Neutrino effects in a SN mantle with strong magnetic field

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- Neutrino dynamical effects in SN I b/c, II astro-ph/040311

- SN do not explode!

- - Magneto-rotational mechanism of SN-explosion

- - - The neutrino force density along the magnetic field direction

- - P-violation in neutrino-nucleon processes, as a possible source of a one-side SN explosion

The main problem of Spherically Sym. Model

$\boxed{\text{SN do not explode !}}$

- Neutrino-driven mechanism
  [H. Bethe, J. Wilson, 1985] $\Longrightarrow$ SN do not explode

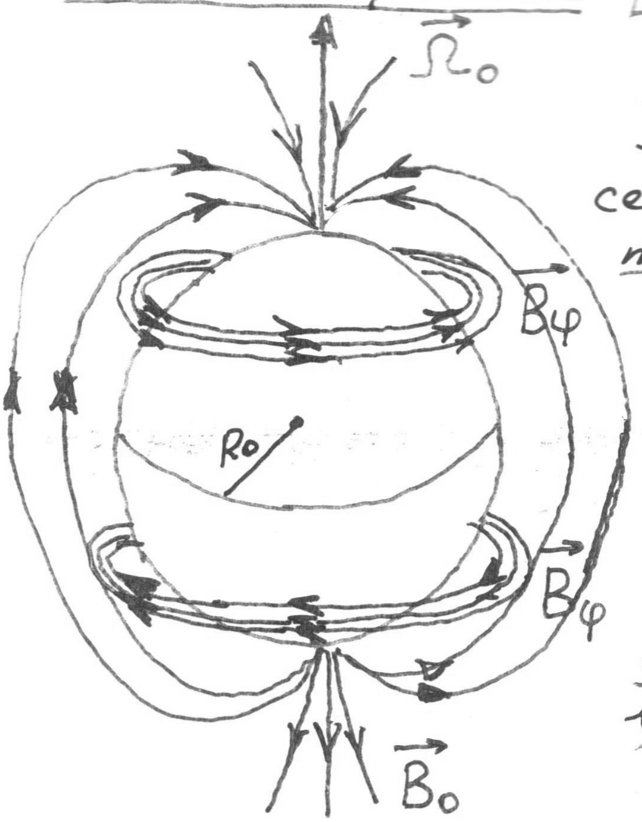
- Neutrino-driven convection

2D-simulation [Buras et al., 2003; Fryer et al., 2003] $\Rightarrow$ SN do not explode

3D-simulation (preliminary) [Janka et al., 2003; 2004] $\Rightarrow$ SN do not yet explode

It is clear that our understanding of the physical mechanisms of core-collapse SN remains rather incomplite.

II Magneto-rotational mechanism of SN-explosion [Bisnovatyi-Kogan, 1971]



In a differently rotating central core poloidal magnetic field $\vec{B}_0$ will be wound up into a toroidal configuration

Toroidal magnetic field $\vec{B}_\varphi$ will be generated mirror-symmetrically and amplificated linearly with time

$$\boxed{B_\varphi = \Omega_0 \cdot B_0 \cdot \Delta t \cdot F(r,\theta)}$$

[Bisnovatyi-Kogan, Moiseenko, 1992]

$$B_\varphi^{max} \approx \underbrace{3 \cdot 10^{13} G \cdot \left(\frac{\Omega_0}{1/s}\right)}_{10^{17} G \cdot \left(\frac{\Omega_0}{3\cdot 10^3 \, 1/s}\right)} \cdot \left(\frac{M_c}{M_\odot}\right)^{1/2} \cdot \left(\frac{10^6 cm}{R_0}\right)^{1/2}$$

$\tau \sim 0.7 сек \left(\frac{B_e}{B_0}\right.$

It is enough for shock acceleration outward and succesful SN-explosion

But, it is very difficult to generate such a strong toroidal magn. field

→ (The main problem of Magn-Rot. SN-explosion)

Is it possible, that a new dynamical effects appears, when a huge neutrino flux propagate through a magnetized medium?

