THE VELA PULSAR’S PROPER MOTION AND PARALLAX DERIVED FROM VLBI OBSERVATIONS

R. Dodson, D. Legge, J. E. Reynolds, and P. M. McCulloch

ABSTRACT

The Vela pulsar is the brightest pulsar at radio wavelengths. It was the object that told us (via its glitching) that pulsars were solid rotating bodies not oscillating ones. Along with the Crab pulsar, is it the source of many of the models of pulsar behavior. Therefore it is of vital importance to know how far away it is and its origin. The proper motion and parallax for the Vela pulsar have been derived from 2.3 and 8.4 GHz very long baseline interferometry (VLBI) observations. The data span 6.8 years and consist of 11 epochs. We find a proper motion of \( \mu_\cos \delta = -49.68 \pm 0.06 \) mas yr\(^{-1} \) and a parallax of 3.5 \pm 0.2 mas, which is equivalent to a distance of 287 \pm 19 pc. When we subtract out the Galactic rotation and solar peculiar velocity, we find \( \mu_\alpha = 45 \pm 1.3 \) mas yr\(^{-1} \) with a position angle of 301\(^\circ\) \pm 1.8 which implies that the proper motion has a small but significant offset from the X-ray nebula’s symmetry axis.

Subject headings: astrometry — pulsars: individual (Vela pulsar) — stars: neutron — techniques: high angular resolution

1. INTRODUCTION

The Vela pulsar is an archetypal young pulsar. It was the first to be observed to glitch (Radhakrishnan & Manchester 1969) and was always associated with the large Vela supernova remnant (SNR). Since Vela is a young pulsar and displays a significant amount of glitching behavior and timing noise (Cordes et al. 1988), no accurate proper-motion measurements from timing observations have been possible; it is only through direct proper-motion observations that we can trace its path on the sky. This is true of nearly all young pulsars, which are usually the most interesting. These have, for example, the possibility of discovering the associated birth SNR.

The first accurate measurements of Vela’s proper motion were produced using the Parkes-Tidbinbilla Interferometer (PTI) (Bailes et al. 1989). This 275 km baseline at 1.6 GHz gave a resolution of 140 mas. This detected the proper motion and thus, by extrapolation, the birth site. We have extended this work to allow the third dimension to be derived via the parallax. Measurement of relative motion on milliarcsecond scales is a challenging task, and several attempts have been made, with various success. Previous observations have been made with ground-based optical observations, with connected radio interferometers (PTI and the VLA) and the Hubble Space Telescope (HST). We now present results from the Australian Long Baseline Array (LBA).

We have 18 observations of the position and can provide the most accurate measurements of parallax and proper motion. Recent measurements of the position of Vela against a number of background sources has been reported by De Luca et al. (2000) and Caraveo et al. (2001). Our more accurate values, using completely independent methods, are compared with theirs, confirming the parallax values. Differences in the derivation of the proper motion are discussed. We find good agreement if we account for the probable Galactic rotation of the reference stars.

The distance to the Vela pulsar was originally estimated from the SNR distance by comparison to the Cygnus Loop and IC 443. This led to an estimate of 500 pc (Milne 1968); however, it has long been argued that this is an overestimate. Our results have been foreshadowed by the predictions in several papers that have made the case for the distance to the Vela pulsar to be drastically reduced. Analysis of X-ray observations of the pulsar made with ROSAT (Page et al. 1996) and Chandra (Pavlov et al. 2001b), and of the SNR also with ROSAT (Bocchino et al. 1999) and with optical absorption (Jenkins & Wallerstein 1995; Cha et al. 1999), have all suggested that the original distance estimate should perhaps be halved. All of these results, however, are to some extent model dependent and therefore doubt has existed over their accuracy.

