Early evolution of newly born proto-neutron stars

Giovanni Camelio
in collaboration with: Leonardo Gualtieri, Valeria Ferrari,
Jose A. Pons, Morgane Fortin & Omar Benhar

PhD student @ University of Rome "Sapienza"
work supported by an STSM through the COST Action "NewCompStar"

June 15, 2015

Proto-neutron star (PNS)

SNII from $8\,\mathrm{M}_\odot \lesssim M_\star \lesssim 25\,\mathrm{M}_\odot \rightarrow$ neutron star (NS):

- very early evolution (PHASE I): core bounce $\div \sim 0.2\,\mathrm{s}$:
  - fully relativistic, highly dynamical codes;
  - mass accretion;
  - core contraction $150\,\mathrm{km} \rightarrow 30\,\mathrm{km}$;
  - high-temperature PNS envelope;
  - neutrinos are trapped in the low-temperature PNS core.
- early evolution (PHASE II): $\sim 0.2\,\mathrm{s} \div$ minutes:
  - relativistic, quasi-stationary evolution;
  - beta equilibrium;
  - deleptonization stage (heating of the inner core);
  - cooling stage.
- minutes: birth of a mature neutron star (neutrino transparent).

I am interested in the gravitational wave spectrum (from stellar oscillations) of the PNS in PHASE II.

Previous works

Main PNS evolutionary codes (for Phase II):

- Burrows & Lattimer, "The birth of neutron stars", ApJ **307**:178–196 [1986];
- Keil & Janka, "Hadronic phase transitions at supranuclear densities and the delayed collapse of newly born neutron strars", A&A **296**:145–163 [1995];
- Pons, Reddy, Prakash, Lattimer & Miralles, "Evolution of proto-neutron stars", ApJ **513**:780–804 [1999];
- Roberts, "A new code for proto-neutron star evolution", ApJ **755**:126 [2012].

In a PNS: $T \simeq 40\,\mathrm{MeV} \gtrsim E_\mathrm{F} \simeq 10\,\mathrm{MeV} \longrightarrow$ finite temperature (non-barotropic) EoS.
For example, GM3 mean-field EoS (Glendenning & Moszkowski, "Reconciliation of Neutron-Star Masses and Binding of the Λ in Hypernuclei", PRL **67**:2414–2417 [1991]).

PNS evolution

PNS structure from TOV equations with metric

$$\mathrm{d}s^2 = -\mathrm{e}^{2\phi}\mathrm{d}t^2 + \mathrm{e}^{2\lambda}\mathrm{d}r^2 + r^2\mathrm{d}\theta^2 + r^2\sin^2\theta\mathrm{d}\Phi^2\,.$$

ν transport (Boltzmann–Lindquist Eqs, BLE) in β-equilibrium:

$$\begin{aligned}\frac{\partial Y_\mathrm{L}}{\partial t} &= -\frac{\partial(\mathrm{e}^{\phi}4\pi r^2 F_\nu)}{\partial a}\,,\\ T\frac{\partial s}{\partial t} + \mu_\nu\frac{\partial Y_\mathrm{L}}{\partial t} &= -\mathrm{e}^{-\phi}\frac{\partial(\mathrm{e}^{2\phi}4\pi r^2 H_\nu)}{\partial a}\,,\end{aligned}$$

F_ν and H_ν are the neutrino number and energy fluxes:

$$\begin{aligned}F_\nu &= -\frac{2r^2 n_\mathrm{B}\mathrm{e}^{-\phi}T^2}{3\pi\hbar^3}\left(D_3\frac{\partial(T\mathrm{e}^{\phi})}{\partial a} + (T\mathrm{e}^{\phi})D_2\frac{\partial(\mu_\nu/T)}{\partial a}\right),\\ H_\nu &= -\frac{2r^2 n_\mathrm{B}\mathrm{e}^{-\phi}T^3}{3\pi\hbar^3}\left(D_4\frac{\partial(T\mathrm{e}^{\phi})}{\partial a} + (T\mathrm{e}^{\phi})D_3\frac{\partial(\mu_\nu/T)}{\partial a}\right).\end{aligned}$$

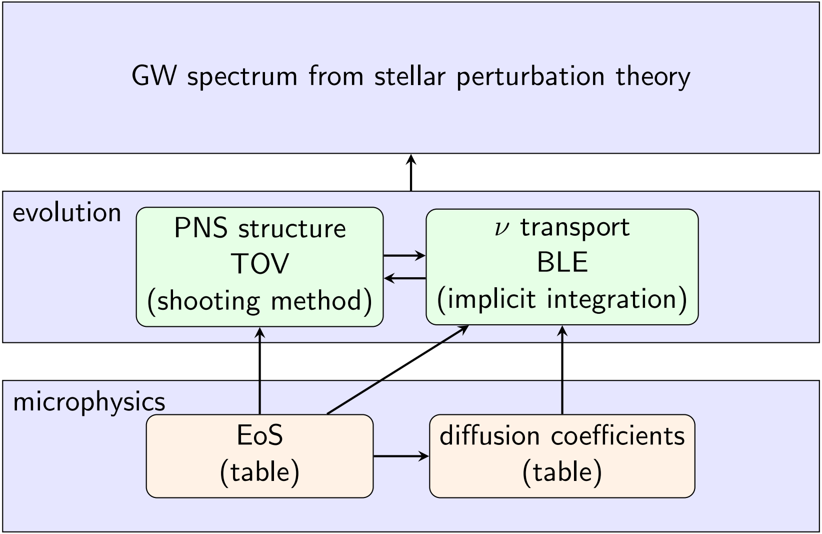
Neutrino diffusion coefficients D_n

From Reddy, Prakash & Lattimer, "Neutrino interactions in hot and dense matter", PRD **58**:013009 [1998]:

$$D_n(T, \mu_i, m_i^\star, U_i^\star) = \int_0^\infty \mathrm{d}(E/T)\,(E/T)^n \lambda_{\rm tot}(E) f(E)\big(1 - f(E)\big)$$

