High Velocity Neutron Stars as a Result of Asymmetric Neutrino Emission *

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Abstract

Formation of a neutron star is accompanied by neutrino emission carrying about 10% of the rest energy of the star. Toroidal field produced by twisting of a dipole field in differentially rotating star is antisymmetric. Its summation with antisymmetric toroidal field results in braking of mirror symmetry of the magnetic field. For large magnetic field the neutron decay rate depends on its strength. Neutrino is emitted more in one direction leading to flux asymmetry and recoil of the neutron star. Estimations show that the neutron star can reach velocities $\sim 1000$ km/s for 3% asymmetry of the neutrino flux.

Introduction

Observations of the pulsars moving at the velocities up to 500 km/s is a challenge to the theory of the neutron star formation. The Blaauw effect during the formation of pulsars in the binaries cannot produce such a high speeds. The plausible explanation for the birth of rapidly moving pulsars seems to be the suggestion of the kick at the birth from the asymmetric explosion. We make estimations for the strength of the kick, produced by the asymmetric neutrino emission during the collapse.

*This work was supported in part by RFFI grant 93-02-17106, Astronomy Programm of RMSTP topic 3-169, and KOSMION
The asymmetry of the neutrino pulse, is produced by the asymmetry of the magnetic field distribution, formed during the collapse and differential rotation [3].

Formation of the asymmetric magnetic field

Consider rapidly and differentially rotating new born neutron star with the dipole poloidal and symmetric toroidal fields. A field amplification during the differential rotation leads to the formation of additional toroidal field from the poloidal one. This field, made from the dipole poloidal one by twisting is antisymmetric with respect to the symmetry plane. The sum of the initial symmetric with the induced antisymmetric toroidal fields has no plane symmetry.

In absence of dissipative processes the neutron star returns to the state of rigid rotation loosing the induced toroidal field and restoring mirror symmetry of the matter distribution. Formation of asymmetric toroidal field distribution is followed by magnetorotational explosion [5], which is asymmetric, leading to neutron star recoil and star acceleration [3]. The neutron star acceleration happens also due to dependence of the cross-section of week interactions on the magnetic field.

The influence of the magnetic field on the neutron decay was studied in [6]. It becomes essential when the characteristic energy of the electron at the Landau level with the Larmor rotation $\frac{eB}{mc}$ becomes of the order of the energy of the decay $\sim mc^2$ for a neutron. That happens at

$$B_c = \frac{m_e^2 c^3}{\hbar} = 4.4 \times 10^{13} \text{Gs}$$  \hspace{1cm} (1)

The probability of the neutron decay $W_n$ in vacuum is

$$W_n = W_0[1 + 0.17(B/B_c)^2 + ...] \quad \text{at} \quad B \ll B_c$$

$$W_n = 0.77W_0(B/B_c) \quad \text{at} \quad B \gg B_c$$  \hspace{1cm} (2)

At high temperatures or densities the critical field increases in $\alpha_T = kT/m_e c^2$ or $\alpha_p = \epsilon_p/m_e c^2$ times. After a collapse of rapidly rotating star the neutron star rotates at the period $P$ about 1 ms. Differential rotation leads to the linear amplification of the toroidal field

$$B_\phi = B_{\phi 0} + B_p(t/P)$$  \hspace{1cm} (3)

The time of the neutrino emission is several tens of seconds [6]. After 20 s the induced toroidal magnetic field will be about $2 \times 10^4 B_p$, corresponding to $10^{15} \div 10^{17}$ Gs for $B_p = 10^{11} \div 10^{13}$ Gs, observed in the pulsars. Adopting the initial toroidal field $B_{\phi 0} = (10 \div 10^3)B_p = 10^{12} \div 10^{16}$, we may estimate an asymmetry of the neutrino pulse. For symmetric $B_{\phi 0}$ and dipole poloidal
field the difference $\Delta B_\phi$ between the magnetic fields absolute values in two hemispheres increases, until it reaches the value $2B_{\phi 0}$. It remains constant later, while the relative difference

$$\delta_B = \frac{\Delta B_\phi}{B_{\phi +} + B_{\phi -}}$$

decreases.

**Neutrino heat conductivity and energy losses**

The main neutrino flux is formed in the region where the mean free path of the neutrino is smaller than the stellar radius. The neutrino energy flux, $H_\nu$, associated with the temperature gradient may be written as

$$H_\nu = -\frac{7}{8} \alpha c T^3 \frac{\partial T}{\partial r}$$  \hspace{1cm} (5)

The quantity $l_T$ having the meaning of the neutrino mean free path is connected with the neutrino opacity $\kappa_\nu$ as

$$\kappa_\nu = \frac{1}{(l_T \rho)}$$ \hspace{1cm} (6)

Calculations of the spherically symmetrical collapse have shown, that during the phase of the main neutrino emission, a hot neutron star consists of the quasiumiform quasiisothermal core with the temperature $T_i$, whose mass increases with time, and the region between the neutrinosphere and the isothermal core, where the temperature smoothly decreases in about 10 times while the density, which finally drops about 6 times decreases nonmonotonically. Neutrino flux is forming in this region, containing about one half of the neutron star mass. We suggest for simplicity a power-law dependences for the temperature and $l_T$:

$$T = T_i \left( \frac{r}{r_i} \right)^m, \quad l_T = \frac{1}{\kappa \rho} = l_{Ti} \left( \frac{r}{r_i} \right)^n$$ \hspace{1cm} (7)

