Scientific report of the STSM "Early evolution of newly born proto-neutron stars", carried on at the University of Alicante from May 4th, 2015 to May 29th, 2015

Giovanni Camelio
Supervisors: Valeria Ferrari *and* Leonardo Gualtieri
Host: José A. Pons

June 24, 2015

In my PhD I am studying the gravitational wave emission from the early evolution of proto-neutron stars (PNSs). Before the Short Term Scientific Mission (STSM) I had written a working code for the PNS evolution, similar to that of Pons et al. (1999), which was composed by the following parts.

1. Numerical resolution of the Tolman-Oppenheimer-Volkoff (TOV) equations to determine the PNS structure at each step of the quasi-stationary evolution.

2. Time evolution of the thermodynamical profiles (integrating the Boltzmann-Lindquist equations).

The thermodynamical profiles and the stellar structure are needed to compute, at each evolutionary step, the frequencies at which the star oscillates emitting gravitational waves (GWs).

1 Purpose of the STSM

The purpose of my STSM was to generalize the proto-neutron star evolutionary code that I wrote following Pons et al. (1999), to include an effective description of convection. This code will then be used to study how convection and rotation affect the PNS gravitational wave emission.

2 Description of the work and the results

During my stay at the University of Alicante,

1. I have terminated a code that computes the neutrino diffusion coefficients, necessary to evolve the PNS, from the Equation of State (EoS. More specifically, the code needs the particles chemical potentials and the barion effective masses and single particle potentials). The diffusion coefficients are determined by an integral in 3 dimensions. During my STSM I have improved the integration applying in different domains the Gaus-Legendre and Gaus-Laguerre quadrature.

2. I have improved the PNS evolution by debugging a thermodynamical inconsistency in the evaluation of the EoS. After this, the energy and the lepton number are conserved within few percents for all the evolution, which is a tipical benchmark for PNS evolutionary codes.

3. I have worked on the inclusion of convection in the evolution (from mixing lenght theory). Now my code is able to identify the parts of the PNS which subdue convection. Our former idea was to enhance the neutrino diffusion coefficients in the convective zones to account for convection in an effective way, using the neutrino convective velocity determined by mixing lenght theory. However, the convective velocity depends on the gradients of the barion number and the presure. Including these gradients explicitly (i.e., using the profiles from the previous time-step) results in noisy enhanced diffusion coefficients profiles which in turn cause a noisy PNS evolution. My previous (non-convective) code is semi-implicit, that is, I multiply the diffusion coefficients computed at the previous (explicit) time-step by the thermodynamical gradients computed at the next (implicit) time-step. In order to include convection in my code, I have to (i) smooth the explicit enhanced diffusion coefficients fitting them with a reasonable function or (ii) make the code fully implicit, at least in the determination of the gradients needed to compute the neutrino convective velocity. This part of the work is still in progress. However, adopting *ad hoc* profiles for the neutrino convective velocity and hence for the neutrino enhanced diffusion coefficients, I obtain a reasonable evolution.

3 Future collabortion and forseen publications

During the STSM I have strenghten my collaboration with J. A. Pons. With his help I have improved and generalized a PNS evolutionary code from which we expect to obtain at least 2/3 pubblications. In these pubblications we want to study the GW spectrum emitted by an evolving PNS varying some physical imputs, that is

- the underlying EoS. In particular, we want to study the changes due to the adoption of a nuclear many-body theory EoS (such as that of

Benhar or that of Burgio et al., 2011);

- the presence of convection;
- the magnetic field (introduced in an effective way in my 1D code);
- the rotation. We want to consider both rigid and differential rotation in an effective way, similarly to Villain et al. (2004). However, at variance with them, we want to study different EoSs and consider convection and magnetic field. We would also study in an approximate way the angular momentum evolution of the PNS.

4 Confirmation of the host institution

See the last page of this document.

References

Burgio, G. F., Ferrari, V., Gualtieri, L., and Schulze, H.-J. (2011). Oscillations of hot, young neutron stars: Gravitational wave frequencies and damping times. *PRD*, 84(4):044017.

Pons, J. A., Reddy, S., Prakash, M., Lattimer, J. M., and Miralles, J. A. (1999). Evolution of Proto-Neutron Stars. *ApJ*, 513:780–804.

Villain, L., Pons, J. A., Cerdá-Durán, P., and Gourgoulhon, E. (2004). Evolutionary sequences of rotating protoneutron stars. *A&A*, 418:283–294.

DEPARTAMENT DE FÍSICA APLICADA
Facultat de Ciències
Universitat d'Alacant
Ap. Correus 99, E-03080 Alacant

Universitat d'Alacant
Universidad de Alicante

May 28, 2015

To whom it may concern:

this is to certify that Giovanni Camelio, from the University of Rome, has been visiting our group in the Department of Physics of the University of Alicante during the period 4-29 May 2015.

Sincerely,

Prof. José A. Pons
Group of Relativistic Astrophysics