THE EVOLUTION OF STARS

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Compared to the human lifespan, the Sun and other stars seem eternal. But stars also are born, and they die. If they did not, we would not be here to tell their story. Life on Earth was, in a very unique way, made possible by stars that died long ago. This article explores the fascinating story of stellar evolution.

We all know what the periodic table of elements looks like, with its many rows and columns featuring the fundamental chemical building blocks of all living and non-living matter on Earth (refer **Fig. 1**). But, have you ever wondered where these elements come from? The oxygen we breathe, the calcium in our bones, the iron in our blood, and the nitrogen in our DNA — what processes lead to such variety?

Incredible as it may seem, there is only one place in the entire universe where naturally occurring elements can be synthesized — the interiors of stars. But for stars that lived and died long ago, a planet like Earth and life as we know it would not have been

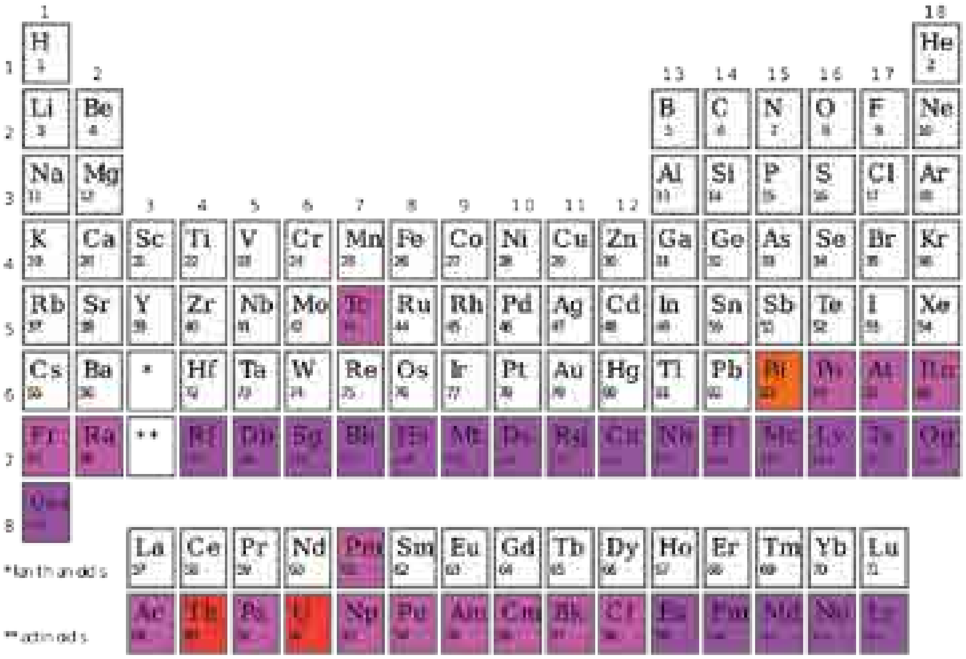

Fig. 1. The periodic table.

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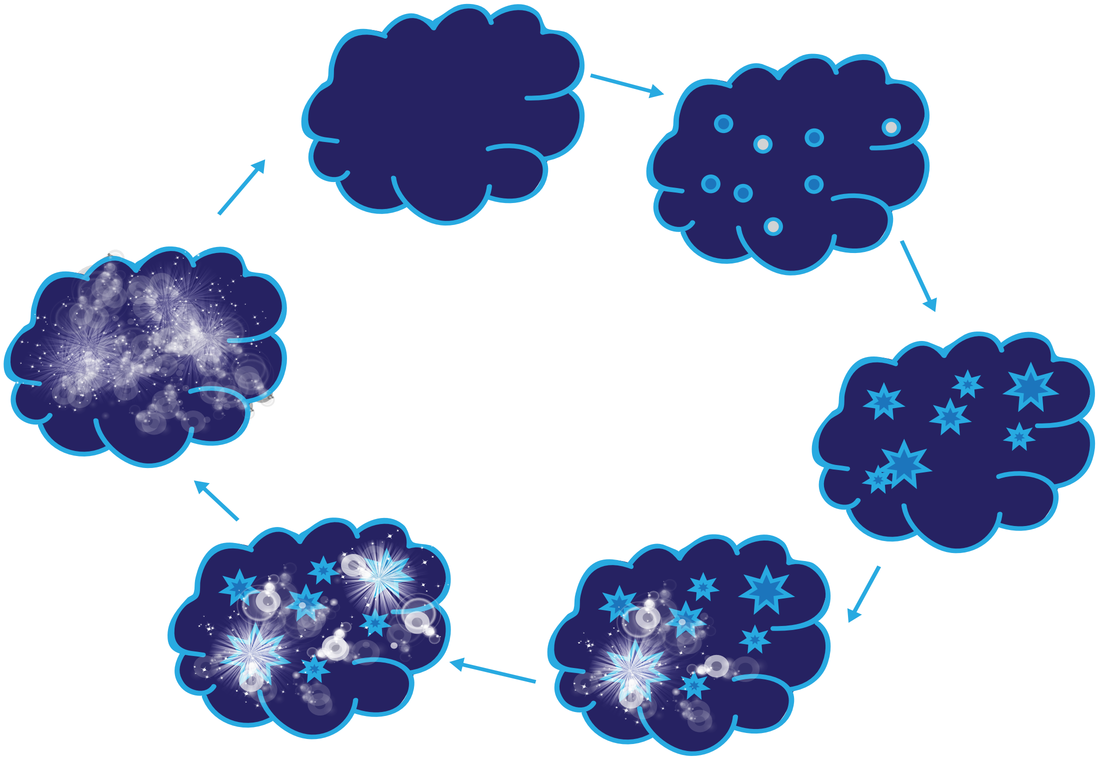

Fig. 2. The stellar life cycle. Stars are born out of interstellar gas clouds. Fragmentation within such a cloud gives birth to not one, but many stars, some of which will be of low mass (like the Sun) and some very massive. The stars live for a few hundred million to billions of years. When they end their life they throw back the heavier elements they synthesized during their life time into the interstellar medium. License: CC-BY-NC.

possible. To understand how the evolution of stars has led to that of life, let's take a closer look at their spectacular lives – what makes them shine so brilliantly and what happens when they cease to do so?

The stellar lifecycle

Astronomers refer to the life of stars – from their birth, their evolution to more mature forms, and finally to their death – as the stellar lifecycle (refer **Fig. 2**). The term 'lifecycle' suggests that this is a process that continually repeats itself, which is indeed so.

Stars are born out of clouds of hydrogen gas in the interstellar medium (the region between stars). When they die, they replenish the interstellar medium with the same gas, with one major difference. The gas the stars fling back into the interstellar medium is abundant in elements heavier than hydrogen, synthesized by the stars in the course of their lives. Thus, the death of every star enriches its surrounding interstellar medium with heavier elements. Since new generations of stars are born out of this interstellar gas, the cycle repeats itself.

The birth of stars

Stars are born as huge balls of hydrogen gas, with trace amounts of helium. Their entire life is characterized by the creation of heavier elements from lighter elements, starting with hydrogen. But, how do we know this?

Although there are a billion stars in our own galaxy, they are too far away for us, and even if we found a way to travel such distances, we could not land on them – we would not survive the enormous amounts of energy that they release (refer **Fig. 3**). In spite of these difficulties, we have found some ingenious ways to study them, many of which are based on the star closest to us – the Sun. Studies of the light from the Sun, initially through prisms, and later by increasingly sophisticated spectrometers, show a curious pattern of dark lines. Our understanding of atomic spectra tells us that these lines are produced because atoms in the surface layers of the Sun absorb light of certain wavelengths. We have also been able to infer that the atoms that produce these lines are most likely to be of elements like hydrogen, sodium, helium, magnesium and calcium. However, these observations only allow us to study the composition of the Sun at its surface.

