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How does stellar evolution affect the dynamics of active stars?

Aryaman Tandon
aryaman.tandon@gmail.com
Dhirubhai Ambani International School, Mumbai, Maharashtra

ABSTRACT

This paper summarises the process of stellar formation and evolution of stars over time and how other processes within the general phenomenon affect the dynamics of life of active stars such as neutron stars, black holes, magnetars, and pulsars. Main sequence life has also been looked into while comparing properties of these active stars with the ones of main sequence stars to see how much their dynamics differ over time. From multiple different sources, this paper has been able to give us an insight into the workings of stars and how the initial states of matter can affect the courses of life of the infinitesimal quantity of stars in the universe.

Keywords- *Active Stars, Black holes, Neutron Stars, Stellar Evolution, Stellar Formation, Supernovae, Hertzsprung-Russell Diagram*

1. INTRODUCTION

In this section I will be talking about the different stars in the universe but declaring that I will be focusing on just the most active stars. For example, these more active stars are mainly high mass stars which behave differently than main sequence stars. These are neutron stars, magnetars, pulsars, and black holes. Further, the papers, literature, and sources I will be referencing in the paper range from scientific articles, research paper publications by academics and reliable websites. The aim of this paper is to examine the general formation and evolution of stars, compare the properties of main sequence stars with those of the most active stars.

2. STELLAR FORMATION AND EVOLUTION

2.1 Interstellar Cloud Formation and Cloud Collapse

Interstellar clouds are regions of accumulation of gas, plasma, and dust which contain a large number of atoms and molecules of mainly hydrogen and helium, the two most abundant elements in the universe [1]. While the interstellar medium is the region of space between stars that contains large interstellar clouds and miniscule solid particles [2]. The process of star formation occurs almost anywhere - right from the arms of a spiral galaxy to the centres of galaxies like our own Milky Way. The process begins where hydrogen gas coalesces to form dense and massive molecular clouds [3]. In addition to this, the interstellar medium of gas and dust in which these molecular clouds form are roughly 73% hydrogen, 25% helium and 2% of other elements [4]. As this accretion and coalition continues these clouds become large enough, with masses of up to 10^6 M_{SM} (solar masses), to develop its own gravitational force of attraction further pulling in more gas, dust and interstellar materials [5]. These molecular clouds are also called dark nebulae because they absorb most of the light from distant stars while also being relatively darker than the brighter backgrounds of galaxies [6].

The phenomenon of interstellar cloud collapse occurs when the kinetic energy due to gas pressure within the cloud (at the centre) succumbs to the gravitational potential energy due to the inward gravitational force. This takes place after approximately 10^8 years [5]. Or in other words, this occurs when the magnitude of the gravitational force exceeds that of the outward force due to nuclear fusion. The threshold mass for which interstellar cloud collapse takes place is called the Jeans Mass which depends on the density and temperature of the cloud but it is proportional to the ratio of the temperature to the mean mass per particle raised to power 3/2 and divided by the square root of the mass density [7]. When this interstellar collapse occurs the result is an open cluster of stars which contains tens of thousands of stars. In three models of “prestellar cloud core collapse”, spherical, collapse with rotation, and collapse with magnetic field enable us to visualise these astronomical phenomena [8]. As discussed in the “spherical collapse” section, the collapse occurs towards the centre of the cloud and only a small fraction of the cloud has high enough density to form a star while the rest of the remaining materials forms an infalling envelope. A small mass protostar is predicted to form at the centre of the cloud that will grow by accreting the material from the surrounding envelope. Therefore, the star forms at the centre of the spherically collapsing cloud. As far as collapse by rotation is concerned, it is observed that cloud cores rotate due to the turbulence in molecular clouds [9]. The angular momentum associated with a rotating cloud core can be as high as a couple of orders of magnitude more than a star can contain. These high orders of magnitude of angular momentum are thought to be due to the rotation of the galaxy in which the cloud formed. [10]. Coming to the section "Collapse with magnetic fields", magnetic fields are thought to support cloud cores against gravity [8], but eventually when the core of the cloud contracts slowly, the influence of gravity increases causing the cloud core to flatten along the magnetic field lines. As this gravitational influence surpasses the influence of the magnetic field, runaway collapse commences (collapse of an astronomical object due to the influence of its own gravity).

