CHAPTER 27

The life cycle of stars

Stars evolve and eventually 'die'

The life cycle of a star from pre-birth to its eventual demise is a very different process for stars with different masses. Smaller stars take their time, last a lot longer and eventually fade away. The more massive stars shine extremely brightly, consume their nuclear fuel relatively quickly and end their lives in one of nature's truly spectacular ways, finally becoming what is probably the most mysterious object known—a black hole.

27.1 The birth of a star

■ *Describe the processes involved in stellar formation*

For a star to be able to fuse hydrogen in its core, extremely high pressure and temperatures are required. These conditions can only exist at the centre of a star that has sufficient mass to allow gravity to first produce them and then maintain them once fusion commences. It is known that there are regions in our galaxy where large quantities of interstellar gas (mainly hydrogen) and dust exist, and that within these, hidden from our view, new stars are forming. With our ability to peer through the veil of dust and gas, modern astronomical observations confirm these theories.

Figure 27.1 A region of dust and gas in our galaxy known as the Eagle Nebula in which new stars are believed to be forming (photo from Hubble Space Telescope)

The larger regions of gas and dust are called large molecular clouds, and are visible as nebula (see Fig. 27.1). It is within these clouds that gravity acts on more dense 'clumps' of matter. If the matter was spread uniformly throughout the cloud, this would not occur.

As a denser region of dust and gas gradually coalesces due to gravitational force, more and more material is drawn in. The gravitational energy lost by this material is transformed into kinetic energy, which is radiated away as heat. The protostar begins to take shape, radiating energy primarily in the infrared part of the electromagnetic spectrum, but it may also begin to glow and emit light. The surrounding interstellar gas and dust keep the protostar hidden from view. If the inward gravitational forces within the protostar continue to overcome the outward expansive forces of heat and radiation, the pressure in the centre of the protostar continues to increase.

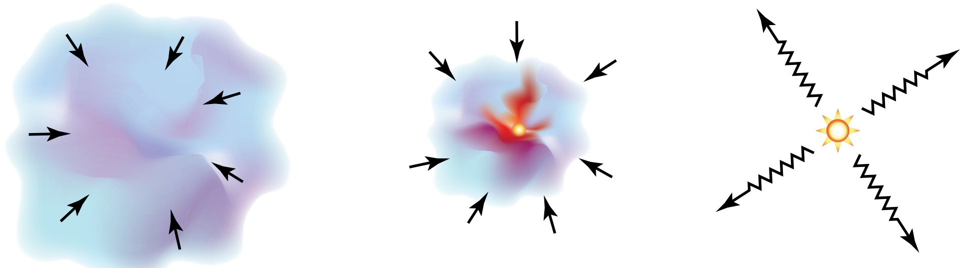
There comes a stage when the core of the protostar becomes so hot and dense that hydrogen fusion commences. The newly born star throws off the veil of surrounding material due to its stellar wind and radiation. Depending on its mass, it will spend the next few tens of millions to over 10 billion years fusing its supply of hydrogen into helium as a main-sequence star. Figure 27.3, an image taken through NASA's Spitzer Space Telescope in the

Figure 27.2 Two images: the first taken in visible light (left) and the same region of space taken in infrared (right); the two protostars are clearly seen in the lower image

Figure 27.3 Stars forming in their molecular clouds, taken by the Spitzer Space Telescope in 2008

infrared region of the spectrum, shows stars forming by being able to see through the blanketing dust and gas clouds that surround such stars.

Our knowledge of star formation has increased dramatically in recent years due largely to the observations made by the Chandra X-Ray Observatory and the Spitzer Space Telescope. The birth of stars is difficult to view using visible light observations as the molecular clouds of dust and gas from which the stars form prevent visible light from passing through. X-rays and infrared radiation, however, can penetrate these clouds, allowing direct observations for the first time. Both observatories were launched into Earth orbit (Chandra in 1999 and Spitzer in 2003) so that the atmosphere would not absorb the desired radiation before being collected in the instruments.



(a) A region of gas and dust gradually coalesces under the attractive force of gravity

(b) A central core becomes hotter and denser, emitting infrared radiation

(c) The star's core begins to fuse hydrogen—the star is born, blowing off surrounding material

Figure 27.4 The stages involved in stellar formation

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USEFUL WEBSITE

More images from NASA's Spitzer Space Telescope and information about star formation: http://www.nasa.gov/mission_pages/spitzer/multimedia/20080211-b.html

27.2 The key stages in a star's life

■ ***Outline the key stages in a star's life in terms of the physical processes involved***