How do we know the composition of the Sun at its core? The idea that hydrogen atoms could fuse to form helium, by a process called **nuclear fusion** (refer **Fig. 4**), that would release huge amounts of energy began to attract attention in the 1930's. However, it was only in 1985 that we started finding evidence to suggest that this process could occur at the core of the Sun and produce the

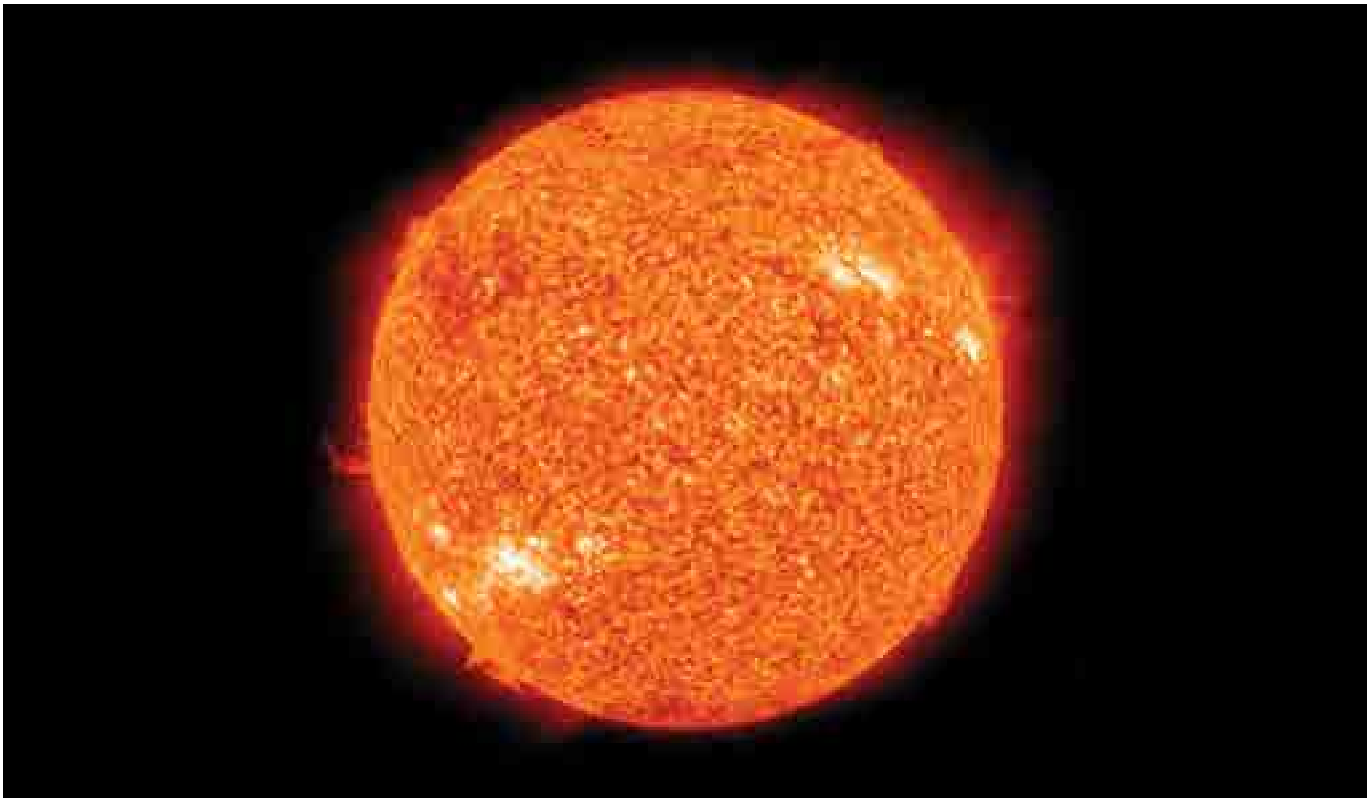

Fig. 3. A photograph of the Sun taken by SOHO space observatory. The surface of the Sun has a temperature of nearly 6500 Kelvin.

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energy to power it. This evidence came from the development of devices called Kamiokande (Super-K) detectors. Buried about 1000m below the Earth's surface, these detectors are designed to trap and study subatomic particles like solar neutrinos. Neutrinos, or ghost particles as they are often called, are tiny, nearly massless and charge-less particles that travel at speeds close to that of light. Since we know of no other method by which they could be produced, the fact that they exist is believed to be direct evidence of the nuclear fusion occurring within the Sun's core.

The surface of the Sun, visible to our unaided eyes, is called its photosphere. Estimates suggest that it is through this layer that about 3.8 x 10^{26} Joules of energy escape into space every second in the form of photons (refer **Box 1**). This is a billion times more than the power produced by all the hydroelectric power plants in India in an entire year! Of course, the Sun produces much more energy than it loses through its photosphere – a great deal of this energy goes back into heating up its interior (refer **Fig. 6**).

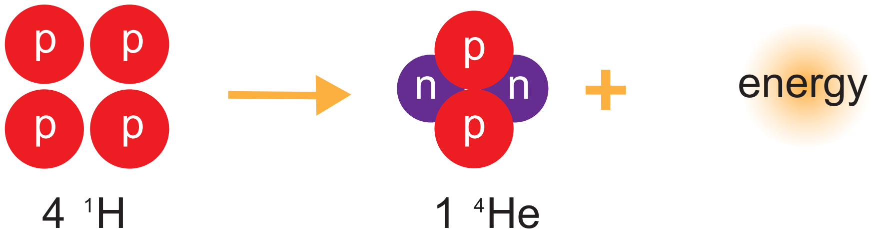

Fig. 4. The Sun is able to shine because of the fusion of hydrogen nuclei (protons) to form a helium nucleus. Four hydrogen nuclei fuse together to form a helium nucleus. The mass of a single helium nucleus is about 0.7 percent less than the combined mass of the four protons. This deficit in mass is released as energy, which heats up the interior of the Sun, and gets radiated from its surface.

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Based on how bright the Sun appears to us, physicists have calculated the rate at which nuclear fusion reactions must be happening at its core – and they are staggeringly high (see **Box 2**). With such a large energy yield, one may wonder why the Sun does not explode. As it turns out, all stars have some kind of in-built safety valve that prevents this from occurring. But, how does this valve work?

A cloud of gas (predominantly consisting of hydrogen) becomes a star when gravity starts pulling its atoms together.

Box 1. The journey of a million years:

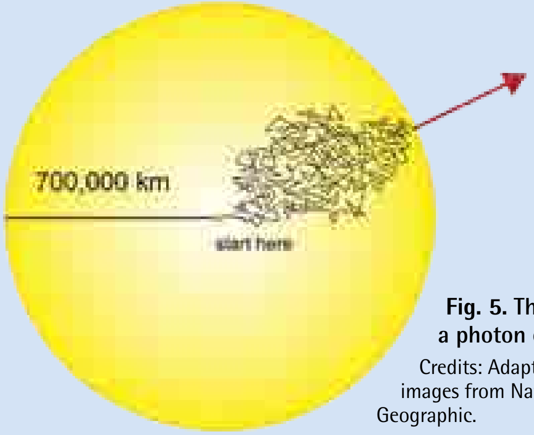

Fig. 5. The path of a photon of light.

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Photons are light particles. While inside a star, photons are constantly scattered by gas particles, losing energy in each of these interactions (refer **Fig. 5**). Thus, by the time they get to the outer layers of the Sun, their energy has become a million times less than what it was in the beginning. It is these photons that free-stream into outer space, and that we see as sunlight.

