Modélisation numérique des étoiles à neutrons

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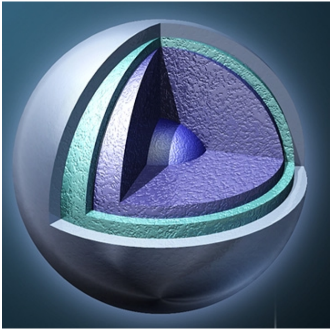
The complex physics of compact stars

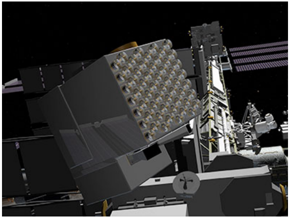
The description of compact stars involves many different fields of physics, with overall conditions that can hardly be tested on Earth:



- cold, highly asymmetric nuclear matter (talk by M. Oertel),
- very strong gravitational field (last stage before black hole),
- intense magnetic field, up to $\sim 10^{17}$ G,
- rapid rotation, implying relativistic fluid velocities.

$\Rightarrow$need for theoretical models, often involving numerical simulations

Some neutron star observation projects

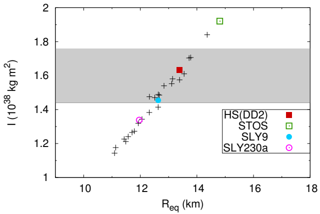


Neutron star Interior Composition ExploreR (NICER)

NICER is a soft X-ray telescope onboard the ISS, to observe X-ray binaries with millisecond pulsars
$\Rightarrow$determination of radius with $\sim 5\%$ accuracy.
$\Rightarrow$results expected very soon...

SKA shall bring many accurate observations able to constrain neutron star:

- Masses (increase of mass determination by a factor ~ 10)
- Moments of inertia $\Rightarrow$radius
- Rotation frequencies / glitches ...



French SKA whitebook (2017)

Need for very accurate models!

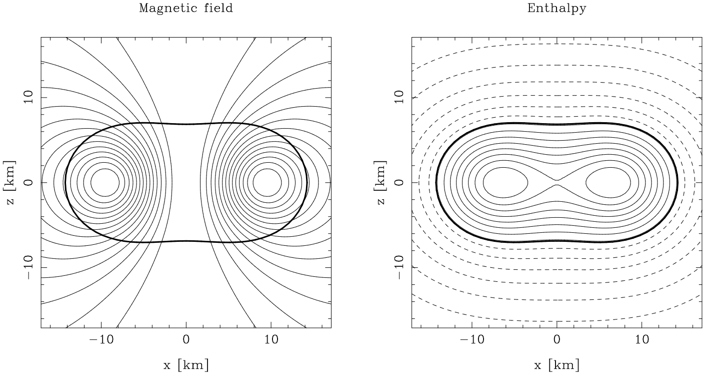
Numerical models of rotating neutron stars with:

- Magnetic field
- Superfluidity
- Thermal effects

Magnetic field

Numerical models

- Perfect conductor + independent currents
- Maxwell equations and equilibrium with Lorentz force.
- Poloidal magnetic field, moment aligned with rotation axis



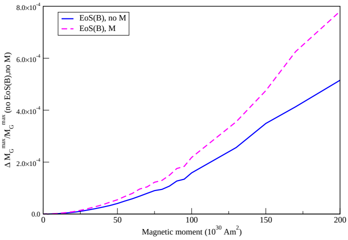
$B_p \sim 5 \times 10^{16}$ G, Bocquet *et al.* (1995)

$\Rightarrow$determination of a "universal" profile for $\|\vec{B}\|$ (Chatterjee *et al.* 2018).

