Neutron stars subject to density dependent magnetic fields

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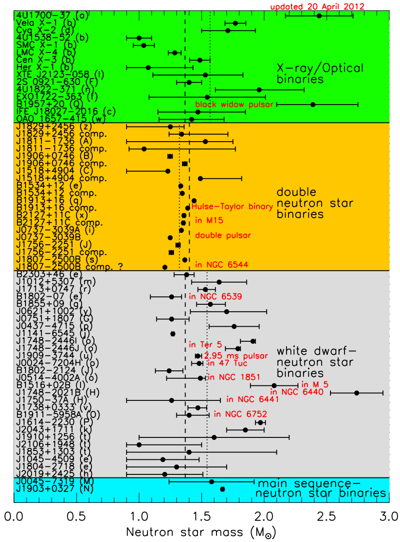
Assignment

- Motivation
  - Introduction
  - Non-Linear Walecka Model
  - Inclusion of hyperons
- Results
  - Effects of magnetic field on the hyperon matter
- Summary

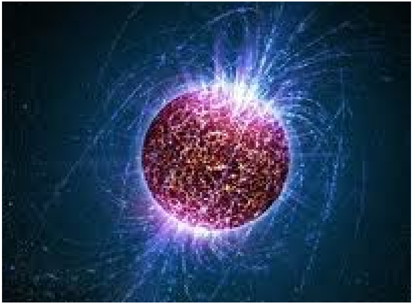


Neutron Stars:

- Masses typically stand around $1.4 - 2.5\ M_0$
- Radius of about 12 km (rather hard to measure!)
- Extremely dense.
- Related to the pulsars
- Magnetic fields of the order of $B = 10^{12}\ G$

*Lattimer, J.M. Ann.Rev.Nucl.Part.Sci.Vol. 62: 485-515 (2012)

Magnetars:



- Young NS
- Magnetic fields of the order of $B = 10^{17} - 10^{18}\ G^{+}$
- Source of high-energy electromagnetic radiation emissions
- Soft Gamma-ray Repeaters (SGRs)
- Anomalous X-ray pulsars (AXPs).

*Casey Reed/Penn State U.

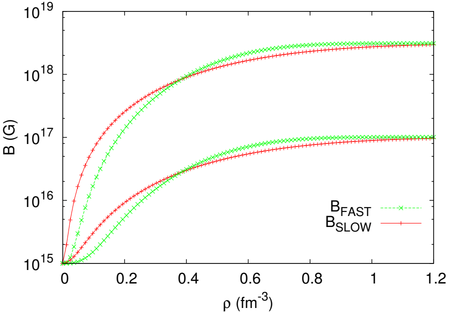
$^{+}$Huang et al., Phys. Rev. D 81, 045015 (2010)

- Composition of neutron stars (NS) remains under discussion. (nuclear matter? hyperon matter?)
- May magnetars/NS be made of hyperon matter?
- What are the effects of the inclusion of magnetic fields?
- May low-Magnetized (10^{17} G) hyperon matter describe NS? (hyperon matter composed magnetars?)
- May High-magnetized (10^{18} G) hyperon matter describe NS? (hyperon matter composed magnetars?)
- What about two solar mass NS?

Density dependent magnetic field $B\left(\frac{\rho}{\rho_0}\right)$:

$$B\left(\frac{\rho}{\rho_0}\right) = B_{\rm surf} + B_0\left\{1 - \exp\left[-\beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}\right]\right\}, \qquad (1)$$

- $B_{surf} = 10^{15}\ G$
- $B_0 = 10^{17}$ a $3.1 \times 10^{18}\ G$
- Fast decay: $\gamma = 3$, $\beta = 0.02$
- Slow decay: $\gamma = 2$, $\beta = 0.05$



Non-linear Walecka Model:

$$\mathcal{L} = \sum_b \mathcal{L}_b + \mathcal{L}_m + \mathcal{L}_B + \sum_l \mathcal{L}_l \tag{2}$$

$$\mathcal{L}_b = \sum_{b=n,p,hyp} \overline{\psi}_b [\underbrace{i\gamma_\mu \partial^\mu}_{\text{Kinetic term}} + \overbrace{q_b \gamma_\mu A^\mu}^{\text{Lorentz}} - \underbrace{g_{\rho b} \tau_{3b} \gamma_\mu \vec{\rho}^\mu}_{\rho\text{-field coupling}} - \overbrace{m_b^*}^{\sigma\text{-field coupling}} \tag{3}$$

$$- \underbrace{g_{\omega b} \gamma_\mu \omega^\mu}_{\omega\text{-field coupling}} - \underbrace{\frac{1}{2} \mu_N k_b \sigma_{\mu\nu} F^{\mu\nu}]}_{\text{AMM-term}} \psi_b$$

