Strange quark matter in neutron stars

Prof. Mark Alford
Washington University in St. Louis

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A. Schmitt, arXiv:1001.3294 (Springer Lecture Notes)
Quark matter in compact stars

Conventional scenario

Neutron/hybrid star

Strange Matter Hypothesis

Bodmer 1971; Witten 1984; Farhi, Jaffe 1984

Strange star

neutron star

hybrid star

nuclear crust

SQM

NM

nuclear crust

strangelet

SQM
Two scenarios for quark matter

**Conventional scenario**

Vac $\rightarrow$ NM $\rightarrow$ QM

- Nuclear $\rightarrow$ quark matter transition at high pressure, $(\mu_{\text{crit}}, p_{\text{crit}})$

- $p_{\text{crit}}$ (310 MeV)

**Strange Matter Hypothesis**

Vac $\rightarrow$ QM

- Vacuum $\rightarrow$ quark matter transition at $\mu = \mu_{\text{sqm}}$, $p = 0$.
- Strange quark matter (SQM) is the favored phase down to $p = 0$. 

$\mu_{\text{sqm}}$ (310 MeV)
Stars under the Strange Matter Hypothesis

- SQM
- Strangelet crust
- Nuclear crust
At zero pressure, if its surface tension is low enough, strange matter, like nuclear matter, will undergo charge separation and evaporation into charged droplets.

\[ \sigma_{\text{crit}} \lesssim 10 \text{ MeVfm}^{-2} \]

Crust thickness
\[ \Delta R \lesssim 1 \text{ km} \]

Jaikumar, Reddy, Steiner, nucl-th/0507055

Alford, Eby, arXiv:0808.0671

Jaikumar, Reddy, Steiner, nucl-th/0507055
Neutral quark matter and neutral vacuum can coexist at zero pressure.

But if they have different electrostatic potentials $\mu_e$ then $p_{\text{sep}} > 0$ and it is preferable* to form a charge-separated phase with intermediate $\mu_e$.

* unless surface costs are too high, e.g. surface tension, electrostatic energy from $E = \nabla \mu_e$. 

Charge density $\rho = \frac{d\Omega}{d\mu_e}$
Strange quark matter objects

Similar to nuclear matter objects, if surface tension is low enough.

Alford, Han arXiv:1111.3937
Strange Matter Hypothesis summary

- Strange matter is the true ground state at zero pressure.
- For a compact star, ground state is strange matter, perhaps with a strangelet or nuclear matter crust.
- Neutron stars will convert to strange stars if hit by a strangelet.
- Regular matter is immune since strangelets are positively charged.
- If surface tension of strange matter is low enough, it will form atoms, planets, dwarfs, compact stars, roughly like nuclear matter.
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Is SMH ruled out by observations of neutron stars?

- X-ray bursts oscillations indicate ordinary nuclear crust (Watts, Reddy astro-ph/0609364). But...
  - Maybe nuclear crust can show similar behavior?
  - Maybe strangelet crust can show similar behavior?

- Would cosmic strangelet flux be large enough to convert all neutron stars? (Friedman, Caldwell, 1991)?
  Depends on SQM params (Bauswein et. al. arXiv:0812.4248).
Conventional hypothesis

Transition from nuclear matter to quark matter occurs at high pressure. Compact stars have nuclear crust/mantle, possible quark matter core.

![Diagram](image_url)

Nuclear matter $\rightarrow$ quark matter at high pressure, $(\mu_{\text{crit}}, p_{\text{crit}})$

Vacuum $\rightarrow$ nuclear matter $\rightarrow$ quark matter

$n$-star

hybrid

star

$\mu$

$\nu$

$p$

$310\text{MeV}$

$\mu_{\text{crit}}$

$p_{\text{crit}}$
Signatures of quark matter in compact stars

Observable ← Microphysical properties (and neutron star structure) ← Phases of dense matter

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# Signatures of quark matter in compact stars

**Observable** \[\text{Microphysical properties (and neutron star structure)} \] \[\text{Phases of dense matter} \]

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<td>spindown (spin freq, age)</td>
<td>bulk viscosity, shear viscosity</td>
<td>Depends on phase: $n,p,e$, $n,p,e, \mu$</td>
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<td>cooling (temp, age)</td>
<td>heat capacity, neutrino emissivity, thermal cond.</td>
<td>Depends on phase: $n,p,e, \Lambda, \Sigma^-$, $n$ superfluid, $p$ supercond, $\pi$ condensate, $K$ condensate, LOFF, $1\text{SC}$, $2\text{SC}$, $\text{CFL}$, $\text{CFL-}K^0$, $\text{CSL}$, $\text{LOFF}$, $\text{1SC}$, ...</td>
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<td>glitches (superfluid, crystal)</td>
<td>shear modulus, vortex pinning energy</td>
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Nucl/Quark EoS $\varepsilon(p) \Rightarrow$ Neutron star $M(R)$

Can quark matter be the favored phase at high density?

Recent measurement:

$M = 1.97 \pm 0.04 M_\odot$

A fairly generic QM EoS

Model-independent parameterization based on Classical Ideal Gas (CIG)

\[ \varepsilon(p) = \varepsilon_{\text{trans}} + \Delta \varepsilon + c_{\text{QM}}^{-2}(p - p_{\text{crit}}) \]

Zdunik, Haensel, arXiv:1211.1231
Alford, Han, Prakash, arXiv:1302.4732

QM EoS params: \( p_{\text{trans}} / \varepsilon_{\text{trans}}, \Delta \varepsilon / \varepsilon_{\text{trans}}, c_{\text{QM}}^{2} \)
Constraints on QM EoS from max mass

QM + Soft Nuclear Matter

QM + Hard Nuclear Matter

Max mass can constrain QM EoS but not rule out generic QM

For soft NM EoS, need $c_{QM}^2 \gtrsim 0.4$
r-modes and old pulsars

r-modes cause fast-spinning stars to spin down \( \Rightarrow \) exclusion regions

\( T \) [K] \( f \) [Hz]

Nuclear, viscous damping only
Nuclear with some core-mantle friction
Nuclear with maximum core-mantle friction
Free quarks
Quarks with non-Fermi corrections

(Schwenzer, arXiv:1212.5242)
r-modes and young pulsar spindown

(Alford, Schwenzer arXiv:1210.6091)
Conventional Scenario summary

- Critical density for nuclear→quark transition is unknown. Neutron stars may have quark matter cores.
- We need signatures that are sensitive to properties of the core
  - Mass-radius curve
  - Cooling (e.g. Cas. A)
  - Spindown (r-mode exclusion regions)
  - Glitches
  - Grav waves? (Spindown, mergers, “mountains”)
- We need to understand quark matter phases and how their properties are manifested in these signature behaviors.
The future

- Neutron stars:
  - More data on neutron star mass, radius, age, temperature, etc.
  - Better understanding of nuclear matter properties
  - r-mode damping mechanisms
  - Color supercond. crystalline phase (glitches) (gravitational waves?)
  - CFL phase: superconductor with unstable vortices

- Quark matter properties:
  - Intermediate density phases
  - Role of large magnetic fields
  - Better models of quark matter: PNJL, Schwinger-Dyson
  - Better weak-coupling calculations
  - Solve the sign problem and do lattice QCD at high density