Impact of the strangeness on the structure of a neutron star

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MATTER TO THE DEEPEST
Ustroń 2015

Introduction

Motivation

- Observations of the binary millisecond pulsars J1614-2230[a] and J0348+0432[b] have led to the precise estimation of neutron star masses: $(1.97 \pm 0.04)M_{\odot}$ and $(2.01 \pm 0.04)M_{\odot}$.
- This fact shifts the maximum neutron star mass towards rather high values and rules out most of the EoSs with hyperons - the models which involve exotic particles predict maximum neutron star masses well below $2M_{\odot}$.
- There is a need to analyze whether it is possible to construct an EoS of neutron star matter which gives adequately high maximum mass despite including hyperons[c].

[a] P. Demorest et al., Nature **467**, 1081 (2010)
[b] J. Antoniadis et al., Science **340**, 6131 (2013)
[c] I. Bednarek et al., *A&A* **543**, A157 (2012)

Lagrangian of the model

$$
\begin{aligned}
\mathcal{L} &= \sum_B \overline{\psi}_B \left(\gamma^\mu i D_\mu - m_{eff,B}\right)\psi_B + \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_3\sigma^3 - \frac{1}{4}g_4\sigma^4 \\
&+ \frac{1}{2}\partial^\mu\sigma^*\partial_\mu\sigma^* - \frac{1}{2}m_{\sigma^*}^2\sigma^{*2} - \frac{1}{2}m_\omega^2(\omega^\mu\omega_\mu) + \frac{1}{2}m_\rho^2(\rho^{\mu a}\rho_\mu^a) + \frac{1}{2}m_\phi^2(\phi^\mu\phi_\mu) \\
&- \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} - \frac{1}{4}R^{\mu\nu a}R^a_{\mu\nu} - \frac{1}{4}\Phi^{\mu\nu}\Phi_{\mu\nu} \\
&+ \Lambda_V(g_{N\omega}g_{N\rho})^2(\omega^\mu\omega_\mu)(\rho^{\mu a}\rho_\mu^a) + \sum_{l=e,\mu,\nu}\overline{\psi}_l(i\gamma^\mu\partial_\mu - m_l)\psi_l \\
&+ \frac{1}{4}c_3(\rho^{\mu a}\rho_\mu^a)^2 + \frac{1}{4}\left(\frac{1}{2}c_3 + \Lambda_V(g_{N\omega}g_{N\rho})^2\right)(\phi^\mu\phi_\mu)^2 \\
&+ \frac{1}{2}\left(\frac{3}{2}c_3 - \Lambda_V(g_{N\omega}g_{N\rho})^2\right)(\omega^\mu\omega_\mu + \rho^{\mu a}\rho_\mu^a)(\phi^\mu\phi_\mu),
\end{aligned}
$$

where the covariant derivative equals $D_\mu = \partial_\mu + ig_{B\omega}\omega_\mu + ig_{B\phi}\phi_\mu + ig_{B\rho}\mathbf{I}_B\boldsymbol{\rho}_\mu$, $\mathbf{I}_B$ denotes isospin of baryon B. The baryon effective mass is defined as follows $m_{eff,B} = m_B - g_{B\sigma}\sigma - g_{B\sigma^*}\sigma^*$, while $\Omega_{\mu\nu}$, $\mathbf{R}_{\mu\nu}$, and $\Phi_{\mu\nu}$ are the field tensors of the ω, ρ, and ϕ mesons.

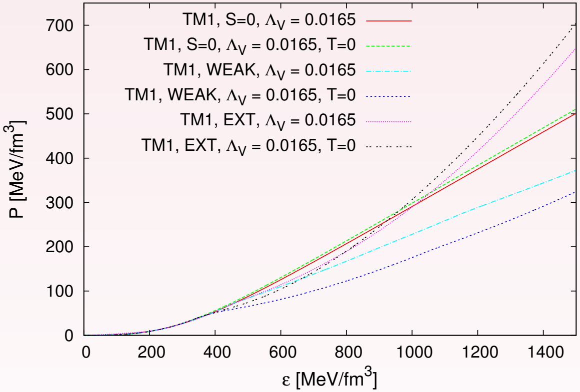
Phases of neutron star evolution

In the simplified scenario it is possible to distinguish three different cases and each of them is represented by relevant physical conditions of a proto-neutron and neutron star matter.

