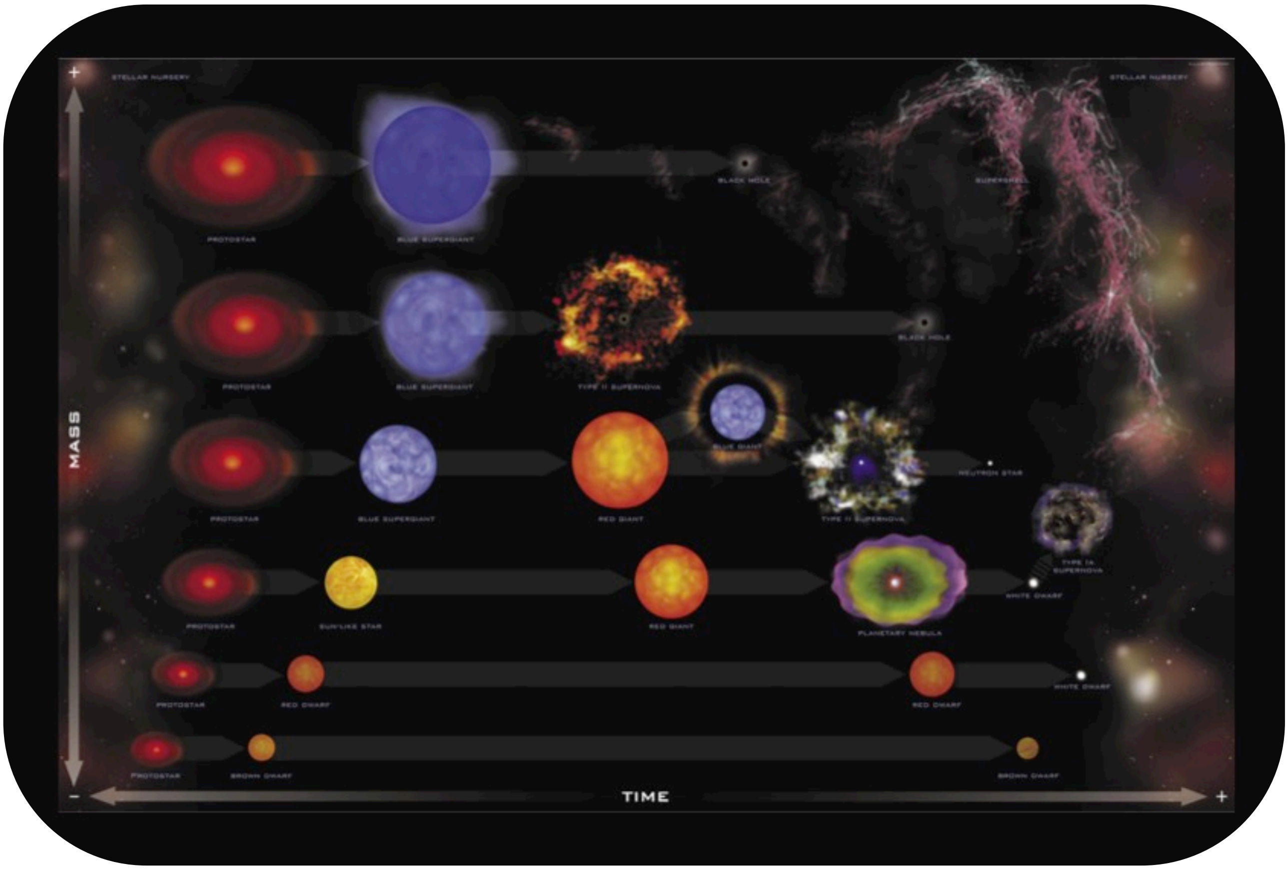
Stellar evolution

CESAR's Booklet



Lives of stars

Stars are not eternal: like people, they are born, they change with time, and they die. And also like people, not all stellar lives are the same. The most critical parameter in a star's life is its mass; more precisely, its Main Sequence mass, the mass it has when it starts the hydrogen fusion processes in its core that keep the balance with gravity, preventing the star from collapsing toward its centre. When the star's core runs out of hydrogen, it undergoes a series of changes until it dies, and these changes depend on the mass of the star.

The whole process takes long, much longer than any living being's life, although how long it takes also depends on the star's mass. But let's start from the very beginning…

How do stars form?

Stars form when a particular type of interstellar cloud, called a *molecular cloud,* starts collapsing by the effect of its own gravity and breaks up into tens or hundreds of smaller clumps. Owing to the gravitational attraction, each cloud fragment attracts more and more matter from its surroundings (see Figure 1).

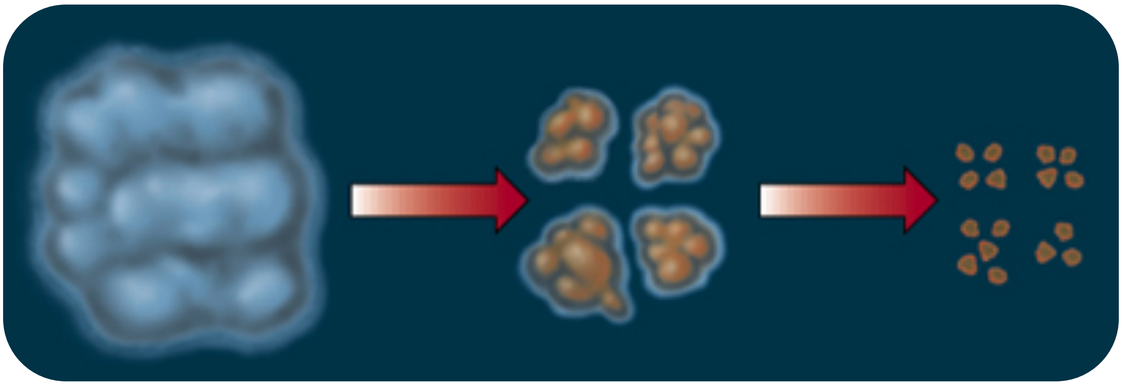


Figure 1: *Collapse and fragmentation of a molecular cloud. (Credit: Pearson Prentice Hall)*

The cloud fragment spins faster and flattens into a rotating *protostellar disk*. The central region, called a *protostar*, keeps growing in mass, shrinking in size and getting warmer and denser thanks to the gravitational pull. Typical temperatures of protostars range from 100 to 10^4 K, emitting radiation mainly in the infrared. For a star like our Sun, it takes about 100,000 years to reach this stage from the moment the cloud started to collapse –very short time compared to the approximately 10 billion years our Sun will live. Figure 2 shows some images from real protostars, observed by the Hubble Space Telescope.

About one million years after the beginning of the collapse, the protostar has reached nearly all the mass it will have when it starts the next stage –the Main Sequence. Now interesting things happen in the disk: Dust grains get stuck and grow in size, forming larger grains, then pebbles, then rocks, and so on to the first *planetoids.* These large chunks of rock may open gaps in the disk, cleaning their way as they scatter or attract more and more matter. If they gather enough mass, they get rounded, turning into Earth-like planets (called *rocky planets* or *telluric planets*); if they get even more massive, they can also attract the gas in the disk (mostly hydrogen and helium) and become Jupiter-like planets (called *giant planets* or *jovian planets*). Figure 3 shows a real image of a circumstellar disk with a gap, where astronomers think that a planet is forming.

