Stellar Evolution:
How Mass Determines the Path from Molecular Clouds to Stellar Remnants

Author:
Yuv Bagaria
Aiglon College Year 12
yuvbagaria@gmail.com

This review paper presents the complete life cycle of stars. The stellar life cycle has created practically every known natural element in the universe and amazingly, every atom in our bodies was forged in the stars of the past. This paper will outline and explain how mass affects the primary pathways of the stellar life cycle, including why and how each stage occurs: from molecular clouds (the birth) to the main sequence (childhood), giants (old age), death (supernovae), and remnants.

1. Introduction

Like humans and all living beings on Earth, every star in the universe has a life cycle. This ‘life cycle’ is known as the stellar life cycle (seen in Figure 1), and stars' lives are arguably the most important phenomenon in the universe: creating every known natural element of life as we know it, except for hydrogen and helium, which were formed during the Big Bang. However, unlike us simple beings, there are several different predisposed paths a star can take during its life that mainly depend on its mass. This paper will outline and explain the primary pathways of the stellar life cycle all the way from the molecular clouds. Section 2 will discuss the birth and creation of stars: how exactly they form. Section 3 will explore the Hertzsprung-Russell diagram (HR diagram) and classify different stars based on the diagram and their mass. Section 4 shows what happens as the star ages and runs out of its fuel source. Section 5 describes the different types of stars’ deaths, and finally Section 6 displays the remnants of stars’ lives depending on their demise.

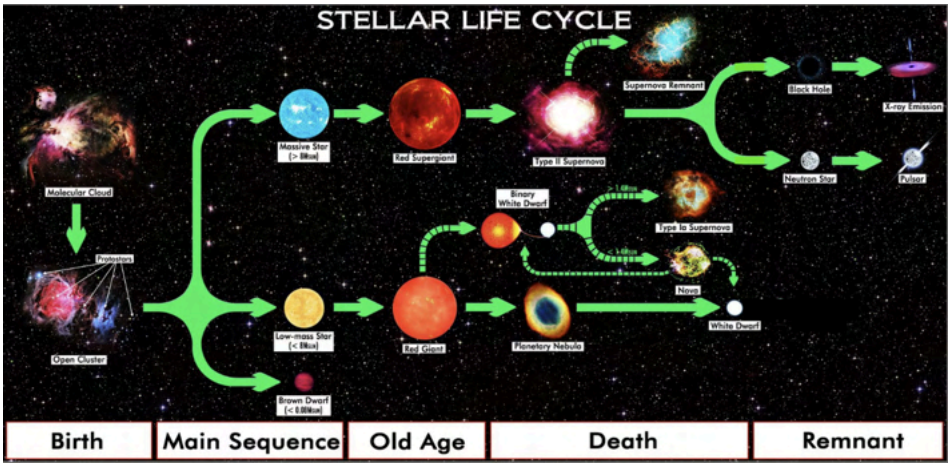

Figure 1: The Stellar Life Cycle: This figure outlines the foundation of this paper [29].

2. The Birth

Just as humans develop within their mother's womb before birth, stars are born within giant molecular clouds (GMCs) in space, often referred to as "star nurseries" [1][2]. These vast clouds are reservoirs composed primarily of molecular hydrogen (H_2) [1], providing the raw material from which stars form. These clouds also contain huge amounts of cosmic dust [2] (miniscule solid particles of iron, silicate or even ice), trace amounts of carbon monoxide (CO) and are at extremely low temperatures – around 10K to 20K [1].

The process of scattered pockets of cosmic gas and dust collapsing can only take place if the gravitational pull within a GMC is strong enough to overcome both the turbulent motion of its particles and the magnetic fields threading through it. However, gravity winning by itself is not possible: it needs external factors to help it win [1].

