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The observational evidence pertinent to possible kick mechanisms in neutron stars

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Abstract. We examine available observations on pulsars for evidence pertaining to mechanisms proposed to explain the origin of their velocities. We find that mechanisms predicting a correlation between the rotation axis and the pulsar velocity are ruled out. Also, that there is no significant correlation between pulsar magnetic field strengths and velocities. With respect to recent suggestions postulating asymmetric impulses at birth being solely responsible for both the spins and velocities of pulsars, single impulses of any duration and multiple extended duration impulses appear ruled out.

Key words: stars: neutron – stars: kinematics – stars: rotation – stars: binaries: general – stars: pulsars: general – stars: supernovae: general

1. Introduction

It is now widely accepted that the velocities observed for pulsars include a significant component from kicks experienced by the neutron stars in the process of their formation. The basis for this view is almost totally empirical, with a variety of different kinds of observations all pointing to the existence of an impulsive transfer of momentum to the protoneutron star at birth (Shklovskii 1970; Gunn & Ostriker 1970; van den Heuvel & van Paradijs 1997). This implies an asymmetry in the ejection process, but as yet there is no consensus on any plausible mechanism for providing such an asymmetry. Mechanisms suggested range from hydrodynamical instabilities to those in which asymmetric neutrino emission is postulated (Burrows 1987; Keil et al. 1996; Horowitz & Li 1997, hep-ph/9701214; Lai & Qian 1998, astro-ph/9802344; Spruit & Phinney 1998).

As far as the latter class is concerned, it appears, and very reasonably so, that if the neutrinos can impart momentum to the matter, the reverse must also happen, and the thermal equilibrium of the matter must necessarily destroy any incipient asymmetry in the neutrinosphere. And any asymmetry developed above the neutrino-matter decoupling layer, is by definition incapable of imparting any momentum to the matter (Bludman 1998, *private communication*).

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Whatever the operative mechanism for creating the asymmetry, it is an important and pertinent question to ask if the resulting direction is a random one, or connected with some basic property of the protoneutron star. Two such essential vectors associated with the core of the collapsing star are its rotational and magnetic axes, and both have been invoked in mechanisms proposed in the literature (Harrison & Tademaru 1975a,b; Burrows & Hayes 1996; Kusenko & Segre 1996). Any such mechanism that is postulated to provide the asymmetry must leave its signature in the direction and magnitude of the imparted velocity, thus enabling a possible test of the theory by comparison with observations.

An important recent investigation in this connection is that of Spruit and Phinney (1998). They argue strongly that the cores of the progenitors of neutron stars cannot have the angular momentum to explain the rotation of pulsars and propose birth kicks as the origin of their spins. These authors do not specify any particular physical process as responsible for the "kick", but emphasize that unless its force is exerted exactly head-on it must also cause the neutron star to rotate. As both the velocity and the spin of the neutron star have a common cause according to this hypothesis, it is not unreasonable to expect testable correlations as we shall discuss a little later. Independently, Cowsik (1998) has also advanced a similar common origin for the proper motion and spin of pulsars. The first suggestion of this possibility was by Burrows et al. (1995)

The quantities on which comparisons with observations can be made are the direction and magnitude of the proper motion, the projected direction of the magnetic axis, the magnitude of the magnetic field, the direction of the rotation axis and the initial period of rotation. Of these it is only the last that is not accessible to observation. We are left with five quantities which may be interrelated, depending on the mechanism which causes the asymmetry. Several types of correlations between these quantities have been sought, and even claimed in the past, motivated by suggestions of possible kick mechanisms. Our approach in this investigation is to examine without prejudice an enlarged body of pulsar data now available for any correlations which could support or rule out various suggested explanations.

As is widely practised, we shall assume that α, the angle the magnetic axis makes with respect to the rotational axis,

Table 1. List of selected pulsars with accurately determined directions of intrinsic position angles (IPA) and proper motions. The second and third columns give the IPA and its measurement error. The fourth and the fifth columns give the direction of PM and its measurement error.

