Stellar Remnants: Black Holes, Neutron Stars and White Dwarfs

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Abstract

The universe is a vast expanse filled with fascinating celestial objects, among which collapsed star remnants such as black holes, neutron stars, and white dwarfs hold a special place due to their unique properties and the final stages of a star's life cycle they represent.

This paper delves into the interesting world of these remnants, covering the current scientific research and the astrophysical phenomena that have led to their identification and study.

The central question of this paper addresses the nature and evidence of these star remains.

Previous research has provided substantial insights into these celestial bodies, but there are still aspects that remain uncharted. This paper aims to analyze existing theories critically and gain thereby new insights in the field.

A significant part of this paper is dedicated to planets orbiting neutron stars. It scrutinizes whether these planets are survivors of supernovae or if they formed later, as it could potentially revolutionize our understanding of planetary evolution.

Another significant part of this paper is dedicated to the information paradox and string theory in context with black holes.

This study's findings will help broaden our astrophysical understanding of stellar evolution and the function of black holes, neutron stars, and white dwarfs.

Definition

There are three main kinds of Stellar Remnants: white dwarfs, neutron stars, and black holes. They represent a final, end stage of evolution for stars. If a star becomes a black hole, neutron star, or white dwarf is only determined by one factor, the mass of the star.

In the universe, there are a lot of opposing forces balancing each other out in an equilibrium, but at some point, this equilibrium can no longer be sustained. In the case of stars, the two opposing forces are:

- gravity and
- energy of fusion.

Gravity tries to collapse the star inward, creating high pressure and temperatures. This makes it possible for hydrogen atoms to fuse, creating helium. The outward pressure is due to the energy of fusion. This release of energy pushes against gravity outwards. As long as the star has enough fuel, it can stay in this equilibrium for billions of years. When all hydrogen resources are depleted, helium fuses, creating heavier elements. The star will continue to fuse heavier elements until there is either not enough gravity pushing on the core or fusion reaches the heaviest possible element that can be formed by fusion, iron. This depends on the mass of the star. When fusion stops, gravity overwhelms the outward pressure and causes a cataclysmic collapse resulting in a

colossal explosion called a supernova. At this point, the star can become one of three types of stellar remnants:

- a neutron star,
- a black hole or
- a white dwarf.

Formation of neutron stars

A neutron star forms when a star of considerable mass, but not quite massive enough to become a black hole, exhausts its nuclear fuel. (Fig. 1) As long as the mass of the initial star is less than 40 times the mass of the sun but more than 8 times the mass of the star, a neutron star can form.

When all the fuel is exhausted, the nuclear fusion in the core of the star can not counteract the gravity and the star collapses. This process makes the core burn hotter and faster. The outer parts expand again, fusing heavier elements. Iron is the last element on the Mendeleev table that can be fused. Fusion with elements lighter than

Iron are exothermic while fusion with elements heavier than iron are endothermic, meaning that they require energy to fuse.

As soon as the iron core stops fusing, it can no longer support itself and gravity crushes the core.

Due to their opposite charges, protons and electrons repel each other, but when the immense pressure of the collapsing star forces them together, canceling their charges out, they form neutrons. (Ash, 2022)

Formation of white dwarfs

White dwarfs form smaller stars ranging in size from >0.08 m_{Sun} to < 8 m_{Sun}. (Fig. 1) During the supernova, the core contracts. For a time, electron degeneracy pressure keeps the core from collapsing further. The degeneracy pressure has to do with the Pauli exclusion principle. It states that two or more identical fermions cannot occupy the same quantum state at the same time. This means that the matter cannot be squished

anymore because otherwise the orbits of the electrons of the atoms would intersect and violate the Pauli Exclusion Principle.

The same quantum state also includes the volume. Electrons can have two different types of spins making them non-identical. This makes it possible for multiple electrons to be in the same orbit. (Ash, 2022)

Generally, atoms have enough space to move around in, but in a collapsing star, the gravity presses the atoms together and limits them to their maximally contracted state. As a result, the outermost shell of the atoms next to the atoms of the outermost shell of the neighboring atom create a physical barrier keeping the atoms from compressing further. The physical barrier is not due to the electrostatic repulsion of the elements in the outer shell of the neighboring atoms based on the argument that like charges repel. There are simply no more free quantum states for the electrons to occupy. There is no more physical space for greater compression.

