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FURTHER EVIDENCE FOR ALIGNMENT OF THE ROTATION AND VELOCITY VECTORS IN PULSARS

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ABSTRACT

We re-examine the evidence for alignment of the proper motion and fiducial polarization-angle directions in radio pulsars given by Johnston et al., and we find that the case is probably stronger than this paper asserts. Other alignments are examined using the published literature and recent Arecibo polarimetry, providing an enlarged case that pulsar rotation axis and supernovae "kick" directions are aligned or orthogonal at birth. Pulsars' "orthogonal" polarization modes complicate fixing the orientation of such "kicks," but we note that determining the absolute geometry of the polarization modes is a key objective for understanding the physical origins of pulsar emission.

Subject headings: pulsars: general — radiation mechanisms: nonthermal — techniques: polarimetric

1. INTRODUCTION

Pulsars have significantly larger space velocities that their (high-mass) progenitors, and apparently these are due to natal "kicks" delivered by asymmetric supernovae events. Investigators have consequently wondered how a pulsar's rotation is oriented with respect to its kick and whether any remnant of its birth dynamics can be discerned.

In a recent paper, Johnston et al. (2005) provide strong evidence for alignment of the rotation and velocity vectors of many pulsars in the sky. Their work is founded on the pulsar-timing analyses of Hobbs et al. (2005), who provide a compendium of proper motion (PM) directions for 233 pulsars from both VLBI and pulse-arrival-timing analyses. Heretofore, timing-derived PMs have often differed from those determined by VLBI and have thus been unreliable of themselves, because of "timing noise." Hobbs et al., however, show fundamentally that reliable pulse-timing PMs can be determined using their new technique of "whitening." Thus they are able to estimate the PMs of a new population of pulsars far too weak for interferometric methods.

Johnston et al. discuss some previous efforts to demonstrate alignment between pulsar-rotation and PM directions. They also review in detail the theoretical debate which has raged over three decades regarding the type of alignment that might be expected and its significance. In particular, they discuss the large space velocities of pulsars and how these may be related to asymmetric supernova kicks. While these questions are very important astrophysically, we will not pursue them further here; instead we refer interested readers to this paper's excellent summaries.

Rather, we focus here on the significance of the alignment for pulsar emission studies. Johnston et al. note that pulsars typically emit radiation in two "orthogonal polarization modes" (OPMs), and that this complicates their alignment analysis by adding a further ambiguity of 90°. They do not mention the primary importance of understanding how these OPMs are oriented with respect to the emission geometry. Pulsarists have come to speak blithely about the OPMs as reflecting polarization orientations both parallel and perpendicular to the projected magnetic field direction. However, there are yet only a handful of cases in which we can be sure about the orientation of a particular mode in a particular pulsar.

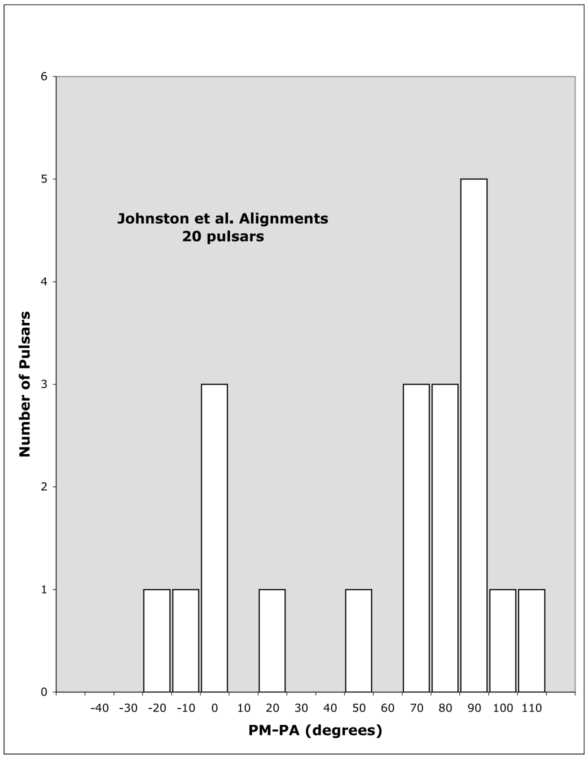
The significance of this ignorance regarding the fundamental OPM orientation is sweeping. Clearly, every attempt to account for the physical circumstances of pulsar emission points to different properties for radiation polarized parallel to or orthogonal to the plane in which the emitting charges move. We simply are not in a position to assess the origins of pulsar emission unless we can fix this geometry. Also, several different groups have in recent years attempted to understand possible propagation effects in the pulsar magnetosphere (e.g., Barnard & Arons 1986; Petrova & Lyubarskii 2000; Weltevrede et al. 2003), and there can be little specificity to the discussions or attempts to test them without the ability to relate modal characteristics to propagation geometry.

