Neutron star kick velocity induced by neutrino chirality flip and a lower bound for the neutrino magnetic moment†

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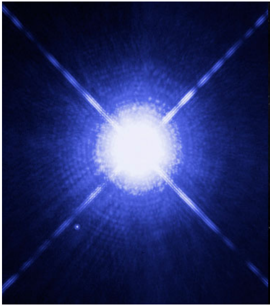
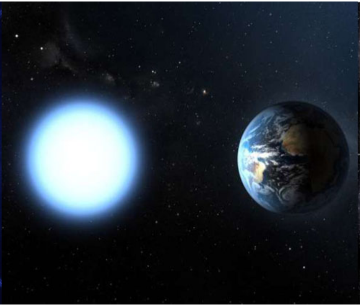
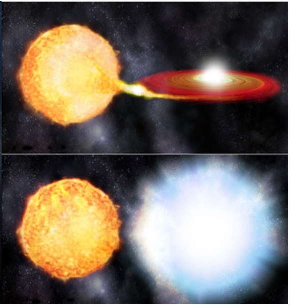
arXiv:1912.10294 [astro-ph.HE]†

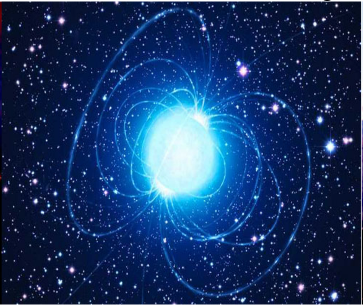
Compact Stars

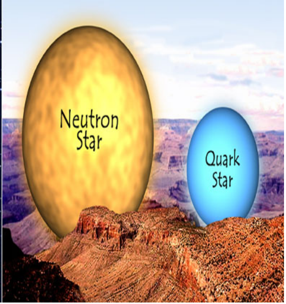






White Dwarfs⇑ Neutron Stars/Extrange Stars⇓





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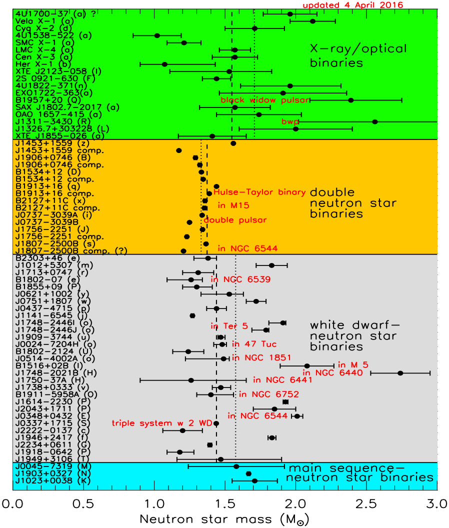
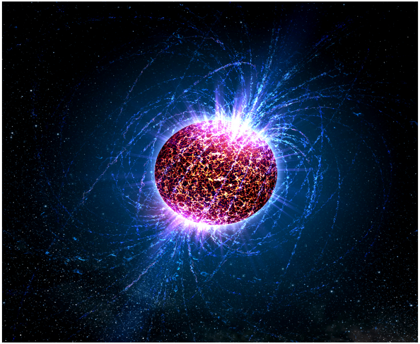


Figure: http://stellarcollapse.org/nsmasses (2017).

Neutron Stars

- $\mathrm{M} \sim 1.4\mathrm{M}_\odot$
- $\mathrm{R} \sim 12\,\mathrm{km}$
- $\rho \sim 10^{14}\,\mathrm{g/cm^3}$
- $B \sim 10^{12} - 10^{15}\,\mathrm{G}$



