Isospin asymmetry and neutron star properties

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Outline

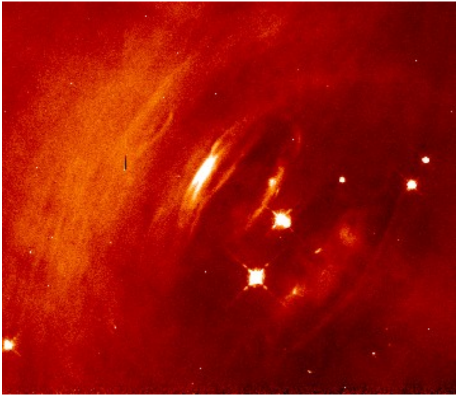
- Neutron stars - introductory remarks
- Characteristics of nuclear matter
- Neutron star matter
- Neutron star structure and parameters
- Macroscopic parameters of neutron stars - measurements of radii and masses
- Neutron-proton asymmetry and neutron star parameters
- Conclusions

Neutron-proton asymmetry - concerns both heavy nuclei and neutron stars.

Astrophysical aspects

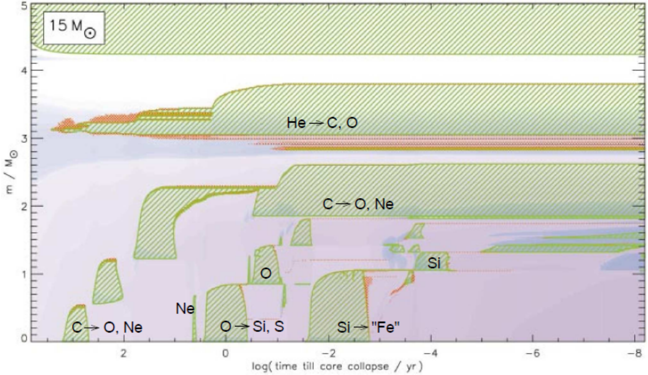
- Supernovae, proto-neutron stars
- Neutron stars
  - QPO
  - Neutron star cooling
  - X-ray bursters
  - Pulsars, millisecond pulsar
- Merger of binary neutron stars - source of short-duration gamma ray bursts or gravitational waves

HST - the center of the Crab Nebla



Introductory remarks

- Stellar evolution tends to produce central regions of very high density
- Stellar evolution can lead to somewhat extreme final stages
- Ejection of matter considered as significant factor in stellar evolution



Physical conditions in the iron core

- The equation of state $\frac{P}{\rho} \sim \frac{Y_e k_B T}{m_N} + K_\Gamma Y_e^\Gamma \rho^{\Gamma-1}$
- The hydrostatic equilibrium $P_c \sim fGM^{2/3}\rho_c^{4/3}$
- The central temperature in a contracting core $\frac{Y_e k_B T_c}{m_N} \sim fGM^{2/3}\rho_c^{1/3} - K_\Gamma Y_e^\Gamma \rho_c^{\Gamma-1}$
- The onset of Si burning $M_{Si,ig} \sim M_{Ch} \sim 5.83 Y_e^2 M_\odot$

The iron core of a $15M_\odot$ star at the onset of the collapse

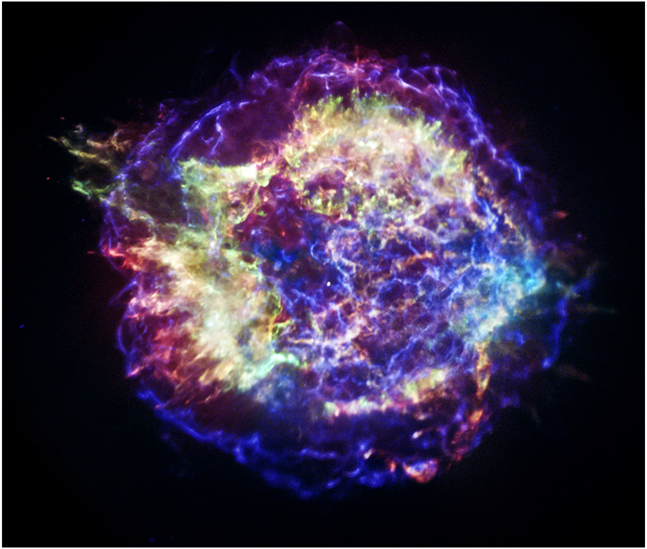
- $M_{core} \sim 1.5M_\odot$
- $T_{c,i} \sim 8 \times 10^9\mathrm{K}$
- $\rho_{c,i} \sim 3.7 \times 10^9 \mathrm{gcm}^{-3}$
- $Y_{e,i} \sim 0.42$