In the remainder of this paper, we first assess the alignments given by Johnston et al. and argue that their case is probably stronger than they submit. We then extend this paper's analysis to a larger population of pulsars using mostly published sources. Finally, we discuss in more detail how the demonstrated alignment can be used to better understand the nature of pulsar emission, and in turn how this understanding can help unravel how pulsars are born and apparently "kicked."

2. THE JOHNSTON ET AL. PM-P.A. POPULATION

Johnson et al. (2005; hereafter JHVKWL) discuss a population of 25 mostly young, southern pulsars, whose proper motion directions on the sky P.A.$_v$ (defined counterclockwise from north like polarization angles) are very well determined either interferometrically or by timing using the Hobbs et al. (2005) new whitening method. Of these, they find 10 for which the fiducial polarization angle P.A.$_0$ is aligned or orthogonal within 10°—that is, $|\Psi| < 10°$, where Ψ = P.A.$_v$ − P.A.$_0$. Six others may be so aligned within some 20°, four show misalignments >20°, and P.A.$_0$ could not be computed for the five remaining. Figure 1 (*top*) gives a histogram of these alignments. If one considers only the younger stars in the group, the evidence for alignment is stronger. A greater portion of the pulsars show a Ψ near 90° rather than 0°, suggesting that it often may be the OPM perpendicular to the projected magnetic field direction which is dominant. These results seem strong and interesting. The question regarding alignment between P.A.$_v$ and P.A.$_0$ has a long history, as we will relate further below. However, the Hobbs et al. work on timing PMs seems finally to have provided a foundation on which a number of definite alignments can be vetted.

Nonetheless, it is useful to examine the JHVKWL population in detail, as some of the specified alignments are stronger than others, several are incorrect, and several additional P.A.$_0$ values



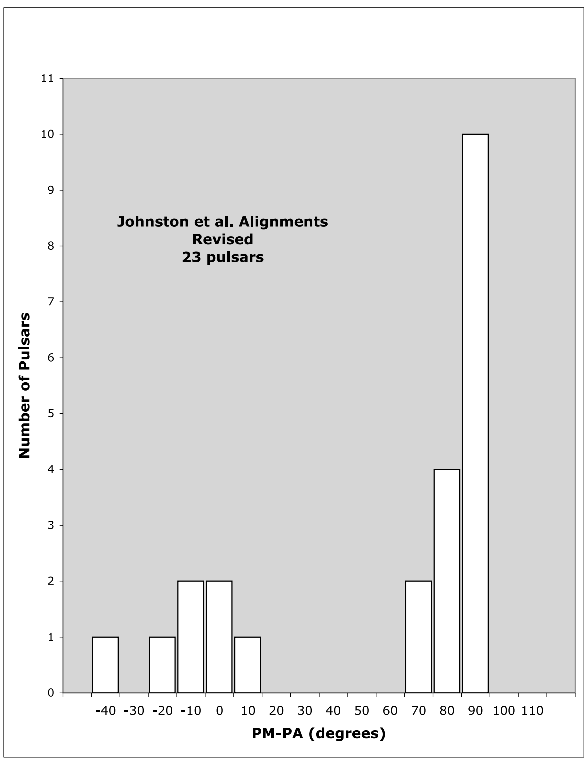


Fig. 1.—Histograms of Ψ, the difference angle between the proper-motion direction P.A.$_v$ and the fiducial polarization angle P.A.$_0$, drawn from a population of 25 pulsars studied by Johnston et al. (2005). *Top*: Published analysis (but with Ψ = P.A.$_v$ − P.A.$_0$ now no longer constrained to fall between 0° and 90°). *Bottom*: Results of the revised analysis. The errors in Ψ here are typically 5°, so we see both alignments and misalignments, the latter mostly of stars with large spin-down ages. A case in point is B1237+25, with a Ψ of −37° in the revised analysis.

