KICK ASYMMETRY ALONG A STRONG MAGNETIC FIELD IN THE PROCESS OF NEUTRINO SCATTERING ON NUCLEONS

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ABSTRACT. The neutrino-nucleon scattering in a collapsing star envelope with a strong magnetic field is investigated. The transferred momentum assymetry along the field direction is obtained. It is shown that neutrino-nucleon scattering gives a contribution to the asymmetry comparable with direct URCA processes. Hence, neutrino-nucleon scattering should be taken into account in estimations of a possible influence of neutrino reemission processes on a collapsing star envelope dynamics.

Key words: neutrino-nucleon scattering: magnetic field: collapsing star remnant.

1. Introduction

The most powerfull star processes (a Supernova II explosion, a coalescense of a closed binary system of neutron stars, an accretion induced collapse) are of a permanent interest in astrophysics. A collapse in such systems can lead to the formation of a millisecond remnant (Bisnovatyi-Kogan, 1970, 1989; Woosley, 1993; MacFadyen et al., 1998; Ruffert et al., 1998; Spruit, 1998). It is assumed usually that the remnant consists of a compact rigid rotating core and a differently rotating envelope. The compact core with the typical size $R_c \sim 10km$, the supranuclear density $\rho \quad 10^{13} g/cm^3$ and the high temperature $T \quad 10MeV$ is opaque to neutrinos. An envelope with the typical size of a few tens of kilometers, the density $\rho \sim 10^{11} - 10^{12} g/cm^3$ and the temperature $T \sim 3-6MeV$ is partially transparent to the neutrino flux. Extremely high neutrino flux with the typical luminosity $L_\nu \sim 10^{52} erg/s$ is emitted from the remnant during 2 - 3 seconds after collapse. As result of a high rotating frequency and a medium viscosity of the remnant a turbulent dynamo and a large gradient of angular velosities are inevitably produced during a star contraction. The extremely strong poloidal magnetic field up to $B \sim 10^{15} G$ could be generated by a dynamo process in the remnant (Duncan et al., 1992). On the other hand, a large gradient of angular velosities in the vicinity of a rigid rotating millisecond core can generate a more strong toroidal magnetic field $B \sim 10^{15} - 10^{17} G$ during a second (Bisnovatyi-Kogan et al., 1993). In the present paper we investigate the influence of neutrino-nucleon processes on the dynamics of collapsing star millisecond remnant.

2. Momentum asymmetry in neutrino-nucleon scattering

Due to the parity-violation in neutrino-nucleon processes, the macroscopic momentum can be transfered by neutrinos to the medium in an external magnetic field. A quantitative estimation of the momentum asymmetry is given by the expression for the four-vector of the energy-momentum transfered to the unit volume in per unit time:

$$\frac{dP_\alpha}{dt} = \left(\frac{dQ}{dt}, \vec{\Im} \right) = = \frac{1}{V} \int \prod_i dn_i f_i \prod_f dn_f (1 - f_f) \frac{|S_{if}|^2}{\mathcal{T}} q_\alpha, \quad (1)$$

where dn_i, dn_f are the numbers of initial and final states in an element of the phase space, f_i, f_f are the distribution functions of the initial and final particles, q_α is the momentum transferred to the medium in the single reaction, $|S_{if}|^2/\mathcal{T}$ is the squared S-matrix element of the process per unit time. We calculate the asymmetry of the momentum transfered to the medium along the magnetic field direction in the processes of the neutrino-nucleon scattering:

$$N + \nu_i \Longrightarrow N + \nu_i, \quad (2)$$

$$N + \tilde{\nu}_i \Longrightarrow N + \tilde{\nu}_i, \quad (3)$$

where $N = n, p$; $\nu_i = \nu_e, \nu_\mu, \nu_\tau$. Under the conditions of the remnant envelope, the nucleonic gas is the Boltzmann and the nonrelativistic one. It is known that the asymmetry of the neutrino momentum is absent in the case of β-equilibrium (Kusenko et al., 1998). Thus, we discribe neutrino by the local nonequilibrium distribution function:

$$f_{(\nu,\tilde{\nu})} = \Phi_{(\nu,\tilde{\nu})}(r,\chi) \cdot \left(\exp\left(\omega/T_{(\nu,\tilde{\nu})} - \eta_{(\nu,\tilde{\nu})}\right) + 1\right)^{-1}. \quad (4)$$

