Quark Star Structure, Formation, and Observational Implications

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1 Background

Quark stars are hypothetical compact objects that share many similarities with neutron stars. However, rather than being made up of dense nuclear matter, they are made of even denser quark matter. Thus, to understand quark stars, I will include a brief introduction to quark matter (without going too deep into particle physics and QCD).

The two main types of quark matter expected to exist within quark stars are ordinary and strange quark matter. Ordinary quark matter contains only up and down quarks, while strange quark matter contains up, down, and strange quarks. Since research in the area of quark matter is ongoing, the exact equation of state of quark matter is uncertain. In addition, the exact transition point between neutron-degenerate matter and quark matter is unknown, making it difficult to form a complete picture of how a quark star may form. What we do know is that at high densities and "cool" temperatures (1012 K), quark matter behaves as a Fermi liquid, and is in the color-flavor-locked (CFL) phase of color superconductivity. Note: color superconductivity is somewhat analogous to the superconductivity seen in electromagnetism. At slightly lower densities which may be found in the higher layers of stars, quark matter may be in a non-CFL phase, a state that is not yet well understood. [1, 2]

One hypothesis developed by Bodmer [3] and Witten [4] (known as the "strange matter hypothesis") suggests that strange quark matter may actually be more stable than ordinary nuclear matter, i.e. the actual ground state of matter is quark matter. If true, then given sufficient time, nuclear matter would eventually decay into quark matter. The droplets of such quark matter would contain roughly equal amounts of up, down, and strange quarks, and can be referred to as strangelets. The source of this stability would be due to the Pauli exclusion principle; since there are more flavors and colors of quarks than there are charges for nuclear matter, there are more low energy slots available, so the overall energy could be lower.

A counterargument to the strange matter hypothesis is that if strange matter was actually the ground state of baryons and stable at zero pressure, then strangelets would rapidly contaminate the interstellar medium. Collisions of strangelets with neutron stars would result in all neutron stars becoming quark stars. Since observations do not support the idea that all observed neutron stars could be quark stars, the hypothesis cannot be true.[5] This counterargument is contested however, with others saying there would not be enough strangelets to turn all neutron stars to quark stars.

If the hypothesis *is* true, strange quark matter would be stable at zero pressure, which has many implications for the structure and stability of quark stars. In fact, finding a compact object with a strange matter surface would effectively prove the strange matter hypothesis. Such a discovery would have major implications for other areas of astrophysics and particle physics. Quark matter cannot be studied in labs because, currently, we have no way to produce a large enough quantity of quark matter to form a stable strangelet; only single particles containing a small number of quarks can be created using particle colliders, and they decay rapidly. Because of these limitations, finding a quark star may be our best shot at studying this exotic state of matter.

2 Quark Star Formation

As mentioned in the Background, quark stars share many similarities with neutron stars. A neutron star forms when a massive star's gravity becomes strong enough to overcome the degeneracy pressure of neutrons. Likewise, a quark star may form if the gravity becomes strong enough to also overcome the degeneracy pressure of quarks (without going too far and collapsing to a black hole). A popular model of the phase transition of neutrons to quarks is called the MIT bag model by Chodos et al. By confining quarks to a finite region (the "bag") that is kept finite by a confining pressure, multiple groups have studied when the phase transition occurs. However, for all neutron equations of state they have tried, the density becomes too high for the neutron star to be stable before the phase transition occurs. But, since our understanding of strong interactions is not very strong, and the bag model is phenomenological, the formation and even existence of stable quark stars is still up for debate. [6]

Because of this lack of definitive understanding of the strong force and quark matter, it may be possible for massive neutron stars to satisfy conditions for the phase transition in their cores. Such a quark matter core could then spread outward to transform the entire interior of the star to quark matter. Another way quark matter could get started within a star is through an extremely energetic supernova, also known as a hypernova or quark nova.

Another path to quark stars was mentioned in the background when discussing the strange matter hypothesis and its counterargument. If the strange matter hypothesis is correct, then strangelets would behave as a kind of quark star seed. A collision of a strangelet with a neutron star would quickly result in the neutron star transforming into a quark star. [5]

A final possibility is primordial quark stars. Assuming the strange matter hypothesis is correct, then in the early universe droplets of ordinary quark matter could have become strange matter before the pressure and temperature of the universe destabilized it. These droplets of strange matter would then clump together, forming quark stars. It is likely such promordial quark stars could still be observed today. [4]

3 Quark Star Structure

While quark stars and neutron stars share many similarities, there are some key differences in their structure. But before discussing these differences, we must differentiate between the two main structural possibilities for quark stars. These two structures are bare quark stars and "dressed" quark stars, where bare quark stars are those made entirely of strange matter, including their surface, and "dressed" quark stars have a crust made of nuclear matter. Dressed quark stars share many more properties with neutron stars due to this crust, which may increase difficulties in distinguishing dressed quark stars from neutron stars in observation.

