The Evolution of the Stars

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Summary

This article contains useful information about stars and stellar evolution for teachers of Physical Science at the secondary school level. It also includes links to the typical school science curriculum, and suggests some relevant activities for students.

Goals

- Understand stellar evolution and the processes that determine it.
- Understand the Hertzsprung-Russel Diagram
- Understand the system of absolute and apparent magnitudes.

Introduction

Stellar evolution means the changes that occur in stars, from their birth, through their long lives, to their deaths. Gravity “forces” stars to radiate energy. To balance this loss of energy, stars produce energy by nuclear fusion of lighter elements into heavier ones. This slowly changes their chemical composition, and therefore their other properties. Eventually they have no more nuclear fuel, and die. Understanding the nature and evolution of the stars helps us to understand and appreciate the nature and evolution of our own Sun - the star that makes life on Earth possible. It helps us to understand the origin of our solar system, and of the atoms and molecules of which everything, including life, is made. It helps us to answer such fundamental questions as “do other stars produce enough energy, and live long enough, and remain stable enough, so that life could develop and evolve on planets around them?” For these and other reasons, stellar evolution is an interesting topic for students.

The Properties of the Sun and Stars

The first step to understand the origin and evolution of the Sun and stars is to understand their properties. Students should understand how these properties are determined. The Sun is the nearest star. The Sun has been discussed in other lectures in this series. In this article, we consider the Sun as it relates to stellar evolution. Students should understand the properties and structure and energy source of the Sun, because the same principles enable astronomers to determine the structure and evolution of all stars.

The Sun

The basic properties of the Sun are relatively easy to determine, compared with those of other stars. Its average distance is $1.495978715 \times 10^{11}$ m; we call this *one Astronomical Unit.* From this, its observed angular radius (959.63 arc sec) can be converted, by geometry, into a linear radius: 6.96265 x 10^8 m or 696,265 km. Its observed flux (1,370 W/m^2) at the earth's distance can be converted into a total power: 3.85 x 10^{26} W.

Its mass can be determined from its gravitational pull on the planets, using Newton's laws of motion and of gravitation: 1.9891 x 10^{30} kg. The temperature of its radiating surface - the layer from which its light comes - is 5780 K. Its rotation period is about 25 days, but varies with latitude on the Sun, and it is almost exactly round. It consists primarily of hydrogen and helium. In activity 2, students can observe the Sun, our nearest star, to see what a star looks like.

The Stars

The most obvious observable property of a star is its apparent brightness. This is measured as a *magnitude*, which is a logarithmic measure of the flux of energy that we receive.

The magnitude scale was developed by the Greek astronomer Hipparchus (c.190-120 BC). He classified the stars as magnitude 1, 2, 3, 4, and 5. This is why fainter stars have more positive magnitudes. Later, it was found that, because our senses react logarithmically to stimuli, there was a fixed *ratio* of brightness (2.512) corresponding to a *difference* of 1.0 in magnitude. The brightest star in the night sky has a magnitude of -1.44. The faintest star visible with the largest telescope has a magnitude of about 30.

The apparent brightness, B, of a star depends on its power, P, and on its distance, D. According to the *inverse-square law of brightness*: the brightness is directly proportional to the power, and inversely proportional to the square of the distance: $B \cong P/D^2$. For nearby stars, the distance can be measured by *parallax*. In Activity 1, students can do a demonstration to illustrate parallax, and to show that the parallax is inversely proportional to the distance of the observed object. The power of the stars can then be calculated from the measured brightness and the inverse-square law of brightness.

Different stars have slightly different *colour*; you can see this most easily by looking at the stars Rigel (Beta Orionis) and Betelgeuse (Alpha Orionis) in the constellation Orion (figure 1). In Activity 3, students can observe stars at night, and experience the wonder and beauty of the real sky. The colours of stars are due to the different temperatures of the radiating layers of the stars. Cool stars appear slightly red; hot stars appear slightly blue. (This is opposite to the colours that you see on the hot and cold water taps in your bathroom!) Because of the way in which our eyes respond to colour, a red star appears reddish-white, and a blue star appears bluish-white.

The colour can be precisely measured with a photometer with colour filters, and the temperature can then be determined from the colour.

Fig. 1: The Constellation Orion. Betelgeuse, the upper left star, is cool and therefore appears reddish. Deneb, the lower right star, is hot and therefore appears bluish. The Orion Nebula appears below the three stars in the middle of the constellation.

The star's temperature can also be determined from its spectrum - the distribution of colours or wavelengths in the light of the star (figure 2). This figure illustrates the beauty of the colours of light from stars. This light has passed through the outer atmosphere of the star, and the ions, atoms, and molecules in the atmosphere remove specific wavelengths from the spectrum. This produces dark lines, or missing colours in the spectrum (figure 2). Depending on the temperature of the atmosphere, the atoms may be ionized, excited, or combined into molecules. The observed state of the atoms, in the spectrum, therefore provides information about the temperature.

