Neutron stars: from astrophysics to nuclear physics

CAMK, Warsaw: Michał Bejger, Paweł Haensel, J. Leszek Zdunik
LUTH, Meudon: Silvano Bonazzola, Brandon Carter, Nicolas Chamel\(^1\), Éric Gourgoulhon, François Limousin\(^2\), Jérôme Novak, Micaela Oertel

Centrum Astronomiczne im. M. Kopernika (CAMK)
Polska Akademia Nauk
Bartycka 18, 00-716 Warszawa, Poland

Laboratoire Univers et Théories (LUTH)
CNRS / Observatoire de Paris / Université Paris Diderot
92190 Meudon, France

LEA Astro-PF, Meudon, 4 October 2007

\(^1\)now at Univ. Libre de Bruxelles (Belgium)
\(^2\)now at Cornell Univ. (USA)
Our (poor) knowledge of matter at supernuclear densities

Internal structure of compact stars

Large discrepancies...

adiabatic index

neutron star mass

[Haensel, Potekhin & Yakovlev (2007)]
Computation of rotating neutron star models

Framework: RotStar code based on Lorene C++ library
http://www.lorene.obspm.fr/

Resolution of Einstein equations for stationary axisymmetric rotating stars

Numerical technique: spectral methods
⇒ high accuracy

Microphysics input: equation of state (EOS)
Hyperon = baryon (i.e. hadron + fermion) made of 3 quarks, with at least one strange quark:

- $\Lambda_0 = uds$
- $\Sigma^- = dds$
- $\Xi^0 = uss$
- etc...

Should appear at high density ($\rho > 2\rho_{nuc}$)

$\Rightarrow$ EOS softening

$N1 = np$, $N1H1,N2H1 = np\Lambda\Sigma$, $N1H2,N2H2 = np\Lambda\Sigma\Xi$

Balberg & Gal (1997)
Hyperon softening of the EOS $\Rightarrow$ back-bending: spin-up by angular momentum loss

Detectability: pulsar with $\dot{P} < 0$

At high density, phase transition to an *exotic* state:

- meson (pion, kaon) condensate
- deconfined quarks

Various kinds of phase transitions:

- Constant pressure phase transition
- Mixed-phase state

Both yield EOS softening

Back-bending phenomenon: spin-up by angular momentum loss

\[ \Rightarrow \text{pulsar age inferred from spin-down formula } \frac{P}{2 \dot{P}} \text{ is underestimated} \]

Energy release due to a phase transition (1/3)

First-order phase transition

\[ P_{\text{nucl}} \leq R \leq P_{\text{crit}} \]

\[ \rho \rightarrow \rho_{\text{S}} \]

\[ N : \text{normal phase (nucleons)} \]

\[ S : \text{superdense phase (exotic matter)} \]

\[ P_{\text{nucl}} : \text{pressure at which compression timescale = nucleation timescale} \]

\[ \text{central overpressure:} \quad \delta \bar{P} = \left( P_{\text{nucl}} - P_0 \right) / P_0 \]

Conservation of baryon number: \[ A^* = A \]

Conservation of angular mom. : \[ J^* = J \]

Energy release:

\[ \Delta E = \left[ M(C) - M(C^*) \right] c^2 \]
Two types of phase transitions:

- **weak**: $\rho_S < \frac{3}{2}(\rho_N + P_0/c^2)$
  
  configurations with arbitrarily small $S$ cores are stable
  
  phase transition $\Rightarrow$ small corequake

- **strong**: $\rho_S > \frac{3}{2}(\rho_N + P_0/c^2)$
  
  configurations with small $S$ core are unstable and collapse to
  
  configurations with large $S$ core
  
  phase transition $\Rightarrow$ large corequake

[Zdunik, Bejger, Haensel & Gourgoulhon, arXiv:0707.3691]
Energy release due to a phase transition (3/3)

Weak phase transitions

\[ \Delta E \text{ depends only on } \delta \bar{P}, \text{ not on the rotation state} \]


Strong phase transitions

[Zdunik, Bejger, Haensel & Gourgoulhon, arXiv:0707.3691]
Constraints on EOS from gravitational radiation (1/2)

GW from inspiraling binary neutrons stars
Primary target for VIRGO / LIGO

← Irrotational binary configurations close to mass-shedding limit for GlendNH3, AkmalPR and BPAL12 EOS

3 nuclear matter EOS
3 strange matter EOS

Inspiraling sequences

[Limousin, Gondek-Rosińska & Gourgoulhon, PRD 71, 064012 (2005)]
Entrainment coefficient and effective mass for conduction neutrons in the crust:
- microscopic models :
  [Carter, Chamel & Haensel, Nucl. Phys. A748, 675 (2005)]
- macroscopic treatment :

BCS mesoscopic treatment of neutron superfluidity in the crust