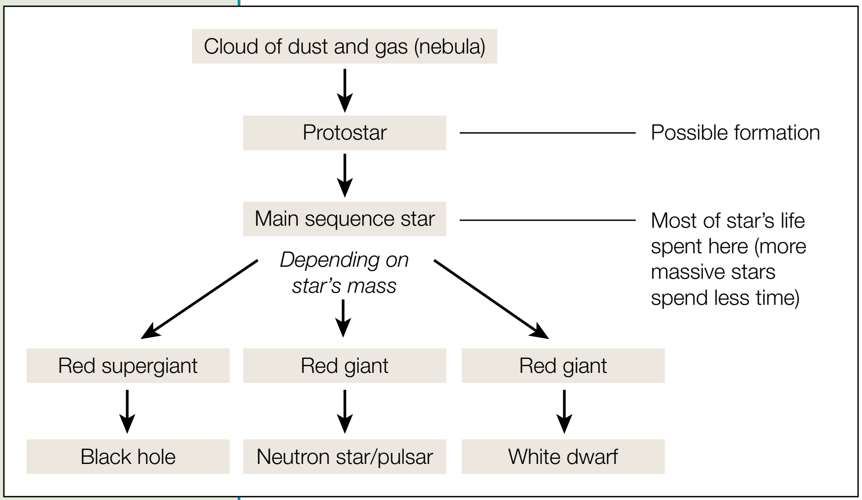


Figure 27.5 Flow chart showing the main stages of a star's life

The stages of a star's life can be summarised in a flow chart (see Fig. 27.5).

The protostar stage, in which gravity is pulling in more material from the surrounding gas and dust cloud, does not involve nuclear reactions. The source of energy is the transformation of lost gravitational potential energy from the material. It is not until the commencement of nuclear fusion of hydrogen into helium within its core that the star is truly 'born'. For the star to remain stable on the main sequence, there must be an equilibrium between the outward radiative force and the pressure of the gas in the star against the inward force of gravity. The greater the mass of the star, the greater the force of gravity, allowing greater density and temperature in the core. This in turn results in the rate of the nuclear fusion reactions being greater, so that the surface temperature of the star is higher. Stars with the same mass as the Sun have surface temperatures of about 5850 K, while stars with about 10 solar masses are very hot blue-white stars of around 20 000 K or greater. These stars may consume their nuclear fuel in only a few tens of millions of years, which is why they are quite rare. The least massive stars of about 0.1 solar masses are small red main-sequence stars, consuming their nuclear fuel so slowly that it is believed they may be as old as the Universe itself.

The following stage of a star's life occurs when the hydrogen fuel has been depleted to the extent that the core of the star collapses. Gravity takes over, elevating the core's density and temperature. The layer of helium that has formed around the core is compressed to such an extent that the fusion of helium into carbon begins—the 'helium flash'. Such processes, known as post-main-sequence nuclear reactions, are discussed in more detail in the following section.

27.3 Types of nuclear reactions within stars and the synthesis of elements

■ ***Describe the types of nuclear reactions involved in Main-Sequence and post-Main Sequence stars***

■ ***Discuss the synthesis of elements in stars by fusion***

Main-sequence stars are ones that, when plotted on an HR diagram, lie within a band stretching from the upper left to the lower right. It is not a sequence as such, but the region can easily be wrongly interpreted as one. It is believed that, due to the relationship with mass, luminosity and size of all main-sequence stars, they have a common nuclear energy source—the fusion of hydrogen nuclei into helium nuclei.

A hydrogen nucleus is a single proton. A star is composed initially of hydrogen. To synthesise a helium nucleus, four hydrogen nuclei are needed. The probability of a collision involving four hydrogen nuclei simultaneously in such a manner that, instead of glancing off one another they react in exactly the right way to form a helium nucleus, is so small that such a mechanism can be discounted. The energy required for this collision to be successful is also too high for it to be considered as contributing to a star's energy output.

The proton–proton chain

A more probable step-wise reaction in the core of stars has a much greater chance of occurring. At the temperatures and pressures present, it is the likely pathway. Known as the proton–proton chain, it only involves the collision of two particles at a time—an event with much greater probability and therefore occurring far more frequently.

Figure 27.6 outlines the reactions involved in the proton–proton chain.

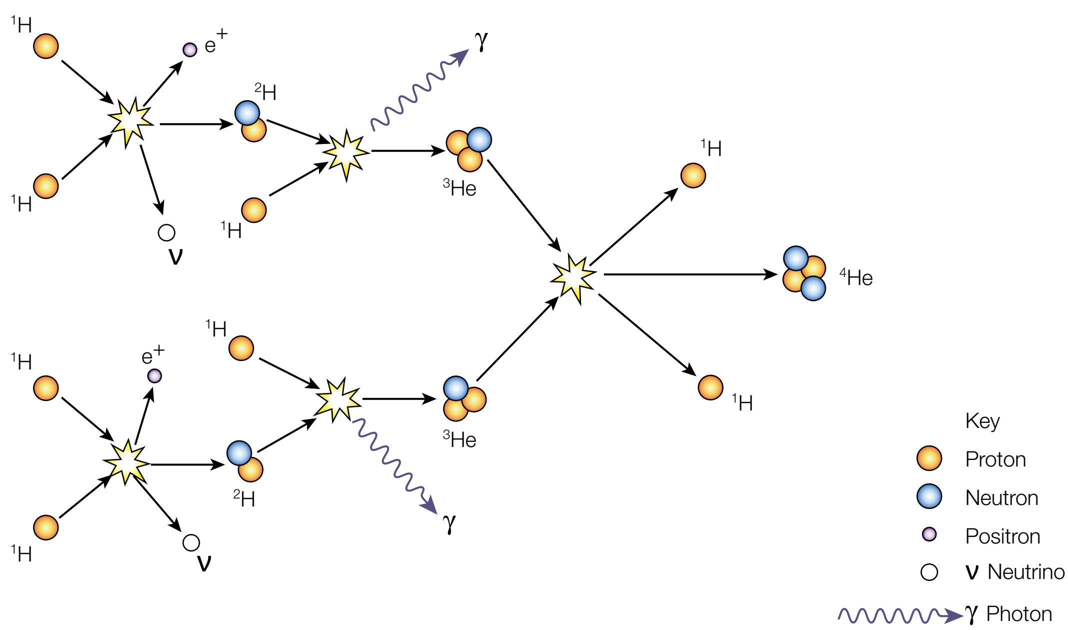


Figure 27.6 Steps in the proton–proton chain

The net equation for this form of the proton–proton chain is:

$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2e^{+} + 2v + 2\gamma$$

Where:
v = a neutrino
γ = a gamma ray

Although six hydrogen nuclei are involved in the production of the helium nucleus, two of these are released. The gamma radiation is released as photons with very high energy, while the positrons are the anti-matter equivalent of electrons. The two near massless neutrinos produced carry away energy at close to the speed of light, rarely interacting with matter.

Interesting fact: Neutrinos interact so rarely that it is estimated that billions pass through us every second. A few neutrinos are detected each day in huge underground water tanks when a neutrino interacts with a water molecule and a small flash of light is subsequently emitted.

WWW→

USEFUL WEBSITES

The Sudbury Neutrino Observatory:
http://www.sno.phy.queensu.ca/

The Ice Cube Neutrino Observatory in Antarctica:
http://icecube.wisc.edu/

While there are believed to be other forms of the proton–proton chain, the above process accounts for an estimated 85% of the energy produced in the Sun. Stars with masses up to approximately 1.5 solar masses with core temperatures of up to 18 million K also produce the majority of their energy in this way.

Another pathway leads to a nearly identical overall reaction, but requires the presence of carbon-12 and temperatures over 18 million K to proceed. It is known as the CNO cycle.

The CNO cycle

The carbon–nitrogen–oxygen (CNO) cycle is a pathway for nuclear fusion that commences with the fusion of one proton with a carbon-12 nucleus, a reaction known to occur at temperatures above 18 million K. The carbon-12 undergoes transmutation to nitrogen-13, but it re-emerges after several more steps in the process, acting in a similar way to a catalyst in a chemical reaction. Figure 27.7 shows the steps involved in the CNO cycle.

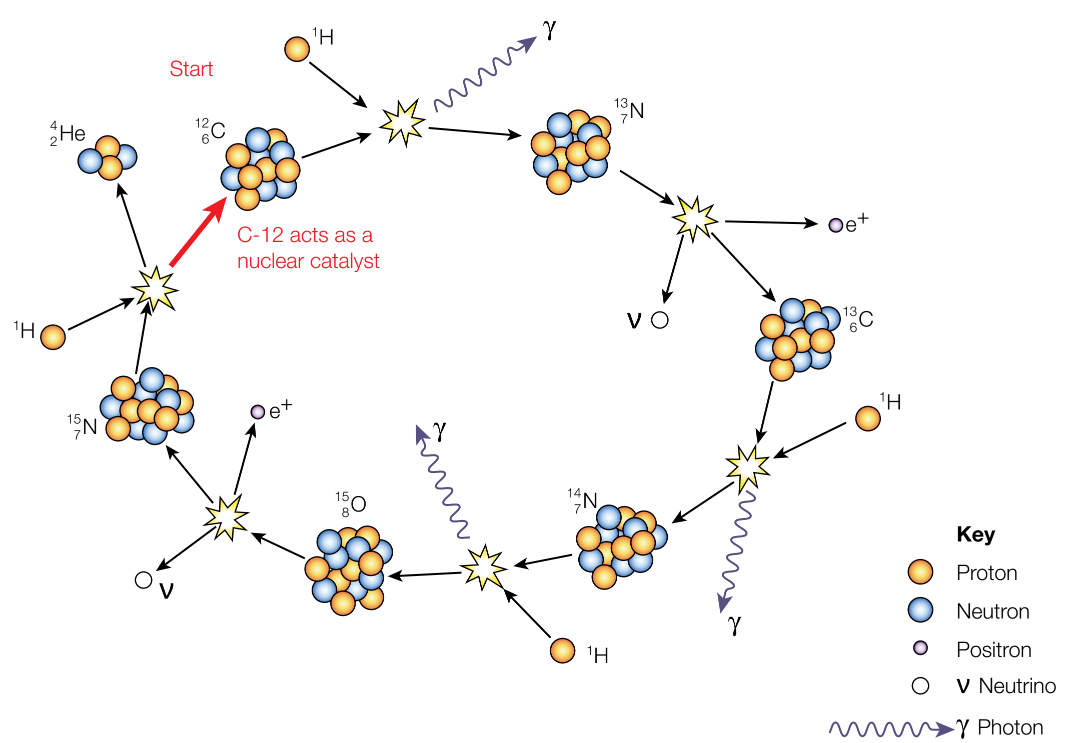


Figure 27.7 The CNO cycle showing the steps in the fusion of hydrogen to helium nuclei

It can be seen that at no stage in the CNO cycle is a collision between more than two particles required. The carbon-12 is transmutated several times until the last step when, by alpha decay, a nitrogen-15 nucleus decays back to the carbon-12 nucleus.