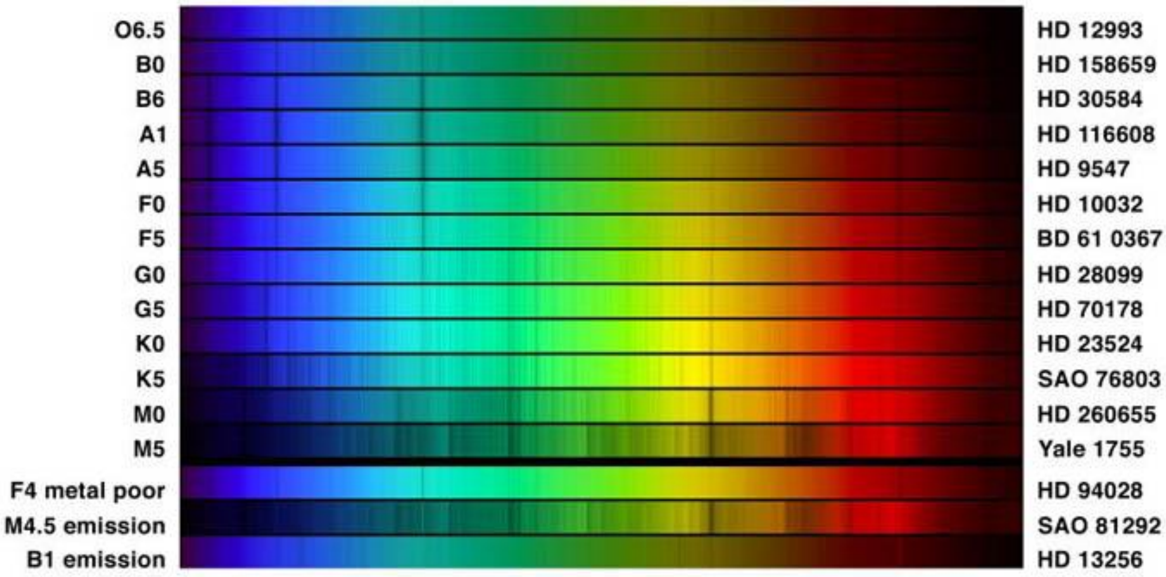

Fig. 2: The spectra of many stars, from the hottest (O6.5: top) to the coolest (M5: fourth from bottom). The different appearances of the spectra are due to the different temperatures of the stars. The three bottom spectra are of stars that are peculiar in some way. Source: National Optical Astronomy Observatory.

A century ago, astronomers discovered an important relation between the power of a star, and its temperature: for most (but not all) stars, the power is greater for stars of greater temperature. It was later realized that the controlling factor was the mass of the star: more massive stars are more powerful, and hotter. A power-temperature graph is called a Hertzsprung-Russell diagram (figure 3). It is very important for students to learn to construct graphs (Activity 8) and to interpret them (figure 3).

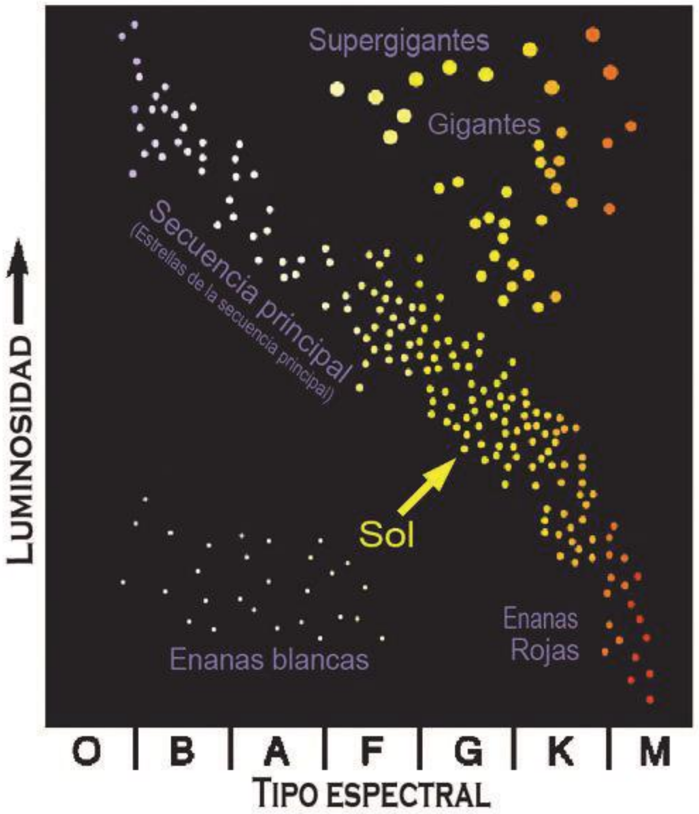

Fig. 3: The Hertzsprung-Russell Diagram, a graph of stellar power or luminosity versus stellar temperature. For historical reasons, the temperature increases to the left. The letters OBAFGKM are descriptive spectral types which are related to temperature. The diagonal lines show the radius of the stars; larger stars (giants and supergiants) are in the upper right, smaller ones (dwarfs) are in the lower left. Note the main sequence from lower right to upper left. Most stars are found here. The masses of main-sequence stars are shown. The locations of some well-known stars are also shown. Source: University of California Berkeley.