There are three main external mechanisms that can trigger the collapse [1], which is the infall of material towards a shared centre of gravity. The first is due to the shockwaves from a nearby supernova (for more information about supernovae, see section 4). These shockwaves are strong enough to go through GMCs and physically clump material together, drastically increasing the local density [1]. The second is due to the GMC's physical movement and spiral through its galaxy and through Spiral Density Waves – regions of high gravity that – therefore –move slowly through its galaxy. As a GMC comes across these regions, they too experience a squeeze: resulting, again, in the increase of local densities [1]. The third trigger for collapse is the collision of a GMC with another GMC; and as one can probably guess, these collisions increase densities at certain points [1]: enough to trigger the inward collapse of all material around that neighbourhood.

GMCs are so immensely large that they can hold thousands of stars [1]. Therefore, as numerous different areas collapse and clump together, the cloud fragments into several high-density cores – each with its own gravitational pull [1]. Each fragment then collapses under its own gravity, rapidly taking in material from the surroundings [1]. Large fragments (approximately the size of Jupiter's orbit) clump up to form the first stable hydrostatic core (around two solar radii, much smaller than the fragment) [2]. Infalling gas – or accretion – is forced into a rotating disk around the core because of the core's angular momentum obtained by its spin [1][2].

The envelope (surrounding gas) and accretion disk allow astronomers to classify protostars into four distinct classes [3]. Class 0 protostars, the first class, are objects whose envelope mass is greater than that of the core [4]. Class I protostars refer to objects whose core mass exceeds the envelope mass and accretion slows down [3]. These two phases take around 0.1-0.5 million years [4]. Class II protostars indicate the evolutionary phase during which the envelope is lost, though there still is a well-defined accretion disk [3]. These protostars are also known as T Tauri stars (young, low-mass stars that haven't yet reached the hydrogen fusion stage) [3]. Finally, Class III protostars refer to the stage when only the T Tauri star is left with a nearly depleted accretion disk [3]. Compared to the first two phases, these take tens of millions of years before hydrogen fusion first occurs [5].

3. Main Sequence Stars

Before we can delve into the stars of the main sequence, we need to do two things: find out what happened to the protostars that never started fusion and understand the Hertzsprung-Russell (HR) diagram.

Brown dwarfs are commonly known as failed stars, as they are the protostars that physically could not begin fusion and thus do not get classified as a real, main sequence star [5]. For fusion to ignite, the temperature of the core has to be at a minimum of 10^7Kelvin [5][6]. There is a fundamental property of matter called the electron degeneracy pressure. In simple terms, this outward pressure arises when electrons are so densely packed together that they release pressure so that they do not get smashed together [5][7]. For cores that are less than 0.08 $M_\odot$, gravity is not strong enough to overcome this degeneracy, consequently squeezing the protostar's core into a smaller and smaller one. However, before it reaches temperatures of around 10^7 K, electron degeneracy halts contraction [5]. Therefore, the remainder of this process is a brown dwarf star: a star that never initiated fusion.

The HR diagram, in a nutshell, reveals a star's physical state and evolutionary stage simultaneously. On the horizontal x-axis, the surface temperature of a star (in Kelvin) and its spectral type (O, B, A, F, G, K, M) are plotted; the hotter temperatures are on the left [2]. The spectral type is used by astronomers as a quick way of classifying stars. For example, O-type stars are the hottest and darkest blue stars. On the vertical y-axis, the stellar luminosity or absolute magnitude (abs mag) is plotted. Stellar luminosity shows the total power output of a star and is on a logarithmic scale with reference to the Sun [2]. Absolute magnitude, however, shows that same power output as a brightness scale of how bright a star would look if it were 10 parsecs (32.6 light-years) away. Interestingly, abs mag has smaller numbers representing a greater brightness. The luminosity formula: $L = 10^{\frac{M-m}{2.5}}$, where 'L' is the luminosity, 'M' is the absolute magnitude of the Sun and 'm' is the apparent magnitude of that star, can be rearranged to prove this. Making 'M' the subject, the formula would look like this: $M - 2.5 \times lg(L) = m$ or in other words – the greater the luminosity of a star, the less its absolute magnitude [2].