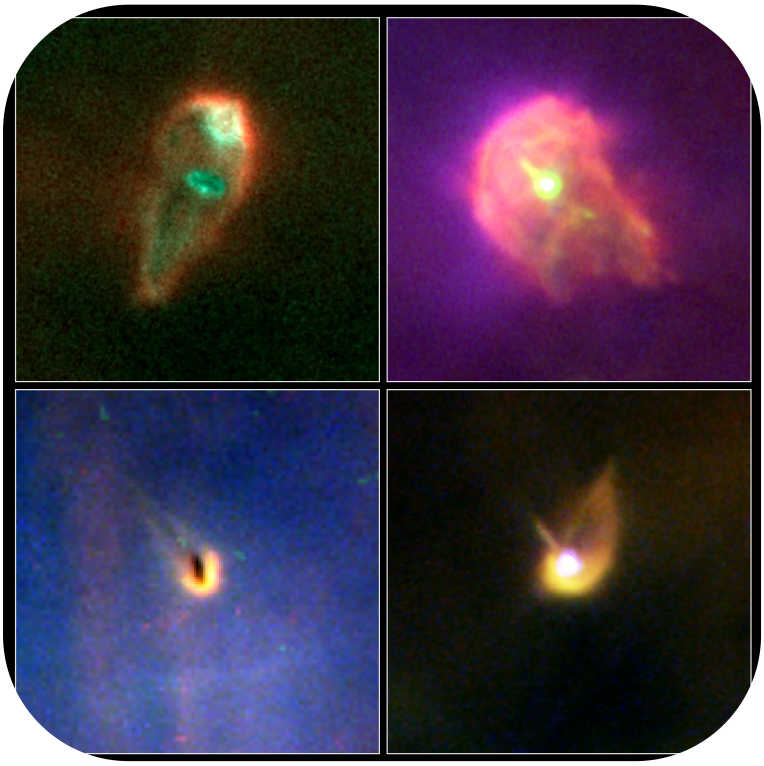


Figure 2: *Protostars in the Orion Nebula observed by the Hubble Space Telescope (Credit: NASA/ESA)*

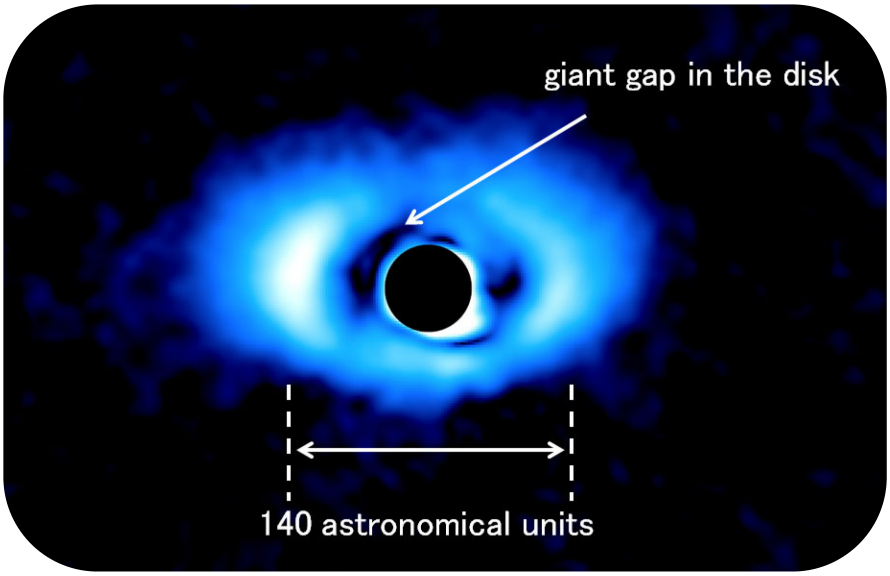


Figure 3: *Protoplanetary disk around star PDS 70 (blocked in the image to prevent it from blending the view of the disk) with a gap where a planet is forming. (Credit: NAOJ)*

Eventually, the disk dissipates, leaving the planets and other smaller bodies and debris (analogous to the dwarf planets, asteroids, comets and meteoroids in our own Solar System). In the centre, the protostar has kept shrinking until it has reached a core temperature of 10 million Kelvin: Hydrogen fusion can begin. A star is born.

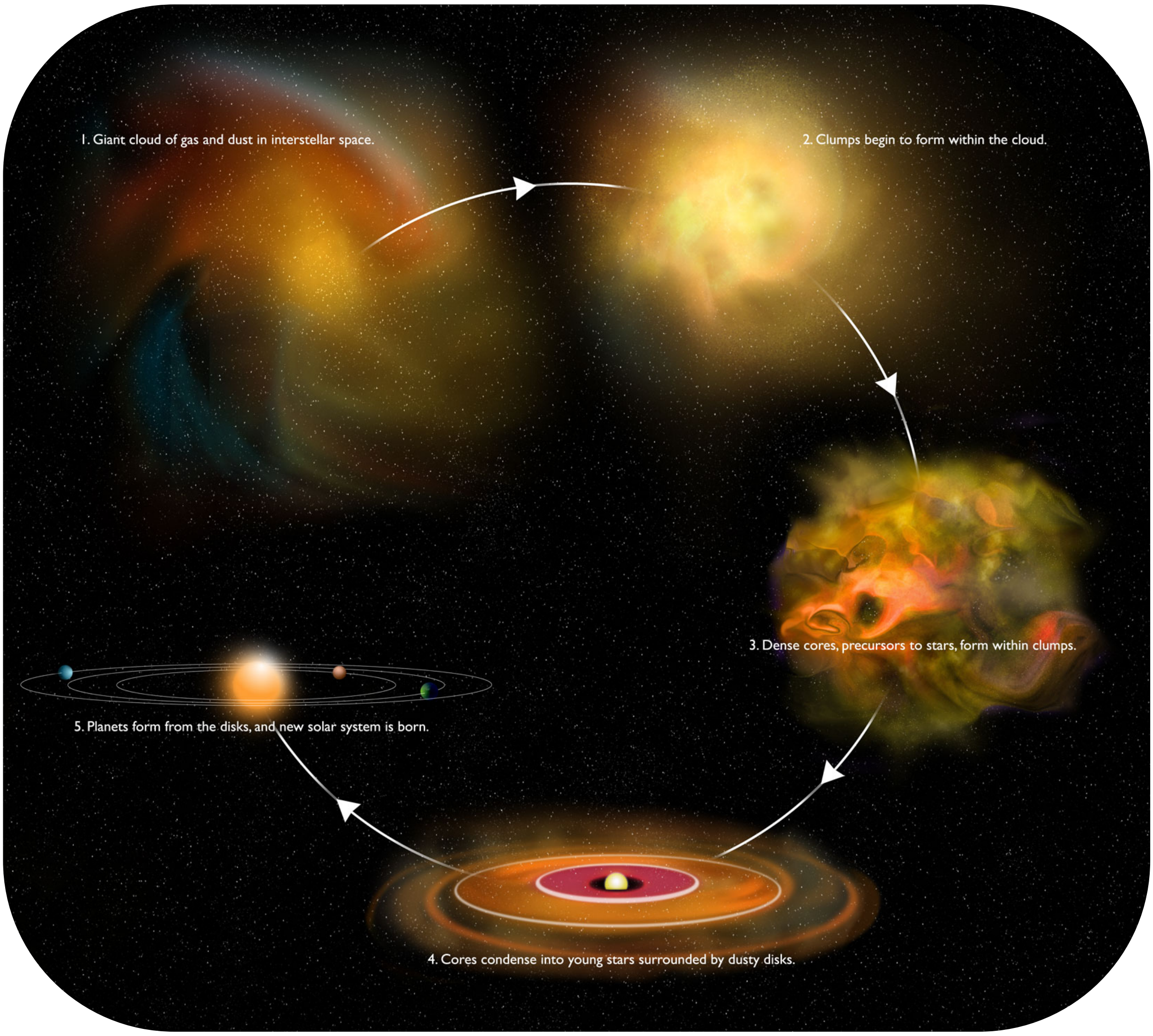


Figure 4: *Summary of the formation process of a star and its planetary system (Credit: Bill Saxton, NRAO/AUI/NSF)*

One might think that a low-mass star should form in shorter time than a massive star, as it requires less matter, but in fact it is the other way round: massive stars form much faster than low-mass stars. The reason is that, although more mass is required, gravity is also stronger, pulling matter faster together. While a star like our Sun forms in a few tens of millions of years, a star of 5 solar masses forms in less than one million year, and it takes only a few hundred thousand years to form stars 15 times more massive than the Sun! In contrast, a star of 0.5 solar masses requires about hundred million years to form.

