Quark Star Structure, Formation, and Observational Implications

Carly Snell
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 $\rightarrow$ gravity overcomes degeneracy pressure of neutrons

- Quark stars $\rightarrow$ 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

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

(Weber et al. 2012)
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 \(0.55 \leq P_K/\text{msec} \leq 0.8\), compared with \(P_K \sim 1\) 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 \(\geq 2\, M_\odot\) 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.
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