Name	**IPA** (°)	**ΔIPA** (°)	**PM**$_{\rm dir}$ (°)	**ΔPM**$_{\rm dir}$ (°)
B0136+57	30	10	210	19
B0301+19	22	4	171	13
B0329+54†	10	4	127	4
B0450-18†	38	5	28	27
B0450+55	56	10	108	7
B0523+11	80	13	98	16
B0540+23	125	15	58	25
B0736-40†	156	5	309	10
B0740-28	90	15	270	2
B0809+74†	167	7	163	11
B0818-13	50	5	164	19
B0823+26	59	3	146	2
B0833-45	35	10	306	3
B0834+06†	76	15	2	6
B1133+16†	100	5	344	1
B1237+25	160	8	292	3
B1449-64†	140	8	217	4
B1508+55	161	5	227	3
B1706-16†	123	7	27	18
B1818-04†	67	13	6	7
B1905+39	68	15	45	12
B1929+10†	53	10	68	4
B1933+16†	150	15	175	16
B2020+28†	161	5	215	17
B2021+51	23	5	19	14
B2045-16†	0	3	117	14
B2154+40	104	6	99	4
B2217+47	58	10	202	19
B2351+61†	124	20	75	8

†Cases where the Intrinsic position angles have an ambiguity due to orthogonal flips.

and β, to the line of sight, can both be derived from accurate measurements of the core-component widths and the sweep of the linear polarisation through the pulse window. The intrinsic angle of polarisation at the point of inflexion of the sweep then gives us the projection of the rotational axis, and $\alpha + \beta = \zeta$ the complement of the angle it makes to the plane of the sky. We shall also assume that the observed proper motion is due only to the kick received at birth, and return later to a discussion of contributions to the velocity from motion of the progenitor in a binary system, or from its runaway velocity from a previous disruption.

The simplest models from the point of view of testability are those which predict an acceleration strictly along the rotational axis such as the rocket mechanism of Harrison & Tademaru (1975a; 1975b). The simplicity is due to projection on the sky plane not affecting the alignment expected of the rotation axis and the velocity direction (Morris et al. 1976). They argued that the direction of the spin axis projected on the plane of the sky must be the same as that of the proper motion. Based on thirteen available samples at that time, they concluded that the acceleration mechanism suggested by Harrison & Tademaru is not supported by observations. A similar conclusion was reached by Anderson & Lyne (1983).

In this paper, we use high quality polarisation and proper motion observations on a larger sample to test for preferential alignment of the pulsar velocity with either the rotation or the magnetic axis.

2. Sample selection

We have carefully selected for our study a sample of 29 pulsars for which we estimated the intrinsic position angle (IPA) from observations available in the literature (Morris et al. 1981; McCulloch et al. 1978; Manchester et al. 1980; Xilouris et al. 1991). The transverse velocities were computed from the proper motion measurements of Lyne et al. (1982) and Harrison et al. (1993), along with distances estimated using the electron density distribution model of Taylor & Cordes (1993). It may be noted that the distance information is required not only for calculating velocities, but also for calculating proper motion direction, as correction for differential galactic rotation needs to be incorporated. The selected list of pulsars together with the calculated directions of the intrinsic position angles and the proper motions are given in Table 1.

It is worth mentioning here that most of the data used by Anderson & Lyne (1983) were from Morris et al. (1979; 1981) where the position angle of polarisation was measured at the centre of the average pulse profiles. This, as we have since found, can be a source of significant error in the estimation of the IPA. We have included in the present comparison only those objects where the point of inflexion in the position angle sweep could be clearly identified.

3. Velocity parallel to rotation axis

If the velocity vector of the neutron star is along its rotation axis, then it means that either the underlying mechanism itself produces acceleration along the rotation axis, or that the time scale over which the asymmetry is produced during the supernova explosion is much longer than the rotation period of the star, thus averaging out the azimuthal component. In both cases, the direction of the proper motion vector in the plane of the sky should be the same as the projected direction of the rotation axis.