A major goal of astronomy is to determine the powers of stars of different kinds. Then, if that kind of star is observed elsewhere in the universe, astronomers can use its measured brightness B and its assumed power P to determine its distance D from the inverse-square law of brightness: $B \cong P/D^2$.

The spectra of stars (and of nebulae) also reveal what stars are made of: the cosmic abundance curve (figure 4). They consist of about 3/4 hydrogen, 1/4 helium, and 2 % heavier elements, mostly carbon, nitrogen, and oxygen.

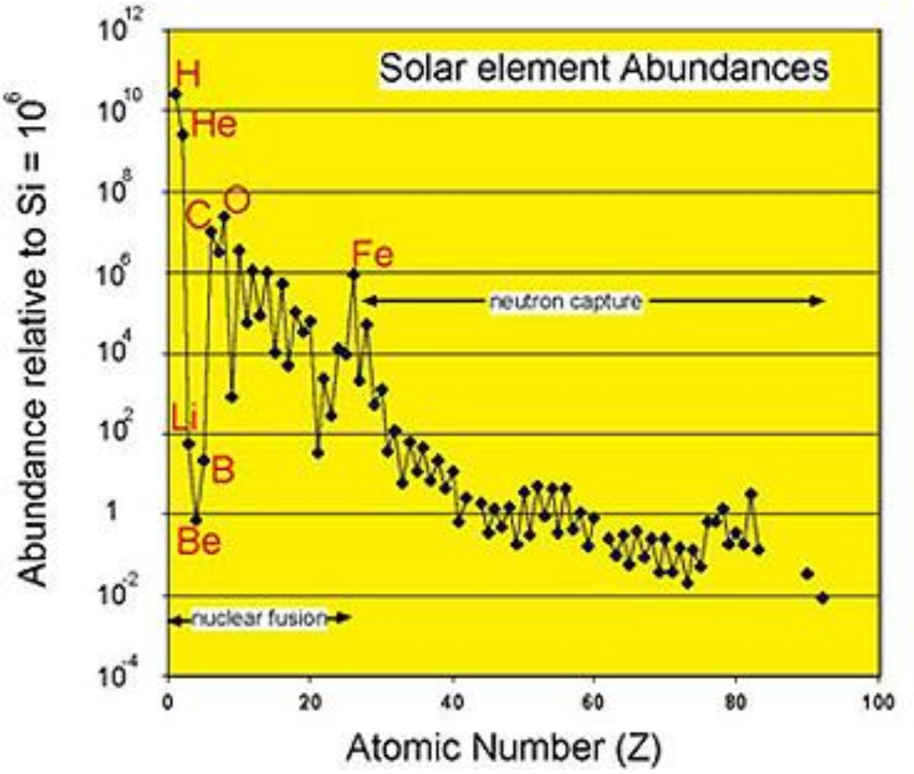

Fig. 4: The abundances of the elements in the Sun and stars. Hydrogen and helium are most abundant. Lithium, beryllium, and boron have very low abundances. Carbon, nitrogen, and oxygen are abundant. The abundances of the other elements decreases greatly with increasing atomic number. Hydrogen is 10^{12} times more abundant than uranium. Elements with even numbers of protons have higher abundances than elements with odd numbers of protons. The elements lighter than iron are produced by nuclear fusion in stars. The elements heavier than iron are produced by neutron capture in supernova explosions. Source: NASA.

About half of the stars in the Sun's neighbourhood are *binary* or *double stars* - two stars in orbit about each other. Double stars are important because they enable astronomers to measure the masses of stars. The mass of one star can be measured by observing the motion of the second star, and vice versa. Sirius, Procyon, and Capella are examples of double stars. There are also *multiple stars*: three or more stars in orbit around each other. Alpha Centauri, the nearest star to the Sun, is a triple star. Epsilon Lyrae is a quadruple star.

As mentioned above, there is an important relationship between the power of a star, and its mass: the power is proportional to approximately the cube of the mass. This is called *the mass-luminosity relation.*

The masses of stars range from about 0.1 to 100 times that of the Sun. The powers range from about 0.0001 to 1,000,000 times that of the Sun. The hottest normal stars are about 50,000 K; the coolest, about 2,000 K. When astronomers survey the stars, they find that the Sun is more massive and powerful than 95 % of all the stars in its neighbourhood. Massive, powerful stars are extremely rare. The Sun is not an average star. It is above average!

The Structure of the Sun and Stars

The structure of the Sun and stars is determined primarily by gravity. Gravity causes the fluid Sun to be almost perfectly spherical. Deep in the Sun, the pressure will increase, because of the weight of the layers of gas above. According to the gas laws, which apply to a perfect gas, the density and temperature will also be greater if the pressure is greater. If the deeper layers are hotter, heat will flow outward, because heat always flows from hot to less hot. This may occur by either radiation or convection. These three principles result in the mass-luminosity law.

If heat flows out of the Sun, then the deeper layers will cool, and gravity will cause the Sun to contract – unless energy is produced in the centre of the Sun. It turns out it is, as the Sun is not contracting but is being held up by radiation pressure created from the process of thermonuclear fusion, described below.