Reaching the Main Sequence… or not

As it contracts, the protostar gets smaller, hotter and denser. This means that a star in the protostellar stage is cooler (redder) and bigger than it will be in the Main Sequence stage (the hydrogen-fusing stage). Because a star's luminosity depends not only on its surface temperature, but also on its size, the protostar will actually be more luminous than the Main Sequence star. Therefore, in the HR diagram, a protostar will be located up and to the right of the corresponding Main Sequence location, and will move down and to the left as it contracts, following a so-called *evolutionary track*.

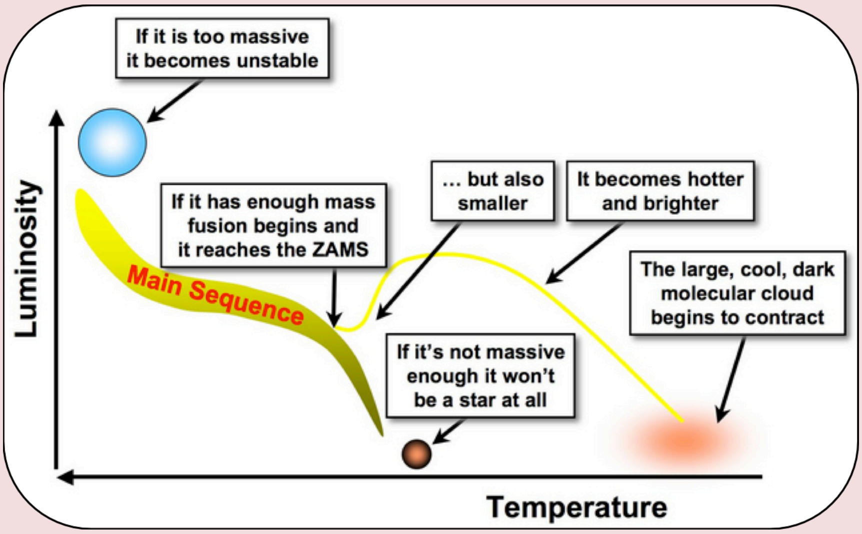


Figure 5: *Evolution of protostars in the Hertzprung-Russell diagram (Credit: Cosmos, the SAO Encyclopedia of Astronomy)*

There are however cases in which a contracting stellar core will never reach the Main Sequence: If the core is too massive, it will contract very fast and collapse completely before hydrogen fusion can begin. On the other hand, if the core's mass is too low, it will keep contracting for a long time without ever reaching the conditions for hydrogen fusion; eventually stabilised by other mechanisms, the failed star will then slowly cool down as it ages. This object is what astronomers call a *brown dwarf.*

Life on the Main Sequence

When the hydrogen fusion process begins, it is said that the star "has reached the Main Sequence". This is the longest-lived stage in the life of any star.

But what does *hydrogen fusion* mean? During this phase, the star stably turns hydrogen into helium in its core through a process called *nuclear fusion.* Concretely, four hydrogen nuclei (four protons) are joined (*fused*) to form a helium nucleus (two protons and two neutrons). But if we compare the masses of the four hydrogen nuclei with the mass of the helium nucleus, it turns out that the mass of the helium nucleus is lower than the mass of the four protons together! Where did the missing mass go? It was turned into energy, and released from the star's core in the form of light.

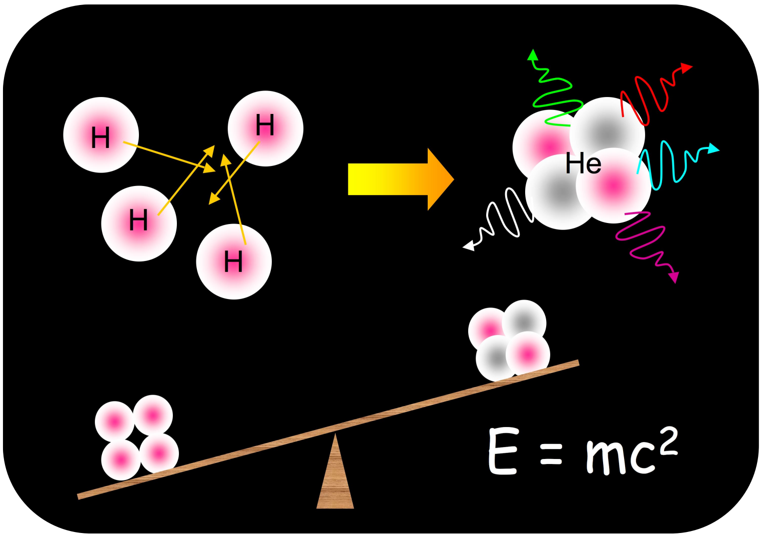


Figure 6: *In the hydrogen fusion process, four hydrogen nuclei fuse to form a helium nucleus. The difference in mass is released in the form of energy. (Credit: B. Montesinos)*

The energy released by the fusion of hydrogen pulls the star outward, preventing the star from collapsing under its own gravity, as shown in Figure 7. This balance is called *hydrostatic equilibrium*. As long as the star is in hydrostatic equilibrium, its temperature, luminosity and size stay the same.

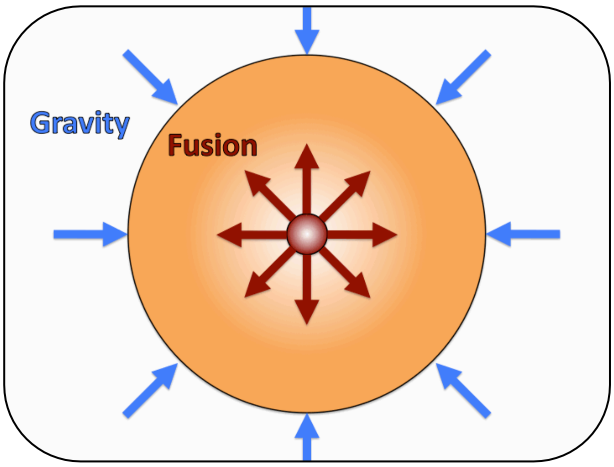


Figure 7: *Hydrogen fusion releases energy outward that stabilises the star against its own gravity (which is pulling inward). (Credit: B. Olson)*

The proton-proton chain

Stars like our Sun convert hydrogen into helium mostly through a series of nuclear reactions called *the proton-proton chain*, or *p-p chain* for short (Figure 8).