Simplified scheme of the evolutionary track of a neutron star

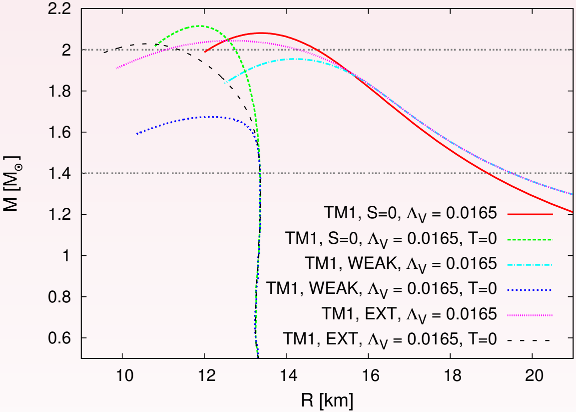
- The post bounce phase - the unshocked inner core settles into a hydrostatic equilibrium. Model that describes this phase of evolution is constructed on the basis of the following assumptions: the low-entropy core with trapped neutrinos is surrounded by a high entropy ($s = 2 - 5$) envelope. The neutrino trapping leads to initially high value of the lepton number $Y_{l_e} = (n_e + n_{\nu_e})/n_b \simeq 0.4$.
- The deleptonization of the core after which the matter of the core is neutrino-free $Y_{\nu_e} = 0$ with the entropy $s = 2$. Thermally produced neutrino pairs of all flavours are abundant. The cooling of the hot neutron star takes place.
- Cold, catalysed object.

Equations of State

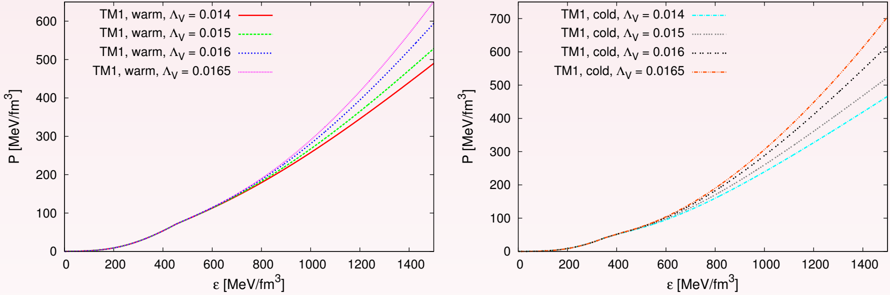


EoSs calculated for a proto-neutron star matter with trapped neutrinos and for a cold neutrino-free matter (T=0), in the case of nuclear matter (S=0) and in the case of hyperon-rich matter. The softest EoSs for strangeness rich neutron star matter represent the case of TM1-weak model, while the stiffest EoSs correspond to results obtained for the extended nonlinear model. Calculations have been done for chosen value of $\Lambda_V = 0.0165$ parameter.