Calculations show that any photon manages to travel only a tenth of a millimeter before slamming into electrons and ions inside the star. Thus, the path a photon takes would have to be extremely zigzag, covering small distances every step of the way. Physicists call such motion a **random walk**, and have devised some models to describe it. In one such model, if 'd' is the distance that a particle travels between successive scatterings, then after 'N' such scatterings, the particle would have covered a net distance of sqrt(N) x d.

Challenge: You can easily calculate how long it would take for a given photon generated at the core of the Sun to find its way to the surface (the photosphere). The radius of the Sun is 700,000 kilometers. Assume that a single photon manages to travel a distance of about one-tenth of a millimeter between successive scatterings. The photon has the speed of light, which is about 300,000 kilometers every second.

Hint: Calculate how many small steps the photon has to take to cover the distance within the Sun (radius of the Sun) = this is the N in the above expression. Multiply that with 0.1 mm = the distance of each step. This will give you the total distance that a photon would have traveled from the core to the surface of Sun. Divide that distance with the speed of light to get the time it would take for a photon produced at the core to reach the surface.

You should get a value that is close to half a million years. That's how long it takes for sunlight to escape the Sun. Think about this for a while. A photon produced at the core of the Sun takes half a million years to travel the 700,000 kilometers to the surface of the Sun. Once it gets past the photosphere, the photon takes only about 8 minutes to cover the 150,000,000 kilometers to the Earth! What causes this difference is the density of material that the photon encounters *en route*. The density of material inside the Sun is a hundred thousand times more than the density of matter in the vastness of space that separates the Earth from the Sun.

The nebula gradually turns into a ball of gas as the gravity between the gas particles keeps compressing the material into smaller sizes. As it shrinks, the density of the gas in this nebula grows, gradually becoming high enough to cause nuclear fusion reactions (refer **Fig. 7**).

However, once fusion begins, a counter pressure to gravity sets in. The photons produced by the fusion of hydrogen at the core of the Sun exert an outward pressure on consecutive layers of gas as they push their way to the photosphere. Physicists refer to this as the radiation pressure. This pressure is highest at the core, and reduces steadily in the outer layers of the sun. As the radiation heats up the gas, another form of pressure called the gas pressure builds up. The hotter the gas, the higher its gas pressure. This gas pressure acts in the same manner as the radiation pressure pushing layers of gas outward. In every layer of gas inside a star, the collective radiation and gas pressure acting outwards gets balanced out by the pressure due to gravity acting inwards.

This balance keeps the star in a state of equilibrium, not allowing it to shrink further due to gravity, or swell in size because of the combined thrust of the

Box 2. The energy yield of the Sun:

It's easy to calculate the energy yield from hydrogen fusion inside the Sun.

Our starting point is a reaction where four hydrogen nuclei (protons) fuse together to form one helium nucleus. Now, we know that the:

Mass of a single proton = 1.67×10^{-27} kg

Mass of a single Helium nucleus = 6.64×10^{-27} kg

The difference in mass, Delta m = $(4 \times 1.67 - 6.64) \times 10^{-27}$ kg

According to Einstein's mass-energy equivalence principle, it is this difference in mass that is converted to energy, or E = Delta mc^2.
For the energy released in this process, we get a value that is approximately 4×10^{-12} Joules (using a light speed of $c = 3 \times 10^8$ m/s).

This is the amount of energy set free from the fusion of four hydrogen nuclei. Inside the Sun, a lot of these reactions are happening at once, and together they drive its energy output. We can also estimate the number of hydrogen fusion reactions happening every second:

Number of fusion reactions every second = total energy released by the Sun every second / energy from a single fusion reaction = 3.8×10^{26} Joules/sec / 4×10^{-12} Joules, which is approximately 10^{38} fusion reactions every second. In other words, at every instant, about 10^{38} hydrogen nuclei in the Sun's core are getting converted into Helium!

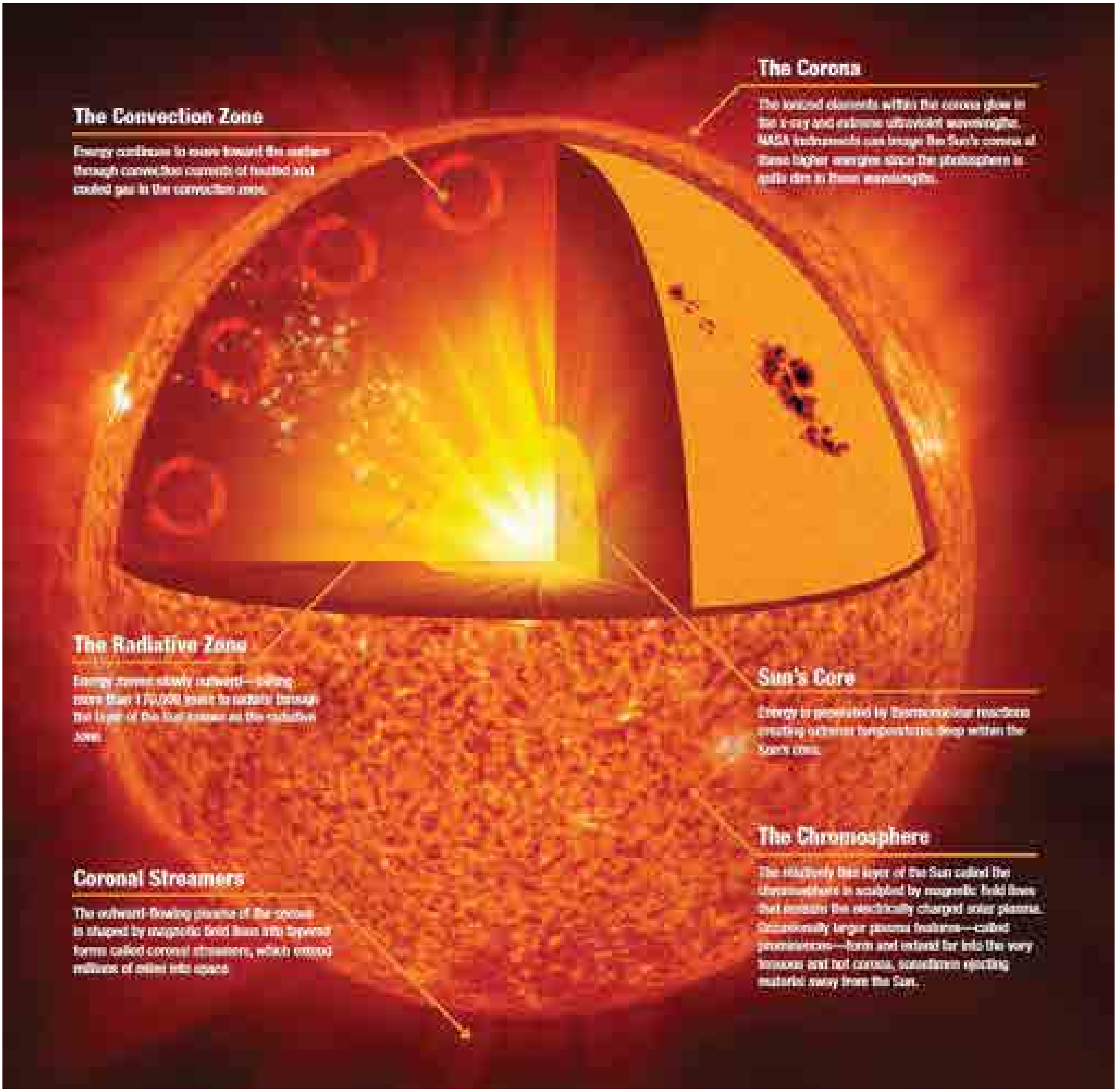

Fig. 6. A cross-section of the Sun. The surface of the Sun is called the photosphere. Below it are several layers of gas that surround and hide the core of the Sun from our view. But, it is only at the core that the density and temperatures are high enough to allow nuclear fusion. The energy generated by this process slowly makes its way through many gas layers to reach the photosphere. Once it reaches the surface of the Sun, it gets radiated outwards in the form of photons.

