

## Pulsar Kicks: Spin and Kinematic Constraints

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**Abstract.** It has been noted that the Crab and Vela pulsar proper motions lie along the symmetry axes of their wind nebulae. In an effort to promote this observation to a serious test of kick physics, we are using CXO images and other data to estimate the angle between the proper motion and PWN (i.e., spin) axis for a number of pulsars. Here we give a progress report on this work and the constraints that these data provide on kick models. Present data suggest that a kick duration of  $\tau_K \sim 3$  s is sufficient to explain the alignment of most pulsars. This rules out electromagnetic and hydrodynamic kick models, but is fairly consistent with proposed anisotropic neutrino emission. However, some objects, especially PSR J0538+2817 show such good alignment that even neutrino models are challenged.

### 1. Introduction

Typical pulsar velocities of  $\sim 500$  km/s represent a lot of momentum, and the nature of the kick that gives neutron stars such speeds has long been one of the major problems in compact object physics. The distribution of kick speeds has important implications for the observed pulsar population, especially those in binaries; thus measurement of pulsar proper motion distributions and application to binary modeling have been major activities (see articles by Burgay et al., Dewi & van den Heuvel, and Podsiadlowski et al. in this volume). However,  $\vec{v}$  is a vector quantity and comparison of its orientation with respect to that other relic of neutron star birth  $\vec{\Omega}$ , promises to provide additional insight into the kick physics.

The letter of Spruit & Phinney (1998) was influential in promoting thinking about the spin-kick connection. These authors, in fact, hypothesized that the initial neutron-star angular momentum was small due to strong core-envelope coupling in pre-collapse stars. They suggested that an off-center kick at impact parameter  $d = R \sin \psi_{\text{kick}}$ , imposed while the bloated proto-NS has radius  $R \sim 3 \times 10^6$  cm, produces a spin of

$$\Omega_{rms} \approx 42 \text{ s}^{-1} \left( \frac{\sin \psi_{\text{kick}}}{0.5} \right) (R_{10}/3) \langle v^2 \rangle_7^{1/2}$$

when the resultant kick velocity was  $100 \langle v^2 \rangle_7^{1/2}$  km/s. This gives a modest initial spin period  $P_0 \sim 150/v_7$  ms. For a single impulse, the resulting  $\vec{\Omega}$  is always orthogonal to the space velocity. Of course, for long duration kicks with  $\tau_K \gg P_0$ ,

the transverse component of the kick rotationally averages to 0, leading to an aligned spin.

More recent treatments of core coupling through collapse (e.g., Heger et al. 2004) do not support the idea of very slow initial spin, instead suggesting  $P_0 \approx 3 - 10$  ms. Such a pre-existing spin will make rotational averaging of the transverse kick component even more effective, increasing the tendency to an aligned proper motion. Lai, Cordes & Chernoff (2001) have discussed several physical mechanisms for producing a kick at core collapse. The most important are the Harrison-Tademaru electromagnetic kick (requiring  $P_0$  of a few ms), hydrodynamically-driven anisotropy-induced kicks ( $\tau_K \sim \tau_{\text{dyn}}|_{R \sim 100 \text{ km}} \sim 100$  ms) and magnetic field-induced neutrino anisotropy kicks ( $\tau_K \sim \tau_\nu \sim 3$  s). They discussed rotational averaging of these kicks, concluding that the spin-kick orientation could be a significant constraint on these models.

For pulsars born in close binaries with aligned angular momenta, the Blaauw mechanism guarantees a component of the proper motion perpendicular to the (pre-SN) spin axis. Similarly the binary-like structure of a maximally rotating core with a strong  $m = 1$  perturbation can, when the lower mass proto-NS disrupts, induce a kick to the main core, as recently discussed by Colpi & Wasserman (2002). This can be thought of as an ‘intra-core Blaauw mechanism’ and similarly gives rise to a kick component orthogonal to the initial spin. So there are viable models for both aligned and orthogonal momenta.

The spectacular CXO images of the Crab and Vela PWNe show clear symmetry axes. It was promptly noted that the proper motion vectors (from HST for the Crab and the LBA for Vela; Dodson et al. 2003) were roughly aligned. A more careful assessment (Ng & Romani 2004), however, shows a statistically significant misalignment; the chance probability of getting two such 2-D projected alignments is  $\sim 3\%$ . Thus, the alignment can provide a significant probe of core collapse physics, but more and better measurements are clearly needed.