The net equation for the CNO cycle is $4\,^{1}_{1}H \rightarrow \,^{4}_{2}He + 2e^{+} + 2v + 3\gamma$

The overall equations for the proton-proton chain and the CNO cycle are nearly identical. Four protons produce one helium nucleus, with the release of energy. The source of the energy is in fact a slight decrease in the mass of the products of the process when compared with the reactants.

Post-main-sequence stars

Once a star has consumed most of its hydrogen fuel, the core will begin to collapse and a layer of extremely hot helium nuclei, which has built up during the main-sequence stage of the star's life, will surround the core. The mass of the star will determine what happens next. With sufficient mass, a star's gravitational force will be able to sustain the density necessary for helium to fuse into heavier elements such as carbon and oxygen. This process commences as the 'helium flash', resulting in the star becoming a red giant. Very massive stars are able to continue fusing elements all the way to the formation of iron. These fusion reactions are all 'exothermic', that is, they release energy and thus provide the outward forces of radiation, preventing the star from collapsing under its own gravity. The formation of elements heavier than iron is unsustainable, as such fusion requires a net input of energy. The existence of these heavier elements found on Earth is due to supernova, which must have occurred before the formation of our solar system.

In large post-main-sequence stars, the heavier elements are drawn towards the centre of the star, building up into layers, with the heavier elements closer to the core in an onion-like fashion (see Fig. 27.8). Once one of these very massive stars has exhausted or depleted its supply of nuclear fuel, the core succumbs to the force of gravity, and begins to collapse. The release of gravitational potential energy causes a temperature increase which, with the increase in pressure, sets off one of the most energetic processes known—a supernova. Layers of synthesised elements surrounding the core fuse into heavier elements, blowing off a large proportion of the outer layers of the star into space at great speed. The equal and opposite action is directed towards the inner core, compressing it to such an extent that elements heavier than iron may be created. The residual core of the star, if sufficiently massive, may continue to collapse as protons and electrons become neutrons. The star shrinks as matter as we know it condenses into neutrons.

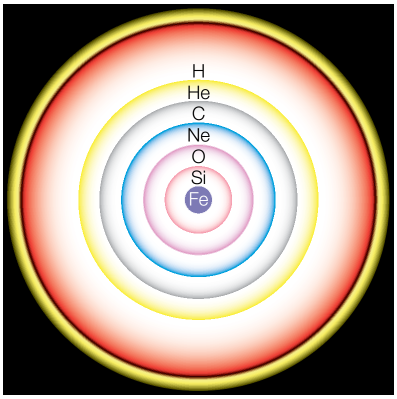


Figure 27.8 The onion-layer-like structure of a post-main-sequence massive star

Plotting stars on a Hertzsprung-Russell diagram

FIRST-HAND INVESTIGATION

PHYSICS SKILLS

H13.1E, F
H12.4B

- ***Present information by plotting Hertzsprung-Russell diagrams for: nearby or brightest stars, stars in a young open cluster, stars in a globular cluster***

WWW→ **USEFUL WEBSITES**

Stellar evolution and the HR diagram:
http://www.mhhe.com/physsci/astronomy/applets/Hr/frame.html

University of NSW information on a globular cluster and its HR diagram plot:
http://www.phys.unsw.edu.au/astro/wwwlabs/gcCm/gcCm_intro.html

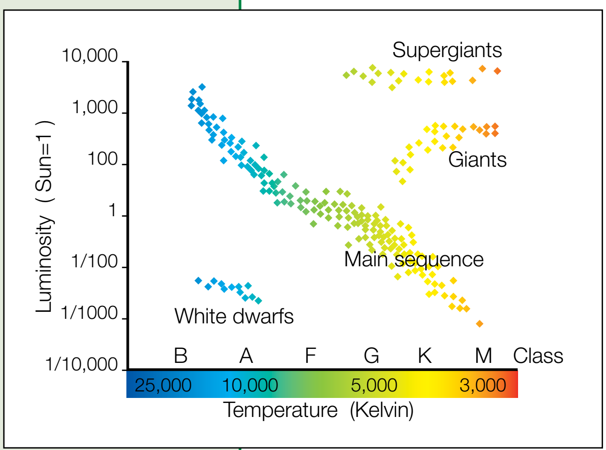


Figure 27.9
A typical HR diagram with stellar types shown

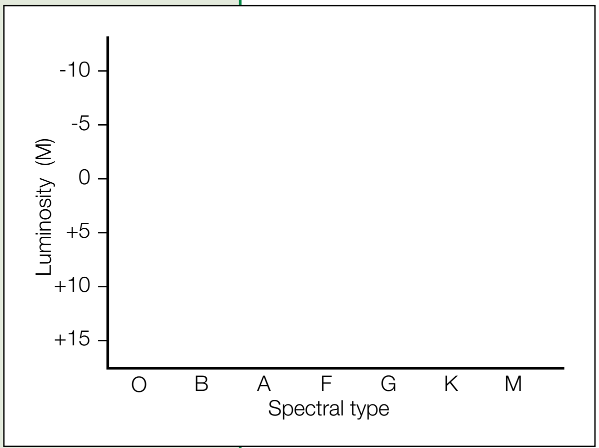
The HR diagram is a very useful tool for astronomers. There are several variations of the labels used for both the vertical (luminosity) and the horizontal (temperature) axes. Figure 27.9 shows a typical HR diagram with the regions where several star types are found.