can be estimated. The revised and reexamined values are given in Table 1 and plotted in Figure 1 (*bottom*). Those that have been significantly revised are indicated with table footnotes, which briefly outline the reasoning behind the revision. All the remaining values are recomputed as in JHVKWL. New P.A.$_0$ estimates are tabulated for pulsars B0559−05, B0919+06, and B1706−44; revised values are given for B0523+11, B1237+25, B1451−68, B1642−03, B1857−26, and B1911−04; and B1919+21's value is culled as unreliable. Our revisions were based on a detailed study of each pulsar's polarized profile, and in particular its frequency evolution. As a majority of the 25 stars have profiles showing the effects of substantial OPM depolarization, we tried to determine the P.A. of the brighter OPM at the fiducial longitude. Detailed studies of particular pulsars (e.g., B2016+28 by Ramachandran et al. 2004) assist us in understanding how to do this. Indeed, we tried to determine the P.A. of the brighter OPM at the central longitude, which reflected an overall rotating-vector model (RVM) traverse (Radhakrishnan & Cooke 1969; Komesaroff 1970).

The revised results in Table 1 and Figure 1 (*bottom*) indicate an even stronger tendency for alignment. Of the 22 stars, 13 show a P.A.$_v$−P.A.$_0$ difference near 90° ± 5°, and five have a Ψ near 0° ± 15°. Of the four remaining, two (B0950+08 and B1929+10) can perhaps be disregarded because their fiducial longitude is determined only by P.A. behavior and reflects no clear profile symmetry point. The final two pulsars however, B1133+16 and B1237+25, appear to have misaligned PM and P.A. directions that are well determined; both stars are old (log τ, where τ is the spin-down age in years, tabulated for each star), and perhaps the latter's position near the north galactic pole contributes to its anomalous alignment.

Of the 18 stars with Ψ values near 0° or 90°, most have roughly comparable OPM contributions, so little can be inferred from whether their alignment is parallel or perpendicular. Only those few having large linear polarization tell us much about the OPMs. Three such pulsars B0628−28, B0740−28, and B0833−45 are almost completely linearly polarized; one B0740−28 has a Ψ near 0°, and thus its radiation appears to be aligned with the projected magnetic field ($\boldsymbol{B}$) direction, whereas the other two have Ψ near 90° and their emission seems to be orthogonal to $\boldsymbol{B}$. In B0833−45's case, this OPM orthogonality at radio wavelengths reiterates what is found in the star's X-ray radiation (Helfand et al. 2001).

3. OTHER PM-P.A. MEASUREMENTS

Ψ values can be computed for a further population of some 25 pulsars from the Hobbs et al. PM values and other absolute P.A. determinations. Accurate values for both B0736−40 and B0835−41 were determined by Karastergiou & Johnston (2006), and five additional less accurate (but still useful) P.A. measurements can be gleaned from Xilouris et al. (1991). These are listed in Table 2 in the same manner as the stars in the previous table. For these values and those which follow, we ignore the effects of ionospheric Faraday rotation as being too small to be significant.

A larger number of absolute P.A. values determined at 18 cm and above can be found in Morris et al. (1979) that draw on the polarimetry that was subsequently published as Morris et al. (1981). We have examined these values carefully, compared the latter polarimetry to more recent work and observations at different frequencies (e.g., Gould & Lyne 1998, hereafter GL), and recomputed each of them using current rotation measure (RM) values and errors from the ATNF Pulsar Catalog. In most cases,