2.2 Protostars

A protostar is a juvenile star that continues to accrete material, gas, and dust from its parent molecular cloud. The collapse of the cloud causes these sub-solar mass protostars to form along with an orbiting protoplanetary disk. A protoplanetary disk is an orbiting disk of gas and dust, 99% and 1% respectively, at the centre of which planets and other celestial bodies are thought to form [11]. The internal temperatures of a protostar are lower than those of normal stars, measured to be about 2000 K compared to 3000 K to 40000 K [12] for normal stars, which then causes dissociation of hydrogen gas molecules. Convection due to nuclear fusion within the protostar coupled with radiation from the surface enables contraction until hydrostatic equilibrium is achieved. Hydrostatic equilibrium is the state of equilibrium achieved by a star when the gravitational force due to its own mass is balanced by the internal gas pressure due to nuclear fusion [13]. After the process of accretion stops and all the gas surrounding the protostar diffuses, the protostar is considered a pre-main sequence star. However, this protostar still does not fuse hydrogen into helium in its core but theory suggests that deuterium and hydrogen fuse together to create helium-3 [14]. Since there is not yet any nuclear fusion occurring at the cores of protostars, most of the energy radiated comes from the surface level shocks, whereas most stars radiate energy due to nuclear fusion. These surface level shocks arise from the collision of falling gas towards the opaque region of an interstellar cloud and the core of the protostar. The radiation from protostar surfaces must therefore travel through the dense core of dust surrounding the protostar. This radiation, however, is in the sub-millimetre range and therefore protostars cannot be represented on a Hertzsprung Russell Diagram.

2.3 Hydrostatic Equilibrium

All models of stars indicate to us that stars are made of gases which are in a state of hydrostatic equilibrium. The outward pressure supplied by ordinary gas pressure and electron degeneracy pressure are balanced by the inward pull of the gravitational force due to a star's mass [15]. However, as stars get more massive and the gravitational force of the star increases, the gas and electron degeneracy pressure are not sufficient to maintain hydrostatic equilibrium. Therefore, when the temperature of the core of a star reaches around 10 million Kelvin, hydrogen begins to fuse into helium, which releases energy [15]. The energy exerts an outward radiation pressure which helps to keep the star in hydrostatic equilibrium.

2.4 Nuclear Fusion

Nuclear fusion is the battery or fuel which powers a star and keeps it alive. The process involves a nuclear reaction between protons or hydrogen atoms especially in stars that are less than 15 million K [16]. Two nuclei are fused together to give the nucleus of a different element or isotope of an element. Proton reactions result in deuterium nuclei, which then fuse to give helium-4 or if they react with protons helium-3. These helium-3 nuclei react to give beryllium-6 which is unstable and breaks down to give two helium-4 nuclei and two protons. These reactions are exothermic meaning they release energy [14].

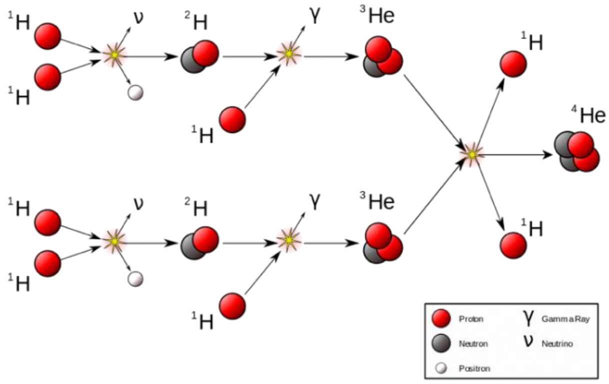

Figure 1: A depiction of the proton-proton chain reaction which takes place in nuclear fusion. This figure is from Wikipedia's page on Nuclear Fusion [17].