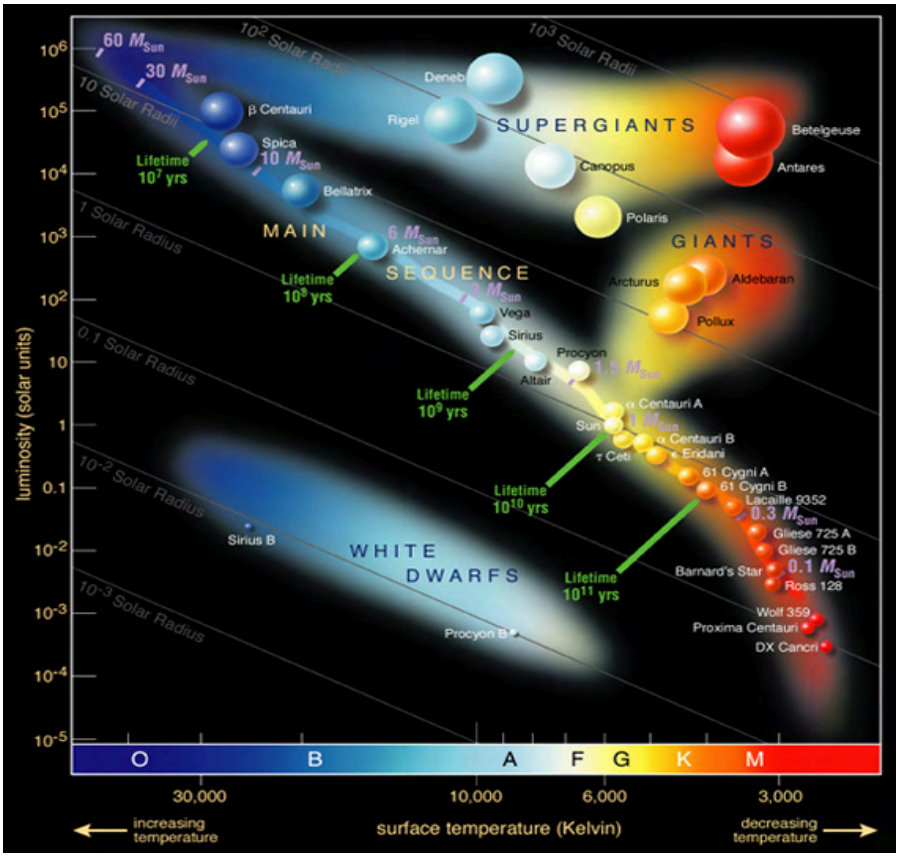

Figure 2: The Hertzsprung-Russell diagram; a graph where every star in the universe can be plotted [30].

The fascinating part about this diagram is the fact that stars are not scattered randomly across the plane; rather, most fall along a diagonal band running from the bottom right to the top left.

This band of stars is called the main sequence, and any star not on this line is either in its dying phase or are remnants of the death of a star [2]. This, however, is not a coincidence, as it directly reflects a star's mass and its effects on itself. The mass of a star determines the rate of hydrogen fusion in the core, which in turn determines a star's surface temperature and luminosity [2]. Furthermore, this diagram also reveals a star's radius even though it is not directly plotted as an axis. The Stefan-Boltzmann law connects a star's luminosity, surface temperature and radius: $L \propto R^2 T^4$ [2]. This is reflected on the graph as the giants and supergiants on the top right have the greatest radii, whereas the white dwarfs on the bottom left have the smallest [2].

Now we can discuss the low-mass, intermediate, and massive stars. First: the low-mass stars. These are stars that are less than 1.3 $M_\odot$ and have the spectral types of G, K or M [2]. Fusion in low-mass stars runs on the proton-proton (pp) chain since their core temperatures are 14 to 17 million Kelvin [6]. The pp chain occurs in three steps. First, two protons fuse to form deuterium (an isotope of hydrogen with one proton, neutron and electron). Then the deuterium grabs onto another proton, forming Helium-3 [6]. Finally, this He-3 fuses with another He-3 to form He-4 while letting out 2 excess protons. Low-mass stars burn through their fuel supply extremely slowly. Mirroring the time taken to reach the main sequence, these stars burn for billions of years [2][6].

