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# The life of the Sun

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**Abstract.** Understanding the development and evolution of the Sun is critical for understanding the origins of our solar system and the circumstances for life on Earth. We can learn about our sun's dynamics, energy output, and magnetic activity by analysing its evolution, and we can even forecast solar events that affect our world. Extensive study has indicated that the Sun is now in its main sequence stage, but research on its future development, such as becoming a red giant or crashing into a white dwarf, is still underway. Solar evolution research also sheds light on the inner workings of other stars and fundamental processes in the cosmos. The Hertzsprung-Russell diagram aids in the classification and understanding of stars by providing essential information about their life cycle and attributes. The pre-main sequence, main sequence, and post-main sequence stages of the Sun's origin and development are discussed in this article. It examines the origin of the Sun from interstellar materials as well as the probable impact of core-collapse supernovae. It also delves into the main sequence period, where stars' masses and ages play important roles in shaping their properties. The main sequence's existence is linked to hydrostatic equilibrium and the balance of energy production and gas weight. The scattering of stars that depart from the main sequence, such as red giants and white dwarfs, is also discussed in the article. Finally, it dives into post-main sequence development, in which the Sun switches from hydrogen fusion to helium fusion, causing the star to expand and cool. Finally, the Sun's ultimate phase of development involves the burning of hydrogen and helium, which results in the expulsion of outer layers and the creation of a planetary nebula. The remaining core cools and transforms into a black dwarf, bereft of nuclear and gravitational energy sources.

**Keywords:** The Life of the Sun, Solar Evolution, Sun.

## 1. Introduction

The Sun, the central star of our solar system, holds a significant place in our universe. Its formation and subsequent evolution have captivated the curiosity of scientists and space enthusiasts for centuries. Understanding the processes involved in the birth and development of the Sun is crucial to comprehending the origins of our solar system and the conditions necessary for life on Earth.

The study of solar evolution is of utmost importance in understanding the dynamics and behavior of our sun. By investigating the various stages of its evolution, scientists can gain valuable insights into the processes that drive its energy production, magnetic activity, and overall lifespan. This study not only improves our understanding of the sun's history and present, but it also aids in the prediction and

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comprehension of future solar occurrences such as solar flares and coronal mass ejections, which may have substantial effects on Earth's climate and technological infrastructure. Therefore, the study of solar evolution plays a crucial role in advancing our understanding of the universe and its impact on our planet.

Over the years, astronomers have conducted extensive research and observations to unravel the mysteries surrounding the life cycle of our closest star. Through meticulous study, they have discovered that the Sun's evolution is a complex and dynamic process, characterized by various stages and phenomena. One of the key findings in this field is the understanding that the Sun is currently in the main sequence stage, where it fuses hydrogen into helium in its core. This knowledge has paved the way for further investigations into the Sun's future evolution, including its eventual transformation into a red giant and subsequent collapse into a white dwarf. In summary, the study of the Sun's evolution has provided astronomers with valuable insights into the workings of stars and the fundamental processes that shape the universe. In addition, the Hertzsprung-Russell diagram, another important discovery in the field of sun evolution, is a graphical tool used in astrophysics to classify and understand stars. It plots the luminosity of stars against their surface temperature or color. This diagram allows scientists to study the evolutionary stages of stars, their sizes, and their spectral types. It is an essential tool in the field of stellar astrophysics, providing valuable insights into the life cycle and properties of stars [1].

This essay aims to review the intricate journey of the sun's formation and evolution, shedding light on the remarkable processes that have shaped our existence. In this paper, solar evolution is divided into three parts chronologically, which are pre-main sequence evolution, main sequence evolution, and post-main sequence evolution respectively.

## 2. Fundamental Physics for solar evolution

### *2.1. Nuclear fusion*

The process through which the Sun and stars produce their energy is nuclear fusion. The production of the helium nucleus (or particle), the second stable element in order of weight, is the earliest example of fusion we can think of. There are several ways to get hydrogen to fuse into helium, but the most frequent reactions that carry out this process in the Sun make up the first branch of the so-called proton-proton chain (known by the abbreviation *ppI*) [2].

$$p + p \rightarrow {}^{2}_{1}H + e^{+} + v_{e} + 1.442\ MeV$$

$$ {}^{2}_{1}H + P \rightarrow {}^{3}_{2}He + \gamma + 5.494\ MeV$$

$$ {}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + 2p + 12.86\ MeV$$

In the first reaction, two protons, merge into a nucleus of deuterium, 2 H, with the emission of a positron, $e^{+}$, the electron antiparticle, and an electronic neutrino.

The deuteron reacts with a third proton in the second process to create tritium, an isotope of helium with just one neutron, or 3 He, which releases both kinetic energy and radiation. Tritium then interacts with a second 3 He nucleus to generate the particle 4 He, which produces two protons and more kinetic energy.

