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Asymmetric Neutrino Emissions in Relativistic Mean-Field Approach and Observables: Pulsar Kick and Spin Deceleration of Strongly Magnetized Proto-Neutron Stars

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We calculate the spin deceleration of neutron stars due to asymmetric neutrino absorption in a toroidal magnetic field configurations in the relativistic mean field theory. We find that the deceleration can be much larger for asymmetric neutrino absorption in a toroidal magnetic field than the usually presumed braking due to magnetic dipole radiation.

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The observed asymmetry in supernova (SN) remnants, pulsar kick velocities [1], and the existence of **magnetars** [2] all imply that strong magnetic fields play an important role in SN explosions and the velocity [3] that the proto-neutron stars (PNS) receive at its birth.

There is accumulating evidence that magnetars spin down faster than expected [4]. Usually it is supposed that magnetars spin down mainly by dissipating rotational energy into magnetic dipole radiation. However, it is possible that they could have a much more rapid spin deceleration early in their formation.

On the other hand, we calculated the neutrino scattering and absorption cross sections in the magnetized PNS matter [5] in fully relativistic mean field (RMF) theory. The calculation results showed that the magnetic contribution increases the neutrino momentum emitted along the direction of the magnetic field and decrease it along the opposite direction.

Recent PNS simulations [6] have show that the magnetic field inside the neutron star may have a toroidal configuration. When we apply the above results on the asymmetric neutrino absorption and scattering to this case, we can easily suppose that the neutrinos are more easily emitted along the direction opposite to the rotation. This would reduce the spin of the PNS. In this work, there we present for the first time a study of the effect of asymmetric neutrino scattering and absorption on the spin deceleration of PNSs.

Even a strong magnetic field has less mass-energy than the baryonic chemical potential in degenerate neutron-star matter, i.e. $\sqrt{eB} \ll \mu_b$, where μ_b is the baryon chemical potential. Hence, we can treat the magnetic field as a perturbation. We then ignore the contribution from convection currents and consider only the spin-interaction. We also assume that $|\mu_b B| \ll E_b^*(\boldsymbol{p}) = \sqrt{\boldsymbol{p}^2 + M_b^{*2}}$, and treat the single particle energies and the wave function in a perturbative way.

In this framework we then obtain the wave function in a magnetic field by solving the Dirac equation:

$$\left[\gamma_\mu p^\mu - M_b^* - U_0(b)\gamma_0 - \mu_b B \sigma_z\right] u_b(p,s) = 0, \tag{1}$$

where $M_b^* = M_b - U_s(b)$, and $U_s(b)$ and $U_0(b)$ are the scalar mean-field and the time-component of the vector mean-field for the baryons b.

In Ref. [5] we calculated the neutrino absorption cross-section σ_A with the above Dirac spinor and demonstrated that the absorption cross-sections are suppressed in the direction parallel to the magnetic field $\boldsymbol{B}$ by about $2-4\%$ in the density region of $\rho_B = (1-3)\rho_0$. in PNS matter for an interior magnetic field strength of $B = 2\times 10^{17}$G and a temperature of $T = 20$ MeV.

We now consider the implications of a toroidal field configuration on neutrino transport in a strongly magnetized PNS. We assume that the system is static and nearly in local thermodynamic equilibrium. Under this assumption the neutrino phase-space distribution function can be expanded as $f_\nu(\boldsymbol{r},\boldsymbol{k}) = f_0(\boldsymbol{r},\boldsymbol{k}) + \Delta f(\boldsymbol{r},\boldsymbol{k})$, where the first term is the local equilibrium part, and the second term is its deviation.

We can obtain Δf solving a Boltzmann equation with the strait line approximation [5] as below.