Intermediate-mass stars sit right in the middle. They have masses from 1.3 to 8 $M_\odot$ with spectral types of A and late B [2]. In contrast to low-mass stars, fusion in intermediate-mass stars runs on the CNO (carbon, nitrogen, oxygen) cycle, as these stars have temperatures ranging from 17 to 25 million Kelvin [2]. This type of fusion has carbon, nitrogen and oxygen acting solely as catalysts to combine four hydrogen nuclei into one helium nucleus [6]. Intriguingly, these three heavier elements were not formed by the star itself: they were forged by previous generations of stars and stayed in space long after those stars died [9]. After their death, the elements were transported into the GMC by stellar winds or supernova explosions [9][10]. Furthermore, intermediate-mass stars live from 20 million to 3 billion years [2][11].

Massive stars contrast with low-mass stars in practically every way, sitting even above the intermediate-mass stars. They are in the O and B spectral ranges and have masses greater than 8 $M_\odot$ [8]. Similarly to intermediate-mass stars, fusion in massive stars runs on the CNO (carbon, nitrogen, oxygen) cycle too, as these stars have temperatures ranging from tens of millions of Kelvin all the way up to 10^8 Kelvin [6]. Additionally, massive stars exhaust their fuel supply extremely fast and are therefore known as live fast, die young stars. These stars only live for a few million years [8].

4. Old Age

Eventually, every star runs out of hydrogen to fuse. The result of this, however, depends on its mass again. Those stars that were less than 8 $M_\odot$ form red giants, while those greater than 8 $M_\odot$ form red supergiants [8][11].

As their name suggests, the red giants have spectral types of G, K and M with high luminosity and large solar radius [11] (in the HR diagram). Once the hydrogen in the core runs out, fusion halts, causing the pressure that was balancing gravity to disappear [11]. As the core contracts, it reaches temperatures north of 100 million Kelvin: enough to overcome electron degeneracy pressure and ignite the burning of helium [11][12]. The fusion of helium occurs via the triple alpha process. Two helium-4 nuclei fuse into beryllium-8, which, despite being extraordinarily unstable, is bombarded by another helium-4, creating carbon-12 [12]. Simultaneously, this carbon-12 undergoes alpha capture, which forms oxygen-16 [9][12]. The competition between the two processes determines the carbon-oxygen ratio in the final core [11]. Intuitively, after it burns through all of this, one might assume that the star would simply collapse; however, there is still a thin shell of hydrogen right around the inert helium core [11]. This shell of hydrogen sits at a much greater temperature and density gradient and therefore, by triggering it, shell burning is significantly more vigorous than the fusion in the core [11]. The enormous amounts of energy released due to this push the outer layers of the star outwards while the core contracts [11]. Red giants can have up to hundreds of solar radii [11], which causes them to have a cool, red surface of 3000- 4000 K [2][11]. A fun fact is that the Sun will become a red giant in around 5 billion years: engulfing Mercury and Venus [2] and leaving no chance for life on Earth (if we're still around, that is).

Red supergiants are like the big brother of red giants. Sitting above the giants with spectral types of K and M (in the HR diagram), they take the same mechanism as red giants but amplify it much more [8]. The key difference between the two is due to the fact that the core of these stars is immensely hotter [8]. Unlike red giants, these supergiants do not just stop after hydrogen. The extreme mass and temperature allow it to fuse not just helium, but also carbon, neon, oxygen and silicon to finally synthesise iron [8]. As soon as one fuel is exhausted, the star turns to the next source, creating onion-like layers of elements in descending masses around the final iron core [8]. Red supergiants, therefore, have hundreds to thousands of solar radii and luminosities while being at about the same temperature as the giants [8]. However, a key fact to remember about iron-56 is that it is the last element that releases more energy during fusion than it takes [8][9]; but we come to this in the next section.

