Understanding the Importance of Stellar Birth and Evolution for a Comprehensive Understanding of the Sun and Other Stars

Astrophysics Literature Review

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Table of Contents

1 Abstract

Stars are massive, luminous celestial bodies that are primarily composed of hydrogen and helium gas, as well as other trace elements. Considered as the building blocks of galaxies, including our own Milky Way, and play a crucial role in the formation and evolution of the universe. In the context of the solar system, the Sun is the most important star. It is the center of the solar system, around which all the planets orbit, and provides the energy and heat necessary for life on Earth to exist. The Sun is a G-type main-sequence star, which means that it is relatively stable and will remain in this state for billions of years. However, other types of stars have different life cycles and characteristics, and studying them can help us better understand the universe and our place in it. Overall, stars are important in the context of the solar system because they provide the energy and gravitational pull necessary to keep planets in orbit, and studying them can help us better understand the formation and evolution of our solar system and the universe as a whole.

1.1 Importance

Among various benefits the Earth endures due to the sun being at the distance it is, there are some key things we can come to note. Here are some of the key ways in which stars are important to the health of our planet:

1) Energy source: Stars, including our sun, are the primary source of energy for all life on Earth. The energy they produce through nuclear fusion is what drives photosynthesis in plants and provides the warmth and light that sustains all living organisms.
2) Navigation: Stars have been used as navigational aids for centuries. This is due to stars having fixed positions in the sky and can be used as reference points to determine direction and location.
3) Astronomy
4) Formation of elements: The stars are responsible for the formation of elements like carbon, nitrogen, oxygen, and iron, which are essential for life as we know it. These elements are produced through nuclear fusion reactions that occur within stars and are then dispersed throughout the universe when supernovas occur.

In summary, stars are essential to the well-being of our planet in numerous ways, from providing energy and navigation to enabling scientific discovery and regulating the Earth's climate. Without stars, life on Earth as we know it would not be possible.

To form a deeper understanding of how important stars are, we need to develop an understanding of how they function and have to come to play such an important role in the universe. Something we must do for this to happen is understand the evolution of stars and what happens as time passes throughout the lifespan of a star, this can include things such as stellar birth, the transition from being a protostar to being main-sequence stars, and the distinction from being a high mass star and what that means towards the end of a stars like to being a low mass star and what that means when the star is nearing its death. Developing a strong understanding of all of this information means that we are able to better comprehend the world that we are in and how the universe came to be.

2 Stellar Formation

Stars can not last forever in space and have an ending to their lifecycle. This can be established by looking at the sun, a low-mass star that comes from thermonuclear reactions in its core. The sun consumes $6 \times 10^{11} kg$ of hydrogen each second and converts it to helium by thermonuclear reactions through a process known as hydrogen fusion. However, there is not an infinite amount of hydrogen in the Sun’s core, therefore the Sun cannot have always been shining nor can it continue to shine forever. This is true for all main-sequence stars. Main sequence stars are stars whose luminosity and surface temperature are placed on the H-R diagram and derive energy from core hydrogen fusion. They are fundamentally made of the same objects as the sun, notably hydrogen, and helium but with differing masses. Mass plays a central role in determining how fast a star forms and joins the main sequence, and how fast a star dies.

2.1 Primary Steps

The following information has been pulled from the NASA Stars article. So what happens when core hydrogen fusion ends? The way a star dies depends on how much matter it contains. Once all the hydrogen in the core is depleted, stars with low mass like our sun will expand and grow to become a red giant but stars with high mass will expand to be a red supergiant. A main-sequence star that has a mass similar to the sun will become a red giant, then a planetary nebula, and eventually become a white dwarf then a black dwarf. However, high-mass stars will become red supergiants, supernovas, then neutron stars or black holes. Depending on a star's matter, its lifecycle will look different. We can predict the lifecycle of a star with our limited knowledge based on calculations supported by observations of star clusters of roughly the same age with differing masses

2.1.1 Protostar

According to the NASA Stars article, a star is born with the occurrence of a gravitational collapse of clouds of dust and gas. The clouds are not visible, and as they collapse, a hot core begins to form the center material. Protostellar winds and jets surrounding the protostar's magnetic field will eventually clear enough of the gas for the protostar to become visible. The hot core will one day become a star, although known as a protostar till then. Additionally, with information from the Max Planck Institute for Astronomy For a protostar to become a main sequence star, its core temperature must exceed 10 million K.

