars may provide valuable clues to the life histories of various classes of stars. Certain kinds of variable stars, such as Cepheids (periodic variables) and novae and supernovae (explosive variables), are extremely important in that they make it possible to establish the distances of remote stellar systems beyond the Galaxy. If the intrinsic luminosity of a recognizable variable is known and this kind of variable star can be found in a distant stellar system, the distance of the latter can be estimated from a measurement of apparent and absolute magnitudes, provided that the interstellar absorption is also known.

## Classification

Variables are often classified as behaving like a prototype star, and the entire class is then named for this star—e.g., RR Lyrae stars are those whose variability follows the pattern of the star RR Lyrae. The most important classes of intrinsically variable stars are the following:

(1) Pulsating variables—stars whose variations in light and colour are thought to arise primarily from stellar pulsations. These include Beta Canis Majoris stars, RR Lyrae stars, and Delta Scuti stars, all with short regular periods of less than a day; Cepheids, with periods between 1 and 100 days; and long-period variables, semiregular variables, and irregular red variables, usually with unstable periods of hundreds of days.

(2) Explosive, or catastrophic, variables—stars in which the variations are produced by the wrenching away of part of the star, usually the outer layers, in some explosive process. They include SS Cygni or U Geminorum stars, novae, and supernovae (the last of which are enormous explosions involving most of the matter in a star [*see below* Later stages of evolution]).

(3) Miscellaneous and special types of variables—R Coronae Borealis stars, T Tauri stars, flare stars, pulsars (neutron stars), spectrum and magnetic variables, X-ray variable stars, and radio variable stars.

## Pulsating stars



An impressive body of evidence indicates that stellar pulsations can account for the variability of Cepheids, long-period variables, semiregular variables, Beta Canis Majoris stars, and even the irregular red variables. Of this group, the Cepheid variables have been studied in greatest detail, both theoretically and observationally. These stars are regular in their behaviour; some repeat their light curves with great faithfulness from one cycle to the next over periods of many years.

Much confusion existed in the study of Cepheids until it was recognized that different types of Cepheids are associated with different groups, or population types, of stars. Cepheids belonging to the spiral-arm Population I (or Type I Cepheids) are characterized by regularity in their behaviour. They show continuous velocity curves indicative of regular pulsation. They exhibit a relation between period and luminosity in the sense that the longer the period of the star, the greater its intrinsic brightness. This period-luminosity relationship has been used to establish the distances of remote stellar systems.

Cepheids with different properties are found in Population II, away from the Milky Way, in globular clusters. These Type II Cepheids are bluer than classic Population I Cepheids having the same period, and their light curves have different shapes. Studies of the light and velocity curves indicate that shells of gas are ejected from the stars as discontinuous layers that later fall back toward the surface. These stars exhibit a relation between period and luminosity different from that for Population I Cepheids, and thus the distance of a Cepheid in a remote stellar system can be determined only if its population type is known.

Closely associated with Population II Cepheids are the cluster-type, or RR Lyrae, variables. Many of these stars are found in clusters, but some, such as the prototype RR Lyrae, occur far from any cluster or the central galactic bulge. Their periods are less than a day, and there is no correlation between period and luminosity. Their absolute magnitudes are about 0.6, but somewhat dependent on metal abundance. They are thus about 50 times as bright as the Sun and so are useful for determining the distance of star clusters and some of the nearer external galaxies, their short periods permitting them to be detected readily.

Long-period variable stars also probably owe their variations to pulsations. Here the situation is complicated by the vast extent of their atmospheres, so that radiation originating at very different depths in the star is observed at the same time. At certain phases of the variations, bright hydrogen lines are observed, overlaid with titanium oxide absorption. The explanation is an outward-moving layer of hot, recombining gas, whose radiation is absorbed by strata of cool gases. These stars are all cool red giants and supergiants of spectral types M (normal composition), R and N (carbon-rich), or S (heavy-metal-rich). The range in visual brightness during a pulsation can be 100-fold, but the range in total energy output is much less, because at very low stellar temperatures (1,500–3,000 K) most of the energy is radiated in the infrared as heat rather than as light.

Unlike the light curves of classic Cepheids, the light curves of these red variables show considerable variations from one cycle to another. The visual magnitude of the variable star Mira Ceti (Omicron Ceti) is normally about 9–9.5 at minimum light, but at maximum it may lie between 5 and 2. Time intervals between maxima often vary considerably. In such cool objects, a very small change in temperature can produce a huge change in the output of visible radiation. At the low temperatures of the red variables, compounds and probably solid particles are formed copiously, so that the visible light may be profoundly affected by a slight change in physical conditions. Random fluctuations from cycle to cycle, which would produce negligible effects in a hotter star, produce marked light changes in a long-period variable.

Long-period variables appear to fall into two groups; those with periods of roughly 200 days tend to be associated with Population II, and those of periods of about a year belong to Population I.

Red semiregular variables such as the RV Tauri stars show complex light and spectral changes. They do not repeat themselves from one cycle to the next; their behaviour suggests a simultaneous operation of two or more modes of oscillation. Betelgeuse is an example of an irregular red variable. In these stars the free period of oscillation does not coincide with the periodicity of the driving mechanism.

Finally, among the various types of pulsating variable stars, the Beta Canis Majoris variables are high-temperature stars (spectral type B) that often show complicated variations in spectral-line shapes and intensities, velocity curves, and light. In many cases, they have two periods of variation so similar in duration that complex interference or beat phenomena are observed, both in radial velocities and in the shapes of spectral lines.

A large body of evidence suggests that all members of this first class of variable stars owe their variability to pulsation. The pulsation theory was first proposed as a possible explanation as early as 1879, was applied to Cepheids in 1914, and was further developed by Arthur Eddington in 1917–18. Eddington found that if stars have roughly the same kind of internal structure, then the period multiplied by the square root of the density equals a constant that depends on the internal structure.

The Eddington theory, though a good approximation, encountered some severe difficulties that have been met through modifications. If the entire star pulsated in synchronism, it should be brightest when compressed and smaller while faintest when expanded and at its largest. The radial velocity should be zero at both maximum and minimum light. Observations contradict these predictions. When the star pulsates, all parts of the main body move in synchronism, but the outer observable strata fall out of step or lag behind the pulsation of the inner regions. Pulsations involve only the outer part of a star; the core, where energy is generated by thermonuclear reactions, is unaffected.

Careful measurements of the average magnitudes and colours of RR Lyrae stars in the globular cluster M3 showed that all these stars fell within a narrow range of luminosity and colour (or surface temperature)

or, equivalently, luminosity and radius. Also, every star falling in this narrow range of brightness and size was an RR Lyrae variable. Subsequent work has indicated that similar considerations apply to most classic Cepheids. Variability is thus a characteristic of any star whose evolution carries it to a certain size and luminosity, although the amplitude of the variability can vary dramatically.

In the pulsation theory as now developed, the light and velocity changes of Cepheids can be interpreted not only qualitatively but also quantitatively. The light curves of Cepheids, for example, have been precisely predicted by the theory. Stellar pulsation, like other rhythmic actions, may give rise to harmonic phenomena wherein beats reinforce or interfere with one another. Beat and interference phenomena then complicate the light and velocity changes. The RR Lyrae stars supply some of the best examples, but semiregular variables such as the RV Tauri stars or most Delta Scuti stars evidently vibrate simultaneously with two or more periods.

## **Explosive variables**

The evolution of a member of a close double-star system can be markedly affected by the presence of its companion. As the stars age, the more massive one swells up more quickly as it moves away from the main sequence. It becomes so large that its outer envelope falls under the gravitational influence of the smaller star. Matter is continuously fed from the more rapidly evolving star to the less massive one, which still remains on the main sequence. U Cephei is a classic example of such a system for which spectroscopic evidence shows streams of gas flowing from the more highly evolved star to the hotter companion, which is now the more massive of the two. Eventually, the latter will also leave the main sequence and become a giant star, only to lose its outer envelope to the companion, which by that time may have reached the white dwarf stage.

Novas appear to be binary stars that have evolved from contact binaries of the W Ursae Majoris type, which are pairs of stars apparently similar to the Sun in size but revolving around one another while almost touching. One member may have reached the white dwarf stage. Matter fed to it from its distended companion appears to produce instabilities that result in violent explosions or nova outbursts. The time interval between outbursts can range from a few score years to hundreds of thousands of years.

In ordinary novas the explosion seems to involve only the outer layers, as the star later returns to its former brightness; in supernovas the explosion is catastrophic. Normally, novas are small blue stars much fainter than the Sun, though very much hotter. When an outburst occurs, the star can brighten very rapidly, by 10 magnitudes or more in a few hours. Thereafter it fades; the rate of fading is connected with the brightness of the nova. The brightest novas, which reach absolute magnitudes of about  $-10$ , fade most rapidly, whereas a typical slow nova, which reaches an absolute magnitude of  $-5$ , can take 10 or 20 times as long to decline in brightness. This property, when calibrated as the absolute magnitude at maximum brightness versus the time taken to decline by two magnitudes, allows novas to be used as

distance indicators for nearby galaxies. The changes in light are accompanied by pronounced spectroscopic changes that can be interpreted as arising from alterations in an ejected shell that dissipates slowly in space. In its earliest phases, the expanding shell is opaque. As its area grows, with a surface temperature near 7,000 K, the nova brightens rapidly. Then, near maximum light, the shell becomes transparent, and its total brightness plummets rapidly, causing the nova to dim.

