

Collapsed Stellar Remnants

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1 Introduction

The distribution of stars in the universe vary extensively by mass. Depending on a star's mass, its evolution and life cycles differ. [5] Stars are characterized as either being low-mass or high-mass. High-mass stars are defined as those that have a mass of 8 or more solar masses (8 or more times the mass of our sun which is 1.989×10^{30} kg).

The main reason for why stars have different masses is due to the amount of matter that exists in the solar nebula from which a star is created from.[4] A planetary nebula is a region of cosmic gas and dust formed from the cast-off outer layers of a dying star. This cloud of gas can extend up to 10 astronomical units in size. Since nebula are expanding, gradually the gravitational force of attraction between dust and gas increases bringing particles together causing them to clump up. This process is known as accretion forming a protostar. Hydrogen is the main gas present in nebulae amongst other elements such as helium, argon, neon and other ionized gases.[1]

As hydrogen spins, material in the center starts to heat up. When the temperatures exceed 10 million kelvin, hydrogen nuclei have enough energy to overcome the electrostatic repulsion causing fusion to occur. In the sun for example, nuclear fusion produces around 3.8×10^{26} joules of energy per second. At this point, the protostar has become a main sequence star. The outward force created by the fusion prevents

the star from collapsing due to its gravity. The life cycle then branches into two paths: one path is for high mass stars and the other is for low and medium mass stars. [2]

1.1 Low and medium mass Stars Life Cycle

Throughout the main sequence phase of low and medium mass stars hydrogen is continuously being converted to helium through fusion. However, there is only a limited supply of hydrogen that a star has. After all of the hydrogen is converted, the outward force due to fusion of hydrogen starts decreasing until the star becomes unstable. The star contracts inwards causing it to expand outwards first forming a subgiant and then a red giant. The expansion causes the star to cool thus causing the red colour of the star. The main sequence phase of low and medium mass stars are relatively long compared to high mass stars. This is because hydrogen is converted slowly.[6]

Inside a red giant, helium atoms are fusing into carbon. The carbon then fuses with helium to form oxygen on a smaller scale. Similar to the previous collapse, once all of the helium has been fused, the red giant collapses again. This collapse causes the outer layers of the star to get expelled outwards.[6] This expulsion is a continued process; it is not immediate like a supernova. The outer layer forms a planetary nebula and the remaining matter including the core forms a white dwarf. If the remaining core is greater than 1.4 solar masses, the Chandrasekhar limit states that the electron degeneracy pressure is not great enough to prevent continued collapse into a supernova explosion and then into a neutron star. White dwarfs are composed of electron-degenerate matter. They are initially very hot but due to the fact that

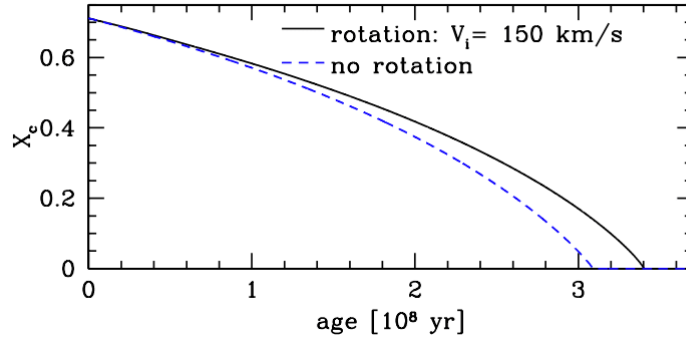


Figure 1: The plot shows the evolution of the mass fraction of hydrogen as a function of time. [3]

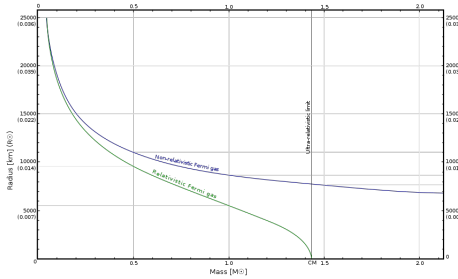


Figure 2: Radius–mass relations for a model white dwarf.

they have no source of energy, white dwarfs quickly become very cold. Many white dwarfs have been detected. As white dwarfs continue to cool, it is theorized that they eventually become dimmer eventually freezing and forming a black dwarf. This process takes a lot of time (much longer than the age of the universe) which is why it is a theory and why black dwarfs have not been detected yet.

1.2 High mass Stars Life Cycle

The life cycles of high mass stars are vastly different to that of low mass stars. The initial process is very similar however. In the core of high mass stars, hydrogen is

fusing and being converted to helium. Once the hydrogen runs out, the star contracts and expands outwards forming a red supergiant which is larger than red giants.