This is the electron degeneracy pressure. The pressure will pick up, from where the radiation pressure fell off, and take up the fight with gravity to try to prevent further collapse of the star. Once the star is in the degenerate state, the gravity cannot compress it anymore. Quantum mechanics dictates that there is no more space to be taken up. So, the core of the star survives not by the outward pressure of fusion but by the quantum mechanical principal that prevents its complete collapse. This core of the star, where the electron degeneracy pressure keeps it from collapsing further, is called a white dwarf. This is what our Sun will become once it exhausts all its fuel. (Luminet, 1998)

Planets Orbiting Neutron Stars

Planets outside our solar system have been found orbiting neutron stars. This poses the question of whether these planets formed before or after the supernova that created the black hole.

It is possible that the planets formed around the progenitor before it exploded in a supernova. This would, however, most likely render the planet uninhabitable and hostile

to life, as the intense amount of radiation and energy released would strip away the atmosphere and could potentially alter the planet's orbit or even eject the planet out of the system. If such planets existed, they would most likely be rocky, having lost their gaseous atmosphere.

The other possibility is that the planet formed after the supernova explosion. This happens because the vast amount of material blown into space by the explosion accumulates in a protoplanetary disk forming bigger and bigger bodies, eventually leading to planets being formed. This process has similar characteristics to planets forming around very young stars but in a much more extreme environment.

The characteristics of planets orbiting neutron stars are different compared to other stars as well. The intense gravitational field would cause very strong tidal forces, and planets could possibly be in tidal locking with the star, making the tides even stronger. The average orbital period would be very short as well. This is due to the compact nature of neutron stars. The orbital period could be as short as a few days.

Formation Of Black Holes

A black hole forms when a massive star (<$40m_{Sun}$) explodes. (Fig. 1) Unlike what happens when a neutron star forms, the core becomes a single, infinitesimally small point in space. Resisting forces like neutron degeneracy pressure can not counteract the gravitational push. This point in space, called the singularity, exerts an immense gravitational pull, as it has infinite density. The singularity is enveloped by a boundary from which nothing can escape, known as the event horizon. The exact nature of the singularity and the event horizon remains an open question in modern physics.

The classical theory of general relativity predicts a point of infinite density, but it is widely believed that a more complete theory of quantum gravity will provide a more physically meaningful description.

Fuzzball Black Hole Hypothesis

Black holes have properties that we can not explain with our current physics. String theory tries to explain these properties. General relativity tells us that when matter is compressed sufficiently, it collapses under its own gravity. At this point, the matter collapses into a single, dimensionless point with infinite density. This is called the singularity. At the singularity, the laws of general relativity and quantum mechanics collide.

General relativity describes the universe at the large scale, while quantum mechanics describes it at the small scale.

These two theories collide at the singularity because general relativity describes gravity as the curvature of spacetime caused by mass and energy. According to quantum mechanics on the other hand, gravity is caused by particles called bosons.

When the mass of the black hole gets concentrated on a single point, density becomes infinite, and space time gets curved infinitely as well.

Another aspect in which general relativity and quantum mechanics collide arises at the event horizon. General relativity states that information of objects entering a black hole is erased and lost except for mass, angular momentum, and charge of the black hole. This is called the no-hair-theorem.

Quantum mechanics, on the other hand, states that information can neither be created, nor be destroyed.

String theory tries to solve this information paradox. This is called the Fuzzball Black Hole Theory.

According to the Fuzzball Black Hole Theory, it is possible to count all possible microstate configurations of the strings at the event horizon. There are also other, more complex structures like Dirchilet Membranes. Research showed that the amount of microstates they can form is the same as predicted by the Beckenstein formula for black hole entropy. (Andrew Strominger, 1996) The formula states that the entropy of a black hole is proportional to the area of the event horizon. This implies that the information content of a black hole is not related to its volume but rather its surface area. It leads to the concept of holography in theoretical physics which asserts that information is not

stored within a volume but encoded within a two-dimensional area. As a result, the storage of information on the area of the event horizon is possible. (Matt O'Dowd, 2021)

String theory tries to solve the information paradox. The profile of the radiation emitted by the strings match the profile of traditional hawking radiation. This enables the black holes to emit the information in form of radiation. This is one approach to solving the information paradox.

Interestingly the Fuzzball Black Hole Hypothesis also predicts that the strings on the outside of the black hole create a boundary. Inside the black hole, spacetime itself does not exist anymore.

When the black hole forms, all the matter is pushed to the event horizon. The extra dimensions string theory predicts contract at the event horizon, and all spacial dimensions end in this direction. This also eliminates the problem of the gravitational singularity, as there cannot be anything, including a singularity.