Magnetic field

effect on the EoS

Many studies on effect of strong ($\gtrsim 10^{16}$ G) magnetic fields on properties of nuclear matter: EoS $p(\varepsilon, B)$.
$\Rightarrow$Starting from a microscopic Lagrangian density of fermions coupled to an electromagnetic field, new model for the energy-momentum tensor and contribution to Einstein-Maxwell equations (Chatterjee *et al.* 2015)



Chatterjee *et al.* (2015)

- First global model including magnetization (microscopic interaction between matter and magnetic field)
- Model shows no additional term in equilibrium equation (cancellation)
- Effect small with quark matter EoS: other possibilities?

Theoretical

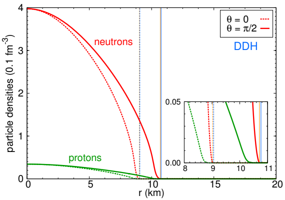
At nuclear density the critical temperature: $T_{\text{crit}} \sim 1$ MeV $\Rightarrow$ superfluid component some minutes after their birth.

Observational: glitches

Some pulsars exhibit sudden changes in the rotation period: instead of regularly slowing down, it shows rapid speed-up.

$\Rightarrow$ Within the two-fluid framework:

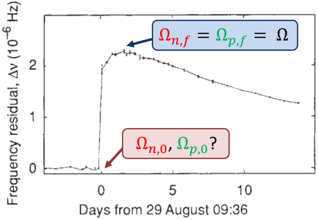
- outer crust (+fluid) is slowed down, not the inner fluid;
- until the stress (or interaction) between both becomes larger than some threshold.

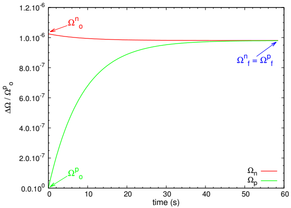


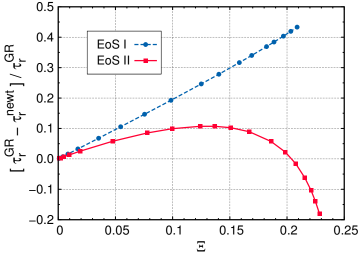
Sourie *et al.* (2016)

$\Rightarrow$ models in the two-fluid approach in Prix *et al.* (2005), Sourie *et al.* (2016)

Modeling of the glitch rise time, *e.g.* for the Vela pulsar







- Observational constraints $\tau \lesssim 30$ s.
- Constraints on superfluid properties in neutron stars (drag to lift ratio).
- Effects of General Relativity are very strong.

Compactness $\Xi = \frac{GM}{Rc^2}$ with $\Xi_{\rm NS} \simeq 0.2$, see also Sourie *et al.* (2017)...

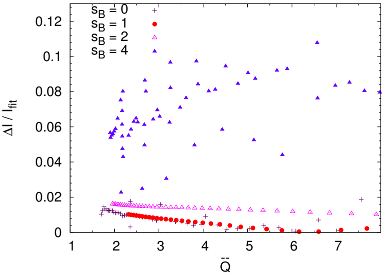
Thermal effects

"Standard" models consider matter at zero temperature : neglect temperature effects.
⇒Important for proto-neutron stars (birth) or, possibly, in the last phases of binary neutron star evolution (tidal heating).
First attempt by Goussard *et al.* (1997) to build models with temperature-dependent EoS.

Similar approach to study universality of I-Λ-Q relations:

- I ⇒moment of inertia
- Λ ⇒tidal deformability (determined by GW observations).
- Q ⇒quadrupole moment

⇒breaking of universality for high, but realistic entropy effects.



Marques *et al.* (2017)

Conclusions

Observation / analysis

- Neutron stars are now well-observed objects.
- Observations acquire much better accuracy (NICER, SKA,...)
- Better understanding of the physics (e.g. EoS)?

Numerical models

- Rotation, magnetic field easy to take into account.
- Superfluid models can give insight on glitch phenomena (more observations?).
- Elastic crust should be modeled, too (tough!).

Not a simple perfect-fluid-one-parameter-EoS approach.
⇒Gravitational waves bring a lot of new information into the game (tidal deformability). Modelling of binary neutron stars...