2005

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Simon Johnston
Australia Telescope National Facility

G. Hobbs
Australia Telescope National Facility

S. Vigeland
Carleton College

M. Kramer
University of Manchester

J. M. Weisberg
Carleton College

See next page for additional authors

Article Author
Simon Johnston, G. Hobbs, S. Vigeland, M. Kramer, J. M. Weisberg, and A. G. Lyne

Chin. J. Astron. Astrophys. Vol. 6 (2006), **Suppl. 2**, 237–240
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Evidence for Alignment of the Rotation and Velocity Vectors in Pulsars

Simon Johnston[1] ⋆, G. Hobbs[1], S. Vigeland[2], M. Kramer[3], J. M. Weisberg[1,4,2] and A. G. Lyne[3]

[1] Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 1710, Australia
[2] Dept. of Physics and Astronomy, Carleton College, Northfield, MN 55057, USA
[3] University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire, SK11 9DL
[4] School of Physics, University of Sydney, NSW 2006, Australia

Abstract We review our case for strong observational evidence for a relationship between the direction of a pulsar's motion and its rotation axis. The information comes from calibrated polarization data for 20 pulsars which display linearly polarized emission from the pulse longitude at closest approach to the magnetic pole. Of these 20 pulsars, 10 show an offset in the angle between the velocity vector and the polarisation position angle which is either less than 10° or more than 80°, a fraction which is very unlikely by random chance. We believe that the bimodal nature of the distribution arises from the presence of orthogonal polarisation modes in the pulsar radio emission. In some cases this orthogonal ambiguity is resolved by observations at other wavelengths so that we conclude that the velocity vector and the rotation axis are aligned at birth. Strengthening the case is the fact that 4 of the 5 pulsars with ages less than 3 Myr show this relationship, including the Vela pulsar.

Key words: pulsars: general

1 INTRODUCTION

The velocities of pulsars are significantly larger than those of their progenitor (high-mass) stars. This implies that the birth process of pulsars also produces their high velocities and that the supernova or events soon thereafter must be asymmetrical. The mechanisms driving this asymmetry are far from clear. Many models, however, predict a correlation between the spin and velocity vectors in radio pulsars as a result (e.g. Tademaru & Harrison 1975; Spruit & Phinney 1998). The observational evidence for such a correlation using polarization techniques has been largely unconvincing (e.g. Anderson & Lyne 1983; Deshpande et al. 1999). More recently, however, observations at high energies have tended to support a correlation (Helfand et al. 2001; Ng & Romani 2004).

Given the recent results, the time was right to re-visit the question, from an observational point of view, of whether pulsar spin axes and velocity vectors align. In order to achieve this, we used proper motion measurements with small errors, high-quality polarization data with absolute position angles, and accurate rotation measures (RM) to remove Faraday rotation from the measured polarization PAs. Our intention was to make high-quality polarization observations on a number of pulsars for which good proper motion data exist (Hobbs et al. 2004; Hobbs et al. 2005).

2 OBSERVATIONS

The observations were carried out using the Parkes radio telescope from 2004 November 27 to 30. For the first two days we used the H-OH receiver at a central frequency of 1369 MHz with a bandwidth of 256 MHz. On the last two days we used the 10/50 cm receiver at a central frequency of 3100 MHz with

⋆ E-mail: `Simon.Johnston@csiro.au`

a bandwidth of 512 MHz. Both receivers have orthogonal linear feeds and also have a pulsed calibration signal which can be injected at a position angle of 45° to the two feed probes. A digital correlator was used which subdivided the bandwidth into 1024 frequency channels and provided all four Stokes' parameters. We also recorded 1024 phase bins per pulse period for each Stokes' parameter. The pulsars in our sample were observed twice for 20 minutes each time, with a feed rotation of 90° between observations. Prior to the observation of the pulsar a 3-min observation of the pulsed calibration signal was made. The data were written to disk in FITS format for subsequent off-line analysis.

Data analysis was carried out using the PSRCHIVE software package (Hotan et al. 2004). A full description of the data analysis and the critical issue of calibration can be found in Johnston et al. (2005).

3 RESULTS

A complete analysis of the polarization on the individual pulsars in the sample can be read in Johnston et al. (2005). Once the calibrated profiles have been obtained, a crucial step was to measure PA_0, the intrinsic position angle of polarization at ϕ_0, the longitude of closest approach of the line-of-sight to the magnetic pole. We took into account evidence such as profile symmetry, profile frequency evolution and the circular polarization in determining our choice.