Furthermore, our results allow the testing of the prediction of Spruit & Phinney (1998) on the alignment of the spin axes of pulsars with their proper-motion vector. The spin axis can be derived from the high-resolution images from Chandra. These allow the symmetry, and thus presumably the spin, axes to be directly discerned. Only two cases have been tested so far, the Crab (Caraveo & Mignani 1999) and Vela. The extra accuracy we can provide refines the conclusion reached by Pavlov et al. (2000) and Helfand et al. (2001) for the Vela alignment. A note of caution should be raised in that an alternative explanation for the X-ray nebula around Vela has been put forward (Radhakrishnan & Deshpande 2001) that explains the structure in terms of the particle beam from the polar cap. This description requires that only the projected spin axis lies along the proper-motion axis. If the model of Spruit & Phinney (1998) is correct, any misalignment of the axes allows us to estimate the timescale of the impulse in terms of the initial rotation period, a value of great importance to understanding the core collapse. The accuracy, therefore, of the alignment of the axes is of great theoretical importance.
2. OBSERVATIONS AND DATA REDUCTION

The LBA array is an Australian national facility and is usually made up of six telescopes, three operated by the CSIRO (Australian Telescope Compact Array, Parkes, and Mopra), two by the University of Tasmania (Hobart and Ceduna), and one in South Africa operated by the Hartebeesthoek Radio Astronomical Observatory. In addition, Deep Space Network telescopes at Tidbinbilla are often included. The observations reported here are between the Tidbinbilla 70 m and the Hobart 26 m antennae, a baseline of 832 km and at two 16 MHz wide frequencies: 2.29 and 8.425 GHz. In addition, there was one observation with the Australian array, 32 MHz centered on 8.417 GHz, although only the Hobart to Tidbinbilla data was directly used for the results in this paper. Details of all the telescopes and their parameters are available via the Australian Telescope National Facility (ATNF) Web site. All data were recorded using beam switching on a ∼5 minute cycle, using the extragalactic phase-reference source Vela-G

\[
(\alpha = 08^h33^m22^s31563, \, \delta = -44^\circ41'38''71463 \, [J2000])
\]

Vela-G is part of the Radio Reference Frame and was an International Celestial Reference Frame (ICRF) candidate source (Ma et al. 1998).

The first three epochs observations of the Vela pulsar (Table 1) were made using Mark III/IIIA very long baseline interferometry (VLBI) recording systems, using recording mode B, which provides 14 contiguous frequency channels each 2 MHz wide in right-hand circular polarization at 2.3 GHz. Sampling was 1 bit (two-level) for all data. None of the Mark III/IIIA observations used the pulsar gating nor binning described later. Only the Mark III positions were available for this analysis. The Mark III/IIIA VLBI data were processed at the Washington Mark IIIA correlator, located at the US Naval Observatory (USNO). Phase modulations were applied with the CALC 6.0 package, supplying the best possible values of station locations, clock models, and Earth orientation parameters. The raw data were then exported in “FRNGX” format and further analyzed following the phase-referencing technique described by Lestrade et al. (1990) and using the software SPRINT, developed by J.-F. Lestrade.

The S2 recordings system and correlator for LBA were commissioned in the mid-1990s and observations were transferred to this system.

In all observations, two separate frequency channels of 16 MHz bandwidth were recorded with 2 bit (four-level) sampling. Most of the observations of the Vela pulsar using the S2 system were made with one 16 MHz channel at 2.3 GHz (13 cm) and one at 8.4 GHz (3 cm), taking advantage of the dual 13/3 cm (right-circular polarization) receivers at both Hobart and Tidbinbilla. In the final epoch, using the whole LBA at 8.4 GHz, two 16 MHz channels were used to form one contiguous 32 MHz band. Full details can be found in Legge (2002).

The S2 correlator is operated by ATNF at its Marsfield headquarters in Sydney. This wonderfully flexible device can pulsar bin (as opposed to pulsar gate) with 32 bins across the Vela pulsar’s period, thereby limiting the dispersion to individual channels rather than the entire band. There is, however, no significant dispersion at these observing frequencies for Vela. We used only those pulsar bins containing significant flux, usually one or two out of 32, gaining up to a factor of 5.6 in signal-to-noise ratio.

Post correlation, the data were fringe fitted at the nominal pulsar position using the binned flux, with 10 minute solution interval in AIPS, and then exported. Further processing was done with DIFMAP (Shepherd 1997). The data were flagged and averaged to generate a statistical weight. The offsets of Vela-G from its nominal reference position were found by fitting a point source to the visibilities. The position of Vela was shifted (phase rotated) to correct for these offsets. We then self-calibrated the Vela phases in AIPS at 5 minute intervals and copied those corrections to the Vela-G visibilities. The final offsets of Vela-G from the reference position, all very small, were used to calculate the final Vela position (see Fig. 1).