The mass of the shell is thought to be rather small, about 10–100 times the mass of Earth. Only the outer layers of the star seem to be affected; the main mass settles down after the outburst into a state much as before until a new outburst occurs. The existence of repeating novae, such as the star T Coronae Borealis, suggests that perhaps all novae repeat at intervals ranging up to thousands or perhaps millions of years; and probably, the larger the explosion, the longer the interval. There is strong evidence that novae are components of close double stars and, in particular, that they have evolved from the most common kind of eclipsing binaries, those of the W Ursae Majoris type.

Stars of the SS Cygni type, also known as dwarf novae, undergo novae-like outbursts but of a much smaller amplitude. The intervals between outbursts are a few months to a year. Such variables are close binaries. The development of this particular type may be possible only in close binary systems.

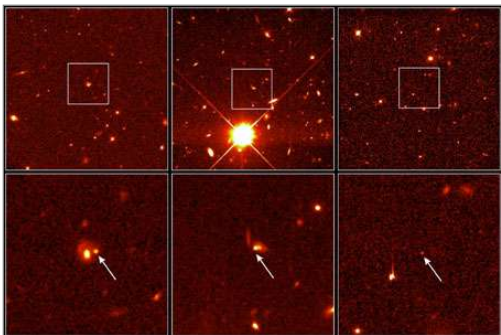
There are two major types of supernovas, designated Type I (or SNe I) and Type II (or SNe II). They can be distinguished by the fact that Type II supernovas have hydrogen features in their spectra, while Type I supernovas do not. Type II supernovas arise from the collapse of a single star more massive than about eight solar masses, resulting in either a neutron star or a black hole. There are three classes of Type I supernovas: Ia, Ib, and Ic. Type Ia supernovas are believed to originate in a binary system containing a white dwarf, rather like the case of ordinary novae. Unlike the latter, however, in which only the outer layers of the white dwarf seem to be affected, in a Type I supernova the white dwarf is probably completely destroyed; the details are not yet fully understood. Certainly, a supernova's energy output is enormously greater than that of an ordinary nova. Type Ib and Ic supernovas are like Type II in that they are each the core collapse of a massive star. However, a Type II supernova retains its hydrogen envelope, whereas the Type Ib and Ic supernovas do not, thus leading to the different hydrogen features in their spectra. Type Ib retains a helium shell and so has a spectrum rich in helium lines; Type Ic does not retain the hydrogen or helium shell.

Empirical evidence indicates that in a Type Ia supernova the absolute magnitude at maximum light can be determined by a combination of data derived from the rate of dimming after maximum, the shape of the light curve, and certain colour measurements. A comparison of the absolute and apparent magnitudes of maximum light in turn allows the distance of the supernova to be found. This is a matter of great usefulness because Type Ia supernovas at maximum light are the most luminous "standard candles" available for determining distances to external galaxies and thus can be observed in more distant galaxies than any other kind of standard candle. In 1999, application of this technique led to the totally



Supernova 1987A in the Large Magellanic Cloud.

*Jason Pun (NOAO) and SINS Collaboration*



### supernova

Three distant Type Ia supernovas, as observed by the Hubble Space Telescope in 1997. The bottom images are details of the upper wide views. The supernovas at left and centre occurred about five billion years ago, the right seven billion years ago.

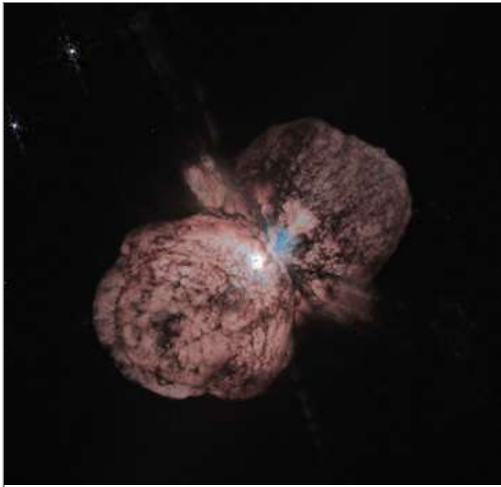
*Photo AURA/STScI/NASA/JPL (NASA photo # STScI-PRC98-02a-js)*

unexpected discovery that the expansion of the universe is accelerating rather than slowing down. This acceleration is caused by dark energy, a gravitationally repulsive force that is the dominant component (73 percent) of the universe's mass-energy.

A peculiar explosive variable with no known counterpart is Eta Carinae (NGC 3372), which appears in telescopes on Earth as a fuzzy red "star" slightly less than two seconds of arc in diameter. Surrounding it is a shell of gas and dust shaped roughly like an hourglass divided by a thin disk. First observed as a star of about the fourth magnitude in 1677, it brightened irregularly, undergoing an outburst in 1843, when it became for a few years the second brightest star in the sky. Thereafter it slowly faded, becoming too faint for the unaided eye around the turn of the 20th century. The fading was due, at least in part, to obscuration by dust emitted in the earlier eruption. The star remained near seventh magnitude with irregular variations for most of the 20th century, but it began brightening again by one or two tenths of a magnitude per year in the mid-1990s. In 2005 astronomers found that Eta Carinae is, in fact, a binary star system with an orbital period of 5.52 years. Its A component has a temperature of about 15,000 K; its B component, about 35,000 K. Eta Carinae is considered to be one of a small class of stars known as luminous blue variables. Its luminosity has been estimated as five million times that of the Sun. Flaring events producing not only visible effects but also X-ray, ultraviolet, and radio-wave effects have been observed.

Probably all variable stars represent more or less ephemeral phases in the evolution of a star. Aside from catastrophic events of the kind that produce a supernova, some phases of stellar variability might be of such brief duration as to permit recognizable changes during an interval of 50–100 years. Other stages may require many thousands of years. For example, the period of Delta Cephei, the prototype star of the Cepheid variables, has barely changed by a detectable amount since its variability was discovered in 1784.

## Peculiar variables



Eta Carinae. The hourglass and disk shapes of the gas and dust clouds, as well as various smaller details, are visible in this enhanced, computer-manipulated composite of eight images taken by the Hubble Space Telescope.

*Photo AURA/STScI/NASA/JPL (NASA photo # STScI-PRC96-23a)*

R Coronae Borealis variables are giant stars of about the Sun's temperature whose atmospheres are characterized by excessive quantities of carbon and very little hydrogen. The brightness of such a star remains constant until the star suddenly dims by several magnitudes and then slowly recovers its original brightness. (The star's colour remains the same during the changes in brightness.) The dimmings occur in a random fashion and seem to be due to the huge concentrations of carbon. At times the carbon vapour literally condenses into soot, and the star is hidden until the smog blanket is evaporated. Similar veiling may sometimes occur in other types of low-temperature stars, particularly in long-period variables.

Flare stars are cool dwarfs (spectral type M) that display flares apparently very much like, but much more intense than, those of the Sun. In fact, the flares are sometimes so bright that they overwhelm the normal light of the star. Solar flares are associated with copious emission of radio waves, and

simultaneous optical and radio-wave events appear to have been found in the stars UV Ceti, YZ Canis Minoris, and V371 Orionis.

Spectrum and magnetic variables, mostly of spectral type A, show only small amplitudes of light variation but often pronounced spectroscopic changes. Their spectra typically show strong lines of metals such as manganese, titanium, iron, chromium, and the lanthanides (also called rare earths), which vary periodically in intensity. These stars have strong magnetic fields, typically from a few hundred to a few thousand gauss. One star, HD 215441, has a field on the order of 30,000 gauss. (Earth's magnetic field has an average strength of about 0.5 gauss.) Not all magnetic stars are known to be variable in light, but such objects do seem to have variable magnetic fields. The best interpretation is that these stars are rotating about an inclined axis. As with Earth, the magnetic and rotation axes do not coincide. Different ions are concentrated in different areas (e.g., chromium in one area and the lanthanides in another).

The Sun is an emitter of radio waves, but, with present techniques, its radio emission could only just be detected from several parsecs away. Most discrete radio-frequency sources have turned out to be objects such as old supernovas, radio galaxies, or quasars, though well-recognized radio stars also have been recorded on occasion. These include flare stars, red supergiants such as Betelgeuse, the high-temperature dwarf companion to the red supergiant Antares, and the shells ejected from Nova Serpentis 1970 and Nova Delphini. The radio emission from the latter objects is consistent with that expected from

an expanding shell of ionized gas that fades away as the gas becomes attenuated. The central star of the Crab Nebula has been detected as a radio (and optical) pulsar.

Measurements from rockets, balloons, and spacecraft have revealed distinct X-ray sources outside the solar system. The strongest galactic source, Scorpius X-1, appears to be associated with a hot variable star resembling an old nova. In all likelihood this is a binary star system containing a low-mass normal star and a nonluminous companion.

A number of globular clusters are sources of cosmic X-rays. Some of this X-ray emission appears as intense fluctuations of radiation lasting only a few seconds but changing in strength by as much as 25 times. These X-ray sources have become known as bursters, and several such objects have been discovered outside of globular clusters as well. Some bursters vary on a regular basis, while others seem to turn on and off randomly. The most popular interpretation holds that bursters are the result of binary systems in which one of the objects—a compact neutron star or black hole (*see below* End states of stars)—pulls matter from the companion, a normal star. This matter is violently heated in the process, giving rise to X-rays. That the emission is often in the form of a burst is probably caused by something interrupting the flow of matter onto (or into) the compact object or by an eclipsing orbit of the binary system.

