X-RAY SPINS AND RADIO SPEEDS: PROBING PULSAR BIRTH KINEMATICS WITH *CHANDRA* AND THE VLBA

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Abstract

The origin of the enormous momentum kicks imparted to pulsars at birth is one of the outstanding problems in core collapse physics. Recent advances in imaging the toroidal structures in pulsar wind nebulae with the *Chandra* X-ray Observatory and obtaining interferometric proper motions with the NRAO Very Long Baseline Array (VLBA) have made it possible to compare the linear and angular momentum vectors of several young pulsars. We describe here our *Chandra* imaging/VLBA astrometry campaign for two young pulsars in nearby supernova remnants: PSR J0538+2817 in S147 and PSR B1706−44 in G343.1−2.3. These objects are particularly interesting since apparent spin-velocity alignment and large initial spin periods allow a significant test of kick models. We show that the data should allow a comparison of the projected spin and kick axes at the 3° level, comment on the implications for the pulsar/supernova remnant associations and discuss briefly the implications of such measurements for neutron star kick physics.

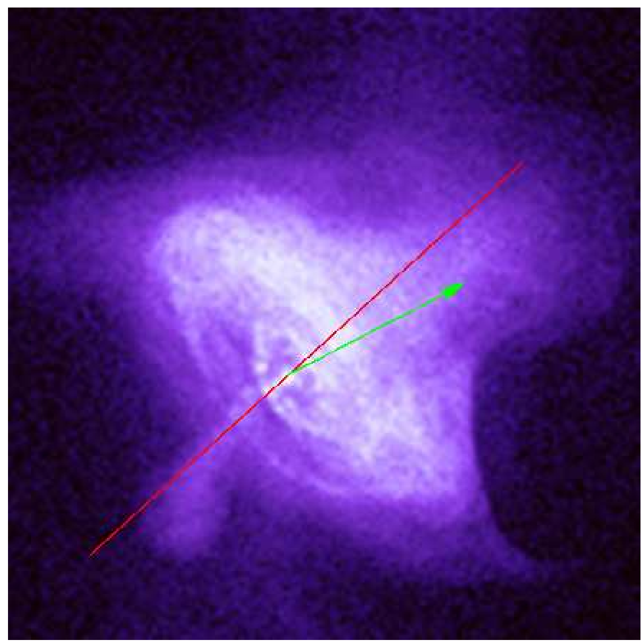

Figure 1: The Crab nebula as seen by *Chandra*. The red line indicates the line of mirror symmetry and the green arrow shows the proper motion of the pulsar as determined by Caraveo & Mignani (1999). Image credit: NASA/CXC/ASU/J. Hester et al.

1 Introduction

Chandra imaging shows that the Crab and Vela pulsars have surrounding X-ray pulsar wind nebulae (PWNe) with clear axes of symmetry (see Fig. 1 and 2). These structures have been interpreted as toroidal termination shocks in a relativistic equatorial outflow. These data provide a nearly model-independent measurement of the 3-D orientation of the neutron star spin axis on the sky. Comparison with astrometric proper motion vectors (green) showed good albeit imperfect alignment. This alignment between spin and proper motion vectors can be used to probe birth kicks.

Several other pulsars exhibit X-ray PWNe with bilateral symmetry. Most are much (100 to 1000 times) fainter than those of the Crab or Vela and host pulsars that tend to be weak (1400 MHz flux densities of a few mJy) as well. The challenge is to measure the X-ray