Fig. 1a shows the distribution of the proper motion directions and the IPAs for 29 pulsars. The values of the IPAs have been obtained after correcting for interstellar Faraday rotation. In the lower panel the distribution of the difference between these two angles is shown. Pulsars (14 out of the 29) with orthogonal flips in the polarisation position angles are included with the IPA assigned two possible values 90° apart. Since the observational errors are not the same for all the points, each point has been weighted proportional to the reciprocal of the error in the angle difference. The distribution has been smoothed

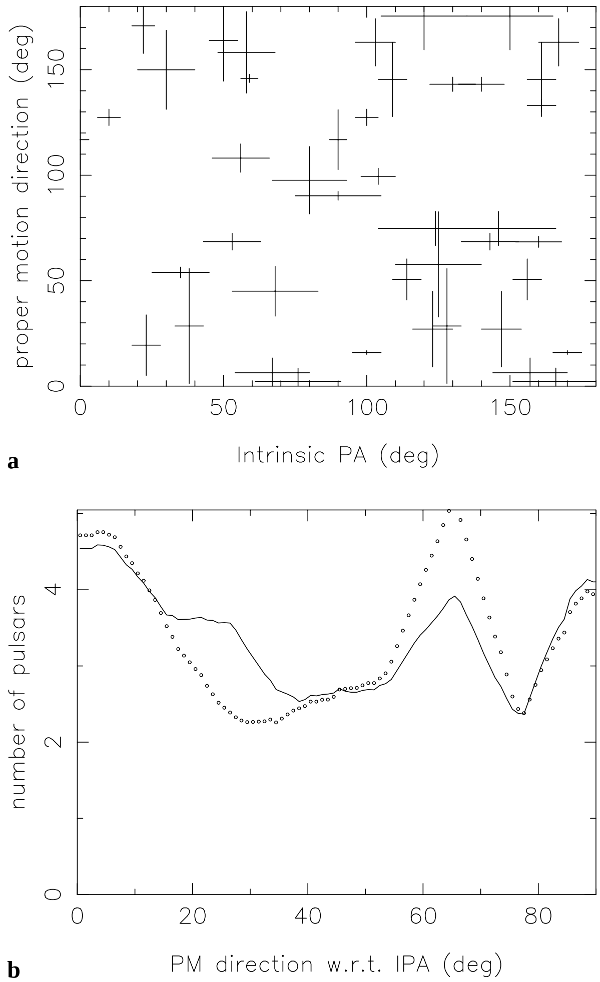

Fig. 1. a Direction of proper motion vs intrinsic position angle in the plane of the sky. **b** Probability distribution of the difference between these two angles. Points have been weighted proportional to the reciprocal of the measurement errors, and the distribution has been smoothed with a window of 10 degree width. The dotted curve shows the distribution when orthogonal flips in the polarisation position angles are *not* accounted for. The sample used here corresponds to 29 pulsars selected on the basis that the measurement error in the angle differences does not exceed 30°.

with a 10 degrees wide smoothing window. As is evident from this figure, there is no significant peak at either 0 or 90 degrees. So, even with the improved data set, any significant matching between the rotation axis and the direction of proper motion is not seen.

4. 'Kicks' along the magnetic axis of the star

We consider next mechanisms that would predict one or more momentum impulses directed along the magnetic axis and proportional to the strength of the field. In such a scenario, the resultant direction of the motion would depend on the duration of the impulse as compared to the (unknown) period of rotation at the epoch of the impulse. Short impulses would accelerate the neutron star along the instantaneous (and unknown) direction of the magnetic axis, and long impulses, with net duration longer than $\sim 50\%$ of the rotation period of the star, would result in motion increasingly along the rotational axis due to averaging, and of a magnitude now proportional to $\cos\alpha$ times the magnetic field strength, B. We have already shown that there is no correlation between the directions of the proper motions and the projected rotation axes. This appears to rule out slow impulses and leave only the case of short impulses along the magnetic axis to be considered. But before going on to the short-impulse case, let us look at a possible correlation between the magnetic field strength and the magnitude of the observed velocity for long duration impulses.