2.1.2 T Tauri Star

T Tauri stars are young variable stars that change in brightness and size, and are associated with interstellar matter and characteristically varying luminosity. Like Protostars, T Tauri stars are pre-main sequence stars and may stay in this phase for a hundred million years until it gains enough mass to become a main sequence star. A star's mass depends on how much hydrogen gas is brought together by gravity during its formation, and we measure the mass of a star by comparing it to the mass of the "parent star", our sun. The mass of a star is a crucial factor in determining the starting point of stellar formation as it affects the speed of the stellar formation. Stellar formation of high mass stars occurs at a slower rate than low mass stars, although the stellar death of a high mass star occurs at a faster rate than a low mass star.

3 Stellar Evolution

On a transition from understanding stars and how they come to be, we move to the next step of understanding what happens after we have a main sequence star. When looking at an overarching view of the stellar evolution process, one stumbles upon the terms stellar birth, but then into the subcategories of what happens after it becomes a main sequence star. Here, we must also differentiate between high mass and low mass stars because they evolve differently.

The following is a short introduction on stellar evolution of high and low mass stars, which will then be proceeded with more detailed explanations as well as calculations. A main sequence star with a low mass typically evolves into red giants, and then this transitions into the formation of a planetary nebula, and the red giant collapses. A main sequence star with a high mass typically evolves into a red supergiant, which then explodes into a supernova, which can then either form a neutron star or black hole.

To understand these processes in a more exact manner, we begin with explanations, and then lead onto calculations.

3.1 Low Mass Star Evolution

Low mass stars are stars with a mass less than about 2 solar masses. They are often referred to as M-dwarfs or red dwarfs, and are the most common type of star in the Milky Way galaxy. After the protostar stage, which is the initial phase of stellar birth, low mass stars enter the T Tauri stage. During this stage, the star is still contracting and increasing in temperature as it settles onto the main sequence, the point at which it will spend most of its life. This phase can last for several million years, during which the star is still surrounded by a disk of gas and dust.

Once the star has reached the main sequence, it begins to burn hydrogen in its core through the process of nuclear fusion. This generates energy and causes the star to emit light and heat. Low mass stars have a slower rate of fusion than higher mass stars, and as a result, they have a longer lifespan. As the star ages, it will eventually exhaust the hydrogen fuel in its core. At this point, the core will contract and heat up, causing the outer layers

of the star to expand and cool. The star will then enter the red giant phase, during which it will become much larger and brighter. This phase can last for several million years, depending on the mass of the star. Once the red giant phase is over, the star will shed its outer layers, leaving behind a hot, dense core known as a white dwarf. The white dwarf will continue to radiate heat and slowly cool over billions of years, eventually becoming a black dwarf.

In summary, low mass stars go through several phases during their lifetime, including the protostar and T Tauri stages, the main sequence, the red giant phase, and the white dwarf stage.

Each phase is characterized by different physical properties and behaviors, and contributes to our understanding of stellar evolution. To better understand these processes we look at them with mathematical calculations in mind.

3.1.1 Main Sequence

As discussed above, the main sequence star begins to burn hydrogen in its core; there are thermodynamic equations that model this situation well.

$H + H \rightarrow D + \beta^{+} + v;\ Q = 1.44\ MeV$

The Q value in this case assumes that the positron and the electron cancel each other out, as in annihilation (Encyclopædia Britannica). According to Britannica, the deuterium could react with other deuterium nuclei, but because there is so much hydrogen, the Deuterium to Hydrogen ratio is held to very low values, so the following equation is:

$H + D \rightarrow 3He + \gamma;\ Q = 5.49\ MeV$, in this case the γ represents the gamma rays that carry off some of the energy yield. The helium isotope then gives rise to ordinary helium and hydrogen through the next reaction:

$3He + 3He \rightarrow 4He + 2(H);\ Q = 12.86\ MeV$. When the helium 4 builds up, there are heavier metals that are eventually formed.

To understand exactly how to calculate how stars remain in the main sequence, we have used this example from the Kaufmann textbook.

To determine how long a star of about 4 $M_{\odot}$ remains in the main sequence. The relationship $t \propto 1/M^{2.5}$. This star hypothetically has 4 times the mass of the sun, which means hydrogen fusion would happen for about 400 million years, calculated using the equations above, and proceeding with the appropriate calculations.

3.1.2 Red Giant

According to Hubble's Red Giant article, as the low mass main sequence star evolves and continuous nuclear fusion occurs within the star's core, a red giant forms. In order for a star to maintain its stability, there is a balance between the gravity of the star and the thermonuclear fusion processes taking place in the core. Once a star's core is depleted of the Hydrogen, the equilibrium state is lost and the core of the low mass star begins to collapse. This then results in the creation of the fusion shell, the extra heat causing the outer layers of the star to expand hundreds of times bigger than the former size of the star. The energy at the star's surface becomes far more dissipated, causing the star's bloated surface to cool, turning from white or yellow to red.

