Stars: Life, Evolution and End

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The Sun is the primary and only star of the solar system. It is located close to the inner rim of the Orion Arm within the Milky Way, about 26000 light years from the Galactic Center and on average 1.496×10^{8} km away from the Earth (the distance is known as 1 Astronomical Unit (AU)). The Sun is a nearly perfect sphere consisting mainly of hydrogen (around 74%) and helium (around 24%) with minuscule amounts of heavier elements such as carbon, oxygen and iron. The core of the Sun has a temperature of almost 15.7 MK (by comparison the temparature at the surface is approximately 5800 K) and although it only constitutes the inner 24% of the Sun's radius, it generates 99% of the energy. The amount of power that reaches the Earth, that is at the distance of 1 AU, is roughly 1368 W/m^2 (also known as solar constant). The Sun formed around 4.6 billion years ago along with possibly many other stars from a molecular cloud and is currently about halfway through its main sequence.

The evolution of stars is a complex process with many possible outcomes due to variety of different masses the stars might have and their large range - from less than 0.1 solar mass up to 150 solar masses. Stars form from the collapse of a molecular cloud. Through an external impulse, such as supernovae explosion, rotational forces of a galaxy or contact with another stellar object, small clamps of mass form. The gravitational forces created by the tiny pieces cause the cloud to further collapse and condense, and eventually become a protostar. The newly formed star continues to amass particles from the cloud at a rate dependent on the size of the cloud with more massive clouds collapsing faster until it reaches its final mass. If a star is massive enough, the temperature of the core will eventually reach 10 MK and the nuclear fusion reactions will begin, at which point the star enters its main sequence. Low mass protostars (mass less than 0.1 solar mass) never reach high enough temperatures to sustain hydrogen fusions in the core and instead they become brown dwarves. The rate at which fusion reactions occur will accelerate with the increase in the temperature eventually causing the star to reach hydrostatic equilibrium balancing the gravitational force and preventing it from collapsing further. A star will stay in its main sequence for hundred thousand years to several trillion years depending on their mass (more massive stars burn their hydrogen supply quicker due to higher temperature). Throughout that period a star is stable and its luminance, temperature and size remain almost constant. After the exhaustion of hydrogen in the core, the star will enter subgiant phase to later evolve further into a red giant or a red supergiant if it is massive enough. The star begins to shrink due to gravitational forces that are no longer balanced by the thermal enegry generated by the fusion reactions. The temperature of the star increases until the core becomes hot enough to initiate hydrogen fusion reactions in the shell around the core, which causes the shell to expand tremendously and cool shifting its color towards red. As the hydrogen in the shell is being fused into helium, the core increases in mass and temperature eventually reaching temparature necessary to fuse helium into carbon through triple-alpha process and is initiated by abrupt fusion of large quantities of helium into carbon known as helium flash.

$$ {}^{4}_{2}He + {}^{4}_{2}He \rightarrow {}^{8}_{4}Be + \gamma $$
$$ {}^{8}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + \gamma $$

The beryllium-8 produced from the fusion of two helium-4 is highly unstable and will decay into two helium-4 nuclei unless another helium-4 fuses with it. Some carbon nuclei might occasionally fuse with another helium to produce oxygen nuclei.