## Stellar structure

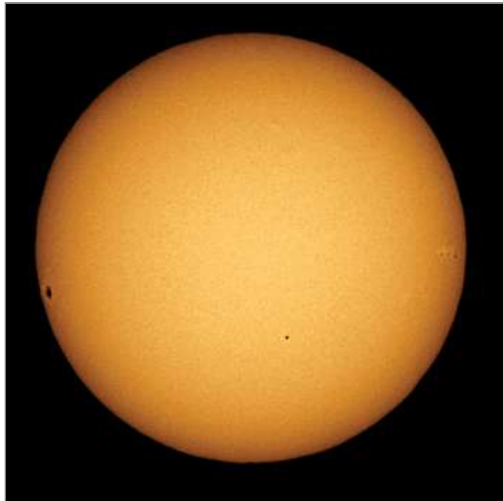
### Stellar atmospheres

To interpret a stellar spectrum quantitatively, knowledge of the variation in temperature and density with depth in the star's atmosphere is needed. Some general theoretical principles are outlined here.

The gradient of temperature in a star's atmosphere depends on the method of energy transport to the surface. One way to move energy from the interior of a star to its surface is via radiation; photons produced in the core are repeatedly absorbed and reemitted by stellar atoms, gradually propagating to the surface. A second way is via convection, which is a nonradiative mechanism involving a physical upwelling of matter much as in a pot of boiling water. For the Sun, at least, there are ways of distinguishing the mechanism of energy transport.

Photographs of the Sun's disk show that the centre of the disk is brighter than the limb. The difference in brightness depends on the wavelength of the radiation detected: it is large in violet light, is small in red light, and nearly vanishes when the Sun is imaged in infrared radiation. This limb darkening arises because the Sun becomes hotter toward its core. At the centre of the disk, radiation is received from deeper and hotter layers (on average) instead of from the limb, and the dependence of temperature on

depth can be shown to correspond to the transport of energy by radiation, not by convection, at least in the outer layers of the Sun's atmosphere.



#### limb darkening in the Sun

Limb darkening on the disk of the Sun.  
The planet Mercury can be seen as a small black dot in the lower middle of the solar disk.

*Mila Zinkova*

The amount of limb darkening in any star depends on the effective temperature of the star and on the variation in temperature with depth. Limb darkening is occasionally an important factor in the analysis of stellar observations. For example, it must be taken into account to interpret properly the observed light curves of eclipsing binaries, and here again the results suggest transport of energy via radiation.

The layers of a normal star are assumed to be in mechanical, or hydrostatic, equilibrium. This means that at each point in the atmosphere, the pressure supports the weight of the overlying layers. In this way, a relation between pressure and density can be found for any given depth.

In addition to the temperature and density gradients, the chemical composition of the atmospheric layers as well as the opacity of the material must be known. In the Sun the principal

source of opacity is the negative hydrogen ion ( $\text{H}^-$ ), a hydrogen atom with one extra electron loosely bound to it. In the atmospheres of many stars, the extra electrons break loose and recombine with other ions, thereby causing a reemission of energy in the form of light. At visible wavelengths the main contribution to the opacity comes from the destruction of this ion by interaction with a photon (the above-cited process is termed photodissociation). In hotter stars, such as Sirius A (the temperature of which is about 10,000 K), atomic hydrogen is the main source of opacity, whereas in cooler stars much of the outgoing energy is often absorbed by molecular bands of titanium oxide, water vapour, and carbon monoxide. Additional sources of opacity are absorption by helium atoms and electron scattering in hotter stars, absorption by hydrogen molecules and molecular ions, absorption by certain abundant metals such as magnesium, and Rayleigh scattering (a type of wavelength-dependent scattering of radiation by particles named for the British physicist Lord Rayleigh) in cool supergiant stars.

At considerable depths in the Sun and similar stars, convection sets in. Though most models of stellar atmospheres (particularly the outer layers) assume plane-parallel stratified layers, photographs of granulation on the Sun's visible surface (see Sun: Photosphere) belie this simple picture. Realistic models must allow for rising columns of heated gases in some areas and descent of cooler gases in others. The motions of the radiating gases are especially important when the model is to be used to calculate the anticipated line spectrum of the star. Typical gas velocities are on the order of 2 km (1.4 miles) per second in the Sun; in other stars they can be much larger.



Temperature, density, and pressure all increase steadily inward in the Sun's atmosphere. The Sun has no distinct solid surface, so the point from which the depth or height is measured is arbitrary. The temperature of the visible layers ranges from 4,700 to 6,200 K, the density from about  $10^{-7}$  to  $4 \times 10^{-7}$  gram per cubic cm, and the gas pressure from 0.002 to 0.14 atmosphere. The visible layers of stars such as the Sun have very low densities and pressures compared with Earth's atmosphere, even though the temperature is much higher. The strata of the solar atmosphere are very opaque compared with the terrestrial atmosphere.

For stars other than the Sun, the dependence of temperature on depth cannot be directly determined. Calculations must proceed by a process of successive approximations, during which the flux of energy is taken to be constant with depth. Computations have been undertaken for atmospheres of a variety of stars ranging from dwarfs to supergiants, from cool to hot stars. Their validity can be evaluated only by examining how well they predict the observed features of a star's continuous and line spectrum, including the detailed shapes of spectral-line features. Considering the known complexities of stellar atmospheres, the results fit the observations remarkably well.

Severe deviations exist for stars with extended and expanding atmospheres. Matter flowing outward from a star produces a stellar wind analogous to the solar wind, but one that is often much more extensive and violent. In the spectrum of certain very hot O-type stars (e.g., Zeta Puppis), strong, relatively narrow emission lines can be seen; however, in the ultraviolet, observations from rockets and spacecraft show strong emission lines with distinct absorption components on the shorter wavelength side. These absorption features are produced by rapidly outflowing atoms that absorb the radiation from the underlying stellar surface. The observed shifts in frequency correspond to ejection velocities of about 100 km (60 miles) per second. Much gentler stellar winds are found in cool M-type supergiants.

Rapid stellar rotation also can modify the structure of a star's atmosphere. Since effective gravity is much reduced near the equator, the appropriate description of the atmosphere varies with latitude. Should the star be spinning at speeds near the breakup point, rings or shells may be shed from the equator.

Some of the most extreme and interesting cases of rotational effects are found in close binary systems. Interpretations of the light and velocity curves of these objects suggest that the spectroscopic observations cannot be reconciled with simple orderly rotating stars. Instead, emission and absorption lines sometimes overlap in such a way as to suggest streams of gas moving between the stars. For example, Beta Lyrae, an eclipsing binary system, has a period of 12.9 days and displays very large shifts in orbital velocity. The brighter member at visible wavelengths is a star of type B6–B8; the other member is a larger, early B-type star that is embedded in an accretion disk and is draining matter from the B6–B8 star. The spectrum of the B6–B8-type component shows the regular velocity changes expected of a binary star, but there is an absorption (and associated emission) spectrum corresponding to a higher temperature (near spectral type B5) and a blue continuum corresponding to a very high-temperature star.

The anomalous B5-type spectrum is from the accretion disk and is evidently excited principally by the star within it. This spectrum shows few changes in velocity with time.

Supergiant stars have very extended atmospheres that are probably not even approximately in hydrostatic equilibrium. The atmospheres of M-type supergiant stars appear to be slowly expanding outward. Observations of the eclipsing binary 31 Cygni show that the K-type supergiant component has an extremely inhomogeneous, extended atmosphere composed of numerous blobs and filaments. As the secondary member of this system slowly moves behind the larger star, its light shines through larger masses of the K-type star's atmosphere. If the atmosphere were in orderly layers, the lines of ionized calcium, for example, produced by absorption of the light of the B-type star by the K-type star's atmosphere, would grow stronger uniformly as the eclipse proceeds. They do not, however.

## Stellar interiors

Models of the internal structure of stars—particularly their temperature, density, and pressure gradients below the surface—depend on basic principles explained in this section. It is especially important that model calculations take account of the change in the star's structure with time as its hydrogen supply is gradually converted into helium. Fortunately, given that most stars can be said to be examples of an “ideal gas,” the relations between temperature, density, and pressure have a basic simplicity.

## Distribution of matter

Several mathematical relations can be derived from basic physical laws, assuming that the gas is “ideal” and that a star has spherical symmetry; both these assumptions are met with a high degree of validity. Another common assumption is that the interior of a star is in hydrostatic equilibrium. This balance is often expressed as a simple relation between pressure gradient and density. A second relation expresses the continuity of mass; i.e., if  $M$  is the mass of matter within a sphere of radius  $r$ , the mass added,  $\Delta M$ , when encountering an increase in distance  $\Delta r$  through a shell of volume  $4\pi r^2 \Delta r$ , equals the volume of the shell multiplied by the density,  $\rho$ . In symbols,  $\Delta M = 4\pi r^2 \rho \Delta r$ .