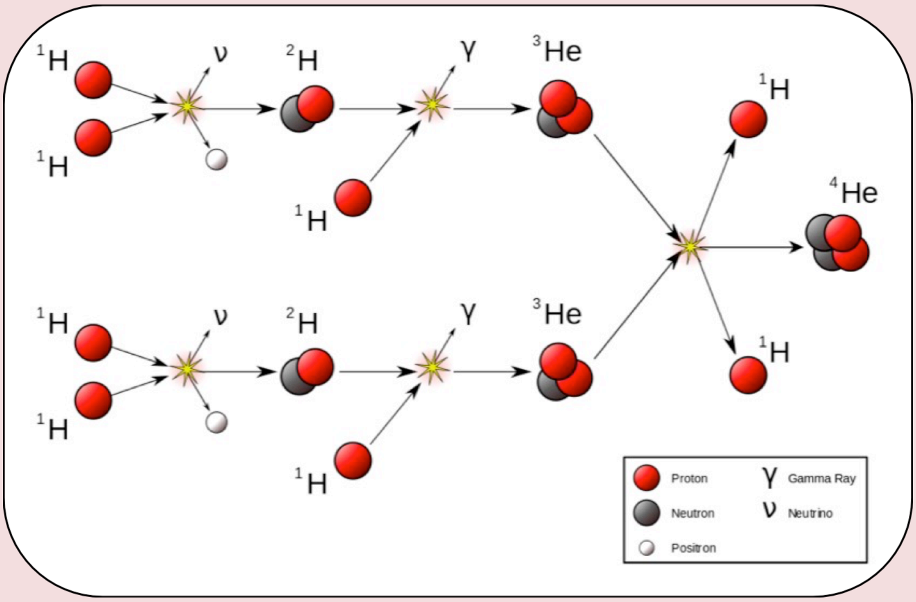


Figure 8: *The proton-proton chain (Credit: Wikimedia Commons)*

The steps are the following:

1. Two hydrogen nuclei (two protons) are brought together to build a deuterium nucleus (a proton and a neutron). The process also creates a positron (a particle with the same mass as the electron and opposite charge) and a neutrino (a very light, hard-to-detect particle):

$$^1H + ^1H \rightarrow ^2H + e^+ + \nu$$

2. The deuterium nucleus fuses with a new hydrogen nucleus, making helium-3 and releasing a photon (that escapes carrying away energy):

$$^2H + ^1H \rightarrow ^3He + \gamma$$

3. Two helium-3 nuclei are brought together to create helium-4 and two protons:

$$^3He + ^3He \rightarrow ^4He + ^1H + ^1H$$

This is the most common path for making helium in solar-mass stars, but not the only one; there are variations of this process involving other chemical elements. On the other hand, in stars more massive than about 1.3 solar masses, the dominant process is a completely different one, called *the CNO cycle*.

For stars on the Main Sequence, there is a relation between their mass and other properties like temperature, brightness and size: The most massive stars are big, bright and hot, and are a blue or blue-white colour; they are *blue giants and supergiants*. On the other end, the least massive stars are small, dim and cool, and their colour is red; they are *red dwarfs*. Stars like our Sun are somewhere in the middle; they are sometimes called *yellow dwarfs*.

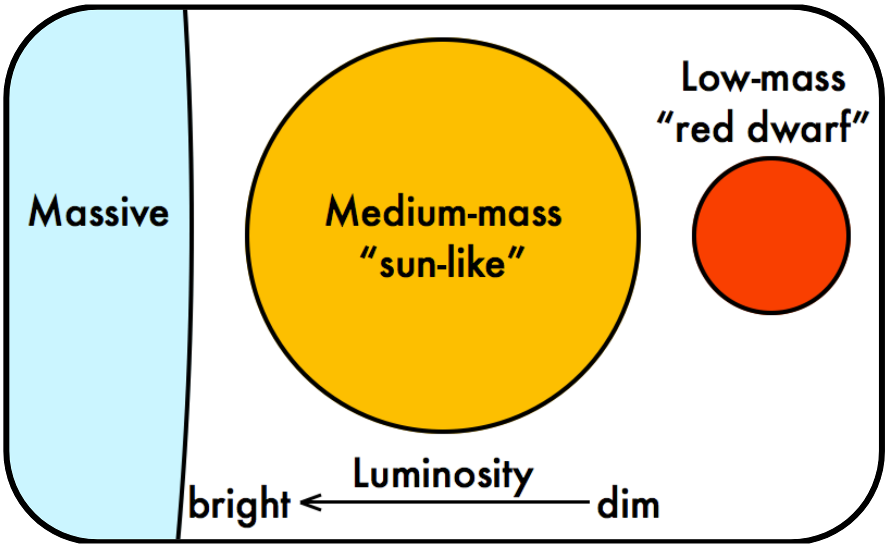


Figure 9: *Different types of Main Sequence stars (Credit: P-dog's blog)*

The time a star spends on the Main Sequence also depends on its mass. Again, it might seem that a massive star would take longer to run out of hydrogen. However, because it has stronger gravity, this type of star also needs to produce more energy to balance the force inward caused by its own mass. Therefore, *the less massive a star is, the longer its Main Sequence life*: Our Sun has been on the Main Sequence for about five billion years, and will stay there for another five billion years. Blue giants have very short lives, of a few million years. Red dwarfs, the least massive stars, spend *trillions* of years on the Main Sequence; this is older than the current age of the Universe!

Post-Main Sequence evolution

Nothing lasts forever and, sooner or later, the hydrogen left in the star's core will not be enough to generate the amount of energy necessary to keep the balance against gravity. What happens now depends, once more, on the mass of the star.

Evolution of a star like the Sun

Stars of mass similar to our Sun evolve slowly and have a non-violent death. A summary of the stages in the life of these stars is shown in Figure 10.

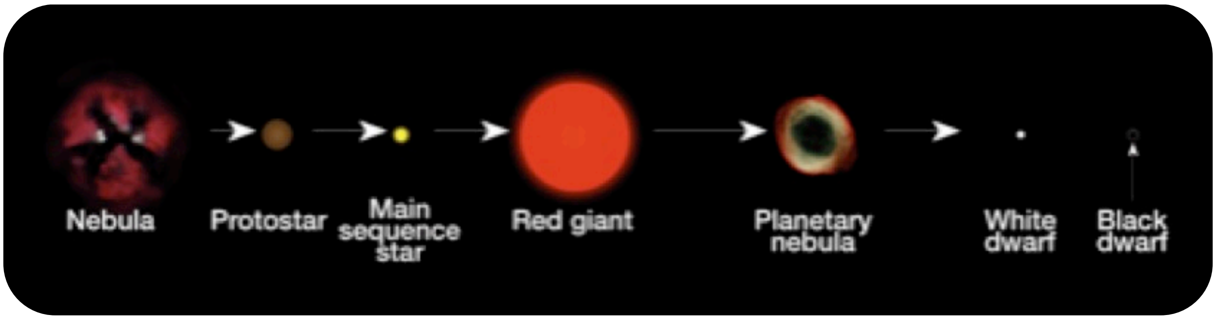


Figure 10: *Evolution of a star like our Sun (Credit: Found in thelifecycleofstars.weebly.com)*

When the star runs out of hydrogen in its core, the balance is broken: Gravity is now the strongest force, and the star's core starts shrinking, getting denser and hotter. On the other side, the outer parts of the star expand, and so the star gets bigger, cooling down as its size increases: It has become a *red giant*.

Eventually, the core reaches the conditions to start fusing helium into carbon. And here the fusion processes end, because the core of a solar-mass star will never reach the conditions for fusing carbon. Eventually, the star will be so big that its outer layers escape the gravitational pull from the centre and disperse into space, enriching the interstellar medium with helium, carbon and some oxygen. For a very brief period of time (not more than one million years), this gas glows, ionised by the energy released by the shrinking, very hot core, creating what is (deceivingly) known as a *planetary nebula*.

