Neutrino-Triggered Asymmetric Magnetorotational Pulsar Natal Kick ("Cherry-Stone Shooting" Mechanism)

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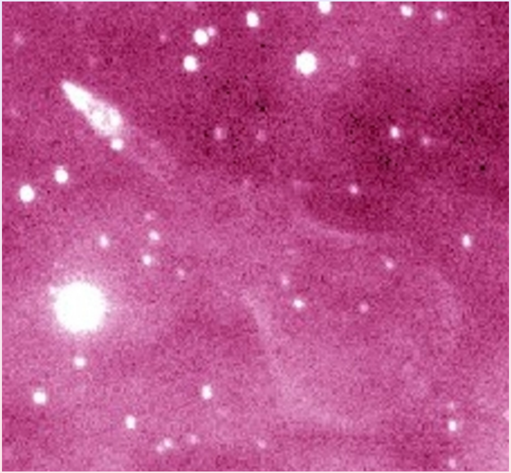
Pulsar proper motion problem

- *Shklovsky*, Astron. Journ., 1969
- *Gunn, Ostriker*, Astrophys. Journ., 1970
- ...
- *Lyne, Lorimer*, Nature, 1994 (99 PSRs)
- ...
- *Hobbs, Lorimer, Lyne, Kramer*, MNRAS, 2005 (233 PSRs)
- ...

«Guitar» Nebula in Cepheus

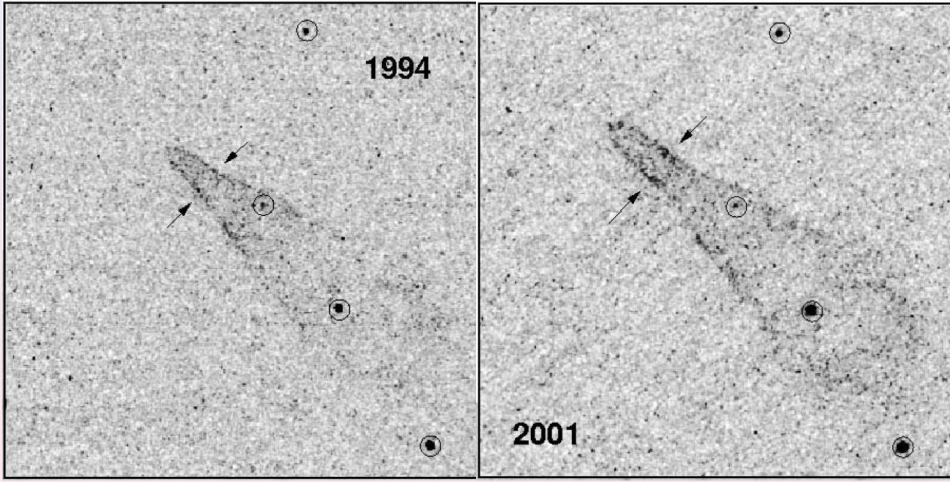


A bright bow shock wave around a *young* neutron star (radio pulsar B2224+64).

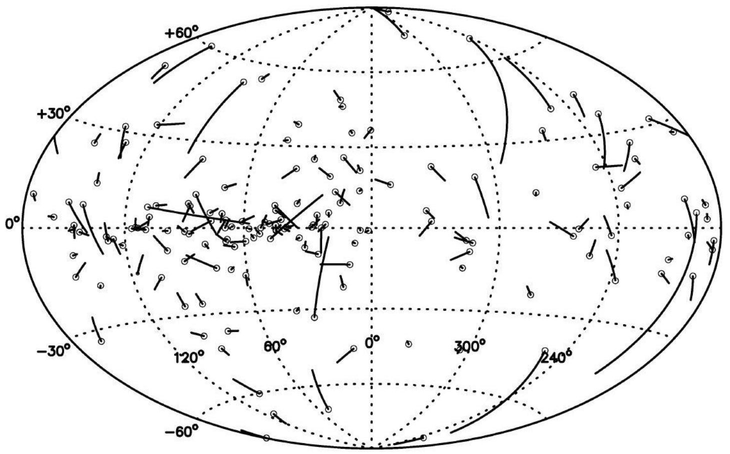
$V \simeq 1600$ km/sec.

H_α image, Palomar Observatory.