Non-linear Walecka Model:

$$\mathcal{L}_m = \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) - \overbrace{\frac{1}{3} b m_n (g_{\sigma b}\sigma)^3 - \frac{1}{4} c (g_{\sigma b}\sigma)^4}^{\text{Scalar self-interaction}} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - \underbrace{\frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu}}_{\omega\text{-field tensor}} + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu - \underbrace{\frac{1}{4}\mathbf{P}^{\mu\nu}\mathbf{P}_{\mu\nu}}_{\rho\text{-field tensor}} \quad (4)$$

$$\mathcal{L}_B = -\underbrace{\frac{1}{4} F^{\mu\nu} F_{\mu\nu}}_{\text{EM-field tensor}} \quad (5)$$

$$\mathcal{L}_l = \sum_{l=e,\mu} \overline{\psi}_l [i\gamma_\mu \partial^\mu + q_l \gamma_\mu A^\mu - m_l] \psi_l \quad (6)$$

Important:

- Relativistic mean field approach.
- β-equilibrium.
- Charge neutrality.
- EoS from Euler-Lagrange equations.

The inclusion hyperons:

The hyperon coupling constants[1]:

$$-\underbrace{g_{\rho H}\tau_{3b}\gamma_\mu\vec{\rho}^{\mu}}_{\rho\text{-field coupling}} - \overbrace{(m_b - g_{\sigma H}\sigma)}^{\sigma\text{-field coupling}} - \underbrace{g_{\omega H}\gamma_\mu\omega^{\mu}}_{\omega\text{-field coupling}} \qquad (7)$$

$$X_\sigma = g_{\sigma H}/g_{\sigma N}, \quad X_\omega = g_{\omega H}/g_{\omega N}, \quad X_\rho = g_{\rho H}/g_{\rho N},$$

	$X_\sigma = 0.6$	$X_\sigma = 0.7$	$X_\sigma = 0.8$
X_σ	0.600	0.700	0.800
X_ω	0.653	0.783	0.913
X_ρ	0.653	0.783	0.913

[1] Glendenning N. K.,Compact Stars. 1° edition. University of California. Springer- Verlag: New-York, USA (2000).

The inclusion of magnetic fields B_0:

- Landau quantization: Quantization of the cyclotron orbits of charged particles in magnetic fields. Only discrete energy value orbits are allowed[2].
- AMM: Difference between theoretical and experimental values founded for the magnetic moment[3] of particles.

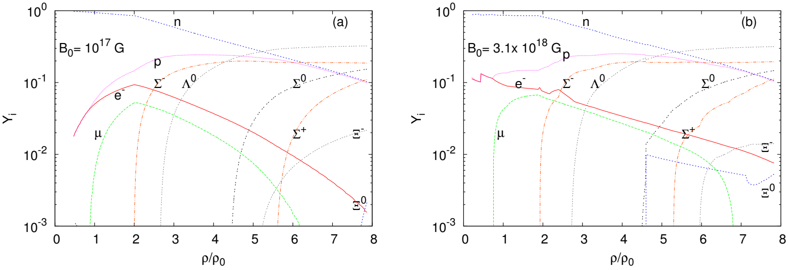
Baryon	p	n	Λ^0	Σ^+	Σ^0	Σ^-	Ξ^0	Ξ^-
k_b	1.79	-1.91	-0.61	1.67	1.61	-0.38	-1.25	0.06

- $\kappa_{b=0}$ - No inclusion of AMM
- $\kappa_{n,p}$ - Inclusion of AMM for neutrons and protons
- $\kappa_{n,p,hyp}$ - Inclusion of AMM for neutrons, protons and all hyperons

[2] Landau, L. D.; E. M. Lifshitz (1977). Quantum Mechanics: Nonrelativistic Theory. Pergamon Press.