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radiation and gas pressure acting inside out. This state of hydrostatic equilibrium (as it is called by physicists) acts as a natural safety valve in stars (refer **Fig. 8**). Any disruption in this balance can lead to dramatic changes that can, at times, be detrimental to the star.

As stars mature

The mass of a star determines its life span. The Sun may be dear to us. But in the vastness of cosmos, the Sun is a mediocre star. There are many stars, even within our own Galaxy that are more massive and, consequently, more luminous than the Sun (see **Fig. 9**). These stars tend to live much shorter lives – the higher their mass, the greater the pressure due to gravity squeezing the star. To resist this inward crush, and sustain its hydrostatic equilibrium, these stars — referred to as high mass stars — burn the hydrogen at their core at a significantly faster rate. So, for example, estimates suggest that a star that is three times the mass of the Sun would burn out all the hydrogen in its core in about half a billion years, while a star that is 15 times more massive than the Sun will do this in less than 15 million years. By that very same token, the hydrogen at the core of a star that is only about 10% of the mass of the Sun will be able to burn for as long as a thousand billion years!

(a) The long life of low mass stars

Astronomers classify the Sun, and stars up to eight times the mass of the Sun, as low mass stars. The major events in the lives of such stars are more or less alike.

The longest stage in any star's life is that involving a hydrogen to helium conversion. For a star like the Sun, this lasts for about 10 billion years. When the core hydrogen is fully consumed, nuclear fusion shuts off. With no radiation or gas pressure to counter the gravitational pressure, the core of the star shrinks. The compression of the core by gravity causes its density and temperature to increase (much like what happens when you compress any fluid in a closed container). This continues till, finally, the temperature and density at the core become large enough to trigger helium fusion.

At this stage, therefore, two kinds of nuclear fusion reactions begin to

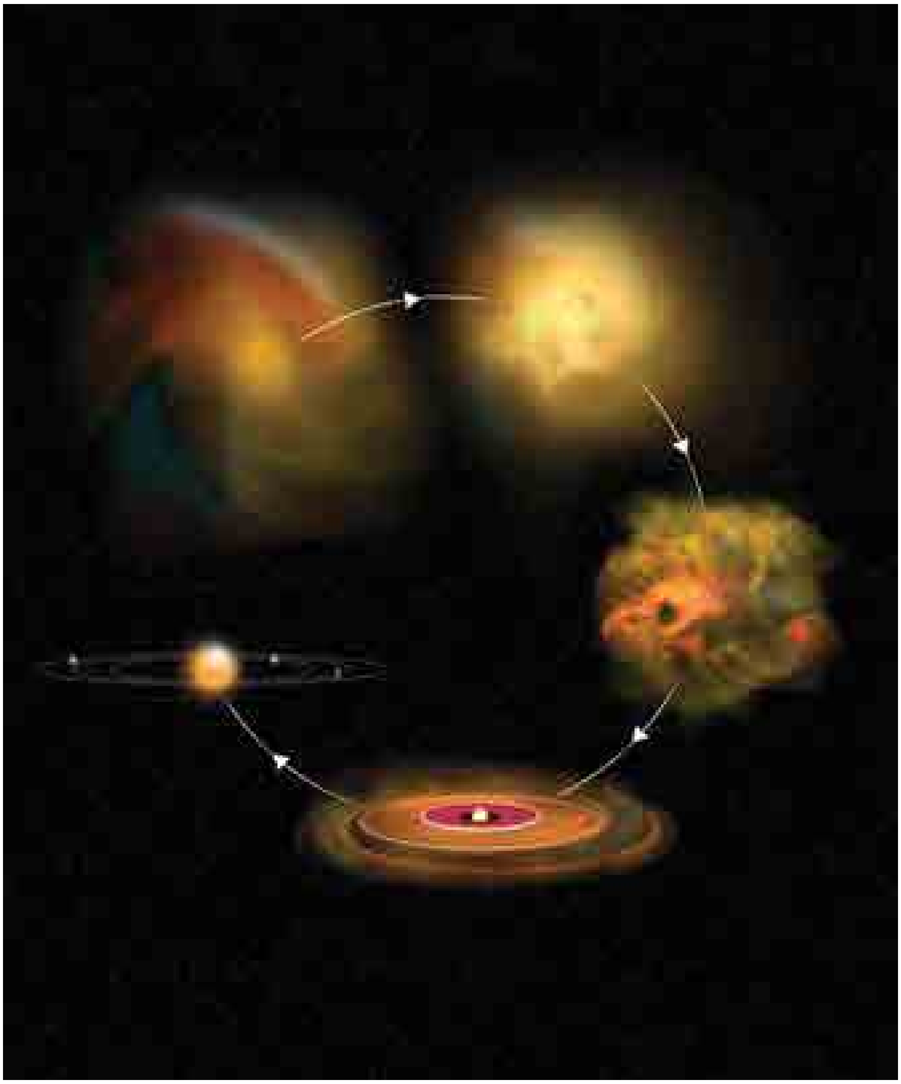

Fig. 7. The sequence of steps that leads to the birth of a star. Inside a cold dense cloud of gas, a fragmented region starts collapsing under its own gravity. The collapse continues until a star forms at its centre, along with planets around it. A star is born when the temperature at the central region of the collapsing fragment equals 10 million Kelvin, and the density approximately 160 gms/cc (about 10 times the density of lead).

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Box 3. The lifespan of the Sun:

Like every other star in the universe, our Sun too is destined to die. How much longer do we have before it burns out?

Fortunately estimating this time scale involves a straightforward calculation. We need to know three things to make this calculation:

1. How much energy does the Sun give out every second?
2. How much mass in the form of hydrogen is available at the core of the Sun for fusion?
3. How efficient is hydrogen fusion in converting mass into energy?

The total mass of the Sun is 2×10^{30} kg. About 10% of this mass, which is 2×10^{29} kg, is at the core where fusion reactions occur.

The hydrogen to helium fusion reaction occurs with an efficiency of 0.7%. In other words, only 0.7% of the total mass in the core of the Sun gets converted to energy. Knowing these two facts, we can calculate the total amount of energy the Sun is likely to radiate over its entire lifetime, which is 0.7% of $2 \times 10^{29} \times c^2$ Joules (using Einstein's $E = mc^2$ equivalence principle).

From this, we can infer that the amount of energy coming out of the Sun every second (also called its luminosity) is 3.8×10^{26} Joules /Sec.

The Sun can continue shining with that luminosity for $t = 1.3 \times 10^{44} / 3.8 \times 10^{26} = 3 \times 10^{17}$ seconds, which is equal to 10 billion years. At present, the Sun is about 5 billion years old, which means that it has completed half of its lifespan. It has another 5 billion years to go, before it uses up all the hydrogen fuel at its core.

occur within the star. One of these occurs within its core, and involves the fusion of helium atoms to form carbon and oxygen (refer **Fig. 10**). The other is the fusion of hydrogen to helium in a shell surrounding the core. The energy released from both these fusion reactions oppose the gravitational pressure acting inwards, re-establishing equilibrium.

As a result of these changes within, the star undergoes a major transformation in its external appearance. It swells up tremendously, becoming a hundred to a thousand times bigger. Astronomers call such inflated stars — red giants (refer **Fig. 11**). Estimates suggest that our Sun will undergo such a transformation in about 5 billion years.