TABLE 1

Johnson et al. Measurements

Pulsar	$\log\tau$ (yr)	P.A.$_v$ (deg)	P.A.$_0$ (deg)	Ψ (deg)
B0523+11[a]	7.88	132(5)	−55(8)	7(9)
B0559−05[b]	6.68	194(8)	−75(20)?	89(22)?
B0628−28	6.44	294(2)	26(2)	88(3)
B0740−28[c]	5.20	278(4)	−82(1)	0(4)
B0818−13	6.97	159(4)	65(2)	94(4)
B0833−45	4.05	301(0)	37(1)	84(1)
B0906−17	6.98	167(2)	. . .	. . .
B0919+06[d]	5.70	12(0)	−77(10)	89(10)
B0950+08	7.24	356(0)	15(1)	−19(1)
B1133+16	6.70	349(0)	−78(2)	67(2)
B1237+25[e]	7.36	295(0)	−28(4)	−37(4)
B1426−66	6.65	236(5)	−29(1)	84(5)
B1449−64	6.02	217(2)	−57(0)	94(2)
B1451−68[f]	7.63	253(0)	−22(4)	95(4)
B1642−03[g]	6.54	353(3)	−1(8)	−6(8)
B1706−16	6.21	192(4)	15(2)	−3(4)
B1706−44[h]	4.24	160(10)	71(10)	89(14)
B1737+13	6.94	228(6)	−46(4)	94(7)
B1842+14	6.50	36(8)	−52(2)	88(9)
B1857−26[i]	7.68	203(0)	−69(10)	92(10)
B1911−04[j]	6.51	166(5)	−99(8)	85(9)
B1919+21[k]	7.20	34(7)	. . .	. . .
B1929+10	6.49	65(0)	−11(0)	77(0)
B1933+16	5.98	176(1)	10(1)	−14(1)
B1937−26	6.82	130(10)	. . .	. . .

[a] The fiducial longitude should be taken closer to the center of the profile; see Weisberg et al. (1999) or Hankins & Rankin (2007).

[b] The GL 1420 MHz profile suggests that the P.A. connects negatively through the depolarized center of the profile, making the P.A. at 0° near −75°.

[c] Some other high-frequency observations (e.g., GL and that of von Hoensbroech at 1.41 GHz) show a strong steepening of the P.A. traverse under the trailing edge of the profile, suggesting that the fiducial longitude may fall some 10° later than JHVKWL's fit indicates. This could simply point to a Ψ value near 0°.

[d] This star's profile extends far out onto its leading edge, and the fiducial longitude should be taken 6°–8° prior to the peak; see Rankin et al. (2006).

[e] The fiducial P.A. lies 90° away from the "flat" values under the conal components; see Srostlik & Rankin (2005).

[f] Most published profiles suggest that the P.A. is distorted negatively in the region where the fiducial longitude is taken by some 10°; see McCulloch et al. (1978), Manchester et al. (1980), and Hamilton et al. (1977).

[g] The low polarization and differences between various published observations suggest significant OPM distortion of the traverse near the center of the profile. Some of the clearest observations (e.g., Manchester [1971] at 410 MHz; von Hoensbroech [1999] at 4.85 GHz) suggest a negative P.A. gradient that would connect the leading and trailing extrema of the paper's profile, bringing the P.A. at the fiducial longitude into close agreement with P.A.$_v$.

[h] The pulsar's unusually complete linear polarization is suggestive of that of B0656+14 (e.g., HR; Weltevrede et al. 2006b) or B0833−45, where again the P.A. sweep suggests that the inflection point is on the trailing edge of the profile (Everett & Weisberg 2001).

[i] The P.A. "kink" at about −3° longitude cannot be geometrical, so is likely modal in origin. Thus, P.A.$_0$ should be estimated by extrapolating the steep initial P.A. traverse toward the fiducial longitude; see GL.

[j] This is a difficult call because most published profiles reveal little about the pulsar's component structure. However, the profiles of both this paper and von Hoensbroech's (1999) 4.85 GHz observation indicate a triple form. This and the weak circular polarization signature suggest that the fiducial longitude should be taken near −3° longitude.

[k] The P.A. of this first Cambridge pulsar is dominated by OPM effects and is not understood well enough for this purpose.