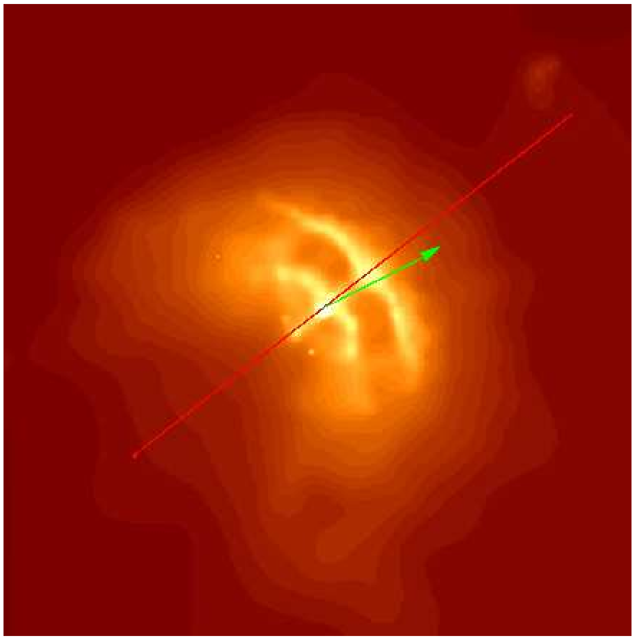

Figure 2: The Vela nebula as seen by *Chandra*. The red line indicates the line of mirror symmetry and the green arrow shows the proper motion of the pulsar as determined by Dodson et al. (2003). Image credit: NASA/PSU/G. Pavlov et al.

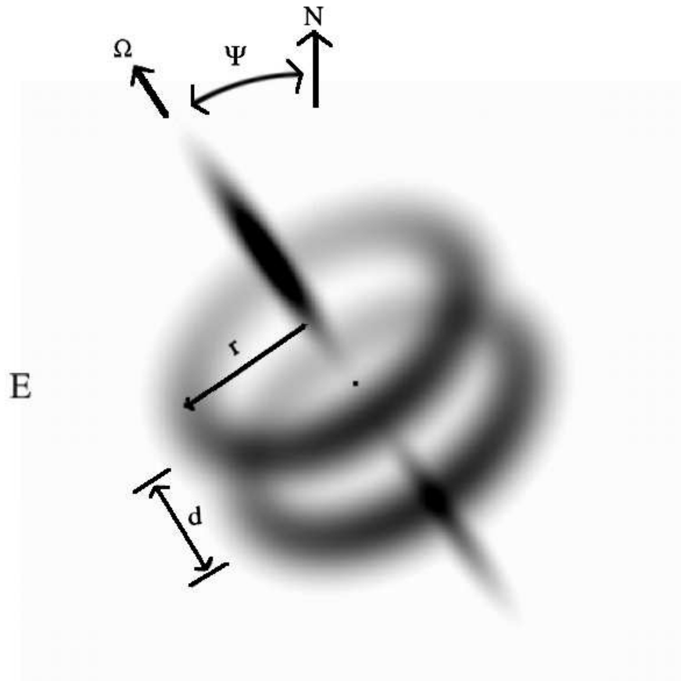

Figure 3: An example model used to determine the geometrical and orientation parameters of X-ray PWNe. This model includes two tori and a pair of polar and is appropriate for fitting PWNe similar to that of the Vela pulsar.

symmetry axes and the proper motion directions to a precision of 3° or better in order to improve the alignment statistics. There are additional benefits to these measurements: 1. Assuming alignment, the pulsar's proper motion can be de-projected to estimate its space velocity, 2. Pulsar-supernova remnant associations can be tested, and 3. The PWNe electron energy spectrum and pitch angle distributions can be constrained.

2 Spin axis measurements

Several geometrical and two orientation parameters of the PWNe are determined though model fitting. The models used are cylindrically symmetric and include one or two Doppler-boosted tori and/or a pair of Doppler-boosted polar jets. Figure 3 shows two tori and jets. The model is fit to Poisson noise limited *Chandra* data to determine the model parameters. The statistical errors for the fit parameters are determined via Monte Carlo simulations. The spin axis determination is largely decoupled from the determination of the PWNe geometry. Useful values can be obtained even for very faint PWNe. Ng & Romani (2004) have used this technique to model several PWNe with orientation uncertainties ranging between 2 and 10°. See Fig. 4 for two examples.

