

# On pulsar velocities from neutrino oscillations

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**Abstract.** It has been recently suggested that magnetically affected neutrino oscillations inside a cooling protoneutron star, created in a supernova explosion, could explain the large proper motion of pulsars. We investigate whether this hypothesis is in agreement with the observed properties of pulsars and find that present data disfavor the suggested mechanism. The relevance of our results for other models proposed to understand the origin of pulsar velocities is also discussed.

**Key words:** elementary particles – pulsars: general – supernovae: general

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## 1. Introduction

One of the challenging problems in pulsar astrophysics is to find a consistent and observationally verified explanation for the high peculiar velocities of pulsars. These velocities can be as high as 1000 km/s and have a mean value of 450 km/s, much greater than the random velocities of ordinary stars (Harrison et al. 1993; Lyne & Lorimer 1994). Several mechanisms have been put forward in the past to explain the origin of the large proper motions. Since it is believed that pulsars are born during the first stages of some Type II or core-collapsing supernovae, an asymmetric core collapse or explosion could give the pulsars the observed velocities (Shklovskii 1970; Woosley 1987; Woosley & Weaver 1992; Janka & Müller 1994; Burrows & Hayes 1996). The evolution of close binary systems could also be responsible for the large pulsar velocities (Gott et al. 1970). Alternatively, the emission of electromagnetic radiation during the first months after the supernova explosion, stemming from an off-centered rotating magnetic dipole in the newborn pulsar, could give the pulsar a substantial kick (Harrison & Tademaru 1975). Another approach is based on the assumption that most of the energy and momentum released during a Type II supernova explosion ( $\sim 10^{53}$  erg) are carried off by the relativistic neutrinos, as was observationally confirmed by the detection of a neutrino burst associated with SN1987A (Hirata et

al. 1987; Bionta et al. 1987). Therefore, an asymmetric neutrino emission, caused for example by convection (Woosley 1987; Woosley & Weaver 1992; Janka & Müller 1994) or strong magnetic fields (Chugaï 1984; Dorofeev et al. 1985; Vilenkin 1995; Horowitz & Piekarewicz 1997), may play an important role when trying to understand the origin of pulsar velocities. Not all these mechanisms, however, seem to be able to produce the required high velocities and many of them suffer from the fact that they need magnetic fields of the order of  $\gtrsim 10^{15}$  G, pulsar periods of  $\sim 1$  ms or that they are not sustained by other observed pulsar properties (Duncan & Thompson 1992).

In a recent paper Kusenko & Segrè (1996a), hereafter KS, have proposed a new mechanism of asymmetric neutrino emission based on resonant neutrino oscillations. The three types of neutrinos,  $\nu_e$ ,  $\nu_\mu$  and  $\nu_\tau$ , are abundantly produced in the core of a collapsing star which later on may become a pulsar. The matter density is so high in the core that the neutrinos do not escape but get trapped. They undergo a diffusion process until they reach higher radii, where the density has decreased and they can freely stream away. The emission surface, the so-called neutrino sphere, is not the same for the three types of neutrinos. Since electron neutrinos can interact via both charged and neutral currents they interact more strongly in the protoneutron star than muon and tau neutrinos. Hence, the electron neutrino sphere is at a larger radius than the muon and tau neutrino spheres. The authors in KS showed that under these conditions neutrinos  $\nu_\tau$  can resonantly turn into  $\nu_e$ , by means of the adiabatic MSW effect (Smirnov 1996), in the region between the tauonic and the electronic neutrino spheres<sup>1</sup>. The emerging electron neutrino, however, will be absorbed by the medium and therefore the resonant surface becomes the effective surface of emission of the  $\nu_\tau$ . Neutrinos propagating in media with a longitudinal magnetic field  $\mathbf{B}$  have different electromagnetic properties than in the vacuum case. They acquire an effective electromagnetic vertex which is induced by weak interactions with the charged particles in the background and generates a contribution  $\propto \mathbf{B} \cdot \mathbf{k}$  to the effective self-energy of the neutrino,  $\mathbf{k}$  being the neutrino momentum (Esposito & Capone 1996; D’Olivo & Nieves 1996; Elmfors et al. 1996). The induced vertex modifies the flavor transformation whilst preserving chirality and, as a result, the