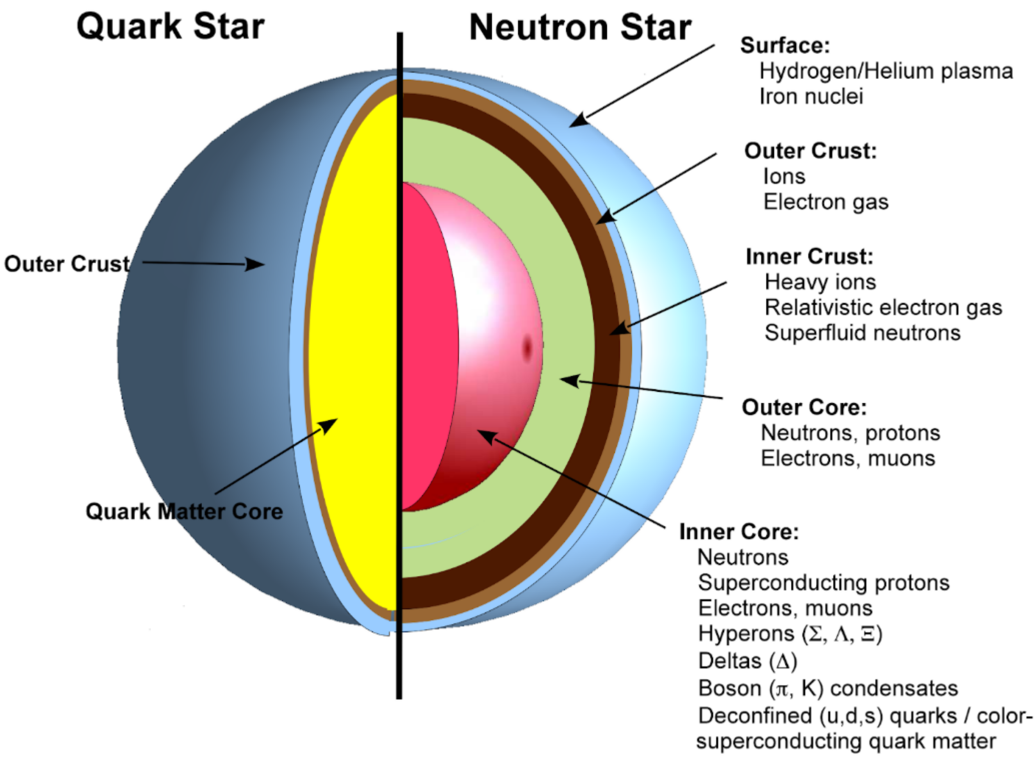

Figure 1: (Weber, 2012) Comparison of the interiors of a dressed quark star and a neutron star

Neutron star crust density is greater than neutron drip, so neutron stars have both an inner and outer crust. In contrast, in the case of a dressed quark star, the density of its crust is less than neutron drip, thus it only has an outer crust.

The mass range of neutron stars is between 0.1-2$M_{\odot}$. Quark stars on the other hand may have no minimum mass if the strange matter hypothesis is true and strange matter is stable at zero pressure. They also have a larger maximum max at around 2.5$M_{\odot}$. Additionally, neutron stars tend to have radii $\geq$ 10-12 km, while quark stars are expected to have radii $\leq$ 10-12 km, due to their increased density.

The mass-radius relation of quark stars with a crust is very similar to that of a neutron star. However, in a bare quark star, the mass-radius relation is not dictated by gravitational forces, but rather by the strong force. Thus, $M \propto R^3$ for bare quark stars, i.e. the volume increases as mass increases. This is a somewhat unexpected result, since neutron star volume decreases as mass increases. [2, 7, 8]

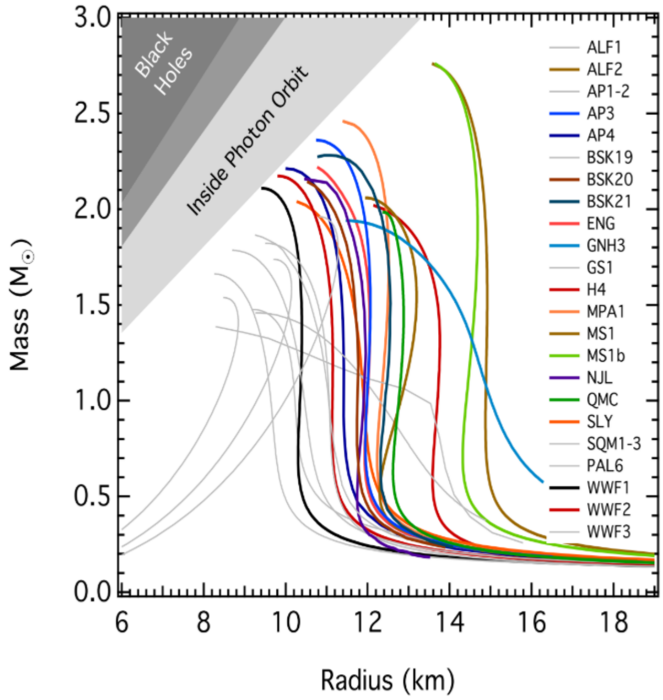

Figure 2: (Ozel, 2016) The three light gray curves to the left of the plot represent bare quark star models, while the other curves represent a variety of neutron star models. The unique M-R relationship of the quark stars is obvious in this plot.

