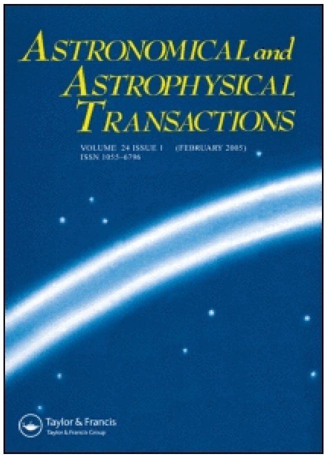

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ASYMMETRIC NEUTRINO EMISSION AND FORMATION OF RAPIDLY MOVING PULSARS

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Formation of a neutron star with a strong magnetic field during the collapse may lead to the violation of the mirror symmetry and formation of an asymmetric magnetic field. The dependence of the weak interaction cross-section on the magnetic field strength leads to asymmetric neutrino flux and formation of rapidly moving pulsars (due to the recoil action) as well as rapidly moving black holes.

KEY WORDS Collapse, supernovae, rapid motion of pulsars.

1. INTRODUCTION

The existence of the pulsars moving at the velocities up to 500 km/s (Harrison, Lyne and Anderson, 1991) is a big challenge to the theory of the neutron star formation in the spherically symmetric collapse. The collapse of a rotating star possessing axial symmetry does not help and the Blaauw effect during the formation of pulsars in the binaries cannot produce such a high speed. The most plausible explanation for the birth of rapidly moving pulsars seems to be the suggestion of a kick at the birth from an asymmetric explosion (Shklovskii, 1970; see also Radhakrishnan, 1991). Below we estimate the strength of the kick produced by the asymmetric neutrino emission during the collapse. Chugay (1984) and Dorofeev, Rodionov and Ternov (1985) estimated the asymmetric neutrino pulse due to the action of a strong magnetic field which makes the electrons to be polarized. This leads to a mirror-asymmetric neutrino emission due to the P-symmetry violation in the weak-interaction Lagrangian. As was shown by Bisnovatyi-Kogan (1989), the strength of the poloidal magnetic field needed for the explanation of the visible velocities is much larger than the fields observed in these pulsars.

The asymmetry of the neutrino pulse considered here is produced by the asymmetry of the field distribution, formed during the collapse and differential rotation (Bisnovatyi-Kogan and Moiseenko, 1992). The qualitative picture of the neutrino pulse asymmetry due to the dependence of the neutrino cross-section on the magnetic field strength was considered by Bisnovatyi-Kogan (1991). Here the quantitative estimations are presented.

2. FORMATION OF THE ASYMMETRIC MAGNETIC FIELD DISTRIBUTION

In order to obtain the mirror-asymmetric magnetic field distribution, let us consider a rotating presupernova star with a dipole poloidal and symmetric toroidal field. The collapse of such star after the loss of stability leads to the formation of a rapidly and differentially rotating neutron star. The field amplification due to the differential rotation leads to the formation of additional toroidal field from the poloidal one. The toroidal field, produced from the dipole poloidal one by twisting of the field lines, is antisymmetric with respect to the symmetry plane. The sum of the initial symmetric with the induced antisymmetric toroidal fields has no plane symmetry and the field in one hemisphere is larger than in the other one. Such symmetry violation always happens when the star rotates differentially and possesses toroidal and poloidal fields with different symmetry properties (the dipole poloidal and symmetric toridal, or quadrupole poloidal with antisymmetric toroidal, etc.).

In the absence of dissipative processes, with the perfect magnetic field freezing the neutron star returns to the state of rigid rotation losing the induced toroidal field and restoring the mirror symmetry of the matter distribution. In the presence of the field dissipation the rigidly rotating star returns to the rigid rotation having an asymmetric toroidal field and an asymmetry of the matter distribution. The formation of the asymmetric toroidal field distribution can be followed by asymmetric magnetorotational explosion, producing a neutron star recoil and a rapidly moving star (Bisnovatyi-Kogan, 1970; Ardelyan *et al.*, 1979; Bisnovatyi-Kogan and Moiseenko, 1992). Even in the case when the magnetorotational explosion is not efficient, the neutron star acceleration may happen due to the dependence of the cross-section of the weak interaction on the magnetic field.