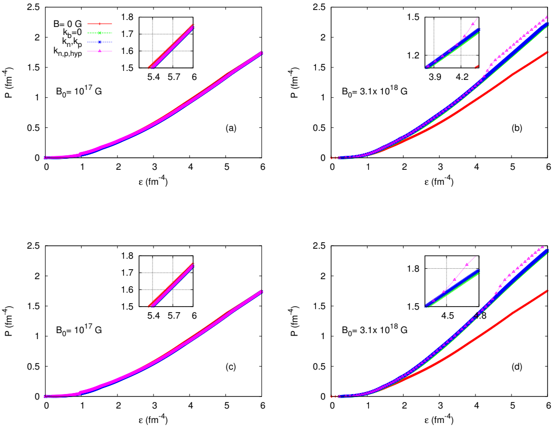
[3] Schwinger J. Phys. Rev. 73, 416 (1947). Kush P., Foley H. M. Phys. Rev. 74, 250 (1947).

Particle fractions - $k_{n,p,hyp}$.



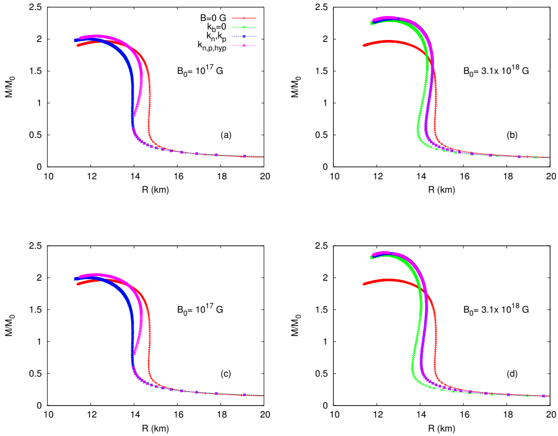
- From (a) $B_0 = 10^{17}$ G to (b) $B_0 = 3.1 \times 10^{18}$ G: Kinks produced on populations of charged particles, due to the filling of Landau levels.

Equations of state - slow: panels (a) and (b), fast: panels (c) and (d).



- $B_0 = 10^{17}$ G: No big deal.
- $B_0 = 3.1 \times 10^{18}$ G: Stiffening on fast and slow decays.
- Progressive stiffening with AMM corrections, on zoom box.
- Evident $k_{n,p,hyp}$ effect at higher ε.

Mass-radius relation - slow: panels (a) and (b), fast: panels (c) and (d).



- $B_0 = 10^{17}$ G: No big deal.
- $B_0 = 3.1 \times 10^{18}$ G: From slow to fast, higher M_{max} and lower R for all AMM conditions.

Results[4]

Magnetic Field	AMM	SLOW					
		M_{max} (M_0)	R (km)	ε_c (fm^{-4})	$\mu_n(\varepsilon_c)$ (MeV)	$\mu_e(\varepsilon_c)$ (MeV)	R($M = 1.4\ M_0$) (km)
$B = 0\ G$		1.97	12.55	5.29	1417.9	93.9	14.69
$B_0 = 10^{17}\ G$	$\kappa_b = 0$	2.00	11.87	5.93	1577.5	122.1	13.90
	$\kappa_{n,p}$	2.00	11.87	5.93	1577.5	122.1	13.91
	$\kappa_{n,p,hyp}$	2.04	12.24	5.56	1549.3	131.4	14.33
$B_0 = 3.1 \times 10^{18}\ G$	$\kappa_b = 0$	2.29	12.58	5.11	1446.1	150.2	14.29
	$\kappa_{n,p}$	2.32	12.77	4.97	1436.7	150.2	14.55
	$\kappa_{n,p,hyp}$	2.33	12.54	5.25	1464.8	150.2	14.55

Magnetic Field	AMM	FAST					
		M_{max} (M_0)	R (km)	ε_c (fm^{-4})	$\mu_n(\varepsilon_c)$ (MeV)	$\mu_e(\varepsilon_c)$ (MeV)	R($M = 1.4\ M_0$) (km)
$B = 0\ G$		1.97	12.55	5.29	1417.9	93.9	14.69
$B_0 = 10^{17}\ G$	$\kappa_b = 0$	2.00	11.87	5.93	1577.5	122.1	13.90
	$\kappa_{n,p}$	2.00	11.87	5.93	1577.5	122.1	13.91
	$\kappa_{n,p,hyp}$	2.04	12.24	5.56	1549.3	131.4	14.34
$B_0 = 3.1 \times 10^{18}\ G$	$\kappa_b = 0$	2.36	12.37	5.27	1427.3	150.2	14.02
	$\kappa_{n,p}$	2.38	12.53	5.16	1417.9	159.6	14.23
	$\kappa_{n,p,hyp}$	2.39	12.38	5.34	1436.7	150.2	14.23

[4] R.H. Casali, L.B. Castro, D.P. Menezes Phys. Rev. C 89, 015805 (2014).