3. STELLAR EVOLUTION

The evolutionary behaviour of every star depends on its initial mass. Low mass and high mass stars have different evolutionary stages depending on their internal structures and the processes of energy production which take place at the core. This is where the Hertzsprung-Russell Diagram comes into consideration. Charting out stars based on their temperature and luminosity, the HR diagram helps astronomers determine the stages of life of a star. Eventually, as the process of nuclear fusion continues in protostars or pre-main sequence stars, hydrogen continues to be fused to give helium in the cores of protostars which will go on for at least 90 percent of their lives and they are thus called main sequence stars.

For stars to remain in hydrostatic equilibrium, two things must occur but their occurrences are determined by the initial mass of the star. One is the outward pressure arising from the fusion of hydrogen (electron degeneracy pressure) balances the inward gravitational influence of the mass of the star and the other is that the core must reach around 100 Mega Kelvin for the fusion of helium into higher elements to take place.

3.1 Low Mass Stars

Some lower mass stars such as red dwarfs which have masses of about 0.1 M_{SM} are thought to remain as main sequence stars for 2 x 10^{12} years and take an additional hundred billion or so years to become a white dwarf [15]. These stars will not go on to become red giants or enter the "mid-mass or mid-sized" main sequence star branch due to there not being any further fusion of heavier elements beyond helium.

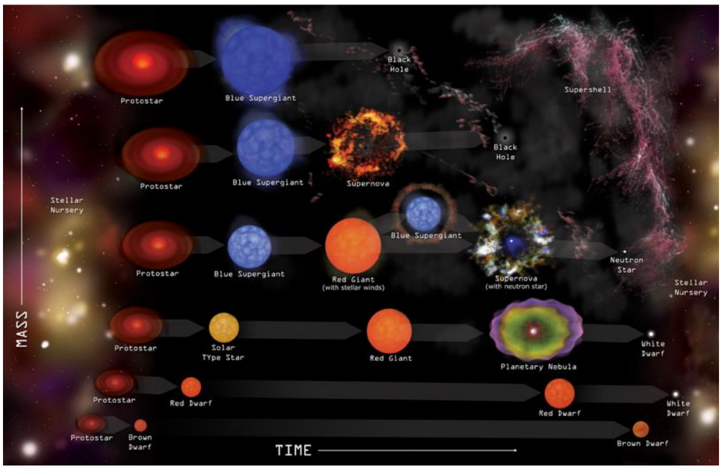

Figure 2: This figure is a diagram with mass versus time plotted to depict the evolutionary paths of stars over time depending on their initial masses [25]

3.2 Mid-Mass or Mid-Size Stars

The stars that are large enough - with masses up to 8 M_{SM} go on to become red giants [19]. These stars undergo some stages of evolution: subgiant phase, red-giant-branch phase and the asymptotic-giant-branch phase. At the end of its main sequence life, a solar mass star burns through a hydrogen shell which encompasses a helium core. Mirror action takes place causing the outer layers of the star to expand and cool moving into the subgiant phase [20]. The mirror action is when a star appears to look like a mirror when a region inside the burning hydrogen shell contracts and the outer region expands and vice versa [20]. In the subgiant phase, once the production of helium begins, the process continues for a couple million to a billion years while the star expands and cools and has a slightly lower luminosity than a main sequence star. As the outer layers of the star continue to expand, the temperature of the star drops below around 5000 K leading to greater luminosity to enter the red-giant phase. In the red-giant-branch phase the helium core heats up significantly because the star is no longer in hydrostatic equilibrium and has reached or crossed the Schönberg-Chandrasekar limit. The Schönberg- Chandrasekhar limit is the maximum stable isothermal mass of a helium core formed by fusion in a main sequence star [21]. This causes fusion rates of hydrogen to increase rapidly. The more massive red giants then have cores which are hot enough to fuse helium. During the asymptotic-red-giant- branch phase, after helium at the core is consumed completely, hydrogen and helium continue to fuse in layers around a core of carbon and oxygen.