Processes that lead to dynamical instability of the core

- Partial dissociation of iron nuclei
- Neutronization

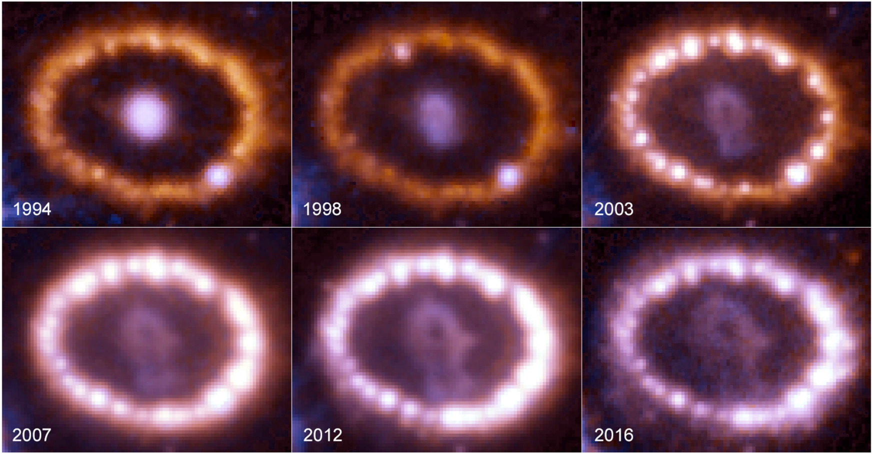
Core collapse supernova - Type II

Cassiopeia A



Core collapse supernova

The evolution of Supernova 1987A (NASA)



Dense nuclear matter

The equation of state of isospin asymmetric nuclear matter is a fundamental quantity that determines neutron star parameters at different stages of their evolution.

The estimation of the properties of nuclear matter from experiments and finding out the way they are related to the structure of neutron stars is one of the most important problem of both nuclear physics and astrophysics.

The equation of state of nuclear matter is a function of baryon density, temperature and composition (proton fraction)

- $\epsilon(n_b, Y_p) = \frac{E(n_b, Y_p)}{n_b}$
- $F(T, n_b, Y_p) = \frac{F(T, n_b, Y_p)}{n_b}$
- Neutron-proton asymmetry
  $f_a = \frac{n_n - n_p}{n_b} = 1 - 2Y_p$, where $Y_p = n_p/n_b$

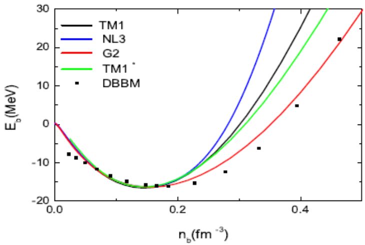
Symmetric nuclear matter (SNM)

Decomposition into an isospin-symmetric and isospin-asymmetric term

$$\varepsilon(n_B, Y_p) = \varepsilon(n_b, Y_p = 1/2) + E_{sym}(n_b)(1-2Y_p)^2 + Q(n_b)(1-2Y_p)^4 + \dots$$

Properties of SNM $\varepsilon(n_b, Y_p = 1/2)$

- Saturation density n_0: 0.16 fm^{-3}
- Energy per particle $\epsilon_0(n_0)$: -16 MeV
- Incompressibility $K(n_0)$: 210-240 MeV
- Symmetry energy $E_{sym}(n_0) \equiv S_v \sim 28 - 32$ MeV



Asymmetric nuclear matter

Symmetry energy is the most important factor for the equation of state of asymmetric nuclear matter.
The nuclear symmetry energy is defined as the difference in energy per nucleon of the symmetric matter $Y_p = 1/2$ and pure neutron matter $Y_p = 0$ (does not saturate). Symmetry energy parameters: Taylor expansion near n_0:

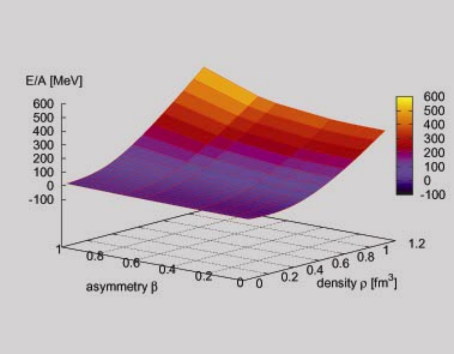
$$E_{sym}(n_b) \simeq S_v + \frac{L}{3n_0}(n_b - n_0) + \frac{K_s}{18n_0^2}(n_b - n_0)^2 + \dots$$

Density dependence of the symmetry energy:

- the symmetry energy increases monotonically with increasing density - stiff dependence
- the symmetry energy increases initially up to saturation density and then decreases at higher densities - soft dependence

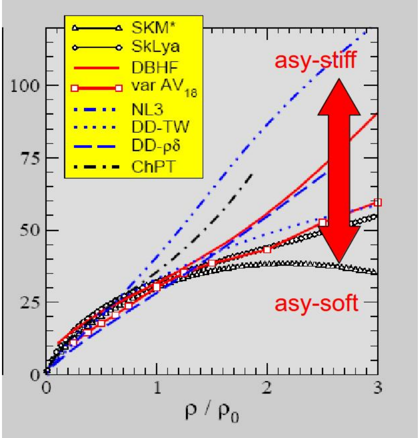
Asymmetric nuclear matter

Equation of state of asymmetric nuclear matter



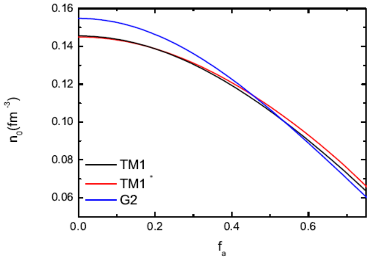
H. Wolter et.al, 2012

The density dependence of the symmetry energy predicted by different theoretical approaches



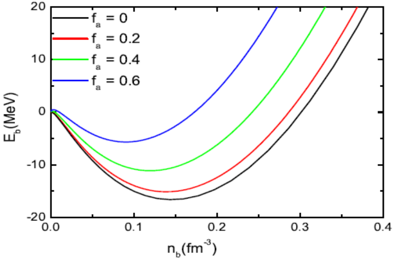
Near the saturation density n_0 the truncation to order f_a^2 is sufficient. The effect of the quartic term must be included for higher densities.

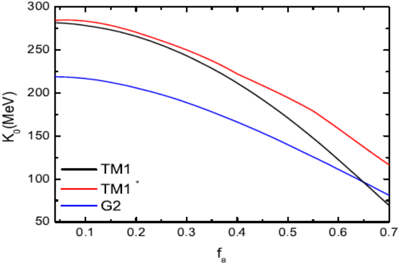
- Saturation density $n_0(f_a) = n_0 + n_{0,2} f_a^2 + n_{0,4} f_a^4, (n_{0,2} = -\frac{3L}{K_0}\rho_0)$
- Binding energy $E_{bin}(f_a) = E_{bin}(n_0) + E_{bin,2} f_a^2 + E_{bin,4} f_a^4$, $(E_{bin,2} = E_{sym}(n_0))$
- Incompressibility $K(f_a) = K_0 + K_2 f_a^2 + K_4 f_a^4$



Asymmetric nuclear matter - higher order effects

Saturation properties of asymmetric nuclear matter: the binding energy and incompressibility.





Macroscopic parameters of neutron stars: masses and radii and the equation of state

Equation of hydrostatic equilibrium:

$$\frac{d\mathcal{P}}{dr} = \frac{-G\left(\mathcal{E}(r)+\mathcal{P}(r)\right)\left(m(r)+4\pi r^3\mathcal{P}(r)\right)}{r^2\left(1-\frac{2Gm(r)}{r}\right)}$$

Supplemented by the equation of state (EoS) $\rightarrow \mathcal{P}(n_b) = \mathcal{P}(\mathcal{E}(n_n))$

- $M - R$ relations
- details about the internal structure of a neutron star for a given equation of state

- atmosphere
- outer crust - lattice of neutron-rich heavy nuclei, degenerate, relativistic electrons
- inner crust - as above plus degenerate non-relativistic neutrons
- outer core - homogeneous nucleonic matter
- inner core - may contain exotic forms of matter

