Seeing into a compact star using precise radio data

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Quark matter in compact stars?

- The interior of a compact star is dense enough that it could contain various novel forms of matter … in particular **quark matter**

  M. Alford, et. al., Rev. Mod. Phys. 80 (2008) 1455

- Requires to connect observables to the microscopic properties:
  - Static properties depend on EoS
  - Dynamic prop. depend on low energy degrees of freedom

“Seeing into …
… a compact star”

- Electromagnetic radiation originates from the surface - connection to the interior very indirect

- Yet, one can use similar methods we use to learn about the interior of the earth or the sun: “Seismology”

- When non-axisymmetric oscillations are not damped away they emit gravitational waves …
  - direct detection via gravitational wave detectors
  - indirect detection via the spin data of pulsars

- Star oscillations are damped by viscosity, which is induced by microscopic particle interactions

… links macroscopic observables to microphysics of dense matter
Millisecond pulsars & timing data

- Gravitational waves emitted by star oscillations would generally quickly spin down a fast spinning star.

- But many fast (“millisecond”) pulsars are observed - they can be grouped into two classes:
  - ms x-ray pulsars in (low mass) binaries (LMXBs) currently accrete from a companion which allows a temperature measurement (10+ sources).
    - $T$'s involve modeling and are uncertain.
  - ms radio pulsars (200+ sources) are very old and don’t accrete any more, but feature extremely stable timing data.
    - one of the most precise data sets in physics!

- Fast pulsars are a puzzle when modes become unstable …
R-mode oscillations

- **R-mode**: Eigenmode of a rotating star which is **unstable** against gravitational wave emission

  L. Lindblom, et. al., PRL 80 (1998) 4843

Large amplitude r-modes could cause a quick spindown

B. J. Owen, et. al.,  

- But r-mode growth has to be stopped by some non-linear damping mechanism, e.g.
  
  - **non-linear viscous damping**  
    M. Alford, S. Mahmoodifar and K.S.,  
    PRD 85 (2012) 044051

  - **non-linear hydro effects - large** $\alpha = O(1)$  
    L. Lindblom, et. al., PRL 86 (2001) 1152,  
    W. Kastaun, Phys.Rev. D84 (2011) 124036

  - **mode-coupling - small** $\alpha \ll 1$  
Dissipation in dense matter

- Shear viscosity from particle scattering (strong/EM interaction)

<table>
<thead>
<tr>
<th>candidate phase</th>
<th>dominant processes</th>
<th>shear viscosity</th>
<th>reference</th>
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<tbody>
<tr>
<td>(ungapped) nuclear matter</td>
<td>$e + e \rightarrow e + e$</td>
<td>$\eta \sim (T/\mu)^{-5/3}$ &amp; $(T/\mu)^{-2}$</td>
<td>Shternin, et. al., PRD 78 (2008) 063006</td>
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<td>hyperonic matter</td>
<td>$n + n \rightarrow n + n$</td>
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</tr>
<tr>
<td>ungapped quark matter</td>
<td>$q + q \rightarrow q + q$</td>
<td>$\eta \sim (T/\mu)^{-5/3}$</td>
<td>Heiselberg, et. al., PRD 48 (1993) 2916</td>
</tr>
<tr>
<td>CFL quark matter</td>
<td>$H \rightarrow H + H$</td>
<td>$\eta \sim (T/\mu)^4$</td>
<td>Manuel, et. al., JHEP 09 (2005) 76; Andersson, et. al., PRD 82 (2010) 023007</td>
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- Bulk viscosity from particle transformation (weak interaction)