The influence of the magnetic field on the processes involving weak interaction was well studied for the neutron decay (O'Connel and Matese, 1969). The influence becomes essential when the characteristic energy of the electron at the Landau level with the Larmor rotation $\hbar eB/m_e c$ becomes of the order of the energy of the decay, which is of the order of $m_e c^2$ for the neutron decay. The equality of these energies determines the critical magnetic field:

$$B_c = \frac{m_e^2 c^3}{e\hbar} = 4.4 \times 10^{13}\text{G}. \tag{1}$$

The probability of the neutron decay W_n in a strong magnetic field without the matter is

$$\begin{aligned} W_n &= W_0[1 + 0.17(B/B_c)^2 + \cdots] \quad \text{at} \quad B \ll B_c, \\ W_n &= 0.77 W_0(B/B_c) \quad \text{at} \quad B \gg B_c. \end{aligned} \tag{2}$$

The formula (2) can be easily generalized for the neutron decay and electron capture in the presence of matter with the Fermi distribution, which requires only the modification of the phase volume of the integration. For fully degenerate electrons, the integration over the phase volume can be done analytically (see, e.g., Shulman, 1977). In the fully degenerate case the smooth dependence of the decay or capture probabilities on the field strength is accompanied by the jumps of the derivatives when the difference between the decay energy and the Fermi energy of the electron connected with the motion along the magnetic field crosses the energy of the corresponding Landau level. The neutrino emissivity from the synchrotron and e^+e^- annihilation processes in the nonrelativistic limit was studied by Kaminker *et al.* (1991).

After the collapse of a rapidly rotating star the newly formed neutron star rotates at the period P of about 1 ms corresponding to the critical rotational velocity. The differential rotation leads to the linear amplification of the toroidal field according to the approximate law

$$B_\phi = B_{\phi 0} + B_P(t/P). \tag{3}$$

Numerical calculations of the spherically symmetric collapse gave (Nadjozhin, 1978) several tens of seconds for the time of the neutrino emission. This time can be even larger if rotation effects are taken into account. After 20 s the induced toroidal magnetic field will become equal to $2\times10^4 B_p$, corresponding to $10^{15}\div10^{17}$ G for $B_p = 10^{11}\div10^{13}$ G observed in pulsars. Adopting the initial toroidal field equal to $B_{\phi 0} = (10\div10^3)B_p = 10^{12}\div10^{16}$, we can start the estimation of the asymmetry of the neutrino pulse produced by the anisotropic neutrino emission. It is easy to see that, for symmetric $B_{\phi 0}$ and dipole poloidal field, the difference ΔB_ϕ between the magnetic field absolute values in the 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.

3. THE NEUTRINO HEAT CONDUCTIVITY AND ENERGY LOSSES

The neutrino flux is formed mainly in the region where the mean free path of neutrino is smaller than the stellar radius. The neutrino energy flux H_ν associated with the temperature gradient can be written as (Imshennik and Nadjozhin, 1972)

$$H_\nu = -\frac{7}{8}\frac{4acT^3}{3} l_T \frac{\partial T}{\partial r}. \tag{4}$$

Here the part of the heat flux connected with the gradient of the lepton charge was neglected. In order to estimate the neutrino flux distribution over the surface of the star we consider for simplicity a set of spherically symmetric stars with different neutrino opacity distributions and the same central temperature. The quantity l_T having the meaning of the neutrino mean free path is connected with the neutrino opacity κ_ν as

$$\kappa_\nu = 1/(l_T\rho). \tag{5}$$

The calculations of the spherically symmetric collapse (Nadjozhin, 1978) have shown that, during the phase of the main neutrino emission, a hot neutron star consists of a quasiuniform 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 by about 10 times while the density, which finally drops by about 6 times decreases nonmonotonically. In this region, containing about a half of the neutron star mass, the neutrino flux is forming. We suggest for simplicity a power-law dependences for the temperature in this region:

$$T = T_i\left(\frac{r_i}{r}\right)^m, \tag{6}$$

anf for l_T,

$$l_T = \frac{1}{\kappa_\nu \rho} = l_{T_i}\left(\frac{r}{r_i}\right)^n. \tag{7}$$

The neutrinosphere with the radius r_ν is determined approximately by the relation

$$\int_{r_\nu}^{\infty} \kappa_\nu \rho \, dr = \int_{r_\nu}^{\infty} \frac{dr}{l_T} = 1. \tag{8}$$