A planetary nebula is a rare event: only about 1500 such nebulae are known in our Galaxy. This low number (in comparison with the 200 billion stars in the Milky Way) is a hint that it is a very short-lived stage. Figure 11 shows some examples of planetary nebulae observed by the Hubble Space Telescope.

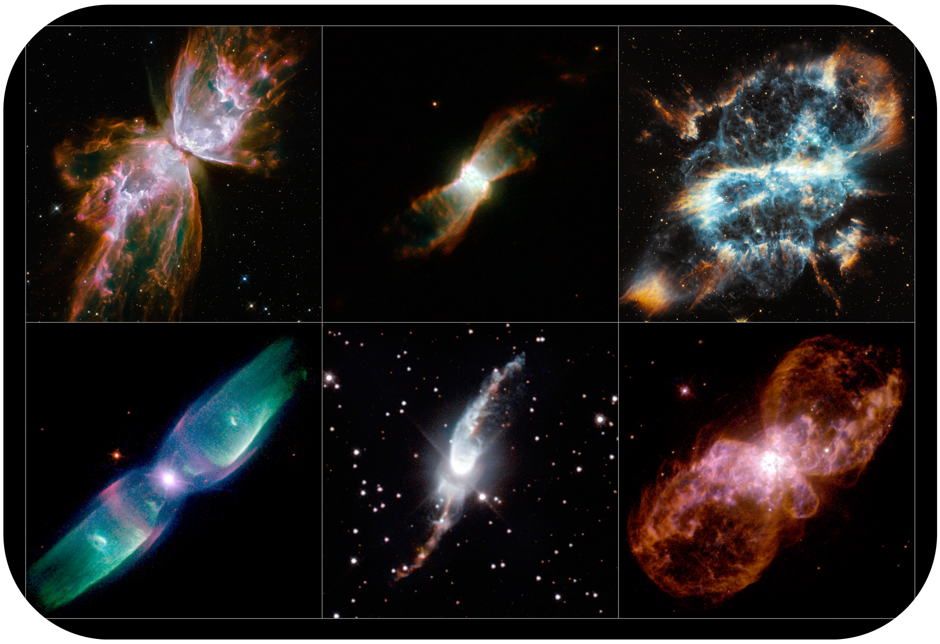


Figure 11: *Some planetary nebulae observed by the Hubble Space Telescope. (Credit: ESA/NASA)*

Why does the star turn into a red giant, and what is happening inside it?

As explained, when the star runs out of hydrogen in its core, gravity is the strongest force: The star's core shrinks, getting denser and hotter. Fusion has not completely stopped in the star, though: On top of the inert helium core, a shell is still fusing hydrogen (left panel of Figure 12). The generated energy is transmitted to the rest of the star, which quickly expands (as gases expand when they are heated up). Thus, although the core gets smaller, the star as a whole gets bigger; so big that the outer layers of the star, being so far away from the core, cool down, and the star turns red: It has become a *red giant*. The change has taken place in only about 100 million years.

As the star's size increases, so does its luminosity. In the HR diagram (Figure 13), the star moves away from the Main Sequence following a track upward and to the right, toward the *Red Giant Branch* (the area of the diagram where red giants are found).

Eventually, the core reaches a temperature of 100 million Kelvin, necessary for helium to fuse into carbon. Helium fusion begins very suddenly, in a *flash*, and balance is re-established. The star becomes hotter and smaller, but its luminosity stays roughly constant. This adjustment occurs rather quickly, in about 100,000 years.

In the HR diagram, we see a knick in the evolutionary track of the star at the point of the helium flash. Then, the star moves to the left on a nearly horizontal path. This region of the diagram is called the *Horizontal Branch*, so this stage is simply called a *Horizontal Branch star*.

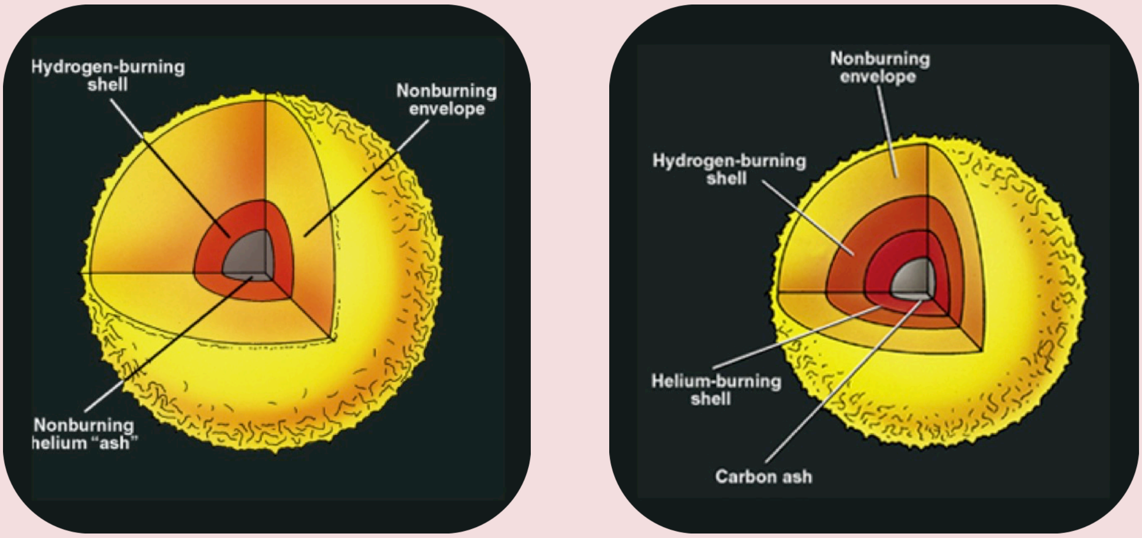


Figure 12: *Structure of a red giant (left) and an AGB star or red supergiant (right). (Credit: Pearson Prentice Hall)*

However, the time it takes for the star to burn all the helium in the core is very short in comparison with the time it was burning hydrogen (no more than a few ten million years after the helium flash); soon enough, the star runs out of helium and balance is broken again. The inert carbon core starts shrinking again, although on top of it there are still a shell of fusing helium and a shell of fusing hydrogen (right panel of Figure 12).

Again, the star expands, increasing in size, and cools down, moving again up and to the right in the HR diagram. It is now even bigger than it was in the Red Giant Branch. It has become a *red supergiant,* or *Asymptotic Giant Branch star* (*AGB star* for short), from the name of this region in the diagram.

