Stellar Evolution

Every star visible in the sky has a story. Some stars burn for billions of years at a steady and calm output of energy. Other stars live fast and die young, but when they die, they end in violent explosions that can outshine other galaxies. They all begin in clouds of gas scattered throughout space and coalesce to form giant balls of light. It's important to understand how and why stars change because, without stars, the universe would be very different. No planets, no humans, and no life. The study of stellar evolution is the study of how stars are born, how they live, and how they die, and why their lives matter to everything we know.

All stars are born in a nebula, a massive region in space that contains stellar matter, gas, and dust. All this matter, gas, and dust are drawn together using Newtonian gravity, and as more and more matter is pulled towards this object, it begins to rotate. At this point, these rotating objects will become young stellar objects, or YSOs. YSOs are also known as protostars. In the protostar phase, there is simply a slow, steady accumulation of stellar dust and gas, increasing the mass and internal temperature of the YSO through condensation. Although this process can be described in a few short sentences, it can last up to millions of years.

Because of the centripetal force inflicted by the rotating star, matter begins to coalesce. After a period of time that lasts around 50 million years, the pressure of the protostar is so high (temperatures in excess of 10 million degrees) that the first hydrogen atoms will be squeezed together through fusion, and helium is formed. Nuclear fusion has been initiated, and since a star is defined by nuclear fusion at its core, the protostar has evolved, and a brand new star is born. Whenever a star is born, it is classified into a category of main-sequence stars, which have nuclear fusion of hydrogen into helium.

Main-sequence stars come in all sizes and colors. For example, the Sun is a main-sequence star, and it's yellow and moderately sized. There can be extremely large main-sequence stars, and they can be different colors as well. One key rule to understand is that the larger the mass of a star, the more fusion it undergoes and the quicker the star burns up and dies. So, on the contrary, if a star is really small, it has less nuclear fusion, and smaller mass stars can live for a long time. Another important rule is that the hotter the star, the bluer it gets, and the colder the star, the redder it gets.

During this main sequence phase, the force and energy from the nuclear fusion at the core of a star are strong enough to resist the inward gravitational pull. This concept is called hydrostatic equilibrium and is a major defining factor of main-sequence stars. This phase of equilibrium can hold for hundreds of thousands to a few billion years. What the star becomes next heavily depends on its mass. From the end of this phase of equilibrium, there are two paths on which a star can proceed. The two categories are stars with less than eight solar masses and stars with greater than eight solar masses. One solar mass is equal to the mass of the Sun.

If the star has less than eight solar masses, the main-sequence star will first expand into a red giant star. This occurs because all the hydrogen at the center of the star's core will run out, causing the star to use hydrogen further from its core. When this happens, the star gradually expands but cools as the color turns from yellow to a dark red. These red giant stars can be hundreds of times larger than the original main-sequence star. The hydrogen used for nuclear fusion will run out and be replaced with helium. Helium can be used for fusion and turned into carbon. It is here in a star's life where many heavy elements are formed due to continued nuclear fusion. After a star exhausts its supply of helium and does not have enough mass to fuse heavier elements, the star begins to shrink against the force of gravity.

The final stage of a low-mass (less than eight solar masses) star is when the star becomes a planetary nebula. When the star begins to shrink, it becomes unstable, and the outer layers are gushed off into the space around it. Layer after layer, the gas drifts into the space around it, leaving a star called a white dwarf. A white dwarf is a very small and incredibly dense star. The light that is seen from a white dwarf is leftover heat and energy from previous stages of stellar evolution. However, if a white dwarf is above 1.44 solar masses, a limit known as the Chandrasekhar limit, the white dwarf will collapse and condense into a black hole. Otherwise, the white dwarf will continue to cool off over the next billions of years until it turns into a black dwarf, a white dwarf that has cooled so much that it cannot emit any detectable light or heat.

Talking back about further evolution of main-sequence stars, if the star has greater than eight solar masses, it becomes a red supergiant. Red supergiants follow a similar pattern to red giants; both stars use hydrogen and helium for fusion. Supergiants then use carbon and keep on using heavier and heavier elements for nuclear fusion until the star has a core of iron. Nuclear fusion halts at iron because iron is endothermic, with a tight nucleus. Because of this property, trying to fuse it will consume energy, not release it, as seen with lighter elements. Because the star now lacks energy from nuclear fusion, there is no resistance to the inward gravitational collapse.

With not enough force to balance the gravity, the star collapses in an event called a supernova. This is a core-collapse supernova, the most common type of supernova. These collapses can occur at up to 30,000 kilometers per second, and once it explodes, there is abundant energy released into space along with new, heavier elements generated from nuclear fusion. Only the core of the star remains, and it will turn into either a neutron star or a black hole. There is another type of supernova that is less common but equally important: Type 1a supernovae. This type of supernova occurs in a binary system with a low-mass star (less than 8 solar masses) or a red giant and a white dwarf. Because of the white dwarf's density, it has a very strong gravitational pull. The white dwarf, using gravity, pulls material from the other paired star, and it becomes larger and larger, in a process called accretion. The white dwarf will gain enough mass to cross the Chandrasekhar limit and will explode as it collapses on itself. The Chandrasekhar limit is the largest (theoretical) mass a white dwarf can have before it collapses due to its own gravity. Nothing of the star is left behind, resulting in one of the brightest events ever visible in the entire universe.

After the core-collapse supernova, the core can either make a neutron star or a black hole. If the star were massive, the core would collapse, and all the matter would condense into a small star that is around 25 km wide. It is the second densest object in the entire universe, after a black hole, of course. These neutron stars are called such because it crushes the star so much that protons and electrons fuse, forming only neutrons. Pulsars are a type of neutron star that rapidly spins hundreds of times every second, releasing beams of radiation.

If before the core-collapse supernova, the star was incredibly massive (even larger than the star that made a neutron star), then the supernova will cause the extremely large star to condense into an extremely small and dense object, called a black hole. The gravity of a black hole is so strong that not even light (which travels at speeds of 300,000,000 m/s) can escape it. The black holes grow by pulling in different gases, dust, other black holes, or any other matter

This is why every star is unique. From the beginning of a star's life to the end, stellar objects change and grow incredibly. This story is about what science has proved about how stars change, and this is the story of a star.

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