Unlike the fusion of hydrogen to helium, the fusion of helium to carbon and oxygen does not last very long. A star like the Sun will be able to sustain the burning of Helium at its core for

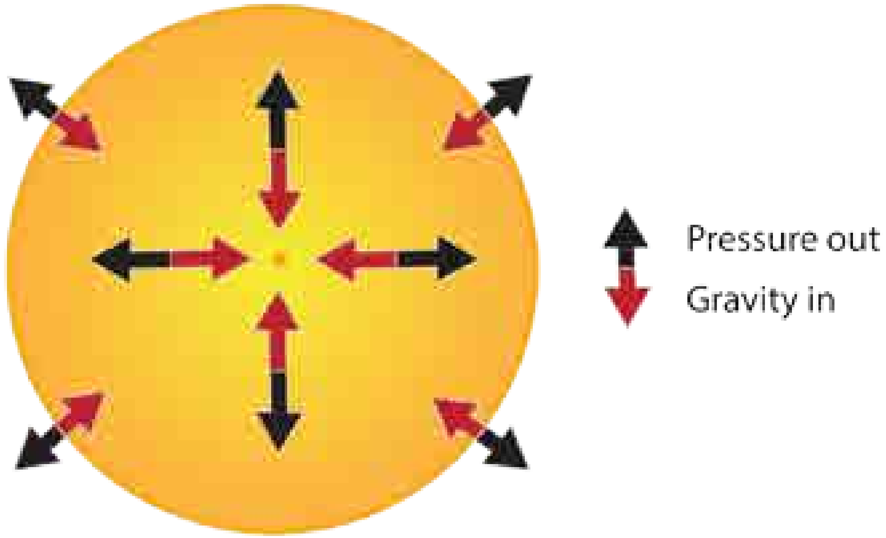

Fig. 8. Hydrostatic equilibrium balances two competing pressures within a star. Every layer of a star exerts its weight on the layer just beneath, to compress the star to a smaller size. This pressure due to gravity is least on the surface of the star, but increases in successive inner layers. Thus, the gravitational pressure is maximum at the core, as it experiences the maximum weight from all the layers of gas above it. At every layer of gas inside a star, the gravitational pressure acting inwards is balanced by a combination of its gas and radiation pressures acting outwards.

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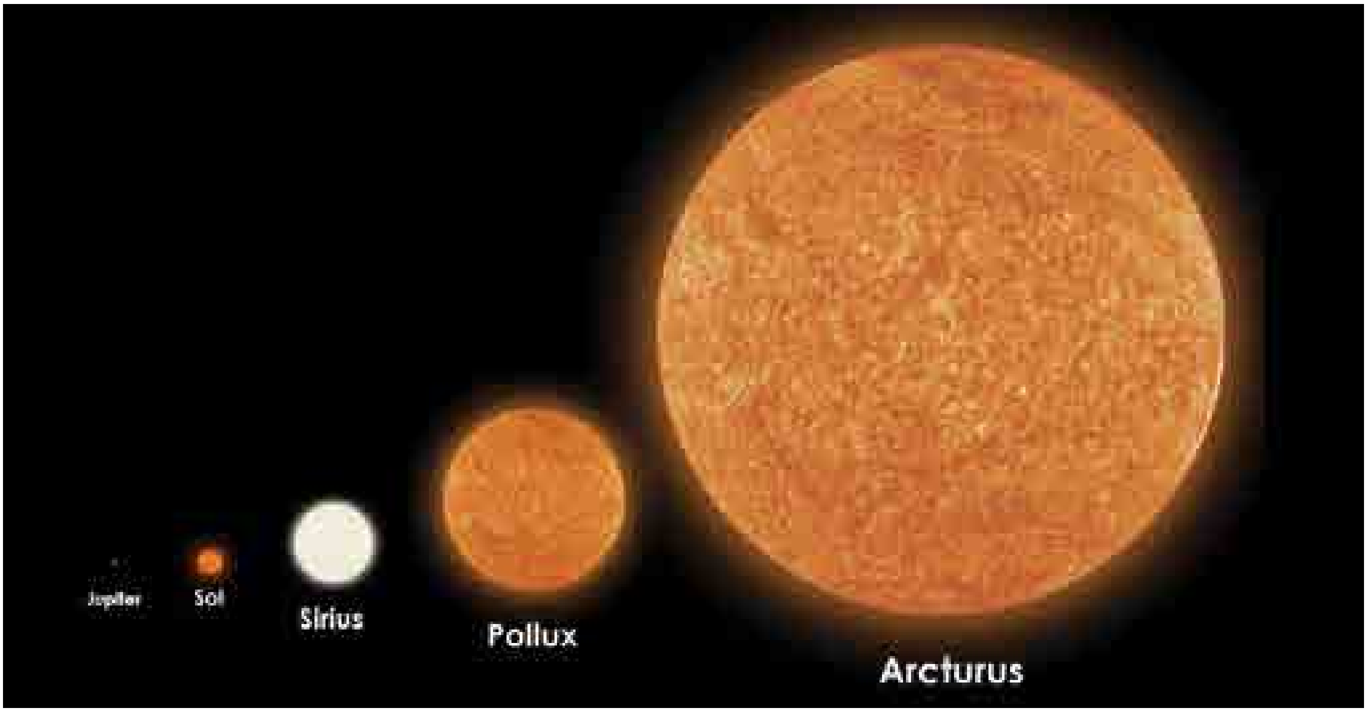

Fig. 9. The size and mass range of stars. Our Sun is an ordinary star with mass, size, temperature and luminosity smaller than many other stars in the Milky Way. This figure shows examples of how big stars can be. Sirius is about two times the mass of the Sun, nearly twice as big, and has an energy output (luminosity) that is about 25 times greater than the Sun's luminosity. The star Pollux is twice as massive as the Sun, but 8 times bigger, and therefore has a luminosity that is much greater than Sirius. The star Arcturus is about the mass of the Sun, but 25 times bigger in size. It is also a lot older than the Sun and, hence, at a much later stage of its life. Arcturus has evolved to become what astronomers call a Red Giant, a star that has blown itself to a large size. Because of its size, Arcturus is also very bright, nearly 150 times brighter than the Sun.

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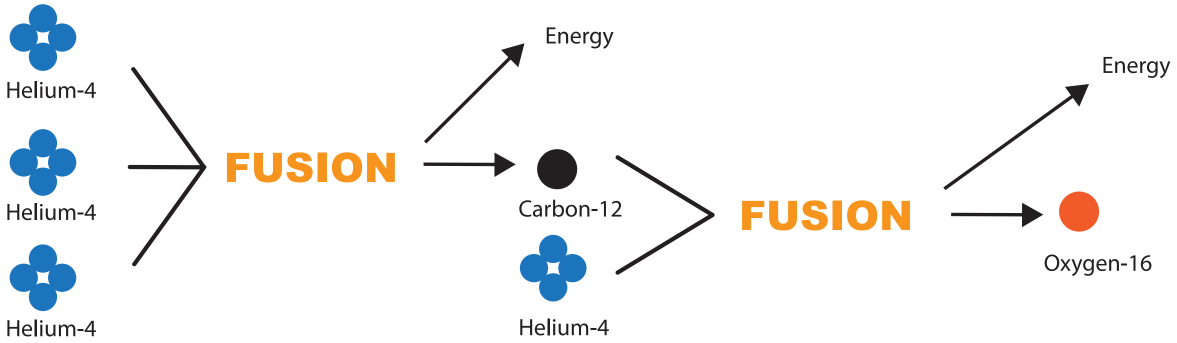

Fig. 10. Helium nuclei fuse to form carbon and oxygen nuclei. These reactions result in the release of energy, some of which goes into heating up the gas in the star, while the rest escapes into outer space.