Conclusions

- $B_0 = 10^{17}$ G: Do not differ considerably from nonmagnetized results.
- $B_0 = 3.1 \times 10^{18}$ G:
  - Maximum masses increase with inclusion of AMM.
  - Fast decay mode yields larger maximum masses.
  - ε_c do not present a common pattern.
  - $\mu_n(\varepsilon_c) < 1500$ MeV for all fast and slow curves.
  - The model and constants chosen were able to describe 2 $M_\odot$ NS.

Conclusions

- 1.4 $M_\odot$ NS: Although some predictions of R=9.7-13.9 km[5], R=$9.1^{+1.3}_{-1.5}$ km[6] and R=10-13.1 km[7] for the radii, for us it depends on the choice of the magnetic field decay rate (γ, β).

[5] K. Hebeler, J. M. Lattimer, C. J. Pethick and A. Schwenk, Phys. Rev. Lett. **105** (2010) 161102.

[6] S. Guillot, M. Servillat, N. A. Webb and R. E. Rutledge, ApJ **772** (2013) 7.

[7] J. M. Lattimer and A. W. Steiner, arXiv:1305.3242[astro-ph.HE]

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- Thanks to:

- And thank you!

Non-linear Walecka Model:

- The index b=H (Hyperons) or b=N (Nucleons)
- (ψ_b) - Baryon field
- (ψ_l) - Lepton field
- (σ) - Scalar meson
- (ω^μ) - Vectorial meson
- (ρ^μ) - Isovetorial meson
- $g_{\sigma b}$, $g_{\omega b}$, $g_{\rho b}$ - Coupling constants between baryon and meson
- $A^\mu = (V, \vec{A})$ - Lorentz tensor
- k_b - Anamalous magnetic momento (AMM)
- τ_{3b} - Isospin projection
- q_b - Eletric charge of the particle b.
- μ_N - Nuclear magnetum.
- μ_b - Bohr magnetum.

Non-linear Walecka Model:

- $m_b^* = (m_b - g_{\sigma b}\sigma)$ - Baryon effective mass
- $\Omega_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu$
- $\mathbf{P}_{\mu\nu} = (\partial_\mu \vec{\rho}_\nu - \partial_\nu \vec{\rho}_\mu) + g_{\rho N}(\vec{\rho}_\mu \times \vec{\rho}_\nu)$
- $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
- $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$ - Electromagnetic tensor
- γ_μ - Dirac matrices
- ξ - Omega-méson self-interaction parameter
- Λ_ω - Parameter the modifies the density dependence of the symmetry energy
- b e c - Related with the weight of the non-linear scalar terms

Densities:

$$\rho_b^s = \frac{|q_b| B m_b^*}{2\pi^2} \sum_{\nu}^{\nu_{\max}} \sum_s \frac{\bar{m}_b^c}{\sqrt{m_b^{*2} + 2\nu |q_b| B}} \ln \left| \frac{k_{F,\nu,s}^b + E_F^b}{\bar{m}_b^c} \right|, \tag{8}$$

$$\rho_b^v = \frac{|q_b| B}{2\pi^2} \sum_{\nu}^{\nu_{\max}} \sum_s k_{F,\nu,s}^b , \quad \rho_b^s = \frac{m_b^*}{4\pi^2} \sum_s \left[E_F^b k_{F,s}^b - \bar{m}_b^2 \ln \left| \frac{k_{F,s}^b + E_F^b}{\bar{m}_b} \right| \right],$$

$$\rho_b^v = \frac{1}{2\pi^2} \sum_s \left[\frac{1}{3} (k_{F,s}^b)^3 \right.$$

$$\left. - \frac{1}{2} s \mu_N k_b B \left(\bar{m}_b \, k_{F,s}^b + (E_F^b)^2 \left(\arcsin \left(\frac{\bar{m}_b}{E_F^b} \right) - \frac{\pi}{2} \right) \right) \right].$$

Densities:

$$m_b^* = m_b - g_\sigma \sigma$$
$$\bar{m}_b^c = \sqrt{m_b^{*2} + 2\nu |q_b| B} - s\mu_N k_b B,$$
$$\bar{m}_b = m_b^* - s\mu_N k_b B,$$

$\nu = n + \frac{1}{2} - \mathrm{sgn}(q_b)\frac{s}{2} = 0, 1, 2, ...$ are the Landau levels for the fermions with electric charge q_b, s is the spin and assumes values $+1$ for spin up and -1 for spin down cases.

