

Are There New Types of Compact Stars?

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Yihong Zhou is a student at the International Department of Affiliated High School of South China Normal University. Spending his childhood in a small village with no light pollution, he is particularly fond of astronomy, astrophysics, cosmology, and metaphysics. While being China's highest scorer in the 2023 International Astronomy & Astrophysics Competition, he won a global silver in the British Astronomy and Astrophysics Olympiad. He also does volunteer work translating astronomy articles into Chinese, exposing more people to a greater world. This research was motivated by his curiosity about matter's behavior under extreme situations and his ceaseless pursuit of the objective truth. My research was largely inspired by Prof. Glendenning's masterpiece *Compact Stars-Nuclear Physics, Particle Physics, and General Relativity*, and I hereby express my utmost gratitude to him.

ABSTRACT

This research examines two hypotheses about the inner structure of neutron stars: the hybrid star theory, which presents neutron stars with different layers, and the strange star theory, which presents neutron stars as an almost homogeneous sphere. Each reveals the possible existence of a new type of compact star. Moreover, possible future discovery of sub millisecond pulsars is vital to justify the strange star hypothesis.

Keywords: Neutron stars, Hybrid star theory, Strange star theory, Compact star.

INTRODUCTION

Compact stars are the densest objects in our universe, possessing an interior structure with extreme similarity to a newborn universe. Human beings cannot create a piece of the early universe on Earth due to technological limitations. Still, space is a perfect laboratory—compact bodies are right there, thousands of light-years away, awaiting our analysis. By researching these exotic objects, humans may better understand the universe's fate and that of themselves, rendering mankind closer to objective reality.

Compact Stars

Before delving into the most intriguing part, some basic concepts should be examined in the first place. Compact stars are ashes of stars—when stars reach the end stage of stellar evolution and stop nuclear fusion, compact stars form. As their name implies, compact stars are extremely tight objects whose density can exceed hundreds of trillions of that of the Earth.

Generally, compact stars are classified into three categories: white dwarfs, neutron stars, and black holes. If the progenitor star has a mass less than the Chandrasekhar limit, around 1.38 solar masses, it will become a white dwarf at the end of its life. (Mazzali et al., 2007) For instance, our Sun will eventually become a white dwarf around 6 billion years later. (Frazier, 2019) An Earth-sized white dwarf will be about two hundred thousand times denser than the Earth, implying extreme gravity on its surface. Such monstrous gravity is counteracted by electron degeneracy pressure, explained by Pauli Exclusion Principle, which renders it stable. (*White Dwarfs*, 2010)

Once gravity overcomes electron degeneracy pressure, another type of compact star forms—a neutron star. The actual

mechanism requires a deep understanding of particle physics; for simplicity, electrons are forced to merge with protons, and neutrons are created. Due to the abundance of neutrons, neutron degeneracy pressure will take place to cope with gravity because neutrons, like electrons, are fermions and follows the same Pauli Exclusion Principle stated previously. (Glendenning, 2012) Inside the star, the gaps inside atoms are eliminated, so its radius is much smaller compared to a white dwarf—around 10km. Using Oppenheimer-Volkoff equations, the upper mass limit for such a neutron star was calculated to be about three solar masses, exceeding twice the Chandrasekhar limit. (Glendenning, 2012) Considering its relatively minute volume and enormous mass, the density and surface gravity of a neutron star will be significantly higher than those of a white dwarf.

Once neutron degeneracy pressure is overpowered by gravity, in a more traditional view, a black hole is formed. (Tillman, 2018) It is a debatable topic, and several more aspects of this question will be examined later in this research; in what follows, black holes are briefly discussed. When a star's surface gravity becomes so enormous that even electromagnetic waves cannot escape, it becomes a black hole. For a non-rotating star, once its radius falls inside Schwarzschild radius (solved by Schwarzschild using Einstein's general relativity equations), it becomes a black hole. (Glendenning, 2012) It is "black" not only because no electromagnetic waves can leave its surface but because people obtain no information from the insides of the event horizon as well. Although black holes are exotic and worth studying, they are not the focus of this research.

Great Mysteries of Neutron Stars

It is a common misunderstanding that

neutron stars are bound by nuclear force—the same force that holds nucleons together—since they predominantly contain neutrons. The fact is, nucleons inside a neutron star do not attract each other but repulse (neutron degeneracy pressure). (Glendenning, 2012) Therefore, neutron stars are gravitationally bound and behave differently than gigantic nuclei.

Another common misunderstanding is that neutron stars are made entirely of neutrons. But a gigantic pure neutron sphere is untenable—the pressure varies dramatically across the interior of a neutron star, implying different phases inside.