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<sup>1</sup> For definiteness, only the two flavors  $\nu_e$  and  $\nu_\tau$  have been discussed with  $\Delta m^2 \equiv m^2(\nu_\tau) - m^2(\nu_e) \approx m^2(\nu_\tau)$  and small mixing.

location at which the resonance occurs is affected, leading to the spherical symmetry of the effective emission surface being replaced by a dipolar asymmetry. The condition for resonant oscillations to take place is accordingly given by

$$\frac{\Delta m^2}{2k} \cos 2\theta = \sqrt{2} G_F N_e(r) + \frac{\epsilon G_F}{\sqrt{2}} \left( \frac{3N_e(r)}{\pi^4} \right)^{1/3} \frac{\mathbf{k} \cdot \mathbf{B}}{k}, \quad (1)$$

where  $\theta$  is the neutrino vacuum mixing angle,  $G_F$  the Fermi constant,  $N_e(r)$  the charge density of the degenerate electron gas in which the neutrino propagates and  $r$  the radial coordinate. Neutrinos emitted from the two magnetic poles of the resonant surface then have slightly different temperatures because the two poles are at slightly different radii. The outcome is an asymmetric emission of momentum carried by neutrinos which gives the neutron star a kick in the direction of the magnetic field and thus leads to a recoil velocity in agreement with observational data. Quantitatively the kick is described by the asymmetry in the third component of momentum and estimated by

$$\frac{\Delta k}{k} = 0.01 \left( \frac{3 \text{MeV}}{\text{T}} \right)^2 \left( \frac{B}{3 \times 10^{14} \text{G}} \right). \quad (2)$$

Since the total momentum carried away by neutrinos emitted by the protoneutron star is  $\sim 100$  times the momentum of the proper motion of the pulsar, an asymmetry of 1% would give a kick in agreement with observation. Assuming an average energy for the tau neutrinos leaving the protoneutron star of  $\approx 10$  MeV, which corresponds to  $T \approx 3$  MeV, the authors in KS obtain the desired asymmetry of 1% for values of  $B \sim 3 \times 10^{14}$  G. As an advantage over other neutrino emission mechanisms the one discussed here works for smaller magnitudes of the magnetic field and does not demand for any constraints on the pulsar period. If the resonant neutrino conversion turned out to be the origin of pulsar velocities, one could use pulsar observations to obtain information on neutrino masses. The implications for particle physics models would be of great importance.

A possible weak point of the model, however, lies in the fact that the mass of the tau neutrino is required to be  $m_{\nu_\tau} \sim 100$  eV in order to have a resonant conversion in the protoneutron star between the electron and the tau neutrino spheres. Although such a mass is not excluded by laboratory experiments, it is difficult to accommodate it in the standard Big Bang cosmological model. Indeed, the present age of the universe can be used to set an upper bound on the mass of any light, stable neutrino species (Gerstein & Zel'dovich 1966; Cowsik & McClelland 1972):  $m_\nu < 92 h^2$  eV, where  $h$  is the Hubble constant in units of  $100 \text{ km s}^{-1}/\text{Mpc}$ . Nevertheless, this problematic point might be overruled by unstable tau neutrinos or by a better understanding of the evolution of the universe. Another comment can be made in the context of the supernova physics. From treatments of neutrino transport it was found that the average energy for tau neutrinos leaving the supernova can be as high as 27 MeV (Janka 1992). Such a value, however, would demand

for a higher magnetic field in Eq. (2) in order to still explain the observed pulsar velocities thus weakening one of the advantages of the proposed model. On the other hand, it is interesting to note that neutrino oscillations between  $\nu_e$  and a tau neutrino with a mass of 10–100 MeV could, for a large range of mixing angles, help to explode supernovae while leaving r-process nucleosynthesis unscathed (Raffelt 1996). A better understanding of supernova explosions and data from future galactic supernovae could be used to test whether the asymmetric resonant neutrino emission model is actually realistic.