When plotting information on an HR diagram, the horizontal axis scale may be either surface temperature or the corresponding spectral types. When using the spectral type scale, each individual type is further divided into its 10 sub-types, from 0 to 9. In the tables shown here, the spectral type is a letter followed by a sub-division number. For example, K2 is a K type spectral type with a sub-type 2. The next spectral type after K9 is M0 in this system. The vertical axis scale of luminosity is either in reference to the Sun or given as absolute magnitude, M. The tables give the values of the stars' absolute magnitudes.

Task 1: The brightest stars

Table 27.1 lists the 20 brightest stars in the night sky. Use the information provided to plot the stars on a HR diagram. Choose the scale of the axes carefully before commencing so that all the stars fit on your diagram. The horizontal axes should always show the full range of stellar spectral types, from O to M. Figure 27.10 shows the axes for a typical HR diagram.

Figure 27.10
A typical HR diagram axes with scales shown using spectral type on the horizontal axis



Task 2: The nearest stars

Use the information available in Table 27.2 to plot the stars onto the same HR diagram as used in Task 1. Use a different colour for this task. Compare and contrast the results of the two groups of stars.

Task 3: Open clusters

Plot the 20 stars from an open cluster found in Table 27.3, on the same HR diagram as previously. Use a different colour. Again, compare and contrast the position of this group of stars with the previous groups.

When the HR plots of the three sets of stars—the brightest stars, the nearest stars and stars in an open cluster—are

Table 27.1 The 20 brightest stars in the night sky

Star	Apparent magnitude, v	Absolute magnitude, M	Spectral type
Sirius	1.45	+ 1.41	A1
Canopus	0.73	+ 0.16	F0
Rigel Kentaurus	0.10	+ 4.3	G2
Arcturus	0.06	– 0.2	K2
Vega	0.04	+ 0.5	A0
Capella	0.08	– 0.6	G8
Rigel	0.11	– 7.0	B8
Procyon	0.35	+ 2.65	F5
Achernar	0.48	– 2.2	B5
Hadar	0.60	– 5.0	B1
Altair	0.77	+ 2.3	A7
Betelgeuse	0.80	– 6.0	M2
Aldebaran	0.85	– 0.7	K5
Acrux	0.9	– 3.50	B2
Spica	0.96	– 3.4	B1
Antares	1.0	– 4.7	M1
Pollux	1.15	+ 0.95	K0
Fomalhaut	1.16	+ 0.08	A3
Deneb	1.25	– 7.3	A2
Mimosa	1.26	– 4.7	B0

Table 27.2 The 20 closest stars

Star	Distance (l.y.)	Apparent magnitude	Absolute magnitude	Spectral type
Proxima Centauri	4.2	11.1	15.5	M5
Rigil Kentaurus	4.3	– 0.01	4.4	G2
Alpha Cen B	4.3	1.33	5.7	K1
Barnard's Star	6.0	9.54	13.2	M4
Wolf 359	7.7	13.5	16.7	M6
BD +362147	8.2	7.5	10.5	M2
Luyten 726-8A	8.4	12.5	15.5	M6
Luyten 726-8B	8.4	13.0	16.0	M6
Sirius A	8.6	– 1.46	1.4	A1
Sirius B	8.6	8.3	11.2	A
Ross 154	9.4	10.45	13.1	M4
Ross 248	10.4	12.29	14.8	M5
Epsilon Eri	10.8	3.73	6.1	K2
Ross 128	10.9	11.1	13.5	M4
61 Cyg A	11.1	5.2	7.6	K4
61 Cyg B	11.1	6.0	8.4	K5
Epsilon Ind	11.2	4.7	7.0	K3
BD +4344A	11.2	8.1	10.4	M1
BD +4344B	11.2	11.1	13.4	M4
Procyon A	11.4	0.4	2.6	F5

Table 27.3 Information on some of the stars in open cluster M44

Star number	Apparent magnitude, v	Absolute magnitude, M	Spectral type
1	6.6	5.3	G0
2	6.8	5.5	A5
3	7.8	6.6	F7
4	7.5	6.2	A9
5	6.7	5.4	F0
6	7.7	6.5	A5
7	7.7	6.4	A7
8	6.6	5.3	K0
9	7.3	6.1	A
10	7.5	6.3	A
11	6.4	5.1	K0
12	6.6	5.4	A1
13	7.5	6.2	F0
14	6.8	5.5	A9
15	7.7	6.5	F2
16	6.4	5.2	K0
17	6.3	5.1	A
18	7.8	6.6	A9
19	6.9	5.6	A9
20	8.0	6.7	A7

Table 27.4 Information on some stars in a typical globular cluster

Star number	Absolute magnitude, M	Spectral type
1	– 2.0	K9
2	+ 0.1	F7
3	– 1.0	K5
4	+ 1.2	G0
5	+ 3.1	F9
6	+ 14.0	M3
7	+ 7.4	G4
8	– 0.8	K5
9	+ 12.8	M0
10	– 1.9	M1
11	+ 6.9	G6
12	– 0.9	K0
13	+ 10.2	K6
14	– 4.9	M5
15	+ 2.9	F6
16	– 2.5	M1
17	+ 4.2	F7
18	+ 5.0	G2
19	+ 7.0	G9
20	+ 8.4	K3

compared and contrasted, it becomes apparent how different they are. The brightest stars have a greater proportion of large, luminous stars, some of which are hundreds of light-years from Earth, yet still rank in the top 20 brightest stars. In contrast, the closest 20 stars include many smaller, less luminous red stars and white dwarfs. The open cluster is seen to have almost all of its stars on the main sequence, showing that they are relatively young, not having evolved into the red giant stage.