«Guitar» Nebula in Cepheus, *Chatterjee*, *Cordes*, Astrophys. Journ., 2004



Data on 233 «runaway» pulsars: MNRAS 369, 974 (2005)



The tail = the estimated path for 1 million years.

Data on 233 «runaway» pulsars: MNRAS 369, 974 (2005)

$< V > \simeq 400$ km/sec.
More than 15 % have $V > 1000$ km/sec.
Fastest pulsars PSRs B2011+38 and B2224+64:
$V \simeq 1600$ km/sec.

Directions of pulsar velocities and rotation axes **are correlated!**

- *Deshpande e.a.*, A & A, 1999 – no correlation.
- *Johnston e.a.*, MNRAS, 2005 – **correlation does exist.**

Asymmetry in supernova explosions.

The initial kick of a pulsar: attempts to explain

Hydrodynamics of the supernova explosion: no large speeds. Three-dimensional simulation with initial asymmetry in the SN core, increasing during the collapse (*Fryer*, Astrophys. J., 2004):
$V < 200$ km/sec.

Multy-dimensional simulation (*H.-T. Janka e.a.*, A & A, 2006): up to $\sim 10^3$ km/sec.

No correlation between the directions of pulsar velocity and the magnetic field or rotation axis.

The initial kick of a pulsar: attempts to explain

Other early mechanisms, $V < 100$ km/sec.

- evolution of **close binary systems** (*Gott e. a.*, Astrophys. J. Lett., 1970);
- **electromagnetic rocket engine,** due to inclination and displacement of the magnetic moment, acceleration within a few months (*Harrison, Tademaru*, Astrophys. J., 1975);
- asymmetric radiation of **neutrinos (antineutrinos)** in the collapse via the URCA-processes in a strong magnetic field $\sim 10^{14} - 10^{15}$ G (*Chugai*, Astron. Journ. Lett., 1984; *Dorofeev, Rodionov, Ternov*, Astron. Journ. Lett., 1985).

The initial kick of a pulsar: attempts to explain

Why neutrinos?

Neutrinos carry away 99 % of the supernova energy $E \sim 3 \times 10^{53}$ erg.
If asymmetry $\sim 3\,\%$, neutrinos carry the momentum of $\sim 0.03\, E/c$.
A neutron star with $M \sim 1.4 M_{\odot}$, gets $V \sim 1000$ km/sec.

However: **small mean free path in matter**. Neutrino cannot cause high-velocity pulsars (*Vilenkin*, Astrophys. J., 1995; *Lai, Qian*, Astrophys. J., 1998; *Arras, Lai*, Astrophys. J., 1999).

The initial kick of a pulsar: attempts to explain

- *Kusenko, Segre*, Phys. Rev. Lett., 1996.
  Neutrino oscillations in matter and intensive magnetic field.
  The for ν_τ-neutrinosphere inside ν_e-neutrinosphere. Resonant transition $\nu_e \to \nu_\tau$ between the neutrinospheres, ν_e (entangled) $\to \nu_\tau$ («free»).
  Effective ν_τ-neutrinosphere **is deformed** along the magnetic field $\Rightarrow$ anisotropy $\Rightarrow$ kick.

Criticism (*Janka, Raffelt*, Phys. Rev. D, 1998): **after the neutrinosphere deformation, the surfaces of the constant temperature will be deformed also, because just neutrinos provide a thermal equilibrium.**

The main problem of the model: the existence of neutrinos with the mass $\sim$ 100 eV is needed.

Restriction on the neutrino mass, $m_\nu < 2$ eV, «closed» the model.

The initial kick of a pulsar: attempts to explain

- Using of **exotic** neutrino properties.
  E. Akhmedov e.a., Phys. Rev. D, 1997: **the resonant spin-flavour precession of neutrinos with a transition magnetic moment** in SN magnetic field.
  $B \sim 10^{16}$ G, neutrino parameters within existing experimental bounds.

Janka, Raffelt, **1998: the magnetic fields are required more than an order of magnitude larger.**

The sterile neutrinos come on stage

- *Kusenko, Segre*, Phys. Lett. B, 1996.
  Deformed by *B*-field neutrinosphere, instead of $\nu_{\mu,\tau} \leftrightarrow \nu_e$, now to «heavy» (a few keV) **sterile** neutrinos, $\nu_{\mu,\tau} \leftrightarrow \nu_s$.

