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LETTER

Letter to the Editor

Origin of the proper motion and spin of pulsars

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Abstract. It is suggested that the proper motion and the spin of pulsars at birth are causally connected. Accordingly, the observed mean values of these parameters can be attributed to the recoil momentum and torque impulse imparted to the neutron star by anisotropic and asymmetric emission of neutrinos during the collapse of the core in a supernova.

Key words: pulsar – spin – proper motion – supernovae – asymmetric neutrino emission

Statistical analysis of the properties of pulsars and their location with respect to the galactic plane or to the supernova remnants in which they were born indicate that they were born with typical speeds v_o of several hundred km s^{-1} (Gunn & Ostriker 1970, Phinney & Blandford 1981, Narayan & Ostriker 1990, Lyne & Salter 1993, Lyne & Lorimer 1994, Deshpande et al. 1995, Nice et al. 1995, Blaauw 1996). Similarly, their evolution on the $(p, \dot{p})$ plane indicates that they are born with periods of duration typically $0.1 - 0.2$ s (Phinney & Blandford 1981, Narayan & Ostriker 1990, Deshpande et al. 1995, Blaauw 1996)]. Here we suggest that the speed and spin of pulsars at birth are both direct consequences of the anisotropic and nonaxisymmetric emission of neutrinos by the stellar core during its collapse, leading to the formation of the neutron star. The familiar example of the Crab pulsar spinning with period of 33 ms will be discussed near the end of this *Letter*. The millisecond pulsars, which are recycled and spun up in accreting binary systems, are excluded in this analysis.

Considerable effort has gone into the understanding of the speeds of pulsars at birth: Pulsars born when one of the stars in a close binary or a multiple stellar system explodes as a supernova may be released by the “sling effect”with high speeds, as discussed in detail by Iben & Tutukov (1995) and others (Gott et al. 1970, Radhakrishnan & Shukre 1985). The speed of pulsars may also be attributed to the recoil that the neutron star will suffer due to possible asymmetries in the explosion (Bazan & Arnett 1994, Colgate & Leonard 1994) or in the emission of neutrinos (Sklovskii 1970, Chugai 1984, Wooseley 1987, Janker & Müller 1994, Shimizu et al. 1994, Burrows & Hayes 1996, Kusenko & Segre 1996). The suggestion that neutrino recoil effects are responsible for the proper motions of pulsars is gaining increasing observational support. Here one notes that during the process of its collapse into a neutron star the core of a presupernova star emits neutrinos with a total energy $S_\nu \approx 3 \times 10^{53}$ erg. The scalar momentum associated with these neutrinos $P_\nu = S_\nu / c \approx 10^{43} g\ cm\ s^{-1}$. If the neutrino emission is perfectly isotropic, then the vector sum of the neutrino momenta $\vec{p}_\nu$ will vanish;

$$\sum \vec{p}_\nu = 0 \tag{1}$$

However, the neutrino emission is expected to be anisotropic either due to its convective-diffusive transport in the asymmetrically collapsing core (Schramm & Arnett 1975, Chugai 1984, Mayle et al. 1987, Burrows 1990, Shimizu et al. 1994, Burrows & Hayes 1996) or due to neutrino flavor oscillations in the material of the core threaded by magnetic fields (Kusenko & Segre 1996). As per this suggestion, the speed of pulsars at birth is given by

$$v_o = \frac{|\sum \vec{p}_i|}{m_*} \equiv \frac{p_o}{m_*} \equiv \frac{\eta P_\nu}{m_*} \approx \left(\frac{\eta}{.01}\right) \times 360\, km\, s^{-1}, \tag{2}$$

where $\vec{p}_i$ are individual momenta of the neutrinos, m_* is the mass of the neutron star (Manchester & Taylor 1977) and the asymmetry parameter $\eta = \left|\sum \vec{p}_i\right| / P_\nu$. A distribution in the value of η, spreading over a factor of 2 to 3 on either side of its mean value of $\sim$0.01, can reproduce the observed proper motions of pulsars.

As much attention has not been focussed on the origin of the spin of pulsars. The catalogue of the properties of 558 pulsars and a search for fast pulsars in the galactic plane (Taylor et al. 1993, Lyne & Lorimer 1994; Nice et al. 1995) show that the observed periods peak at $\sim$0.5 s and more than 90% of the pulsars lie within a factor of $\sim$3 on either side of this central value. When one accounts for the loss of energy and angular momentum through radiation by the pulsars it has been estimated (Phinney & Blandford 1981, Narayan & Ostriker 1990, Deshpande et al. 1995, Blaauw 1996) that their periods at birth peak around 0.2 s with a similar dispersion. Irrespective of these small differences, we note that O-B supergiants, which are the progenitors of most pulsars, are spinning so slowly that the neutron stars formed during the collapse of their core will actually be spinning far too slowly to be pulsars, unless there exist mechanisms other than the initial angular momentum which can spin them up to the requisite periods. Iben and Tutukov (1995, 1996) have already made this point and estimate the spin period of neutron stars born in supernova explosions of single O-B supergiants to be $T_n \sim 300\,s$ far too long to contribute significantly to the spin of pulsars.