## 3. Pre-main sequence evolution

### *3.1. The onset of gravitational collapse*

The Sun, like other stars, evolved from the interstellar medium due to its gravitational instability. Interstellar matter is a combination of gas, dust, and radiation that occupies space between stars in a galaxy. If too much interstellar matter is compressed into a relatively small volume, its gravity will be strong enough to overcome the internal pressure and continue to contract, which will cause what is known as a gravitational collapse [3].

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### *3.2. Contributions from core-collapse supernovae.*

We do not know what causes the gravitational collapse of the Sun, but we can consider the possibility. In this case, the initial compression is caused by a shock wave. The deaths of many stars led to a dramatic explosion. Ancient astronomers used the term nova because these objects suddenly appeared in the sky as novae. An iron core with a mass similar to that of the Sun would instantly shrink to the size of the Earth and collapse into a neutron star just a few kilometers across. The explosion at the edge of the expelled material also produces a pre-shock wave, which corresponds to a sudden change from the high-pressure and high-temperature core material to the outer interstellar medium. So the shock wave that caused the gravitational collapse of the interstellar cloud that formed the solar system five billion years ago could have been caused by a supernova in the Milky Way. However, supernovae can enrich early interstellar material with heavy elements such as C, O, N, Ca, P, and S, thus aiding the formation of life on Earth [4].

## 4. Main sequence evolution

### *4.1. Main sequence evolution*

Most stars are not simple objects. They vary in size and temperature, but the majority can be described by two main factors: their mass and age (Chemical composition also plays a role, but it does not significantly alter the overall understanding of the topic we are discussing here. All stars are composed of approximately 75% hydrogen and 25% helium at birth.) [5].

The influence of mass is because the star's mass determines its central pressure, which in turn affects its rate of nuclear fusion (higher pressure leads to more collisions and more energy). This fusion energy is what drives the star's temperature. Generally, the more massive a star is, the brighter and hotter it becomes. Additionally, the gas pressure at any given depth within the star (which is also influenced by the temperature at that depth) must balance the weight of the gas above it. Lastly, the total energy generated in the core must be equal to the total energy radiated at the surface.

This final observation introduces another constraint as the energy radiation of a sphere suspended in a vacuum follows a law called the Stefan-Boltzmann Equation [6]:

$$L = CR^2T^4$$

Luminosity (L), a constant (C), the star's radius (R) in meters, and the star's surface temperature (T) in K° are the variables in the equation. It is noteworthy how rapidly a star's energy radiates with an increase in T: doubling the temperature results in a sixteen-fold increase in energy output.

A star that fulfills these conditions is deemed to be in hydrostatic equilibrium, a quality that greatly contributes to its stability. If the star's core undergoes compression, the process of nuclear burning intensifies, resulting in the generation of additional heat. This increase in heat leads to a subsequent rise in pressure, causing the star to expand. This expansion process brings the star back to a state of equilibrium [7]. Conversely, if the core experiences decompression, the nuclear burning diminishes, leading to the cooling of the star and a subsequent reduction in pressure. This causes the star to contract and return to its state of equilibrium. Remarkably, the energy output of the Sun has remained relatively stable throughout human history, fluctuating by no more than 0.1% to 0.2%. This enduring stability is particularly impressive considering that the Sun has been functioning as a nuclear reactor for nearly five billion years without necessitating the intervention of a regulatory committee, engineers, or safety inspections.

The existence of the main sequence can be attributed to the inherent rigidity of hydrostatic equilibrium. Stars with lower masses (as little as 7.5% of the Sun's mass) are situated in the lower right quadrant of the H-R diagram, precisely where they are expected to be. This particular region of the H-R diagram denotes extremely low luminosity, sometimes as low as one ten-thousandth of the Sun's luminosity, as well as low surface temperatures reminiscent of the dull orange-yellow glow exhibited by molten metal. These stars lack the necessary mass to generate the requisite pressure for facilitating nuclear burning within their cores. In contrast, high-mass stars (over 40 solar masses) are positioned in

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the upper left quadrant, as anticipated. Unlike their low-mass counterparts, these massive stars possess extraordinary masses and high central pressures, resulting in giants that can emit up to 160,000 times more luminosity than the Sun. They emit a greater proportion of their energy in the ultraviolet spectrum rather than as visible light. The Sun, lying approximately midway between these extremes, neither exhibits an extreme dimness nor an extreme brightness when compared to other stars. It emits a vibrant yellowish-white hue.

The correlation between mass and hydrostatic equilibrium implies that any alterations in a star's mass will inevitably result in a predetermined trajectory concerning its other physical attributes. This trajectory is commonly referred to as the main sequence. However, upon conducting a more thorough analysis of the H-R diagram, one can discern a dispersion of stars that deviate from the main sequence. These stars are concentrated within distinct "islands" situated in the upper right and lower left quadrants [8]. Astronomers frequently designate the stars in the upper right quadrant as red giants, owing to their elevated luminosity and their manifestation of cool, reddish surfaces. Similarly, the stars in the lower left quadrant are identified as white dwarfs, distinguished by their diminished luminosity and formidable heat. We have previously encountered white dwarfs in a theoretical context. Now, let us delve into their origins within the realm of reality.