Lobe ambiguity was not an issue even though this was a single baseline experiment, as observing with two widely separated frequencies broke any degeneracy. The final observation, which was with two 8.4 GHz bandpasses, had multiple baselines with which to identify the correct lobe. Only the Tidbinbilla to Hobart baseline was used for measurements of the positions.

3. RESULTS

We find a pulsar position of

\[
\begin{align*}
\alpha &= 08^h35^m20^s61149 \pm 0\,00002, \\
\delta &= -45^\circ10'34''8751 \pm 0\,0003 \, (J2000)
\end{align*}
\]

for a reference epoch of 2000.0. The proper motion is \(\mu_\alpha \cos \delta = -49.68 \pm 0.06\), \(\mu_\delta = 29.9 \pm 0.1\) mas yr\(^{-1}\), and the parallax is 3.5 ± 0.2 mas, equivalent to a distance of 287 \pm 17 pc.

4 http://www.atnf.csiro.au/vlbi.

| Central Frequency (MHz) | Integration (hr) | Residual (mJy) |
|------------------------|-----------------|----------------|
| 2290                   | 1993 Apr 24     | 13             | ...            |
| 2290                   | 1994 Jun 17     | 13             | ...            |
| 2290                   | 1995 Apr 22     | 12             | ...            |
| 2290                   | 1996 Jul 14     | 3              | 0.6            |
| 8425                   | 1996 Jul 14     | 3              | 0.9            |
| 2290                   | 1996 Nov 23     | 8              | 0.7            |
| 8425                   | 1996 Nov 23     | 8              | 2.6            |
| 2290                   | 1997 May 26     | 10             | 0.7            |
| 8425                   | 1997 May 26     | 7              | 2.5            |
| 2290                   | 1998 Mar 26     | 11             | 2.3            |
| 8425                   | 1998 Mar 26     | 11             | 1.2            |
| 2290                   | 1999 Jan 31     | 5              | 0.9            |
| 8425                   | 1999 Jan 31     | 5              | 0.9            |
| 2290                   | 1999 Feb 17     | 10             | 1.1            |
| 8425                   | 1999 Feb 17     | 10             | 1.5            |
| 2290                   | 1999 Oct 26     | 5              | 1.0            |
| 8425                   | 1999 Oct 26     | 5              | 2.0            |
| 2290                   | 2000 Feb 21     | 9              | 1.1            |

* Mark III observations. The image residuals after the subtraction of the point source are also quoted.

* Astronomical Image Processing System (AIPS) developed and maintained by the NRAO.
triangles for 13 cm (traction of the proper motion, in right ascension and declination. Solutions for local structure, we were able to use self-calibration. Imaging of both Vela-G and the pulsar. As we were looking for our final observation we used the full array to allow intrinsic zero phase, degrading the source fitting. Therefore front arriving at the baseline will not have the assumed case. If the source is nonsymmetrical, the incoming wave structure around the pulsar has been reported to resolve out at resolutions finer than a few arcseconds (Dodson et al. 2003; Lewis et al. 2002).

As pulsar radiospheres have angular sizes much less than 1 mas, they may be treated as point sources. (Scattering caused by the interstellar medium may cause observable angular broadening of the pulsar image but is unlikely to bias the observed position significantly.) The phase-reference source has not been optically identified but is most likely a distant active galactic nucleus, and might well have source structure that produces systematic errors in the positions determined at each epoch for the pulsar. The fact that in these observations we used the Vela pulsar as the reference source for the weaker Vela G makes no essential difference in this respect. With this in mind, the final epoch of our observations was used to image the reference source with the full LBA array. No structure brighter than 1 mJy was found around Vela-G (18 mJy) at 8.4 GHz, with an image rms of 0.3 mJy. The phase residuals had an rms of 4”. We note here that Vela-G is a well-known extragalactic source and considered for the ICRF (candidate source ICRF J083322.3–444138) (Ma et al. 1998).

3.1.1. Source Structure of the Phase-Reference Source

Fig. 1.—Residual offsets in the position for the Vela pulsar, after subtraction of the proper motion, in right ascension and declination. Solutions for 13 cm (triangles) and 3 cm (boxes) observations are in shown with error bars in red (13 cm) and green (3 cm). The errors are the range of acceptable fits of the to model to the data, as described in the text, and are significantly smaller for the 3 cm observations, as would be expected.