A third relation, termed the equation of state, expresses an explicit relation between the temperature, density, and pressure of a star's internal matter. Throughout the star the matter is entirely gaseous, and, except in certain highly evolved objects, it obeys closely the perfect gas law. In such neutral gases the molecular weight is 2 for molecular hydrogen, 4 for helium, 56 for iron, and so on. In the interior of a typical star, however, the high temperatures and densities virtually guarantee that nearly all the matter is completely ionized; the gas is said to be a plasma, the fourth state of matter. Under these conditions not only are the hydrogen molecules dissociated into individual atoms, but also the atoms themselves are broken apart (ionized) into their constituent protons and electrons. Hence, the molecular weight of ionized hydrogen is the average mass of a proton and an electron—namely,  $\frac{1}{2}$  on the atom-mass scale noted

above. By contrast, a completely ionized helium atom contributes a mass of 4 with a helium nucleus (alpha particle) plus two electrons of negligible mass; hence, its average molecular weight is  $\frac{4}{3}$ . As another example, a totally ionized nickel atom contributes a nucleus of mass 58.7 plus 28 electrons; its molecular weight is then  $58.7/29 = 2.02$ . Since stars contain a preponderance of hydrogen and helium that are completely ionized throughout the interior, the average particle mass,  $\mu$ , is the (unit) mass of a proton, divided by a factor taking into account the concentrations by weight of hydrogen, helium, and heavier ions. Accordingly, the molecular weight depends critically on the star's chemical composition, particularly on the ratio of helium to hydrogen as well as on the total content of heavier matter.

If the temperature is sufficiently high, the radiation pressure,  $P_r$ , must be taken into account in addition to the perfect gas pressure,  $P_g$ . The total equation of state then becomes  $P = P_g + P_r$ . Here  $P_g$  depends on temperature, density, and molecular weight, whereas  $P_r$  depends on temperature and on the radiation density constant,  $a = 7.5 \times 10^{-15}$  ergs per cubic cm per degree to the fourth power. With  $\mu = 2$  (as an upper limit) and  $\rho = 1.4$  grams per cubic cm (the mean density of the Sun), the temperature at which the radiation pressure would equal the gas pressure can be calculated. The answer is 28 million K, much hotter than the core of the Sun. Consequently, radiation pressure may be neglected for the Sun, but it cannot be ignored for hotter, more massive stars. Radiation pressure may then set an upper limit to stellar luminosity.

Certain stars, notably white dwarfs, do not obey the perfect gas law. Instead, the pressure is almost entirely contributed by the electrons, which are said to be particulate members of a degenerate gas (see *below* White dwarfs). If  $\mu'$  is the average mass per free electron of the totally ionized gas, the pressure,  $P$ , and density,  $\rho$ , are such that  $P$  is proportional to a  $\frac{5}{3}$  power of the density divided by the average mass per free electron; i.e.,  $P = 10^{13} (\rho/\mu')^{5/3}$ . The temperature does not enter at all. At still higher densities the equation of state becomes more intricate, but it can be shown that even this complicated equation of state is adequate to calculate the internal structure of the white dwarf stars. As a result, white dwarfs are probably better understood than most other celestial objects.

For normal stars such as the Sun, the energy-transport method for the interior must be known. Except in white dwarfs or in the dense cores of evolved stars, thermal conduction is unimportant because the heat conductivity is very low. One significant mode of transport is an actual flow of radiation outward through the star. Starting as gamma rays near the core, the radiation is gradually "softened" (becomes longer in wavelength) as it works its way to the surface (typically, in the Sun, over the course of about a million years) to emerge as ordinary light and heat. The rate of flow of radiation is proportional to the thermal gradient—namely, the rate of change of temperature with interior distance. Providing yet another relation of stellar structure, this equation uses the following important quantities:  $a$ , the radiation constant noted above;  $c$ , the velocity of light;  $\rho$ , the density; and  $\kappa$ , a measure of the opacity of the matter. The larger the

value of  $\kappa$ , the lower the transparency of the material and the steeper the temperature fall required to push the energy outward at the required rate. The opacity,  $\kappa$ , can be calculated for any temperature, density, and chemical composition and is found to depend in a complex manner largely on the two former quantities.

In the Sun's outermost (though still interior) layers and especially in certain giant stars, energy transport takes place by quite another mechanism: large-scale mass motions of gases—namely, convection. Huge volumes of gas deep within the star become heated, rise to higher layers, and mix with their surroundings, thus releasing great quantities of energy. The extraordinarily complex flow patterns cannot be followed in detail, but when convection occurs, a relatively simple mathematical relation connects density and pressure. Wherever convection does occur, it moves energy much more efficiently than radiative transport.

## Source of stellar energy

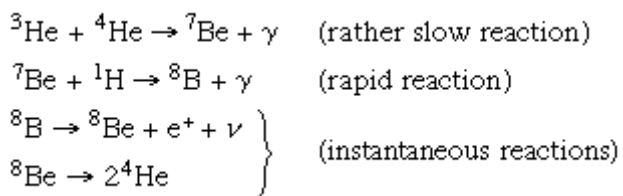
The most basic property of stars is that their radiant energy must derive from internal sources. Given the great length of time that stars endure (some 10 billion years in the case of the Sun), it can be shown that neither chemical nor gravitational effects could possibly yield the required energies. Instead, the cause must be nuclear events wherein lighter nuclei are fused to create heavier nuclei, an inevitable by-product being energy (*see* nuclear fusion).

In the interior of a star, the particles move rapidly in every direction because of the high temperatures present. Every so often a proton moves close enough to a nucleus to be captured, and a nuclear reaction takes place. Only protons of extremely high energy (many times the average energy in a star such as the Sun) are capable of producing nuclear events of this kind. A minimum temperature required for fusion is roughly 10 million K. Since the energies of protons are proportional to temperature, the rate of energy production rises steeply as temperature increases.

For the Sun and other normal main-sequence stars, the source of energy lies in the conversion of hydrogen to helium. The nuclear reaction thought to occur in the Sun is called the proton-proton cycle. In this fusion reaction, two protons ( ${}^1_1\text{H}$ ) collide to form a deuteron (a nucleus of deuterium,  ${}^2_1\text{H}$ ), with the liberation of a positron (the electron's positively charged antimatter counterpart, denoted  $e^+$ ). Also emitted is a neutral particle of very small mass called a neutrino,  $\nu$ . While the helium "ash" remains in the core where it was produced, the neutrino escapes from the solar interior within seconds. The positron encounters an ordinary negatively charged electron, and the two annihilate each other, with much energy being released. This annihilation energy amounts to 1.02 megaelectron volts (MeV), which accords well with Einstein's equation  $E = mc^2$  (where  $m$  is the mass of the two particles,  $c$  the velocity of light, and  $E$  the liberated energy).

Next, a proton collides with the deuteron to form the nucleus of a light helium atom of atomic weight 3,  ${}^3\text{He}$ . A “hard” X-ray (one of higher energy) or gamma-ray ( $\gamma$ ) photon also is emitted. The most likely event to follow in the chain is a collision of this  ${}^3\text{He}$  nucleus with a normal  ${}^4\text{He}$  nucleus to form the nucleus of a beryllium atom of weight 7,  ${}^7\text{Be}$ , with the emission of another gamma-ray photon. The  ${}^7\text{Be}$  nucleus in turn captures a proton to form a boron nucleus of atomic weight 8,  ${}^8\text{B}$ , with the liberation of yet another gamma ray.

The  ${}^8\text{B}$  nucleus, however, is very unstable. It decays almost immediately into beryllium of atomic weight 8,  ${}^8\text{Be}$ , with the emission of another positron and a neutrino. The nucleus itself thereafter decays into two helium nuclei,  ${}^4\text{He}$ . These nuclear events can be represented by the following equations:



In the course of these reactions, four protons are consumed to form one helium nucleus, while two electrons perish.

The mass of four hydrogen atoms is  $4 \times 1.00797$ , or 4.03188, atomic mass units; that of a helium atom is 4.0026. Hence, 0.02928 atomic mass unit, or 0.7 percent of the original mass, has disappeared. Some of this has been carried away by the elusive neutrinos, but most of it has been converted to radiant energy. In order to keep shining at its present rate, a typical star (e.g., the Sun) needs to convert 674 million tons of hydrogen to 670 million tons of helium every second. According to the formula  $E = mc^2$ , more than four million tons of matter literally disappear into radiation each second.

This theory provides a good understanding of solar energy generation, although for decades it suffered from one potential problem. The neutrino flux from the Sun was measured by different experimenters, and only one-third of the flux of electron neutrinos predicted by the theory was detected. (Neutrinos come in three types, each associated with a charged lepton: electron neutrino, muon neutrino, and tau neutrino.) Over that time, however, the consensus grew that the solar neutrino problem and its solution lay not with the astrophysical model of the Sun but with the physical nature of neutrinos themselves. In the late 1990s and the early 21st century, scientists discovered that neutrinos oscillate (change types) between electron neutrinos, the state in which they were created in the Sun, and muon or tau neutrinos, states that are more difficult to detect when they reach Earth.