TABLE 2

Other PM-P.A. Measurements

Pulsar	$\log\tau$ (yr)	P.A.$_v$ (deg)	P.A.$_0$ (deg)	Ψ (deg)
Karastergiou & Johnston (2006)				
B0736−40	6.57	313(5)	−44(5)	−3(7)
B0835−41	6.53	187(6)	−83(5)	90(8)
Xilouris et al. (1991)				
B0136+57	5.61	210(13)	32(17)	−2(21)
B0450+55	6.36	108(2)	−87(16)	16(16)
B1905+39	7.56	45(5)	38(7)	7(9)
B2310+42	7.69	72(10)	20(15)	52(31)
B2351+61	5.96	75(5)	−1(18)	76(19)
Morris et al. (1979)/Morris et al. (1981)				
B0301+19	7.23	171(10)	6(3)	−15(11)
B0329+54	6.74	119(1)	20(4)	99(4)
B0355+54	5.75	48(1)	−41(4)	89(5)
B0540+23	5.40	58(19)	−44(3)	101(19)
B0809+74	8.09	151(0)	−27(5)	−2(5)
B0823+26	6.69	146(1)	48(3)	98(3)
B1508+55	6.37	−130(0)	5(4)	45(4)
B1946+35[a]	6.21	−93(3)	−74(15)	−19(15)
B2016+28[b]	7.78	−157(2)	−76(6)	99(7)
B2020+28	6.46	−169(1)	−4(3)	15(3)
B2021+51	6.44	−24(1)	29(2)	−53(2)
B2045−16	6.45	92(2)	−3(5)	95(5)
B2154+40	6.85	81(3)	95(5)	−14(6)
B2217+47[c]	6.49	−158(13)	98(8)	−64(16)
This paper				
J0538+2817[d]	5.79	328(4)	−38(10)	6(11)
B0656+14[e]	5.05	93(0)	−83(3)	−4(3)
B2303+30[f]	6.94	174(6)	−8(10)	2(12)

[a] This value benefits from a better determined RM value as well as slightly better determined fiducial angle measurements.

[b] The P.A. has a 90° "flip" just prior to the profile peak (e.g., Ramachandran et al. 2004); the leading P.A. slope is extrapolated here to the profile peak.

[c] P.A. values remeasured from Morris et al. (1981).

[d] The fiducial longitude was taken near the trailing edge of the 1525 MHz profile near the apparent inflection point. RM taken as +41.7 ± 0.4 rad m^2.

[e] The fiducial longitude was taken 15° longitude after the profile peak, as indicated by the fitting of Everett & Weisberg (2001); see their Fig. 5. RM taken as −75.5 ± 4.0 rad m^2.

[f] The fiducial longitude was taken just after the profile peak; RM +23.5 ± 0.4 rad m^2.

we found that these early P.A.$_0$ values were well determined within their errors, but reliable PMs were then available for only 12 of them. Thus only in a few cases did we find cause to modify the earlier values, and these are again shown with notes indicating the motivation behind the revision.

Finally, we have been able to add a few absolute P.A. determinations from our own recent L-band observations at the Arecibo Observatory (AO). Using a correlated calibration signal with a known relationship to the parallactic angle, these observations can easily be calibrated in an absolute manner. Again, we ignore any ionospheric Faraday rotation as being insignificant for our current purposes. These three P.A.$_0$ values were computed from the average-polarization profiles in Figure 2 (plotted with respect to the estimated fiducial longitude) and then derotated in the manner of Morris et al. (1979).

One other study devoted to PM-P.A. determinations is that of Deshpande et al. (1999), but unfortunately their method of determining P.A.$_0$ values is not described in detail. Their source list is weighted with older pulsars, and this together with some inaccurate P.A.$_v$ values apparently prevented them from finding a PM-P.A. correlation.