Since none of the above mentioned points represent a serious danger to the discussed mechanism, but its implications for astrophysics and physics beyond the standard model of the fundamental interactions would be significant, it is worthwhile to examine further related observational consequences with the aim of arriving at independent constraints. In addition, the derived constraints can be used to test the viability of some of the other proposed models for the origin of pulsar velocities. In this paper we derive, using the mechanism introduced in KS, a new expression relating the transverse velocity, the magnetic field and geometric parameters of fast spinning pulsars. We analyze observational data on pulsars to see whether this relation is fulfilled. Our work, however, seems to indicate that pulsars do not satisfy this relation, and therefore present data do not support the neutrino oscillation mechanism.

## 2. Observational tests

According to the authors of KS the asymmetric neutrino emission from a magnetically distorted neutrino sphere gives a net momentum to a pulsar along the magnetic axis. It is believed that, in general, the spin and magnetic axes of pulsars are not aligned, and thus the magnetic field rotates around the spin axis with the period  $P$  of the pulsar. From this it can be seen that a net velocity along the magnetic axis is only obtained if the pulsar period is much larger than the characteristic time scale  $t_\nu$  on which the neutrino flux from the cooling protoneutron star remains constant. For such a case, the length of the velocity vector  $\mathbf{v}$  and magnetic field vector  $\mathbf{B}$  in the core of the pulsar should be proportional:

$$v \propto B. \quad (3)$$

In a different paper Kusenko & Segrè (1996b) apply the model to pulsars which are slow spinning at birth,  $P > 1$  s and  $P > 1.3$  s, and argue that this  $B - v$  correlation should become increasingly more significant as the period of rotation approaches a few seconds. They claim that observational data show such an increase in the correlation for the examined periods, which would support the investigated model.

In the present paper we consider fast spinning pulsars,  $P < 1$  s, instead. The characteristic time  $t_\nu$  is of the order 1–10 s (Suzuki 1994). Therefore, a reliable test of the mentioned correlation between  $B$  and  $v$  for slow spinning pulsars should only be possible for periods  $P \gtrsim 10$  s which are not observed. We believe that pulsars with  $P < 1$  s form a better set to test the model. A period  $P < 1$  s is sufficiently smaller than the

time interval in which neutrinos are emitted and therefore it can be safely assumed that the magnetic field and thus the net momentum vector rotate around the spin axis several times during the neutrino emission. The momentum component on the plane orthogonal to the spin axis averages out and only the component parallel to the spin axis survives. Thus, for fast spinning pulsars, the proper motion should be in the direction along the pulsar spin axis. As an important consequence of this alignment of the velocity and spin axis for fast spinning pulsars one can easily prove that the relation

$$v_T \propto B \cos \alpha \sin(\alpha + \beta) \quad (4)$$

must apply where  $v_T$  is the projected pulsar velocity in the sky,  $\alpha$  the angle between the magnetic and spin axes, and  $\beta$  is the angle between the magnetic axis and the line of sight (impact parameter). We will see that observational data allow a test of this relation.

Pulsar proper motions are determined by radio interferometry (Harrison et al. 1993) and by interstellar scintillation observations (Cordes 1986). In order to determine the emission geometry parameters  $\alpha$  and  $\beta$  one has to rely on some emission model for pulsars. The so-called magnetic-pole model assumes that the electromagnetic radiation originates in the vicinity of a magnetic pole. The radiation is emitted in a narrow cone-shaped beam centered around the magnetic axis. The nonvanishing angle  $\alpha$  between the spin axis and the magnetic axis produces the characteristic pulses every time the beam sweeps the line of sight (Lyne & Graham-Smith 1990). Two different groups (Lyne & Manchester 1988; Rankin 1990, 1993a, 1993b) have determined  $\alpha$  and  $\beta$  for more than one hundred pulsars. The method used by both groups is based on the apparent increase of pulse width as  $1/\sin \alpha$ . The classification scheme of pulsars, however, differs between the two groups and, for calculating the angles, they find different empirical laws relating the pulse width and the pulsar period: while Lyne & Manchester (1988) use width  $\propto P^{-1/3}$ , Rankin (1990, 1993a, 1993b) employs width  $\propto P^{-1/2}$ . The results of both groups show, in general, a remarkable agreement for angles  $\alpha < 40^\circ$  but they can widely differ for larger angles (Miller & Hamilton 1993).

