Evolution of proto-neutron stars and gravitational wave emission

MORGANE FORTIN$^{1,2,3}$

$^1$Italian Institute for Nuclear Physics, Rome1 division, Italy
$^2$N. Copernicus Astronomical Center, Polish Academy of Sciences, Poland
$^3$Laboratory Universe and Theories, Paris-Meudon Observatory, France

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Formation of a proto-neutron star (PNS)

Stage 0
- collapse of a massive star and bounce;
- outward propagation of a shock wave;
- birth of a PNS.

Stage 1: $t = 0$
- stagnation of the shock wave at $\sim 200$ km;
- unshocked, low entropy core in which the neutrinos are trapped;
- high entropy, low density mantle losing energy due to electron captures and thermally-produced neutrino emission.

$T_c \sim 2 \times 10^{10}$ K
$R \sim 200$ km
Formation of a proto-neutron star (PNS)

Stage II: $t = 0.5$ s

- the shock is revived (neutrinos and/or convection) and lifts off the envelope;
- extensive neutrino losses and deleptonization in the envelope → loss of pressure;
- the PNS shrinks from a radius of 200 km to 30 km;
- the core is left unchanged.

$T_c \sim 2 \times 10^{10}$ K

$R \sim 30$ km
Formation of a proto-neutron star (PNS)

Stage III: $t \sim 15$ s

The diffusion of the neutrinos from the core up to the surface dominates:

- deleptonization of the core;
- neutrino-matter interactions $\rightarrow$ heating of the PNS up to $\sim 50$ MeV;
- decrease of the entropy gradient between the core and the envelope.

$T_c \sim 2 \times 10^{10}$ K

$R \sim 30$ km
Formation of a proto-neutron star (PNS)

Stage IV: $t \sim 50$ s

- lepton-poor PNS but
- thermal production of neutrinos that diffuse up to the surface;
- cooling down of the PNS.

$T_c \sim 5 \times 10^{10}$ K
$R \sim 15$ km
Formation of a proto-neutron star (PNS)

Stage V : $t \gtrsim 50$ s

- the PNS becomes neutrino-transparent;
- birth of a NS;
- cooling of the whole NS by the emission of neutrinos from the interior and of photons from the surface.

$T_c \sim 5 \times 10^9$ K
$R \sim 12$ km
Formation of a proto-neutron star (PNS)

Kelvin-Helmholtz (KH) phase

- stages III and IV,
- quasi-stationary evolution → sequence of equilibrium configurations.

Purpose

Modelling of KH phase:

- up-to-date description of the microphysical properties of PNSs;
- study of their oscillations and the associated gravitational wave (GW) emission.

\[ T_c \sim 2 \times 10^{10} \text{ K} \]
\[ R \sim 30 \text{ km} \]

\[ T_c \sim 5 \times 10^{10} \text{ K} \]
\[ R \sim 15 \text{ km} \]
Overview

Equation of state
\[ P = P(n_b, T, Y_L) \]

Evolution equations:
- Transport equations
- Structure equations
Profiles in \( P, n_b, T \) and \( Y_L \)

Diffusion coefficient
\[ D = D(n_b, T, Y_L) \]

Oscillations and GW emission
Frequency and damping time of the quasinormal modes
Equation of state (EoS)

Describes the properties and composition of the interior of the PNS.

Properties

Include the dependence on:

- the density $n_\nu$ : up to few times $n_0$, the nuclear saturation density ($n_0 = 0.16$ fm$^{-3}$),
- the temperature : $0 \lesssim T \lesssim 50$ MeV,
- the lepton fraction : $0 \lesssim Y_L = \frac{n_\nu + n_e}{n_p + n_n} \lesssim 0.4$, ie. the composition.

Model


- High-density part :
  - finite temperature many-body approach (Brueckner-Hartree-Fock),
  - nucleon-nucleon potential : Argonne $V_{18}$,
  - three body forces : phenomenological Urbana model,
  - for neutrino-trapped $\beta$-stable nuclear matter ie. $\nu_e$, $e^-$, $n$, $p$.