Here χ is the cosine of the angle between the neutrino momentum and the radial direction, ω is the energy of the neutrino, $T_{(\nu,\tilde{\nu})}$ is the neutrino spectral temperature, $\eta_{(\nu,\tilde{\nu})}$ is a fitting parameter. Here we are neglected the influence of the magnetic field on the neutrino distribution (see detailes in A.A. Gvozdev, I.S. Ognev, this Proceedings). In calculation of S-matrix element of the processes (**??**), (**??**) we used the vacuum wave functions of the nucleons with polarization $S = \pm 1$ along the magnetic field. We also should take into account the interaction energy of the magnetic moment of nucleon with the magnetic field: $E = m + \vec{P}^2/2m - geBS/2m$ ($g \simeq -1.91$ for neutron, $g \simeq 2.79$ for proton).

Under these assumptions we obtain the following expression for the force density along the field:

$$\begin{aligned}\Im_{\parallel}^{(\nu)} &= -\frac{G_F^2 g}{2\pi}\,\frac{eB}{m_{n,p}T}\,N_{n,p}\,N_\nu\,\times\\ &\times\Bigg\{\left(c_v c_a\langle\omega_\nu^3\rangle + c_a^2 T\langle\omega_\nu^2\rangle\right)\left(\langle\chi_\nu^2\rangle - 1/3\right) -\\ &-c_a^2\left(\langle\omega_\nu^3\rangle - 5T\langle\omega_\nu^2\rangle\right)\left(5/3 - \langle\chi_\nu^2\rangle\right) +\\ &+2c_a^2 J\left(\langle\omega_\nu^3\rangle - 5T_\nu\langle\omega_\nu^2\rangle\right)\left(1 - \langle\chi_\nu^2\rangle\right)\Bigg\}. \quad (5)\end{aligned}$$

Here G_F is the Fermi constant, c_v, c_a are the vector and axial nucleonic current constants ($c_v = -1/2$, $c_a \simeq -0.91/2$ for neutron; $c_v = 0.07/2$, $c_a \simeq 1.09/2$ for proton); $N_{n,p}, N_\nu$ are local neutron (proton) and neutrinos numbers densities respectively,
$\langle\omega_\nu^n\rangle = N_\nu^{-1}\int \omega^n\, f_\nu\, d^3k$
is the mean energy in the n'th power,
$\langle\chi^2_{(\nu,\tilde{\nu})}\rangle = \int \chi^2\,\omega\, f_{(\nu,\tilde{\nu})}\, d^3k (\int \omega\, f_{(\nu,\tilde{\nu})}\, d^3k)^{-1}$
is the mean square cosine,
$J = (4\pi)^{-1}\int \Phi_\nu(r,\chi) d\Omega$.
In the case of antineutrino we have to change $c_a^2 \to -c_a^2$:

$$\Im_{\parallel}^{(\tilde{\nu})} = \Im_{\parallel}^{(\nu)}(c_a^2 \to -c_a^2). \quad (6)$$

We note, that the process of the neutrino scattering on protons is supressed by the smallness of the proton number density (for the conditions under consideration $N_p/N_n \simeq 0.07$). As one can see from exp. (**??**), the momentum asymmetry exist if the spectral neutrino temperature differs from the medium temperature ($T_\nu \neq T$) or the neutrino distribution is anisotropic ($\langle\chi_\nu^2\rangle \neq 1/3$).

In the case of the Boltzmann neutrino distribution function: $f_{(\nu,\tilde{\nu})} = \Phi_{(\nu,\tilde{\nu})}(r,\chi)\exp\left(-\omega/T_{(\nu,\tilde{\nu})}\right)$, the expression for the force density is simplified:

$$\begin{aligned}\Im_{\parallel}^{(\nu_i)} &= -\frac{6G_F^2 g}{\pi}\,\frac{eB}{m_{n,p}}\,N_{n,p}\,N_\nu\,T_\nu^2\,\times\\ &\Bigg\{4c_a^2\left(2 - \langle\chi_\nu^2\rangle\right) + 5T_\nu/T\Bigg[c_v c_a\left(\langle\chi_\nu^2\rangle - 1/3\right) -\\ &-c_a^2\left(5/3 - \langle\chi_\nu^2\rangle\right)\Bigg]\Bigg\}. \quad (7)\end{aligned}$$