3.1.2. Source Structure of the Ionospheric Delay

A considerable phase error can be caused by the different ionospheric delay encountered over the different antennae. Several approaches exist to address these problems, the best being using multiple frequencies in the VLBI observations and solving for the ionosphere as part of the reduction (Brisken et al. 2000). Unfortunately, the S2 system used in our experiments does not have enough spanned bandwidth to allow this approach to be used. We therefore we have looked into using the measured total electron count (TEC) from GPS observations (Walker & Chatterjee 1999). However, the best data are on a 5” grid. The separation of our phase-reference source and the target source is 0”, and therefore GPS data cannot provide a useful correction.

As no correction was possible, we modeled the data quality using DIFWRAP (Lovell 2000), which allows an error estimate that includes all possible contributions without attempting to identify them. This approach involves exploring a range of model parameters and identifying the range of acceptable fits, which should be the bounds of the multidimensional 1 σ contour. The errors found are indeed approximately equivalent to 1 σ, as confirmed by fact that the proper-motion fit has a reduced χ^2 of 1.1.

3.2. Space Velocity

Two corrections need to be applied to our results to calculate the motion of the Vela pulsar in its local environment. Our observations are directly tied to the ICRF, therefore the solar peculiar motion and the Galactic rotation contribute to the observed proper motion and need to be removed. We have used the solar constants from Dehnen & Binney (1998) of 10 ± 0.36, 5.25 ± 0.62, 7.17 ± 0.38 km s^{-1} in Galactic coordinates.

We have used a flat rotation curve (Ω_0 = 220 km s^{-1}, R_0 = 8.5 kpc; Fich et al. 1989), which produces a local...
proper motion of $-5.4\mu\text{ mas yr}^{-1}$. This compares with $-5.7\mu\text{ mas yr}^{-1}$ from the local values for the Oort constants, as found by Feast & Whitelock (1997).

The dominant source of error is from the uncertainties in the solar peculiar-motion parameters. We have used the measured uncertainties in our observations and combined those with the models. We have ignored the possibilities of systematic errors or alternative models. This gives us an angular motion, at Vela's local standard of rest, of $\mu_\alpha = -38.6 \pm 1.2 \text{ mas yr}^{-1}$, $\mu_\delta = 23 \pm 1.5 \text{ mas yr}^{-1}$, or $\mu_\delta = 45 \pm 1.3 \text{ mas yr}^{-1}$ at a position angle of $30^\circ \pm 1.8^\circ$. The pulsars' transverse space velocity is therefore $61 \pm 2 \text{ km s}^{-1}$. The position angle no longer lies quite along the spin axis (e.g., $310^\circ \pm 1.5^\circ$ [Helfand et al. 2001] or $307^\circ \pm 2^\circ$ [Pavlov et al. 2001a]), which may strengthen the case that the impulse timescale was not quite long enough to average the off-axis component to zero (Spruit & Phinney 1998).

4. DISCUSSION

4.1. Fitting Methods

We used the publicly available proper-motion fitting routines, PMPAR, created by W. Brisken. As each epoch had quite different observation spans and phase stability, great care was required to ensure that the error estimates were accurate. The traditional approach has been to assume that the errors are a fraction of the beam size, but these ignore variations in the observing conditions during the experiment. We used DIFWRAP (Lovell 2000) to measure the complete range of errors and derived error estimates that are realistic. Where we only had the archival positions, and not the data, we have used the median value of the difference between the formal errors and the errors found with DIFWRAP. It is particularly important to get the errors correct, as the effect to be measured is small and the variation between the data quality is large.

De Luca et al. (2000) point out that as they calculate the proper motion using data collected on nearly identical day numbers, their proper-motion measurement is not contaminated by the parallax. They refer to this as a “pure” proper motion. This is a concern with very short time baselines, which would blend the parallax and proper motion. We, however, have data spanning 7 years, and the correlation between the parameters is low.