The main source of energy in hotter stars is the carbon cycle (also called the CNO cycle for carbon, nitrogen, and oxygen), in which hydrogen is transformed into helium, with carbon serving as a catalyst. The reactions proceed as follows: first, a carbon nucleus,  $^{12}\text{C}$ , captures a proton (hydrogen nucleus),  $^1\text{H}$ , to form a nucleus of nitrogen,  $^{13}\text{N}$ , a gamma-ray photon being emitted in the process; thus,  $^{12}\text{C} + ^1\text{H} \rightarrow ^{13}\text{N} + \gamma$ . The light  $^{13}\text{N}$  nucleus is unstable, however. It emits a positron,  $e^+$ , which encounters an ordinary electron,  $e^-$ , and the two annihilate one another. A neutrino also is released, and the resulting  $^{13}\text{C}$  nucleus is stable. Eventually the  $^{13}\text{C}$  nucleus captures another proton, forms  $^{14}\text{N}$ , and emits another gamma-ray photon. In symbols the reaction is represented by the equations  $^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu$ ; then  $^{13}\text{C} + ^1\text{H} \rightarrow ^{14}\text{N} + \gamma$ . Ordinary nitrogen,  $^{14}\text{N}$ , is stable, but when it captures a proton to form a nucleus of light oxygen-15,  $^{15}\text{O}$ , the resulting nucleus is unstable against beta decay. It therefore emits a positron and a neutrino, a sequence of events expressed by the equations  $^{14}\text{N} + ^1\text{H} \rightarrow ^{15}\text{O} + \gamma$ ; then  $^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu$ . Again, the positron meets an electron, and the two annihilate each other while the neutrino escapes. Eventually the  $^{15}\text{N}$  nucleus encounters a fast-moving proton,  $^1\text{H}$ , and captures it, but the formation of an ordinary  $^{16}\text{O}$  nucleus by this process occurs only rarely. The most likely effect of this proton capture is a breakdown of  $^{15}\text{N}$  and a return to the  $^{12}\text{C}$  nucleus—that is,  $^{15}\text{N} + ^1\text{H} \rightarrow ^{12}\text{C} + ^4\text{He} + \gamma$ . Thus, the original  $^{12}\text{C}$  nucleus reappears, and the four protons that have been added permit the formation of a helium nucleus. The same amount of mass has disappeared, though a different fraction of it may have been carried off by the neutrinos.

Only the hottest stars that lie on the main sequence shine with energy produced by the carbon cycle. The faint red dwarfs use the proton-proton cycle exclusively, whereas stars such as the Sun shine mostly by the proton-proton reaction but derive some contribution from the carbon cycle as well.

The aforementioned mathematical relationships permit the problem of stellar structure to be addressed notwithstanding the complexity of the problem. An early assumption that stars have a uniform chemical composition throughout their interiors simplified the calculations considerably, but it had to be abandoned when studies in stellar evolution proved that the compositions of stars change with age (*see below* Later stages of evolution). Computations need to be carried out by a step-by-step process known as numerical integration. They must take into account that the density and pressure of a star vanish at the surface, whereas these quantities and the temperature remain finite at the core.

Resulting models of a star's interior, including the relation between mass, luminosity, and radius, are determined largely by the mode of energy transport. In the Sun and the fainter main-sequence stars, energy is transported throughout the outer layers by convective currents, whereas in the deep interior, energy is transported by radiation. Among the hotter stars of the main sequence, the reverse appears to be true. The deep interiors of the stars that derive their energy primarily from the carbon cycle are in

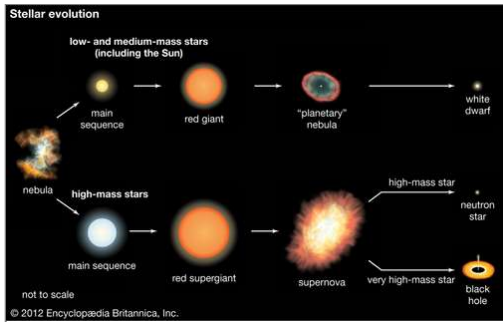
convective equilibrium, whereas in the outer parts the energy is carried by radiation. The observed masses, luminosities, and radii of most main-sequence stars can be reproduced with reasonable and uniform chemical composition.

Chemically homogeneous models of giant and supergiant stars cannot be constructed. If a yellow giant such as Capella is assumed to be built like a main-sequence star, its central temperature turns out to be so low that no known nuclear process can possibly supply the observed energy output. Progress has been made only by assuming that these stars were once main-sequence objects that, in the course of their development, exhausted the hydrogen in their deep interiors. Inert cores consequently formed, composed mainly of the helium ash left from the hydrogen-fusion process. Since no helium nuclear reactions are known to occur at the few tens of millions of kelvins likely to prevail in these interiors, no thermonuclear energy could be released from such depleted cores. Instead, energy is assumed to be generated in a thin shell surrounding the inert core where some fuel remains, and it is presumably produced by the carbon cycle. Such models are called shell-source models. As a star uses up increasing amounts of its hydrogen supply, its core grows in mass while the outer envelope of the star continues to expand. These shell-source models explain the observed luminosities, masses, and radii of giants and supergiants.

The depletion of hydrogen fuel is appreciable even for a dwarf, middle-aged star such as the Sun. The Sun seems to have been shining at its present rate for about the last 20 percent of its current age of five billion years. For its observed luminosity to be maintained, the Sun's central temperature must have increased considerably since the formation of the solar system, largely as a consequence of the depletion of the hydrogen in its interior along with an accompanying increase in molecular weight and temperature. During the past five billion years, the Sun probably brightened by about half a magnitude; in early Precambrian time (about two billion years ago), the solar luminosity must have been some 20 percent less than it is today.

## Star formation and evolution

Throughout the Milky Way Galaxy (and even near the Sun itself), astronomers have discovered stars that are well evolved or even approaching extinction, or both, as well as occasional stars that must be very young or still in the process of formation. Evolutionary effects on these stars are not negligible, even for a middle-aged star such as the Sun. More massive stars must display more spectacular effects because the rate of conversion of mass into energy is higher. While the Sun produces energy at the rate of about two ergs per gram per second, a more luminous main-sequence star can release energy at a rate some 1,000 times greater. Consequently, effects that require billions of years to be easily recognized in the Sun might occur within a few million years in highly luminous and massive stars. A supergiant star such as Antares, a bright main-sequence star such as Rigel, or even a more modest star such as Sirius cannot have endured as long as the Sun has endured. These stars must have been formed relatively recently.



### stellar evolution

Stellar evolution.

*Encyclopædia Britannica, Inc.*

## Birth of stars and evolution to the main sequence

Detailed radio maps of nearby molecular clouds reveal that they are clumpy, with regions containing a wide range of densities—from a few tens of molecules (mostly hydrogen) per cubic centimetre to more than one million. Stars form only from the densest regions, termed cloud cores, though they need not lie at the geometric centre of the cloud. Large cores (which probably contain subcondensations) up to a few light-years in size seem to give rise to unbound associations of very massive stars (called

OB associations after the spectral type of their most prominent members, O and B stars) or to bound clusters of less massive stars. Whether a stellar group materializes as an association or a cluster seems to depend on the efficiency of star formation. If only a small fraction of the matter goes into making stars, the rest being blown away in winds or expanding H II regions, then the remaining stars end up in a gravitationally unbound association, dispersed in a single crossing time (diameter divided by velocity) by the random motions of the formed stars. On the other hand, if 30 percent or more of the mass of the cloud core goes into making stars, then the formed stars will remain bound to one another, and the ejection of stars by random gravitational encounters between cluster members will take many crossing times.



Centre of the Orion Nebula (M42). Astronomers have identified some 700 young stars in this 2.5-light-year-wide area. They have also detected over 150 protoplanetary disks, or proplyds, which are believed to be embryonic solar systems that will eventually form planets. These stars and proplyds generate most of the nebula's light. This

Low-mass stars also are formed in associations called T associations after the prototypical stars found in such groups, T Tauri stars. The stars of a T association form from loose aggregates of small molecular cloud cores a few tenths of a light-year in size that are randomly distributed through a larger region of lower average density. The formation of stars in associations is the most common outcome; bound clusters account for only about 1 to 10 percent of all star births. The overall efficiency of star formation in associations is quite small. Typically less than 1 percent of the mass of a molecular cloud becomes stars in one crossing time of the molecular cloud (about  $5 \times 10^6$  years). Low efficiency of star formation presumably explains why any interstellar gas remains in the Galaxy after  $10^{10}$  years of evolution. Star formation at the present time must be a mere trickle of the torrent that occurred when the Galaxy was young.

A typical cloud core rotates fairly slowly, and its distribution of mass is strongly concentrated toward the centre. The slow



picture is a mosaic combining 45 images taken by the Hubble Space Telescope.

NASA, C.R. O'Dell and S.K. Wong (Rice University)



W5 Star Formation Region Spitzer Space Telescope • IRAC  
NASA / JPL-Caltech / L. Allen & X. Koenig (Harvard-Smithsonian CfA) 2006-10

### W5 Star Formation Region

The W5 Star Formation Region in an image taken by the Spitzer Space Telescope.

L. Allen and X. Koenig (Harvard Smithsonian CfA)—JPL-Caltech/NASA

rotation rate is probably attributable to the braking action of magnetic fields that thread through the core and its envelope. This magnetic braking forces the core to rotate at nearly the same angular speed as the envelope as long as the core does not go into dynamic collapse. Such braking is an important process because it assures a source of matter of relatively low angular momentum (by the standards of the interstellar medium) for the formation of stars and planetary systems. It also has been proposed that magnetic fields play an important role in the very separation of the cores from their envelopes. The proposal involves the slippage of the neutral component of a lightly ionized gas under the action of the self-gravity of the matter past the charged particles suspended in a background magnetic field. This slow slippage would provide the theoretical explanation for the observed low overall efficiency of star formation in molecular clouds.