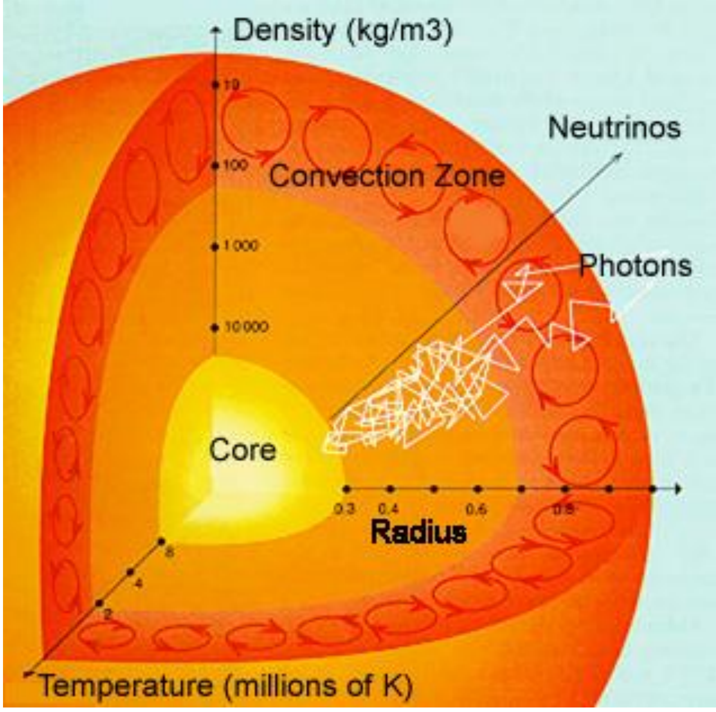

Fig. 5: A cross-section of the Sun, as determined from physical models. In the outer convection zone, energy is transported by convection; below that, it is transported by radiation. Energy is produced in the core. Source: Institute of Theoretical Physics, University of Oslo.

These four simple principles apply to all stars. They can be expressed as equations, and solved on a computer. This gives a *model* of the Sun or any star: the pressure, density, pressure, and energy flow at each distance from the centre of the star. This is the basic method by which astronomers learn about the structure and evolution of the stars. The model is constructed for a specific assumed mass and composition of the star; and from it astronomers are able to predict the star's radius, power and other observed properties. (figure 5).

Astronomers have recently developed a very powerful method of testing their models of the structure of the Sun and stars - *helioseismology* or, for other stars, *asteroseismology*. The Sun and stars are gently vibrating in thousands of different patterns or modes. These can be observed with sensitive instruments, and compared with the properties of the vibrations that would be predicted by the models.

The Energy source of the Sun and Stars

Scientists wondered, for many centuries, about the energy source of the Sun and stars. The most obvious source is the chemical burning of fuel such as oil or natural gas but, because of the very high power of the Sun (4 x 10^{26} W), this source would last for only a few thousand years. But until a few centuries ago, people thought that the ages of the Earth and Universe were only a few thousand years, because that was what the Bible seemed to say!

After the work of Isaac Newton, who developed the Law of Universal Gravitation, scientists realized that the Sun and stars might generate energy by slowly contracting. Gravitational (potential) energy would be converted into heat and radiation. This source of energy would last for a few tens of millions of years. Geological evidence, however, suggested that the Earth, and therefore the Sun, was much older than this.

In the late 19th century, scientists discovered radioactivity, or nuclear fission. Radioactive elements, however, are very rare in the Sun and stars, and could not provide power for them for billions of years.

Finally, scientists realized in the 20th century that light elements could fuse into heavier elements, a process called nuclear fusion. If the temperature and density were high enough, these would produce large amounts of energy - more than enough to power the Sun and stars. The element with the most potential fusion energy was hydrogen, and hydrogen is the most abundant element in the Sun and stars.

In low-mass stars like the Sun, hydrogen fusion occurs in a series of steps called the pp chain. Protons fuse to form deuterium. Another proton fuses with deuterium to form helium-3. Helium-3 nuclei fuse to produce helium-4, the normal isotope of helium (figure 6).

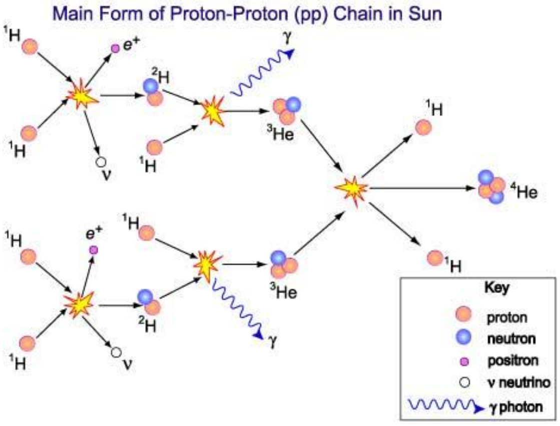

Fig. 6: The proton-proton chain of reactions by which hydrogen is fused into helium in the Sun and other low-mass stars. In this and the next figure, note that neutrinos (ν) are emitted in some of the reactions. Energy is emitted in the form of gamma rays (γ-rays) and the kinetic energy of the nuclei. Source: Australia National Telescope Facility.