Neutron star matter

- β-stable nuclear matter
  - $p + e^- \leftrightarrow n + \nu_e$
  - $n \leftrightarrow p + e^- + \bar{\nu}_e$
- $\sum_i Q_i n_i = 0$
- $\sum_i B_i n_i = n_b$

Equilibrium conditions:
$\mu_i = B_i \mu_i - Q_i \mu_e$.
Constituents of the neutron star matter:

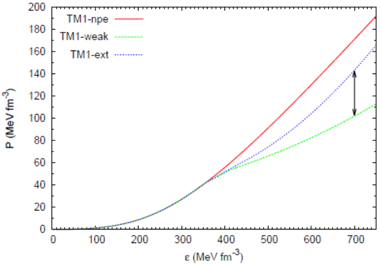
- baryons: nucleons + (Λ, Σ, Ξ)
- leptons
- mesons: σ, ω_μ, ρ^a_μ

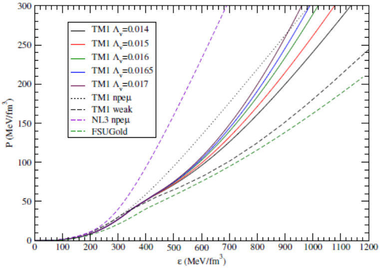
Nonlinear RMF model supplemented with couplings between isoscalar and isovector mesons

- allows for modification of the high density limit of the symmetry energy
- requires adjustment of parameters to reproduce the symmetry energy $E_{sym} = 25.68$ MeV at $n_b \sim 0.1 fm^{-3}$

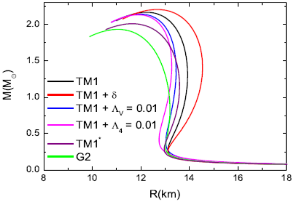
Equation of state:
$\varepsilon = \varepsilon^n_{kin} + \varepsilon^p_{kin} + \varepsilon_M$

Neutron star matter equations of state





Macroscopic parameters of neutron stars: masses and radii



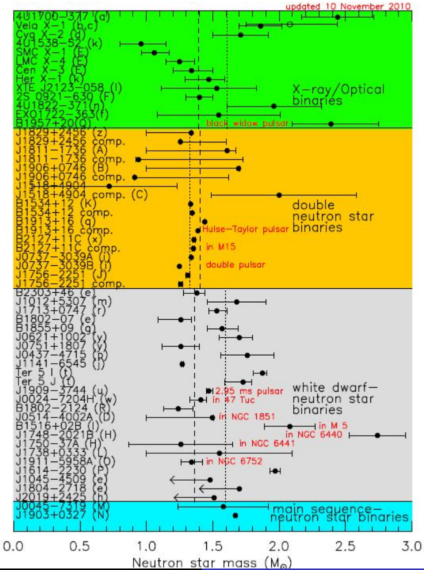
Parameter set	$M_{max}(M_\odot)$	$M_b(M_{max})(M_\odot)$	R(M_{max})(km)	ρ_c(g/cm^3)
TM1	2.17	2.51	12.21	7.64
TM1+δ	2.21	2.54	12.66	7.12
TM1+Λ_V	2.14	2.52	11.91	7.80
TM1+Λ_4	2.13	2.47	11.88	7.92
TM1*	2.01	2.30	11.60	8.52
TM1*+δ	2.06	2.35	12.11	7.92
G2	1.94	2.23	11.04	9.60
G2+δ	2.03	2.37	11.81	8.32

For calculated EoS there exists the maximum achievable neutron star mass M_{max}.
Maximum mass of a neutron star is a decisive factor for observational distinguishing between neutron stars and black holes.
The following condition has to be satisfied:
Measured neutron star masses $\leq M_{max}$

- Limits the value of a neutron star mass
- Constrains the equation of state of high density nuclear matter
    - lower value of M_{max} - softer equation of state - results obtained for binary neutron stars: $M_{obs} \sim 1.4 M_{\odot} \leq M_{max}$
    - higher value of $M_{obs} \simeq M_{max}$ - stiff equation of state, massive neutron stars: PSR J1614-2230 and PSR J0348+0432