At some point in the course of the evolution of a molecular cloud, one or more of its cores become unstable and subject to gravitational collapse. Good arguments exist that the central regions should collapse first, producing a condensed protostar whose contraction is halted by the large buildup of thermal pressure when radiation can no longer escape from the interior to keep the (now opaque) body relatively cool. The protostar,

which initially has a mass not much larger than Jupiter, continues to grow by accretion as more and more overlying material falls on top of it. The infall shock, at the surfaces of the protostar and the swirling nebular disk surrounding it, arrests the inflow, creating an intense radiation field that tries to work its way out of the infalling envelope of gas and dust. The photons, having optical wavelengths, are degraded into longer wavelengths by dust absorption and reemission, so that the protostar is apparent to a distant observer only as an infrared object. Provided that proper account is taken of the effects of rotation and magnetic field, this theoretical picture correlates with the radiative spectra emitted by many candidate protostars discovered near the centres of molecular cloud cores.

An interesting speculation concerning the mechanism that ends the infall phase exists: it notes that the inflow process cannot run to completion. Since molecular clouds as a whole contain much more mass than what goes into each generation of stars, the depletion of the available raw material is not what stops the accretion flow. A rather different picture is revealed by observations at radio, optical, and X-ray

wavelengths. All newly born stars are highly active, blowing powerful winds that clear the surrounding regions of the infalling gas and dust. It is apparently this wind that reverses the accretion flow.

The geometric form taken by the outflow is intriguing. Jets of matter seem to squirt in opposite directions along the rotational poles of the star (or disk) and sweep up the ambient matter in two lobes of outwardly moving molecular gas—the so-called bipolar outflows. Such jets and bipolar outflows are doubly interesting because their counterparts were discovered sometime earlier on a fantastically larger scale in the double-lobed forms of extragalactic radio sources, such as quasars.

The underlying energy source that drives the outflow is unknown. Promising mechanisms invoke tapping the rotational energy stored in either the newly formed star or the inner parts of its nebular disk. There exist theories suggesting that strong magnetic fields coupled with rapid rotation act as whirling rotary blades to fling out the nearby gas. Eventual collimation of the outflow toward the rotation axes appears to be a generic feature of many proposed models.

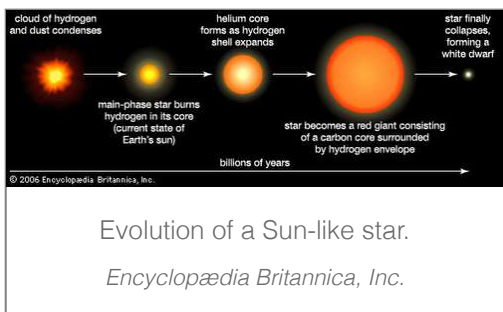
Pre-main-sequence stars of low mass first appear as visible objects, T Tauri stars, with sizes that are several times their ultimate main-sequence sizes. They subsequently contract on a time scale of tens of millions of years, the main source of radiant energy in this phase being the release of gravitational energy. As the internal temperature rises to a few million kelvins, deuterium (heavy hydrogen) is first destroyed. Then lithium, beryllium, and boron are broken down into helium as their nuclei are bombarded by protons moving at increasingly high speeds. When their central temperatures reach values comparable to  $10^7$  K, hydrogen fusion ignites in their cores, and they settle down to long stable lives on the main sequence. The early evolution of high-mass stars is similar; the only difference is that their faster overall evolution may allow them to reach the main sequence while they are still enshrouded in the cocoon of gas and dust from which they formed.

Detailed calculations show that a protostar first appears on the Hertzsprung-Russell diagram well above the main sequence because it is too bright for its colour. As it continues to contract, it moves downward and to the left toward the main sequence.

## **Subsequent development on the main sequence**

As the central temperature and density continue to rise, the proton-proton and carbon cycles become active, and the development of the (now genuine) star is stabilized. The star then reaches the main sequence, where it remains for most of its active life. The time required for the contraction phase depends on the mass of the star. A star of the Sun's mass generally requires tens of millions of years to reach the main sequence, whereas one of much greater mass might take a few hundred thousand years.

By the time the star reaches the main sequence, it is still chemically homogeneous. With additional time, the hydrogen fuel in the core is converted to helium, and the temperature slowly rises. If the star is sufficiently massive to have a convective core, the matter in this region has a chance to be thoroughly mixed, but the outer region does not mix with the core. The Sun, by contrast, has no convective core, and the helium-to-hydrogen ratio is maximum at the centre and decreases outward. Throughout the life of the Sun, there has been a steady depletion of hydrogen, so that the concentration of hydrogen at the centre today is probably only about one-third of the original amount. The rest has been transformed into helium. Like the rate of formation of a star, the subsequent rate of evolution on the main sequence is proportional to the mass of the star; the greater the mass, the more rapid the evolution. Whereas the Sun is destined to endure for some 10 billion years, a star of twice the Sun's mass burns its fuel at such a rate that it lasts about 3 billion years, and a star of 10 times the Sun's mass has a lifetime measured in tens of millions of years. By contrast, stars having a fraction of the mass of the Sun seem able to endure for trillions of years, which is much greater than the current age of the universe.



The spread of luminosities and colours of stars within the main sequence can be understood as a consequence of evolution. At the beginning of their lives as hydrogen-burning objects, stars define a nearly unique line in the Hertzsprung-Russell diagram called the zero-age main sequence. Without differences in initial chemical composition or in rotational velocity, all the stars would start exactly from this unique line. As the stars evolve, they

adjust to the increase in the helium-to-hydrogen ratio in their cores and gradually move away from the zero-age main sequence. When the core fuel is exhausted, the internal structure of the star changes rapidly; it quickly leaves the main sequence and moves toward the region of giants and supergiants.

As the composition of its interior changes, the star departs the main sequence slowly at first and then more rapidly. When about 10 percent of the star's mass has been converted to helium, the structure of the star changes drastically. All of the hydrogen in the core has been burned out, and this central region is composed almost entirely of inert helium, with trace admixtures of heavier elements. The energy production now occurs in a thin shell where hydrogen is consumed and more helium added to a growing but inert core. The outer parts of the star expand outward because of the increased burning there, and as the star swells up, its luminosity gradually increases. The details of the evolutionary process depend on the metal-to-hydrogen ratio, and the course of evolution differs for stars of different population types.

## Later stages of evolution

The great spread in luminosities and colours of giant, supergiant, and subgiant stars is also understood to result from evolutionary events. When a star leaves the main sequence, its future evolution is precisely determined by its mass, rate of rotation (or angular momentum), and chemical composition and whether it

is a member of a close binary system. Giants and supergiants of nearly the same radius and surface temperature may have evolved from main-sequence stars of different ages and masses.

## Evolution of low-mass stars

Theoretical calculations suggest that, as the star evolves from the main sequence, the hydrogen-helium core gradually increases in mass but shrinks in size as more and more helium ash is fed in through the outer hydrogen-burning shell. Energy is carried outward from the shell by rapid convection currents. The temperature of the shell rises; the star becomes more luminous; and it finally approaches the top of the giant domain on the Hertzsprung-Russell diagram. By contrast, the core shrinks by gravitational contraction, becoming hotter and denser until it reaches a central temperature of about 120 million K. At that temperature the previously inert helium is consumed in the production of heavier elements.

When two helium nuclei each of mass 4 atomic units ( ${}^4\text{He}$ ) are jammed together, it might be expected that they would form a nucleus of beryllium of mass 8 atomic units ( ${}^8\text{Be}$ ). In symbols,  ${}^4\text{He} + {}^4\text{He} \rightarrow {}^8\text{Be}$ . Actually, however,  ${}^8\text{Be}$  is unstable and breaks down into two helium nuclei. If the temperature and density are high enough, though, the short-lived beryllium nucleus can (before it decays) capture another helium nucleus in what is essentially a three-body collision to form a nucleus of carbon-12—namely,  ${}^8\text{Be} + {}^4\text{He} \rightarrow {}^{12}\text{C}$ .

This fusion of helium in the core, called the triple alpha process, can begin gradually in some stars, but in stars with masses between about half of and three times the Sun's mass, it switches on with dramatic suddenness, a process known as the "helium flash." Outwardly the star shows no discernible effect, but the course of its evolution is changed with this new source of energy. Having only recently become a red giant, it now evolves somewhat down and then to the left in the Hertzsprung-Russell diagram, becoming smaller and hotter. This stage of core helium burning, however, lasts only about a hundredth of the time taken for core hydrogen burning. It continues until the core helium supply is exhausted, after which helium fusion is limited to a shell around the core, just as was the case for hydrogen in an earlier stage. This again sets the star evolving toward the red giant stage along what is called the asymptotic giant branch, located slightly above the main region of giants in the Hertzsprung-Russell diagram.

In more massive stars, this cycle of events can continue, with the stellar core reaching ever-higher temperatures and fusing increasingly heavy nuclei, until the star eventually experiences a supernova explosion (*see below* Evolution of high-mass stars). In lower-mass stars like the Sun, however, there is insufficient mass to squeeze the core to the temperatures needed for this chain of fusion processes to proceed, and eventually the outermost layers extend so far from the source of nuclear burning that they cool to a few thousand kelvins. The result is an object having two distinct parts: a well-defined core of mostly carbon ash (a white dwarf star; *see below* End states of stars) and a swollen spherical shell of

cooler and thinner matter spread over a volume roughly the size of the solar system. Such shells of matter, called planetary nebulas, are actually observed in large numbers in the sky. Of the roughly 3,500 examples known in the Milky Way Galaxy alone, NGC 7027 is the most intensively studied.