In the core of red supergiants, helium fuses into carbon. Carbon forms heavier elements such as iron, magnesium, neon and sulfur similar to red giants. The core will turn into iron, which is stable, and it will stop burning causing the star to become unstable. Due to the stop in energy being produced, the star collapses in seconds. The repulsion between nuclei overcomes gravity causing a rapid explosion outwards in the form of a supernova. After the supernova, the stellar remnants of the core can follow two paths. If the mass of the remnant core is less than 3 solar masses, hydrogen nuclei absorb electrons forming neutrons. A dense ball of only neutrons is formed called a neutron star. If the mass is greater than 3 solar masses, the core collapses into a black hole. Black holes are points in space where the gravity is so strong that nothing can escape it. Black holes are complex structures that warp space time.

2 Evidence for the Existence of White Dwarfs, Neutron Stars and Black Holes

2.1 Evidence of White Dwarfs

The first evidence for the existence of white dwarfs was in 1844. It was detected by Friedrich Wilhelm Bessel who was a German astronomer and mathematician. In the early 19th century, Bessel was able to measure the parallax of stars which showed the slight variations in the positions of stars due to secondary objects.[7] Bessel sought

to calculate the precise positions of the brightest star in the night sky: Sirius. Whilst performing his calculations, he found that Sirius was changing its position. In 1844, he determined that there is another heavenly body causing these positional variations and that Sirius in fact had a companion. In 1862, Alvan Clark came across a faint star close to Sirius using the world's largest refracting telescope at the time. Following this discovery, in 1915, Walter Adams obtained the spectrum of light coming from the fainter star. By this time, spectral types of stars were established as OBAFGKM. He classified the fainter star as an A star which meant it was hot and white. And thus, the first white dwarf was discovered and it was called Sirius B.

Sirius A and B are in a binary system which is why it was easy to discover the presence of Sirius B. Another reason why binary star systems composed of a white dwarf makes it easier to be detected is another influence on the companion. At some point, the main sequence star will run out of hydrogen causing it to expand outwards. At some point, the radius will become so large that the outer layer of the star gets more gravitationally attracted by the white dwarf than the core of the star causing it to drift towards it. Since the gas has angular momentum, an accretion disk forms around the white dwarf.[7] Hydrogen and Helium from the companion star accumulate on the white dwarf's surface until a certain point when the Hydrogen burns violently into Helium and thermonuclear reactions begin. This reaction is explosive, and ejects the burning layer of gas into space. Under certain conditions the result is a type 1a supernova.

Since then, almost 10,000 white dwarfs have been discovered. Detecting the X-rays and ultraviolet waves emanating from the atmosphere of white dwarfs have helped to detect some of them. The Gaia satellite is also one of the primary satellites targeting

the discovery of white dwarfs. Gaia measures the positions and brightness of billions of celestial bodies and through these measurements, it has been able to discover hundreds of thousands of white dwarfs.

2.2 Evidence of Neutron Stars

Most neutron stars are observed as pulsars which are rotating neutron stars that periodically emit radiation every time they rotate.

Jocelyn Bell helped discover the first pulsar ever detected. In 1967, when analyzing data from a newly built radio telescope she created, she noticed a pulse in the measurements originally dismissing it as interference. However, these signals kept being recorded at the same declination and right ascension thus confirming that it could not be interference. On 28 November 1967 the signals appeared again and a string of pulses 1.33 seconds apart were recorded. Similar sorts of pulses kept getting recorded after this initial discovery by other astronomers and different telescopes. Thus, pulsars and hence neutron stars were detected.

Today, neutron stars are still detected by the electromagnetic radiation they emit. If the poles of the neutron star are facing the Earth, due to their fast rotation and immense gravity, radio waves can be detected on the Earth coming from these pulsars. Magnetars are an example of neutron stars with much stronger magnetic fields than those of pulsars. Typically, Magnetars produce strong bursts of X-rays and gamma rays due to the magnetic field which can also be detected on Earth.

2.3 Evidence of Black Holes

Black holes were first theorized after Einstein published his paper on general relativity which was an extension on his work on special relativity. General relativity describes gravity being the curvature of space and time. Karl Schwarzschild, having read Einstein's paper, described gravity for very dense stars. He presented a mathematical solution that encompassed the concept of light and all matter getting gravitationally trapped due to these dense stars.

We have detected the presence of Black Holes through various ways in the past century. However, it has been especially difficult due to the fact that Black Holes do not radiate any light. Light cannot escape Black Holes which means they produce no visible light. However, they do produce other waves from the electromagnetic spectrum such as X-rays. During a rocket flight in 1964, astronomers discovered a very large source of X-rays coming from the sky. They detected it coming from the Cygnus constellation in the binary star system called Cygnus X-1. Technically, the source of the X-rays were not from the black hole itself but from the accretion disk that was formed from matter going from the companion star to the black hole - a similar process of the detection of white dwarfs.

Additionally, the detection of gravitational waves have played a major role in the detection of black holes. Occasionally, a black hole can be gravitationally bound to another black hole. These interactions and mergings cause ripples in space-time in the form of gravitational waves. They propagate at the speed of light and on Earth they can be detected by LIGO (Laser Interferometer Gravitational-Wave Observatory) and Virgo.

The main evidence of black holes we have found so far is an actual image of one.

