Phase conversion dissipation at the quark/nuclear matter interface

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Alford, Han, Schwenzer,
arXiv:1404.5279 (Phys Rev C)
Nuclear matter and quark matter
Is there quark matter in neutron stars? Hybrid stars
An anomaly in pulsar spins: damping needed!
Damping of local density oscillations: bulk viscosity
Damping of global oscillations of a hybrid star: phase conversion dissipation
Conclusions
Schematic QCD phase diagram

A. Schmitt, arXiv:1001.3294 (Springer Lecture Notes)
Hybrid stars

Is there quark matter in nature?

How could we distinguish hybrid stars from neutron stars?

Quark matter has
• different EoS?
• different transport properties
Signatures of quark matter in compact stars

<table>
<thead>
<tr>
<th>Observable</th>
<th>Microphysical properties (and neutron star structure)</th>
<th>Phases of dense matter</th>
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# Signatures of quark matter in compact stars

**Observable** $\leftarrow$ **Microphysical properties** (and neutron star structure) $\leftarrow$ **Phases of dense matter**

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<td>spindown (spin freq, age)</td>
<td>bulk viscosity</td>
<td>Depends on phase: $npe$</td>
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<td>shear viscosity</td>
<td>$npe, \mu$</td>
</tr>
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<td></td>
<td></td>
<td>$npe, \Lambda, \Sigma^-$</td>
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<td>cooling (temp, age)</td>
<td>heat capacity</td>
<td>$n$ superfluid</td>
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<td>neutrino emissivity</td>
<td>$p$ supercond</td>
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<td></td>
<td>thermal cond.</td>
<td>$\pi$ condensate</td>
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<tr>
<td></td>
<td></td>
<td>$K$ condensate</td>
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<tr>
<td>glitches (superfluid, crystal)</td>
<td>shear modulus</td>
<td>...</td>
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<td>vortex pinning energy</td>
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A viscosity-sensitive signature: spindown

- Instability region depends on viscosity of star's interior.
- Behavior of stars inside instability region depends on saturation amplitude of r-mode.

Shear viscosity grows at low $T$ (long mean free paths).

Bulk viscosity has a resonant peak when beta equilibration rate matches r-mode frequency.
An anomaly in binary pulsar spin rates

**Possible explanations:**

- **Astrophysical** extra damping
- **Microphysical** extra damping (e.g. quark matter)
  - “tiny r-mode”: very low saturation amplitude, due to strong nonlinear damping

**Hypothesis:** Neutron stars are hybrid stars, and **Phase conversion dissipation** due to expansion/contraction of the quark matter core provides nonlinear damping that stops r-mode growth at $\alpha_{\text{sat}} \lesssim 10^{-8}$
Density oscillation dissipation in hybrid stars

Dissipation arises from phase lag in the response of baryon density to pressure oscillation \( \Rightarrow pdV \) work.

(1) *Local* dissipation.

*Bulk viscosity* at each point in the star damps oscillations.

Quark matter may have enhanced bulk viscosity:

- different flavor content (more strangeness)
- different phase space for flavor changing interactions (quarks are relativistic)

(2) *Global* dissipation.

Energy is dissipated by expansion and contraction of quark matter core in response to a pressure oscillation. *Phase Conversion Dissipation.*
Bulk viscosity: phase lag in system response

Baryon density \( n \) and hence volume \( V \) gets out of phase with applied \( p \):

\[
\text{Dissipation} = -\int p \, dV = -\int p \frac{dV}{dt} \, dt
\]

No phase lag
Dissipation = 0

Some phase lag
Dissipation > 0
Bulk viscosity: a resonant phenomenon

- Energy dissipation (heating) in response to applied pressure oscillation of frequency $\omega$
- Some component in the material is equilibrating slowly, at rate $\gamma$, in response to pressure change
- Bulk viscosity is maximum when $\gamma = \omega$

$$\eta = C \frac{\gamma}{\gamma^2 + \omega^2}$$

What quantity would equilibrate on the timescale of neutron star oscillations like r-modes (milliseconds)?
Bulk viscosity: a resonant phenomenon

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What quantity would equilibrate on the timescale of neutron star oscillations like $r$-modes (milliseconds)?

Flavor, via weak interactions
Bulk viscosity and flavor equilibration

$d \leftrightarrow s$ stays in equilibrium

$\mu_d = \mu_s$

$\mu_{\text{high}}$ $\mu_{\text{low}}$

$p$ $V$
Bulk viscosity and flavor equilibration

$d \leftrightarrow s$ stays in equilibrium \[ \mu_d = \mu_s \]

$d \leftrightarrow s$ goes out of equil. \[ \mu_\Delta = \mu_d - \mu_s \]
Density oscillation dissipation in Hybrid stars

(1) *Local* dissipation.
Bulk viscosity at each point in the star damps oscillations.
Quark matter may have a different bulk viscosity:
- different flavor content (more strangeness)
- different phase space for flavor changing interactions (quarks are relativistic)

(2) *Global* dissipation.
The size of the quark matter core has a lagging response to the applied pressure oscillation.
Phase Conversion Dissipation.
The Power of Phase conversion dissipation

Phase Conversion Dissipation...