- β-decay is enhanced by a strong magnetic field. That enhancement could be a possible source for an anomalously large pulsar kick velosities [N. Chugai, 1984]
[O. Dorofeev, V. Rodionov, I. Ternov 1984, 1985]

- Direct URCA

$$\boxed{\begin{array}{ll} \nu_e + n \to p + e^- & p + e^- \to \nu_e + n \\ \tilde{\nu}_e + p \to n + e^+ & n + e^+ \to \tilde{\nu}_e + p \end{array}}$$

in a strong magnetic field

The asymmetry of a momentum transferred by neutrino to a medium along the magnetic field direction [D. Baiko, D. Yakovlev, 1998
A. Gvozdev, I. Ognev, 1999]
D. Lai, F. Arras, 1999

$$\boxed{2eB \gtrsim m_e^2, T^2}$$

e^+, e^- occupy in general ground Landay level

$\to B \sim 10^{16} - 10^{17}\ G$

Not fantastic!

Physical assumptions

- $\rho \sim 10^{11}\,g/cm^3 - 10^{12}\,g/cm^3$
  $T \sim 3 - 6$ MeV

  → nucleonic gas is Boltzmann and nonrelativistic

- $m_B T \gg eB \gtrsim \mu_e^2 > T^2 \gg m_e^2$

  → Ultrarelativistic e^+e^--plasma occupies the ground Landau level

  protons occupy many Landau levels

- Non-equilibrium neutrino distribution function

$$f_\nu(\omega, r, \chi) = \frac{\Phi(r, \chi)}{e^{\omega/T_\nu - \eta_\nu} + 1}$$

ω is the neutrino energy,
T_ν is the neutrino spectral temperature,
η_ν is a fitting parameter,
χ is cosin of the angle between the radial direction and the neutrino momentum.

4 - energy-momentum transferred to a unite volume of a medium per unite time:

$$\frac{d\mathcal{P}_\alpha}{dt} = \left(\frac{dQ}{dt}, \vec{\mathcal{F}}\right) = \frac{1}{V}\int \prod_i dn_i\, f_i \prod_f dn_f (1-f_f)\cdot q_\alpha \cdot \frac{|S_{if}|^2}{\tau}$$

Reaction rate:

$$\boxed{\Gamma = \frac{1}{V}\int \prod_i dn_i f_i \prod_f dn_f\,(1-f_f)\,\frac{|S_{if}|^2}{\tau}}$$

$$\longrightarrow \overline{\ell_\nu} = N_\nu / \Gamma_\nu^{tot}$$

Direct URCA:

$$\boxed{\frac{d\mathcal{P}_\alpha^{(\nu,\tilde{\nu})}}{dt} = \int \frac{d^3k}{(2\pi)^3}\cdot k_\alpha \cdot K^{(\nu,\tilde{\nu})}\cdot \left[\left(1+e^{-\omega/T \pm \delta\eta}\right) f_{\nu,\tilde{\nu}} - e^{-\omega/T \pm \delta\eta}\right]}$$

$\delta\eta = (\mu_e + \mu_p - \mu_n)/T$, $k_\alpha = (\omega, \vec{k})$ - neutrino momentum

In β-equilibrium:

$$\mu_n + \mu_\nu = \mu_p + \mu_e \implies \delta\eta = \mu_\nu / T$$

$$\boxed{\frac{d\mathcal{P}_\alpha^{(\nu,\tilde{\nu})}}{dt} = \int \frac{d^3k}{(2\pi)^3}\cdot k_\alpha \cdot \left[1 + e^{-\frac{\omega \pm \mu_\nu}{T}}\right]\cdot K^{(\nu,\tilde{\nu})}\cdot \delta f_{\nu,\tilde{\nu}}}$$

$\delta f_\nu \equiv f_\nu - f_\nu^{eq}$ - deviation of the neutrino distribution from equilibrium.