Mass – radius relations

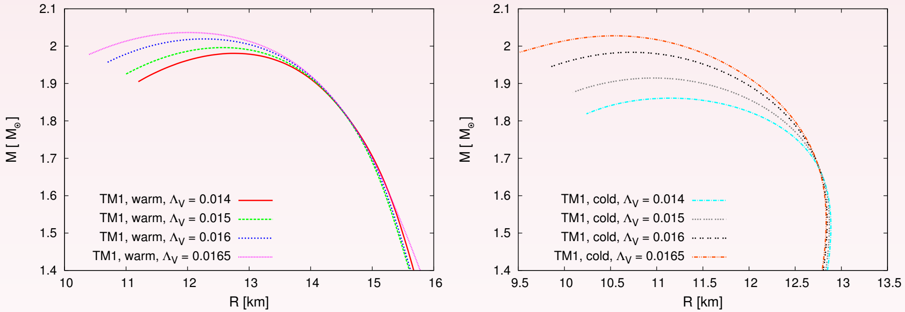


The mass–radius relations calculated for chosen value of $\Lambda_V = 0.0165$ parameter, in the case of warm proto-neutron star with $Y_{le} = 0.4$ and in the case of cold deleptonized neutron star. The maximum mass value obtained for the extended nonlinear model is much larger than the value obtained for the minimal TM1-weak model, in the case of cold hyperon star as well as in the case of warm strangeness-rich proto-neutron star.

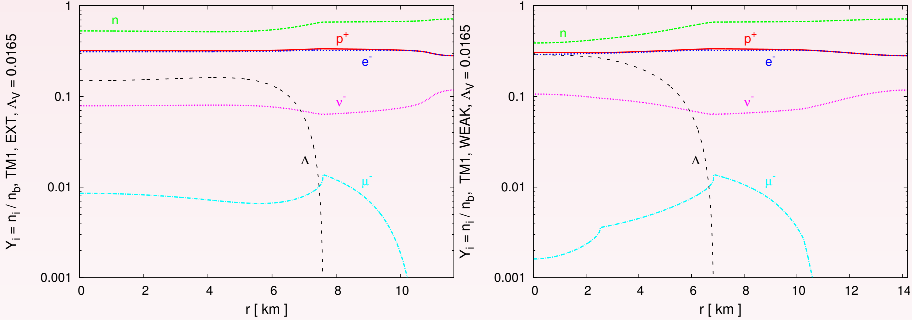


The EoSs calculated for models with different vector meson coupling terms.
Results have been obtained for different values of Λ_V parameter.
Left panel: warm proto-neutron star matter with trapped neutrinos.
Right panel: cold, deleptonized neutron star matter.
In both cases the increase of parameter Λ_V leads to the stiffening of the EoS.

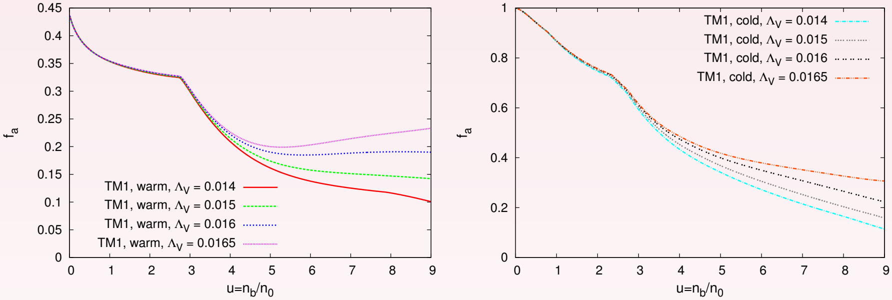
Mass – radius relations



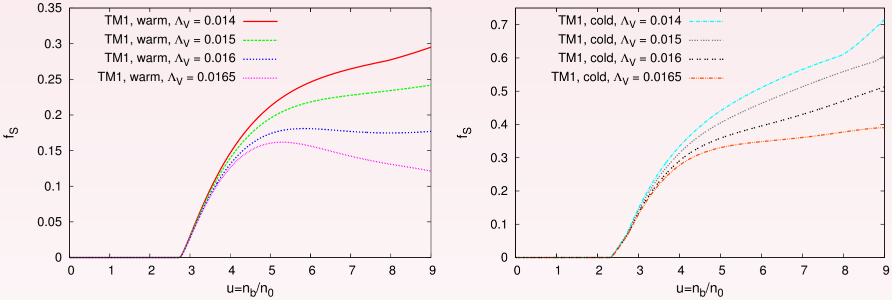
The mass–radius relations calculated for the nonlinear model for different values of parameter Λ_V.
Left panel: warm proto-neutron star matter with trapped neutrinos.
Right panel: cold, deleptonized neutron star matter.
The increase of parameter Λ_V gives higher values of maximum mass even close to $2M_\odot$.