## 2. CXO Measurements of PWNe Symmetry Axes

In Ng & Romani (2004) we developed a fitting method that can extract PWN orientations from sparse, Poisson statistics dominated CXO images by modeling relativistic central tori and jets in pulsar wind nebulae. This fitting is most sensibly applied to young  $\tau_c = 10^4 \tau_4$  yr, high-field  $B_s = 10^{12} B_{12}$  G pulsars in the high-pressure interiors of supernova remnants. There we will see the axial symmetry of the PWN when the wind termination shock (torus) scale

$$r_{\text{ws}} \approx (\dot{E}/4\pi P_{\text{ext}})^{1/2} = 0.17 \text{ pc } (B_{12} \tau_4 P_{-9})^{-1}$$

is smaller than the bow shock standoff distance

$$r_{\text{bs}} \approx (\dot{E}/4\pi c \rho_{\text{ext}} v^2)^{1/2} = 0.42 \text{ pc } (B_{12} \tau_4 v_7)^{-1},$$

i.e., the pulsar motion must be subsonic. Van der Swaluw et al. (2003) have emphasized that the PWN structure can also be affected when it is ‘crushed’ by the SNR reverse shock. Interestingly, since our study of the PWNe requires that

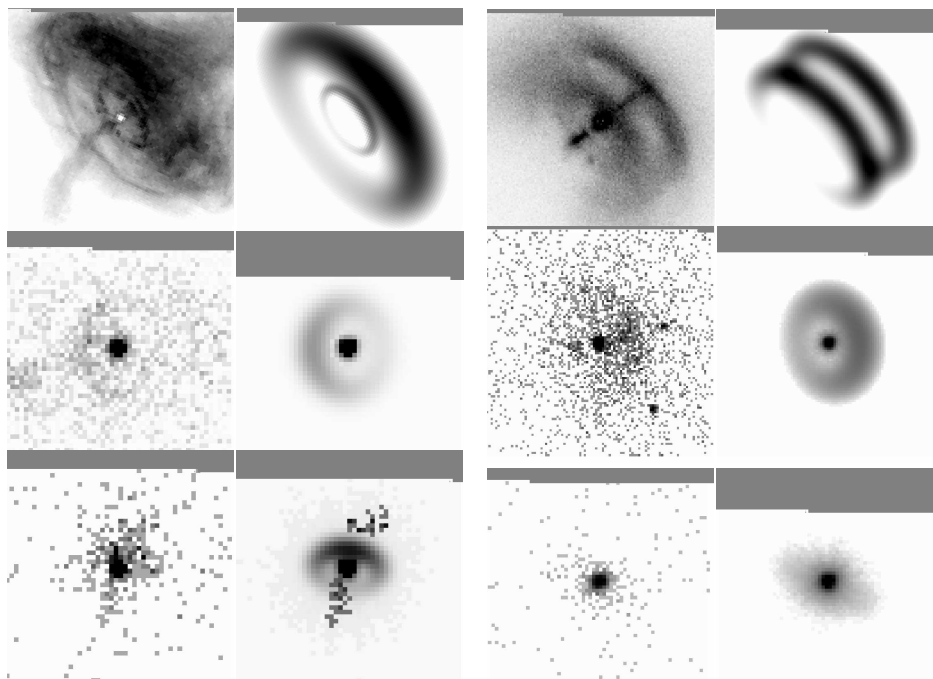


Figure 1. CXO PWNe and best-fit torus models (Ng & Romani 2004). The data quality trend from obvious tori (top row: Crab, Vela) through clear tori (PSR J2229+6114, PSR J1930+1852) to possible tori (bottom row: PSR B1706–44, PSR J0538+2817).

they be spatially resolved, one selects by angular scale  $\theta_{\text{ws}} = r_{\text{ws}}/d \propto \dot{E}^{1/2}/d$ , which is the same scaling expected for the non-thermal X- and  $\gamma$ -ray flux. So these objects are also interesting for study of their magnetospheric emission and, not coincidentally, study of the PWNe can constrain the pulsar viewing geometry and aid in the understanding of their high-energy pulsations.