  Initial velocity of pulsars + dark matter.

However, as the analysis shows, the result for the asymmetry was overvalued in the paper at 15 times.

Magnetic field strength needed **15 times larger,** not $\sim 3 \times 10^{16}$ G, but $\sim 4.6 \times 10^{17}$ **G.**

Off-resonance transitions

- *Fuller, Kusenko e.a.*, Phys. Rev. D, 2003.
  Due to *small* mixing, sterile neutrinos could be born in β-processes:

  (1) neutrino energies in the core: ~ 150 MeV (at neutrinosphere ~ 20 MeV);
  (2) emission from the volume, not from the surface.

However, the asymmetry was overvalued at 40 times at least.

Magnetic field strength needed **40 times larger,** not $\sim 10^{16}$ G, but **$\sim 4 \times 10^{17}$ G.**

MSW-like resonance transition into sterile neutrinos

- *C. Kishimoto* (arXiv:1101.1304, version 1 and version 2): a detailed numerical analysis of $\nu_{\text{active}} \to \nu_{\text{sterile}}$ transformation through MSW-like resonance in the protoneutron star.

We have found a numerical error in version 1, where the coefficient in a starting formula was overvalued at 280 times.

The magnetic field needed should be not $\sim 10^{16}$ G, but $\sim 3 \times 10^{18}$ G.

Are sterile neutrinos necessary?

If we really need such strong magnetic fields,

isn't it possible to manage with standard neutrinos?

Asymmetry with strong magnetic field and *standard* neutrinos

Due to **parity violation** in the **neutrino-electron and neutrino-nucleon processes,** an asymmetry arises of neutrino emission in a strong magnetic field (*A. K., N. Mikheev*, Phys. Lett. B, 1997; Phys. At. Nucl., 1997; Mod. Phys. Lett. A, 1999; JETP, 2000; *A. Gvozdev, I. Ognev*, JETP Lett., 1999; JETP, 2002):

$$A \; = \; \frac{|\sum_i \mathbf{p}_i|}{\sum_i |\mathbf{p}_i|}.$$

Poloidal field, the $\nu \to \nu e^- e^+$ process (*A. K., N. Mikheev*, 1997):

$$A \sim 3 \times 10^{-3} \left(\frac{B}{10^{16}\ \mathrm{G}} \right) \left(\frac{\bar{E}}{20\ \mathrm{MeV}} \right)^3 \left(\frac{\Delta \ell}{20\ \mathrm{km}} \right).$$

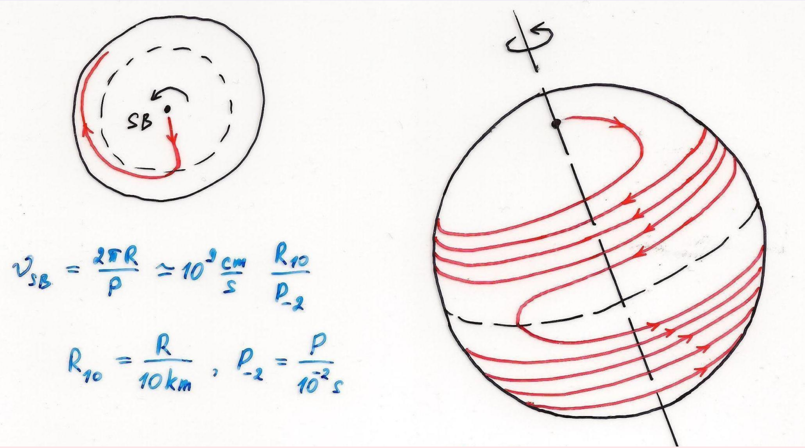
Magnetars: $B \sim (\mathrm{a\ few}) \times 10^{15}$ G. **Critical:** $B_e = 4.41 \times 10^{13}$ **G.**

Toroidal magnetic fields could be stronger than poloidal ones

A poloidal magnetic field being enhanced during the SN core collapse and being frozen in plasma, due to the **differential rotation,** generates a strong toroidal magnetic field.

This toroidal field can be in order of magnitude greater than the original poloidal field.