## Origin of the chemical elements

The relative abundances of the chemical elements provide significant clues regarding their origin. Earth's crust has been affected severely by erosion, fractionation, and other geologic events, so that its present varied composition offers few clues as to its early stages. The composition of the matter from which the solar system formed is deduced from that of stony meteorites called chondrites and from the composition of the Sun's atmosphere, supplemented by data acquired from spectral observations of hot stars and gaseous nebulas. The table lists the most abundant chemical elements; it represents an average pertaining to all cosmic objects in general.

**The most abundant chemical elements**  
(by numbers of atoms per  $10^9$  atoms of hydrogen)

element	symbol	abundance	element	symbol	abundance	element	symbol	abundance
helium	He	$9.8 \times 10^7$	magnesium	Mg	38,000	potassium	K	133
carbon	C	501,000	aluminum	Al	3,000	calcium	Ca	2,200
nitrogen	N	100,000	silicon	Si	35,000	titanium	Ti	91
oxygen	O	794,000	phosphorus	P	320	chromium	Cr	473
fluorine	F	33	sulfur	S	17,400	manganese	Mn	288
neon	Ne	123,000	chlorine	Cl	250	iron	Fe	33,000
sodium	Na	2,100	argon	Ar	3,600	nickel	Ni	1,800

The most obvious feature is that the light elements tend to be more abundant than the heavier ones. That is to say, when abundance is plotted against atomic mass, the resulting graph shows a decline with increasing atomic mass up to an atomic mass value of about 100. Thereafter the abundance is more nearly constant. Furthermore, the decline is not smooth. Among the lighter elements, those of even atomic number tend to be more abundant, and those with an atomic number divisible by four are especially favoured. The abundances of lithium, beryllium, and boron are rare compared with those of carbon, nitrogen, and oxygen. There is a pronounced abundance peak for iron and a relatively high peak for lead, the most stable of the heavy elements.

The overwhelming preponderance of hydrogen suggests that all the nuclei were built from this simplest element, a hypothesis first proposed many years ago and widely accepted for a time. According to this now-defunct idea, all matter was initially compressed into one huge ball of neutrons. As the universe began to expand, its density decreased and the neutrons decayed into protons and electrons. The

protons then captured neutrons (*see* neutron capture), one after another, underwent beta decay (ejection of electrons), and synthesized the heavy elements. A major difficulty with this hypothesis, among various other problems, is that atomic masses 5 and 8 are unstable, and there is no known way to build heavier nuclei by successive neutron capture.

A large body of evidence now supports the idea that only the nuclei of hydrogen and helium, with trace amounts of other light nuclei such as lithium, beryllium, and boron, were produced in the aftermath of the big bang, the hot explosion from which the universe is thought to have emerged, whereas the heavier nuclei were, and continue to be, produced in stars. The majority of them, however, are fashioned only in the most massive stars and some only for a short period of time after supernova explosions (*see below* Evolution of high-mass stars).

The splitting in the spectral sequence among the cooler stars can be understood in terms of composition differences. The M-type stars appear to have a normal (i.e., solar) makeup, with oxygen more abundant than carbon and the zirconium group of elements much less abundant than the titanium group. The R-type and N-type stars often contain more carbon than oxygen, whereas the S-type stars appear to have an enhanced content of zirconium as compared with titanium. Other abundance anomalies are found in a peculiar class of higher temperature stars, called Wolf-Rayet (or W) stars, in which objects containing predominantly helium, carbon, and oxygen are distinguished from those containing helium and nitrogen, some carbon, and little observed oxygen. Significantly, all these abundance anomalies are found in stars thought to be well advanced in their evolutionary development. No main-sequence dwarfs display such effects.

A most critical observation is the detection of the unstable element technetium in the S-type stars. This element has been produced synthetically in nuclear laboratories on Earth, and its longest-lived isotope, technetium-99, is known to have a half-life of 200,000 years. The implication is that this element must have been produced within the past few hundred thousand years in the stars where it has been observed, suggesting furthermore that this nucleosynthetic process is at work in at least some stars today. This heavy element upwells from a star's core (where it is produced) to the surface (near where it is observed) in a phase called the third dredge-up, when material in deep helium-burning layers is brought to the surface through convection.

Researchers have been able to demonstrate how elements might be created in stars by nuclear processes occurring at very high temperatures and densities. No one mechanism can account for all the elements; rather, several distinct processes occurring at different epochs during the late evolution of a star have been proposed.

After hydrogen, helium is the most abundant element. Most of it was probably produced in the initial big bang. Furthermore, as described earlier, helium is the normal ash of hydrogen consumption, and in the

dense cores of highly evolved stars, helium itself is consumed to form, successively, carbon-12, oxygen-16, neon-20, and magnesium-24. By this time in the core of a sufficiently massive star, the temperature has reached some 700 million K. Under these conditions, particles such as protons, neutrons, and helium-4 nuclei also can interact with the newly created nuclei to produce a variety of other elements such as fluorine and sodium. Because these “uneven” elements are produced in lesser quantities than those divisible by four, both the peaks and troughs in the curve of cosmic abundances can be explained.

As the stellar core continues to shrink and the central temperature and density are forced even higher, a fundamental difficulty is soon reached. A temperature of roughly one billion K is sufficient to create silicon (silicon-28) by the usual method of helium capture. This temperature, however, is also high enough to begin to break apart silicon as well as some of the other newly synthesized nuclei. A “semi-equilibrium” is set up in the star’s core—a balance of sorts between the production and destruction (photodisintegration) of silicon. Ironically, though destructive, this situation is suitable for the production of even heavier nuclei up to and including iron (iron-56), again through the successive capture of helium nuclei.

## **Evolution of high-mass stars**

If the temperature and the density of the core continue to rise, the iron-group nuclei tend to break down into helium nuclei, but a large amount of energy is suddenly consumed in the process. The star then suffers a violent implosion, or collapse, after which it soon explodes as a supernova. In the catastrophic events leading to a supernova explosion and for roughly 1,000 seconds thereafter, a great variety of nuclear reactions can take place. These processes seem to be able to explain the trace abundances of all the known elements heavier than iron.

Two situations have been envisioned, and both involve the capture of neutrons. When a nucleus captures a neutron, its mass increases by one atomic unit and its charge remains the same. Such a nucleus is often too heavy for its charge and might emit an electron (beta particle) to attain a more stable state. It then becomes a nucleus of the next higher element in the periodic table of the elements. In the first such process, called the slow, or s-, process, the flux of neutrons is low. A nucleus captures a neutron and leisurely emits a beta particle; its nuclear charge then increases by one.

Beta decay is often very slow, and, if the flux of neutrons is high, the nucleus might capture another neutron before there is time for it to undergo decay. In this rapid, or r-, process, the evolution of a nucleus can be very different from that in a slow process. In supernova explosions, vast quantities of neutrons can be produced, and these could result in the rapid buildup of massive elements. One interesting feature of the synthesis of heavy elements by neutron capture at a high rate in a supernova explosion is that nuclei much heavier than lead or even uranium can be fashioned. These in turn can decay by fission, releasing additional amounts of energy.

The superabundant elements in the S-type stars come from the slow neutron process. Moreover, the observation of technetium-99 is ample evidence that these processes are at work in stars today. Even so, some low-abundance atomic nuclei are proton-rich (i.e., neutron-deficient) and cannot be produced by either the s- or the r-process. Presumably, they have been created in relatively rare events—e.g., one in which a quantum of hard radiation, a gamma-ray photon, causes a neutron to be ejected.

In addition, no known nuclear process is capable of producing lithium, beryllium, and boron in stellar interiors. These lightweight nuclei are probably produced by the breakdown, or spallation, of heavier elements, such as iron and magnesium, by high-energy particles in stellar atmospheres or in the early stages of star formation. Apparently, these high-energy particles, called cosmic rays, originate by means of electromagnetic disturbances in the neighbourhood of starspots and stellar flares, and they also arise from supernova explosions themselves. Some of these light-element nuclei also might be produced by cosmic rays shattering atoms of carbon, nitrogen, oxygen, and other elements in the interstellar medium.

Finally, the peculiar A-type stars comprise a class of cosmic objects with strange elemental abundance anomalies. These might arise from mechanical effects—for example, selective radiation pressure or photospheric diffusion and element separation—rather than from nuclear effects. Some stars show enhanced silicon, others enhanced lanthanides. The so-called manganese stars show great overabundances of manganese and gallium, usually accompanied by an excess of mercury. The latter stars exhibit weak helium lines, low rotational velocities, and excess amounts of gallium, strontium, yttrium, mercury, and platinum, as well as absences of such elements as aluminum and nickel. When these types of stars are found in binaries, the two members often display differing chemical compositions. It is most difficult to envision plausible nuclear events that can account for the peculiarities of these abundances, particularly the strange isotope ratios of mercury.

## **End states of stars**

The final stages in the evolution of a star depend on its mass and angular momentum and whether it is a member of a close binary.