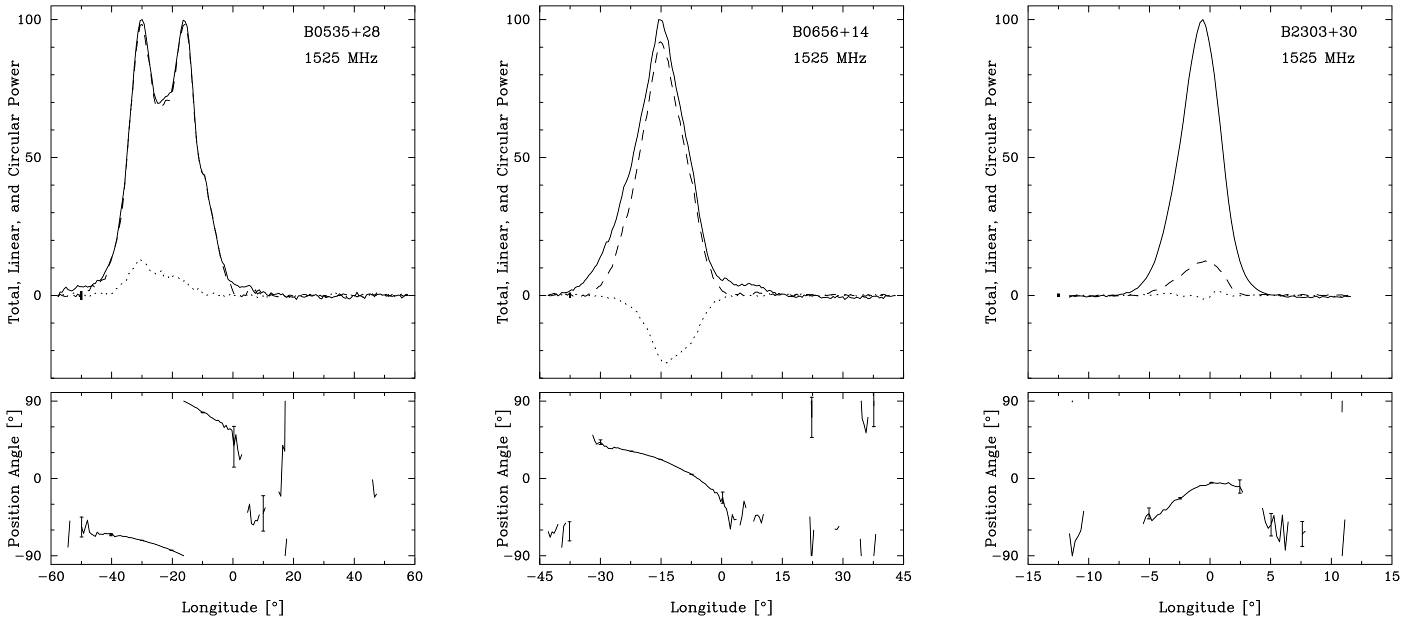


FIG. 2.—Aggregate polarization profiles of pulsars J0538+2817 (B0535+28), B0656+14, and B2303+30 at 1525 MHz. *Top*: Total intensity (Stokes *I*; *solid curve*), the total linear (Stokes *L*; *dashed curve*), and the circular polarization (Stokes *V*; *dotted curve*). *Bottom*: P.A. with 2 σ error bars. The longitude origin is taken at the estimated fiducial longitude.

A histogram corresponding to the full set of 46 Ψ values is given in Figure 3. It indicates a preponderance of perpendicular and parallel alignments, as well as a significant number of misalignments. The increased errors are such that many of the values falling in the bins adjacent to 0° or 90° can be regarded as alignments and the others not.

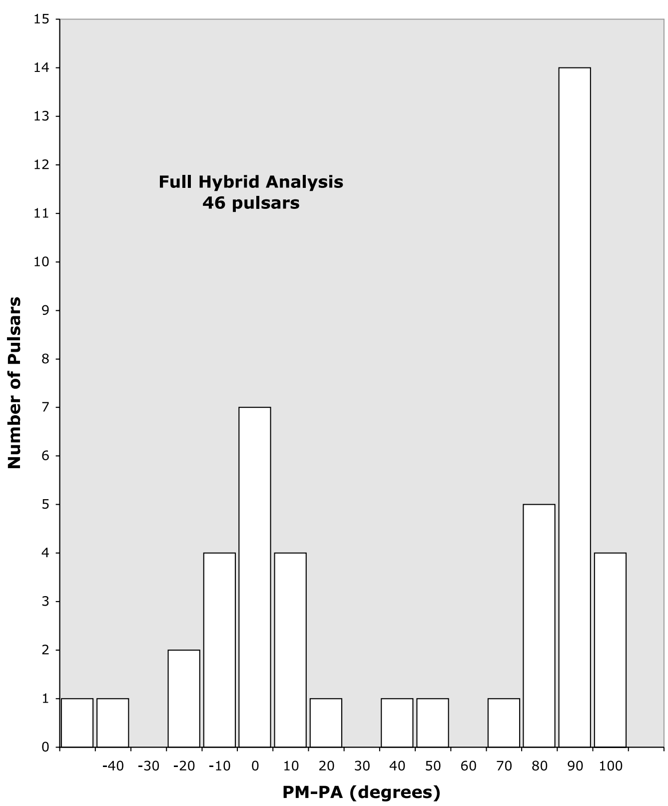


FIG. 3.—Histograms of the alignment angle Ψ as in Fig. 1. Here all the values are included, those of Johnston et al. as revised in Fig. 1 (*bottom*), as well as the values determined from Karastergiou & Johnston (2006), Xilouris et al. (1991), Morris et al. (1979), and three in this paper. The errors in some of the latter values are larger, typically 10°, and this in part explains the larger spread around 0° and 90°.