In this paper, we propose that the same asymmetric neutrino emission that generates the proper motion also provides just the right amount of angular momentum to yield the spin period of pulsars at birth. Qualitatively, the basic idea is that when the asymmetric neutrino emission imparts momentum to the neutron star it would, with a high probability, also impart angular momentum that will make the neutron star spin. If this asymmetry in the neutrino emission is characterized by an effective impact parameter b, with respect to the centre of the neutron star, then the neutron star would be subjected to a torque impulse $m_* v_o b$. This will cause the neutron star of moment of inertia $I \approx 4 \times 10^{44}$ (Ruderman 1972, Shapiro & Teukolsky 1983, Datta 1988), to spin with an angular frequency $\omega_o = m_* v_o b/I$ or, in other words, the spin period t_o at birth will be

$$t_o = \frac{2\pi}{\omega_o} \approx 2\pi \left\{ \frac{m_* v_o b}{I} \right\}^{-1} \approx \frac{1}{\eta} \left(\frac{r_*}{b} \right)\, 2.5 \times 10^{-4}\, s \qquad (3)$$

If $\eta \approx 0.01\, and\, b \approx 0.1\, r_*$, the spin period of pulsars at birth can be reproduced. Note that this is the same value of η which gives the correct translational speed for the pulsar. To see this result in some detail, we write Eq. 3 more precisely:

$$t_o = \frac{2\pi}{\omega_o} = 2\pi I \left\{ \left| \sum \vec{p}_i \times \vec{b}_i \right| \right\}^{-1} \qquad (4)$$

where $\vec{b}_i$ is the impact parameter of the neutrino with momentum $\vec{p}_i$. The Eqs. 3, 4 imply a interrelationship between the period and the speed of the pulsars, both arising from a common cause, namely, asymmetric neutrino emission.

Before assessing the possible distribution of initial pulsar periods implied by the hypothesis of spin-up by neutrino recoil torques, we wish to note, following Burrows and Hayes (1996) for example, that asymmetries in neutrino emission are quite generic and will occur whether neutrino oscillations play a role or not. According to this picture, the collapsing core receives a series of small impulses as the neutrinos spurt out of a matrix of advection cells. To see this, note that the neutrino mean free path in the collapsing core is a small fraction ∼0.01–0.1 of the typical dimensions of the neutron star so that the neutrinos diffuse outwards as they are being convected inwards by the collapsing flow. Thus the neutrinos exert pressure $\wp$ on the infalling material and the gradient of this pressure exerts a force comparable to the gravitational force responsible for the infall (Chugai 1984, Herant et al. 1992, Shimizu et al. 1994, Burrows et al. 1995, Burrows & Hayes 1996). This makes the system suffer Rayleigh-Taylor-like instabilities whose dispersion relation may be written as

$$\omega^2 = \frac{k}{\rho} \frac{\partial \wp}{\partial r}, \qquad (5)$$

which indicates that disturbances with the largest k have the highest growth rates and are consequently the most important. The largest k or the smallest $\lambda = 2\pi/k$ that is relevant in the present context is the neutrino mean free path. Thus the picture that emerges is that the collapsing core has isodensity and isovelocity contours that undulate with typical wavelengths of the order of the neutrino mean free path. These undulations grow rapidly releasing minijets of neutrinos which tend to stabilise the further collapse of the material under gravity. It is the statistical sum of the momenta associated with these minijets which yields the net momentum $m_* v_o$ to the pulsar.

The observations of pulsars, as mentioned earlier, show that their periods are broadly peaked around a central value, and imply a similar distribution of periods at their birth. To see, qualitatively, that minijets of neutrinos can lead to such a distribution, note that each of these minijets will have impact parameters $\vec{b}$ distributed randomly in the three directions according to some distribution dictated by the instabilities in the neutrino transport. By the central-limit theorem, the sum of these will lead to Gaussian distributions of impact parameters along each of the three axes with a clear maximum of r_*. The scalar impact parameter will therefore be distributed as

$$P(b)db \sim b^2\, exp\big(- \frac{b^2}{b_c^2} \big) db \qquad (6)$$

As b approaches r_* the distribution will become steeper than Gaussian and will be cut off sharply. Thus we may expect that the initial periods may be peaked at the value obtained by inserting into Eq. 3 the value of b at which P(b) has a maximum, or more explicitly

$$P(t_o)\, dt_o \;\sim\; t_o^{-4}\, exp\left(-t_c^2/t_o^2 \right)\, dt_o \qquad (7)$$

With $t_c \sim 0.25$ s, or $b_c \sim 0.1 r_*$ the observed distribution of t_o can be reproduced, as noted above.