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

$$r_\nu = r_i\left(\frac{r_i}{(n-1)l_{T_i}}\right)^{1/(n-1)}. \tag{9}$$

From (4)–(7), using (9) we get the temperature of the neutrinosphere T_ν and the heat flux at this level H_ν, which outside the neutrinosphere is approximately $\sim r^{-2}$, corresponding to the constant neutrino luminosity L_ν:

$$T_\nu = T_i\left(\frac{(n-1)l_{T_i}}{r_i}\right)^{m/(n-1)}, \tag{10}$$

$$L_\nu = 4\pi r_\nu^2 H_\nu = \tfrac{7}{8} m \frac{16\pi ac T_i^4}{3}(n-1)^{(4m-n+1)/(n-1)} r_i^2 \left(\frac{l_{T_i}}{r_i}\right)^{(4m-2)/(n-1)}. \tag{11}$$

In order 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 (different l_{T_i}). Consider for simplicity a star where l_{T_i} is different and constant in the two hemispheres, the laws (6) and (7) are the same and each hemisphere radiates independently with the luminosities equal to one half of (11), with different l_{T_i}. The anisotropy of the flux,

$$\delta_L = \frac{L_+ - L_-}{L_+ + L_-}, \tag{12}$$

with L_+ and L_- the luminosities in the different hemispheres, can be calculated using (11). For a small difference between the hemispheres, we get from (11)

$$\delta_L = \frac{\Delta L}{L} = \frac{4m-2}{n-1}\frac{\Delta l_{T_i}}{l_{T_i}}. \tag{13}$$

It is clear from (10) that the neutrinosphere exists only for $n > 1$. It follows from (11) that for $m = \frac{1}{2}$ the neutrino fluxes in both hemispheres are equal because the smaller opacity and larger neutrinosphere temperature T_ν from (10) is compensated by the smaller neutrinosphere radius r_ν from (9), so that the luminosity determined by the product $T_\nu^4 r_\nu^2 \sim T_\nu^4 r_\nu l_{T\nu}$ is constant. For $m > \frac{1}{2}$, larger l_{T_i} corresponds to larger luminosity, which implies a net excess of the more energetic neutrino, and the opposite situation happens for $m < \frac{1}{2}$. Let us emphasize that this conclusion is valid only for the similar power-law dependences (6) and (7) for T and l_T with different values of l_{T_i} at the boundary of the isothermal core. It is not possible to apply this conclusion directly in the case of different opacity laws, e.g. in the case of stellar neutrino luminosity in different neutrino sorts (electron, muon and tau).

4. THE NEUTRON STAR ACCELERATION BY THE ANISOTROPIC NEUTRINO PULSE

The equation of motion of the neutron star with the mass M_n radiating an anisotropic neutrino flux is

$$M_n \frac{dv_n}{dt} = \frac{1}{c} \int_0^\pi L_\nu(t, \theta) \cos\theta \, d\theta. \tag{14}$$

The total neutrino luminosity,

$$L_\nu(t) = \int_0^\pi L_\nu(t, \theta)\, d\theta, \tag{15}$$

can be taken from the spherically symmetric calculations of Nadjozhin (1978) or Mayle *et al.* (1987). Consider for simplicity that the neutrino fluxes in the upper, L_+, and lower, L_-, hemispheres are constant over θ. Then (14) and (15) can be written as

$$M_n \frac{dv_n}{dt} = \frac{L_+ - L_-}{c}, \tag{16}$$

$$L_+ + L_- = \frac{2}{\pi} L_\nu(t). \tag{17}$$

For the power-law distributions (9) and (10), it follows from (11), it follows from (11) that

$$L_\pm = A l_{T_i\pm}^{(4m-2)/(n-1)}, \tag{18}$$

where $l_{T_i\pm}$ are the average values of l_{T_i} in the two hemispheres. 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 an interpolation between the two asymptotic forms we obtain

$$l_{T_i\pm} \sim \frac{1}{W} = l_{T_0} \frac{1 + \left(\dfrac{B}{B_c}\right)^3}{1 + 0.17\left(\dfrac{B}{B_c}\right)^2 + 0.77\left(\dfrac{B}{B_c}\right)^4}. \tag{19}$$

The time dependence of the average value of B in each hemisphere can be found from (3) using the average values of $B_{\phi 0\pm}$ and $B_{p\pm}$, so that

$$B_{p+} = -B_{p-}, \qquad B_{\phi 0+} = B_{\phi 0-}. \tag{20}$$

The values of $L_{\pm}$ in each hemisphere can be written as

$$L_{\pm} = A l_{T_0}^{(4m-2)/(n-1)} F_{\pm} = D(t) F_{\pm}, \tag{21}$$

where $F\pm$ can be found as a function of B from the comparison with (18) and (19) and B, as a function of time, is taken from (3) with account of (20). From (17) and (21) we get

$$D(t) = \frac{2L_\nu(t)}{\pi(F_+ + F_-)}. \tag{22}$$

Eq. (16), with account of (21) and (22), can be finally written as

$$M_n \frac{dv_n}{dt} = \frac{2}{\pi} \frac{L_\nu}{c} \frac{F_- - F_+}{F_- + F_+}, \tag{23}$$

where the time dependence of L_ν is taken from the spherically symmetric collapse calculations and dimensionless time functions $F\pm$ are determined by the structure of the neutron star above the isothermal core and the average time dependence of B_ϕ in the two hemispheres.

