Angular asymmetry of neutrino emission in a strong magnetic field and possible consequences

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The neutrino emission in a magnetic field should have an angular asymmetry because of magnetobremsstrahlung, photonuclear processes, and other processes. Certain objects may undergo an intense self-acceleration, as has been discussed elsewhere.

Since a magnetic field singles out a certain direction as a special one, we would expect it to modify processes which result from weak interactions. For example, we would expect that an electron with a positive angular momentum L_3 in a magnetic field would, by virtue of the correlation between L_3 and the spin states of ν_e neutrinos, generate magnetobremsstrahlung neutrinos ν_e with primarily the same spin orientation (along the field). The effect would be equivalent to a preferential emission of these neutrinos in the direction opposite the field. Antineutrinos interacting with positron state should, for the same reasons, have the opposite predominant polarization and thus the same angular asymmetry. As a result, the electrons should begin a self-accelerated motion along the field. The results of Ref. 2 can be used to find[1] the average change per unit time in the electron momentum component (p_3^e) which is collinear with the field B:

$$< \dot{p}_3^e > = \frac{5G^2 m^6}{54\pi^3} \left(\frac{m}{E}\right) \chi^7 \tag{1a}$$

if $\chi \ll 1$ or

$$< p_3^e > = \frac{11\Gamma\,(4/3)}{3^{2/3}\,(9\pi)^3}\, G^2 m^6 \left(\frac{m}{E}\right) \chi^{7/3} \tag{1b}$$

if $\chi \gg 1$, where E is the energy of the electron, $\chi = (E/m)(B/B_{\rm Cr})$, and $B_{\rm Cr} = m^2/|e|$.

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The effective energies of the $\nu_e \bar{\nu}_e$ pairs produced by the electron are on the order of χE and E in the cases $\chi \ll 1$ and $\chi \gg 1$, respectively, and the reciprocal relaxation times of the emission are

$$\tau^{-1} = \frac{119 G^2 m^5}{36\sqrt{3}(2\pi)^3}\left(\frac{m}{E}\right)\chi^5 \tag{2a}$$

in the case $\chi \ll 1$ and

$$\tau^{-1} = \frac{2G^2 m^5}{(6\pi)^3}\left(\frac{m}{E}\right)\chi^2\left[\ln\frac{\chi}{\sqrt{3}} - \frac{5}{6} - C\right] \tag{2b}$$

in the case $\chi \gg 1$. If this process occurs under the conditions prevailing in a neutron star (during its evolutionary stage), then by the time τ the star will acquire a velocity $v \sim 6\times 10^6\, \delta_e \chi^2$ cm/s parallel to its own field (in the interior) if $\chi \ll 1$, or it will acquire a velocity $v \sim 10^7 \delta_e\, [\chi^{1/3}/(\ln(\chi/\sqrt{3}) - (5/6) - C)]$ if $\chi \gg 1$; here $\delta_e = n_e/(n_n + n_p)$, where n_e, n_n, and n_p are the densities of electrons, neutrons, and protons, respectively. If $B \sim B_{cr}$, $\chi \sim 10^2$, and $n_e \sim n_n \sim n_p$, we would have

$$\tau \sim 2\cdot 10^3 \text{ s} \quad \text{and} \quad v \sim 10^7 \text{ cm/s}.$$

In magnetic fields near the Schwinger field, the motion of electrons of limited energy ($m^2 \leqslant E^2 < m^2 + 2|e|B$) in the direction transverse with respect to the field will be suppressed, and the dynamics will degenerate into an effectively one-dimensional dynamics. For this reason, we would expect spin states ζ with an orientation along the field to be suppressed (in the Landau ground level, the state with $\zeta = -1$ is the only one possible). The correponding states of virtual electrons and positrons will be suppressed in a corresponding way. The matrix elements for processes involving virtual electrons and positrons will accordingly be dominated by their states with a definite spin orientation, and for "weak" processes involving neutrinos this situation should by virtue of the electron-neutrino spin correlation, give rise to an asymmetry in the distribution of neutrinos in spin states with respect to the field and thus an asymmetry of the angular distribution of the neutrinos. Because of the positron-antineutrino spin correlation, the distribution of antineutrinos in spin states will be the opposite, so that there will be an angular asymmetry which is the same as that for the ν_e's. Because of the coupling of the real and virtual states, we would expect that the neutrinos and antineutrinos produced in the reactions of originally unpolarized particles (not involving the real electrons and positrons at the beginning and end of the process) will have a predominant spin orientation along and opposite the field, respectively, and the distribution in the resultant momentum of the $\nu_e \bar{\nu}_e$ pair will contain a term which corresponds to their predominant emission opposite the field.

Using Ref. 3, we can show that in the case of $\nu_e \bar{\nu}_e$ photo-production in nuclei in a strong magnetic field the ratio of the number of $\nu_e \bar{\nu}_e$ pairs with a negative projection of the resultant momentum onto the field direction to the number of $\nu_e \bar{\nu}_e$ pairs with the corresponding positive projection will be on the order of 1.5. The reciprocal relaxation time τ^{-1} and the average change per unit time in the momentum of the nuclei (or protons, with $Z = 1$) collinear with the field are,[1] according to calculations based on Ref. 3,

$$\tau^{-1} = 1{,}537\times 10^4\,(Ze)^2\alpha^2 G^2 m^5\left(\frac{kT}{m}\right)^9, \qquad <\dot{p}_3^p> = 0{,}8\,\frac{kT}{\tau}\,, \tag{3}$$

where we have adopted a Planckian photon distribution in order to obtain some estimates. If these arguments apply to a neutron star, then we find that by the time τ the velocity acquired by the star can reach $v\sim 1.2\times 10^7\,\delta_p\,(\mathrm{kT/m})$ cm/s. Calculations for the case of the photoproduction of $\nu_e\bar{\nu}_e$ at electrons yield[1]

$$\tau^{-1} = \frac{2^9}{7\pi^3}\,\alpha G^2 m^5\left(\frac{kT}{m}\right)^7, \qquad <\dot{p}_3^e> = -\frac{28}{135}\,\frac{kT}{\tau}\,. \tag{4}$$

Applying these results to a neutron star, we estimate its velocity to be $v\sim -3\times 10^6\,\delta_e\,(\mathrm{kT/m})$ cm/s. An analysis of the $\nu_e\bar{\nu}_e$ bremsstrahlung in electron-nucleus (or electron-proton) collisions, based on Ref. 4, yields[1]

$$\tau^{-1} = 2{,}7\cdot 10^{-2}\,(Ze)^2\alpha G^2 m^2 n_0\left(\frac{kT}{m}\right)^{7/2}, \qquad <\dot{p}_3^p> = -0.1\,\frac{kT}{\tau}\,, \tag{5}$$

where the electrons are assumed to have a Maxwellian distribution. We then find $v\sim -1.5\times 10^6\,\delta_e\,(\mathrm{kT/m})$ cm/s.

The angular asymmetry should also occur during direct and inverse β decay in a strong magnetic field[1)] if the transverse motion of the electrons is suppressed. Rough estimates[1] of the velocities acquired by neutron stars due to the direct and inverse processes yield $v\sim -10^6\delta_n$ cm/s and $v\sim -4.5\times 10^6\,\delta_e(E_{\nu_e}/m)$ cm/s, respectively, where E_{ν_e} is the effective energy of the neutrinos that are produced. We should add that if the inverse β decay prevails over the direct β decay, then the angular momentum of the star may change slightly because of the angular momentum carried off by the neutrinos.

[1)]Private communication from N. N. Chugaĭ (Astronomical Council, Academy of Sciences of the USSR).

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