Measurements of neutron star masses

J.M. Lattimer, M. Prakash



Neutron-proton asymmetry and neutron star parameters

Observational constraints

- Maximum and minimum masses - binary pulsars
- Minimum rotational period
- Radiation radius or redshift
- Neutron star thermal evolution - URCA or not
- X-ray bursts from accreting neutron stars
- Moment of inertia
- Proto-neutron star neutrinos (binding energy, opacities, radii)

J.M. Lattimer

Proton fraction in neutron star matter

$$\mu_n - \mu_p = 4E_{sym}(n_b)(1-2Y_p)$$

at saturation $n_b = n_0$

$$Y_p \approx \frac{1}{3\pi^2 n_0}\left(\frac{4S_v}{\hbar c}\right)^3 \approx 0.04$$

At higher densities, $Y_p(n_b)$ follows the behaviour of $E_{sym}(n_b)$

Pressure of nuclear matter for different value of the proton fraction

- Neutron star matter is nearly pure neutron matter at $n_b \simeq n_0$ and core-crust boundary just below saturation density

$$p_N(n_0) \simeq \frac{L}{3} n_0$$

- For matter in β-equilibrium

$$p_\beta(n_0) =\simeq \frac{L}{3} n_0 \left(1 - \left(\frac{4S_v}{\hbar c}\right)^3 \frac{4-3S_v/L}{3\pi^2 n_0} + \dots\right)$$

Correlations of neutron-proton asymmetry with basic neutron star properties

- pressure-radius correlation

$$R = C(n_b, M)(p_\beta / MeVfm^{-3})^{1/4}$$

- radius-slope correlation

$$R \approx 0.5 C(n_0, M) L^{1/4}$$

for $M = 1.4 M_\odot$, $C(n_0, M) \approx 9.3$

- compactness-slope correlations

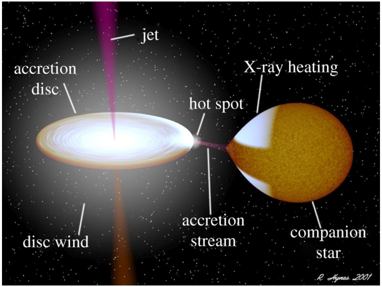
$$\beta = \frac{2GM}{C(n_0, M)} L^{-1/4}$$

- crust-core transition pressure
- the relative crust thickness, mass and moment of inertia

Measurements of neutron star radii

There are no precise simultaneous measurements of a neutron star mass and radius. Estimation of a neutron star radii - distant measurement and atmospheric modelling required.

Accreating neutron stars-LMXBs



J.C. Wheeler, 2011

Photospheric Radius Expansion Bursts

- Accreation from the companion (MS star) - overflowing the Roche lobe
- Unstable burning of the accreated material
- Spread of the nuclear burning accros stellar surface - sudden increase in X-ray luminosity and temperature
- X-ray bursts

The average neutron star mass and radius implied by these results: $\bar{M} = 1.65 \pm 0.12 M_{\odot}$, $\bar{R} = 10.77 \pm 0.65$

Neutron star cooling and the neutron-proton asymmetry

The critical density for the direct URCA process ($n \to p + e + \bar{\nu}_e$ and $p + e \to n + \nu_e$) is very sensitive to the number of protons in neutron star matter

The critical proton fraction

$$Y_p^{crit} = \frac{1}{1 + (1 + Y_{e,l}^{1/3})^3},$$

where $Y_{e,l} = n_e/(n_e + n_\mu)$. Fast cooling requires

$$Y_p > 0.12 - 0.14$$

only massive stars cool rapidly $M > 2M_\odot$

Parameter set	n_b(URCA)(fm^{-3})	ρ_c/ρ_0(URCA)	M(URCA)($\mathrm{M}_\odot$)
TM1	0.235	1.65	0.99
TM1+δ	0.207	3.65	2.01
TM1+Λ_V	0.303	2.17	1.19
TM1+Λ_4	0.314	2.29	1.24
TM1*	0.247	1.75	0.95
G2	0.273	1.95	0.91

Conclusions

- Different neutron star properties are sensitive to the neutron-proton asymmetry
- Results from terrestial experiments and astrophysical observations help to understand the form of the equation of state at different density ranges
- Detailed analysis may provide additional valuable constraints on the high density limit of the symmetry energy