Our aim has been to find out whether the relation given by Eq. (4) is corroborated by observational data. Bearing in mind the lack of complete agreement between the different measurements of the emission angles, we have studied three different sets of data: (a) angles from Lyne & Manchester (1988), (b) angles from Rankin (1993b) and (c) the average of the angles from sets (a) and (b) for those pulsars which are common in both of these sets and which have similar  $\alpha$  values, namely  $\Delta\alpha < 12^\circ$ . Furthermore, it has to be taken into account that Eq. (4), true at the pulsar birth, may be spoiled by the temporal evolution of pulsar parameters (angles and magnetic field). It is believed that the magnetic field of a pulsar decays with a characteristic time  $\sim 10^7$  years (Harrison et al. 1993). There is also observational evidence supporting that the magnetic and spin axes become aligned when the pulsar ages (Lyne & Manchester 1988). To avoid these problems associated with time evolution we have selected from the data the pulsars younger than  $10^7$  years and,

**Table 1.** Pulsars of case (a) as described in the text. The pulsars with an asterisk have ages of less than 3 Myr, all the others of less than  $10^7$  yr. The pulsars which are also members of set (c) are primed.

|                |                |                |
|----------------|----------------|----------------|
| PSR B0136+57** | PSR B0329+54*  | PSR B0450–18** |
| PSR B0458+46** | PSR B0559–05   | PSR B0656+14*  |
| PSR B0736–40'  | PSR B0823+26   | PSR B1508+55*  |
| PSR B1642–03'  | PSR B1706–16** | PSR B1929+10   |
| PSR B1933+16** | PSR B1946+35** | PSR B2020+28** |

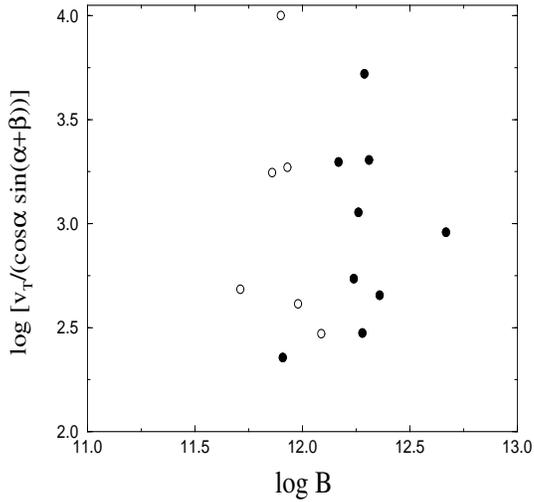
**Table 2.** Pulsars of case (b) as described in the text. The pulsars with an asterisk have ages of less than 3 Myr, all the others of less than  $10^7$  yr. The pulsars which are also members of set (c) are primed.

|                |                |                |
|----------------|----------------|----------------|
| PSR B0136+57** | PSR B0329+54'  | PSR B0355+54*  |
| PSR B0450–18** | PSR B0450+55*  | PSR B0458+46** |
| PSR B0736–40'  | PSR B0740–28*  | PSR B0823+26   |
| PSR B0919+06*  | PSR B1449–64*  | PSR B1508+55*  |
| PSR B1642–03'  | PSR B1706–16** | PSR B1818–04*  |
| PSR B1822–09*  | PSR B1842+14   | PSR B1933+16** |
| PSR B1946+35** | PSR B2020+28** | PSR B2021+51*  |
| PSR B2217+47   | PSR B2224+65*  |                |