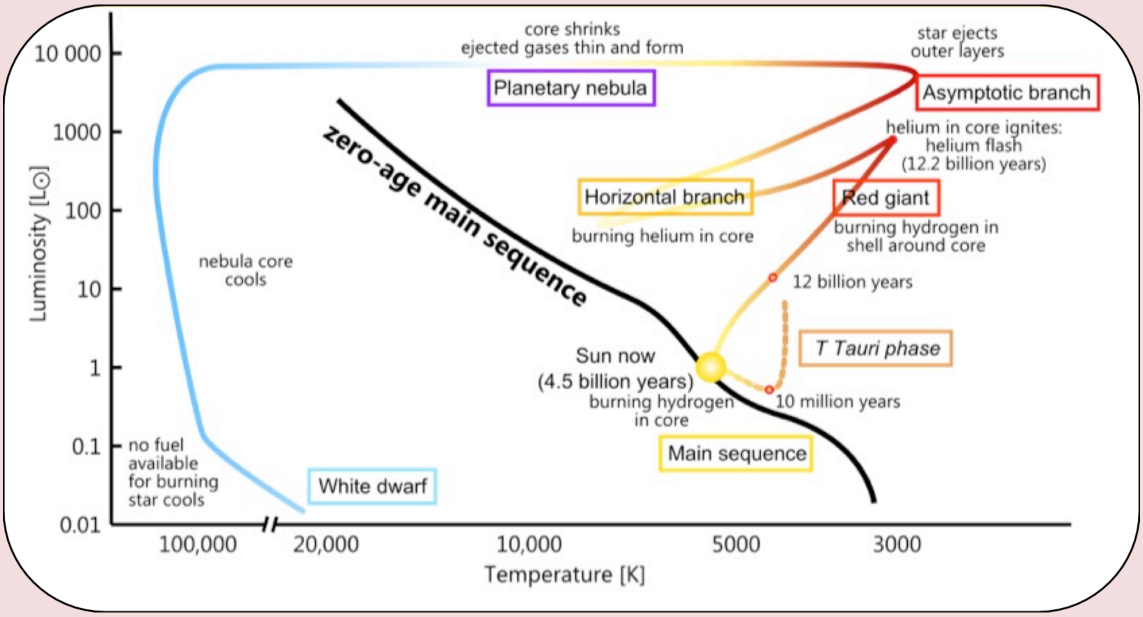


Figure 13: *Evolutionary track of a solar-mass star in the HR diagram (Credit: Wikimedia Commons)*

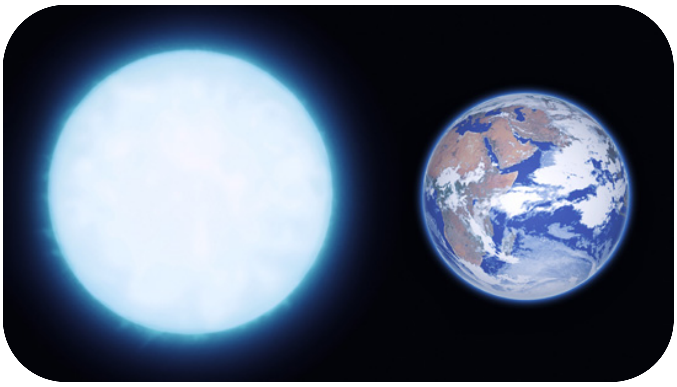


Figure 14: *Comparison of the white dwarf Sirius B (artist impression) with the Earth. (Credit: ESA/NASA)*

The bare carbon core left at the once centre of the star is called a *white dwarf*. This is a very dense, hot and small object; for comparison, Sirius B, a white dwarf in the nearby Sirius binary system, has almost the same size as our planet Earth (Figure 14). White dwarfs slowly cool down, and it is hypothesised that they will eventually turn into something called a *black dwarf*. However, so far no black dwarfs are known, presumably because the universe is too young for any star to have reached this stage.

Why do white dwarfs not collapse?

A star's life is a continuous fight against gravity, generating energy enough in its core to balance it and prevent collapse. We have seen how this is achieved by fusion of chemical elements. But how does a white dwarf prevent collapse, if it is not fusing anything and it is getting cooler and cooler with time?

A white dwarf is very small and dense: a ton of matter is compressed into the volume of a grape. Under such conditions, atoms are not free to move like in normal gas, and electrons are no longer bound to the nuclei. As the white dwarf cools down, it tries to shrink, but the electrons fight being pushed into a smaller volume. This generates some pressure outward, called *electron degeneracy pressure*, which does not depend on the temperature and keeps the size of the white dwarf stable.

Evolution of a red dwarf

What happens after a red dwarf ceases to produce energy through fusion has not been directly observed: The Universe is thought to be around 13.8 billion years old, which is less time than it takes for fusion to stop in such stars.

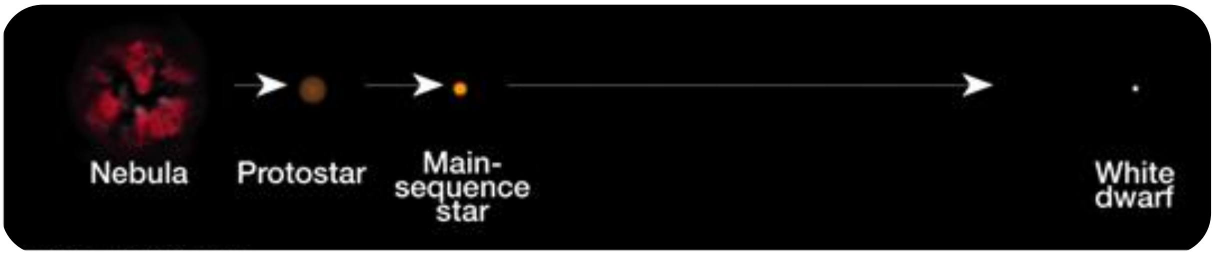


Figure 15: *Evolution of a red dwarf (Credit: Found in thelifecycleofstars.weebly.com)*

Red dwarfs will never reach the point of helium fusion. Eventually, the star's envelope will be ejected in a manner similar to that of a more massive star, forming a "helium white dwarf", as summarized in Figure 15.

Evolution of a massive star

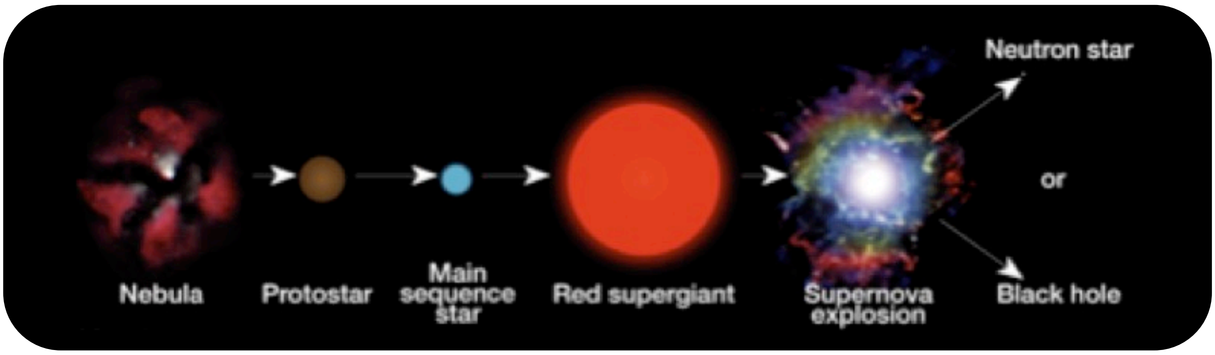


Figure 16: *Evolution of a massive star (Credit: Found in thelifecycleofstars.weebly.com)*

High-mass stars evolve much faster than stars of lower masses, going through the stages shown in Figure 16. Because they are already very big when they are on the Main Sequence (they are blue giants and supergiants), they directly turn into *red supergiants* when the hydrogen fusion process stops. The next steps are similar to the ones in the life of solar-mass stars, but these stars do reach the conditions in their cores to fuse carbon, and also successively heavier elements, until iron. This is the most stable element and cannot produce nuclear reactions. Thus, nuclear burning stops, and the core begins to shrink; the iron atoms get so close that they are broken into their components –electrons, protons and neutrons. As the core gets even smaller, the protons and electrons combine to form more neutrons, and so the whole core turns into a hot ball of neutrons.

When the core cannot stand being compressed any longer, the star explodes as a *supernova*, throwing away all its outer layers. Astronomers have found many glowing clouds of gas in the spots where supernovae had been observed, with the gas moving away from the central point at very high speeds; they are called *supernova remnants*. Figure 17 shows the Crab Nebula, the remnant of a supernova reported by Chinese astronomers in 1054.