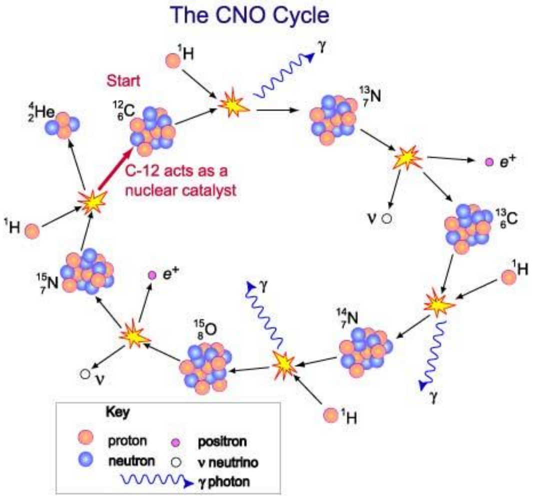

Fig. 7: The CNO cycle by which hydrogen is fused into helium in stars more massive than the Sun. Carbon-12 (marked ``start'') acts as a catalyst; it participates in the process without being used up itself. Source: Australia National Telescope Facility.

In massive stars, hydrogen fuses into helium through a different series of steps called the *CNO cycle*, in which carbon-12 is used as a catalyst (figure 7). The net result, in each case, is that four hydrogen nuclei fuse to form one helium nucleus. A small fraction of the mass of the hydrogen nuclei is converted into energy; see Activity 9. Since nuclei normally repel each other, because of their positive charges, fusion occurs only if the nuclei collide energetically (high temperature) and often (high density).

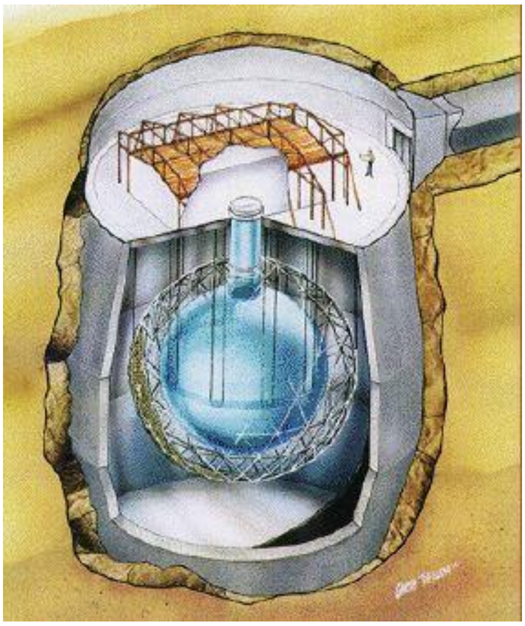

Fig. 8: The Sudbury Neutrino Observatory, where scientists confirmed the models of nuclear fusion in the Sun by observing the predicted flux of neutrinos. The heart of the observatory is a large tank of heavy water. The deuterium nuclei (see text) occasionally interact with a neutrino to produce an observable flash of light. Source: Sudbury Neutrino Observatory

If nuclear fusion powers the Sun, then the fusion reactions should produce large numbers of subatomic particles called neutrinos. These normally pass through matter without interacting with it. There are billions of neutrinos passing through our bodies each second. Special "neutrino observatories" can detect a few of these neutrinos. The first neutrino observatories detected only a third of the predicted number of neutrinos. This "solar neutrino problem" lasted for over 20 years, but was eventually solved by the Sudbury Neutrino Observatory (SNO) in Canada (figure 8). The heart of the observatory was a large tank of heavy water - water in which some of the hydrogen nuclei are deuterium. These nuclei occasionally absorb a neutrino and emit a flash of light. There are three types of neutrino. Two-thirds of the neutrinos from the Sun were changing into other types. SNO is sensitive to all three types of neutrinos, and detected the full number of neutrinos predicted by theory.

The Lives of the Sun and Stars:

Because "the scientific method" is such a fundamental concept in the teaching of science, we should start by explaining how astronomers understand the evolution of the stars:

- by using computer simulations, based on the laws of physics, as described above;
- by observing the stars in the sky, which are at various stages of evolution, and putting them into a logical "evolutionary sequence";
- by observing star clusters: groups of stars which formed out of the same cloud of gas and dust, at the same time, but with different masses. There are thousands of star clusters in our galaxy, including about 150 *globular clusters* which are among the oldest objects in our galaxy. The Hyades, Pleiades, and most of the stars in Ursa Major, are clusters that can be seen with the unaided eye. Clusters are "nature's experiments": groups of stars formed from the same material in the same place at the same time. Their stars differ only in mass. Since different clusters have different ages, we can see how a collection of stars of different masses would appear at different ages after their birth.
- by observing, directly, rapid stages of evolution; these will be very rare, because they last for only a very small fraction of the stars' lives;
- by studying the changes in the periods of pulsating variable stars. These changes are small, but observable. The periods of these stars depend on the radius of the star. As the radius changes due to evolution, the period will, also. The period change can be measured through systematic, long-term observations of the stars.

The first method, the use of computer simulations, was the same method that was used to determine the *structure* of the star. Once the structure of the star is known, we know the temperature and density at each point in the star, and we can calculate how the chemical composition will be changed by the thermonuclear processes that occur. These changes in composition can then be incorporated in the next model in the evolutionary sequence.