## 5. Post-main Sequence Evolution

### *5.1. Hydrogen Shell Fusion and Red Giant Phase*

During the MS phase, hydrogen is burned in the solar core, maintaining a relatively constant effective temperature and gradually raising solar brightness [9]. Due to the continual depletion of hydrogen, a constant increase in temperature is required to maintain the same degree of nuclear reaction efficiency. Due to the increase in temperature, a large amount of hydrogen is still present in the core's outer layers where fusion first takes place. Ultimately, only when the core is made entirely of helium can hydrogen burning take place in the shell around the center area. The commencement of hydrogen shell burning is signaled by the expansion of the outer layers and a brightness that is practically constant. As a result, there is increased convection in the layers under the shell due to a fall in effective temperature and an increase in temperature gradient. While this is happening, the hydrogen in the shell progressively runs out and turns into helium. As a result, the mass of the helium core increases while the hydrogen-burning shell approaches the outer layers. Due to a shortage of energy sources, the helium core first becomes virtually isothermal, but this state cannot last [10]. The helium-induced weight gain results in a contraction that raises the density and returns the system to hydrostatic equilibrium. Before stopping, hydrogen shell fusion lasts for around 1.75 Gy. The Sun enlarges over this epoch, extending throughout the majority of the 1.5 Gy period, reaching up to 3.3 RS, and cooling its surface to around 4300 K while almost tripling its brightness. As of right now, the Sun is a sub-red giant, a kind of star distinguished by a decreased surface temperature and an enlarged size (giant). Over the next 0.25 Gy, when the bulk of the hydrogen around the core is converted to helium, the surface temperature, brightness, and the expansion of the outer layers all decrease. By the time this phase is complete, the Sun will have a radius of 256 RS, or a little over 1 AU, and Mercury, Venus, and Earth will all be encircled by it. The Sun is now 2730 times brighter than it is right now, and its surface has an effective temperature of 2602 K. The Sun's mass reduces to 0.668 MS after the red giant phase, according to Schröder and Smith (2008). The Sun's post-main sequence development is uncertain since it is challenging to quantify exactly how much of the Sun's mass is lost to space.

### *5.2. Final phase of evolution*

The current physical state will eventually lead to a new source of nuclear energy: helium fusion, during the red giant phase's conclusion. Helium starts fusing in the solar core calmly at around 12 Gy of age. Additionally, hydrogen fusion occurs in the outer layers, which are still sufficiently hot and hydrogen-rich. The Sun's outer layers, loosely connected to the core by gravity, experience additional pressure due to the intense outward radiation flow. Consequently, a powerful wind ejects the Sun's outer layers into space. This scattering leaves the core in an electron degenerate state. A thin layer surrounding the core contains burning hydrogen and helium, which gradually ceases. As the core gets stripped away, the outer layers continue to be expelled until the entire outer envelope is gone. This results in a planetary nebula. Only the center of the planetary nebula remains after the complete disintegration of the envelope, appearing as a blazing star with roughly half the mass of the Sun. Compared to the Sun's current structure, this evolved Sun is quite peculiar. At this point, the Sun will continue to evolve for a few billion years, but its fate is already determined. Through radiation loss, the Sun cools down and eventually becomes a black dwarf, having exhausted its nuclear and gravitational energy sources.

## 6. Conclusion

Studying the Sun's formation and evolution is crucial for understanding our solar system's origins and the conditions necessary for life on Earth. By examining its pre-main, main, and post-main sequence evolution, we gain insights into its dynamics, energy production, and magnetic activity. This knowledge helps predict solar events impacting Earth and enhances our understanding of stars and universal processes. The Sun maintains stable energy output during its main sequence by balancing gas weight with radiated energy. The main sequence's existence is explained by hydrostatic equilibrium's rigidity, with stars of different masses occupying specific regions on the Hertzsprung-Russell diagram. Low-mass stars lack the pressure for nuclear burning, while high-mass stars emit more luminosity than the Sun. During the post-main sequence, hydrogen depletion leads to hydrogen shell burning, causing the Sun to expand and cool. The Sun becomes a sub-red giant with reduced mass and radius. Helium burning in the core forms a planetary nebula, expelling outer layers. The remaining core becomes a black dwarf. Understanding the Sun's formation and evolution provides insights into star life cycles, properties, and universal processes. This knowledge has implications for predicting solar events and unraveling cosmic mysteries, expanding our understanding of the universe.

## Authors' Contributions

Lingqiao Mu: Writing and Collecting Information
Qianrun li: Information Collecting

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