Figure 17: *The Crab Nebula, a famous supernova remnant. (Credit: NASA/ESA)*

A stellar onion

What happens inside the massive star is analogous to the processes in the solar-mass star, but repeated again and again. The drop in temperature is compensated by the increased size, and so the luminosity of the massive star does not change so dramatically as in the case of the solar-mass star. In the HR diagram, the star moves toward the right nearly horizontally as it cools down (Figure 18). There is no helium flash; evolution proceeds so rapidly for stars bigger than 10 solar masses that they don't even reach the red giant region before helium fusion begins.

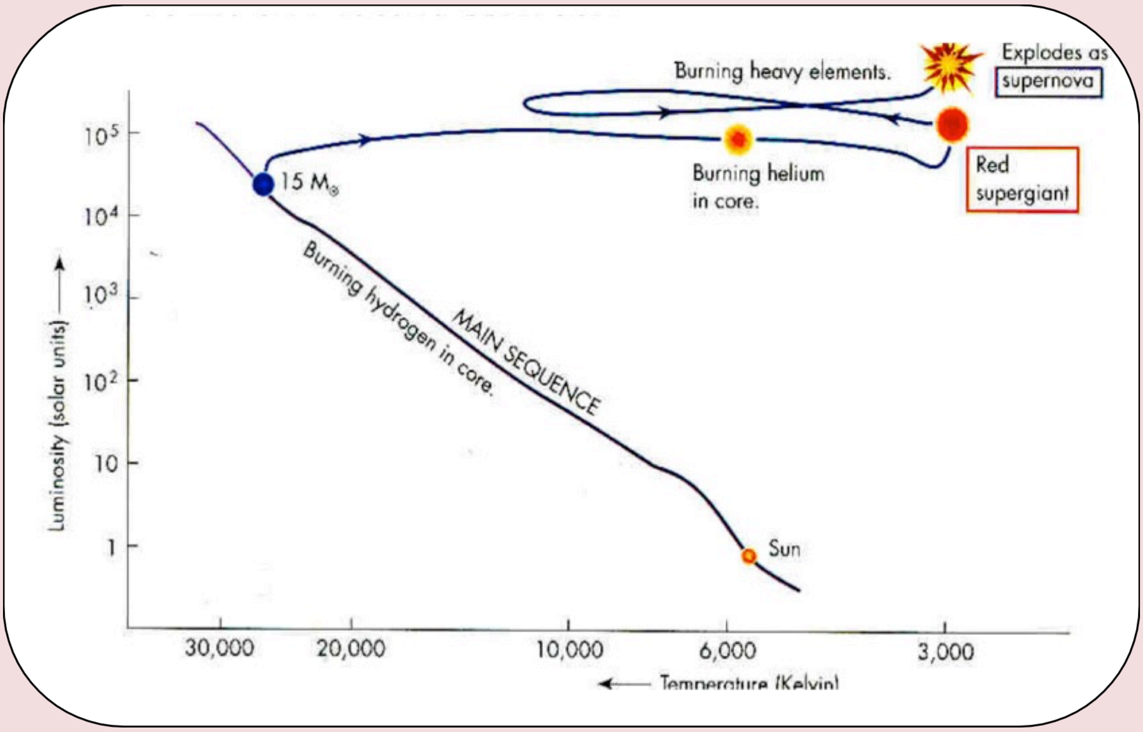


Figure 18: Evolutionary track of a high-mass star in the HR diagram (Credit: E. Zirbel)

The evolutionary track of a massive star loops back and forth across the diagram as it evolves. As the core runs out of each element, it contracts, heats up, and fusion starts again. A new inner core forms, contracts again, heats again, and so on. The star's luminosity stays roughly constant as its radius increases and its surface temperature drops.

Each fusion step takes shorter time than the previous one. As an example, a star of 20 solar masses will burn:

- hydrogen for 10 million years;
- helium for one million years;
- carbon for 1,000 years;
- oxygen for one year;
- silicon for a week;
- iron for less than one day.

When fusion ends up completely in the core, the interior of the star looks like is depicted in Figure 19: a core of inert carbon covered by a number of shells where fusion of successively lighter elements is taking place. It is similar to an onion, and in fact, it is called an *onion layer structure*.

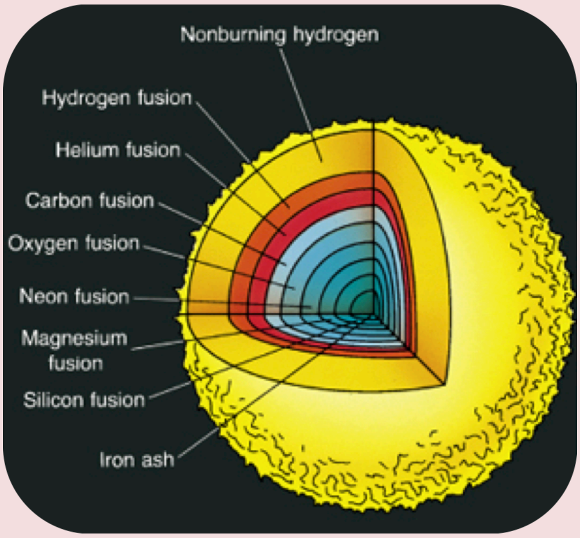


Figure 19: *Onion layer structure in an evolved high-mass star (Credit: Pearson Prentice Hall)*

The fate of the core depends on its mass: If it is lower than three times the mass of the Sun, it will reach equilibrium and remain as a *neutron star*. This is an incredibly small and dense object: A mass larger than the Sun compressed in a diameter of 10 to 20 km, similar to the size of a city! Because of this, the gravitational force is very intense, and it spins very fast, completing one full rotation in one second or less.

The neutron star also has a strong magnetic field and emits two beams of energy through the magnetic poles. Because of the high rotation, the effect is similar to a lighthouse, as shown in Figure 20. If the beams of light are oriented toward Earth, we can observe them in the form of periodic flashes of light as the neutron star spins; this is what astronomers call a *pulsar.* At the centre of the Crab Nebula, a pulsar blinks on and off 30 times each second.

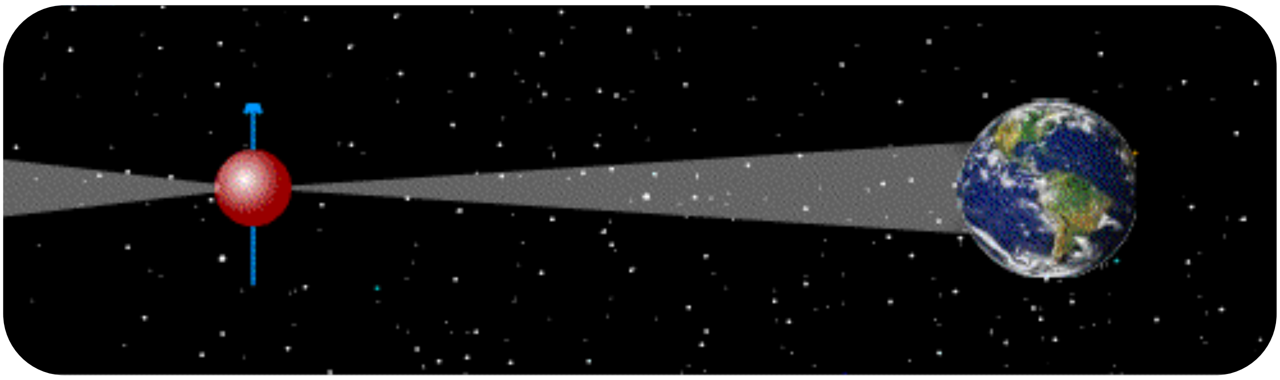


Figure 20: *The lighthouse effect in neutron stars. (Credit: NASA)*

If the mass of the bare neutron core is higher than three solar masses, however, gravity wins the battle once and forever: the core completely collapses toward its centre, and all the mass is compressed in just one dot of infinite density, forming a *black hole* (Figure 21).