The most famous pulsating variable stars are called Cepheids, after the star Delta Cephei which is a bright example. There is a relation between the period of variation of a Cepheid, and its power. By measuring the period, astronomers can determine the power, and hence the distance, using the inverse-square law of brightness. Cepheids are an important tool for determining the size and age scale of the universe.

In Activity 5, students can observe variable stars, through projects such as Citizen Sky. This enables them to develop a variety of science and math skills, while doing real science and perhaps even contributing to astronomical knowledge.

The Lives and Deaths of the Sun and Stars

Hydrogen fusion is a very efficient process. It provides luminosity for stars throughout their long lives. The fusion reactions go fastest at the centre of the star, where the temperature and density are highest. The star therefore develops a core of helium which gradually expands outward from the centre. As this happens, the star's core must become hotter, by shrinking, so that the hydrogen around the helium core will be hot enough to fuse. This causes the outer layers of the star to expand -slowly at first, but then more rapidly. It becomes a red giant star, up to a hundred times bigger than the Sun. Finally the centre of the helium core becomes hot enough so that the helium will fuse into carbon. This fusion balances the inward pull of gravity, but not for long, because helium fusion is not as efficient as hydrogen fusion. Now the carbon core shrinks, to become hotter, and the outer layers of the star expand to become an even bigger red giant. The most massive stars expand to an even larger size; they become *red supergiant stars*.

A star dies when it runs out of fuel. There is no further source of energy to keep the inside of the star hot, and to produce enough gas pressure to stop gravity from contracting the star. The type of death depends on the mass of the star.

The length of the star's life also depends on its mass: low-mass stars have low luminosities and very long lifetimes- tens of billions of years. High-mass stars have very high luminosities, and very short lifetimes -millions of years. Most stars are very low-mass stars, and their lifetimes exceed the present age of the universe.

Before a star dies, it loses mass. As it uses the last of its hydrogen fuel, and then its helium fuel, it swells up into a red giant star, more than a hundred times bigger in radius, and more than a billion times bigger in volume than the Sun. In Activity 4, students can make a scale model, to visualize the immense changes in the size of the star as it evolves. The gravity in the outer layers of a red giant is very low. Also it becomes unstable to pulsation, a rhythmic expansion and contraction. Because of the large size of a red giant, it takes months to years for every pulsation cycle. This drives off the outer layers of the star into space, forming a beautiful, slowly-expanding *planetary nebula* around the dying star (figure 9). The gases in the planetary nebula are excited to fluorescence by ultraviolet light from the hot core of the star. Eventually, they will drift away from the star, and join with other gas and dust to form new nebulae from which new stars will be born.

Fig. 9: The Helix Nebula, a planetary nebula. The gases in the nebula were ejected from the star during its red giant phase of evolution. The core of the star is a hot white dwarf. It can be seen, faintly, at the centre of the nebula. Source: NASA.

The lives of massive stars are slightly different from those of low-mass stars. In low-mass stars, energy is transported outward from the core by radiation. In the core of massive stars, energy is transported by convection, so the core of the star is completely mixed. As the last bit of hydrogen is used up in the core, the star very rapidly changes into a red giant. In the case of low-mass stars, the transition is more gradual.

Stars must have a mass of more than 0.08 times that of the Sun. Otherwise, they will not be hot and dense enough, at their centres, for hydrogen to fuse. The most massive stars have masses of about a hundred times that of the Sun. More massive stars would be so powerful that their own radiation would stop them from forming, and from remaining stable.

Common, Low-Mass Stars

In stars with an initial mass less than about eight times that of the Sun, the mass loss leaves a core less than 1.4 times the mass of the Sun. This core has no thermonuclear fuel. The inward pull of gravity is balanced by the outward pressure of electrons. They resist any further contraction because of the Pauli Exclusion Principle – a law of quantum theory that states that there is a limit to the number of electrons that can exist in a given volume. This core is called a *white dwarf*. White dwarfs have masses less than 1.44 times that of the Sun. This is called the *Chandrasekhar limit*, because the Indian-American astronomer and Nobel Laureate Subrahmanyan Chandrasekhar showed that a white dwarf more massive than this would collapse under its own weight.

White dwarfs are the normal end-points of stellar evolution. They are very common in our galaxy. But they are hard to see: they are no bigger than the earth so, although they are hot, they have very little radiating area. Their powers are thousands of times less than that of the Sun. They radiate only because they are hot objects, slowly cooling as they radiate their energy. The bright stars Sirius and Procyon both have white dwarfs orbiting around them. These white dwarfs have no source of energy, other than their stored heat. They are like embers of coal, cooling in a fireplace. After billions of years, they will cool completely, and become cold and dark.