Model for the generation of the toroidal magnetic field by *G.S. Bisnovatyi-Kogan* (Astron. Journ., 1970)



Integral effect of neutrinos on a magnetized plasma (*A. K., N. Mikheev*, JETP, 2000)

A complete set of neutrino-electron processes in plasma:
$\nu e^{\mp} \to \nu e^{\mp}$, $\nu \to \nu e^- e^+$, $\nu e^- e^+ \to \nu$.

Energy and force neutrino flux impact on plasma:

$$(\dot{\mathcal{E}}, \mathcal{F}_z) = \int \mathrm{d}n_\nu \, \mathrm{d}W \, (P - P')_{0,z} \,, \qquad \mathrm{d}n_\nu = \frac{\mathrm{d}^3 P}{(2\pi)^3} \, \frac{\Phi(\vartheta, R)}{\mathrm{e}^{(E-\mu_\nu)/T_\nu} + 1} .$$

Spectral temperatures for different types of neutrinos:

$$T_{\nu_e} \simeq 4\,\mathrm{MeV}, \quad T_{\bar{\nu}_e} \simeq 5\,\mathrm{MeV}, \quad T_{\nu_{\mu,\tau}} \simeq T_{\bar{\nu}_{\mu,\tau}} \simeq 8\,\mathrm{MeV}.$$

β – processes ($\nu_e + n \leftrightarrow e^- + p$) dominate the energy balance, $T \simeq T_{\nu_e}$.

Integral effect of neutrinos on a magnetized plasma (*A. K., N. Mikheev*, JETP, 2000)

The total contribution of $\bar{\nu}_e$, $\nu_\mu, \bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$ by ν-e-processes:

$$(\dot{\mathcal{E}}, \mathcal{F})_{\nu_i} \simeq \mathcal{A} \left[\left(C_V^{(i)} \right)^2 + \left(C_A^{(i)} \right)^2, 2 C_V^{(i)} C_A^{(i)} \right] \psi(T_{\nu_i}/T).$$

$$C_V^{(e)} = \frac{1}{2} + 2\sin^2\theta_{\mathrm{W}} \, , \; C_A^{(e)} = \frac{1}{2} \, , \; C_V^{(\mu,\tau)} = -\frac{1}{2} + 2\sin^2\theta_{\mathrm{W}} \, , \; C_A^{(\mu,\tau)} = -\frac{1}{2} \, .$$

Combined effect of all neutrino types interacting with $e^- e^+$ plasma:

$$\mathcal{F}_B^{(\nu e)} \simeq 3.6 \times 10^{20} \left(\frac{B}{10^{16} \mathrm{G}} \right) \left(\frac{T}{4 \ \mathrm{MeV}} \right)^7 \frac{\mathrm{dyne}}{\mathrm{cm}^3} \, .$$

Contribution of the neutrino-nucleon processes (*A. Gvozdev, I. Ognev*, JETP Lett., 1999; JETP, 2002)

In the shell of a supernova ($Y_e \simeq 0.2$, $\rho \simeq 10^{11-12}$ g/cm^3):

$$\mathcal{F}_B^{(\nu N)} \simeq 2.4 \times 10^{20} \left(\frac{B}{10^{16} \mathrm{G}} \right) \frac{\mathrm{dyne}}{\mathrm{cm}^3} \,.$$

'νN' are both urca-processes and νN-scattering.

Important: the contributions of both νe and νN processes **are of the same sign!**

$$\mathcal{F}_B^{(total)} \simeq 0.6 \times 10^{21} \left(\frac{B}{10^{16} \mathrm{G}} \right) \frac{\mathrm{dyne}}{\mathrm{cm}^3} \,.$$

To be compared with?

The gravity force density: $\mathcal{F}^{(grav)} \sim 10^{26}\, \mathrm{dyne/cm}^3$.

However, the neutrino force is directed along the toroidal field.