5. Death

In monostellar systems of low-mass stars, succeeding the red giant phase – which can take up to a billion years – is its death: the planetary nebula [10][11]. Disappointingly, the name acts as a complete red herring towards reality, as they have no connections to planets whatsoever [10]. As stars enter this phase, they move slightly more towards the top right of the HR diagram where the cool and extremely luminous stars lie [10]. The internal structure at this point is like an onion: there is the carbon-oxygen core, a shell of helium and the outer shell composed of hydrogen [11]. However, as the ongoing battle between gravity and radiation pressure commences, the star experiences pulsations during which it can lose enormous amounts of mass – up to 10^{-4} M$_\odot$ per year in extreme cases [10][11]. This progressively strips the hydrogen and helium shells of a star over thousands to tens of thousands of years [10]. Planetary nebulae glow because ultraviolet photons emitted from the star have enough energy to photoionise elements in the vicinity by extracting their electrons [10]. But it is the recombination of electrons to the hydrogen nuclei that creates light through the emission of photons: different elements emit photons at different wavelengths, giving the nebula its several vivid colours [10].

Before we discuss the numerous types of supernovae, we need to understand what binary systems are. A binary system starts in the GMC itself as it fragments into different clusters of high densities [1][13]. If two different fragments are close enough to each other, gravity pulls them together and therefore forms one protostar, but if those fragments are far enough apart, two independent protostars form [1]. However, there is a Goldilocks zone where two clumps form in close enough proximity that they orbit a shared centre of mass [1]. This signifies the birth of a binary system, and counterintuitively, these systems are way more common than people assume: around 40-70% of solar-type stars form in either binary or multiple systems [13][14]. Depending solely on their respective mass ratios, the two stars in this system have a possibility of evolving at the same rate, and this determines their death [8]. As we pointed out earlier, the greater the mass, the greater the rate of evolution [8].

The first type of supernova I will explain is called the Type Ia Supernova. In a binary white dwarf stellar system, the two stars constantly emit gravitational waves towards each other: spiralling them closer and closer to each other [15][16]. The Roche lobe is a region around a star in which material remains gravitationally bound to it rather than its companion [16]. Once the smaller star enters the more massive one's Roche lobe, it gets pulled inwards, combining the two into one singular object [16]. Evidently, the mass of the new star would increase, and as it climbs to the Chandrasekhar limit (roughly 1.44 M$_\odot$), the core temperatures rise enough to ignite the fusion of carbon and oxygen nuclei [7][16]. This converts a large fraction of its stores into heavier elements such as silicon, sulfur, calcium and nickel, releasing nearly 10^{44} joules of energy within just a couple of seconds [16]: enough energy to sustain the current global civilisation for the next

2.5×10^{23} years [25]– a number too unfathomably large to grasp. Similarly, this is enough energy to completely unbind the gravity of the entire white dwarf – destroying and blowing apart the entire star, leaving no compact remnants behind [16]. However, our observations of this process can only take place months later, after nickel-56 and cobalt-56 radioactively decay into stable iron-56 atoms, releasing gamma rays [16] that travel at the speed of light towards us.

The next type of death of a star in a binary system is called the nova. A nova requires a white dwarf star and a main sequence star evolved enough to fill or even nearly fill its Roche lobe. Unlike type 1a supernovae, where the merger causes the explosion, here hydrogen-rich material flows from the main-sequence star towards the white dwarf, forming an accretion disk which funnels the material onto it [17]. Initially, the accretion is not hot enough to ignite hydrogen fusion; however, as material keeps getting accumulated, the base layer experiences an immense increase in density and temperature, crossing the fusion threshold. Intuitively, one would assume that this marks the beginning of hydrogen fusion to make helium, but though hydrogen fusion does begin, the accreted layer cannot expand and cool in response to the heating. Therefore, this intense temperature causes the shell's thermal pressure to take over, driving its explosive expansion [17]. The hydrogen envelope with a mass of 10^{-5} to 10^{-4} $M_\odot$ is blasted away at thousands of kilometres per second from the surface of the white dwarf [17]. This ejection is what can be observed by astronomers: a rapid brightening followed by a slow decline as the material cools down and thins out. The main contrast between novae and type Ia supernovae is the fact that the system is mainly unchanged: the white dwarf survives, and only a thin layer of hydrogen gets ejected [17]. This allows the entire process to repeat from every year to every 10^5 years. When the main sequence star loses all of its material to donate, the nova ends – leaving the system as a binary white dwarf [17].