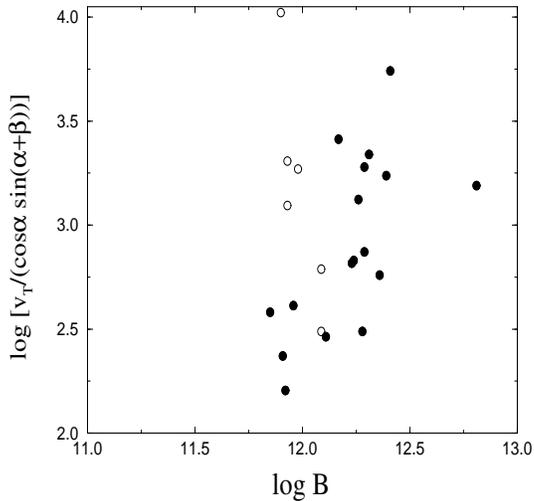
to be even safer, younger than  $3 \times 10^6$  years (Lorimer et al. 1995) thus creating two subsets for each of the sets (a), (b) and (c). We disregard older pulsars since their present properties may be rather different from those at birth. We do not consider pulsars in binary systems either since for them Eq. (4) could be affected by the evolution of close binary systems. The selected pulsars for the three cases (a), (b) and (c) are listed in Tables 1 and 2.

We plot  $\log [v_T / \cos \alpha \sin(\alpha + \beta)]$  versus  $\log B$  for young, fast spinning pulsars ( $P < 1$  s) in Figs. 1, 2 and 3, for the cases (a), (b) and (c), respectively. The transverse velocity  $v_T$  is calculated from the measured angular velocity  $\mu_T$  using the pulsar distance  $D$  derived from its dispersion measure. The pulsar velocities have been corrected for galactic rotation by removing a flat rotation curve of rotational velocity 225 km/s, with the sun at a distance of 8.5 kpc from the galactic center. They have also been corrected for the peculiar solar motion of the sun which was assumed to have a velocity of 15.6 km/s in the direction  $l = 48^\circ.8$  and  $b = 26^\circ.3$  (Murray 1983). The parameters  $D$ ,  $B$ ,  $P$  and the pulsar ages as well as the parameters needed to compute  $\mu_T$  have been taken from Taylor et al. (1993, 1995), an updated catalog containing 706 pulsars.

The scatter of points in the plots we depict suggests that there is hardly any correlation. To evaluate rigorously their significance, we use the Spearman rank-order correlation coefficient  $r_S$  and its probability  $\mathcal{P}(r_S)$ . The coefficient  $r_S$  ranges from 1 (perfect correlation) to  $-1$  (perfect anticorrelation). Further information is given by  $\mathcal{P}(r_S)$ , the probability that  $r_S$  for two uncorrelated data sets would be larger than the Spearman coefficient found. Hence, to have a significant correlation between two sets, one must obtain  $r_S \sim 1$  and  $\mathcal{P}(r_S) \ll 1$ . The calculated  $r_S$  and  $\mathcal{P}(r_S)$  corresponding to our three cases are



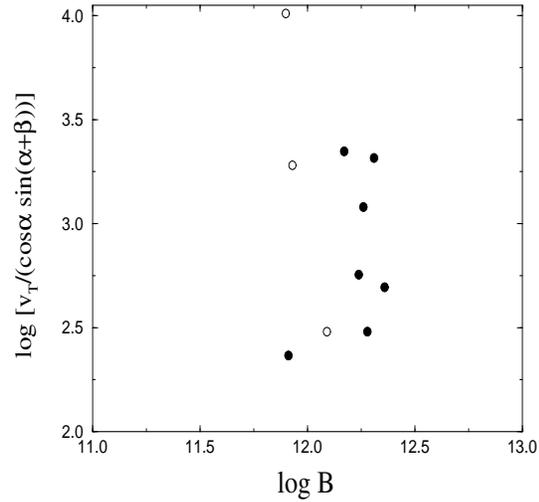
**Fig. 1.** This figure shows  $\log [v_T / (\cos \alpha \sin(\alpha + \beta))]$ , where  $v_T$  is in km/s, versus the surface magnetic field  $\log B$ , where  $B$  is in Gauss, for pulsars with period  $P < 1$  s and age less than  $10^7$  yr (all circles). Those pulsars among them which have an age of less than  $3 \times 10^6$  yr are indicated by filled circles. The angles  $\alpha$  and  $\beta$  taken correspond to case (a). The logarithm is to base 10.