The fitting of Ng & Romani (2004) gives values for the size, orientation and post-shock flow speed  $\beta$  for equatorial tori (sometimes double) and/or polar jets. Crucially, we also provide simulations that give statistical errors on the fit parameters. Of course, when the image counts are large, statistical errors are an underestimate of the true uncertainties and when the image is particularly sparse, the uniqueness of the model is questionable. Happily, the unmodeled extra structures seem to have little effect on the determination of the overall symmetry axis (the key parameter for the present discussion) and reasonable CXO exposures can provide enough counts to give well exposed images of many sources. For example in the PSR B1706–44 PWN image in Figure 1 (lower left) the torus + jet structure is perhaps less than convincing. Our new CXO image (Fig. 2), however, shows that this interpretation is in good shape—extended jets and the bright arc of the near side of the torus are now well seen.

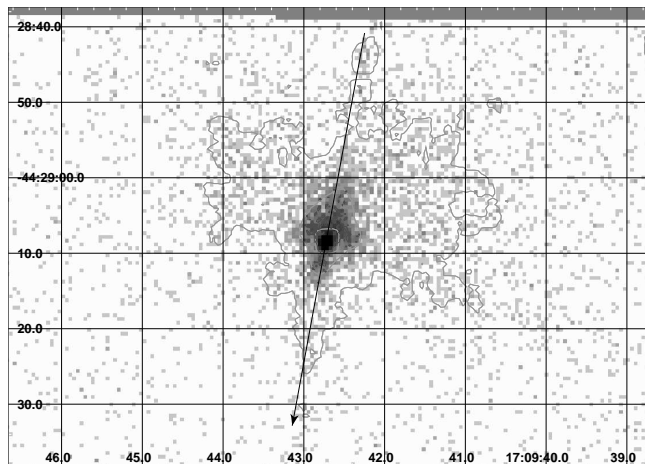


Figure 2. A raw 0.5–7 keV image of the PWN of PSR B1706–44 from a follow-on 100 ks CXO pointing. Such moderately deep exposures can make the PWN PA fitting quite robust.

### 3. Spin-Kick Correlation

We now wish to compare the PWN-measured spin axes with the kick vectors. Establishing  $\vec{v}$  is difficult and we must rely on a variety of methods. Optical or radio interferometric proper motions are of course best, and these are becoming available for several young objects. When we lack direct proper motions, we can often make estimates from the offset from the birth site, since as discussed above toroidal PWNe will almost invariably be inside their parent SNR. This method is limited by the accuracy with which the explosion center can be measured, and we will always prefer direct measurements. For example, the offset of PSR J0538+2817 from the center of S147 was used by Romani & Ng (2003) to estimate the proper motion direction. This was supported by a timing proper motion (Kramer et al. 2003), which solidified the association with the SNR and gave a more precise pulsar age. However, a precise position angle is still required and with Walter Brisken (NRAO) we have a program underway to measure this.

In Ng & Romani (2004) we described six proper motion – spin axis comparisons. The Crab and Vela pulsars are well known (although the substantial errors are not always appreciated). For PSR B1951+32 we compared the interferometric proper motion (Migliazzo et al. 2002) with the spin axis PA fit from the optical jets. For PSRs B1706–44 and J0538+2817 we compare (for now) with offsets from the SNR centers. These last measurements have at present limited accuracy, but we are working toward improved CXO imaging and precision proper motions for these objects. For PSR B0656+14 we show that the spin axis pointed nearly at Earth is consistent with the small interferometric proper motion (Brisken et al. 2003), but unfortunately, the PWN appears to have a surface brightness too low for an accurate independent spin axis position angle. We mention one additional alignment here: PSR J1124–5916 in G292.0+1.8 shows a clear offset from its nearly circular SNR center. We have measured the elonga-

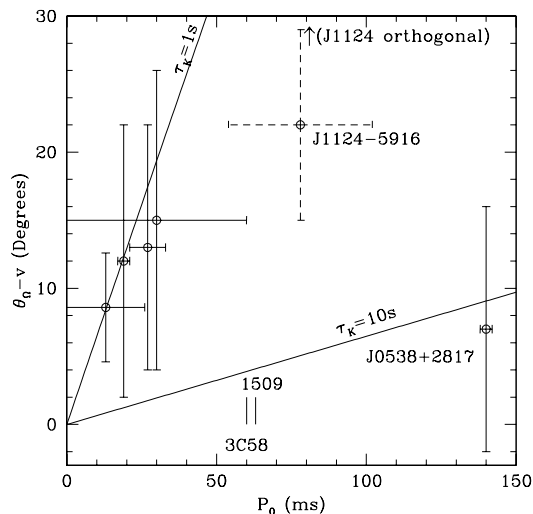


Figure 3. Spin-kick angles vs estimated initial spin periods. The lower limit to the residual alignment after rotational averaging is shown for two characteristic kick durations. The value for PSR J1124–5916 is shown dashed, since the orthogonal solution still remains viable. The  $P_0$  of two other pulsars with slow initial spins, but no proper motion estimates presently available, are also shown.