It is important to say that string theory, although mathematically promising, is not experimentally proven yet. It is not fully understood, and mathematical models do not

necessarily match our real world. Currently Fuzzy Black Holes require four spacial dimensions to be mathematically viable. Nevertheless, string theory is currently our best approach to combine general relativity and quantum gravity. (Matt O'Dowd, 2021) (Andrew Strominger, 1996)

Conclusion

The unique properties and formation of stellar remnants – black holes, neutron stars and white dwarfs – hinge on the original star's mass and the equilibrium between gravity and nuclear fusion. The existence of planets around neutron stars – either formed before or after a supernova - poses compelling questions about the evolution of planets. The Fuzzball Black Hole Hypothesis, although unverified, offers a different solution to the information paradox.

Works Cited

Andrew Strominger, C. V. (1996, 02 15). *Microscopic Origin of the Bekenstein-Hawking Entropy*. Retrieved from Arxiv: https://arxiv.org/pdf/hep-th/9601029.pdf

Ash, A. (2022, 12 10). *Why Do Some Stars Explode in a SUPERNOVA, But Others Don't?* Retrieved from YouTube: https://www.youtube.com/watch?v=7xCgnMqIgPI&t=1s

Luminet, J.-P. (1998, 02). *Black holes : A General Introduction*. Retrieved from researchgate: https://www.researchgate.net/publication/1818209_Black_Holes_A_General_Introduction

Matt O'Dowd. (2021, 11 17). *Are Black Holes Actually Fuzzballs?* Retrieved from YouTube: https://www.youtube.com/watch?v=351JCOvKcYw&t=391s

Ryosuke Hirai, Philipp Podsiadlowski. (2020, 10 20). *Neutron stars colliding with binary companions: formation of hypervelocity stars, pulsar planets, bumpy superluminous supernovae and Thorne–Żytkow objects*. Retrieved from Oxford Academic: https://academic.oup.com/mnras/article/517/3/4544/6764732

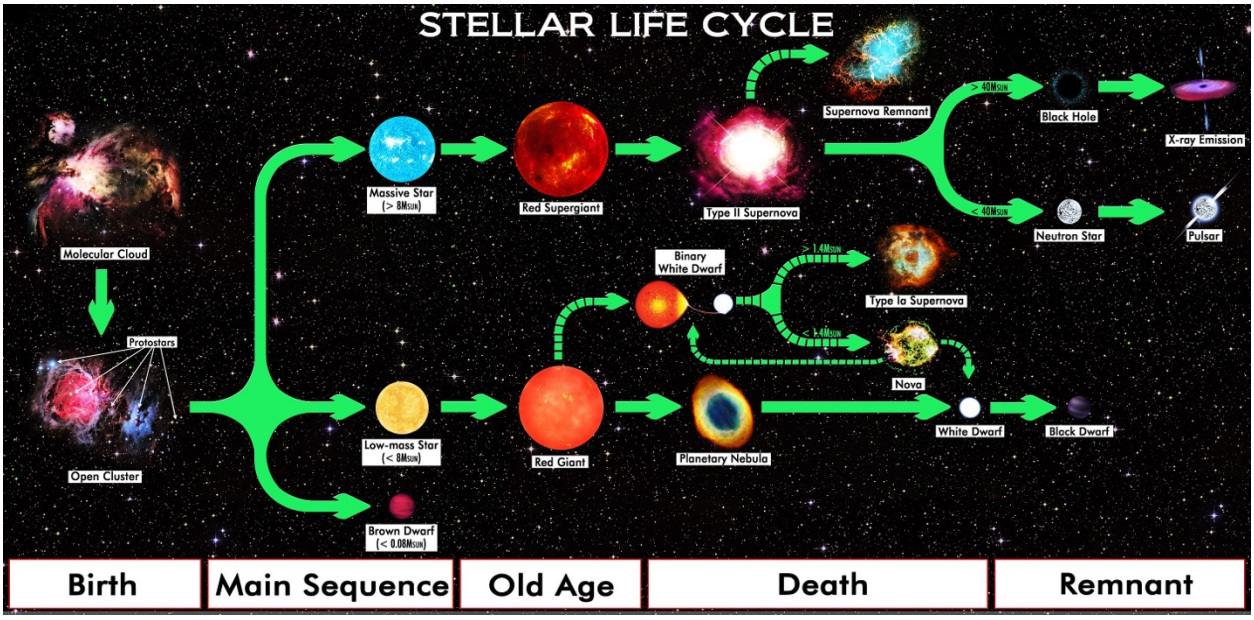

Fig. 1

https://en.wikipedia.org/wiki/Stellar_evolution