Near a black hole, the gravitational force is so strong, that nothing can escape its pull. Even light gets trapped and falls toward the centre of the black hole!

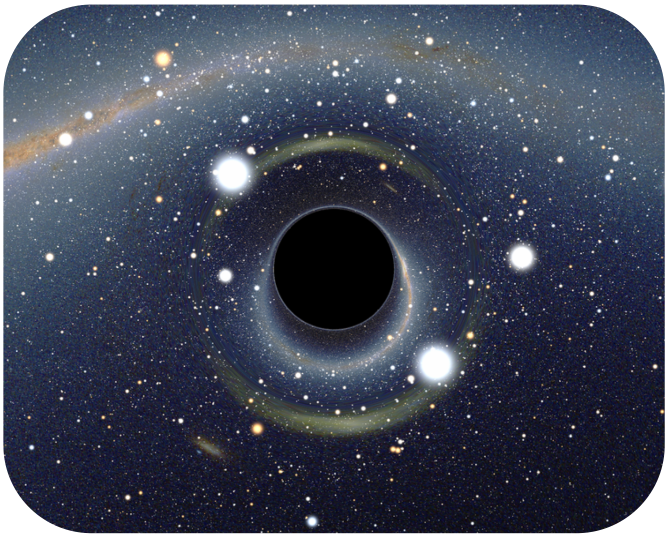


Figure 21: *A black hole (artist's impression). (Credit: Wikimedia Commons)*

If black holes are black, how do astronomers know they are there?

A body needs to move fast to escape from the gravitational pull of another; and the closer it is to the second body's centre, the faster it will have to move. The speed necessary to escape from the gravitational attraction of a body is called the *escape speed*; it depends on the mass of the body and the distance from it.

Near a black hole, a body would need to move faster than light to escape the gravitational pull. But Physics tells us this is impossible: Nothing can travel faster than light! Yet, because the escape speed depends on the distance, there will be a distance from the black hole where the escape speed precisely equals the speed of light. Beyond that distance, a body could prevent falling onto the black hole –provided it moves sufficiently fast. There can even be bodies orbiting a black hole!

The imaginary sphere whose radius equals the distance at which the escape speed is the speed of light is called the black hole's *event horizon*. Astronomers cannot know what happens below the event horizon, because no light is coming from that zone; but they can study what happens near the black hole and above the event horizon.

For example, some astronomers discovered a group of stars that were moving around an invisible object close to the centre of the Milky Way (Figure 22). They monitored these stars over many years to study their orbits and, this way, estimate their masses and that of the mysterious object at the centre. They concluded that the central object must have a mass of about 4 million solar masses. Such an extremely massive object that is emitting no light at all can only be a black hole.

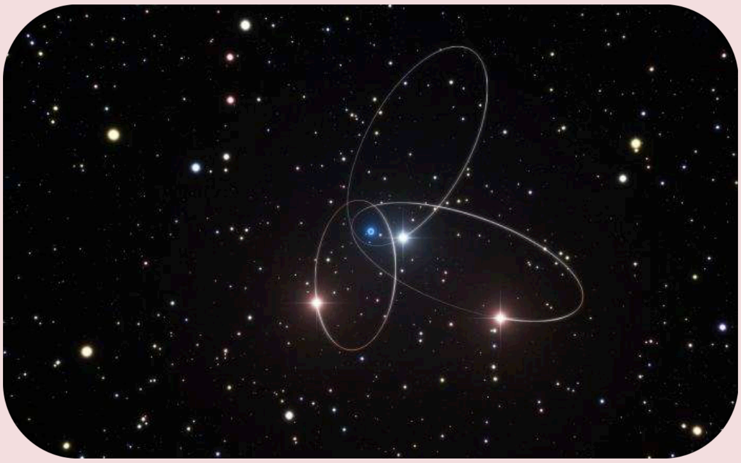


Figure 22: *Stars orbiting the black hole at the centre of the Milky Way. (Credit: ESO)*

Another way of studying black holes is thanks to the matter that is falling onto them. When a body falls onto a black hole, it gets stretched and squeezed by the extreme gravitational pull. The result is numerous and violent collisions among the resulting debris; the infalling matter gets heated up, emitting high-energy radiation (X-rays) that telescopes can detect.

Figure 23: *A star falling onto a black hole (artist's impression). (Credit: NASA)*

The cosmic cycle of matter

We have seen how helium and heavier elements up to iron are created in the cores of stars through nuclear fusion reactions. When a star dies, either as a planetary nebula or as a supernova, all these elements are dispersed into the interstellar medium, enriching it. Moreover, in the last stages in the life of a massive star, and especially in the supernova explosion, the amount of energy released is so huge that it is possible to create elements heavier than iron, up to uranium.

Astronomers think that all the hydrogen and most of the helium in the Universe are primordial; in other words, they date back to the very earliest times, long before the first stars formed. The rest of chemical elements have been created by the stars. Many of the heaviest elements were formed after their parent stars had already died!

Thus, matter in the Universe follows a cycle: It forms clouds where stars are born, those stars evolve and die creating new elements and bringing them back to the interstellar medium in the form of new clouds, so that the process can begin again and again.

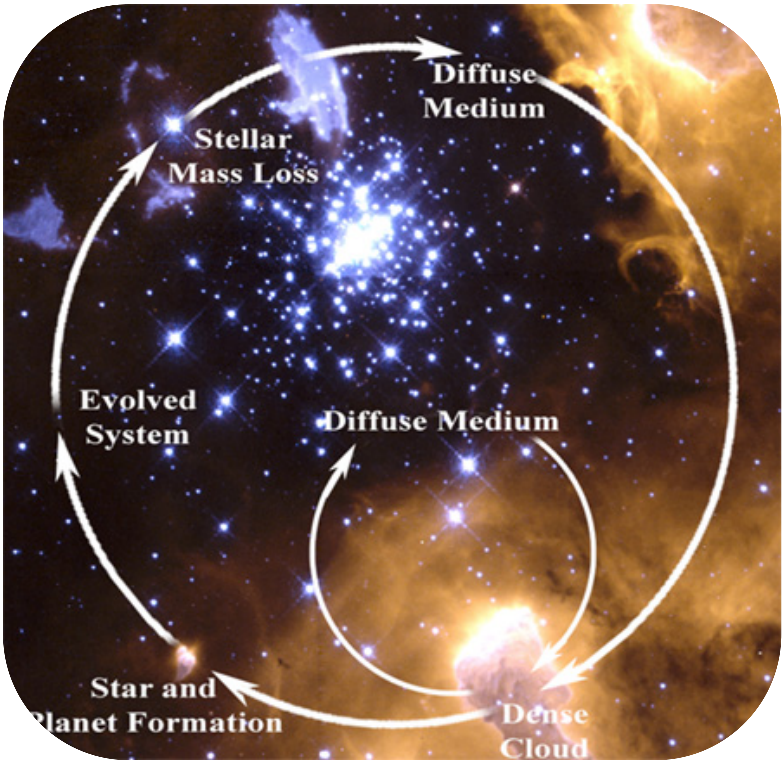


Figure 24: *The cycle of matter in the Universe (Credit: NASA/ESA)*

So almost everything that surrounds you, and even yourself, all the atoms and molecules that make up the world you know, were once part of a star! As the famous astronomer and science communicator Carl Sagan put it:

"The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of stardust."

References

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