The main result

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$$\mathcal{F}_{\parallel}^{URCA} \simeq \mathcal{N}\cdot\left[\frac{N_p}{N_B}\left(3\overset{\neq 1/3}{\langle\chi^2\rangle_\nu}-1\right)\cdot\mathcal{J}(a) + \right.$$

$$\left. + \frac{N_n}{N_B}\left(3\overset{\neq 1/3}{\langle\chi^2\rangle_{\tilde\nu}}-1\right)\cdot\mathcal{J}(-a)\right] -$$

$$-\frac{1}{2}\,\frac{(g_a^2-1)}{(3g_a^2+1)}\cdot\left[\left(1-\langle\chi^2\rangle_\nu\right)\underset{\neq 0}{\frac{dQ_\nu}{dt}}+\left(1-\langle\chi^2\rangle_{\tilde\nu}\right)\underset{\neq 0}{\frac{dQ_{\tilde\nu}}{dt}}\right]$$

$$\mathcal{J}(a) = \int_0^\infty \frac{dy\, y^3}{e^{y-a}+1} \qquad a = \frac{\mu_e}{T} - \frac{(m_n-m_p)}{T}$$

$$\langle\chi^2\rangle_{\nu,\tilde\nu} = \frac{\int d^3k\cdot\chi^2\cdot\omega\cdot f_{\nu,\tilde\nu}(\omega,r,\chi)}{\int d^3k\cdot\omega\cdot f_{\nu,\tilde\nu}(\omega,r,\chi)}$$

$$\mathcal{N} \equiv \frac{G_F^2\cos^2\theta_c}{(2\pi)^3}\cdot\frac{g_a^2-1}{3}\cdot eB\cdot N_B\cdot T^4$$

$$N_B = N_n + N_p \qquad g_a \simeq 1.26$$

Asymmetry is not zero if neutrino distributio[n] is anisotropic ($\langle\chi^2\rangle \neq 1/3$) or energy transfer by URCA per unite time to a unite volume ($\frac{dQ_{\nu,\tilde\nu}}{dt} \neq 0$).

Neutrino - nucleon scattering

$$N + \nu_i \longrightarrow N + \nu_i \qquad N + \tilde{\nu}_i \longrightarrow N + \tilde{\nu}_i$$

$$\mathcal{P}_\alpha + K_\alpha = \mathcal{P}'_\alpha + K'_\alpha \qquad N \equiv (n, p) \quad \nu_i = (\nu_e, \nu_\mu, \nu_\tau)$$

- We used the nonrelativistic vacuum wave function with a certain projection of spin along the magnetic field direction

•• We take into account the interaction energy of the anomalous nucleon magnetic moment with the magnetic field:

$$\boxed{E_N \simeq m_N + \frac{\vec{\mathcal{P}}^2}{2m_N} - g_N \cdot S \cdot \frac{eB}{2m_N}}$$

g_N is the nucleon magnetic factor ($g_n \simeq -1.91$, $g_p \simeq 2.79$)
S is the nucleon polarization ($S = \pm 1$)

••• We note, that

$$\boxed{\left.\frac{|S_{if}|^2}{\tau}\right|_{\tilde{\nu}_i} = \left.\frac{|S_{if}|^2}{\tau}\right|_{\nu_i} \quad (K_\alpha \longleftrightarrow K'_\alpha)}$$

The main result ($\nu_i + (n,p) \to \nu_i + (n,p)$)

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$$\mathcal{F}_{\parallel}^{(\nu_i)} = -\frac{G_F^2}{2\pi}\cdot g_N \cdot \frac{eB}{m_N T}\cdot N_N \cdot N_\nu \,*$$
$$*\Big\{ \left(C_v C_a \langle \varepsilon_\nu^3 \rangle + C_a^2 \cdot T \cdot \langle \varepsilon_\nu^2 \rangle \right) * \left(\langle \chi^2 \rangle - 1/3 \right) -$$
$$- C_a^2 \left(\langle \varepsilon_\nu^3 \rangle - 5T \cdot \langle \varepsilon_\nu^2 \rangle \right) \cdot \left(5/3 - \langle \chi^2 \rangle \right) +$$
$$+ 2 C_a^2 J_\nu \cdot \left(\langle \varepsilon_\nu^3 \rangle - 5T_\nu \langle \varepsilon_\nu^2 \rangle \right) \cdot \left(1 - \langle \chi^2 \rangle \right) \Big\}$$

where $\langle \varepsilon_\nu^n \rangle \equiv \dfrac{\int \omega^n f_\nu d^3k}{\int f_\nu d^3k}$ is the n-th moment of the neutrino energy

$\langle \chi^2 \rangle \equiv \dfrac{\int \chi^2 \omega f_\nu d^3k}{\int \omega f_\nu d^3k}$ is the mean square of the cosine on the angle between $\vec{k}\,\widehat{\ }\,\vec{n}_r$