The particle fraction Yi as a function of the radius of the proto-neutron star, for the maximum mass configuration.
Left panel: the extended nonlinear model with $\Lambda_V = 0.0165$. The hyperon core includes only Λ hyperons, $M_{hc} = 1.22 M_{\odot}$, $R_{hc} = 7.57 km$.
Right panel: the TM1-weak model with $\Lambda_V = 0.0165$. In this case the hyperon core icludes only Λ hyperons, $M_{hc} = 0.76 M_{\odot}$, $R_{hc} = 6.84 km$.



The asymmetry parameter $f_a = \frac{n_n - n_p}{n_b}$ as a function of baryon number density calculated for different values of Λ_V.
Left panel: warm proto-neutron star matter with trapped neutrinos.
Right panel: cold, deleptonized neutron star matter.
The differences in the asymmetry parameter between the proto-neutron and neutron star matter is connected with the fixed high value of the electron lepton number for warm, neutrino-trapped matter.

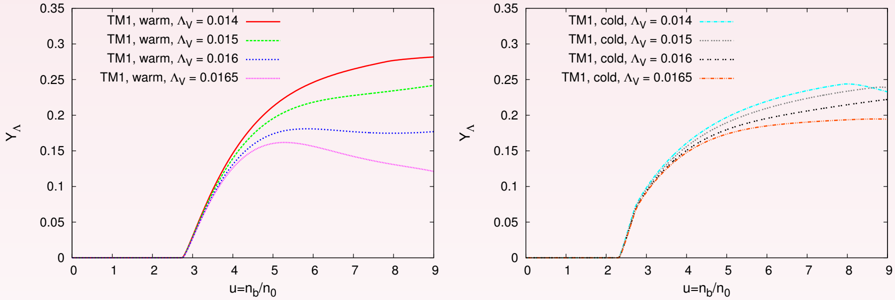


The strangeness content of the system $f_S = \sum_B \frac{S \cdot n_B}{n_b}$ as a function of baryon number density calculated for different values of Λ_V.

Left panel: warm proto-neutron star matter with trapped neutrinos.

Right panel: cold, deleptonized neutron star matter.

In the case of warm, neutrino-trapped matter the hyperons are less abundant and their onset point is shifted to higher density. Increase in the value of the parameter Λ_V leads to the matter with considerably reduced strangeness content.

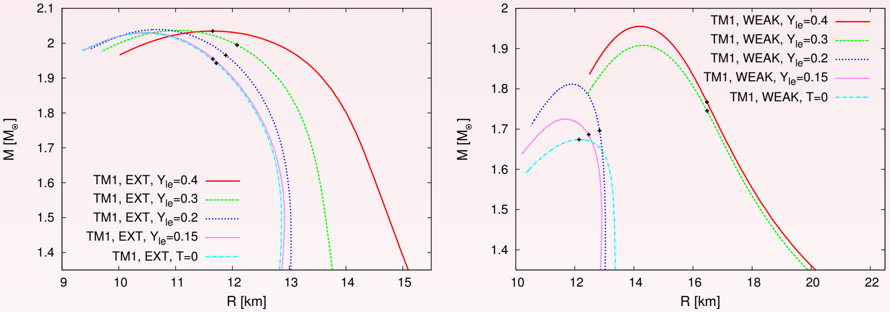


The relative concentration of Λ hyperons as a function of baryon number density calculated for different values of Λ_V.

Left panel: warm proto-neutron star matter with trapped neutrinos.

Right panel: cold, deleptonized neutron star matter.