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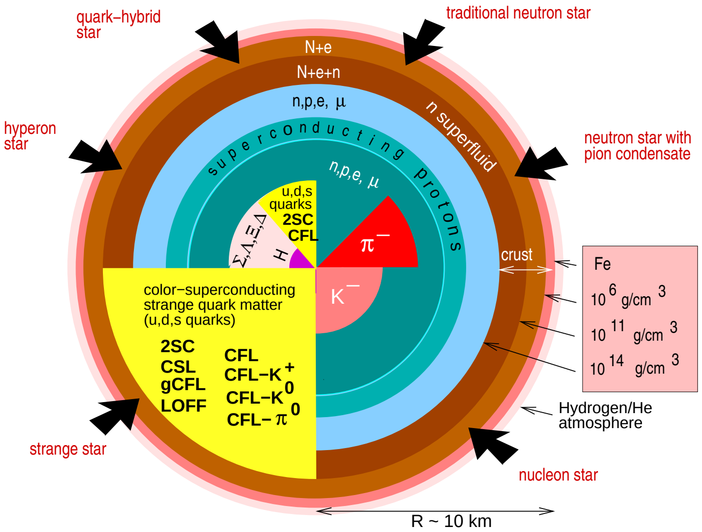
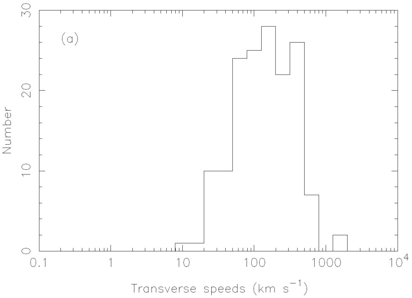


† F. Weber. doi:10.1016/j.ppnp.2004.07.001.

Pulsar kicks
Observational evidences for NS kicks

- Pulsar kicks refers to peculiar translational velocities observed on pulsars with respect to surrounding stars and with respect to their progenitors.
- Kicks can be natal or post-natal: a natal kick is imparted to the neutron stars at birth while post-natal kicks are due to some inner process of the NS.
- Hobbs et al.[†] have studied the data from the proper motion of 233 pulsars, obtaining velocities as high as 1000 km s^{-1} and that the mean velocity of young pulsar is 400 km s^{-1}.



[†] Hobbs, G., Lorimer, D., Lyne, A., & Kramer, M. 2005, Mon. Not. R. Astron. Soc., 360, 974.

Pulsar kicks

Models to describe NS kicks

Some mechanism to explain the kicks are:

1. **Hydrodynamically Driven Kicks:** This mechanism explains a natal kick during the core collapse and supernova explosion due to hydrodynamical perturbations that could lead to asymmetric matter ejection.

2. **Electromagnetic rocket effect:** Electromagnetic radiation from an off-centered rotating magnetic dipole imparts a kick to the pulsar along its spin axis.

3. **Neutrino–Magnetic Field Driven Kicks:** Asymmetric neutrino emission induced by strong magnetic field.

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   - The polarisation of the electron spin will fix the neutrino emission in one direction along the magnetic field,
   - The neutrinos work as a propulsion mechanism for the neutron star.

Pulsar kick velocity

The produced kick velocity for NS can be computed from

$$dv = \frac{\chi}{M_{NS}} \frac{4}{3} \pi R^3 \epsilon dt,$$

where M_{NS} and R are the NS mass and radius, ϵ is the neutrino emissivity and χ is the electron spin polarization, which determines the fraction of neutrinos asymmetrically emitted. The pulsar kick velocity can be rewritten in the following form

$$v = -803.925 \, \frac{\text{km}}{\text{s}} \left(\frac{1.4 \, M_\odot}{M_{NS}} \right) \left(\frac{R}{10 \, \text{km}} \right)^3 \left(\frac{I}{\text{MeV fm}^{-3}} \right),$$

where

$$I = \int_{T_i}^{T_f} \chi_e(B, T, \mu_i) \, C_v(B, T, \mu_i) dT, \quad i = e, u, d, s.$$

Pulsar kick velocity

The electron spin polarization χ is given by $\chi = \frac{n_- - n_+}{n_- + n_+}$,

$$\chi_e = \left\{ 1 + \frac{2 \sum_{\nu=1}^{\infty} \int_0^{\infty} dx_3 \frac{1}{e^{\left(\frac{m_e}{T}\sqrt{x_3^2+1+2\nu B/B_c^e} - x_e\right)}+1}}{\int_0^{\infty} dx_3 \frac{1}{e^{\left(\frac{m_e}{T}\sqrt{x_3^2+1} - x_e\right)}+1}} \right\}^{-1} .$$