tion of the central PWN and compared this with the direction to the explosion center as determined from the radio image of the forward shock (Gaensler & Wallace 2004). The resulting angle  $\theta_{\Omega-v} \approx 22 \pm 7^\circ$  shows substantial misalignment if the PWN major axis is identified with the polar jets. Unfortunately, better imaging is needed here to make the jet interpretation secure and so at present  $\theta_{\Omega-v}$  has a  $\pi/2$  ambiguity for this source.

Now we can compare these angles with other pulsar parameters to constrain the kick physics. With detailed modeling it is interesting to compare with the amplitude of the proper motion (Ng & Romani, in preparation), but for now we describe only the simplest comparison: that with the initial spin  $P_0$ . Estimating  $P_0$  is itself non-trivial and generally requires a kinematic age and some constraint on the effective braking index. Several useful estimates are in Migliazzo et al. (2002); others can be made. For Vela, we can for example use the measured braking index  $n = 1.4 \pm 0.2$  and the kinematic age (dominated by the explosion center uncertainty) to get  $P_0 = 13 \pm 13$  ms, which is of some use. However, pulsars with large  $P_0$  are of the greatest interest. For PSR J1124–5916 there remains some uncertainty in the distance. Combined with the braking index uncertainty, we derive  $P_0 = 78 \pm 24$  ms. PSR J0538+2817 is, on this score, truly outstanding as, with a kinematic age  $\ll \tau_c$ , it must have  $P_0$  very close to its present 143 ms period.

The first thing that we infer from these data is that there is a true causal correlation between the spin and kick position angles. Even ignoring PSR J1124–5916, we find a chance probability of  $4 \times 10^{-4}$  that the projections of the kick and spin angles are aligned (2-D) within the  $1\sigma$  upper limits (the probability of getting a

set of angles as small as the best fits is  $2 \times 10^{-5}$ ). However, we also infer that the kicks are significantly misaligned—the mean offset is  $10^\circ$ , a  $4\sigma$  difference from 0. Finally, we see that there is a general trend toward poorer alignment at large  $P_0$ . This trend is consistent with the residual misalignment from a few-second kick. This is the timescale for momentum imparted by anisotropic  $\nu$  emission during the quasi-static core cooling phase, which seems fairly reasonable. The exception is PSR J0538+2817, which requires  $\tau_K$  of 10 s or more, rather difficult to reconcile with neutrino cooling times.

This trend to alignment must be contrasted with the model of PSR B1913+16 by Wex, Kalogera, & Kramer (2000), which shows that for initially aligned spins, the second pulsar was kicked at  $\theta_{\Omega-\nu} = 80 \pm 5^\circ$ . Should we infer that natal kicks are aligned for single stars, orthogonal for binaries? Not necessarily. Clearly the precession of the pulsar – B star binaries (e.g., Kaspi et al., in this volume) implies a kick component out of the original orbital plane. The orbit and scintillation velocity data for PSR J0737–3039 (see Willems & Kalogera, 2004; Ransom et al., in this volume) also indicate a large out-of-plane kick. Detection and calibration of the geodetic precession cone angle should give a uniquely precise measurement of this pulsar’s kick direction. When we recall that binary survival puts a strong selection bias toward (retrograde) kicks in the orbit plane, it seems likely that a trend toward kick alignment can be present in binaries, as well.

This is work in progress, but at the moment a substantial, but incomplete kick alignment seems present in most young pulsars. The degree of alignment suggests kicks lasting a few seconds, so a neutrino mediated kick seems tenable. As discussed by Lai et al. (2001), the most plausible mechanisms for producing a long-lived anisotropy invoke large  $\geq 10^{15}$  G organized fields in the proto-NS interior. However, a few of the larger  $P_0$  pulsars are a challenge for this picture. If good alignment persists for these, some sort of post-collapse momentum kick, such as the super-Eddington accretion / asymmetric-jet picture suggested in Romani & Ng (2003) may be required. Even if  $\tau \sim 3$  s neutrino kicks dominate, rotational averaging has serious implications for the survival of pulsar binaries, since in-plane kick components should be greatly reduced. Thus further observation and modeling to constrain the *vector* properties of neutron-star kicks seems essential to understand both kick physics and the pulsar population.

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