The neutrinosphere with the radius $r_\nu$ is determined approximately by the relation

$$\int_{r_\nu}^{\infty} \kappa_\nu \rho dr = \int_{r_\nu}^{\infty} \frac{dr}{l_T} = 1$$ \hspace{1cm} (8)

Using (7) outside the neutrinosphere we get from (8) the relation

$$r_\nu = r_i \left( \frac{r_i}{(n-1)l_{Ti}} \right)^{\frac{1}{n-1}}$$ \hspace{1cm} (9)
From (3)-(5), using (9) we get the temperature of the neutrinosphere $T_\nu$ and the heat flux on this level $H_\nu$, which outside the neutrinosphere is approximately $\sim r^{-2}$, corresponding to the constant neutrino luminosity $L_\nu$

$$T_\nu = T_i \left( \frac{(n-1)l_{T_i}}{r_i} \right)^{\frac{2}{n-1}}$$

To estimate the anisotropy of the neutrino flux we compare two stars with the same radius and temperature of the core $r_i$ and $T_i$ and different opacities. Let $l_{T_i}$ is different and constant in two hemispheres, and each one is radiating according to (11). The anisotropy of the flux

$$\delta L = \frac{L_+ - L_-}{L_+ + L_-}$$

Here $L_+$, $L_-$ are luminosities in the different hemispheres, calculated, using (11). For small difference between hemispheres

$$\delta L = \frac{\Delta L}{L} = \frac{4m - 2}{n - 1} \frac{\Delta l_{T_i}}{l_{T_i}}$$

Neutron star acceleration.

The equation of motion of the neutron star with the mass $M_n$

$$M_n \frac{dv_n}{dt} = \frac{L_+ - L_-}{c}, \quad L_+ + L_- = \frac{2}{\pi} L_\nu(t)$$

For the power distributions (3),(4) it follows from (11) that

$$L_\pm = Al_{T_i}^{m-\frac{2}{n-1}}$$

In general $l_{T_i}$ is determined by various neutrino processes and depends on $B$. As an example consider the dependence on $B$ in the form (2). Making interpolation between two asymptotic forms we get dependence

$$l_{T_i} \sim \frac{1}{W} = l_{T_0} \frac{1 + \left( \frac{B}{B_c} \right)^3}{1 + 0.17 \left( \frac{B}{B_c} \right)^2 + 0.77 \left( \frac{B}{B_c} \right)^4} = l_{T_0} F^{\frac{m-1}{n-1}}(B)$$
The time dependence of the average value of $B$ in each hemisphere can be found from (3) with

$$B_{p+} = -B_{p-}, \quad B_{\phi 0+} = B_{\phi 0-}$$

(17)

By $B_p$ we mean a radial component of the poloidal field taking part in amplification of $B_{\phi}$. The time dependence of $L_\nu$ is taken from the spherically symmetric calculations of the collapse.

**Quantitative estimations**

For $\frac{4m-2}{\pi x} = 1$ and in condition when the neutron star is accelerated at $B \gg B_c$, we have $F_\pm = \frac{B_p}{0.17 B_\pm}$. Equation of motion (14) may be written as

$$M_n \frac{dv_n}{dt} = \frac{2 L_\nu}{\pi} \frac{|B_+| - |B_-|}{c |B_+| + |B_-|}$$

(18)

with the linear functions for $B_\pm$. Take constant $L_\nu = \frac{0.1 M_n c^2}{200}$. With these simplifications, the final velocity of the neutron star $v_{nf}$ follows as a result of the solution of (13) in the form

$$v_{nf} = \frac{2}{\pi} \frac{L_\nu}{M_n c} \frac{PB_{\phi 0}}{|B_p|} (0.5 + \ln \left( \frac{20 s |B_p|}{P B_{\phi 0}} \right))$$

(19)

For $P = 10^{-3} s$ we obtain from (19)

$$v_{nf} = \frac{2}{\pi} \frac{c}{10} \frac{P}{20 s} x (0.5 + \ln \left( \frac{20 s 1}{P x} \right)) \approx 1 \frac{km}{s} x (0.5 + \ln \left( \frac{2 \times 10^4}{x} \right))$$

(20)

For the value $x = \frac{B_{\phi 0}}{|B_p|}$ ranging between 20 and $10^3$, we have $v_{nf}$ between 140 and 3000 km/s, what can explain the nature of the most rapidly moving pulsars. The formula (20) can be applied when $B_{\phi 0} \gg B_c$ and $x \gg 1$.

The acceleration of the collapsing star by anisotripic neutrino emission can happen even when the star collapses to the black hole, the efficiency of acceleration decreases with increasing of mass. We may expect black holes of stellar origin moving rapidly, like radiopulsars, and they may be found high over the galactic disk. This is observed among the soft X ray novae - most probable candidates for black holes in the Galaxy [9].

After magnetorotational explosion we may expect tens of ms periods for a neutron star rotation. Remaining in binary, star either accelerates its rotation (in LMXB) or decelerates it (in high mass XB). The first ones are transformed into recycled (msec, binary) pulsars, and the last ones (after explosion of the massive component and disruption of binary) may form a family of very slowly rotating neutron stars, one of which was observed in the strongest GRB of 5 March 1979.
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