$J_\nu \equiv \frac{1}{4\pi} \int \Phi_\nu(r,\chi)\, d\Omega$ has the meaning of the ratio $N_\nu(r,\chi)/N_\nu(T_\nu)$

C_v and C_a are the vector and axial constants for a neutral nucleon current

[$C_v = -1/2$, $C_a \simeq -\frac{0.91}{2}$ $(N=n)$; $C_v = \frac{0.07}{2}$, $C_a \simeq \frac{1.09}{2}$ $(N=p)$]

- $\tilde{\nu}_i + (n,p) \to \tilde{\nu}_i + (n,p)$

$$\boxed{\mathcal{F}_{\parallel}^{(\tilde{\nu}_i)} = \mathcal{F}_{\parallel}^{(\nu_i)} \Big|_{C_a^2 \to -C_a^2}}$$

- Under the conditions:

$$\langle \varepsilon^n_{\nu_\mu} \rangle \simeq \langle \varepsilon^n_{\nu_\tau} \rangle , \quad \langle \chi^2 \rangle \big|_{\nu_\mu} \simeq \langle \chi^2 \rangle \big|_{\nu_\tau}$$

$$\boxed{\mathfrak{F}_{\parallel}^{(\nu_x + \tilde{\nu}_x)} \Big|_{x \equiv \mu, \tau} \simeq - \frac{G_F^2}{\pi} \cdot g_N \cdot \frac{eB}{m_N T} \cdot N_N \cdot N_\nu \cdot C_V \cdot C_a * \langle \varepsilon^3_{\nu_x} \rangle * \left(\langle \chi^2 \rangle_{\nu_x} - 1/3 \right)}$$

- As can be seen from the expression obtained:

$$\boxed{\mathfrak{F}_{\parallel}^{(\nu, \tilde{\nu})} \neq 0, \quad \text{if} \begin{cases} \langle \chi^2 \rangle \neq 1/3 , \ J_\nu \neq 1, \\ T_\nu \neq T \end{cases}}$$

- Interestingly: $g_n = -1.91$, $g_p = 2.79 \Longrightarrow$

$$\Longrightarrow \boxed{\mathfrak{F}_{\parallel} \Big|_{N=n} \uparrow\downarrow \mathfrak{F}_{\parallel} \Big|_{N=p}}$$

However, in the SN mantle $N_p / N_n \ll 1$

Thus, the scattering on neutrons mainly contribute to the force density

$\Rightarrow$ The asymmetry of momentum transfer along the MF is accumulated in URCA and SCATTERING

- Estimation of the force density asymmety along the magnetic field:

$$\mathcal{F}_{\parallel}^{URCA} \sim G_F^2 \cdot eB \cdot N_N \cdot T^4$$

$$\mathcal{F}_{\parallel}^{SC} \sim G_F^2 \cdot \underbrace{\frac{eB}{m_N T}}_{\ll 1} \cdot N_N \cdot \langle \varepsilon_\nu^3 \rangle \cdot N_\nu$$

The ratiois:

$$\boxed{\mathcal{F}_{\parallel}^{SC} / \mathcal{F}_{\parallel}^{URCA} \sim \frac{\langle \varepsilon_\nu^3 \rangle N_\nu}{m_N T^5} \sim \left(\frac{T_\nu}{T}\right)^5 * \underbrace{\left(\frac{T_\nu}{m_N}\right)}_{\text{smallness}}}$$

But, more accurately estimation of the ratio can be represented, as:

$$\underbrace{\frac{\mathcal{F}_{\parallel}^{SC}}{\mathcal{F}_{\parallel}^{URCA}}}_{\sim 1\,!!} \simeq \underbrace{\frac{4 c_v c_a g_n}{g_a^2 - 1}}_{\sim 10} \cdot \underbrace{\frac{\mathcal{J}_5(\eta_{\nu x})}{\mathcal{J}_3(a)}}_{\sim 10^2} \cdot \underbrace{\frac{J_{\nu x}}{Y_p}}_{\sim 0.1} \cdot \underbrace{\left(\frac{T_{\nu x}}{T}\right)^5}_{\sim 10} \cdot \underbrace{\left(\frac{T_{\nu x}}{m_N}\right)}_{\sim 10^{-3}}$$