4.1. Field strength vs velocity

The fact that we see a given pulsar means that the angle between the rotation axis and the plane of the sky is $[90-(\alpha+\beta)]^\circ$, where β is the minimum angle between the line of sight and the magnetic axis (impact angle). Therefore, if the magnitude of the extended impulse is proportional to the strength of the magnetic field, the net transverse velocity of the pulsar must be proportional to $B\cos(\alpha)\sin(\alpha+\beta)$. In most pulsars, β is much smaller than α (and often its sign is not known) and the observed transverse velocity should be approximately proportional to $B\sin(2\alpha)/2$, i.e., the transverse velocity will at maximum have half of the potential kick when $\alpha = 45$ degrees.

Incorporating all these considerations, we examined $V_{\rm pm}/\sin(\alpha+\beta)$ vs $B\cos\alpha$ for a sample of 44 pulsars for which the relevant quantities are known reliably (for example, pulsars with more than 50% uncertainty in proper motion have been excluded). The values of α, β used here are taken from Rankin (1993).[1]. Any correlation present does not appear to be statistically robust. For normal pulsars (rotation periods longer than 25 milliseconds), the correlation coefficient is 0.35 ± 0.15 (see Fig. 2). This seems to improve marginally, to 0.65 ± 0.25 if pulsars with large errors in their proper motion are weighted down, but the correlation is, by no means, statistically significant. This is in agreement with the earlier work of Lorimer et al. (1995), Birkel & Toldra (1997) and Cordes & Chernoff (1998).

4.2. The case of single short-lived kicks

As pointed out above, the direction of the magnetic axis projected on the plane of the sky at the time of explosion is an unknown quantity. If the rotation axis is located in the plane of the sky, then the projected magnetic axis in the plane of the sky will be within $\pm\alpha$ of the rotation axis. However, when the direction of the rotation axis is oriented close to the line of sight, the varying angle between the projected magnetic and rotation axes will always exceed the above range.

To assess this issue in detail, let us define the z-axis as pointing towards the observer, then x-y is the plane of the sky. Choose the x-axis to be along the projected rotation axis on the plane

[1] Use of α, β values from Lyne & Manchester (1988) leads to a slight worsening of the correlation.

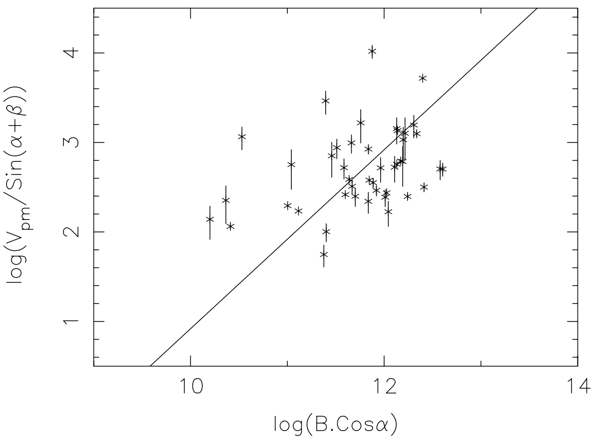

Fig. 2. A plot of $V_{pm}/\sin(\alpha+\beta)$ versus $B\cos(\alpha)$, where V_{pm} is in $\mathrm{km\,s^{-1}}$ and B in Gauss. The straight line corresponds to the linear best-fit dependence. See text for details.

of the sky (i.e. aligned with the intrinsic PA). Then it is easy to see that, as the star rotates, the components of the kick imparted along the instantaneous magnetic-field-direction (and proportional to B, the magnetic-field strength) are given by

$$V_x = k.B\,[\cos\alpha\ \sin(\alpha+\beta) - \sin\alpha\ \cos(\alpha+\beta)\ \cos\phi] \quad (1)$$

$$V_y = k.B[\sin\alpha\ \sin\phi] \quad (2)$$

$$V_z = k.B[\cos\alpha\ \cos(\alpha+\beta) + \sin\alpha\ \sin(\alpha+\beta)\ \cos\phi] \quad (3)$$

where k is a constant of proportionality, and ϕ is the rotation phase (like the pulse longitude; ϕ=0 for the closest angle between the magnetic-field direction and the sight-line).