Until now, we have discussed the three unique possible deaths of a low-mass star. The next supernova is a result of a massive star after its red supergiant phase [8]. Do you remember the key fact about iron-56 in the red supergiant section? Well, it was the fact that iron fusion releases zero energy and therefore, as silicon shell fusion continuously adds mass to the iron core, the core exceeds the Chandrasekhar limit [8]. Furthermore, as the core collapses, two physical processes act as catalysts, drastically accelerating it: photodisintegration and electron capture [8][18]. Photodisintegration is high-energy gamma-ray photons smashing into iron nuclei, breaking them into helium nuclei and free protons and neutrons [18]. Absorbing massive amounts of energy, it robs away pressure from the core right when it needs it the most [18]. Electron capture occurs when free protons merge with electrons to create neutrons [18]. This strips away the core of its electrons that were creating the degeneracy pressure to fight gravity, catastrophically hastening the process [18]. However, the collapse does not continue forever. As the collapsing core's density reaches nuclear density – around $2.7 \times 10^{14} g/cm^3$– Neutron degeneracy pressure becomes enormously strong [18]. Neutron degeneracy pressure is like a

twin to electron degeneracy: the same mechanism with neutrons instead of electrons [19]. At this point, the collapse halts almost instantly before rebounding outwards [18]. However, this shockwave stalls after it reaches 100- 200 km away from the core as it needs to photodisintegrate the iron that is still infalling [18]. Therefore, without support aided by neutrino (tiny, neutral subatomic particles) luminosity, the core directly collapses, leading to a failed supernova: all the mass collapses inwards with no explosion at all [18]. On the other hand, if the shockwave is facilitated by neutrino luminosity – releasing 10^{46} joules of energy – it creates a shockwave that pushes away the infalling outer core material [18]. The shockwave propagates through all the other onion-shelled layers, compressing and heating each one [18]. Because the bounce is so extraordinarily strong, it triggers explosive nucleosynthesis: fusion that creates several new elements like radioactive nickel-56, which grants us the ability to see the supernova [18]. A supernova remnant (or SNR) is the expanding outer shell material, which we can observe, ejected from the star that travels at thousands of km/s [8][18].

6. The Remnants

The death of a star always leaves behind a remnant: the type of core left behind depends on its type of demise [8]. For low-mass stars, the result is the same for novae and planetary nebulae: a white dwarf star [11][17]. As the outer shell material is propelled outwards, a dense, luminous yet hot carbon-oxygen core is left behind. This naked core remnant is what we call a white dwarf star. The only property preventing a white dwarf's collapse due to its own gravity is electron degeneracy pressure, which supports the star forever as we know it [5][7].

On the other hand, for massive stars, there are two possible outcomes: a black hole or a neutron star [20][21]. These remnants can be determined by the initial mass of the massive star in its main sequence stage. For massive stars of less than 20-25 $M_\odot$ (it is important to note that this number is an approximation rather than an exact number set in stone, as it is still debated between astronomers), the result is a neutron star [20]. In the stage of a type II supernova where the core is collapsing, if the core's mass is less than the Tolman-Oppenheimer-Volkoff (TOV) limit – approximately 2.2-2.3 $M_\odot$ – neutron degeneracy pressure is strong enough to withstand the gravity of the core [19]. Therefore, similar to white dwarfs, neutron stars are those cores held up by neutron degeneracy pressure, spanning just 10- 20 km across: insanely small for that amount of mass [19]. However, for massive stars of greater than 20-25 $M_\odot$ (here too: approximation and not exact), the result is a black hole [20], an object that we still do not understand in its entirety. Black holes form when the collapsing core exceeds the TOV limit and neutron degeneracy pressure can no longer keep up with gravity. The result: a region where gravity is so extreme that not even light – the speed limit of the universe – can escape past a point known as the event horizon [8] (the point with no return).