Energy spectra:

$$E_{\nu,s}^{b} = \sqrt{(k_z^b)^2 + (\sqrt{m_b^{*2} + 2\nu|q_b|B} - s\mu_N k_b B)^2} + g_{\omega b}\omega^0 \qquad (9)$$

$$+\tau_{3b} g_{\rho b}\rho^0$$

$$E_s^b = \sqrt{(k_z^b)^2 + (\sqrt{m_b^{*2} + (k_\perp^b)^2} - s\mu_N k_b B)^2} + g_{\omega b}\omega^0 + \tau_{3b} g_{\rho b}\rho^0.$$

Momentum and leptonic density:

$$(k_{F,\nu,s}^{b})^2 = (E_{F,\nu,s}^{b})^2 - (\bar{m}_b^c)^2 \tag{10}$$
$$(k_{F,s}^{b})^2 = (E_{F,s}^{b})^2 - \bar{m}_b^2$$
$$(k_{F,\nu,s}^{l})^2 = (E_{F,\nu,s}^{l})^2 - \bar{m}_l^2\,, \qquad l = e, \mu,$$

$$\rho_l^v = \frac{|q_l|B}{2\pi^2} \sum_{\nu}^{\nu_{\max}} \sum_{s} k_{F,\nu,s}^{l}, \tag{11}$$

Landau levels:

$$\nu_{\max} = \left[\frac{(E_F^l)^2 - m_l^2}{2|q_l|B} \right], \qquad \text{leptons} \tag{12}$$

$$\nu_{\max} = \left[\frac{(E_F^b + s\mu_N k_b B)^2 - m_b^{*2}}{2|q_b|B} \right], \qquad \text{charged baryons.}$$

Chemical potencials:

$$\mu_b = E_F^b + g_{\omega b}\omega^0 + \tau_{3b} g_{\rho b}\rho^0, \qquad (13)$$
$$\mu_l = E_F^l = \sqrt{(k_{F,\nu,s}^l)^2 + m_l^2 + 2\nu |q_l| B}\,.$$

EoS:

$$\varepsilon_m = \sum_b (\varepsilon_b^c + \varepsilon_b^n) + \frac{1}{2} m_\sigma \sigma_0^2 + U(\sigma) + \frac{1}{2} m_\omega \omega_0^2 + \frac{1}{2} m_\rho \rho_0^2 \,, \tag{14}$$

EoS:

$$\varepsilon_b^c = \frac{|q_b|B}{4\pi^2}\sum_{\nu}^{\nu_{\max}}\sum_s\left[k^b_{F,\nu,s}E^b_F + (\bar{m}^c_b)^2\ln\left|\frac{k^b_{F,\nu,s}+E^b_F}{\bar{m}^c_b}\right|\right], \quad (15)$$

$$\varepsilon_b^n = \frac{1}{4\pi^2}\sum_s\left[\frac{1}{2}k^b_{F,\nu,s}(E^b_F)^3 - \frac{2}{3}s\mu_N k_b B(E^b_F)^3\left(\arcsin\left(\frac{\bar{m}_b}{E^b_F}\right)-\frac{\pi}{2}\right)\right.$$
$$\left. - \left(\frac{1}{3}s\mu_N k_b B + \frac{1}{4}\bar{m}_b\right)\left(\bar{m}_b k^b_{F,\nu,s}E^b_F + \bar{m}_b^3\ln\left|\frac{E^b_F + k^b_{F,\nu,s}}{\bar{m}_b}\right|\right)\right].$$