3 Proper motion measurements

Very long baseline interferometry (VLBI) has proven to be an effective technique to measure proper motions, and in some cases trigonometric parallaxes, of pulsars. In recent years, the Very Long Baseline Array (VLBA) has been used to determine proper motions and parallaxes of 11 pulsars (Brisken et al. 2002, Brisken et al. 2003, Chatterjee et al. 2001). Factors such as resolution, sensitivity, ionospheric distortion, and steep spectra pushed most of these observations to the 20 cm band. The ionosphere dominates interferometric phase errors. Careful calibration using very nearby in-beam sources or ionosphere modeling are needed to achieve sub-milliarcsecond precision. Figure 5 shows the effect of ionosphere on the imaging and astrometry of PSR B0950+08. The modeling of the ionosphere takes advantage of the frequency dependence of the ionospheric phase errors. Chatterjee et al. (2004) have shown that for brighter pulsars, the 6 cm band can be used with simpler calibration techniques to achieve results with comparable precision. Parallaxes precise to < 0.1 mas are possible in favor-

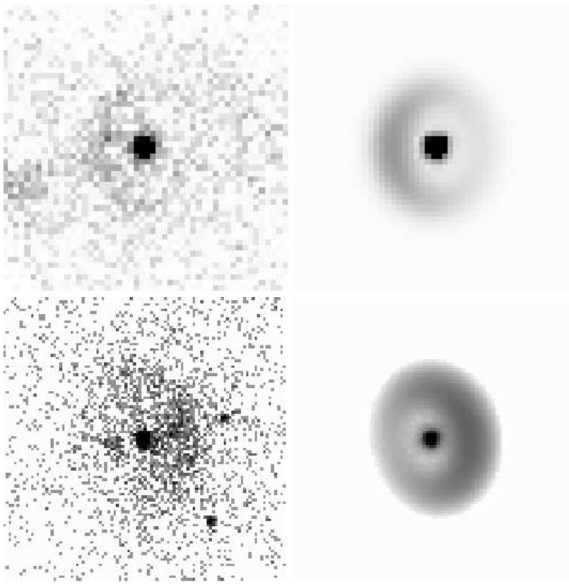

Figure 4: Two example PWNe fits. Shown are a cleaned *Chandra* image of PSR J1930+1852 (top left) and its best fit torus model (top right), and similar for PSR J2229+6114 (bottom, left and right).

able conditions and proper motions accurate to 0.1 mas are attainable in a few years of observing even in more typical conditions.

4 Two interesting (but difficult) examples

S147 (see Fig. 6) is a rather circular remnant with a well defined center and contains J0538+2817, a young pulsar with timing age $\tau_{\rm char} \sim 6\times10^5$ yr. The remnant age and pulsar cooling age are however $< 10^5$ yr. This is confirmed by a 3×10^4 yr timing proper motion age estimate (Kramer et al. 2003). Romani & Ng (2003) find a faint elliptical X-ray PWN with a symmetry axis that agrees with the geometrical and (crude) timing proper motion axes (Fig. 7). Additional *Chandra* imaging is being pursued to improve measurement of the spin axis angle. This pulsar is being monitored with the VLBA. Initial epochs suggest that a parallax precise to 0.2 mas and a 0.3 mas yr^{-1} proper motion should be attainable. This is sufficient to test the $d \sim$ 1.2 kpc distance estimate and to determine the proper motion position angle to less than 1°. B1706−44 is a Vela-like pulsar that is possibly associated with SNR G343.1−2.3. A faint dis-jet structure seen in archival 15 ks data is well measured in a new 100 ks exposure; this structure determines the spin axis position angle to $< 1°$. On larger scales a toroidal radio nebula also surrounds the pulsar. A rough proper motion axis can be inferred if one assumes the tentative association with G343.1−2.3. Its position angle is in reasonable agreement with the symmetry axes of both the X-ray and radio nebulae. Ongoing VLBA observations will likely provide a much improved proper motion vector,