only about a billion years or less. Thus, for low mass stars like the Sun, the formation of carbon and oxygen marks the last stage of their lives (see **Box 3**). As the nuclear reaction in their core shuts off, such stars prepare for their death in a slow but spectacular way. As it reaches its final stages, energy in the star is generated in a fairly unsteady manner, causing the star to rapidly pulsate (grow and shrink in size, and in brightness). As a result of these pulsations, the star begins to slowly puff out its layers of gas. The blown-out outer layers recede to the ambient space, gradually exposing the star's inner core of carbon and oxygen nuclei. These dying stars, called **planetary nebulae** by astronomers, look stunning (refer **Fig. 12**). The brightly-shining exposed core of the star is called a **white dwarf.**

There are as many as 10,000 planetary nebulae within the Milky Way. A minor fraction of the helium, carbon and

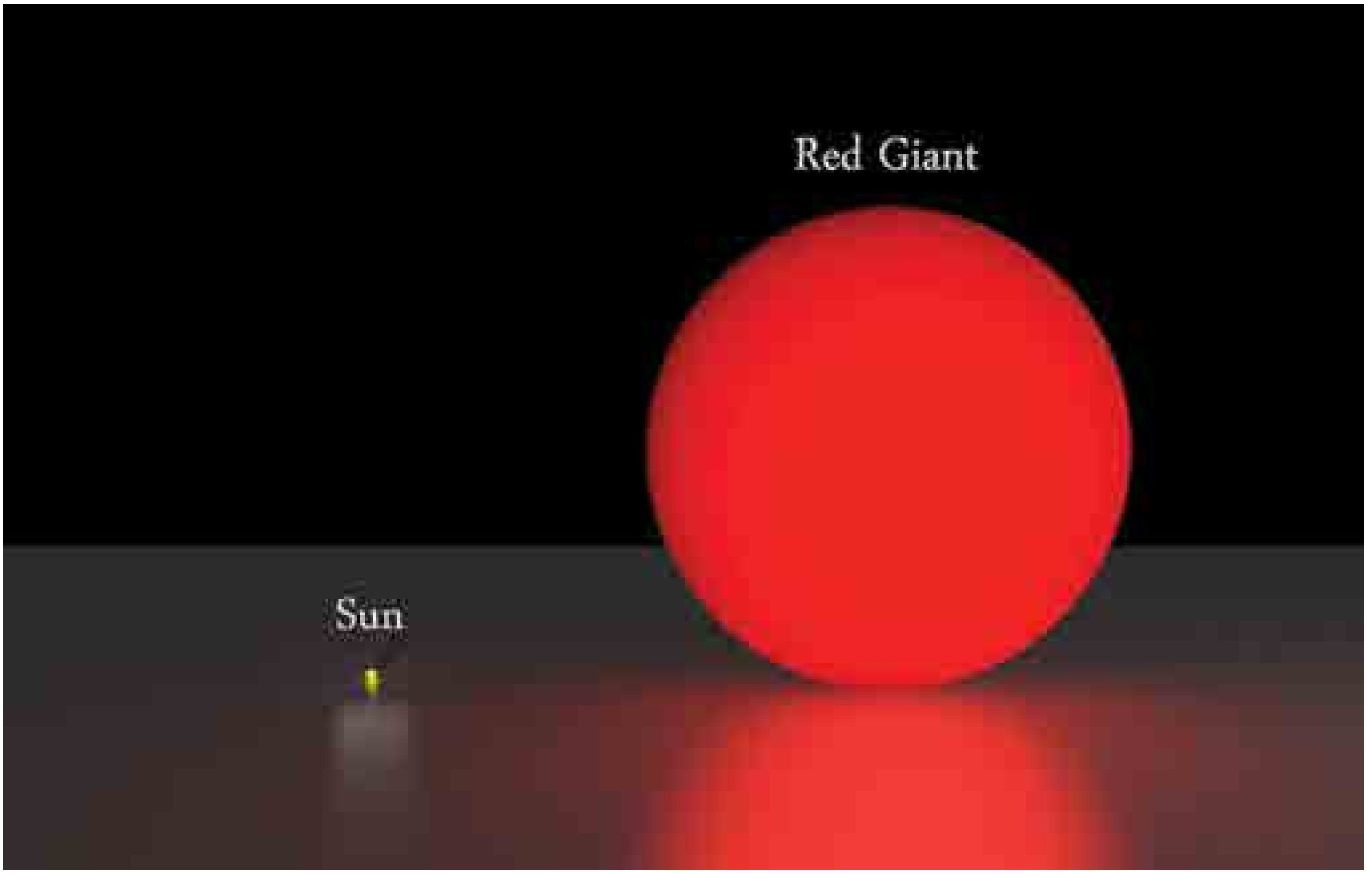

Fig. 11. The present Sun compared with its future as a red giant. As it ages, the Sun will swell up and fill the inner solar system. It will engulf Mercury, and grow to a size close to the orbit of Venus. The Earth will become much hotter, oceans will evaporate, and the hot atmosphere will escape Earth's gravity to outer space, all because of the blazing Red Giant Sun.

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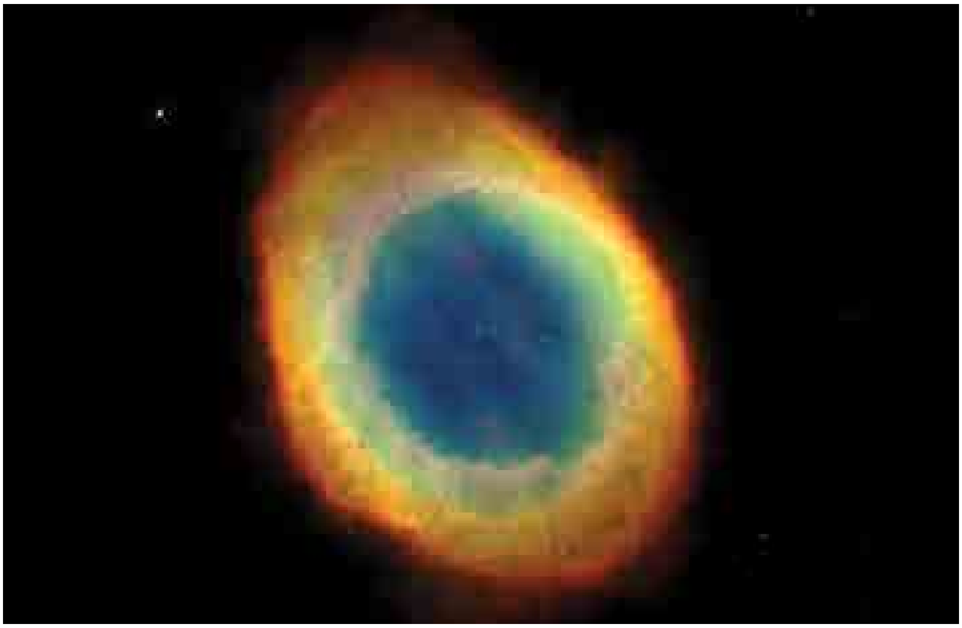

Fig. 12. The Ring Nebula, a famous planetary nebula, remains a low mass star that once used to shine like the Sun. The red, orange and blue glow comes from diffuse gas that was once part of the star. At the end of its life, the star slowly ejects its outer envelope, revealing the core. The exposed core is a white dwarf, where nuclear reactions used to take place. It is composed of carbon and oxygen nuclei. Despite its relatively small size, the white dwarf shines bright because it is at a temperature of about 100 million Kelvin. As the white dwarf radiates energy in the form of photons, it slowly cools.