- is very weak at low amplitude but becomes very strong as amplitude grows
- can stop the growth of an r-mode at $\alpha_{\text{sat}} \sim 10^{-10}$

\[ f=600\text{Hz}, \quad T=10^8\text{K} \]

\[
\alpha_{\text{sat}}^\text{max}
\]

\[
\alpha_{\text{sat}}
\]

\[
(\bar{R}_b/R)_{\text{crit}} \quad \text{vs} \quad \bar{R}_b/R
\]

\[
10^{-12} \quad 10^{-11} \quad 10^{-10}
\]
Core size phase lag

NM→QM conversion is slow because flavor changing weak interactions are required \[ n \rightarrow u \ d \ s \]

The core size is always chasing its “ideal” value, always lagging behind.

The higher the amplitude of the oscillation, the faster the “ideal” boundary moves, and the actual boundary can’t keep up.

Damping increases nonlinearly with amplitude of oscillation.
Ignoring GR corrections,\[ \frac{dp}{dr} = -g(r)\varepsilon(r) \]

Kink in \( p(r) \) at transition where there is a discontinuity in \( \varepsilon \).

What happens when there is a density oscillation in the star?
1) Star in equilibrium
2) Sudden compression: core is compressed
3) Core grows via nuclear $\rightarrow$ quark matter transition
   This is slow because deconfinement $n \rightarrow u\,d\,s$ requires weak interaction.
Nuclear $\rightarrow$ quark conversion

Speed of boundary is determined by two processes in quark matter:
- Rate of $d \rightarrow s = \gamma_Q$
- Strangeless diffusion coefficient $D_Q$

$$v \sim \sqrt{D_Q \gamma_Q}$$

If “ideal” boundary wants to move faster than boundary can move, core size will lag behind pressure oscillation $\Leftrightarrow$ strong damping.
Nonlinear dissipation of r-mode

\[ P_{\text{gr}} = \text{driving power from gravitational back-reaction} \]

\[ P_{\text{dis}} = \text{dissipation due to phase conversion dissipation} \]

r-mode is saturated at very low amplitude

\[ \alpha_{\text{sat}} \sim 10^{-12} \]

\[ f = 600 \text{ Hz}, \ T = 10^8 \text{ K}, \ \frac{\tilde{R}_{\text{core}}}{R_{\text{star}}} = 0.56 \]
Summary: dissipation in dense matter

- Density oscillations can be damped strongly by hysteresis: phase lag in response of density to pressure.
  - Local flavor equilibration: bulk viscosity
  - Global phase equilibration: phase conversion dissipation (PCD)
- PCD at nuclear/quark matter interface can saturate r-mode in hybrid stars at $\alpha_{\text{sat}} \lesssim 10^{-10}$ (if the core is not too small).
- How would we test this hypothesis?
Are r-modes saturated by PCD?

(See the gravitational waves from r-modes? Not intense enough.)

We need measurements of temperature of isolated millisecond pulsars.

**Cold millisecond pulsars**
If we see ms pulsars ($f \gtrsim 300$ Hz) that are outside the r-mode instability region ($T \lesssim 10^6$ K) then they must have had $\alpha_{\text{sat}} \lesssim 10^{-8}$ and PCD is the only known mechanism for this.
These stars should be heavy enough to have quark matter cores.

**Warm millisecond pulsars**
If we see ms pulsars inside the r-mode instability region ($T \gtrsim 10^6$ K) then this tells us what value of $\alpha_{\text{sat}}$ would explain their warmth, and if we can also measure their $\dot{f}$ then we can check whether this is consistent with r-mode heating.
If their $\alpha_{\text{sat}} \gg 10^{-10}$ then these stars should be light enough to not have quark matter cores.
The bigger picture

What do we need to detect quark matter in neutron star cores?

- More accurate data on observable properties of neutron stars:
  - mass and radius
  - spindown (spin and age);
  - cooling (temperature and age)
- Better modeling of neutron stars:
  - astrophysical damping and saturation mechanisms for r-modes
  - Use existing knowledge of r-mode spindown to survey all known phases of dense matter for their spindown predictions
  - mechanism of glitches
- Understand high-density matter
  - better models of quark matter: Functional RG, Schwinger-Dyson
  - solve the sign problem and do lattice QCD at high density.