5. NUMERICAL ESTIMATIONS

Consider for simplicity the distributions (6) and (7) with

$$\frac{4m-2}{n-1} = 1. \tag{24}$$

The acceleration of the neutron star occurs mainly when $B \gg B_c$, so the functions $F_{\pm}$ reduce to

$$F_{\pm} = \frac{B_c}{0.77 B_{\pm}}, \tag{25}$$

and the equation of motion (23) can be written as

$$M_n \frac{dv_n}{dt} = \frac{2}{\pi} \frac{L_\nu}{c} \frac{|B_+| - |B_-|}{|B_+| + |B_-|}. \tag{26}$$

with the linear functions

$$B_{\pm} \equiv B_{\phi\pm} = a \pm bt, \tag{27}$$

$$a = B_{\phi 0},\ b = \frac{|B_p|}{P},$$

with a and b determining by (3) and (20). Take constant L_ν:

$$L_\nu = \frac{0.1 M_n c^2}{20s}. \tag{28}$$

With these simplifications, the final velocity of the neutron star v_{nf} follows as a result of the solution of (26) in the form

$$v_{nf} = \frac{2}{\pi} \frac{L_\nu}{M_n c} \frac{P B_{\phi 0}}{|B_p|} \left(0.5 + \ln\left(\frac{20s}{P} \frac{|B_p|}{B_{\phi 0}}\right)\right). \tag{29}$$

For $P = 10^{-3}$ s and L_ν from (28), we obtain from (29):

$$v_{nf} = \frac{2}{\pi} \frac{c}{10} \frac{P}{20s} x \left(0.5 + \ln\left(\frac{20s}{P} \frac{1}{x}\right)\right) \approx 1 \frac{km}{s} x \left(0.5 + \ln\left(\frac{2 \times 10^4}{x}\right)\right). \tag{30}$$

For $x = \dfrac{B_{\phi 0}}{|B_p|}$ ranging between 20 and 10^3, we have v_{nf} between 140 and 3000 km/s, which can explain the nature of the most rapidly moving pulsars. Eq. (30) is applicable when $B_{\phi 0} \gg B_c$ and $x \gg 1$.

For a nonlinear dependence in (18), an analytical estimation of v_n can be done when the acceleration occurs mainly when

$$bt \gg a \tag{30}$$

in (27). Using the same conditions $B_\pm \gg B_c$, we have

$$F_\pm = \left(\frac{B_c}{0.77 B_\pm}\right)^{(4m-2)/(n-1)} \tag{31}$$

Expanding (31) and using (27) and (30), we obtain from (23):

$$M_n \frac{dv_n}{dt} = \frac{2}{\pi} \frac{L_\nu}{c} \frac{4m-2}{n-1} x \frac{P}{t}. \tag{32}$$

Integrating (32) we obtain the result which differs from (30) essentially only by the factor $(4m-2)/(n-1)$:

$$v_{nf} = \frac{2}{\pi} \frac{c}{10} \frac{P}{20s} x \frac{4m-2}{n-1} \ln\left(\frac{20s}{P} \frac{1}{x}\right) \approx 1 \frac{km}{s} \frac{4m-2}{n-1} x \ln\left(\frac{2 \times 10^4}{x}\right). \tag{33}$$

The acceleration of a collapsing star by the anisotropic neutrino emission can happen even when the star does not stop at the stage of the neutron star and collapses to the black hole. We may expect the black holes of stellar origin to move with high velocities, like radiopulsars. This implies that they can be situated much higher over the galactic disk than their progenitors, very massive stars.

6. CONCLUSION

The results obtained above show that the anisotropy of the neutrino pulse produced by the mirror asymmetric magnetic field distribution can explain the observed high velocities of radiopulsars for realistic magnetic field strengths. This mechanism of acceleration acts in all cases of anisotropic neutrino emission, including the case of the formation of a black hole. This means that black holes could be found at the distances from the galactic plane much larger than the thickness of the galactic disk of very massive stars.

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