3.1.3 Planetary Nebula

With information from Schools Observatory, we find that the next step that occurs in this process is the formation of a planetary nebula, this happens when the outer layers of a star shed from an expanding shell of gas and dust around the remains of a star. This creates an expanding glowing shell of hot gas. Towards the end of the lifetime of a red giant the star becomes very unstable and begins to do something called pulsating, this produces stellar winds which is what causes the outer layers of the star to fall away.

3.1.4 White Dwarf

The out layers drift away leaving a small hot core called the white dwarf. This small star remains and gives off ultraviolet radiation which lights up the layers of gas around the low mass star. The material from the planetary nebula is scattered into space. An example of this would be the Helix Nebula. In this space is where potentially new stars begin to form.

3.1.5 Black Dwarf

The white dwarf that remains eventually suns out of energy and fades away into a dimmer star resulting in the end of the life cycle of a low mass main sequence star.

It is however a different case for high mass stars as various things could happen, the following section discusses this in detail.

3.2 High Mass Star Evolution

To better understand high mass star evolution we follow one particular star, which allows us to deeper understand and visualize exactly what happens with stars that have a much higher mass than our sun. For this particular project, we look at the evolution of Sanduleak -69 202 which resulted in a supernova.

The evolution of Sanduleak −69 202. An obscure blue B3 supergiant star with the unlikely name of Sanduleak -69 202 had exploded, becoming type II supernova SN1987A. Sanduleak -69 202 before exploding had a mass 15-20 times greater than that of our sun and was located in the Large Magellanic Cloud, a sort of suburb of our galaxy some 160,000 light years distant. To the despair of residents of North America, SN1987A is visible only in the southern hemisphere.

What's a type II supernova? It's the explosion of a large star that has burned up all of its nuclear fuel and literally ran out of gas. One might think that would produce a dead cinder rather than a giant explosion. But for stars, out of fuel does not mean out of energy. A burned-out star still has a very large amount of gravitational energy. As soon as the nuclear power plant switches off the gravitational energy is "cashed in" as the outer part of the star falls inward.

To understand these processes more in detail, we look at the following subsections.

3.1.1 Red Supergiant

Red Supergiants have characteristically low surface temperatures and are red in color because so although its luminosity is great. Once hydrogen is exhausted in the core of a high mass star, the high mass star evolves off of the main sequence to a red supergiant, and the helium core shrinks and increases in temperature while hydrogen continues to burn in the outer shell. The red supergiant phase continues as helium fusion occurs in the core. Following, the red supergiant continues to burn heavier elements until the core consists of iron, and fusion ceases to an end and the star collapses under gravity. Which creates a supernova explosion.

3.1.2 Supernova

Essentially the next step following the red supergiant stage is when the pressure drops low enough in a massive star, gravity takes over and the star collapses in seconds, and this collapse is what produces a supernova. This produces a shockwave that can induce fusion reactions in the star and these create atomic nuclei that are heavier than that of Hydrogen and Helium originally within the star. Supernovae are also considered one of the original sources of heavier elements (*Doe explains…supernovae)*.

3.1.3 Neutron Star

Neutron stars are the collapsed core of a high mass star, and the remains after a supernova explosion. When the outer layers of a high mass star collapse onto its core at the end of its lifetime, the atoms in the star’s core are crushed only to expose neutrons, subatomic particles with no electric charge. This causes a shock wave as the outer layers are essentially thrown out into space consequently leaving a fast spinning neutron star. This means that a neutron star has a lot of mass compacted into a small area, being very dense, only less than a black hole.

3.1.4 Black Hole

Black holes are made during supernova explosions and are anything consequently left of a high mass star that has been squashed and compacted into a dense, small object. A black hole will grow by consuming and pulling surrounding gas, dust, stars, and other blackholes. Black holes have significantly strong surrounding gravity that light is distorted from perspective galaxies and cannot be reflected, emitted or escape.

4 Conclusion

In the end you can see that stellar birth, evolution, and death is important in the way our universe works and continues to pass through time, because stars play an important role for us on Earth as well as play an important role in the regards of gravitational forces, and chemical reaction in the star also forms fundamental elements that make up a lot of the technology and materials we use in our everyday lives. Beyond this, understanding stellar evolution also forms a deeper understanding of how the universe came to be and where it is headed.

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