Due to neutron stars' extreme gravity mentioned in the previous section, the composition of the core and the pressure inside go beyond human understanding of particle physics. Therefore, different hypotheses are proposed regarding the structure of neutron stars, especially their cores. For the rest of this research, two premises will be presented—the hybrid star hypothesis and the strange star hypothesis. Methods to recognize strange stars will be examined later. However, for hybrid stars, distinguishing them from pure neutron stars has been almost impossible hitherto.

Quark Stars

Before the hypotheses are introduced, a fundamental understanding of particle physics is needed.

Nucleons are comprised of even smaller particles called quarks. There are six types, or flavors, of them—down quark (d), up quark (u), strange quark (s), charm quark (c), bottom quark (b), and top quark (t). A proton comprises two up quarks and one down quark; a neutron comprises two down quarks and one up quark. Gluons, a type of boson, deliver the strong force binding two quarks together. (Augustyn, 2019)

Quark stars are compact stars that contain quark matter. In this hypothesis, the neutron

star's core is said to be composed of deconfined quarks that are asymptotically free. (Glendenning, 2012) The term “asymptotically free” is a fundamental concept of quantum chromodynamics (QCD)—within a distance of 10^{-15}m , quarks behave as though they were nearly free, and this condition is called asymptotically free. As the distance increases, the force between quarks will increase as more gluons are produced. (Augustyn, 2019) In this sense, if the core of a neutron star can provide enough pressure to diminish the distance between particles, the quarks will no longer be confined.

Two hypotheses, namely the hybrid star hypothesis, and the strange star hypothesis, will be addressed in this research. These hypotheses rely on the MIT bag model, a simplified representation of quark matter, where the “asymptotically free” theory holds significance. (Glendenning, 2012)

Hybrid Star

Recent studies suggest that applying simplifications, such as the constant-pressure phase transition, to the stellar model may result in the inner regions of more massive neutron stars being occupied by quark matter. (Glendenning, 2012)

It is unlikely that quark matter will solely exist in the core—there might be mixed phases where quark matter and confined hadronic matter are in equilibrium with one another. When a neutron star has a composition of pure quark matter or mixed phases in its interior, it is classified as a hybrid star.

Two graphs from the book *Compact Stars-Nuclear Physics, Particle Physics, and General Relativity*, authored by venerable particle astrophysicist Norman K. Glendenning, are used for a more intuitive interpretation of hybrid stars.

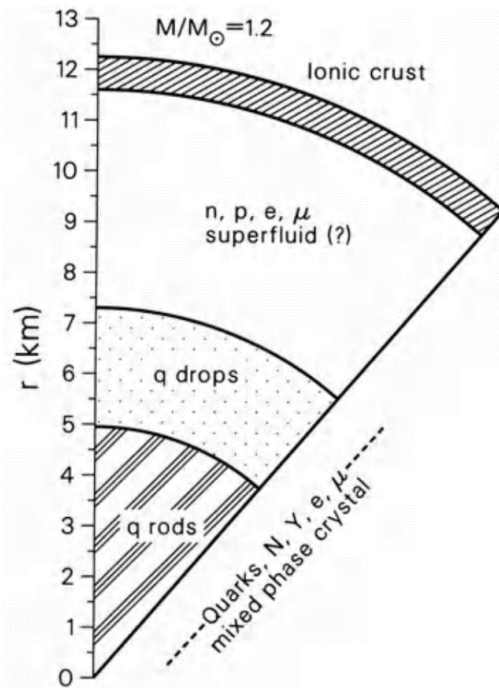


FIGURE 1 Structure of a hybrid star with 1.2 solar masses, where n, p, e, μ , and q represent neutron, proton, electron, muon, and quark, respectively.

(Credits: Glendenning, 2012, p. 304)

This graph appears that quark matter occurs inside a hybrid star with 1.2 solar masses at a radius of about 7.3km. At first, they take the form of tiny drops. As the pressure increases (i.e. the radius decreases), the drops connect and form quark rods. This phase of quark rods and the confined hadronic matter will persist through the core of this star.