$$ {}^{12}_{6}C + {}^{4}_{2}He \rightarrow {}^{16}_{8}O + \gamma $$

The star continues to burn helium at the core and fuse hydrogen and helium in its shells until it runs out at which point the star contracts and exposes its dense carbon-oxygen core as a super hot central star with a planetary nebula formed from the shells outside the core. The nebula will disperse within several thousand years, but the core will cool down and enter the white dwarf phase. The remnant will continue to lower its temperature over billions or even trillions of years to eventually become a black dwarf. No black dwarves have been observed in the visible universe because the time it takes for white dwarves to cool to low temperatures is much longer than the age of the universe. The coldest known white dwarves have only recently cooled below 3900 K. Larger stars (with mass grater than 10 solar masses) evolve into supergiants. The stars that fall in the range of 10 to 40 solar masses become red supergiants. Extremely massive stars (mass above 40 solar masses) become yellow or blue supergiants because of the radiation pressure that strips off their outer shells and allows them to maintain high surface temperature. Due to their high core temperature the helium fusion is initiated gradually and before the hydrogen is exhausted instead of abruptly after the hydrogen fusions stop which is the case in less massive stars. Those stars are capable of fusing heavier elements, e.g. iron, through alpha process creating dense supermassive cores that eventually collapse under their own gravitational field in a spectacular supernova explosion into supermassive supermassive neutron stars or, if the neutron star formed from the collapsing star exceeded the Tolman-Oppenheimer-Volkoff limit of around 2.2 to 2.9 solar masses, directly into a black hole.

The Sun creates energy primarily at its core through nuclear fusion reactions that transform hydrogen comprising the core into helium although the core constitutes only about 25% of Sun's total radius. The two types of fusion that occur in the core are proton-proton chain reaction and carbon-nitrogen-oxygen cycle (CNO cycle) with the former being the dominant reaction type due to the fact that CNO cycle requires temperature above $17 * 10^6$ K to become self sustainable and dominant, which is not possible in the fairly low temperature of the core (around $15.7 * 10^6$ K). The proton-proton chain combines four hydrogen-1 nuclei into a helium-4 nucleus. The whole process consists of multiple reactions and might progress in one of the four ways depending on the conditions in the core, but the first stages are common to all of them. First, two hydrogen-1 nuclei are fused into helium-2 which then undergoes β^+ decay to transform into hydrogen-2 nucleus (deuterium). The deuterium rapidly combines with another hydrogen-1 forming helium-3. From that point the reaction may proceed in four different ways:

- PP-I:

$$ {}^3_2He + {}^3_2He \rightarrow {}^4_2He + 2\,{}^1_1H + energy $$

- PP-II:

$$\begin{aligned} {}^3_2He + {}^4_2He &\rightarrow {}^7_2Be + \gamma \\ {}^7_2Be + e^- &\rightarrow {}^7_3Li^- + \nu_e + energy \\ {}^7_3Li^- + {}^1_1H &\rightarrow 2\,{}^4_2He + energy \end{aligned}$$

- PP-III:

$$\begin{aligned} {}^3_2He + {}^4_2He &\rightarrow {}^7_4Be + \gamma + energy \\ {}^7_4Be + {}^1_1H &\rightarrow {}^8_5B + \gamma \\ {}^8_5B &\rightarrow {}^8_4Be + e^+ + \nu_e \\ {}^8_4Be &\rightarrow 2\,{}^4_2He \end{aligned}$$

- PP-IV:

$$ {}^3_2He + {}^1_1H \rightarrow {}^4_2He + e^+ + \nu_e + energy $$

PP-I is the dominant type of reaction in the solar core comprising about 83% of helium-4 production, while PP-II produces only around 17% of helium-4 and PP-III less than 0.1%. PP-IV is extremely rare, therefore its contribution is insignificant.

The Sun is expected to remain in the main sequence for about 5 billion more years, which is directly correlated to the hydrogen deposit at its core. Throughout the rest of its main sequence lifetime the sun will slowly expand and its temperature and luminosity will rise making the Earth less and less habitable. After the exhaustion of hydrogen, the Sun will enter the red giant phase and rapidly expand to the size of Venus' orbit absorbing Mercury and Venus, but it's speculated that it might even expand to the size of Earth's orbit annihilating the Earth. The Sun will become a white dwarf after it burns all of its helium out and will continue to shine for billions of years before it turns into a black dwarf.

The Sun is an essential element of our lives. The sunlight it generates has allowed life to thrive on the Earth and is essential for it to continue to do so. However, the evolution of stars happens on a timescale way beyond the lifetime of a human and the size of the universe makes it impossible to scrutinize all stellar objects using available tools. Even despite thousands of years of observation and research, much remains to be unravelled about the Sun and other stars. Nevertheless new techniques and tools are being developed every day to aid us in the discovery of the universe, the stars and our Sun that might help us understand the world better.