In Table 1 we summarise our results for the 20 pulsars with measured values of PA_0. Columns 3 and 4 show the position angles of the velocity vector, PA_v, and of the linear polarisation, PA_0, at ϕ_0, the closest approach of the line-of-sight to the magnetic pole. Column 5 shows the offset, $|\Psi|$, between PA_v and PA_0 where Ψ is defined as

$$\Psi = \mathrm{PA}_v - \mathrm{PA}_0; \quad -90^\circ \leq \Psi \leq 90^\circ. \tag{1}$$

We force Ψ to lie between $-90°$and 90°by rotating PA_0 by $\pm 180°$ as necessary (note that any polarized PA has by nature a 180° ambiguity). The error in Ψ comes from a quadrature sum of the errors in PA_v and PA_0.

The table is divided into two sections. The top section lists those pulsars for which we find a good relationship between PA_0 and PA_v defined as where $|\Psi|$ is less than 10° or greater than 80°. There are 10 pulsars in this category. The second section lists the 10 pulsars for which there is no clear relation between PA_0 and PA_v i.e. where $|\Psi|$ lies between 10°and 80°.

Table 1 PA_v, PA_0 and their offset, $|\Psi|$, for our sample of 20 pulsars. The figure in brackets gives the error in the last digit(s).

Jname	Bname	PA_v (deg)	PA_0 (deg)	$\lvert\Psi\rvert$ (deg)
Pulsars with $\lvert\Psi\rvert < 10°$ or $\lvert\Psi\rvert > 80°$				
J0630−2834	B0628−28	294(3)	26(2)	88(4)
J0742−2822	B0740−28	278(5)	−81.7(1)	0(5)
J0820−1350	B0818−13	159(6)	65(2)	86(6)
J0835−4510	B0833−45	301.0(1)	36.8(1)	84.2(2)
J1239+2453	B1237+25	295.0(1)	−66(1)	1(1)
J1430−6623	B1426−66	236(9)	−28.5(7)	85(9)
J1453−6413	B1449−64	217(3)	−56.9(4)	86(3)
J1709−1640	B1706−16	192(16)	15(2)	3(16)
J1740+1311	B1737+13	227(6)	−46(4)	87(7)
J1844+1454	B1842+14	36(15)	−52(2)	88(15)
Pulsars with $10° < \lvert\Psi\rvert < 80°$				
J0525+1115	B0523+11	132(16)	−65(4)	17(16)
J0953+0755	B0950+08	355.9(2)	14.9(1)	19.0(2)
J1136+1551	B1133+16	348.6(1)	−78(2)	67(2)
J1456−6843	B1451−68	252.7(6)	−31.6(6)	76(1)
J1645−0317	B1642−03	353(3)	56(4)	63(5)
J1900−2600	B1857−26	202.8(7)	−43(2)	66(2)
J1913−0440	B1911−04	166(11)	−68(2)	54(11)
J1921+2153	B1919+21	34(12)	−35(2)	69(12)
J1932+1059	B1929+10	65.2(2)	−11.3(1)	76.5(2)
J1935+1616	B1933+16	176(1)	10.1(7)	14(1)

4 DISCUSSION

The top left panel of Figure 1 shows the observed distribution of $|\Psi|$ as a histogram for the 20 pulsars for which we have measured $|\Psi|$. If we assume that PA$_v$ and PA$_0$ are unrelated then the expectation is that the offsets between them should be randomly distributed in the range 0° to 90°. This is shown by the dashed line on the bottom left panel of Figure 1. The probability of having 7 objects in the top bin, as observed, is very small, 2.6×10^{-4}. A Kolmogorov-Smirnov (KS) test rules out a random distribution at the 94 per cent confidence level. Clearly our measurements show that PA$_v$ and PA$_0$ must be related in some fashion. Consider now some possible types of relationship between the observables PA$_v$ and PA$_0$; namely that they are either parallel or perpendicular. To start, we ignore the confounding factor of the orthogonal emission so that PA$_0$=PA$_r$.

The case where PA$_v$ is parallel to PA$_r$ is a simple one - all the pulsars should fall in the first bin of the histogram. However, measurement errors will broaden this distribution as shown by the solid line on the bottom left panel of Figure 1. This also does not represent the data; the KS test rules out that these distributions are the same at greater than the 99.9 per cent confidence limit.