Then it follows that the angle (θ) which the proper-motion direction would make with respect to the intrinsic PA direction is given by

$$\tan\theta = \frac{\sin\alpha\ \sin\phi}{\cos\alpha\ \sin\zeta - \sin\alpha\ \cos\zeta\ \cos\phi} \quad (4)$$

where $\zeta = \alpha + \beta$. This is exactly the expression describing the sweep of the position angle of pulsar polarisation in the model of Radhakrishnan & Cooke (1969). The magnitude of the transverse velocity is then simply $V_{xy} = \sqrt{V_x^2 + V_y^2}$. With this understanding, we explore the following two approaches.

a) We take the IPA and proper-motion direction at their face value. Their relative angle (i.e. the difference) should allow us to compute ϕ (never mind the sense of rotation)— giving us 8 possible solutions, of which we need to consider only the 4 independent ones (say ϕ_1 to ϕ_4) given the symmetry in the problem[2]. We used these values, ϕ_1 to ϕ_4, to estimate the expected magnitudes of the proper-motions and compared them with the measured values[3]. Even in the best case any correlation present was not significant and hence no clear inference was possible.

b) In a second more statistical approach, we compute for each of the sample pulsars, the distribution of the relative angle $\angle(V_{pm} - IPA)$ based on the known geometry (along with the above equations) and by assuming that ϕ is distributed uniformly over its range. A combined distribution computed this way for a single short impulse is not significantly different from the observed distribution in Fig. 1. Assuming impulses of longer durations leads to a significantly greater expectation of alignment which is not seen. The observations therefore suggest that if impulses are along the magnetic axis, they must be confined to a small fraction of the rotational phase cycle of the star.

5. Birth kicks as the origin of pulsar rotation

The mechanisms examined so far assumed ‘radial kicks’ which did not affect the rotation rate of the star. As noted already, Spruit & Phinney (1998, hereafter SP) and Cowsik (1998) have explored the possibility of non-radial random kicks which would impart both net linear and angular momenta to the star. Noting the significance of this mechanism, we have looked at this issue in some detail.

SP give the results of their simulations for a case of 4 random non-radial kicks that impart velocities and spins of magnitudes such as observed. We examine this model over a range of parameters, such as the number of momentum impulses, their magnitudes and durations. For each combination of the parameters, we examine the resultant distribution of the angle that the apparent motion would make relative to the projection of the rotation axis of the star in the plane of the sky. We of course compare the resultant distribution with what is observed (Fig. 1). We select for our examination only the subset that most corresponds to the expected dispersion in the velocity and in the rotation rates of the sample.

From our numerical simulation[4], we find the following. As noted by SP, a single impulse gives linear motion in a plane perpendicular to the rotation axis. In the plane of the sky, the projected direction of the star motion relative to that of the spin axis would be expected to show a significant bias towards 90°, as illustrated in Fig. 3a. This is *not* observed, as seen in Fig. 1. Hence, single impulses being responsible for both the birth velocity and spin can be ruled out. This holds irrespective of their duration as the rotation axis itself is defined by the action of the impulse. The strongest basis for this conclusion comes from the knowledge of the particular orientation angles of the pulsars in our sample.

Hence, in such models, there must be two or more randomly directed impulses to be consistent with the observations. As might be expected, the strength of the impulses required to obtain the observed range of velocities and spin rates will be weaker (by a factor $\sqrt{N}$) for an increasing number of impulses (N). The velocity dispersion as a function of the duration of a momentum impulse of a given magnitude remains constant up to a certain critical duration (τ_c), above which the azimuthal averaging reduces the resultant velocities. Following SP, if we

[2] The allowance for any orthogonal-flips in the polarisation position angle makes the possible solutions 8 instead of the 4 that come from simple projection considerations, and the left-right symmetry.

[3] Note that the sample size here is smaller than that shown in Fig. 2, due to limited measurements of IPA & proper-motion direction.

[4] 5000 sample stars considered in each case.

