EOS of neutron star cores and spin down of pulsars

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Isolated Neutron Stars

April 24-28, 2006, London (UK)

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Motivation

Isolated pulsar looses J due to radiation. In response to $\dot{J}$ it changes $f = 1/\mathrm{period} = \Omega/2\pi$ (observable!) and increases central density and pressure $\rho_\mathrm{c},\ P_\mathrm{c}$. Response to $\dot{J}$ depends on the EOS of the neutron-star core, and is sensitive to appearance of new particles or of a new phase. Crossing the phase-transition region by ρ_c is reflected by specific "nonstandard" behavior of $f(t)$.

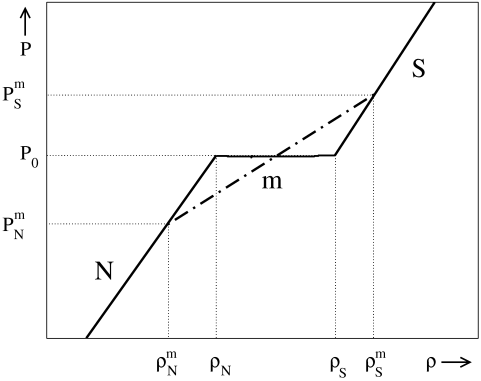
Plan

- Phase transitions and EOS - full equilibrium
- Back bending and stability
- Stability and rotation
- Instability and corequakes
- Metastability and EOS
- Energy release in a corequake

1st order N-S :thermodynamic equilibrium

pure N-S, density jump

Between two pure phases N and S, at some P_0, with density jump: $\rho_N < \rho_S$. Occurs for sufficiently strong pion or kaon condensation. Characteristic for many models of quark deconfinement.



pure N - mixed NS - pure S

Above $P_N^{(m)}$ NS preferred over the pure N, with fraction of the S phase increasing from zero to one at $P = P_S^{(m)}$, and above $P_S^{(m)}$ pure S phase is preferred. Might be possible for: meson condensations or quark matter, provided **surface tension** at the N-S interface is suffiently small.

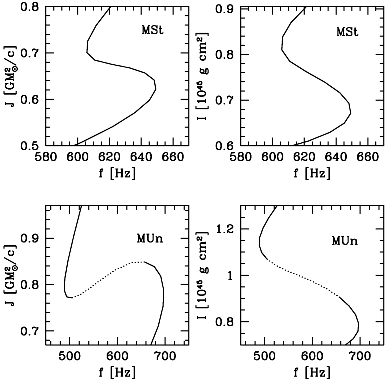
Stability of hydrostatic equilibria

Stability criteria - nonrotating stars

Wheeler & collaborators (1958)...

One-parameter family - configurations $\mathcal{C}(x)$, $x = \rho_{\rm c}, P_{\rm c}$

radial perturbations:
stable if $\mathrm{d}M/\mathrm{d}x > 0$
ustable if $\mathrm{d}M/\mathrm{d}x > 0$



Stability criteria - rotating stars

Friedman, Ipser, Sorkin (1988)...

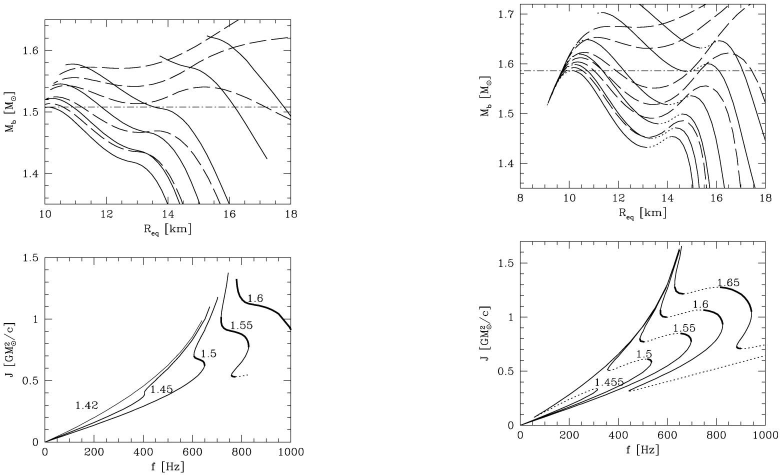
Two-parameter family: $\mathcal{C}(x, \Omega)$ - **axially symmetric perturbations** - 2-D

Criteria I stable if $(\partial M/\partial x)_{J=const.} > 0$ unstable if $(\partial M/\partial x)_{J=const.} < 0$

Criteria II stable if $(\partial J/\partial x)_{M_{\rm b}=const.} > 0$ unstable if $(\partial J/\partial x)_{M_{\rm b}=const.} < 0$