4.2. Comparison of Proper Motion with Other Studies

Our calculated proper motion and parallax can also be compared with recent values obtained by optical proper motion studies and phase-referencing VLBI. We ignore the historic observations, which were blighted by poor resolution and low elevation, and concentrate on the two radio VLBI observations, this one and Bailes et al. (1989), and the four optical observations, one purely ground based (Nasuti et al. 1997), one ground based and HST (Markwardt & Ogelman 1994), and two reports from the HST data set (De Luca et al. 2000; Caraveo et al. 2001) for which we take only the latest results. The results found by each of these studies are shown in Table 2. The table shows the proper motions in right ascension and declination for the pulsar along with the reference for this work. The proper motions listed do not account for the rotation of the Galaxy or the peculiar motion of the Sun in the local Galactic potential, being only with reference to the calibrators used. The radio reference is an extragalactic source, and the optical references are a significant number of field stars. Both styles of observations are internally consistent to within 2 standard deviations (see Fig. 2), with improvement of errors over time. With the reduction of errors, however, the radio and optical results are steadily becoming less compatible.

The major advantage our observation has over the HST ones (other than the formal resolution being approximately 100 times better) is that the reference is tied to a well-defined reference frame. For the optical observations only field stars were available. The distance to the reference stars in the HST must be significantly greater than that of the pulsar, otherwise they would have had observable parallaxes themselves. Not knowing a distance, we have assumed that they lie between 1 and 10 kpc and calculated what the apparent proper motion would be for these limits using the standard flat rotation curve. We find that the Galactic rotation contributes between $-5$ and $-3 \text{ mas yr}^{-1}$ to the proper motion in $l$. As all the sources would have proper motions within this range the scatter is within the HST errors of 1 mas. This contribution was not included in the calculations of Caraveo et al. (2001), and when it is the two sets of observations are consistent. Figure 2 includes a line representing the shift in our proper motions that would occur if the reference source was at 2–10 kpc. If this correction is applied to the

\begin{table}[h]
\centering
\caption{Vela Proper Motion Determinations}
\begin{tabular}{cccc}
\hline
No. & Method & $\mu_\alpha$ (mas yr$^{-1}$) & $\mu_\delta$ (mas yr$^{-1}$) & Reference \\
\hline
1 & Phase-referencing VLBI & $-48 \pm 4$ & $34 \pm 2$ & 1 \\
2 & Ground-based optical and HST & $-41 \pm 3$ & $26 \pm 3$ & 2 \\
3 & Ground-based optical & $-47 \pm 3$ & $22 \pm 3$ & 3 \\
4 & HST & $-45 \pm 1$ & $26 \pm 1$ & 4 \\
5 & This result & $-49.68 \pm 0.06$ & $29.9 \pm 0.1$ & \\
\hline
\end{tabular}
\end{table}

\textbf{Note.}—Historic and inaccurate observations have not been included. These are the proper motions as seen against the calibrators; i.e., the optical and radio results are aligned to different reference frames.

\textbf{References.—} (1) Bailes et al. 1989; (2) Markwardt & Ogelman 1994; (3) Nasuti et al. 1997; (4) Caraveo et al. 2001.
optical results, they would be consistent with the radio results. This contribution, of course, needs to be removed to produce the correct space velocity and position angle for the pulsar, but it has no effect on the parallax result. There is

7 Recent communications with Caraveo et al. have revealed that the HST position angle published was incorrect and is in fact 302° ± 1°, in excellent agreement with our own result.

REFERENCES

Bailes, M., Manchester, R. N., Kesteven, M. J., Norris, R. P., & Reynolds, J. 1989, ApJ, 343, L53
Bocchino, F., Maggio, A., & Scintino, S. 1999, A&A, 342, 839
Brisken, W. F., Benson, J. M., Beasley, A. J., Fomalont, E. B., Goss, W. M., & Thorsett, S. E. 2000, ApJ, 541, 959
Caraveo, P. A., De Luca, A., Mignani, R. P., & Bignami, G. F. 2001, ApJ, 561, 930
Caraveo, P. A., & Mignani, R. P. 1999, A&A, 344, 367
Cha, A. N., Sembach, K. R., & Danks, A. C. 1999, ApJ, 515, L25
Cordes, J. M., Downs, G. S., & Krause-Polstorff, J. 1988, ApJ, 330, 847
De Luca, A., Mignani, R. P., & Caraveo, P. A. 2000, A&A, 354, 1011
Dehnen, W., & Binney, J. J. 1998, MNRAS, 298, 387
Dodson, R., Lewis, D., McConnell, D., & Deshpande, A. 2003, MNRAS, 343, 116
Feast, M., & Whitelock, P. 1997, MNRAS, 291, 683
Fich, M., Blitz, L., & Stark, A. 1989, ApJ, 342, 272
Helfand, D. J., Gotthelf, E. V., & Halpern, J. P. 2001, ApJ, 556, 380
Jenkins, E. B., & Wallerstein, G. 1995, ApJ, 440, 227
Legge, D. 2002, Ph.D. thesis, Univ. Tasmania
Lestrade, J.-F., Rogers, A. E. E., Whitney, A. R., Neill, A. E., Phillips, R. B., & Prest, R. A. 1990, AJ, 99, 1663
Lewis, D., Dodson, R., McConnell, D., & Deshpande, A. 2002, in ASP Conf. Ser. 271, Neutron Stars in Supernova Remnants, ed. Patrick O. Slane & Bryan M. Gaensler (San Francisco: ASP), 191
Lovell, J. 2000, in Astrophysical Phenomena Revealed by Space VLBI, 2000, ed. H. Hirabayashi, P. G. Edwards, & D. W. Murphy (Sigamahara: ISAS), 301