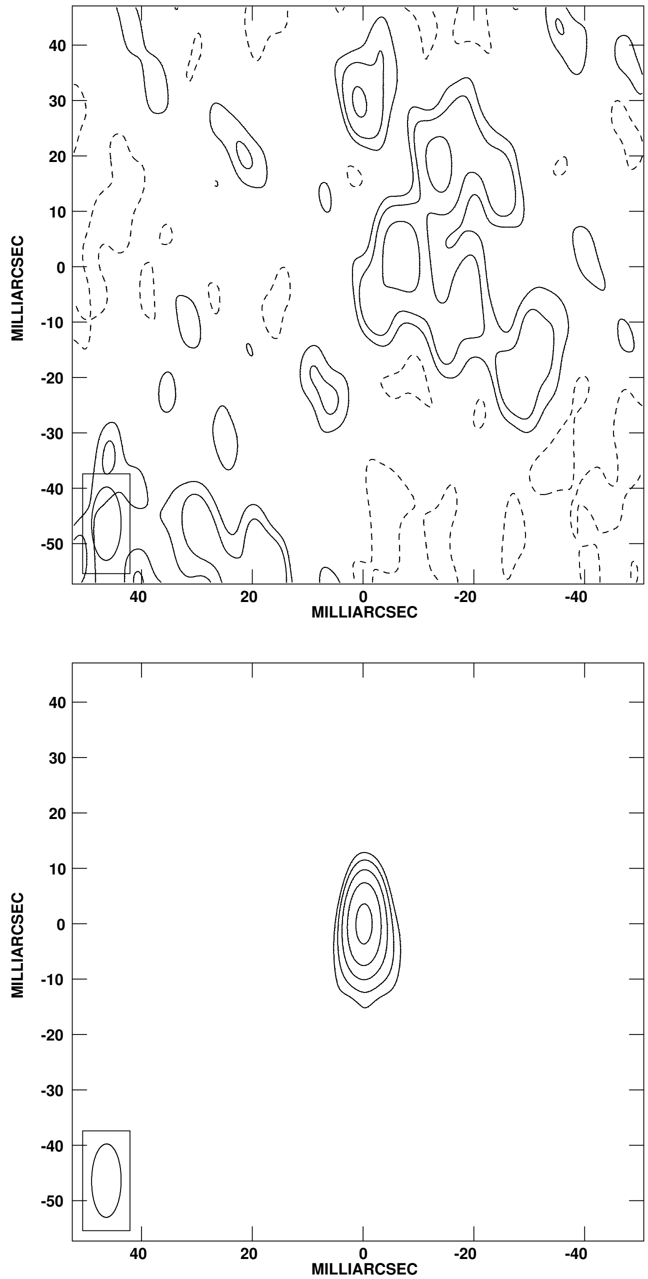

Figure 5: The effect of the ionosphere on VLBI imaging and the effectiveness of its removal. The top figure shows a phase-referenced image of PSR B0950+08 without ionospheric modeling. Below is the same after modeling and removal of the ionosphere's distortion. The contours are the same in each, increasing by factors of 2 from the lowest contour at 5 mJy beam^{-1}.

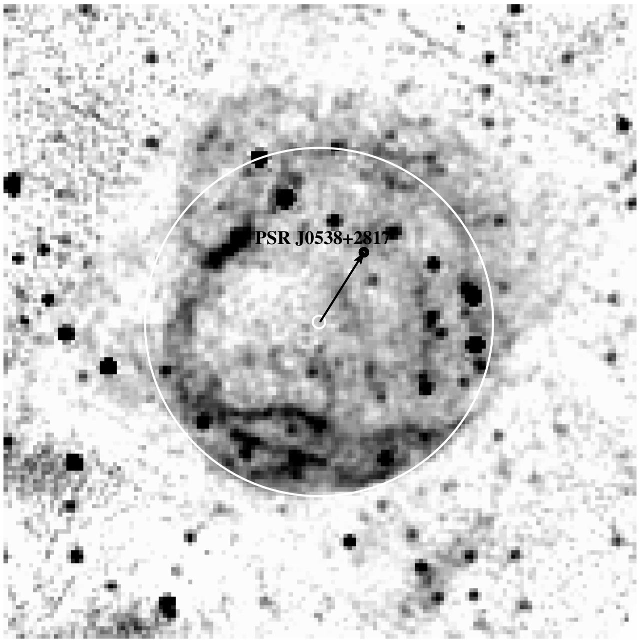

Figure 6: SNR S147. The superposed arrow shows the position of PSR J0538+2817 (head) and the estimated center of the SNR (tail). Timing proper motion measurements and early results from VLBI astrometry are consistent with this geometry.

but measuring a parallax to this source is unlikely due to severe calibration issues that arise when observing at such low elevations.