Under an envelope conditions neutrino and antineutrino parameters for μ and τ species are equal approximately (Yamada et al., 1998): $T_\nu = T_{\tilde{\nu}}$, $\langle\chi_\nu^2\rangle = \langle\chi_{\tilde{\nu}}^2\rangle$. Thus, the expression for summary (neutrino and antineutrino) force density for each of these species is simplified and can be presented in the form:

$$\begin{aligned}\Im_{\parallel}^{(\nu_i)} + \Im_{\parallel}^{(\tilde{\nu}_i)} &= -\frac{G_F^2 c_v c_a g}{\pi}\,\frac{eB}{m_{n,p}T}\,\times\\ &\times N_{n,p}\,N_\nu\,\langle\omega_\nu^3\rangle\left(\langle\chi_\nu^2\rangle - 1/3\right), \quad (8)\end{aligned}$$

and this force density not equal to zero when the neutrino distribution is anisotropic only.

3. Numerical estimations

We estimate the momentum asymmetry in collapsing star envelope in the presence of the strong toroidal magnetic field on the stage of the basic neutrino emission. For numerical estimations we used the typical value of the envelope density $\rho = 5 \cdot 10^{11} g/cm^{-3}$ and the magnetic field strength $B = 4.4 \cdot 10^{16} G$.

The neutrino parameters are taken from the paper by Yamada et al. (1998):

$$\begin{aligned}&T_{\nu_e} \simeq 4MeV,\ T_{\tilde{\nu}_e} \simeq 5MeV,\ T_{\nu_{\mu,\tau}} \simeq T_{\tilde{\nu}_{\mu,\tau}} \simeq 8MeV,\\ &N_{\nu_e} \simeq 5 \cdot 10^{32} cm^{-3},\ N_{\tilde{\nu}_e} \simeq 2.1 \cdot 10^{32} cm^{-3},\\ &N_{\nu_{\mu,\tau}} \simeq N_{\tilde{\nu}_{\mu,\tau}} \simeq 1.8 \cdot 10^{32} cm^{-3},\\ &\langle\chi_{\nu_i}^2\rangle \simeq \langle\chi_{\tilde{\nu}_i}^2\rangle \simeq 0.4,\ \ \eta_{\nu_i} \simeq \eta_{\tilde{\nu}_i} \simeq 0.\end{aligned}$$

With these parameters we obtained the following numerical estimation on the total (summarised over all neutrino species) force density in the neutrino-nucleon scattering:

$$\begin{aligned}\Im_{\parallel}^{(scat)} &\simeq 3.4 \cdot 10^{20} dynes/cm^3\,\times\\ &\times\left(\frac{B}{4.4 \cdot 10^{16} G}\right)\left(\frac{\rho}{5 \cdot 10^{11} g/cm^3}\right). \quad (9)\end{aligned}$$

Let us compare this result with the estimation of the force density in URCA processes (see A.A. Gvozdev, I.S. Ognev, this Proceedings):

$$\Im_{\parallel}^{(urca)} \simeq 2 \cdot 10^{20} dynes/cm^3 \times$$
$$\times \left(\frac{B}{4.4 \cdot 10^{16} G}\right) \left(\frac{\rho}{5 \cdot 10^{11} g/cm^3}\right). \quad (10)$$

We stress that these quantities are of the same sign and sufficiently large numerically. The total force spins up quickly the envelope along the magnetic field direction. The estimation of the angular acceleration:

$$\dot{\Omega} \sim 10^3 s^{-2} \left(\frac{B}{4.4 \cdot 10^{16} G}\right) \left(\frac{R_c}{10 km}\right) \quad (11)$$

shows that the "neutrino spin up" effect can influence substantially on the envelope dynamics.

4. Conclusions

In the processes of neutrino-nucleon scattering the macroscopic momentum is transfered to the envelope along the magnetic field direction. This momentum is large enough in the case of the strong magnetic field and coincides in the sign with the similar momentum in the direct URCA processes. The force which appears in the neutrino-nucleon processes in the toroidal magnetic field generates the torque. This torque can spin up quickly the part of the envelope filled by the strong magnetic field. Therefore the "neutrino spin up" effect could essentially influence on the dynamics of the remnant envelope.

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