A possible observational confirmation of this idea might come from the search for the correlations between v_o and t_o, since high v_o implies small t_o statistically; however, establishing the relationship between spin and transational kicks may be difficult unless the number of effective impulses is small. It is prudent to note here that the correlations mentioned are not simply one to one but indeed we may have occasionally high v_o and high t_o or low v_o and a low t_o as shown by the examples described below. The pulsar inside the Crab-nebula has a period of ∼33 ms and yet with a speed of ∼150 km s^{-1}, it is not displaced substantially with respect to the centre. Could such a situation obtain if the phenomenon of neutrino recoil was responsible for its spin-up? Let two subsets of mini-jets generate recoils $\vec{p}_1$ and $\vec{p}_2$ with impact parameters $\vec{b}_1$ and $\vec{b}_2$; if fortuitously $\vec{p}_1 \approx -\vec{p}_2$ and $\vec{b}_1 \approx -\vec{b}_2$ then the torques due to the two subsets will add and momentum impulses would cancel each other, giving rise to a situation like the crab-nebula and its pulsar. Similarly, a slowly rotating run away pulsar without any nebula associated with it can be generated when there is a large $\left|\vec{p}\right|$ and a small $\left|\vec{b}\right|$. Also three dimensional simulations of the collapse should lead to a deeper understanding of this problem (Chugai 1984, Shimizu et al. 1994, Arnett 1997).

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References

Arnett D., 1997 Private Communication.
Bazan G., Arnett D., 1994 ApJ 433, 41;
Bethe H.A., 1990 Rev.Mod.Phys. 62, 801.
Blaauw A., 1996 Raman Research Institute Lecture.
Burrows A., 1990 Ann.Rev.Nucl.Part. Sci. 40, 181.
Burrows A., Hayes J., 1996 Phys.Rev.Lett. 76, 352.
Chugaii N.N., 1984 Sov.Astron.Lett. 10, 87.
Colgate S.A., Leonard P.J.T., 1994 in: *Gamma Ray Bursts*, J.J.Fishman, J. Brainerd and K. Hurley (eds), (A.I.P. Press,) New York.
Datta B., 1988 Fundamental of Cosmic Physics, 12, 151.
Deshpande A.A., Ramachandran R., Srinivasan G., 1995 JAA 16, 69
Gott J.R., Gunn J.E., Ostriker J.P., 1970 ApJ Lett. 160, L91.
Gunn J.E., Ostriker J.P., 1970 ApJ 160, 979.
Herant M., Benz W., Colgate A., 1992 ApJ 395, p 42.
Hupert H.E., Spiegel E.A., 1977 ApJ 213, 157.
Iben I. Jr., Tutukov A.V., 1995 in Millisecond Pulsars: Decade of Surprises, A.S.Fructer, M.Travani & D.C.Bacher (eds), (ASP Conference Series), p. 119.
Iben I. Jr., Tutukov A.V., 1996 ApJ 456, 738.
Janker H.Th., Müller E., 1994 A & A 290, 496.
Kusenko A., Segre G., 1996 Phys.Rev.Lett. 77, 4872.
Lyne A.G., Lorimer D.R., 1994;
Lyne A.G., Salter M.J., 1993 MNRAS 261,113.
Mayle R., Wilson J.R., Schramm, D.N., 1987 ApJ, 318, 288.
Manchester R.N., Taylor J.H., 1977 *Pulsars* W. H. Freeman & Co., San Francisco.
Narayan, R., Ostriker J.P., 1990 ApJ 352, 222;
Nice D.J., Fruchter, A.S., Taylor J.H., 1995 ApJ 449, 156.
Phinney E.S., Blandford R.D., 1981 MNRAS 261, 113;
Radhakrishnan V., Shukre C.S., 1985 Supernovae, Progenitors and Remnants, G.Srinivasan, V.Radhakrishnan (eds), Indian Academy of Sciences, Bangalore.
Ruderman M., 1972 Ann. Rev. Astron. Astrophys. 10, 427.
Schramm D.N., Arnett W.D., 1975 ApJ 198, 629.
Shapiro S.L., Teukolsky S.A., 1983 *Black Holes, White Dwarfs and Neutron Stars* (Wiley Interscience Publ. New York.
Shimizu T., Yamada S., Sato K., 1994 ApJ, 434, 268;
Sklovskii J.S., 1970 Sov.Astr. 13, 562; [1970 Astr.Zh. 46, 715].
Taylor J.H., Manchester A.N., Lyne A.G., 1993 ApJ 88, 155; Nature 369, 127;
Wooseley S.E., 1987, in Proc. 125th IAU Symp. '*Origin and Evolution of Neutron Stars*'.