EoS:

$$\varepsilon_l = \frac{|q_l|B}{4\pi^2} \sum_l \sum_\nu^{\nu_{\max}} \sum_s \left[k^l_{F,\nu,s} E^l_F + \bar{m}_l^2 \ln \left| \frac{k^l_{F,\nu,s} + E^l_F}{\bar{m}_l} \right| \right]. \tag{16}$$

$$\begin{aligned} P_m &= \mu_n \sum_b \rho^v_b - \varepsilon_m, \\ P_l &= \sum_l \mu_l \rho^v_l - \varepsilon_l, \end{aligned} \tag{17}$$

$$\varepsilon^{\mathrm{H}} = \varepsilon_m + \varepsilon_l + \frac{\left(B\left(\frac{\rho}{\rho_0}\right)\right)^2}{2}, \qquad P^{\mathrm{H}} = P_m + P_l + \frac{\left(B\left(\frac{\rho}{\rho_0}\right)\right)^2}{2} \tag{18}$$

Tables:

Parametrization	m_σ (MeV)	m_ω (MeV)	m_ρ (MeV)	g_σ	g_ω	g_ρ
GM1	512.000	783.000	770.000	8.910	10.610	8.196
GM1-2	512.000	783.000	770.000	8.910	10.610	8.196
GM1-3	512.000	783.000	770.000	8.910	10.610	8.196
NL3	508.194	783.000	763.000	10.217	12.868	8.948
FSU	491.500	782.500	763.000	10.592	14.302	11.767
GM3	512.000	783.000	770.000	8.175	8.712	8.259

Parametrization	c	b	ξ	Λ_ω
GM1	-0.001070	0.002947	0.00	0.00
GM1-2	-0.001070	0.002947	0.00	0.01
GM1-3	-0.001070	0.002947	0.00	0.03
NL3	-0.002651	0.002052	0.00	0.00
FSU	0.003960	0.000756	0.06	0.01
GM3	-0.002421	0.008659	0.00	0.00

Tables:

Parametrization	K (MeV)	-B/A (MeV)	a_{sym}(MeV)	L(MeV)	m^*/m	$n_0(fm^{-3})$
GM1	300	16.3	32.5	94	0.70	0.153
NL3	271.76	16.299	37.4	118	0.60	0.148
FSU	230	16.3	32.6	61	0.62	0.148
GM3	240	16.3	32.5	90	0.78	0.153

Baryon	p	n	Λ^0	Σ^+	Σ^0	Σ^-	Ξ^0	Ξ^-
M_b (MeV)	939	939	1115.7	1189.4	1189.4	1189.4	1314.9	1314.9
q_b	1	0	0	1	0	-1	0	-1
μ_b/μ_N	2.79	-1.91	-0.61	2.46	1.61	-1.16	-1.25	-0.65
k_b	1.79	-1.91	-0.61	1.67	1.61	-0.38	-1.25	0.06
τ_{3b}	+1/2	-1/2	0	+1	0	-1	+1/2	-1/2

Theoretical curves that cross the observational data for PSR J0737-3039.

STAR	PARAM.	X_σ	B_0	γ	AMM	M_{max}/M_0	$R(Km)$	$\varepsilon_0(fm^{-4})$
S-1	GM1	0.6	3.1×10^{18}	4	$k_b = 0$	1.82	11.91	5.73
S-2	GM1	0.6	3.1×10^{18}	4	$k_{n,p,hyp}$	1.91	11.85	5.94
S-3	GM1	0.7	3.1×10^{18}	4	$k_{n,p}$	2.06	11.91	5.74
S-4	GM1	0.7	3.1×10^{18}	4	$k_{n,p,hyp}$	2.06	11.69	6.05
S-5	GM1	0.8	3.1×10^{18}	4	$k_{n,p}$	2.23	11.77	5.76
S-6	GM1	0.8	3.1×10^{18}	4	$k_{n,p,hyp}$	2.23	11.77	5.76
S-7	GM1-2	0.6	3.1×10^{18}	4	$k_{n,p}$	2.06	13.37	4.42
S-8	GM1-2	0.6	3.1×10^{18}	4	$k_{n,p,hyp}$	2.08	12.83	5.14
S-9	GM1-2	0.7	3.1×10^{18}	4	$k_{n,p}$	2.24	13.02	4.74
S-10	GM1-2	0.7	3.1×10^{18}	4	$k_{n,p,hyp}$	2.24	12.73	5.02
S-11	GM1-3	0.6	10^{17}	1	$k_b = 0$	2.06	13.58	4.29
S-12	GM1-3	0.6	10^{17}	1	$k_{n,p}$	2.06	13.60	4.29
S-13	GM1-3	0.6	10^{17}	1	$k_{n,p,hyp}$	2.14	14.26	3.77
S-14	GM1-3	0.7	10^{17}	1	$k_b = 0$	2.22	13.17	4.64
S-15	GM1-3	0.7	10^{17}	1	$k_{n,p}$	2.22	13.16	4.64
S-16	GM1-3	0.7	10^{17}	1	$k_{n,p,hyp}$	2.27	13.52	4.32
S-17	GM1-3	0.8	10^{17}	1	$k_b = 0$	2.35	12.83	4.83
S-18	GM1-3	0.8	10^{17}	1	$k_{n,p}$	2.53	12.83	4.83
S-19	GM1-3	0.8	10^{17}	1	$k_{n,p,hyp}$	2.38	13.01	4.65
S-20	GM1-3	0.6	10^{17}	4	$k_b = 0$	2.06	13.58	4.29