Figure 27.11 M15, a typical globular cluster

Using the HR diagram to determine a star's evolutionary stage

FIRST-HAND INVESTIGATION

PHYSICS SKILLS

H14.1A, B, E, F, G, H
14.3A, C, D

■ ***Analyse information from a HR diagram and use available evidence to determine the characteristics of a star and its evolutionary stage***

Figure 27.9 shows the regions on a HR diagram where the different classes of stars are found. Figure 27.13 shows the evolutionary paths of stars with different masses. From these diagrams, it can be seen that a star will move in from the left of the main sequence, the vertical position being dependent upon the mass of the forming star. Once the protostar commences hydrogen fusion, it will 'land' on the main sequence, the exact location again being dependent on its mass. Analysis of a star's spectrum, especially the width of the spectral lines, reveals information about the density of the atmosphere of the star and hence whether the star is indeed a main-sequence star, a giant or supergiant (which have less dense atmospheres and thinner, sharper spectral lines).

Towards the end of a star's life, the giant stage can be identified by the vertical position (highly luminous) and the thin, sharp spectral lines (less dense atmosphere). At the end of its life on the HR diagram, a white dwarf has low luminosity, relatively high temperature but spectral lines indicating that it has a thicker, denser atmosphere.

27.4 Determining the age of globular clusters

■ ***Explain how the age of a globular cluster can be determined from its zero-age main-sequence plot for a HR diagram***

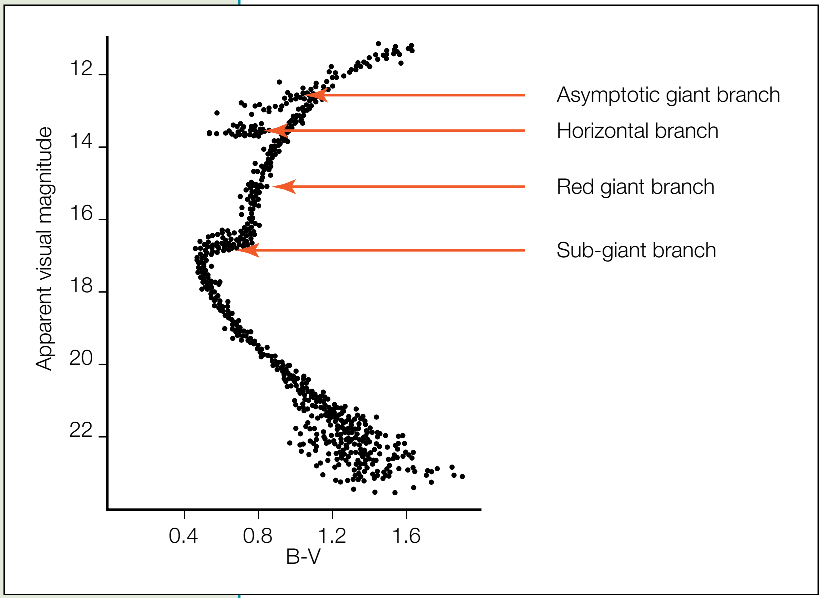
Figure 27.12 shows the HR diagram plot for stars in a globular cluster called 47 Tucanae. Over 100 globular clusters have been found around the edges of our galaxy. It is believed that they are some of the oldest objects in the Universe, having coalesced around 12 billion years ago. Their age rivals that of our galaxy, the Milky Way. They are called 'globular' due to the way they appear through a telescope. With hundreds of thousands or even millions of stars in the cluster, individual stars closer to the centre cannot be resolved. Astronomers are able to assign an individually resolved star to a cluster due to its common proper motion with the cluster. (Proper motion is the motion of a star or group of stars against very distant background stars.) Such stars are the ones which can be plotted to give HR diagram plots such as Figure 27.12 for 47 Tucanae.

WWW→

USEFUL WEBSITE

Animations and movies showing the appearance and the structure of globular clusters:
http://terpsichore.stsci.edu/~summers/viz/starsplatter/spz/spz.html

Figure 27.12
A HR diagram plot of the stars in the globular cluster 47 Tucanae



It is clear that, despite so many stars being plotted in Figure 27.12, there are no large, luminous main-sequence stars in the cluster. The larger, more massive stars have depleted their supply of hydrogen and have moved off the main sequence onto the 'red giant branch' or 'sub-giant branch' of the HR diagram. The smaller, less massive stars, which take longer to consume their hydrogen, are still on the main sequence, despite their comparatively old age. Our Sun is expected to take about 10 billion years to deplete its hydrogen with less massive stars taking a lot longer.

The point on the main sequence where the star plot turns off onto the sub-giant and red giant branches is known as the turn-off point. Once the position of the turn-off point for a globular cluster is found, its age can be determined.