also only a small effect on the local motion as the difference in the Galactic rotation for Vela and the reference stars is only a few mas yr⁻¹.

5. CONCLUSIONS

We have measured the proper motion and parallax of the Vela pulsar to an unprecedented accuracy (μₚ = 29.9 ± 0.1 mas yr⁻¹, π = 3.5 ± 0.2 mas) and have been able to convert these back to the space velocity and position angle of the pulsar in its local environment with greater precision that previously possible (61 ± 2 km s⁻¹ at 301° ± 1°), because of the unambiguity in the radio reference frame. This allows the precise comparison of the Vela X-ray nebula symmetry axis and the proper motion of the Vela pulsar, opening insights into the timescale of the core-collapse processes.

The Long Baseline Array is part of the Australia Telescope, funded by the Commonwealth of Australia and operated by ATNF and the University of Tasmania as a National Facility. This research has made use of the SIMBAD database operated at CDS, Strasbourg, France. This research has made use of NASA’s Astrophysics Data System Abstract Service. The author would like to expressly thank Warwick Wilson, head of Engineering for the ATNF, for always being prepared to listen to even the most outlandish correlator configuration request and often implementing them. Dr Brisken provided extremely helpful remarks and comments, as did the referee, Dr Caraveo, and we thank both.

Ma, C., Arias, E. F., Eubanks, T. M., Fey, A. L., Gontier, A.-M., Jacobs, C. S., Sovers, O. J., Archinal, B. A., & Charlton, P. 1998, AJ, 116, 516
Markwardt, C. B., & Ogelman, H. B. 1994, BAAS, 26, 871
Milne, D. K. 1968, Proc. Astron. Soc. Australia, 1, 93
Nasuti, F. P., Mignani, R., Caraveo, P. A., & Bignami, G. F. 1997, A&A, 323, 839
Page, D., Shibakov, Y. A., & Zavlin, V. E. 1996, in Roentgenstrahlung from the Universe, ed. H. U. Zimmermann, J. E. Trümper, & H. Yorke (MPE Rep. 263; Munich: MPE), 173
Pavlov, G. G., Kargaltsev, O. Y., Sanwal, D., & Garmire, G. P. 2001a, ApJ, 554, L189
Pavlov, G. G., Sanwal, D., Garmire, G. P., Zavlin, V. E., Burwitz, V., & Dodson, R. G. 2000, AAS Meeting, 396, 3704
Pavlov, G. G., Zavlin, V. E., Sanwal, D., Burwitz, V., & Garmire, G. P. 2001b, ApJ, 552, L129
Radhakrishnan, V., & Deshpande, A. A. 2001, A&A, 379, 551
Radhakrishnan, V., & Manchester, R. 1969, Nature, 222, 228
Shepherd, M. C. 1997, in ASP Conf. Ser. 125, Astronomical Data Analysis Software and Systems VI, ed. G. Hunt & H. E. Payne (San Francisco: ASP), 77
Spruit, H. C., & Phinney, E. S. 1998, Nature, 393, 139
Walker, C., & Chatterjee, S. 1999, Ionospheric Corrections using GPS Based Models (VLA Sci. Memo 23; Ithaca: Cornell Univ.)