Here, we define the variables $x_L \equiv (\boldsymbol{r}\cdot\boldsymbol{k})/|\boldsymbol{k}|$ and ct$\boldsymbol{R}_T \equiv \boldsymbol{r} - (\boldsymbol{r}\cdot\boldsymbol{k})\boldsymbol{k}/\boldsymbol{k}^2$, and then obtain analytically

$$\Delta f(x_L, R_T, \boldsymbol{k}) = \int_0^{x_L} dy \left[-\frac{\partial \varepsilon_\nu}{\partial y} \frac{\partial f_0}{\partial \varepsilon_\nu} \right] \exp\left[-\int_y^{x_L} dz \frac{\sigma_A(z, R_T, \boldsymbol{k})}{V} \right], \tag{2}$$

where the center of the neutron-star is at $\boldsymbol{r} = (0,0,0)$, and all of the integrations are performed along a straight line.

In this work we utilize an equation of state (EOS) at a fixed temperature and lepton fraction by using the parameter set PM1-L1 [7] for the RMF.

We show the baryon density in Fig. 1a as a function of the neutron-star radius. For this figure we assume a neutron star mass of $M_{NS} = 1.68 M_\odot$, a temperature of $T =$ 20MeV, and a lepton fraction of $Y_L = 0.4$. The ratio of the total rate of angular momentum loss to the total power radiated by neutrinos at a given spherical surface S_N is

$$\left(\frac{cdL_z/dt}{dE_T/dt}\right) = \frac{< L_z >}{< E >} \tag{3}$$

with

$$< L_z >= \int_{S_N} d\Omega_r \int \frac{d^3k}{(2\pi)^3} \Delta f(\boldsymbol{r},\boldsymbol{k}) (\boldsymbol{r}\times\boldsymbol{k})\cdot\boldsymbol{n},$$
$$< E >= \int_{S_N} d\Omega_r \int \frac{d^3k}{(2\pi)^3} \Delta f(\boldsymbol{r},\boldsymbol{k}) \boldsymbol{k}\cdot\boldsymbol{n},$$

where $\boldsymbol{n}$ is the unit vector normal to S_N. We can then obtain the spin-down rete as

$$\frac{\dot{P}}{P} = \frac{P}{2\pi c I_{NS}} \left(\frac{cdL_z/dt}{dE_T/dt}\right) \mathscr{L}_\nu \quad . \tag{4}$$

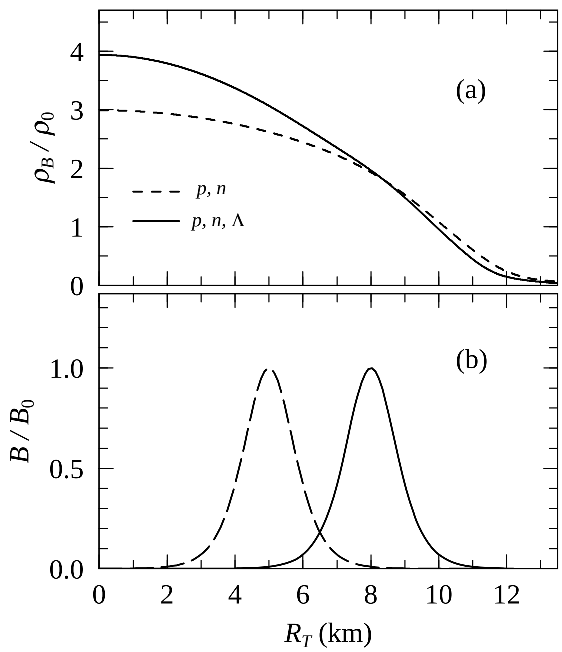

Figure 1: The upper panel (a) shows the baryon density distribution for a PNS with T = 20 MeV and $Y_L = 0.4$. The solid and long-dashed lines show results with and without Λs, respectively. The lower panel (c) shows the field strength distribution at $z = 0$ for the toroidal magnetic fields considered here. The solid and dashed lines represent those for $r_0 = 8$km (Mag-A) and $r_0 = 5$km (Mag-B), respectively.