4 Observation

I will end this report by discussing the many possible ways we could detect quark stars through observation. As mentioned in the background, the discovery of a quark star, whether bare or dressed, would have major implications for physics and astrophysics, and may be our only opportunity to study the properties of strange matter due to experimental limitations. Therefore, it is worthwhile to study objects that exhibit the following quark star signs.

- Due to their smaller radii, quark stars may be able to sustain higher rotation rates. For example, a strange star with a mass about 1.45 $M_\odot$ could rotate 0.55 PK/msec 0.8, compared with PK $\sim$ 1 msec for NS of same mass [9, 10, 11]
- Quark stars may be radio quiet. However this is not proof alone, since there are other reasons a neutron star could be radio quiet, including a pulsar that simply does not point toward us.
- A quark star would likely have an ultra high electric field on its surface, of around 10^{18-20} V/cm. Such high energy density can result in mass increases. Thus, compact stars with masses ≥ 2 $M_\odot$ could indicate quark star.
- Electrons on the surface can rotate with respect to the star. At rotation rates of around 10 Hz, they generate magnetic fields such as those observed in several central compact objects (CCOs)

- Vortex hydrodynamical oscillations can be caused by the star's magnetic field acting on the electrons on the surface, and can be seen in x-ray emissions

- The Eddington luminosity limit does not apply to bare quark stars; electrons and quarks at the surface are not held gravitationally, but rather electrostatically. Thus, photon luminosity from e+ e- pair production can be many orders of magnitude higher than the Eddington limit. [7]

- Finally, superluminous supernovae may signal the birth of a quark star. Modern searches that include dwarf populations find a significant number of supernovae with peak magnitudes < -21. The energy radiated can exceed 10^{51} erg, which rivals the total explosion energy available to a typical core collapse supernova. Such supernovae are not well explained by standard models; quark novae have been suggested as a possible explanation. Some examples of superluminous supernovae include SN 2006gy and ASASSN-15lh. [12]

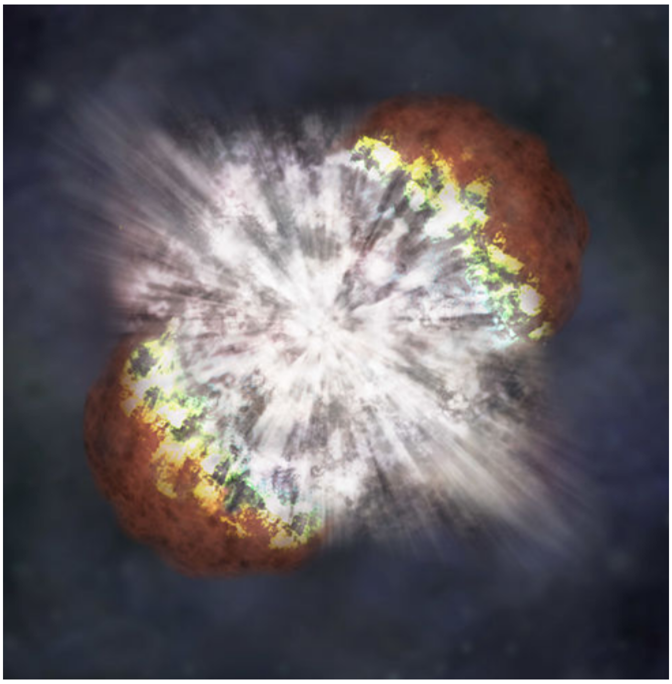

Figure 3: NASA artist's impression of the explosion of SN 2006gy

Figure 4: SN 2006gy, right, and core of galaxy NGC 1260, left. Viewed in x-ray light from the Chandra X-ray Observatory

A note on possible candidates: since I have only discussed the possible ways to observe quark stars but not the possible candidates we have already observed, I am including the following (which is copied directly from Wikipedia) that lists a number of possible quark star candidates that I have not yet had a chance to investigate further. I am sure there are more, but this list seems to be a good starting place.

"Quark stars and strange stars are entirely hypothetical as of 2018, but there are several candidates.

Observations released by the Chandra X-ray Observatory on April 10, 2002 detected two possible quark stars, designated RX J1856.5-3754 and 3C58, which had previously been thought to be neutron stars. Based on the known laws of physics, the former appeared much smaller and the latter much colder than it should be, suggesting that they are composed of material denser than neutron-degenerate matter. However, these observations are met with skepticism by researchers who say the results were not conclusive;[9] and since the late 2000s, the possibility that RX J1856 is a quark star has been excluded.

Another star, XTE J1739-285,[10] has been observed by a team led by Philip Kaaret of the University of Iowa and reported as a possible quark star candidate.

In 2006, Y. L. Yue et al., from Peking University, suggested that PSR B0943+10 may in fact be a low-mass quark star.[11]

It was reported in 2008 that observations of supernovae SN 2006gy, SN 2005gj and SN 2005ap also suggest the existence of quark stars.[12] It has been suggested that the collapsed core of supernova SN 1987A may be a quark star.[13][14]"

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