Invariance of structure of (one-parameter) families $\{\mathcal{C}_X\}$

$X = M_\mathrm{b}, J, f$ *Zdunik, Bejger, Haensel, Gourgoulhon (2005,2006)*



stable static $\Longrightarrow$ stable rotating

unstable segment static $\Longrightarrow$ unstable segment rotating

Invariance of structure of $\{\mathcal{C}_X\}$ families - continued

$X = M_{\rm b}, J, f$

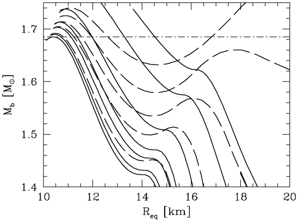
Marginal instability

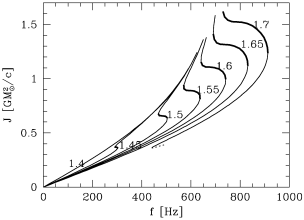
Marginally unstable configuration-inflection point $(\partial M/\partial x)_{J=const.} = 0$ and $(\partial^2 M/\partial x^2)_{J=const.} = 0$

$(\partial J/\partial x)_{M_{\rm b}=const.} = 0$ and $(\partial^2 J/\partial x^2)_{M_{\rm b}=const.} = 0$

Conjectures

I All stable $\{\mathcal{C}\}_{\rm stat}$ static remains all stable $\{\mathcal{C}_X\}_{\rm rot}$
II If $\{\mathcal{C}\}_{\rm stat}$ contains unstable segment then every $\{\mathcal{C}_X\}$ contains unstable segment too
III If $\{\mathcal{C}\}_{\rm stat}$ contains a marginally unstable $\mathcal{C}$ then each $\{\mathcal{C}_X\}$ contains a marginally unstable $\mathcal{C}_X$





Conjectures ≈ Theorems because exceptions from them form a set of

single family of stable static configurations $\Leftrightarrow$ single family of stable rotating configurations

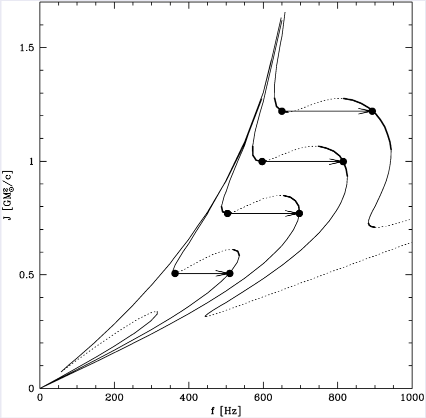
two disjoint families of stable static configurations separated by a family of unstable configurations $\Leftrightarrow$ two disjoint families of stable rotating configurations separated by a family of unstable configurations (constant $M_{\rm b}$, or constant J, or constant f)

generic feature of EOSs with phase transitions, not changed by rigid rotation

Instability and starquakes

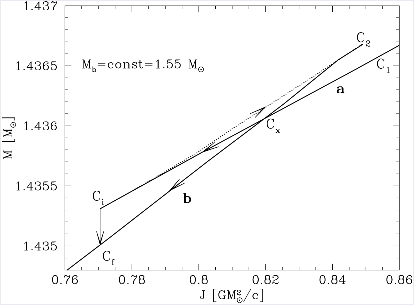
A spinning down pulsar reaches instability point and collapses (**spin up**!) into a new **stable** $\mathcal{C}$ and then continues its evolution

Tracks in $J - f$ plane



Track in $M - J$ plane

The only way out from $\mathcal{C}_\mathrm{i}$ is collapse to $\mathcal{C}_\mathrm{f}$, keeping M_b and J constant. Energy released $\Delta E = (M_\mathrm{i} - M_\mathrm{f})c^2$

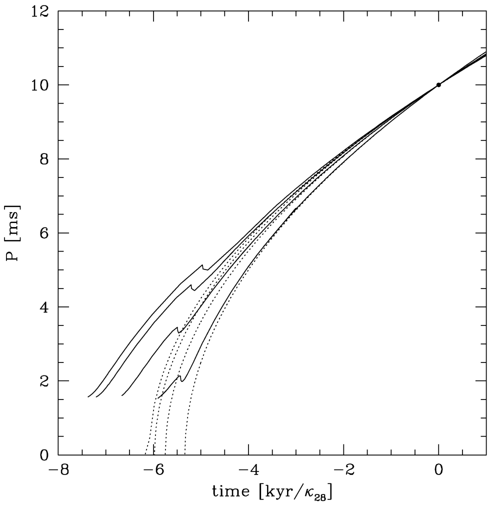


Back bending and pulsar timing

Isolated pulsar energy balance
$\dot{M}c^2 = -\kappa\Omega^\alpha$
Standard model: $I = I(0) = const.$.
However, in the phase transition epoch $I(\Omega)$ is **crucial**. Standard approximation: overestimates spindown rate and underestimates age.

