60th Karpacz Winter School on Theoretical Physics Hadronic matter and Equation of State

1 Neutron star EoS and TOV

1.1 Units in nuclear physics

energy: MeV

momentum: MeV/c

mass: MeV/c^2

length: fm

natural units $\hbar = c = 1$ with $\hbar c = 197.26$ MeV fm,

natural units MeV to fm^{-1}: 1MeV=1/197.26 fm^{-1}

energy density and pressure (E/V), p: MeV fm^{-3} or fm^{-4}.

baryonic density: fm^{-3}

1.2 Crust EoS

1. There are four data files containing baryonic density rho(fm^{-3}), energy density e (fm^{-4}) and pressure p (fm^{-4}). BPS is the outer crust. DH, NL3 and NL3wr are three inner crust EoS. DH is based on the non-relativistic Skyrme force SLy4 (L=46 MeV) and NL3 (L=118 MeV) and NL3wr (L=55 MeV) in relativistic mean field models (RMF).

2. Build the crust EoS matching the BPS EoS to any other of the three having the care that the EoS is an increasing function of rho, e and p. You may need to cut some points of the inner crust EoS. There is not total consistency but this does not affect properties as the mass and radius of a neutron star.

1.3 Crust-core EoS

1. Run the programs with beta-equilibrium implemented *nlwr_np.f* for npeμ matter and RMF with constant couplings.

2. the file fort.7 has the input for the TOV. Determine where the crust and the core EoS cross and cut the entries of the crust or the core EoS so that you get an increasing function of rho, e and p. Verify how sensitve are the M/R curves that result from the integration of the TOV equations to the inner crust.

1.4 TOV program

The program needs two input files: tov.inp and tov.dat

1. number of points> 1

   tov.inp

0.7	lowest central energy (fm^{-4}) - choose the lowest energy density. For the core we have $e > 0.1$
7.5	highest central energy (fm^{-4}) - choose the highest energy density: you should be able to get to the maximum of the M/R curve
200	number of points - number of stars calculated.

   (a) tov.dat - input of the complete EoS from very low densities to high densities. The data should be rho (fm^{-3}), energy density (fm^{-4}), pressure (fm^{-4}). for the program to know when to finish reading the data include in the last line -1. -1. -1.

   (b) output tov.out is: e_0, M, R, M_b, ρ_c (e_0 and ρ_c are the energy density and density at the center of the star, M and Mb are the gravitational and baryonic masses, R is the radius of the star)

   (c) output star.out : properties of the star with the largest mass

2. if number of points= 1 we will study the structure of the star with central energy density e_0

   tov.inp

3.	central energy density of the star (fm^{-4})
7.5	not important - not read
1	number of points

   (a) the output tov.out is : r, e, p, ρ_b

   (b) the output star.out: properties of the star with central energy e_0

1.5 Core-EoS for a fixed proton fraction

EoS for a fixed proton fraction is obtained from *nlwreos_karpacz.f*. You can run it for different proton fractions yp and compare the energy per particle, energy density and pressure as a function of density. Identify the proton fraction below which the imcompressibility is always positive. The program also calculates the properties of the EoS at saturation for symmetric nuclear matter ($E\_binding$, $K0$, $Q0$, $J = E_{sym}(\rho_0), L, K_{sym}, Q_{sym}$). In fort.60 the program ipar, rho0,EB, pressure, K0, Q0, Esym, L, Ksym, Qsym. All quantities in MeV except rho0 in fm^{-3} and pressure in MeVfm^{-3}

1.6 To run the programs

The programs are in Fortran... To compile them you can use gfortran. I generally do

```
>gfortran -o name_executable -w name.f
>./name_executable
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2 Exercises

1. Calculate the β-equilibrium EoS of models NL3, NL3wr, TM1, FSU2R, FSU2H and integrate the TOV equations. Make plots M versus R and M versus central baryonic density. Include the constraints: $M = 2.01 \pm 0.04 M_\odot$ (PSR J0348+0432), $M = 2.14^{0.10}_{0.09} M_\odot$ (MSP J0740+6620), $M = 1.908 \pm 0.016 M_\odot$ (PSR J1614-2230), with a mass $R(M_{1.4}) = 11.9 \pm 1.4$ km [Abbott et al (LIGO/Virgo collaboration), PRL121, 161101 (2018)]. Compare the radii of the NL3 (L=118 MeV) and NL3wr families and discuss the effect of L (L=55 MeV).

2. Run nlwreos_karpacz.f for yp=0.5 and compare the EoS of symmetric nuclear matter of the models ipar= NL3, NL3wr, TM1, FSU, FSU2R, FSU2H. In fort.60 the program ipar,rho0,EB,pressure, K0,Q0,Esym,L,Ksym, Qsym. All quantities in MeV except rho0 in fm^{-3} and pressure in MeVfm^{-3}

3. Run nlwreos_karpacz.f for yp=0.0 and compare the EoS of neutron matter of the models NL3, NL3wr, FSU, FSU2, FSU2R, FSU2H. Compare with the data of Hebeler *et al*, Astrophys.J. 773 (2013) 11, obtained from effective field theory, file $Hebeler\_NM.dat$ with baryonic density, lower and upper limit of the energy density.