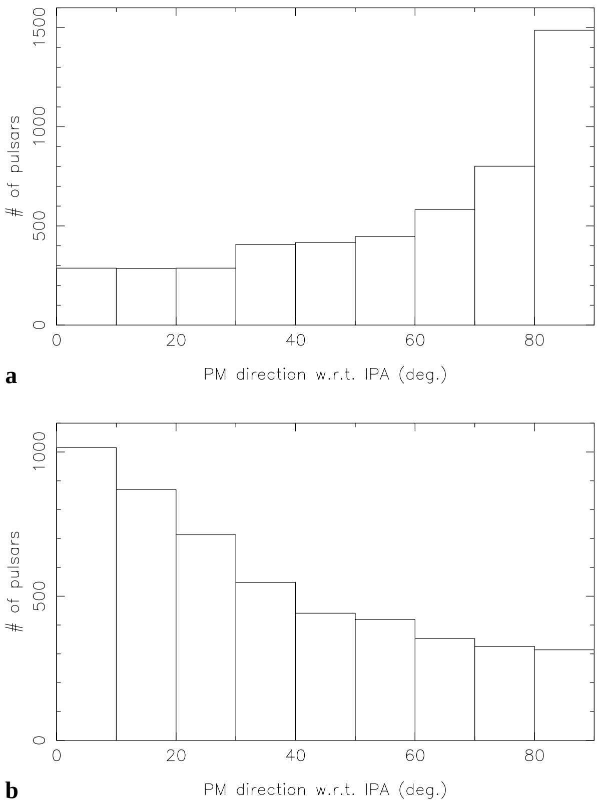

Fig. 3a and b. The expected distributions of the angles between the proper motion and the spin axis projected on the sky. **a** For a single non-radial impulse of any duration, there is a significant bias towards 90 degrees. **b** In the case of of a number of long duration impulses, the bias is towards zero degrees.

assume the impact radius (radius of the protoneutron star) to be three times the radius of the neutron star, we find τ_c to be about 9 times the corresponding resultant rotation period of the star, as also pointed out by SP. The velocity dispersion levels off (at a reduced value) when the impulse duration is much larger than τ_c. In contrast, the resultant spin rate is independent of the impulse duration but varies linearly with its average magnitude (I). Thus, the product $(I \times \tau_c)$ is a constant that depends on the number of impulses and the star's mass and its moment of inertia.

For impulse durations (τ) much smaller than τ_c, both the linear and angular momenta grow as $\sqrt{N}$ but the angle between them becomes random. However, for relatively longer-duration impulses a significant preference of the direction of the linear momentum develops towards the spin axis, which itself is evolving. This bias is illustrated in Fig. 3b. Since the data on the relative inclinations do not show such a preference, we conclude that the impulse durations must be shorter or equal to the corresponding critical duration τ_c. This also means that no significant reduction[5] in the expected net velocities occurs due to azimuthal averaging during rotation and therefore somewhat weaker impulses can account for the observed velocities. However, the corresponding spin rate would then be smaller than with long-duration impulses. If the duration of each kick in the 4-kick situation considered by SP is 0.32 seconds, we find that about 55% of the population should appear to have relative inclinations between 0–30° compared to about 20% in the 60°–90° range. Even after due allowance for possible selection effects etc., we find that the expected distribution of the relative directions is far from what is observed. Hence, both the duration and the magnitude of the impulses in the example considered by SP are to be reduced by factors of 5 or more and of 2, respectively.

[5] the reduction in the net velocity/spin due to the randomness in the impulse direction will continue to exist.

6. Discussion

We have shown in this work that given the present sample of radio pulsars for which we have reliable proper motion and polarisation measurements, no significant correlation exists between the magnetic field strength and the magnitude of the spatial velocities of pulsars, or between the projected directions of the rotation axis (and/or the magnetic axis) and the direction of the proper motion vector. This has fundamental implications for the mechanisms producing the asymmetric supernova kick velocities, as the observations do not support any mechanism producing net kick velocities parallel to the rotation axis. This rules out therefore, momentum impulses of any duration along the rotation axis, and any long duration (compared to the rotation period) impulses along any one fixed axis, for example, the magnetic axis.

