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Reply to *Comment on "Pulsar velocities and neutrino oscillations"*

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The explanation to pulsar birth velocities proposed in Ref. [1] assumes that neutrino oscillations take place in the vicinity of the neutrinospheres, where the matter density is $\rho = 10^{10} - 10^{12}$ g/cm^3 [2]. A $\Delta k/k \sim 1\%$ asymmetry in the momentum distribution of outgoing neutrinos can explain the observed motion of pulsars. We evaluated $\Delta k/k$ using the approximation $dN_e/dT \approx (\partial N_e/\partial T)_{\mu_e}$ and obtained

$$\frac{\Delta k}{k} = 0.01 \left(\frac{B}{3\times 10^{14}\mathrm{G}}\right). \tag{1}$$

In this approximation the total kick does not depend on Y_e or ρ.

An alternative approximation was proposed in the preceding Comment [3]. Replacing dN_e/dT by its value at constant Y_e yields an upper estimate of

$$\frac{\Delta k}{k} = 0.01 \left(\frac{0.1}{Y_e}\right)^{2/3} \left(\frac{10^{11}\mathrm{g/cm}^3}{\rho}\right)^{2/3} \left(\frac{B}{2\times 10^{15}\mathrm{G}}\right). \tag{2}$$

Neutrino oscillations must take place below the electron neutrinosphere, but above the τ neutrinosphere. (We note in passing that several different definitions of neutrinosphere are found in the literature and refer the reader to Refs. [2, 4] for discussion.) For $\rho \sim (1-3)\times 10^{11}$ g/cm^3 [4] and the time average of $Y_e \approx 0.1$, Qian's approximation yields a somewhat higher prediction for the magnetic field inside the neutron star.

These two estimates are in reasonable agreement with each other, given the uncertainties in the input parameters, the geometry of the magnetic field and the simplified picture of neutrino emission that comes with the notion of a neutrinosphere.

References

[1] A. Kusenko and G. Segrè, Phys. Rev. Lett. **77**, 4872 (1996).

[2] H. Suzuki, in *Physics and Astrophysics of Neutrinos*, ed. by M. Fukugita and A. Suzuki (Springer-Verlag, Tokyo, 1994).

[3] Y.-Z. Qian, *Comment on "Pulsar velocities and neutrino oscillations"* (astro-ph/9705055).

[4] J. Cooperstein, Phys. Rep. **163**, 95 (1988).