In both cases it is evident that the increase of Λ_V parameter leads to reduced concentration of Λ hyperons.



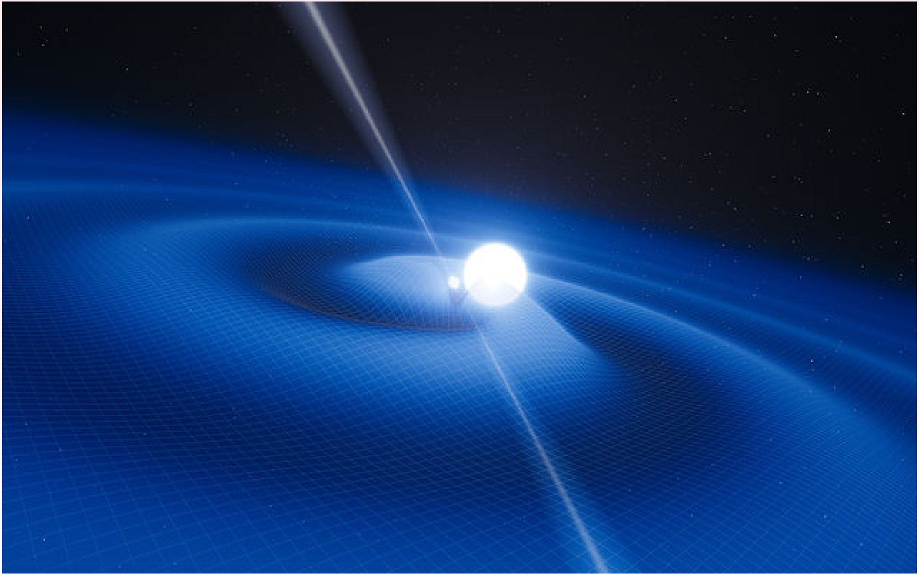
The M-R relations calculated for different stages of neutron star evolution for the chosen value of parameter $\Lambda_V = 0.0165$.

Left panel: the extended nonlinear model - black points illustrate the evolutionary path of proto-neutron star starting with the phase when $Y_{le} = 0.4$. The proto-neutron star in the maximum mass configuration evolves into stable cold deleptonized neutron star.

Right panel: the TM1-weak model - the evolutionary sequence for choosen star which leads to the maximum mass configuration of cold neutron star $(T = 0)$. In this case there exist non-stable configurations and it is possible to collapse into a black hole.

Conclusions

- Analysis of the results obtained for the matter of proto-neutron stars with nonzero strangeness indicates a clear stiffening of the EoS in the case of extended nonlinear model.
- Comparing the mass-radius relations obtained for the minimal TM1-weak model and the extended nonlinear model, a significant increase in mass of the star is evident ($M^{ext}_{max} \approx 2M_{\odot}$).
- For the maximum mass configuration a proto-neutron star model with the extended vector meson sector (EXT) results in a hyperon core with a much larger mass and radius.
- When a proto-neutron star includes hyperons there exists the possibility that during the process of deleptonisation the star loses stability and collapses to the black hole.



Artist's impression of the pulsar PSR J0348+0432 and its white dwarf companion.
http://www.eso.org/public/images/eso1319c/

TM1 parameter set[1] with the extended isovector sector

TM1		
m_σ = 511.2 MeV	g_σ = 10.029	g_3 = 7.2325 fm^{-1}
m_ω = 783 MeV	g_ω = 12.614	g_4 = 0.6183
m_ρ = 770 MeV	g_ρ = 9.264	c_3 = 71.0375

TM1 nonlinear (isovector sector)						
Λ_V	0	0.014	0.015	0.016	0.0165	0.017
g_ρ	9.264	9.872	9.937	10.003	10.037	10.071
L (MeV)	108.58	77.52	75.81	74.16	73.36	72.56

[1] Y. Sugahara and H. Toki, Prog. Theor. Phys. **92**, 803 (1994)