Among the most elegant suggestions to explain the origin of kick speeds and the initial rotation periods of pulsars are the ones suggested by Spruit & Phinney (1998) and Cowsik (1998). It has been possible to quantitatively assess the expectation regarding the distribution of proper-motion directions using the framework of the SP model. Our simulations and comparison of the results with the observations show that single impulses are ruled out, but not 2 or more impulses of relatively short duration. The durations have to be short enough not to cause any significant azimuthal averaging of the radial component of the impulse. The same conclusions should also apply to the model of Cowsik (1998). However, his expectation of an inverse correlation between velocity and initial rotation period (also applicable to SP) can not be tested readily.

In the above analysis, we have ignored an important aspect of the evolutionary history of pulsars. As we know, a good fraction of massive stars in the sky are in binary or multiple systems. This implies that almost by definition, a considerable fraction of pulsars are born in binary systems. Most of them get disrupted during the first supernova explosion in the binary. Therefore, the spatial velocities of such pulsars must still retain some memory of their binary origin. The possible contribution to the post-explosion speeds from the pre-explosion orbital-motion can be appreciable (Radhakrishnan & Shukre 1985; Bailes 1989), particularly noting that a predominant number of pulsars seem to have speeds of the order of only about 200 km s^{-1} (Hansen & Phinney 1997; Blaauw & Ramachandran 1998). Moreover, the analysis of Deshpande et al. (1995) shows that a considerable fraction of pulsars may be born at large heights from the galactic plane, suggesting that a considerable fraction of pulsars are born in binary systems, which have *run away* from the plane. It must be emphasized therefore that our conclusions above are valid only if the velocities are derived solely from natal kicks.

To estimate this 'contamination' from the progenitor orbital velocities, an identification of an origin in OB-associations for as many pulsars as possible might throw much light. In some of these cases, the pulsar progenitor may perhaps be identified with the progenitor of a runaway OB star. We thank the referee for pointing out this possibility, as also the inadequacy of the present proper motion determinations for such accurate back-tracking; and for emphasizing that for this problem, increased accuracy of the proper motions of known pulsars is more important than increasing the sample of known pulsars. More accurate information on the statistics of orbital velocities in the pre-explosion stage of massive double star systems would also be very important.

An interesting case of observational evidence relating to the direction of the birth-kick is the recent work by Wex et al. (1999, private communication). Through a detailed modelling of the pre-explosion binary progenitor of PSR B1913+16, they find that the direction of the kick velocity must have been almost opposite to that of the orbital velocity of the exploding component to have not disrupted the system. In such binary systems, one expects the rotational angular momentum of the star to be parallel to that of the binary orbit due to the evolutionary history. The kick velocity could therefore not have been along the rotation axis of the star.

An orbital velocity contribution can be viewed as from a 'kick', but one which is radial, i.e. it does not contribute to the spin of the star. It is easy to see that such a contribution to the velocity can influence the direction of the net motion, significantly so when its magnitude is comparable to or greater than the contribution from the natal kicks. In such cases, the resultant proper motion direction (with respect to the spin axis) should become more and more random as the relative contribution from the orbital motion increases. We have verified this expectation through simulation by including an initial velocity component in a random direction and of a varying magnitude. In all the cases discussed earlier, where the relative directions of the proper motion were biased towards the projection of the spin axis (or orthogonal to it), we see, as would be expected, a significant reduction in the bias. In fact, when the two possible contributions to the motion are about equal, the expected distribution of the relative directions becomes indistinguishable from the observed one (Fig. 1)! This is so, independent of the kick durations, thus not necessarily requiring short duration kicks. The role of the duration of kicks is limited to only deciding whether azimuthal averaging occurs or not. Long duration kicks will only reduce the net contribution of the natal kicks to the proper motion and will no longer be relevant in deciding the direction of the 'net' motion.

Our conclusions are therefore,

1. Mechanisms predicting a correlation between the rotation axis and the pulsar velocity are ruled out by the observations. This includes single long duration radial kicks along any fixed axis of the star.
2. There is no significant correlation between the magnetic field strength and the velocity.
3. If asymmetric acceleration at birth is responsible for both the rotation and the velocity of the pulsar, *the observations rule out single impulses of any duration and multiple extended duration impulses.*
4. The above conclusions lose their significance if there is a substantial contribution to pulsar velocities from the orbital (or runaway) motion of the progenitor.

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