From the thermodynamical potential we can compute the specific heat as

$$C_{vf} = T\frac{\partial S_f}{\partial T}, \quad S_f = -\frac{\partial \Omega_f}{\partial T},$$

obtaining

$$C_{vf} = \frac{e_f d_f B}{2\pi^2} \int_0^{\infty} dp_3 \sum_{l=0}^{\infty} (2 - \delta_{l0}) \frac{(E_{lf} - \mu_f)^2}{2T^2[1 + \cosh \frac{E_{lf} - \mu_f}{T}]}.$$

where

$$E_{lf} = \sqrt{p_3^2 + 2|e_f|Bl + m_f^2},$$

† A. Ayala, D. Manreza Paret, A. Pérez Martínez, G. Piccinelli, A. Sánchez and J. S. Ruíz Montaño, Phys. Rev. D **97**, no. 10, 103008 (2018)

Neutrino quirality flip

The production rate of a right-handed neutrino, with energy p_0 and momentum $\vec{p}$ from left-handed neutrinos is given by[†]

$$\Gamma(p_0) = \frac{\mu_\nu^2}{32\pi^2 p_0^2} \int_0^\infty dk\, k^3 \int_{-k}^{k} dk_0\, \theta(2p_0 + k_0 - k)\,[1 + f(k_0)]\tilde{f}(p_0 + k_0 - \mu)$$
$$\times \quad (2p_0 + k_0)^2 \left(1 - \frac{k_0^2}{k^2}\right)^2 \left[\rho_L(k_0) + \left(1 - \frac{k^2}{(2p_0 + k_0)^2}\right)\rho_T(k_0)\right],$$

we can compute the total reaction rate as the integral of $\Gamma(p_0)$ over the available phase space, namely,

$$\Gamma = V \int \frac{d^3p}{(2\pi)^3} \Gamma(p_0)$$

[†] Ayala, A., D'Olivo, J. C., Torres, M. 1999, Phys. Rev. D, 59, 111901

Neutrino quirality flip

The typical time required for the chirality flip process to take place is given as the inverse of Γ, namely

$$\tau = 1/\Gamma.$$

This time should be smaller than the time required for a neutrino to travel one mean free path λ

$$c\tau \leq \lambda.$$

Taking typical values of the core of Quark Stars, we obtain the lower bound for the neutrino magnetic moment

$$4.7 \times 10^{-15} \mu_B \leq \mu_\nu,$$

where μ_B is the Bohr magneton.
A similar analysis applied to the core collapse during a supernova explosion give us the range for the neutrino magnetic moment as[†]

$$4.7 \times 10^{-15} \leq \mu_\nu/\mu_B \leq (0.1 - 0.4) \times 10^{-11}.$$

[†] Ayala, A., D'Olivo, J. C.,Torres, M. 2000, Nucl. Phys., B564, 204

Pulsar kick velocity

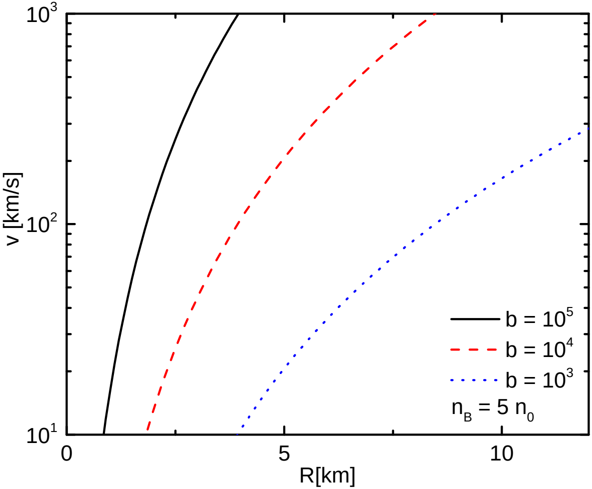

Figure: Kick velocities as a function of the NS radius for a NS with 1.4 solar masses, for different values of the magnetic field. The obtained kick velocities are within the observed ones.

Conclusions

1. We have shown that neutrino quirality flip during the birth of a SQM NS is an efficient mechanism to allow the produced neutrinos to escape from the NS core provided the neutrino magnetic moment is not smaller than $4.7 \times 10^{-15} \mu_B$.

2. The results of this work set a range for the neutrino magnetic moment given by $4.7 \times 10^{-15} \leq \mu_\nu / \mu_B \leq (0.1 - 0.4) \times 10^{-11}$.

3. The obtained kick velocities for natal NS conditions are consistent with the observed ones and span the correct range of radii for typical magnetic field intensities.

MUCHAS GRACIAS