Numerical estimation:

$$\boxed{\begin{aligned} \mathcal{F}_{\parallel}^{URCA} &\simeq 1.4 * 10^{20} \frac{dyne}{cm^3} * \left(\frac{B}{4.4 \cdot 10^{16} G}\right) \\ \mathcal{F}_{\parallel}^{scat} &\simeq 3.0 * 10^{20} * \frac{dyne}{cm^3} * \left(\frac{B}{4.4 \cdot 10^{16} G}\right) * \left(\frac{\rho}{5 \cdot 10^{14} g/cm^3}\right) \end{aligned}}$$

Quasi-equilibrium conditions

$N_p = N_{e^-} - N_{e^+}$ – electroneutrality cond.

$\Gamma_{n \to p} = \Gamma_{p \to n}$ – chemical equilibrium cond.

$\dfrac{dQ^{tot}}{dt} = 0$ – thermal equilibrium cond.

$\Gamma_{n \to p}$ – the numbers of transitions from neutron to proton in the unite volume per unite time

$\boxed{dQ^{tot}/dt \simeq dQ^{URCA}/dt}$!

$\rho = 5 \cdot 10^{11}\, g/cm^3$, $B = 4 \cdot 10^{16}\, G$,

$T_{\nu_e} \simeq 4\, MeV$, $T_{\tilde{\nu}_e} \simeq 5\, MeV$, $T_{\nu_x} \simeq T_{\tilde{\nu}_x} \simeq 8\, MeV$,

$\eta_\nu \simeq \eta_{\tilde{\nu}} \simeq 0$

$N_{\nu_e} \simeq 5 \cdot 10^{32}\, 1/cm^3$, $N_{\tilde{\nu}_e} \simeq 2.1 \cdot 10^{32}\, 1/cm^3$, $N_{\nu_x} \simeq N_{\tilde{\nu}_x} \simeq 1.8 \cdot 10^{32}\, 1/cm^3$

$\langle \chi^2 \rangle \simeq 0.4$

[Yamada S, Janka T.-H., Suzuki H, 1999]

$T \simeq T_{\nu_e}$ $\mu_e/T \simeq 2.8$

$N_p/N_B \simeq 0.07$

The medium parameters in quasi-equilibrium conditions

The angular acceleration

$$\boxed{\dot{\Omega} \approx 0.6 \cdot (\Omega_0 \cdot t) \cdot F(r,\theta) \cdot \left(\frac{10\,km}{R}\right) \cdot \left(\frac{B_0}{4 \cdot 10^{13} G}\right) \, 1/s^2}$$

The typical time of the „flatness" of the angular velosity gradient:

$$\Omega(\tau) \approx \Omega_0 \Longrightarrow \boxed{\tau \approx \left(\frac{4 \cdot 10^{13} G}{B_0}\right)^{1/2} sec}$$

The condition of the „efficiency" of the neutrino „spin-up" mechanism:

$$\tau_\nu \approx 3\,sec \Longrightarrow \boxed{B_0 \gtrsim 4 \cdot 10^{12} G}$$

The estimation of the maximum field strength:

$$\boxed{B_{max}(\tau) \approx 1.6 \cdot 10^{17} G \cdot \left(\frac{10^{-3} s}{P_0}\right) \left(\frac{B_0}{4 \cdot 10^{13} G}\right)^{1/2}}$$

!

The estamation of kick velosity in the case of one-side SN explosion:

$$\boxed{\vartheta_{kick} \approx 10^3 \frac{km}{s} * \left(\frac{\Delta E_{jet}}{10^{51} erg}\right) * \left(\frac{1{,}5 M_\odot}{M_R}\right)}$$

Conclusions

- The effect of P-violation in reactions of neutrino interaction with strongly magnetized SN envelope <u>could be a natural source of one-side SN explosion</u>

- The one-side SN explosion can be realized under reasonable choise of collapsar initial parameters (ρ_0, B_0, L_ν)

- The one-side SN explosion [redacted] could give the natural explanation of the SN explosion asymmetry and anomalously large kick velosity of SNR's.