3.3 High Mass or Massive Stars

These types of stars begin helium consumption before electron degeneracy pressure increases to a larger extent causing them to have lower luminosity than low-mass stars but higher luminosity than main sequence stars and eventually contain the potential to evolve into highly luminous supergiants. Massive stars that have masses that are 40 M_{SM}, are highly luminous and tend to lose their mass through radiation pressure and they retain high surface temperatures and a blue-white colour. The largest stars have masses of up to 100 to 150 M_{SM}. The core of a massive star grows denser and hotter as it accretes material from the fusion of hydrogen outside the core [22]. When the core temperature reaches a threshold temperature heavier element such as carbon, oxygen, neon, sodium and magnesium begin to fuse until electron degeneracy occurs causing a neon-oxygen white dwarf to form. In heavier stars, elements continue to fuse by the alpha process until iron is reached which is the peak of nuclear fusion. After the Chandrasekhar limit is reached, which is a mass of 1.34 to 1.8 M_{SM} depending on the size of the star, the star is no longer able to sustain itself and collapses into a supernova or a blackhole [23].

3.4 Stellar Composition

The two basic and most abundant elements found in the universe and stars are hydrogen and helium. The Sun for example is 73% hydrogen and 25% helium in terms of elements but in terms of nuclei it is made up of 92% hydrogen and 7.8% helium. The remaining 2% or 0.2% are the heavier elements which are commonly referred to as "metals" by astronomers including carbon and oxygen. Metallicity is the measure of the abundance of metals of atomic number greater than 2 in the composition of a star. Therefore, a young star would have a high metallicity value and vice versa [15].

3.5 Supernovae

Supernovae are explosions that occur at the end of a star's life. They are formed when some amount of the gravitational potential energy from a star's collapse is converted into a Type Ib, Ic, II supernova. The energy produces neutrinos, some of it is used up in the release of neutrons and the rest is converted to kinetic and heat energy, magnifying the shock wave initiated by the collapse of the core [24].

4. EVOLUTIONARY TRACKS OF MAIN SEQUENCE STARS

Main sequence stars make up the majority of stars which are charted on the Hertzsprung-Russell Diagram. The timespan a star spends as a main sequence star on the Hertzsprung-Russell diagram depends on the initial mass of the star and how it started off. For example, stars that have masses less than 0.23 M_{SM} [26] usually evolve directly to white dwarfs when energy production in the core due to nuclear fusion ceases. Stars with these masses have a main sequence lifetime of more than the current age of the universe (about 13.77 billion years). Stars that have masses larger than 0.23 M_{SM} have a high enough temperature and pressure to cause the helium shell to undergo nuclear fusion. As these stars fall off the main sequence track they join the subgiant branch which is a relatively short - lived period. Conversely, when electron degeneracy in the helium cores begins in low - mass stars, and the outer layers of mid-sized stars cool till opacity is reached, the temperatures of the hydrogen shell begins to increase, leading to the stars increasing in luminosity. Electron degeneracy is when matter is compressed to such an extent that electrons acquire the same and lowest quantum state which is described by Pauli's exclusion principle that no two electrons can acquire the same state at the same time [27]. These stars have now entered the red-giant branch which lasts 10^9 years [28]. High mass stars, however, do not become red giants. Their cores become sufficiently hot enough to fuse helium and then heavier elements. They are then known as supergiants which follow horizontal evolutionary tracks across the main sequence which goes across the top of the Hertzsprung - Russell diagram. Due to their high masses, these stars' cores will eventually collapse into a supernova giving either a blackhole or a neutron star. A star's time spent in the main sequence is dependent on its initial mass - the heavier the star the shorter its main sequence lifespan and vice versa.

5. PROPERTIES OF MORE ACTIVE STARS

The origins of life for both low mass and high mass stars are the same - in interstellar clouds and nebulae. However, what distinguishes a low mass star from a high mass star and what gives the differences in their formations is a difference in the evolutionary path they take. The process is the same for both classes of stars, nevertheless, the process is faster in high mass stars, and hydrogen fusion takes place via the CNO cycle. The CNO cycle (Carbon- Nitrogen-Oxygen) is one of the two types of nuclear fusion - conversion of hydrogen to helium - which takes place in stars that have masses above 1.3 M_{SM} [30]. The CNO cycle is a catalytic reaction - carbon, nitrogen and oxygen are used as catalysts when four protons fuse; these catalysts are used up at each cycle and then regenerated later for use.