5 Early conclusions

Chandra/*HST*/astrometry measurements now compare at least six proper motion spin axis position angles for young pulsars at varying, but useful accuracy. All show a preference for alignment (chance probability $< 0.04\%$), but there is a statistically significant, finite

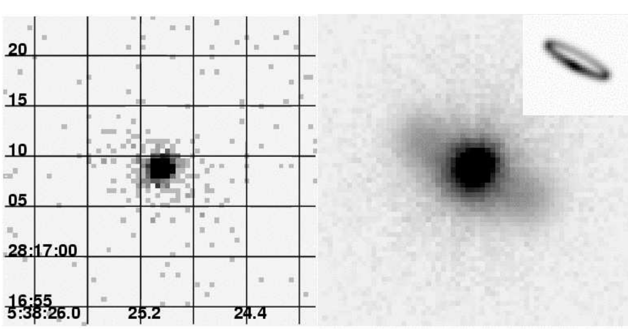

Figure 7: Early *Chandra* image of J0538+2817. The faint inclined disk suggests a symmetry axis that is nearly parallel with the proper motion axis.

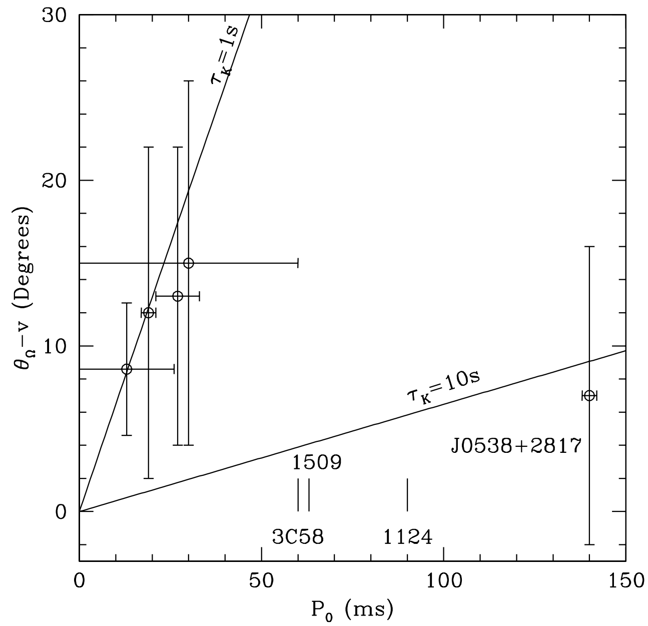

Figure 8: Spin axis/proper motion axis misalignment plotted against estimated birth spin period for 5 pulsars. Data to date are consistent with a kick duration of $\sim$ 2–3 s.

misalignment $\sim 10°$. For several of these pulsars, an estimate of the initial spin period can be made. If a randomly directed birth kick is rotationally averaged (Spruit & Phinney 1998) to produce alignment, these data probe the kick duration timescale.

A plot of initial spin period, P_0 versus alignment angle suggests that the characteristic timescale for the kicks is $\sim$ 2–3 s (Fig. 8). This matches well with a B-induced neutrino anisotropy In the initial cooling phase. PSR J0538+2817, however seems to require a longer, $>$ 10–20 s, kick. If the improved astrometry confirms this, long lived, post-collapse kick models must be considered.

Several neutron star binaries (including the newly discovered double pulsar binary, PSR J0737−3039) require kicks with a component in the binary plane (presumably orthogonal to the spin). The relation to the spin-aligned kicks of the single pulsars discussed here is not yet clear. Improved astrometry and PWN imaging can greatly refine this new probe of core collapse conditions.

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