4. THE OPM AMBIGUITY

These alignments are intriguing, but so far prove little. First, as Johnston et al. point out at some length, supernova theories differ about whether the kick is parallel or perpendicular to the neutron-star rotation axis $\mathbf{\Omega}$. Second, the fiducial P.A.s refer to one of the two currently indistinguishable OPMs, introducing a second 90° ambiguity. The particular OPM could be identified, as they characteristically exhibit distinct behaviors (e.g., especially under outer cones; see Rankin & Ramachandran 2003), but so far they have not been, largely because pulsar astronomers have had little hope of determining their orientation relative to the projected magnetic field $\boldsymbol{B}$.

Only for a few of these pulsars do we have some further information, this for stars that are also X-ray pulsars. The early example was the Vela pulsar, B0833−45, where X-ray images showed arcs from which it could be inferred that its rotation-axis orientation $\mathbf{\Omega}$ lies parallel to its PM direction $\boldsymbol{P.A.}_v$ (Helfand et al. 2001; Radhakrishnan & Deshpande 2001). In addition, this pulsar's radio emission is highly linearly polarized and thus nearly unimodal, so there is no OPM ambiguity. Shockingly, the Ψ value was almost 90°, indicating that the pulsar's main emission is in the mode polarized orthogonally to the $\boldsymbol{B}$ plane. Johnston et al. confirm this orthogonal Ψ for the radio emission.

Two other pulsars with X-ray emission are B0656+14 and J0538+2817. The former has a PM orientation of 93° (Brisken et al. 2003) and a 98° fiducial P.A. value using the central longitude determined by the RVM fitting analysis of Everett & Weisberg (2001). This makes Ψ some 5° and indicates that this star's primary emission is parallel to projected $\boldsymbol{B}$ (see also Ng & Romani 2004). We confirm this alignment using recent AO observations (see Table 2), and our other studies reiterate this star's great interest in terms of its giant pulses, and the unusual character of its weak radiation and unimodal linear polarization (Weltevrede et al. 2006a, 2006b). For J0538+2817, Ng & Romani's analysis of its X-ray torus implies a Ψ value near 0°, a circumstance we have again been able to confirm with recent AO observations.

5. DISCUSSION

In short, the problems of understanding the absolute OPM geometry and the orientation of supernovae kicks are closely coupled with each other. Insight into one provides a basis for resolving the other. In only a handful of cases can the latter be directly studied. The absolute OPM geometry, by contrast, is much more tractable. Most radio pulsars exhibit the phenomenon, and we already know that it shows a great deal of regularity from pulsar to pulsar (e.g., Rankin & Ramachandran 2003).

Reference to the OPMs as the primary/secondary polarization mode (PPM/SPM) will no longer do. We must attempt wherever possible to determine which mode represents the ordinary (O) or extraordinary (X) propagation mode. This may now be possible for a considerable number of the brighter pulsars whose OPMs can be clearly distinguished. In pulsar B0329+54, for example, Mitra et al. (2007) found that its perpendicular Ψ value was associated with its brighter (former PPM) OPM. The PPM could then be associated with the X propagation mode as long as P.A.$_v$ was aligned with $\boldsymbol{\Omega}$. It is the O mode which is subject to refraction, and this refraction is expected to be outward—i.e., away from the magnetic axis (Barnard & Arons 1986; Lyubarskii & Petrova 1998; Weltevrede et al. 2003). Such outward refraction of this putative O-mode emission is seen prominently in the strong outer conal components of B0329+54, and this in turn supports the premise that the SN kick was indeed parallel to $\boldsymbol{\Omega}$.

Some of the older pulsars in the tables above showed clear misalignments between their P.A.$_v$ and P.A.$_0$ directions. One of the best examples was B1508+55, with a well-determined Ψ value of 45 ± 4. We note that such cases appear very interesting in their own right. Once presumably aligned, they presumably have gradually become misaligned, and this dynamical history can be traced as Chatterjee et al. (2005) demonstrate. Such analyses for other older pulsars can help to identify their OPM orientation as well as establish the location and direction of their supernovae kicks.

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