Example: 10 ms pulsar observed at time $= 0$. Evolution back in time using $I = const.$ can be misleading if a phase transition region was crossed
huge values of $n = \Omega\ddot{\Omega}/\dot{\Omega}^2$ $\longrightarrow$

Period evolution in time

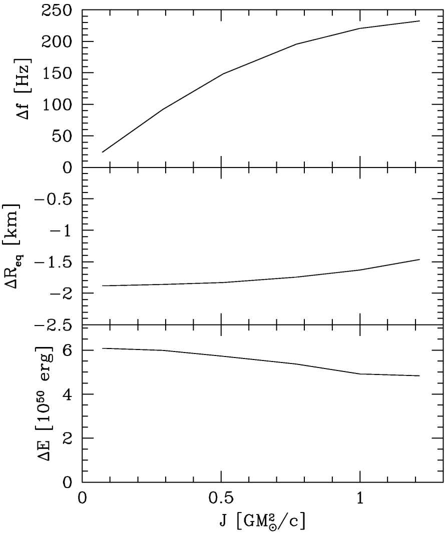


Δf, ΔR, and ΔE in starquakes

$\mathcal{C}_{\rm i} \longrightarrow \mathcal{C}_{\rm f}$
conditions $M_{\rm b,i} = M_{\rm b,f}$, $J_i = J_{\rm f}$

Energy release $\Delta E = -\Delta M c^2$
Characteristic dependence on $J_{\rm i}$

Very weak dependence of ΔE on J_i
Therefore ΔE can be calculated using 1-D code for non-rotating stars and this gives excellent prediction (within better than 20%) even for high $J_{\rm i}$! No need for 2-D to get reliable estimate.

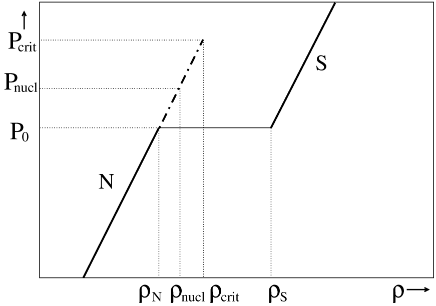


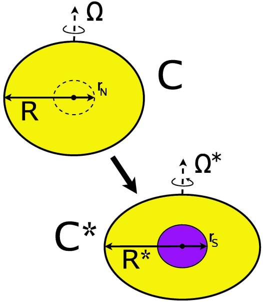
Metastability and two cases of corequakes

non-rotating stars: *Haensel,Zdunik,Schaeffer (1986,87)*

Two cases of starquakes
(1) weak and moderate 1st order phase transitions $\rho_{\rm S}/\rho_{\rm N} < \frac{3}{2} + P_0/\rho_{\rm N}c^2$;
starquake due to nucleation of S phase in a metastable core of N phase
(2) strong 1st order phase transitions $\rho_{\rm S}/\rho_{\rm N} > \frac{3}{2} + P_0/\rho_{\rm N}c^2$ - non-rotating configurations with $P_{\rm c} > P_0$ with small S cores are unstable (collapse)

rotating stars: *Zdunik, Bejger, Haensel, Gourgoulhon(2006)*

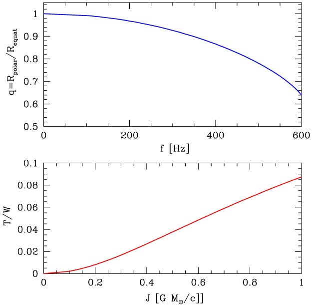


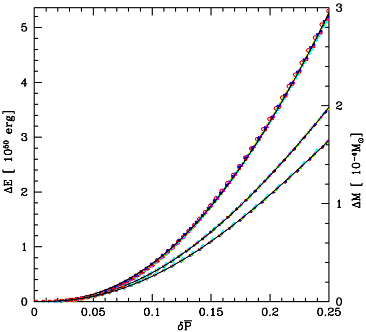


ΔE independent of J !

Overcompression in the N-star center $\delta\overline{P} \equiv (P_\mathrm{c} - P_0)/P_0$. Starquake triggered for $P_\mathrm{c} = P_\mathrm{nucl}$

Zdunik, Bejger, Haensel, Gourgoulhon (2006)





Energy release independent of J_i also for strong 1st order phase transition. 1-D static calculations are sufficient to get energy release for rotating stars

Zdunik, Bejger, Haensel, Gourgoulhon (2006)