**Fig. 2.** Same plot as Fig. 1 but now the angles  $\alpha$  and  $\beta$  taken correspond to case (b).

shown in Table 3. We calculate the two numbers using pulsars younger than  $3 \times 10^6$  yr and pulsars younger than  $10^7$  yr. We are unable to find any correlation of the sort given by Eq. (4) (except possibly for the case (b) with pulsars younger than  $3 \times 10^6$  yr).

It is interesting to point out the existence of fast spinning pulsars like PSR B0833-45 which have large peculiar velocities whilst the magnetic and spin axes are nearly perpendicular. Clearly, the mechanism presented in KS cannot account for the proper motion of these pulsars. We have also examined the case of young, fast spinning pulsars with small angles  $\alpha < 15^\circ$ . In the framework of the studied mechanism those pulsars should have small transverse velocities  $v_T$  (since  $\beta$  is small for most



**Fig. 3.** Same plot as Fig. 1 but now the angles  $\alpha$  and  $\beta$  taken correspond to case (c).

**Table 3.** Spearman rank-order correlation coefficient  $r_S$  and associated probability  $\mathcal{P}(r_S)$  for the three cases discussed in the text, considering pulsars younger than  $10^7$  yr and  $3 \times 10^6$  yr. The number of pulsars in each set is also given.

| Case | Age [ $10^7$ yr] < | Number | $r_S$                | $\mathcal{P}(r_S)$   |
|------|--------------------|--------|----------------------|----------------------|
| (a)  | 1                  | 15     | $6.1 \times 10^{-2}$ | 0.83                 |
| (a)  | 0.3                | 9      | 0.25                 | 0.52                 |
| (b)  | 1                  | 23     | 0.31                 | 0.15                 |
| (b)  | 0.3                | 17     | 0.68                 | $2.9 \times 10^{-3}$ |
| (c)  | 1                  | 10     | -0.10                | 0.78                 |
| (c)  | 0.3                | 7      | $7.1 \times 10^{-2}$ | 0.88                 |

pulsars). For the mean transverse velocity of the pulsars fulfilling the selection criteria we obtain 344 km/s. This has to be compared with the mean average transverse velocity for pulsars without any restrictions on  $\alpha$  or the pulsar period. Such mean values were computed to be  $345 \pm 70$  km/s for 29 pulsars which are younger than 3 Myr, and  $300 \pm 30$  km/s for 99 pulsars without the age constraint (Lyne & Lorimer 1994). The fact that there is no significant difference between the mean transverse velocity we obtain and the latter ones above does not support the model examined here.

There is yet another important consequence of the alignment of the spin axis and the velocity vector for fast spinning pulsars, which has been explored some time ago (Tademaru 1977; Anderson & Lyne 1983) in the context of the asymmetric emission of electromagnetic radiation mentioned in the introduction of this paper. If these two vectors are aligned, the difference between the projected pulsar velocity angle in the sky  $\psi_v$  and the position angle of the linear polarization vector in the center of a pulse (corrected for Faraday rotation)  $\psi_p$  should be either  $0^\circ$  or  $90^\circ$  depending on the emission mechanism and the inclination of the spin and magnetic axes to the line of sight. While Tade-