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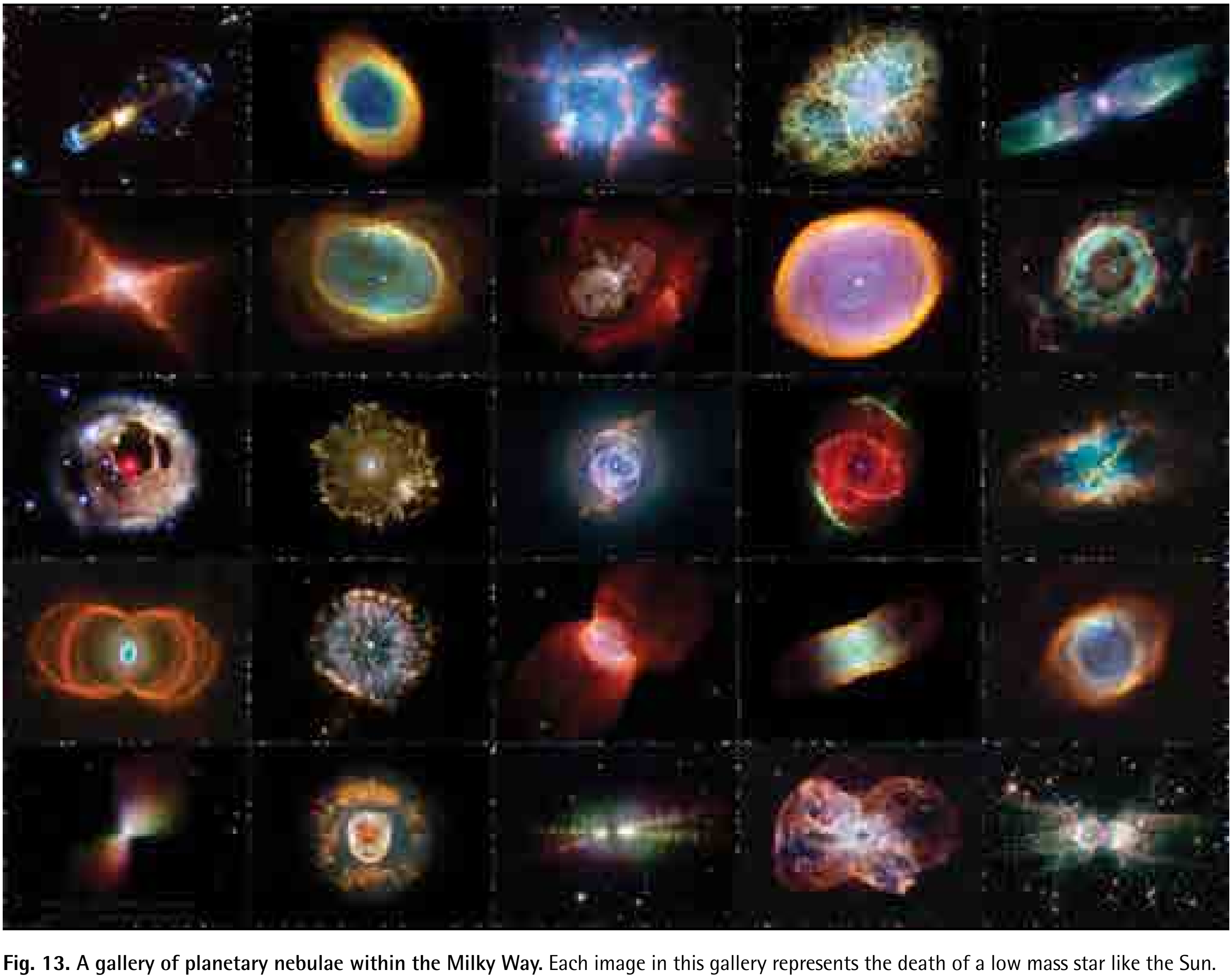

Fig. 13. A gallery of planetary nebulae within the Milky Way. Each image in this gallery represents the death of a low mass star like the Sun. The ring like structure is gas that was once part of the star and is now pushed out in a slow outburst. At the center of each planetary nebula is the white dwarf.

Credits: © NASA/ESA Hubble Space Telescope.

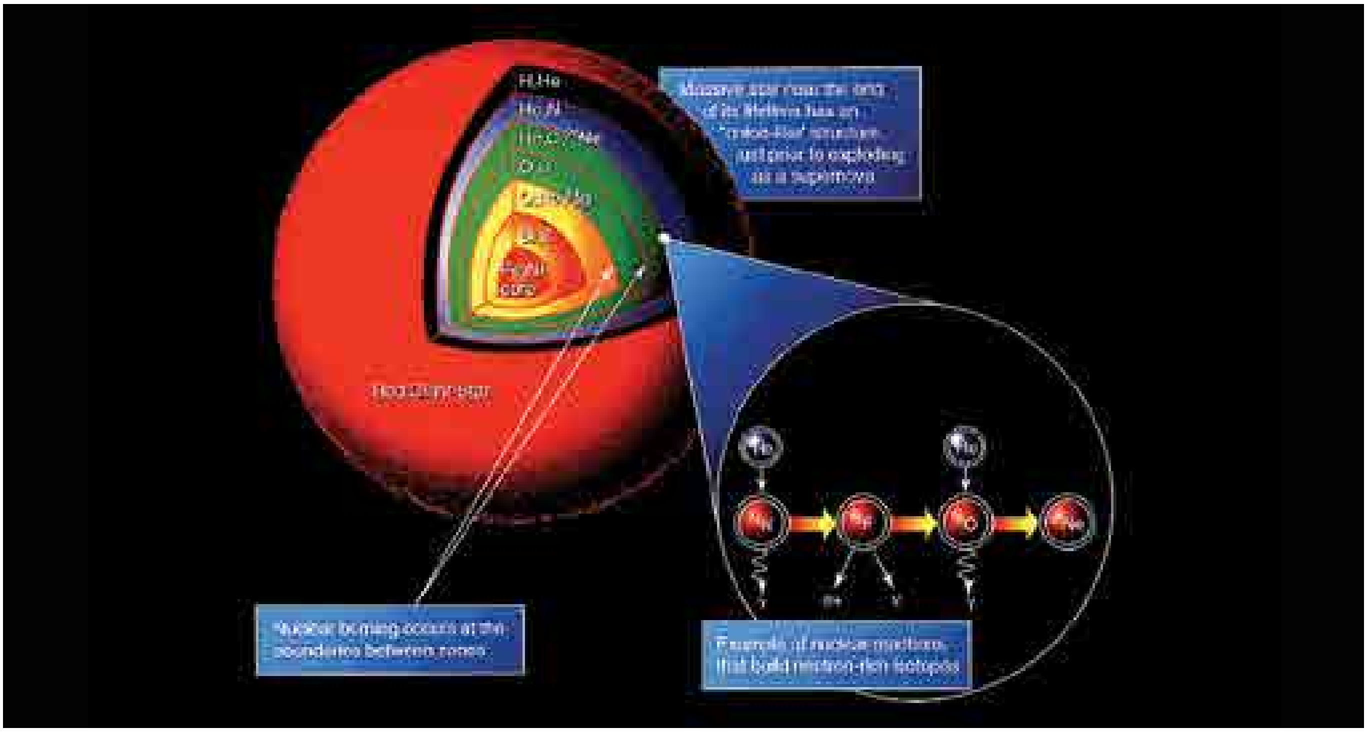

Fig. 14. Fusion reactions in a high mass star. From an initial phase of hydrogen fusion, different fusion reactions occur at different stages of the star's life in its core and the layers of gas close to the core. This results in the synthesis of various elements, a process that continues until iron nuclei start forming at the core.