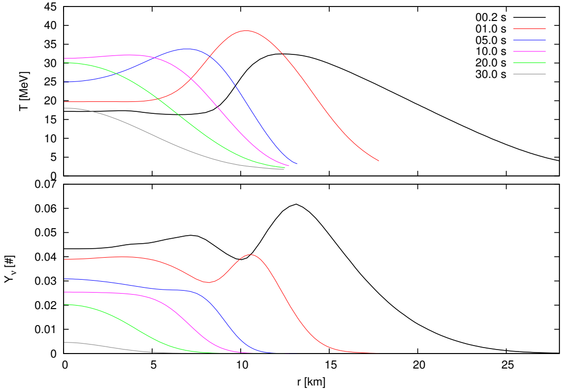
- finite-temperature and arbitrary degeneracy (p, n, e^-, e^+, ν);
- ν distribution function is Fermi-Dirac $f(E) = \left(1 + e^{\frac{E-\mu_\nu}{T}}\right)^{-1}$;
- the reactions considered are ν scattering on p, n, e^- and e^+ and ν absorption on neutrons (and the inverse process);
- neutrino mean-free paths depend on the nuclear theory adopted. For now, only for mean-field EoSs (e.g., GM3).

(Very) gross-grain structure of my code



Results: PNS evolution

My code reproduces the results of Pons, Reddy, Prakash, Lattimer & Miralles, "Evolution of proto-neutron stars", ApJ **513**:780–804 [1999]:

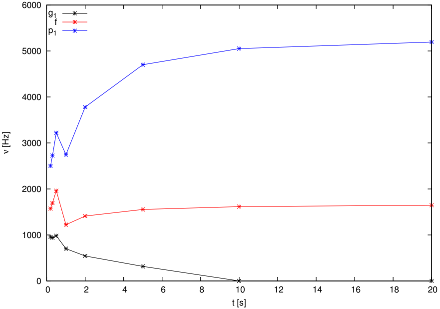


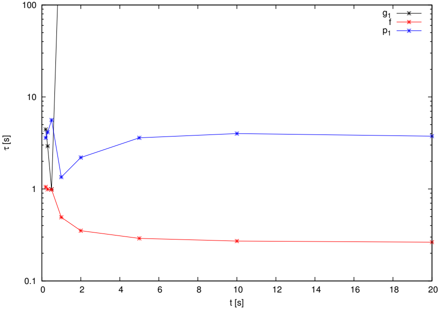
- low T core;
- high T envelope;
- trapped ν;
- inner core heating;
- cooling;
- deleptonization.

Figure: PNS evolution, GM3 EoS (my code).

Results: GW asteroseismology

I have reproduced the results of Ferrari, Miniutti & Pons, "Gravitational waves from newly born, hot neutron stars", MNRAS **342**:629–638 [2003] who determined the gravitational wave spectrum (from stellar oscillations) of a non-rotating PNS with GM3 EoS:





I am determining the gravitational wave spectrum for a PNS with nuclear many-body theory EoSs, convection, and rotation (work in progress, see next slides).

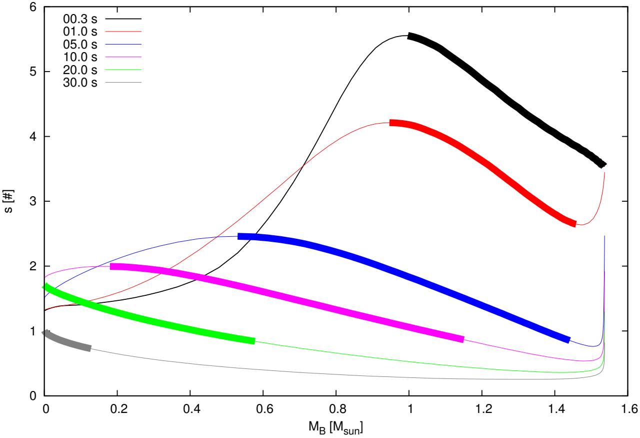
Work in progress: other EoS

Previous PNS evolution studies used relativistic mean-field EoSs.

I am implementing in the code new finite temperature nuclear many-body theory EoSs (NMBT, see Burgio, Ferrari, Gualtieri & Schulze, "Oscillation of hot, young neutron stars: Gravitational wave frequencies and damping times", PRD **84**:044017 [2011]) with a consistent determination of the neutrino diffusion coefficients and PNS evolution.

For this I need the NMBT EoS and the effective barion masses and potential (In collaboration with Omar Benhar, Alessandro Lovato & Fiorella Burgio)

Work in progress: convection



I am implementing the convection in the PNS evolution (using the mixing-lenght theory, e.g. Roberts et al., PRL **108**:061103 [2012]).

Work in progress: rotation

I am including the effects of rotation using the profiles obtained from my 1D code as an effective EoS for 2D structure codes (extending the results of Villain, Pons, Cerdá-Durán & Gourgoulhon, "Evolutionary sequences of rotating protoneutron stars", A&A **418**:283–294 [2004]).

I will consider slow differential rotation (in collaboration with Grégoire Martinon) and rapid differential rotation (in collaboration with Michael Jasiulek).

Conclusions

- new PNS evolution code to study the GW spectrum;
- nuclear many-body theory EoSs (work in progress);
- convection (work in progress);
- slow and rapid differential rotation (work in progress);
- postmerger hypermassive stars (?);

Thanks!

Contact: giovanni.camelio@roma1.infn.it