Neutrino flux, pushing the plasma, torques the toroids in different directions

Angular acceleration for a plasma element at the distance R from the axis:

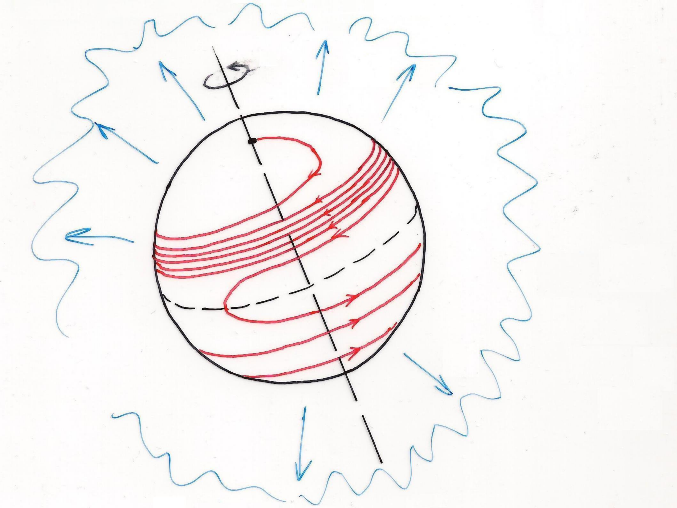
$$\dot{\Omega} = \frac{\mathcal{F}}{\rho\, R} \simeq 1.2 \times 10^{3} \frac{1}{\text{sec}^{2}} \left(\frac{B}{10^{16}\text{G}} \right) .$$

During the time ~ 1 sec, we have

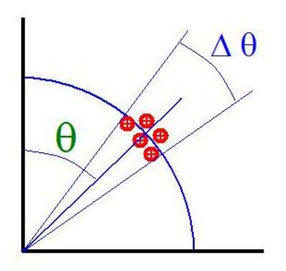
$$\Delta\Omega \sim 10^{3} \frac{1}{\text{sec}} \left(\frac{B}{10^{16}\text{G}} \right) .$$

In the one hemisphere, the angular acceleration coincides with the direction of the initial rotation, while in another hemisphere, they are opposites.

Neutrino flux, pushing the plasma, torques the toroids in different directions



Pulsar kick



Pressure difference in the two hemispheres:

$$\Delta p \simeq \frac{B^2}{8\pi} = \frac{(eB)^2}{8\pi\alpha}$$

$$\alpha = \frac{1}{137}$$

Acceleration:

$$\frac{\mathrm{d}V_{kick}}{\mathrm{d}t} \simeq 1.6 \times 10^5 \, \frac{\mathrm{km}}{\mathrm{sec}^2} \left(\frac{B}{10^{16}\mathrm{G}}\right)^2 \left(\frac{R}{20\,\mathrm{km}}\right)^2 \left(\frac{1.4\,M_\odot}{M}\right) \sin 2\theta \; \Delta\theta$$

at $\Delta\theta \sim 15^0 \sim \frac{1}{4}$, $\theta \sim 45^0$

$$\frac{\mathrm{d}V_{kick}}{\mathrm{d}t} \simeq 4 \times 10^4 \, \frac{\mathbf{km}}{\mathbf{sec}^2} \left(\frac{B}{10^{16}\mathbf{G}}\right)^2 \left(\frac{R}{20\,\mathbf{km}}\right)^2 \left(\frac{1.4\,M_\odot}{M}\right)$$

Pulsar kick

In fact the magnetic field volume is expanded, and the field decreases. The magnetic flux conservation provides: (pressure) $\times$ (volume)^2 $=$ const.

With the same geometry:

$$V_{kick} \simeq 600\,\frac{\mathbf{km}}{\mathbf{sec}} \left(\frac{B_0}{10^{16}\mathbf{G}}\right) \left(\frac{R}{20\,\mathbf{km}}\right) \left(\frac{\Delta\, z}{5\,\mathbf{km}}\right)^{1/2} \left(\frac{1.4\,M_{\odot}}{M}\right)^{1/2}$$

Conclusions

- Pre-supernova core is collapsing with rotation during 0.1 sec; a strong **toroidal** magnetic field is generated due to the **differential rotation.**
- The neutrino outburst, pushing the plasma by the tangential force along the toroidal magnetic field frozen in plasma, leads to **a magnetic field asymmetry.** The field strength is **enhancing** in one hemisphere and is **decreesing** in another one, during ~ 1 sec.
- The **pressure difference** arising in the two hemispheres, causes the **kick** to a core, providing the pulsar kick velocity $\sim 10^3$ km/sec during very short time, like in a shot. We may have a kind of «Cherry-Stone Shooting» Mechanism for pulsar natal kick.

A detailed multy-dimensional numerical simulation of the process is needed. We believe it would confirm the effect.

Thank you for your attention!