where P is a NS spin period P, and $\mathscr{L}_\nu = (dE_T/dt)$ is the neutrino luminosity,

As for the toroidal magnetic field configuration, we adopt the following parameterization in cylindrical coordinate (r_T, ϕ, z),

$$\vec{B} = B_\phi G_L(z) G_T(r_T) \hat{e}_\phi, \tag{5}$$

where $\hat{e}_\phi = (-\sin\phi, \cos\phi, 0)$ in terms of the azimuthal angle ϕ, and

$$G_L(z) = \frac{4e^{z/a_0}}{\left[1+e^{z/a_0}\right]^2}, \qquad G_T(r_T) = \frac{4e^{(r_T-r_0)/a_0}}{\left[1+e^{(r_T-r_0)/a_0}\right]^2}. \tag{6}$$

In Fig. 1b we show the magnetic field strength $|\boldsymbol{B}/B_\phi|$ for different field configurations, with $a_0 = 0.5$ km and $r_0 = 8.0$ km (Mag-A) or $r_0 = 5.0$ km (Mag-B). We here take $\mathscr{L}_\nu \approx 3\times 10^{52}$ erg·s^{-1} [8] as typical value of the neutrino luminosity from the proto-neutron star, and a spin period is chosen to be $P = 10$ms, while the observed spin period of magnetars is about 10 s [9].

Numerical simulations [10, 11] have shown that the strength of the toroidal magnetic field can easily reach $B_\phi = 10^{16}$G or more due to the winding effects on the poloidal magnetic field line of order $\sim 10^{14}$G for the rapid rotation of PNS. We therefore adopt these typical values for both components $B_{pol} = 10^{14}$G and $B_\phi = 10^{16}$G, respectively.

We summarize the calculated results in Table 1. It includes two cases by taking PNS surface S_N at $\rho_B = \rho_0$. In this table the fifth column shows $\dot{P}/P$, for reference, which was calculated with the usual magnetic dipole radiation (MDR) formula [12],

$$P\dot{P} = B_{pol}^2 \left(\frac{3M_{NS}^3 c^3}{125\pi^2 I_{NS}^2}\right)^{-1} . \tag{7}$$

For these particular parameters we see that the spin deceleration from asymmetric neutrino emission can be more effective than that of MDR when the neutrino luminosity is high.

Comp.	Mag.	$\frac{cdL_z/dt}{dE_T/dt}$	$\dot{P}/P$ (s^{-1}) Ours	$\dot{P}/P$ (s^{-1}) MDR
p, n	Mag-A	3.34	3.5×10^{-6}	9.9×10^{-8}
	Mag-B	0.48	5.0×10^{-7}	
p, n, Λ	Mag-A	5.45	6.4×10^{-6}	7.8×10^{-8}
	Mag-B	0.39	4.6×10^{-7}	

Table 1: The 1st column shows the presumed composition of nuclear matter. The 2nd column gives the model for the toroidal magnetic field configuration. The 3rd column denotes results from Eq. (3), and the 4th column is a result obtained using Eq. (4). The 5th column shows the usually presumed spin-down rate from magnetic dipole radiation, Eq. (7).The spin period is taken to be $P = 10$ms, and the magnetic field strengths of $B_{pol} = 10^{14}$G and $B_\phi = 10^{16}$G are used in these calculations.

There are some uncertainties for our estimate of $\dot{P}/P$, e.g. the interior strength of the magnetic field, the spin period of the NS core, etc. Nevertheless, since our value of $\dot{P}/P$ is at least 10^2 times larger than that for MDR, spin-down mechanism through the asymmetric neutrino emission could be indispensable under many possible early stages of SNe. Furthermore, other processes such as the neutrino scattering and production tend to increase the asymmetry in neutrino emission, and lead to additional spin deceleration. Thus, we can conclude that asymmetric neutrino emission from PNSs may play an important role in the spin deceleration of a magnetic PNS.

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