## **White dwarfs**

All stars seem to evolve through the red-giant phase to their ultimate state along a straightforward path. In most instances, especially among low-mass stars, the distended outer envelope of the star simply drifts off into space, while the core settles down as a white dwarf. Here the star (really the core) evolves on the horizontal branch of the Hertzsprung-Russell diagram to bluer colours and lower luminosities. In other cases, in which the mass of the star is several solar masses or more, the star may explode as a supernova. Even for these more massive stars, however, if the residual mass in the core is less than 1.4 solar masses (the Chandrasekhar limit), the stellar remnant will become a white dwarf. The matter in such



a dwarf becomes a degenerate gas, wherein the electrons are all stripped from their parent atoms. Gas in this peculiar state is an almost perfect conductor of heat and does not obey the ordinary gas laws. It can be compressed to very high densities, typical values being in the range of 10 million grams per cubic cm (i.e., about 10 million times the density of water). Such a white dwarf no longer has any source of energy and simply continues to cool down, eventually becoming a black dwarf.

The energy output of a white dwarf is so small that the object can go on shining mainly by radiating away its stored energy until virtually none is left to emit. How long this might take is unknown, but it would seem to be on the order of trillions of years. The final stage of this kind of low-mass star is typically a ball not much larger than Earth but with a density perhaps 50,000 times that of water.

The Sun is destined to perish as a white dwarf. But, before that happens, it will evolve into a red giant, engulfing Mercury and Venus in the process. At the same time, it will blow away Earth's atmosphere and boil its oceans, making the planet uninhabitable. None of these events will come to pass for several billion years.

The first white dwarf to be recognized was the companion to Sirius. It was originally detected by its gravitational attraction on the larger, brighter star and only later observed visually as a faint object (now called Sirius B), about 10,000 times fainter than Sirius (now called Sirius A) or 500 times fainter than the Sun. Its mass is slightly less than that of the Sun, and its size a little less than that of Earth. Its colour and spectrum correspond roughly to spectral type A, with a surface temperature of about 25,000 K. Hence, the energy emission per unit area from the surface must be much greater than that of the Sun. Because Sirius B is so faint, its surface area and thus its volume must be very small, and its average density is on the order of 100,000 times that of water.

Another well-known white dwarf, designated BD + 16°516, is paired with a much cooler K0 V dwarf in an eclipsing system. The two stars, whose centres are separated by 2,092,000 km (about 1,300,000 miles), revolve around each other with a period of 12.5 hours. The white dwarf produces pronounced excitation and heating effects in the K-type star's atmosphere. The white dwarf's mass is about 0.6 that of the Sun, but its diameter is only 16,000 km (10,000 miles); hence, its density is about 650,000 times that of water.

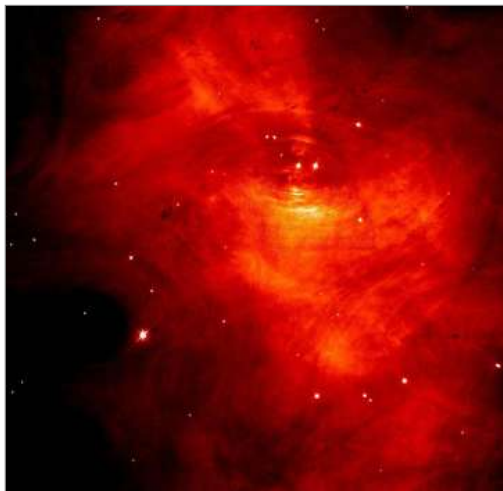
## **Neutron stars**

When the mass of the remnant core lies between 1.4 and about 2 solar masses, it apparently becomes a neutron star with a density more than a million times greater than even that of a white dwarf. Having so much mass packed within a ball on the order of 20 km (12 miles) in diameter, a neutron star has a density that can reach that of nuclear values, which is roughly 100 trillion ( $10^{14}$ ) times the average density of solar matter or of water. Such a star is predicted to have a crystalline solid crust, wherein bare atomic nuclei would be held in a lattice of rigidity and strength some 18 orders of magnitude greater than that of

steel. Below the crust, the density is similar to that of an atomic nucleus, so the residual atomic cores lose their individuality as their nuclei are jammed together to form a nuclear fluid.

Although neutron stars were predicted in the 1930s, it was not until the late 1960s that observers accidentally discovered a radio source emitting weak pulses, each lasting about 0.3 second with a remarkably constant period of approximately 1.337 seconds. Other examples of such an object, dubbed a pulsar for “pulsating radio star,” were soon found.

A large body of evidence now identifies pulsars as rotating magnetized neutron stars. All the energy emitted in the pulses derives from a slowing of the star’s rotation, but only a small fraction is released in the form of radio-frequency pulses. The rest goes into pulses observed elsewhere in the electromagnetic spectrum and into cosmic rays, with perhaps some going into the emission of gravitational energy, or gravity waves. For example, the pulsar at the centre of the Crab Nebula, the most well-known of modern supernovas, has been observed not only at radio frequencies but also at optical and X-ray frequencies, where it emits 100 and 10,000 times, respectively, as much radiation as in the radio spectrum. The slowing of the pulsar’s spin also supplies the energy needed to account for the nonthermal, or synchrotron, emission from the Crab Nebula, which ranges from X-rays to gamma rays.



#### **Crab pulsar**

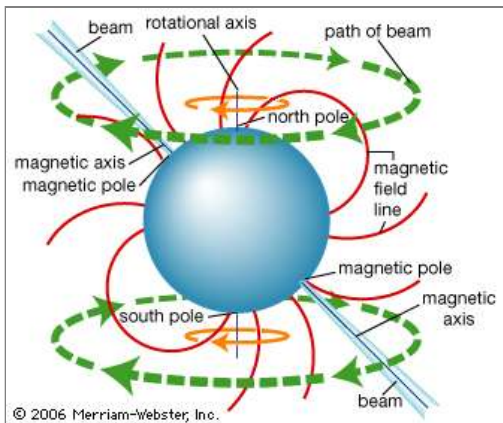
Crab pulsar (NP 0532), as observed by the Hubble Space Telescope. The pulsar is the left member of a pair of stars near the centre of the picture. Its energy fuels the glowing centre of the Crab Nebula.

*Photo AURA/STScI/NASA/JPL (NASA photo # STScI-PRC96-22a)*

Pulsar radiation is polarized, both linearly and circularly, and can be understood in terms of a rotating star having a powerful magnetic field of a trillion gauss. (By contrast, Earth’s magnetic field is about 0.5 gauss.) Various mechanisms have been proposed whereby charged particles can be accelerated to velocities close to that of light itself. Possibly most, if not all, galactic cosmic rays originate from supernovas and remnant pulsars.

Modern observations have recorded sudden changes in the rotation rates of pulsars. The Vela pulsar, for instance, has abruptly increased its spin rate several times. Such a period change or “glitch” can be explained if the pulsar altered its radius by about one centimetre; this sudden shrinkage of the crust is sometimes called a “starquake.” Pulsar phenomena apparently last much longer than the observable supernova remnants in which they were born, since well more than 2,500 pulsars have been cataloged and only a few are associated with well-known

remnants. Even so, the statistics of pulsars are likely to be observationally biased, since signals from pulsars at great distances in the Galaxy become distorted by ionized regions of interstellar space.



### pulsar

A pulsar emits two beams of electromagnetic radiation along its magnetic axis. If the magnetic axis is offset from the rotational axis, as the star rotates, the beams will sweep out circular paths instead of remaining in one position. An observer in the path of such a beam will thus detect a periodic pulse of radiation as the beam sweeps by.

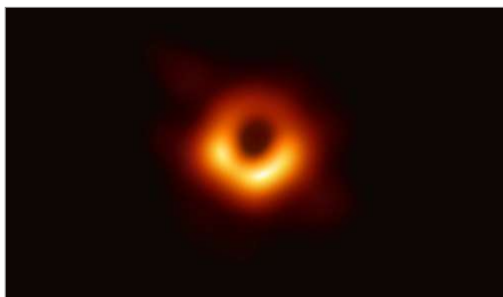
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## Black holes

If the core remnant of a supernova exceeds about two solar masses, it continues to contract. The gravitational field of the collapsing star is predicted to be so powerful that neither matter nor light can escape it. The remnant then collapses to a black hole—a singularity, or point of zero volume and infinite density hidden by an event horizon at a distance called the Schwarzschild radius, or gravitational radius. Bodies crossing the event horizon, or a beam of light directed at such an object, would seemingly just disappear—pulled into a “bottomless pit.”

The existence of black holes is well established, both on a stellar scale, such as exists in the binary system Cygnus X-1, and on a scale of millions or billions of solar masses at the centre of some galaxies, such as M87. (See quasar.)

Lawrence Hugh Aller Eric J. Chaisson John Donald Fernie  
Kenneth Brecher



### black hole in M87

Black hole at the centre of the massive galaxy M87, about 55 million light-years from Earth, as imaged by the Event Horizon Telescope (EHT). The black hole is 6.5 billion times more massive than the Sun. This image was the first direct visual evidence of a supermassive black hole and its shadow. The ring is brighter on one side because the black hole is rotating, and thus material on the side of the black hole turning toward Earth has its emission boosted by the Doppler effect. The shadow of the black hole is about five and a half times larger than the event horizon, the boundary marking

the black hole's limits, where the escape velocity is equal to the speed of light.

*Event Horizon Telescope collaboration et al.*

#### **CITATION INFORMATION**

**ARTICLE TITLE:** Star

**WEBSITE NAME:** Encyclopaedia Britannica

**PUBLISHER:** Encyclopaedia Britannica, Inc.

**DATE PUBLISHED:** 22 August 2019

**URL:** <https://www.britannica.com/science/star-astronomy>

**ACCESS DATE:** November 19, 2019