In April of 2019, the Event Horizon Telescope was able to capture first images of the event horizon of a black hole at the center of active galaxy Messier 87. Several small radio telescopes were focused on the black hole almost acting as one giant telescope and captured the hot, glowing gas surrounding the event horizon which lights up in the pictures.

3 Planets Orbiting Neutron Stars

Pulsar planets are the name given to planets orbiting pulsars. The presence of these planet causes tugging on pulsars due to their gravitational influence on them. Thus, causing a measurable delay in the detection of pulses on Earth compared to the average timing of observing the pulsar. By using the delay, we can calculate the size of the planet.

A time of arrival (TOA) is a single “average arrival time” representing the entire collection of pulses coming from a pulsar.

The first pulsar planets were discovered in 1992 by Aleksander Wolszczan. In fact pulsar planets were the first types of planets discovered outside of the solar system. Wolszczan used the Arecibo radio telescope and discovered planets orbiting the PSR B1257+12 pulsar. The presence of planets orbiting pulsars is particularly exciting because it was long not thought possible for a planet to exist in such extreme conditions. However, recent analysis has even stated that habitable planets could be found around pulsars. These planets must have extremely thick atmospheres however to deter the onslaught of X-rays and high energy particles that the planets would be exposed to from the pulsars. For this reason, the planet must be a super Earth - 1

to 10 times the mass of the Earth. This is because smaller planets will have a lower surface gravity and would not be able to retain thick atmospheres.

The appearance of pulsar planets have been quite rare so far. Fewer than 1% of pulsars have been found to host planets. [8] It is not certainly known how these planets are formed, however there are many suggestions for possible scenarios. One of these scenarios describes these planets surviving supernovae. In this case, a planet may have formed in the original stellar system. When the star got to the end of its life and exploded into a supernova and became a neutron star, the planet survived the force of the supernova and continued orbiting the neutron star like it orbited the original star. This particular scenario has been debated quite a lot. In order for the star to eventually form a neutron star, it would have to have a minimum mass of 8 solar masses. Many have argued that stars with such a mass cannot form planets. In the scenario that the planets could form, they would likely get engulfed as the star grew to a red supergiant and survive a supernova explosion which is one of the most violent events in the universe. The pulsar planet, PSR J1719-1438 b, is thought to have formed in a different way. Specifically, PSR J17191438 b was a yellow dwarf star in a binary system alongside PSR J17191438, a high - mass star. Due to its larger mass, PSR J17191438 became a red supergiant, but the yellow dwarf star survived its supernova after the end of the life of PSR J1719-1438. Billions of years later, PSR J17191438 b became a red giant due to it being a medium-mass star and then a white dwarf. The gravity from the pulsar it was orbiting stole hydrogen and helium due to its immense gravity. The remaining carbon after the accretion crystallized, forming the diamond planet which we see today. In this scenario, the planet formed after the formation of the pulsar. This it did not have to survive the supernova that created

the pulsar. Finally, another plausible scenario is that, after the supernova, excess material coalesce into a disk similar to the initial protoplanetary disk and might form planets. In this case, the disk would receive intense radiation from the pulsar. Thus, if the surface density of the disk is great enough, it would be able to withstand the radiation and form dead zones that could form planets which eventually go on to orbit the pulsar. It is thought that the three planets in the PSR 1257+12 system were formed in this way. [8]

4 Planets Orbiting a Binary Stellar System

A circumbinary planet is a planet that orbits around two stars instead of one.

The first circumbinary planet that was ever discovered was in 2000. This planet was found in the M4 globular cluster orbiting the PSR B1620-26 system which contained a pulsar and a white dwarf. After this initial discovery, other planets have been discovered orbiting other binary systems.

Binary systems in themselves are quite important to astronomy because they can be analyzed to calculate the masses of the stars. The discovery of planets orbiting binary star systems is also important as it gives us an insight into the habitability of these planets in unique orbits as well as more insight into the formation and interactions of planetary bodies in our universe. Astronomers and astrophysicists have determined that the distance of these planets from the stars must be greater than the star-to-star distance for them to be in stable orbits. This is because the gravitational influence of the individual stars almost add when a star is orbiting both of them, causing a multiplied effect on the planet. Due to this gravitational

influence, there will be variations in the orbit of the planet which causes a continuous exposure to radiation from the stars and thus changing temperatures on the planet. This is important as such temperatures can be analyzed for being suitable enough for sustaining water. If temperatures allow for liquid water to form, planets orbiting these binary systems could harbour life.

5 Conclusion

With the dawn of a new revolution of technological advancements, astronomers are able to analyze and detect collapsed stellar remnant much more precisely than ever before. Looking at white dwarfs, neutron stars and black holes will allow us to get a better understanding of the origin of the universe and the evolution from the early universe until now. Analyzing various systems that exist due to collapsed stellar remnants can even answer different questions such as habitability of extrasolar planets when looking at the orbit of planets around binary star systems for example. IT is definitely an extremely exciting field of study and there is much to be discovered.

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