The evolutionary paths of stars with different masses

SECONDARY SOURCE INVESTIGATION

PFAs

H5

PHYSICS SKILLS

H13.1E, F
H12.4B

■ *Present information by plotting on a HR diagram the pathways of stars of 1, 5 and 10 solar masses during their life cycle*

The position of a star on the main sequence is determined by its mass, as discussed. The evolutionary path the star will take as a post-main-sequence star is also dependent on the star's mass. A star with a mass equal to the Sun is said to have one solar mass. On the main sequence, its position as a G2 star with an absolute magnitude of +5 is how the star spends most of its existence. At around 10 billion years of age, it evolves off the main sequence into a red sub-giant, as depicted in Figure 27.9.

A five solar mass star on the main sequence is approximately 100 times more luminous than the Sun, with an absolute magnitude around –2. Its surface temperature, close to 13 000 K, means that its spectral type is B. In a much shorter time than a one solar mass star, this star will evolve into a red giant once it has depleted its reserves of hydrogen. A star with 10 solar masses may have a surface temperature of around 20 000 K, still of spectral type B, but about 1000 times more luminous than the Sun. Conditions within its core are so severe that, despite having much more hydrogen to begin with, the star will evolve rapidly into a red giant in around 100 million years. Figure 27.12 shows this information on an HR diagram.

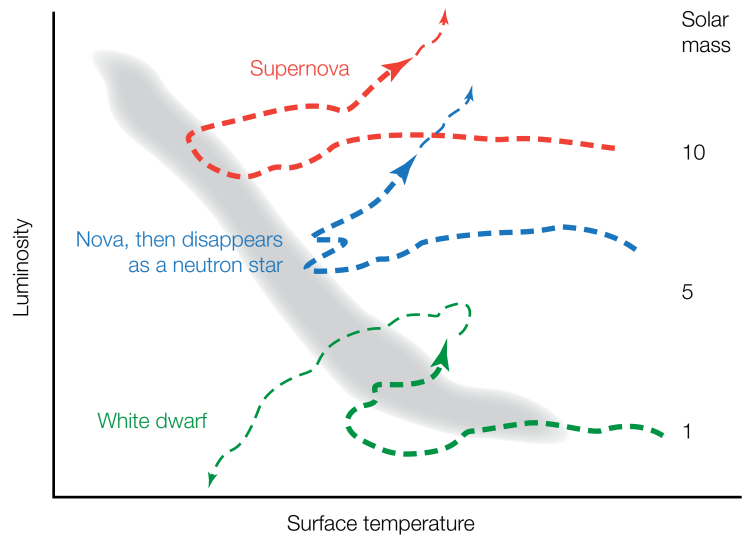


Figure 27.13 The evolutionary pathways of stars with one, five and 10 solar masses

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USEFUL WEBSITES

Stellar evolution and the HR diagram:
http://www.mhhe.com/physsci/astronomy/applets/Hr/frame.html

Simulations of stellar evolution with user input of the mass of the star:
http://instruct1.cit.cornell.edu/courses/astro101/java/evolve/evolve.htm

Stellar evolution on an HR diagram for stars with different masses, until near the end of their lives:
http://www.astro.ubc.ca/~scharein/a311/Sim/hr/HRdiagram.html

27.5 The death of stars

- ***Explain the concept of star death in relation to:***
  - ***planetary nebula***
  - ***supernovae***
  - ***white dwarfs***
  - ***neutron stars/pulsars***
  - ***black holes***

Figure 27.14 A Hubble Space Telescope photograph of the Cat's Eye Nebula

Planetary nebula

Planetary nebulae are so called because of how they first appeared to astronomers using telescopes. The first planetary nebula observed were fuzzy discs of light that looked similar to a planet. Improved resolution and photographic techniques revealed the true nature of the discs as glowing gas surrounding a central star.

Planetary nebulae are formed when a star of about two solar masses or less comes to the final stages of fusing helium in the shell surrounding a core of carbon and oxygen that has built up as products of the fusion. The star becomes unstable, but is not capable of fusing heavier elements due to its smaller mass. Eventually the star pulsates so violently that it throws off its outer layers of material into space. This gaseous material glows from the radiation being emitted from the remaining central part of the star. The leftover material no longer fuses elements, and collapses to form a white dwarf. The colours and patterns observed in fine detail make planetary nebulae some of the most spectacular objects in the sky. Figure 27.14 is a planetary nebula known as the Cat's Eye, one of about 1500 known such nebulae in the Milky Way.

Supernovae

A very large star nearing the end of its evolutionary life cycle has built up layers of heavier elements, with iron being the heaviest possible. The heavier elements sink towards the core. The depletion of sufficient nuclear fuel for the process to continue results in the collapse of the star under its own gravitational force. When this happens, a huge amount of gravitational potential energy is released, super-heating the collapsing matter and igniting an explosion that has such force that the star is blown apart. The energy released can be greater than all the energy released in 10 billion years by the Sun, and can, for a short time, rival the energy from an entire galaxy. The matter spreading out from the exploding star glows and emits gamma radiation and X-rays. This highly luminous matter can become visible from Earth to the naked eye. Early astronomers wrongly assumed that this was a new star, hence the name. However supernovae only glow with such intensity for a few days or weeks. The left-over material, if having a mass of more than 1.4 solar masses, will collapse into a neutron star and possibly further into a black hole, from which not even light can escape.