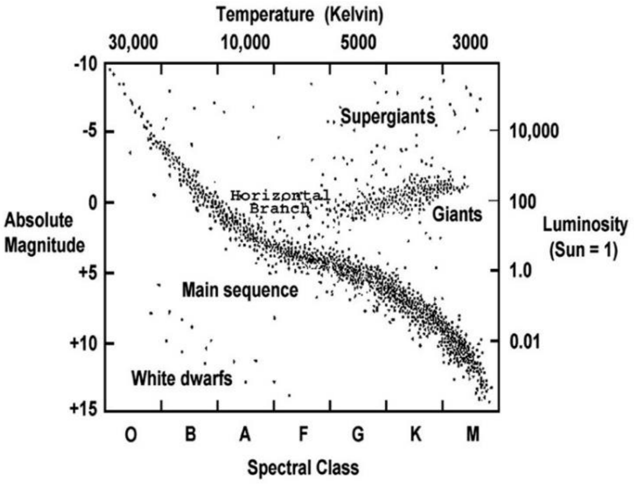

Figure 3: Hertzsprung-Russell Diagram. This figure is from Chandra's X- Ray Observatory NASA page [29]

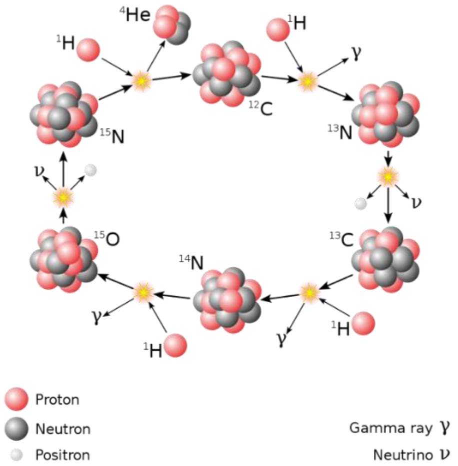

Figure 4: A depiction of the CNO cycle which takes place in all main sequence stars. This figure is from Wikipedia's page on CNO cycles [31]

5.1 Neutron Stars

A neutron star is a stellar remnant that is formed when the core of a supermassive star such as a massive supergiant collapses onto itself when the gravitational attractive force towards the centre of the star exceeds the out- ward pressure exerted by nuclear fusion. These astrophysical objects are created usually from stars that were of 9 to 10 M_{SM} [32] in mass and are known to be the smallest and the densest objects in the universe (after black- holes). Neutron stars themselves have radii in the order of magnitude of 10 kilometres with masses up to 1.4 M_{SM}. The electrons and protons present in the matter of neutron stars combine to form neutrons due to the conditions found within the star. Neutron stars are extremely hot at about 600,000 K but tend to cool over time. Electron degeneracy pressure helps in the structural support of a neutron star, however, this may not be sufficient in stars with masses of 0.7 M_{SM}. Neutron stars with masses above the Tolman-Oppenheimer-Volkoff Limit (around 2.2 to 2.9 M_{SM}) [33] experience a combination of electron degeneracy pressure and nuclear forces which are sufficient enough to cause the star to collapse into a black hole.

5.1.1 Properties

- **Mass and Temperature:** Neutron stars usually have masses of about 1.1 to 2.1 M_{SM} with 2.16 M_{SM} being the upper limit of the Tolman- Oppenheimer-Volkoff Limit [34]. Temperatures in the cores of neutron stars can initially be as high as 10^{11} to 10^{12} Kelvin [35], but due to the high emission of neutrinos, large amounts of heat are radiated away leading to temperatures dropping to 10^6 Kelvin.
- **Density and Pressure:** Densities of neutron stars vary from 3.7×10^{17} to 5.9×10^{17} kgm^{-3} which is relatively similar to that of an atomic nucleus (3.7×10^{17} kgm^{-3}) [36] which is why it shares similar properties to those of a nucleus. Pressures increase from 3.2×10^{34} to 1.6×10^{34} Pa from the crust to the centre compared to Earth's crust to core which increases from 101,325 Pa to 3.8×10^{11} Pa [37].
- **Gravity:** The gravitational field strength at the surface of a neutron star is about 2.0×10^{12} [38], compared to earth's which is about 9.80665 mss^{-2} [39] which is strong enough to act as a gravitational lens and make visible the rear of the neutron star. Any material that falls to the surface would first be broken down into a stream of material.

