Quark Star Structure, Formation, and Observational Implications

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Quark matter

- Ordinary quark matter: up and down quarks
- Strange quark matter: up, down, and strange quarks
- Strange quark matter may be more stable than ordinary nuclear matter
- EOS of quark matter uncertain, as well as transition point between neutron-degenerate and quark matter
- At high densities and “cool” temperatures (10^{12} K): Fermi liquid, color-flavor-locked (CFL) phase of color superconductivity
- At slightly lower densities found in the higher layers of stars: non-CFL, a state that is not well understood

Strange matter hypothesis (Bodmer 1971, Witten 1984)

- States that strange quark matter may actually be the most stable ground state of matter
- A large collection of quarks with roughly equal amounts of up, down, and strange quarks is called a **Strangelet**
- Stability comes from Pauli exclusion principle
- If true, such matter would be stable at zero pressure

⟶ Finding a “neutron star” with a strange matter surface would prove the hypothesis, with major implications in other areas of astrophysics

Formation of quark stars

Analogous to NS formation:

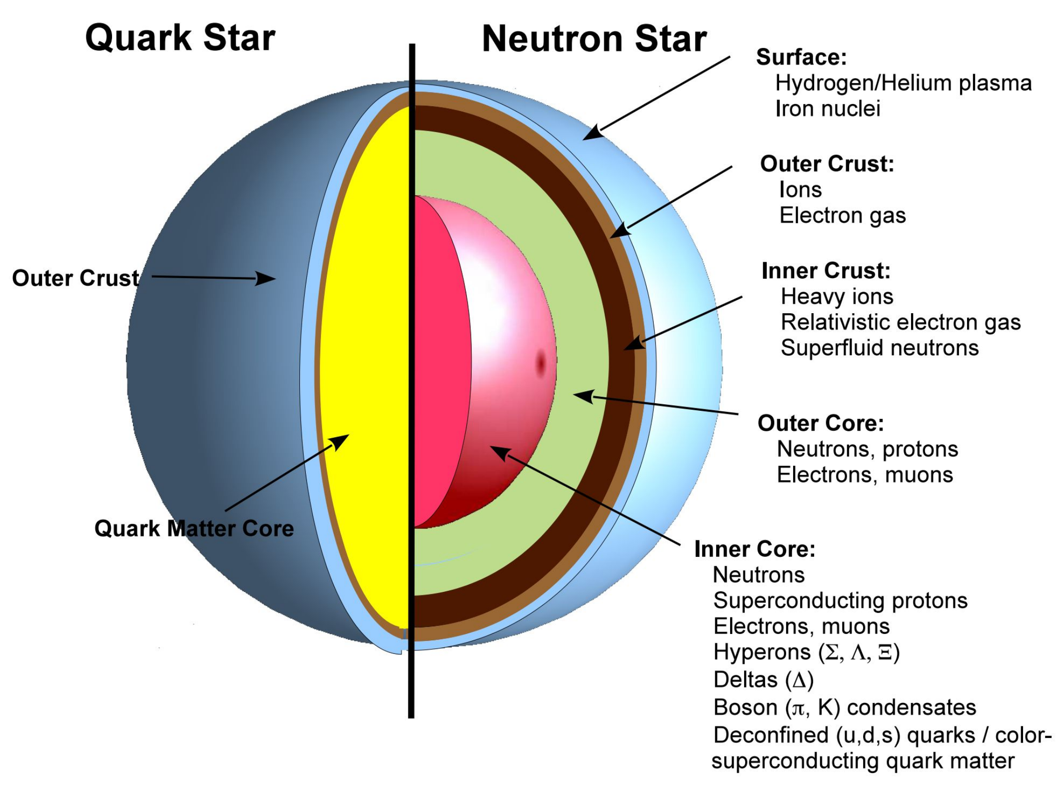
NS ⟶ gravity overcomes degeneracy pressure of neutrons

Quark stars ⟶ under more extreme conditions, it may be possible to overcome degeneracy pressure of quarks

- Quark matter is already theorized to exist in cores of massive NS
- Supernovae
- Primordial strange stars?