Another type of supernova, type 1a, is not associated with star death. White dwarf stars caught in a binary system may be drawing in matter from their partner star. This increases their mass until it triggers a burst of nuclear fusion. The outer layers of the star are blown off, causing it to increase in luminosity by a million times, again for only a short period of time.

White dwarfs

White dwarfs are not true stars, as they are not fusing hydrogen or other elements in their cores. A white dwarf is the collapsed inner portion of an older star that has remained behind after the planetary nebula stage. It is comprised primarily of oxygen and carbon. The surface of a white dwarf is white hot due to the small surface area for the amount of residual heat being radiated. A white dwarf is about the same size as Earth, which has one-thousandth the diameter of the Sun. In time, a white dwarf will cool until it becomes almost undetectable; however, it is thought that no white dwarf has yet had sufficient time for this to occur. The mass of a white dwarf must be less than 1.4 solar masses, otherwise the gravitational force will cause electrons and protons to combine to form a neutron star.

Figure 27.15 The Crab Nebula, remnants of the 1054 supernova

A white dwarf has a very low luminosity due to the comparatively small surface area of these objects. They have a typical absolute magnitude of around +11 to +15, that is, between 250 and 10 000 times less luminous than the Sun.

Neutron stars/pulsars

The residual matter left over after a star has passed through the planetary nebula or supernova stage may form a white dwarf. If the total residual mass exceeds 1.4 solar masses, the collapse of normal matter as we know it occurs as gravity forces the electrons and protons to merge and form a continuous type of extremely dense matter: a neutron star. Instead of being the size of the Earth, a neutron star may have a diameter of only 10 to 20 km.

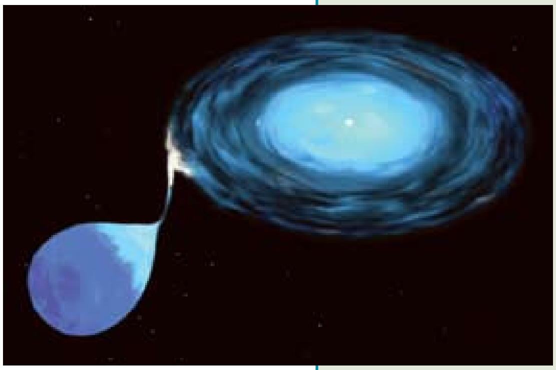
Like a spinning top, most stars possess angular momentum. This angular momentum is conserved as the star collapses, which results in the speed of rotation increasing. The original star may have been rotating with a period of days or weeks, but with the conservation of angular momentum, the period of rotation of the neutron star may be in the order of milliseconds. A dancer or ice-skater uses the same principle to increase their speed of rotation by pulling in their arms when spinning.

When radio signals from pulsars were first detected using radio telescopes, it was thought by some that they were originating from another advanced life form, such was their regular nature. It is now known that rapidly spinning neutron stars can emit an intense, focused beam of radio waves similar to a lighthouse and its sweeping beam of light. If Earth happens to be in the line of this emission, radio telescopes pick up the regular radio pulses. The name 'pulsars' reflects this nature.

Black holes

With a mass of greater than five solar masses, the remnant core of a supernova will contract into a neutron star and then continue to contract further into what is known as a singularity. Surrounding this point in space is a region where gravity is so strong that not even light can escape. Black holes are believed to exist due to the emission of X-rays from material being accelerated as it is drawn into the black hole, and by the calculations of the mass that must exist at the centre of our galaxy. If a black hole were to pass between us and a distant galaxy or star, its gravity would bend the light around it, causing 'gravitational lensing', which causes the brief brightening of the distant galaxy. The accretion disc, depicted in Figure 27.16, is formed by the encircling material being consumed by the black hole. Black holes are perhaps the most mysterious objects in the Universe, and are subject to much debate among astronomers. With an infinite density, the core of a black hole has no real dimensions, a concept referred to as a 'singularity'. The matter being pulled into a black hole disappears before reaching the singularity. The point at which it vanishes is called the 'event horizon'.

Figure 27.16 The accretion disk surrounding a black hole pulling matter from a grey star



CHAPTER REVISION QUESTIONS

1. Outline the stages in the formation of a star from a gas and dust (molecular) cloud.
2. Explain why the HR diagram plot of the 20 brightest stars differs significantly from the HR diagram plot of the 20 nearest stars.
3. What event signals the 'birth' of a star from the protostar stage?
4. Four protons are required to fuse to form a helium nucleus. Why are the proton–proton chain and the CNO cycle the suggested mechanisms for fusion within main-sequence stars rather than a single collision between four protons?

5. On suitable axes for an HR diagram, show the regions in which: (a) main-sequence stars; (b) red giants; (c) white dwarfs; and (d) protostars are found. Annotate the diagram to indicate the primary source of energy for stars or protostars for each of the regions.
6. Why is the existence of elements heavier than iron evidence for supernovae?
7. Describe what is meant by the term ‘helium flash’.
8. The HR diagram plots of hundreds of stars in a globular cluster show that there are no main-sequence stars with a mass greater than the Sun. However, there are many red giant stars. What does this tell us about the approximate age of the globular cluster?
9. Outline the differences in the evolutionary paths of stars with one, five and 10 solar masses.
10. Why is a white dwarf not considered a true star?

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Answers to chapter revision questions