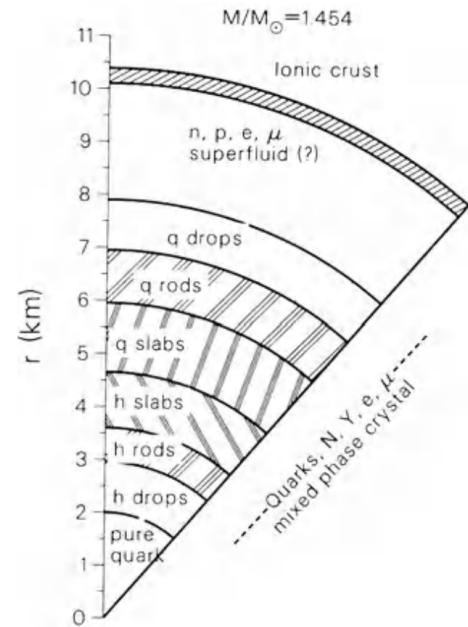


FIGURE 2 Structure of a hybrid star with 1.454 solar masses, where n, p, e, μ , q, and h represent neutron, proton, electron, muon, quark, and hadronic matter, respectively.

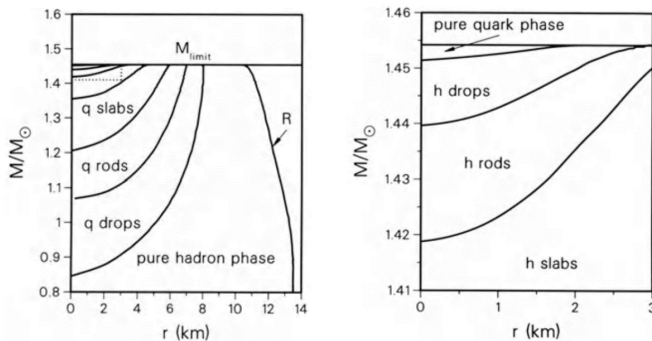
(Credits: Glendenning, 2012, p. 4)

If the hybrid star possesses a greater mass (1.454 solar masses in this graph), more phases are predicted using the same simplified stellar model (MIT bag model). As the pressure increases, quark rods will combine and form quark slabs. As quark slabs grow thicker, the hadronic matter will lose its dominance gradually, and that is why the h-slabs phase is right inside the q-slabs phase—quark slabs are now thicker than hadronic slabs. Inside the h-slabs phase, similar phase transitions described previously will repeat inversely for hadronic matter: h-slabs become h-rods and then h-drops; ultimately, the hadronic matter will completely deconfine, leading into a pure quark core.

It is worth noting that such a hybrid star's radius decreases as the mass increases. For detailed mass-radius relation and exact radius for phase transitions, Glendenning provides

another paired graph.

FIGURE 3 The left panel shows phase transition radii for hybrid stars heavier than 0.8 solar masses. The right panel shows the details for the dotted box of the left panel. (Credits:



Glendenning, 2012, p. 326)

It is evident that the radius of a hybrid star decreases gradually as the mass increases (starting from 0.8 solar masses). Based on the data presented in this graph, it appears that the maximum weight for a hybrid star slightly exceeds 1.45 solar masses, and its radius measures approximately 10.5 km.

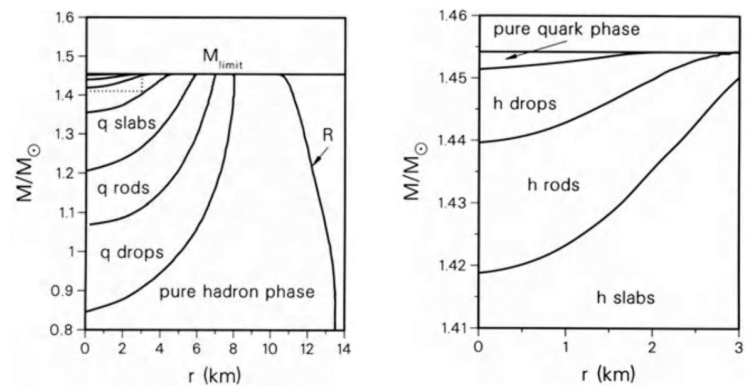
Strange Star

Strange star is strange—its structure is unique and almost perfect. Before the examination of its structure, some background should be introduced first.

It is conventionally assumed that the ground state of hadronic matter is the state in which quarks are confined in individual hadrons. (Glendenning, 2012) This seems evident because most matter humans have observed is made of confined hadronic matter, even deep in space (i.e. when the universe is much younger). However, just as the concept of vacuum decay (Mack, 2015) challenges the existence of the true ground state of vacuum, Bodmer and Witten both independently proposed the strange matter hypothesis to question the actual ground state of

hadronic matter. (Glendenning, 2012)

Quarks are fermions, which means they follow the Pauli exclusion principle: “The probability to find two identical particles of half-integral spin (fermions) in the same quantum state must always vanish.” (Krane &