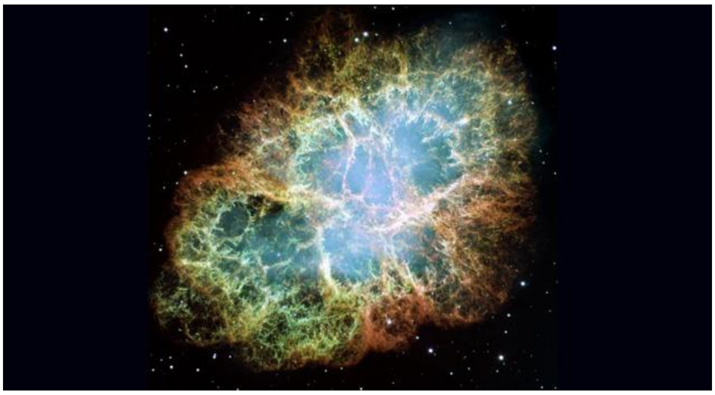

Fig. 10: The Crab Nebula, the remnant of a supernova explosion that was recorded by astronomers in Asia in 1054 AD. The core of the exploded star is a rapidly-rotating neutron star, or pulsar, within the nebula. A small fraction of its rotational energy is being transmitted to the nebula, making it glow. Source: NASA.

Rare, Massive Stars

Massive stars are hot and powerful, but very rare. They have short lifetimes of a few million years. Their cores are hot and dense enough to fuse elements up to iron. The iron nucleus has no available energy, either for fusion or for fission. There is no source of energy to keep the core hot, and to resist the force of gravity. Gravity collapses the core of the star within a second, converting it into a ball of neutrons (or even stranger matter), and liberating huge amounts of gravitational energy. This causes the outer layers of the star to explode as a s*upernova* (figure 10). These outer layers are ejected with speeds of up to 10,000 km/sec.

A supernova, at maximum brightness, can be as bright as a whole galaxy of hundreds of billions of stars. Both Tycho Brahe and Johannes Kepler observed and studied bright supernovas, in 1572 and 1604 respectively. According to Aristotle, stars were perfect and didn't change; Brahe and Kepler proved otherwise. No supernova has been observed in our Milky Way galaxy for 400 years. A supernova, visible with the unaided eye, was observed in 1987 in the Large Magellanic Cloud, a small satellite galaxy of the Milky Way.

The mass of the core of the supernova star is greater than the Chandrasekhar limit. The protons and electrons in the collapsing core fuse to produce neutrons, and neutrinos. The burst of neutrinos could be detected by a neutrino observatory. As long as the mass of the core is less than about three times the mass of the Sun, it will be stable. The inward force of gravity is balanced by the outward quantum pressure of the neutrons. The object is called a *neutron star*. Its diameter is about 10 km. Its density is more that 10^{14} times that of water. It may be visible with an X-ray telescope if it is still very hot, but neutron stars were discovered in a very unexpected way -- as sources of pulses of radio waves called *pulsars*. Their pulse periods are about a second, sometimes much less. The pulses are produced by the neutron star's strong magnetic field, being flung around at almost the speed of light by the star's rapid rotation.

There is a second kind of supernova that occurs in binary star systems in which one star has died and become a white dwarf. When the second star starts to expand, it may spill gas onto its white dwarf companion. If the mass of the white dwarf becomes greater than the Chandrasekhar limit, the white dwarf "deflagrates"; its material fuses, almost instantly, into carbon, releasing enough energy to destroy the star.

In a supernova explosion, all of the chemical elements that have been produced by fusion reactions are ejected into space. Elements heavier than iron are produced in the explosion, though in small amounts, as neutrons irradiate the lighter nuclei that are being ejected.

Very rare, Very Massive Stars

Very massive stars are very rare - one star in a billion. They have powers of up to a million times that of the Sun and lives which are very short. They are so massive that, when they run out of energy and their core collapses, its mass is more than three times the mass of the Sun. Gravity overcomes even the quantum pressure of the neutrons. The core continues to collapse until it is so dense that its gravitational force prevents anything from escaping from it, even light. It becomes a *black hole*. Black holes emit no radiation but, if they have a normal-star companion, they cause that companion to move in an orbit. The observed motion of the companion enables astronomers to detect the black hole, and measure its mass. Furthermore: a small amount of gas from the normal star may be pulled toward the black hole, and heated until it glows in X-rays before it falls into the black hole (figure 11). Black holes are therefore strong sources of X-rays, and are discovered with X-ray telescopes.

At the very centre of many galaxies, including our Milky Way galaxy, astronomers have discovered *supermassive black holes*, millions or billions of times more massive than the Sun.

Their mass is measured from their effect on visible stars near the centres of galaxies. Supermassive black holes seem to have formed as part of the birth process of the galaxy, but it is not clear how this happened. One of the goals of 21st-century astronomy is to understand how the first stars and galaxies and super-massive black holes formed, soon after the birth of the universe.

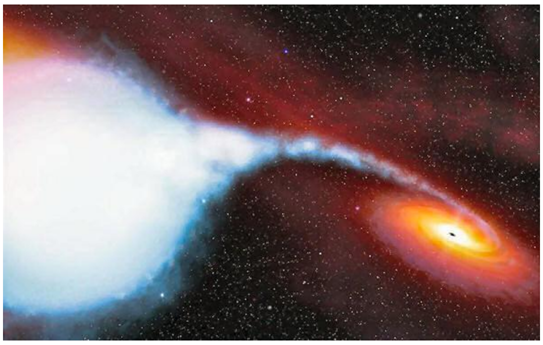

Fig. 11: An artist's conception of the binary-star X-ray source Cygnus X-1. It consists of a massive normal star (left), and a black hole (right), about 15 times the mass of the Sun, in mutual orbit. Some of the gases from the normal star are pulled into an *accretion disc* around the black hole, and eventually into the black hole itself. The gases are heated to very high temperatures, causing them to emit X-rays. Source: NASA.