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<th>candidate phase</th>
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<th>bulk viscosity: low T</th>
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<tr>
<td>(ungapped) nuclear matter</td>
<td>$n(+n) \rightarrow p(+n) + e + \bar{\nu}$</td>
<td>$\zeta \sim (T/\mu)^6$ or $(T/\mu)^4$</td>
<td>Sawyer, PLB 233 (1989) 412; Haensel, et. al., PRD 45 (1992) 4708</td>
</tr>
<tr>
<td>hyperonic matter</td>
<td>$n + n \rightarrow p + \Sigma^-$, ...</td>
<td>$\zeta \sim (T/\mu)^2$</td>
<td>Haensel, et. al., A&amp;A 381 (2002) 1080</td>
</tr>
<tr>
<td>superfluid nuclear matter</td>
<td>$e + l \leftrightarrow \mu + l + \nu + \bar{\nu}$</td>
<td>$\zeta \sim (T/\mu)^7$</td>
<td>Alford, et. al., PRC 82 (2010) 055805</td>
</tr>
<tr>
<td>ungapped quark matter</td>
<td>$d + u \leftrightarrow s + u$</td>
<td>$\zeta \sim (T/\mu)^2$</td>
<td>Madsen, PRD 46 (1992) 3290</td>
</tr>
<tr>
<td>CFL quark matter</td>
<td>$K_0 \rightarrow H + H$</td>
<td>$\zeta \sim e^{-c(\mu/T)}$</td>
<td>Alford, et. al., PRC 75 (2007) 055209</td>
</tr>
</tbody>
</table>

Alternative forms of matter show dramatically different damping, since $T/\mu \sim O(10^{-4})$
“Effective Theory of pulsars”

- Observable macroscopic properties depend only on quantities that are integrated over the entire star:

\[
I = \tilde{I} M R^2 \quad \text{(MOMENT OF INERTIA)}
\]

\[
P_G = \frac{32\pi (m-1)^2 m (m+2)^2}{((2m+1))} \tilde{J}_m \frac{GM^2 R^{2m+2} \alpha^2 \Omega^{2m+4}}{(m+1)^2 (m+2)}
\quad \text{(POWER RADIATED IN GRAVITATIONAL WAVES)}
\]

\[
P_S = -\frac{(m-1)(2m+1) \tilde{S}_m A^{3+\sigma}_{QCD} R^3 \alpha^2 \Omega^2}{T^\sigma}
\quad \text{(DISSIPATED POWER DUE TO SHEAR / BULK VISCOSITY)}
\]

\[
P_B = -\frac{16m}{(2m+3)(m+1)^5 \kappa^2} \frac{A^{9-\delta}_{QCD} \tilde{V}_m R^8 \alpha^2 \Omega^4 T^\delta}{A^{4}_{EW} \tilde{J}_m}
\]

\[
L_{\nu} = 4\pi R^3 A^{4}_{EW} A^{1-\theta}_{QCD} \tilde{L} T^\theta
\quad \text{(NEUTRINO LUMINOSITY)}
\]
"Effective Theory of pulsars"

- Observable macroscopic properties depend only on quantities that are integrated over the entire star:
  \[ I = \tilde{I} MR^2 \]
  \[ P_G = \frac{32\pi (m-1)^2 (m+2)^{2m+2}}{((2m+1)!!)^2 (m+1)^{2m+2}} \tilde{J}_m^2 GM^2 R^{2m+2} \alpha^2 \Omega^{2m+4} \]
  \[ P_S = -(m-1)(2m+1) \tilde{S}_m \frac{\Lambda_{QCD}^3}{T} \frac{R^3 \alpha^2 \Omega^2}{T^\sigma} \]
  \[ P_B = -\frac{16m}{(2m+3)(m+1)^5 \kappa^2} \tilde{V}_m \frac{\Lambda_{QCD}^{9-\delta}}{\Lambda_{EW}^{4-\delta}} \frac{R^8 \alpha^2 \Omega^4 T^\delta}{\tilde{J}_m} \]
  \[ L_\nu = 4\pi R^3 \Lambda_{EW}^4 \Lambda_{QCD}^{1-\theta} \tilde{L} T^\theta \]

- Pulsar evolution for r-mode amplitude \( \alpha \), angular velocity \( \Omega \) and temperature \( T \) are obtained from global conservation laws.