Theoretical curves that cross the observational data for PSR J0737-3039.

STAR	PARAM.	X_σ	B_0	γ	AMM	M_{max}/M_0	$R(Km)$	$\varepsilon_0(fm^{-4})$
S-21	GM1-3	0.6	10^{17}	4	$k_{n,p}$	2.06	13.60	4.29
S-22	GM1-3	0.6	10^{17}	4	$k_{n,p,hyp}$	2.14	14.26	3.77
S-23	GM1-3	0.7	10^{17}	4	$k_b = 0$	2.22	13.16	4.64
S-24	GM1-3	0.7	10^{17}	4	$k_{n,p}$	2.22	13.16	4.64
S-25	GM1-3	0.7	10^{17}	4	$k_{n,p,hyp}$	2.27	13.52	4.32
S-26	GM1-3	0.8	10^{17}	4	$k_b = 0$	2.35	12.82	4.83
S-27	GM1-3	0.8	10^{17}	4	$k_{n,p}$	2.35	12.83	4.83
S-28	GM1-3	0.8	10^{17}	4	$k_{n,p,hyp}$	2.38	13.01	4.65
S-29	GM1-3	0.6	3.1×10^{18}	1	$k_{n,p}$	2.47	14.52	3.65
S-30	GM1-3	0.6	3.1×10^{18}	1	$k_{n,p,hyp}$	2.49	14.56	3.64
S-31	GM1-3	0.6	3.1×10^{18}	4	$k_b = 0$	2.06	13.39	4.35
S-32	GM1-3	0.8	3.1×10^{18}	4	$k_b = 0$	2.36	12.61	4.95
S-33	GM3	0.6	10^{17}	1	$k_{n,p,hyp}$	1.61	11.69	6.08
S-34	GM3	0.6	10^{17}	4	$k_b = 0$	1.55	10.99	7.12
S-35	GM3	0.6	10^{17}	4	$k_{n,p}$	1.55	11.00	7.13
S-36	GM3	0.6	10^{17}	4	$k_{n,p,hyp}$	1.61	11.68	6.08
S-37	GM3	0.6	3.1×10^{18}	1	$k_{n,p}$	1.96	12.77	4.74
S-38	GM3	0.6	3.1×10^{18}	1	$k_{n,p,hyp}$	1.96	12.77	4.74
S-39	GM3	0.8	3.1×10^{18}	1	$k_b = 0$	2.16	12.18	5.19
S-40	GM3	0.6	3.1×10^{18}	4	$k_b = 0$	1.57	11.04	6.92

Theoretical curves that cross the observational data for PSR J0737-3039.

STAR	PARAM.	X_σ	B_0	γ	AMM	M_{max}/M_0	$R(Km)$	$\varepsilon_0(fm^{-4})$
S-41	GM3	0.6	3.1×10^{18}	4	$k_{n,p}$	1.57	11.04	6.92
S-42	GM3	0.6	3.1×10^{18}	4	$k_{n,p,hyp}$	1.64	10.94	7.16
S-43	GM3	0.7	3.1×10^{18}	4	$k_b = 0$	1.73	10.88	7.13
S-44	GM3	0.7	3.1×10^{18}	4	$k_{n,p}$	1.76	11.10	6.78
S-45	GM3	0.7	3.1×10^{18}	4	$k_{n,p,hyp}$	1.77	10.77	7.45
S-46	GM3	0.8	3.1×10^{18}	4	$k_b = 0$	1.87	10.71	7.20
S-47	GM3	0.8	3.1×10^{18}	4	$k_{n,p}$	1.89	10.87	6.93
S-48	GM3	0.8	3.1×10^{18}	4	$k_{n,p,hyp}$	1.89	10.87	6.93