Cataclysmic Variable Stars

About half of all stars are binary stars, two or more stars in mutual orbit. Often, the orbits are very large, and the two stars do not interfere with each other's evolution. But if the orbit is small, the two stars may interact, especially when one swells into a red giant. And if one star dies to become a white dwarf, neutron star, or black hole, the evolution of the normal star may spill material onto the dead star, and many interesting things can happen (figure 12). The binary star system varies in brightness, for various reasons, and is called a *cataclysmic variable star*. As noted above, a white dwarf companion could explode as a supernova if enough mass was transferred to it. If the normal star spilled hydrogen-rich material onto the white dwarf, that material could explode, through hydrogen fusion, as a *nova*. The material falling toward the white dwarf, neutron star, or black hole could simply become very hot, as its gravitational potential energy was converted into heat, and produce high-energy radiation such as X-rays.

In the artist's conception of a black hole (figure 11), you can see the *accretion disc* of gas around the black hole, and the stream of gas from the normal star, flowing towards it.

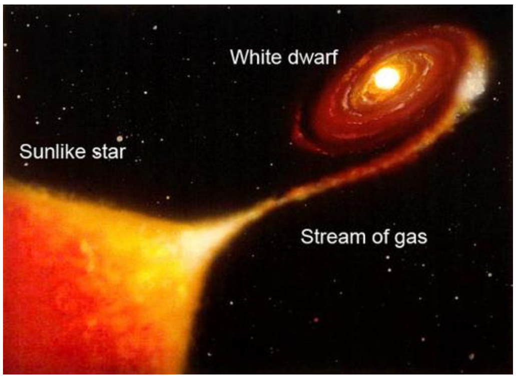

Fig. 12: A cataclysmic variable star. Matter is being pulled from the normal star (left) towards the white dwarf (right). It strikes the accretion disc around the white dwarf, which causes a flickering in brightness. The matter eventually lands on the white dwarf, where it may flare up or explode. Source: NASA.

The Births of the Sun and Stars

Stars are being born now! Because the most massive stars have lifetimes of only a few million years, and because the age of the universe is over ten billion years, it follows that these massive stars must have been born quite recently. Their location provides a clue: they are found in and near large clouds of gas and dust called nebulae. The gas consists of ions, atoms, and molecules, mostly of hydrogen, with some helium, and a very small amount of the heavier elements. The dust consists of grains of silicate and graphite, with sizes of less than a micrometer. There is much less dust than gas, but the dust plays important roles in the nebula. It enables molecules to form by protecting them from the intense radiation from nearby stars. Its surface can provide a catalyst for molecule formation. The nearest large, bright nebula is the Orion Nebula (figure 13). Hot stars in the nebula make the gas atoms glow by fluorescence. The dust is warm, and emits infrared radiation. It also blocks out light from stars and gas behind it, causing dark patches in the nebula.

Gravity is an attracting force, so it is not surprising that some parts of a nebula would slowly contract. This will happen if the gravitational force is greater than the pressure of the turbulence of that part of the cloud. The first stages of contraction may be helped by a shock wave from a nearby supernova or by the radiation pressure from a nearby massive star. Once gravitational contraction begins, it continues. About half of the energy released, from gravitational contraction, heats the star. The other half is radiated away. When the temperature of the centre of the star reaches about 1,000,000K, thermonuclear fusion of deuterium begins; when the temperature is a bit hotter, thermonuclear fusion of normal hydrogen begins. When the energy being produced is equal to the energy being radiated, the star is "officially" born.

Fig. 13: The Orion Nebula, a large cloud of gas and dust in which stars (and their planets) are forming. The gas glows by fluorescence. The dust produces dark patches of absorption that you can see, especially in the upper left. Source: NASA.

When the gravitational contraction first begins, the material has a very small rotation (angular momentum), due to turbulence in the cloud. As the contraction continues, "conservation of angular momentum" causes the rotation to increase. This effect is commonly seen in figure skating; when the skater wants to go into a fast spin, they pull their arms as close to their axis of rotation (their body) as possible, and their spin increases. As the rotation of the contracting star continues, "centrifugal force" (as it is familiarly but incorrectly called) causes the material around the star to flatten into a disc. The star forms in the dense centre of the disc. Planets form in the disc itself -rocky planets close to the star, and gassy and icy planets in the cold outer disc.

In nebulae such as the Orion Nebula, astronomers have observed stars in all stages of formation. They have observed proplyds - protoplanetary discs in which planets like ours are forming. And starting in 1995, astronomers have discovered *exoplanets* mor *extra-solar planets* -planets around other Sun-like stars. This is dramatic proof that planets really do form as a normal by-product of star formation. There may be many planets, like earth, in the universe!

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