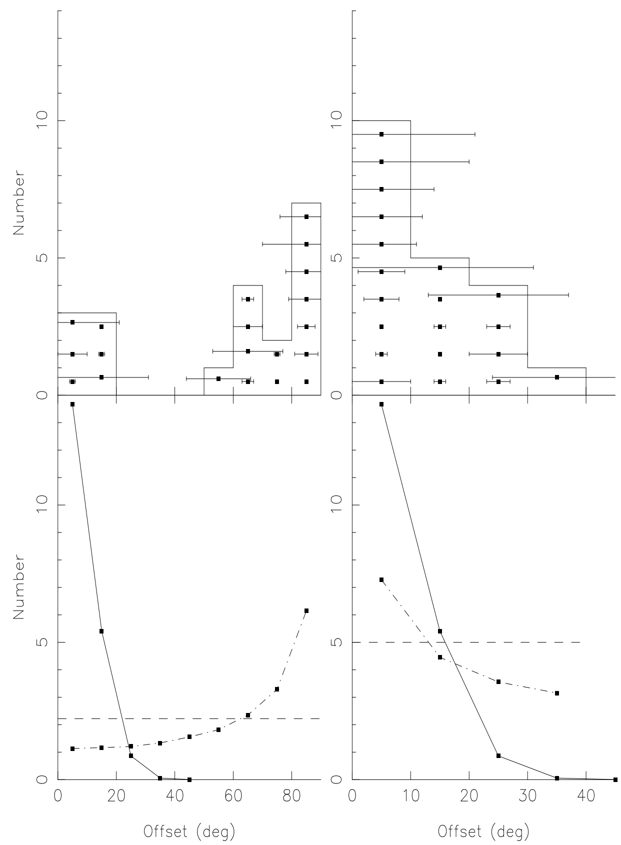

Fig. 1 Histograms of observed (top) and simulated (bottom) values of $|\Psi|$. The left hand panels ignore the possibility of orthogonal mode emission so that PA$_0$=PA$_r$. The right hand panels include this possibility which then reduces the maximum offset to 45°. Also included is measurement uncertainties in the data with typical value of 10°. Top panels: Observed values of $|\Psi|$ in bins of 10° for 20 pulsars. Bottom panels: Simulated histogram for PA$_r$ parallel to PA$_v$ (thick line), uncorrelated PA$_r$ and PA$_v$ (dashed line) and PA$_r$ perpendicular to PA$_v$ (dot-dash line).

The case where PA_v is perpendicular to PA_r is slightly more complex. In this case, the projection effects from the true 3-D vector to the 2-D sky vector will cause the (observed) offset between PA_v and PA_0 to spread away from 90°. This is shown by the dash-dot line on the bottom left panel of Figure 1 The result looks remarkably similar to the real data apart from the excess in the first two bins. The KS test here does *not* rule out the possibility that the distributions are the same.

However, the statistics do not take into account the possible presence of orthogonal mode emission which complicates the underlying relationship between PA_r and PA_0. Either PA_r is parallel to PA_0 if the pulsar is emitting in the 'normal' mode or PA_r is perpendicular to PA_0 if the pulsar emission is in the 'orthogonal mode'. Simultaneously allowing for either possibility serves to reduce the maximum offset between PA_0 and PA_v to only 45°. The right hand panel of Figure 1 shows the data and the simulations for such a scenario. The observed histogram appears somewhat broader than the simulation but this may be caused by the possible sources of contamination discussed below. In any case, the results show that we can confidently rule out that PA_r and PA_v are unrelated (dashed line) at the 98 per cent confidence limit. The KS test also rules out the case where PA_r is perpendicular to PA_v (dash-dot line) at greater than the 99 per cent confidence limit but does *not* rule out that the case where PA_r is parallel to PA_v (solid line) is the same as the observed distribution.

5 SUMMARY

We have observed 20 pulsars at both 1369 and 3100 MHz. Careful polarization calibration, including accurate RM determination, has enabled us to compute the PA of the polarized radiation at the pulsar to within an accuracy of 2°–3°. We have used all available information to deduce ϕ_0, the longitude of the closest approach to the magnetic pole of the star. We then compared the PA of the radiation at this longitude, which is related to the position angle of the axis of rotation, with the velocity vector derived from proper motion measurements. We find a clear relationship between the velocity vector and the rotation axis. The presence of orthogonal modes in pulsar emission makes it difficult to determine whether the velocity vector is parallel to the rotation axis or perpendicular to it. However, additional information from the optical and X-ray bands for PSR B0656+14, the Crab and Vela pulsars allows us to break this ambiguity: the velocity vector is parallel to the rotation axis and many pulsars emit linear polarisation with PA predominantly perpendicular to the magnetic field lines.

Acknowledgements The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by the CSIRO. SV and JMW acknowledge financial support from U.S. National Science Foundation grant AST 0406832.

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