- Universal hierarchy of evolution time scales: \( \tau_\alpha \ll \tau_T \ll \tau_\Omega \)

- Semi-analytic results for the r-mode evolution …

\[ f_f^{(NS)} \approx 61.4 \text{ Hz} \frac{\Delta \tilde{S}}{29} \frac{\Delta \tilde{L}}{5} \left( \frac{1.4 M_\odot}{M} \right)^{29} \left( \frac{11.5 \text{ km}}{R} \right)^{87} \]

Extremely insensitive to microscopic details … but not to the form of dense matter!
Static instability regions vs. x-ray data

- R-modes are unstable at large frequencies if the damping is not sufficient.

- Boundary given by \( P_G = P_D |_{\alpha \to 0} \).

- Requires temperature measurements which are only available for a few low mass x-ray binaries.

- Two scenarios to explain data: “no r-mode”: completely damped, “tiny r-mode”: unstable, but saturated at small \( \alpha_{sat} \).

- Many sources are clearly within the instability region for neutron stars with standard damping (tiny r-mode scenario required).

- Quark matter (incl. gauge interactions) fully damps mode (no r-mode).

K. S., arXiv:1212.5242

analytic result: \( \Omega_{ib}(T) = \left( \hat{D} T^\delta \chi^\Delta / \hat{G} \right)^{1/(8-\psi)} \)
Evolution of millisecond pulsars

- Pulsars are spun up by accretion in low mass x-ray binaries (LMXBs), which heats them strongly.

- When accretion stops, they cool quickly until either …
  1. they leave the instability region (low frequencies)
  2. r-mode heating balances cooling (high frequencies)

  ➡ very slow spindown along steady state curve

… without enhanced damping, fast spinning stars cannot escape the instability region.
Pulsar evolution & r-mode instability

- Spindown solution allows to connect to timing data of radio pulsars …

Spindown (heating=cooling) curves depend strongly on saturation amplitude … data implies that $\alpha_{\text{sat}} \lesssim O(10^{-8})$ but all proposed saturation mechanisms can only saturate at $\alpha_{\text{sat}} \gtrsim O(10^{-6})$

Enhanced damping required!

Haskell, et. al., MNRAS 424 (2012) 93

observed spindown rates are upper limits for r-mode contribution

Manchester, et. al., astro-ph/0412641
We only measure the total spindown rate which can stem from various mechanisms, so that the sources could be outside of the instability region …

- However, to cool out of the instability region would even require \( \alpha_{\text{sat}} \lesssim O(10^{-10}) \)

Spindown data is restrictive despite our ignorance what fraction is due to r-modes!
R-mode instability regions vs. thermal x-ray & radio timing data

Dynamic Instability boundaries in timing parameter space:

Interacting quark matter consistent with both x-ray and radio data (no r-mode scenario)

\[ \Omega_{ib}(\dot{\Omega}) = \left( \hat{D}^\theta I^\delta |\dot{\Omega}|^\delta / \left( 3^\delta \hat{G}^\theta \hat{L}^\delta \right) \right)^{1/(8-\psi-\theta-\delta)} \]


independent of saturation physics!
“R-mode temperatures“

- The connection between the spindown curves allows to determine the R-mode temperature of a star with saturated r-mode oscillations (tiny r-mode scenario) for given timing data

\[ T_{rm} = \left( \frac{I \Omega \dot{\Omega}}{3 \dot{L}} \right)^{1/\theta} \]

- Independent of the saturation mechanism ... but depends on the cooling

- Temperatures only upper bounds since the observed spindown rate can also stem from electromagnetic radiation

- Measurements of temperatures (or bounds) of fast nearby radio pulsars would allow us to test if saturated r-modes can be present

⇒ falsifiable scenario!

If radio pulsars spin down by r-mode emission, they would be warm enough to observe thermal x-rays
Conclusions and Outlook

- Timing data of radio pulsars ... can be used to probe the interior of compact stars

- Standard neutron stars cannot damp r-modes in LMXBs and cannot explain the radio pulsar data for proposed r-mode saturation mechanisms

  ★ Quark matter can simultaneously explain the data on LMXBs and radio pulsars

- Thermal x-ray or gravitational wave measurements for nearby millisecond pulsars would tell us which scenario is realized

- Need to rule out other possible mechanisms of enhanced damping (crust, superfluidity, ...)