5.2 Black Holes

A black hole is a region in space where the gravity is strong enough to not let any matter or even light and electromagnetic radiation escape. The event horizon is the boundary from which the escape velocity of a body exceeds the speed of the light, which is the fastest possible speed for anything in the universe [40]. It is the boundary in which nothing can escape which makes it hard to find blackholes visually. Black holes form when the cores of massive stars collapse after hydrostatic equilibrium fails at the end of a star's lifespan (when Iron is formed in the core) [41]. They can grow into supermassive black holes by merging with other blackholes, accreting mass from its surroundings or by absorbing nearby stars. These supermassive blackholes are usually found at the centres of galaxies such as Sagittarius A* at the centre of the Milky Way Galaxy.

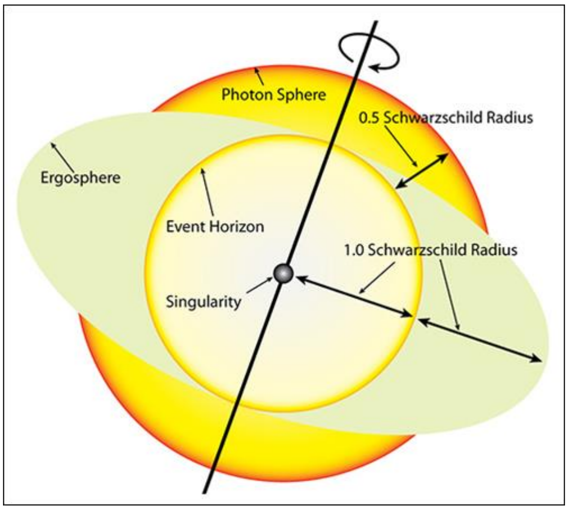

Figure 5: A diagram of the regions of a blackhole. This figure is from darkspacecentral's webpage on black holes [46]

5.2.1 Properties and Structure

- **Event Horizon:** The event horizon is the boundary in spacetime through which light and matter can pass only inward towards the centre of a black hole. This is the point at which gravitational time dilation and gravitational redshift take place [42]. The radius of this event horizon is called the Schwarzschild radius [43].
- **Singularity:** Also commonly referred to as the gravitational singularity, the singularity is the region in space where density is infinite (because a finite mass is packed into a zero volume space) and so is the curvature of spacetime [44]. The entire mass of the blackhole (typically millions of solar masses) is concentrated here at this point. Once matter has passed the event horizon, it undergoes "spaghettification" due to strong gravitational forces. This matter then eventually reaches the singularity where it is packed to an infinite density and adds to the mass of the black hole [45].
- **Ergosphere:** The ergosphere is the region around a blackhole in which any material will tend to move along the direction of rotation of the black hole - a region of instability. The volume bounded by the event horizon and ergosurface is this region of the ergosphere. Matter and radiation are able to escape this region due to the fact that objects gain energy from the rotational kinetic energy of the black hole, slowing down the black hole and speeding up the matter and radiation till they reach the required escape velocity.

5.3 Magnetars

Magnetars are a specific type of neutron star with the strongest magnetic field of about 10^{15} Gauss which is a thousand trillion times stronger than the Earth's magnetic field [47]. The formation for these astrophysical objects is similar to that for an ordinary neutron star. According to the discoverers of magnetars, if calculations of the spin, temperature and magnetic field are correct a dynamo mechanism could take place [48]. This mechanism involves the conversion of heat and rotational energy into magnetic energy increasing magnetic field strengths to as high as 10^{11} Tesla. However, the conditions these stellar remnants meet are still a work in progress for astrophysicists. The notion, nevertheless, is that in order for a magnetic field strength of such a large magnitude of 10^{15} Gauss, the initial rotation of a magnetar must be between 100 and 1,000 rotations per second [48]. Another theory for the origin of this strong magnetic field is the magnetohydrodynamic dynamo process which takes place in the dense ferrous conducting liquid which is inside the neutron star before equilibrium is reached. Magnetars when first discovered in 1987 were used to explain soft gamma repeaters and anomalous X-ray pulsars. The understanding of the decay of the magnetic field of a magnetar is made possible by the first magnetar model which mentioned that X-rays and gamma rays are the drivers for this decay [49].