Object	Support mechanism	Failure point
White dwarf	Electron degeneracy pressure	1.44 $M_\odot$ (Chandrasekhar limit)
Neutron star	Neutron degeneracy pressure	2.2 $M_\odot$ (TOV limit)
Black hole	N/A - no known force counters gravity	N/A - no known failure point

Table 1: Types of Remnants and their Properties

Category	Mean mass (kg)	Mean mass ($M_\odot$)	Mean radius (m)	Mean radius ($M_\odot$)
Stellar	1.05×10^{32}	5.26×10^{1}	1.55×10^{5}	2.23×10^{-4}
Intermediate	9.59×10^{34}	4.82×10^{4}	1.42×10^{8}	2.04×10^{-1}
Supermassive	1.01×10^{40}	5.1×10^{9}	1.51×10^{13}	2.17×10^{4}

Table 2: Classification of Black Holes, all values derived from 200 simulated black holes based on classified boundaries as discussed in [24]. Mean radius indicates Schwarzschild radius in meters and solar radius.

One might assume that the stellar life cycle has finally reached its end. However, this is not the case. Both neutron stars and black holes have one more possible outcome: turning into pulsars and X-ray binaries, respectively [22][23]. Each neutron star has two ingredients to make it a pulsar: angular momentum and magnetic fields [22]. As the progenitor core collapses, it spins ever so slowly. The angular momentum of a point mass is given by the formula $L = mvr$, where 'L' is the angular momentum, 'm' is mass, 'v' is velocity and 'r' is radius. Therefore, to conserve angular momentum, as the progenitor's core radius decreases, the velocity has to increase proportionally as mass stays constant. This allows the star to spin. Furthermore, magnetic field lines grow denser and denser, increasing the field strength by a ton [22]. Fun fact: neutron stars have some of the strongest magnetic fields known – ranging from 10^4 to 10^{11} teslas, up to a quadrillion times stronger than the Earth's [22]. This combination accelerates particles at the magnetic poles, producing beams of radiation [22]. However, not every neutron star can be

classified as a pulsar for two reasons. The first is that the radiation beams are simply not lined up towards the Earth, and the second is due to the spin rate slowly but surely decreasing as it radiates away energy [22]. In contrast, X-ray binaries occur solely based on the chance that a black hole comes in contact with another star [23]. Due to its gravity, the black hole could pull the companion star close enough to overflow the Roche lobe, forming an accretion disk around it [23]. The infalling material is heated to temperatures of millions of Kelvin in the innermost regions of the black hole, and gas at those temperatures radiates thermal energy in the X-ray wavelengths [23]. Frighteningly, X-ray binaries are one of the only possible ways that we can observe black holes [23].

7. Future Directions and Conclusion

Though this paper's framework presents the well-established broad pathways of stellar evolution, there are a few significant uncertainties that we are yet to resolve. Firstly, planetary nebulae should be spherical as the mass loss is spherically symmetric. In real findings, however, the majority of them are non-spherical (bipolar, elliptical or point symmetric) and single-star models struggle to explain why [26]. Secondly, in type II supernovae, though the core collapse is understood, the process of the stalled shock revival via neutrino luminosity is still an active problem still being debated [27]. Finally, and most importantly for this paper, is the correlation of a star's initial mass to its final mass. Indeed, semi-empirical relations, measured from white dwarfs in open clusters, still have substantial scatter [28].

In this paper, we have outlined and described every major road a star can take. Beginning in giant molecular clouds, we have seen how a star's life is a predisposed path based on its initial mass as a protostar – the baby star. If the mass of the core is less than 0.08 $M_\odot$, a brown dwarf forms. Anything greater than that but less than 1.3 $M_\odot$ results in the formation of a low-mass, main sequence star, and stars with 1.3 to 8 $M_\odot$ form intermediate-mass stars. These stars form red giants and die by a planetary nebula. Similarly, binary systems could form one red giant and die via a nova, or the two stars could merge and face their demise through a type Ia supernova. Planetary nebulae and novae leave behind a shared remnant: the white dwarf star. On the other hand, stars of greater than 8 $M_\odot$ – or massive stars – form red supergiants. These stars result in a type II supernova with the possibility of leaving behind a supernova remnant but with a certainty of leaving behind either a neutron star or a black hole. These, in turn, have a possibility of becoming a pulsar or an X-ray binary, respectively. All in all, the stellar life cycle is an immensely complex yet fascinating evolutionary process.

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