Quark Star Structure

Two possibilities: bare quark stars and "dressed" quark stars

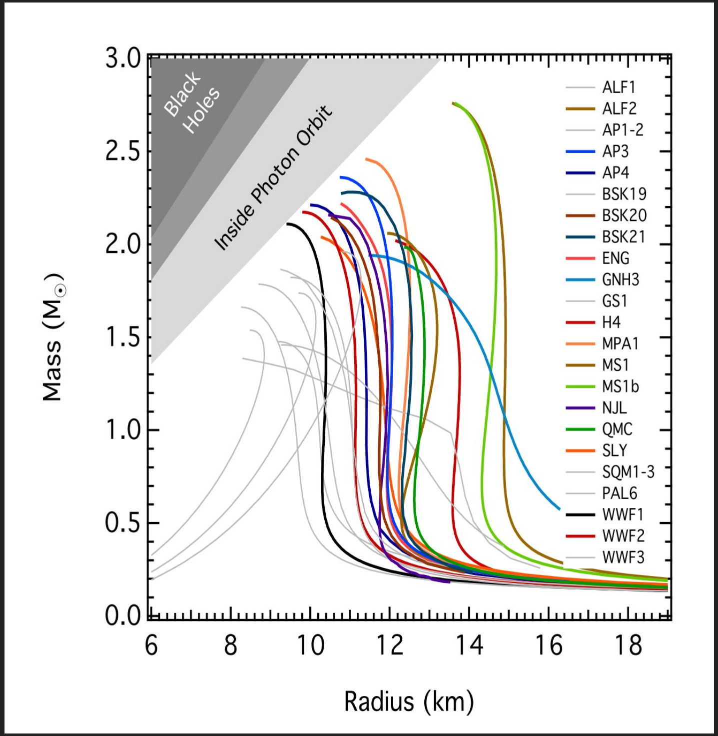


(Weber et al. 2012)

Quark Stars vs. Neutron Stars

Quark Stars	Neutron Stars
Bare are self bound ($M \propto R^3$)	Bound by gravity
Mass range: no minimum - ~2.5 $M_\odot$	Mass range: ~0.1 - 2 $M_\odot$
Radii $R \lesssim 10 - 12$ km	$R \gtrsim 10 - 12$ km
Can be bare, or have thin nuclear crust	Always has nuclear crust
Density of crust is less than neutron drip; only outer crusts	Density of crust above neutron drip; inner and outer crust

(Weber et al. 2012)



(Özel and Freire 2016)

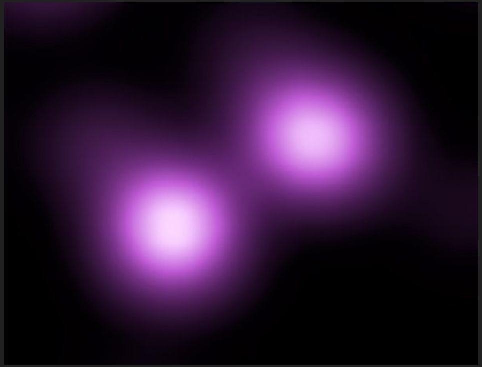
Can we observe quark stars?

- Due to smaller radii, quark stars may sustain higher rotation rates

  A strange star mass ~1.45 $M_\odot$ could rotate $0.55 \lesssim P_K/\text{msec} \lesssim 0.8$, compared with P_K ~ 1 msec for NS of same mass
- Quark stars may be radio quiet
- Likely have ultra high electric field on surface, 10^{18-20} V/cm. Such high energy density can increase stellar mass up to 30%. Thus, compact stars with masses $\gtrsim 2\ M_\odot$ could indicate quark star.

Can we observe quark stars? (cont.)

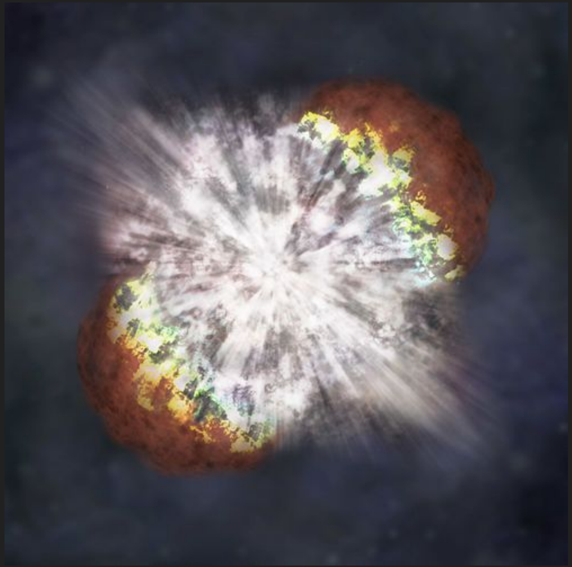
- Electrons on surface can rotate with respect to star (~10 Hz), generating magnetic fields such as those seen in several CCOs
- Vortex hydrodynamical oscillations caused by effects of magnetic field on electrons, can be seen in x-ray emissions
- Eddington luminosity limit does not apply to bare quark stars; electrons and quarks at surface are not held gravitationally, but rather electrostatically. Thus, photon luminosity from e+ e- pair production can be many orders of magnitude higher than Eddington limit



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

Superluminous supernovae

- Modern searches that include dwarf populations find a significant number of supernovae with peak magnitudes > −21
- Energy radiated can exceed 10^{51} erg, which rivals total explosion energy available to a typical core collapse supernova
- Such supernovae are not well explained by standard models; quark novae have been suggested
- SN 2006gy, ASASSN-15lh



NASA artist's impression of the explosion of SN 2006gy