5.4 Pulsars

A pulsar or pulsating radio source is a highly magnetised neutron star that emits electromagnetic radiation from the magnetic poles [51]. It is an extra-terrestrial object that emits radio signals in the form of pulses or short periodic bursts of radio emission. Smaller pulsars are also found to emit X-rays and gamma rays. These are only observed when the radio emission pulse is directed towards the earth. The spin rates of pulsars vary from once per second to 650 per second. The pulsar usually forms from the collapse of the core of a star that had a mass 6-10 times that of the earth that is compressed during a supernova explosion [52]. After formation the neutron star retains most of its angular momentum which allows it to spin at high speeds. Radiation is emitted as a beam from the magnetic poles of the neutron star which continues to spin. Since the magnetic pole axis is not always perpendicular, the beam of radiation is misaligned at an acute angle from the normal, which gives the pulsar its pulsating nature. The main observational property of a pulsar is the pulses of radiation it emits. Each pulsar has a unique periodicity and hence pulsating pattern which distinguishes it from other pulsars and other astrophysical objects which emit radio waves [53].

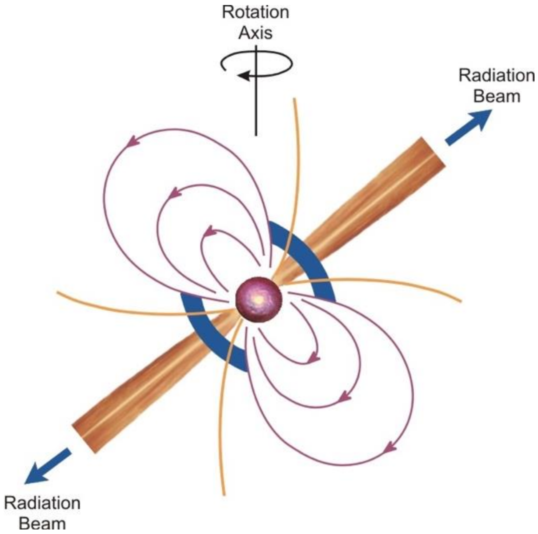

Figure 6: Diagram of a pulsar. This figure is from the National Radio Astronomy Observatory's page on Pulsars [50]

6. COMPARISON WITH THE PROPERTIES OF MAIN SEQUENCE STARS

From the above subsections on the different high mass stars and stellar remnants, it is clear that main sequence stars are nothing like high mass stars and do not share most properties.

6.1 Main Sequence Lifespan

The main sequence is the phase in a star's life in which it spends the majority of its lifetime. For example, our Sun is about 4.6 billion years old but it will spend at least 10 billion years of its lifespan as a main sequence star before becoming a red giant [15]. What determines the main sequence lifespan of a star is its mass. Heavier, more massive stars have relatively shorter lifespans. This is due to the fact that the strong gravitational forces, due to their large masses, tend to heat up the core. All the fusion reactions and nuclear reactions take place faster so the more massive stars run out of "fuel" faster than smaller stars [15].

As seen from the above properties, there is a difference between not only the structural by also the behavioural properties of the main sequence stars and active high mass stars in the sense that there are many more complexities that go behind the formation and evolutions of these classifications of astrophysical objects and astronomical bodies.

7. CONCLUSION AND SUMMARY

In this paper, the process of star formation and stellar evolution has been looked at to help us get an idea of the early behaviours of stars. Focussing on the main sequence track of the Hertzsprung-Russell and the behaviours of main sequence stars, we have got an idea of how and why main sequence stars are different from other stars on the HR diagram and how different internal processes contribute to different fates for these stars. We have also looked at the different "by-products" of high mass stars and compared their properties to those of main sequence stars to better get an understanding of the dynamics of these active stars. The major differences between the properties of these more active high mass stars/stellar remnants and main sequence stars and low mass stars are their physical structures and features which determine their lifespans, functionalities, and behaviours. There is still, however, lots to be learnt about the lesser known magnetars, pulsars, and neutron stars on which there exist more hypothetical models than experimental data.

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