maru (1977) found that the histogram of  $|\psi_v - \psi_p|$  showed two peaks at  $0^\circ$  and  $90^\circ$ , a subsequent study performed by Anderson & Lyne (1983) concluded that such peaks were not present. The latter result was argued to be in disagreement with the mechanism introduced by Harrison & Tademaru (1975). It would not support the resonant neutrino emission model discussed here either. Given the significant increase in the amount and quality of available pulsar data over the last years it would be of interest to carry out the  $|\psi_v - \psi_p|$  test again. This could not only help to resolve the contradicting conclusions of the previous studies but also yield an additional test of the neutrino emission model if only fast spinning pulsars are selected from the updated and enlarged sets of observational data. Moreover, both tests have different sources of errors. While the  $|\psi_v - \psi_p|$  test does not depend on the angles  $\alpha$  and  $\beta$  the derivation of which is model dependent, it relies on the measurement of the rotation measure RM of a pulsar. The contribution from Faraday rotation,  $\text{RM} \times \lambda^2$ , has to be subtracted from the measured polarization angle to obtain the intrinsic polarization angle  $\psi_p$ . Our test relies on the measurement of  $\alpha$  and  $\beta$  but does not need the value of RM for each pulsar which can be a significant source of errors. In this sense, both tests constitute complementary ways of checking whether the model given in KS and related models are realistic or not.

### 3. Discussion and conclusions

We have looked into possible ways of testing the new mechanism suggested by KS to explain the large proper motion of pulsars.

It was argued that for fast spinning pulsars this mechanism forces the vector velocity of a pulsar to be aligned with its spin axis. Making use of this alignment we have found Eq. (4), which is a relation between the magnetic field of a pulsar, its proper motion, the angle  $\alpha$  between the magnetic and spin axes and the impact parameter  $\beta$ . This relation should be true as long as pulsar velocities are produced by asymmetric emission from a magnetically distorted resonant neutrino-sphere. We have studied whether pulsar data actually show this correlation. To carry out this study we have had to face the fact that there is some controversy about the true values of  $\alpha$  and  $\beta$  in the sense that the angles from two different groups show discrepancies for  $\alpha > 40^\circ$ . Therefore, we have in a first step considered separately the data from each group. In addition, we have also selected the pulsars studied by both groups for which there is a reasonable agreement between the angles measured by either group. We believe that the results we derive in the latter case are the most reliable. In this case, observational data do not show any significant correlation and therefore, the mechanism introduced in KS is unlikely to explain the proper motion of pulsars. We have indicated that the temporal evolution of pulsars may spoil any initial correlation. To diminish this effect we have only considered young pulsars. Another possible caveat is the fact that Eq. (4) involves the magnetic field in the core of the pulsar whilst what is measured is the surface magnetic field. It is, however, plausible and accepted to assume that both fields

are proportional (Manchester & Taylor 1977; Ruderman 1991). Looking at Table 3 one can see that the number of pulsars with available data which satisfy all the requirements regarding period, age and availability of emission angles as well as proper motions is small in all the cases considered. Although our results cast doubt on the resonant neutrino emission as the mechanism responsible for the proper motion of pulsars, clearly one needs more data, and clarify the uncertainties related to the true emission angles, to rule out definitely or support this mechanism.

As a final remark we would like to point out that our conclusions also apply to other mechanisms proposed to explain the large velocities of pulsars. This is the case for fast spinning pulsars in all models where the momentum kick is collinear to the magnetic axis and the resulting velocity proportional to  $B$ . Under these conditions velocities along the spin axis are predicted. Hence, the work by Chugaï (1984) and Dorofeev et al. (1985) is affected. They study how the polarization of electrons and positrons by a high magnetic field in a newborn neutron star will generate an anisotropic neutrino emission. Also the mechanism suggested by Vilenkin (1995) is disfavored for a uniform magnetic field, as is the mechanism in Horowitz & Piekarewicz (1997). Pulsar velocities from resonant spin-flavor precession of neutrinos are studied by Akhmedov et al. (1997). Again, this mechanism is put under pressure by our work as well as the model suggested by Kusenko & Segrè (1997) where a resonant conversion to sterile neutrinos induced by neutral currents is considered.

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