- consistent with the mass measurements of PSR J1614-2230 and J0348+0432 (Demorest et al., Nature, 2010 & Antoniadis et al., Science, 2013) :

$$M_{\text{max}}(T = 0) = 2.03 \, M_\odot.$$
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Evolution equations


Hypothesis

- spherically symmetric PNS,
- with a constant baryon mass (no accretion),
- stationary evolution,
- in the framework of general relativity.

Transport equations

Diffusion approximation:

- neutrinos in thermal and chemical equilibrium with the ambient matter,
- Boltzmann equation becomes a system of two diffusion equations:
  - one for the energy-integrated lepton flux,
  - another one for the energy-integrated energy flux,
  - in terms of the neutrino diffusion coefficient . . .

Structure equations

- Tolman Oppenheimer Volkoff equations.
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Oscillations and GW emission
Frequency and damping time of the quasinormal modes
**Diffusion coefficient**

Describes the interactions of the neutrinos with the ambient matter during their diffusion.

**Processes**

For nuclear matter:

- **Neutral current (scattering):**
  
  \[ \nu_e + e^- \rightarrow \nu_e + e^- \]
  
  \[ \nu_e + n \rightarrow \nu_e + n \]
  
  \[ \nu_e + p \rightarrow \nu_e + p \]

- **Charged current (absorption):**
  
  \[ \nu_e + n \rightarrow e^- + p \]

**Mean free path of a given reaction : \( \lambda_i \)**

Reddy et al., PRD (1998)

Calculations take into account the effects of the strong interaction by:

- being consistent with the model for nuclear interaction so with the EoS,
- depending on the composition in addition to the temperature and density.

**Diffusion coefficient**

\[
D^{-1} = \sum_{\text{all processes}} \frac{1}{\lambda_i}.
\]
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Oscillations and GW emission
Frequency and damping time of the quasinormal modes
Oscillations and GW emission
Burgio et al., PRD (2011)

Quasinormal modes

- Solution of the equations describing the nonradial perturbations of a star that behave as a pure outgoing wave at infinity.
- Use of Lindblom & Detweiler formulation.
- Solution characterized by a pulsation frequency $\nu$ of the given mode and its damping time due to gravitational wave emission $\tau_{GW}$.

Mode classification

According to the restoring force dominating when a fluid element is displaced, eg. :

- the $f$-mode (fundamental mode) : global oscillation of the star,
- the $g$-modes (gravity-modes) : due thermal and composition gradients,
- the $p$-modes (pressure-modes) : the restoring force is due to a pressure gradient,…

GW emission

Comparison between :

- the damping time of a given mode $\tau_{GW}$,
- the time scale associated with dissipative processes competing with GW emission (eg. neutrino diffusion) $\tau_{diss}$.

If $\tau_{diss} > \tau_{GW}$, the GW emission is the main source of dissipation.
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Oscillations and GW emission
Frequency and damping time of the quasinormal modes
Previous modellings

**QNM properties**

Ferrari et al., MNRAS (2003); Burgio et al., PRD (2011)

- stronger dependence of the QNM frequencies on the temperature profile than on the lepton fraction profile;
- modes properties different from the ones of cold NSs;
- $f$-mode: $\nu$ does not scale as $\bar{\rho} \rightarrow$ doubles during the PNS evolution; efficient source of GW emission after few seconds;
- $g$-modes: smaller $\nu$ than the $f$-mode, increases for $t \lesssim 1$ s and then decreases; efficient source in the first few seconds.

**Detectability**

Andersson et al., GRG (2011)

- Results for a SNR of 8 with ET: at 10 kpc, radiation of $10^{-11} \rightarrow 10^{-12} \, M_\odot c^2$ through the modes.
- Note that the oscillation spectrum evolves during the observation.

EoS: relativistic mean field (cf. Pons et al. 1998).
Perspectives

- Calculation of the evolution of a PNS and the GW emission due to oscillations for the Burgio & Schulze EoS.
- Influence of the microphysical properties on the QNMs properties:
  - use of different EoSs, including ones with a phase transition;
- Inclusion of rotation in the model: generation of two branches of modes (co-rotating and counter-rotating with the star). The latter would have lower $\nu$ than for no rotation.

Purpose

Constraining the microphysical properties of PNSs, and ultimately the nuclear interaction, by the observation of their GW emission . . .