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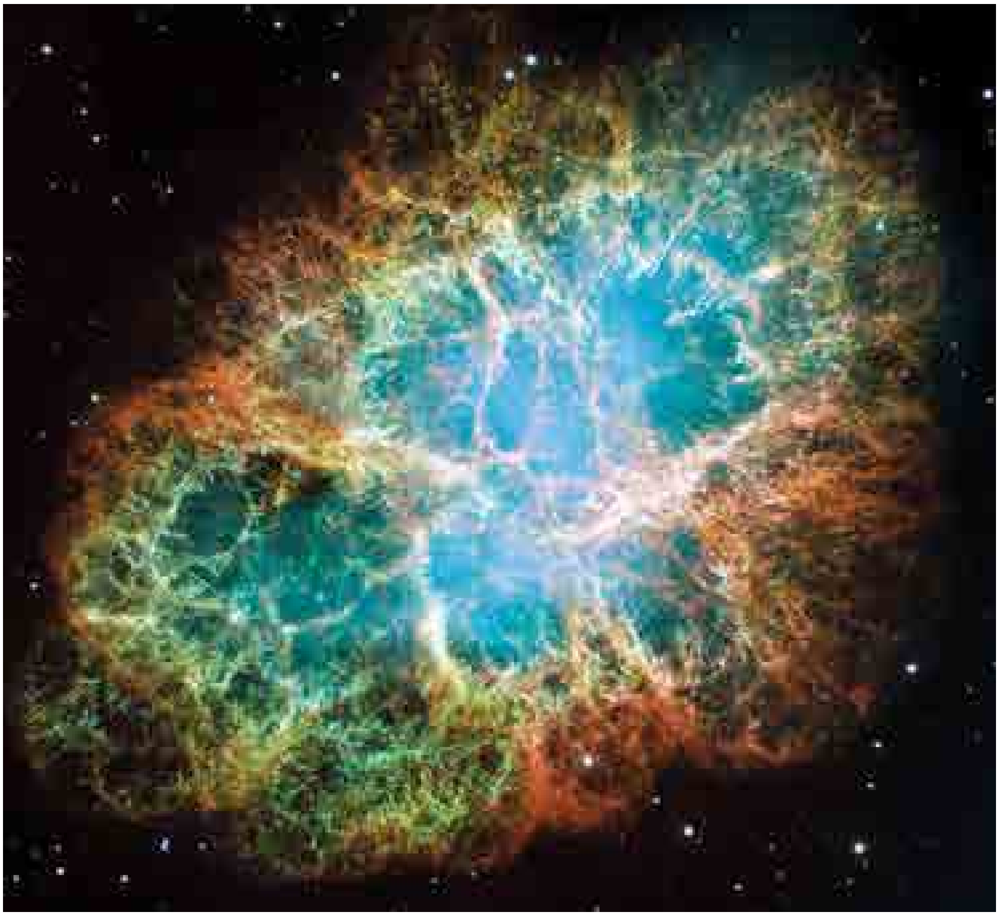

Fig. 15. The remains of a supernova explosion in our own galaxy. Astronomers estimate that this star must have exploded sometime around 1054 CE. The glowing gaseous structure was once part of the star. The gas expanding outwards from the explosion contains many heavier elements synthesized by the star. At the centre of this supernova is a neutron star, which is not visible in this image.

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oxygen in our galaxy is thought to have come from previous generations of planetary nebulae, and the stellar winds that preceded them. Thus, the death of every low mass star supplies the surrounding interstellar medium with these heavier elements (refer **Fig. 13**). Nonetheless, the heavy element contribution from the death of low mass stars is meager. The true source of chemical elements is the death of high mass stars.

(b) The short spectacular life of high mass stars

High mass stars live comparatively shorter lives, but play a more important role in enriching the interstellar medium with heavier elements. Much like low mass stars, nuclear fusion at the core of high mass stars starts with the conversion of hydrogen to helium, and then moves to the conversion of helium to carbon and oxygen. However, both these reactions in high-mass stars occur at a much faster rate in order to keep the pressure due to gravity in balance. High mass stars thus inflate into **Red Super-Giants** (which are bigger than Red Giants) much sooner than a star like the Sun. Also, the synthesis of carbon and oxygen is not the end of the road for fusion in high mass stars. Instead, fusion reactions continue to occur beyond this stage, forming much heavier elements, such as neon, magnesium, silicon, sulphur etc. In fact, a new element is synthesized at every stage of nuclear fusion; and such reactions occur not just at the star's core, but also in the different gas layers surrounding it. This is a stage in stellar evolution that low mass stars never get to.

This cascading process of nuclear fusion continues till the formation of the first few iron nuclei at the core of the star. Since iron nuclei are very stable, they are incapable of fusing together to release energy. Thus, with the core getting entirely converted to iron, the star reaches the end of its life (refer **Fig. 14**). But just before dying off, the star treats us with one last spectacle. The core of the star collapses rapidly, sending a shock-wave which literally shreds the star apart in a violent explosion. Such explosions are called supernovae, after the Latin word *nova* meaning 'new'. When such an explosion happens within a galaxy, the supernova outshines the light from all the stars in the galaxy. Thus, for an observer looking at the night sky, these supernovae reveal themselves as sudden bright objects in the sky. Such events are so spectacular that they can be seen from distances at which even galaxies are hard to detect.

Box 4. Unsolved questions:

The life history of stars is a favorite topic of astronomers. Nearly a century of painstaking research has yielded many fascinating insights into the secret lives of stars. But many questions still remain unanswered. For example, one of the big unknowns in astronomy is the exact nature of the first objects to have formed in the universe? The consensus seems to be that these were stars, but not quite the kind that we see in our Galaxy at present. The first stars, that formed billions of years ago, were a 100 times or more massive than the Sun, living very short (a few hundred thousand years) but spectacular lives. Astronomers are still trying to figure out how these first stars formed, and how they affected the environment around them when they went supernovae.

Another area of active investigation concerns the remains of stars — white dwarfs and neutron stars. Both of these are some of the densest objects in the universe. There are no laboratories on Earth where one can create such dense material. Our understanding of the physics of these exotic objects is far from complete. With the aid of supercomputers, astronomers are creating virtual stars, watching them evolve in fast forward, and testing out the best models that match with observations.

Only the inner core of the star, with its high density, survives the explosion (refer **Fig. 15**). This core transforms itself into either a neutron star (made entirely of neutrons) or a black hole (which is so dense that nothing, not even light, can escape from it). Both neutron stars and black holes are objects that are studied with great interest by astronomers. The rest of the material that was once part of the star is flung out into space as a result of the explosion. The brilliance of a supernova does not last very long. Its light fades out slowly, over a span of several weeks. Observations of the dimming of light from many supernovae have shown that it captures free neutrons to synthesize many new elements heavier than iron.

Thus, over a period of a hundred million years, a high mass star transforms some of its hydrogen into an assortment of heavier elements — all of which, become part of the neighbouring interstellar gas clouds. It is out of these clouds that a new generation of stars and planets are formed, with a mixture of all these elements blended into them.

Rough estimates suggest that there could be about 100 million neutron stars and as many black holes within the Milky Way. This gives us an estimate of the number of supernova events that must have occurred in the past. Astronomers reckon that in a galaxy like the Milky Way, there could be at least one supernova explosion every century. Given that this seems like a very rare occurrence, imagine how long the Milky Way and other galaxies must have been in existence.

The cosmos is also within us

The story of stellar evolution is as much about the stars, as it is about us (refer **Box 4**). Imagine this for a moment: what if stars never existed? Or, even if they did, what if it was not in their destiny to die? What if they produced their energy by some process other than fusion? The universe would have never synthesized elements heavier than hydrogen and some helium. Planets like the Earth, made mostly of heavier elements, would have never formed. Life, as we know it, would never have taken shape.

That's how important stellar evolution is to us. Every atom in our body had its origin in some star that lived and died more than 5 billion years ago. And with some stretch of imagination we could even say that the atoms in our body could have come from not one, but possibly a few different stars that went supernovae long before the birth of the solar system. In a more poetic sense, we are literally stardust.

The next time you are out in the open on a clear night, under the vast canopy of a starry sky, remember that the stars that are out there at vast distances from us, are also very much within us.

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