Halliday, 1988) According to the principle, every quantum state in a system can be occupied by only one quark with a specific combination of quantum numbers, including flavor. In this sense, quarks of different flavors can be treated as a different combination of quantum numbers. This allows them to occupy a lower energy state together, rendering the matter more stable (i.e. with lower energy) overall. In this strange matter hypothesis, the absolute ground state of matter is called strange quark matter, which is in a deconfined state where an equal number of up quarks (u), down quarks (d), and strange quarks (s) co-exist. With the introduction of this extra quark flavor, a greater number of quarks can now exist at a lower energy level. This idea is essential for this study because under intense pressure, like in a core-collapse supernova, 2-flavored ordinary matter (e.g. protons and neutrons) can restore 3-flavor symmetry (up, down, and strange) to occupy lower energy states. (Lai et al., 2023) Glendenning’s book shows the exact energy comparison: “Three-flavor quark matter has an energy per baryon of approximately 0.9 times that of 2-flavor, or about 100 MeV lower.” (Credits: Glendenning, 2012, p. 339)

It was hypothesized that once the core of a neutron star deconfines, a third of down quarks will spontaneously convert into strange quarks since strange quark matter is more energetically favorable. The conversion of the remaining part of the star will happen relatively quickly. (Glendenning, 2012) That is why the strange star is so strange—it is made almost entirely of strange quark matter.

strange stars have an uncommonly abrupt edge (indicating an incredibly smooth surface) for its unique structure. (Glendenning, 2012) Relatively, neutron stars have a more natural transition toward the surface. Additionally, the graph also exhibits that the average density for strange stars increases rapidly as their mass increases. In fact, a strange star follows a mass-radius relationship similar to a hybrid star. Then why has no strange quark matter been observed? Didn't the extreme pressure near the universe's beginning create strange quark matter? Both of these questions are worth considering. Some assert that the strange quark matter is almost impossible to observe and can even be the candidate for dark matter. However, a more reliable explanation rebuts by suggesting strange matter would have evaporated in the early universe into ordinary hadronic matter. The conversion from normal matter to strange matter can occur over a long period of time (much longer than the universe's age). (Glendenning, 2012)

Charm Stars? Bottom Stars? Top Stars?

As stated in the section Quark Star, there are six flavors of quarks. Since strange matter is said to be more energetically favorable than ordinary matter, could the "charm matter," "bottom matter," or "top matter" be even more stable than strange matter?

This idea seems natural since more flavors allow more particles to stay at a lower energy state (see section Strange Star), rendering the

matter more stable. However, charm quark is absent in strange stars due to their requirement for a much higher density than the core of a strange star can provide. (Glendenning, 2012) Therefore, there will be no charm, bottom, or top stars.

Recognizing Strange Stars

Neutron stars are gravitationally bound stars, but strange stars are not. This difference is vital in the method I will introduce—a self-bound star can spin faster than a gravitationally bound star.

Before getting into the method, one basic concept should be explained: Kepler frequency is the maximum rotational frequency at which a star can rotate. (De-Hua et al., 2007) If a neutron star spins faster than its Kepler frequency, it cannot be a neutron star, but it could be a self-bound star such as a strange star. A gravitationally bound star's Kepler period ($P_k = \frac{2\pi}{f_k}$) is calculated to be:

$$P_k \approx 10.1 \left(\frac{R^3}{M} \right)^{\frac{1}{2}} = 0.0276 \left(\frac{\left(\frac{R}{\text{km}} \right)^3}{\left(\frac{M}{M_\odot} \right)} \right)^{\frac{1}{2}} \text{ ms}$$

(Credits: Glendenning, 2012, p. 280)

when the mass is low, gravitationally bound stars possess much larger radii than self-bound stars. Additionally, self-bound stars have a higher upper limit for spinning frequency.

However, the limit calculated by this method is conservative, because the structure of stars is usually not optimized to minimize their rotational period. Glendenning used another more complicated approach, which will not be addressed in this research, to give a less stringent constraint. The conclusion is that a pulsar that rotates at a frequency faster than 1 ms is probably not bound by gravity (i.e. not a neutron star) (2012).

Aside from detecting sub millisecond

pulsars, there were other approaches for distinguishing strange stars. For instance, some suggested that a strange star will cool faster than an ordinary neutron star since the conversion from a down quark to a strange quark will absorb some heat. (Zapata et al., 2022) However, they are not the focus of this study.

Conclusion:

In this research, the structure of hybrid stars and strange stars are examined. A possible approach to recognizing strange stars is discussed as well. Though all information is from reputable sources, it strongly relies on simplified models for stellar structure (e.g. MIT bag model) and certain fields without definite conclusions (e.g. quantum chromodynamics); therefore, the hypothetical nature of this research should not be ignored. Human beings still have a long way to go on the road to reality; more studies should be done to unveil the truth.

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