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THE PROPER MOTION OF THE VELA PULSAR

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ABSTRACT

We have measured the proper motion of the Vela pulsar using the Parkes-Tidbinbilla Interferometer over a 2 yr period and obtain a value of 49 ± 5 mas yr^{-1} at a position angle of 305°. This proper motion implies that the pulsar was not born at the geometric center of the Vela supernova remnant nor at the peak of radio emission in Vela X. We conclude that Vela X is not pulsar-driven, and that, like many other Galactic supernova remnants, the Vela supernova remnant has expanded asymmetrically since its birth.
Subject headings: pulsars — stars: proper-motion

I. INTRODUCTION

The Vela pulsar is one of only four radio pulsars associated with a supernova remnant (SNR). Support for the association is provided by the similarity of the pulsar characteristic age and the estimated age of the SNR (Clark and Caswell 1976), both about 12,000 yr. Although the pulsar distance, estimated from the dispersion measure (Manchester and Taylor 1981) is rather uncertain, it is comparable to the estimated distance of 500 pc to the SNR (Milne 1970). The pulsar and SNR rotation measures are also comparable.

The Vela SNR extends over about 5°, and the pulsar is offset from the center of the remnant by about 1°. Although there are three regions of enhanced radio emission within the remnant, referred to as Vela X, Y, and Z, respectively, we assume that the entire remnant is the product of a single supernova event. The largest enhancement, Vela X, is about 2° in diameter and is centered 40′ SW of the pulsar. Weiler and Panagia (1980) suggested that Vela X has a flatter spectrum than the rest of the remnant and that its radio emission is driven by the pulsar, not unlike the Crab SNR. If this association is correct, the pulsar would be expected to have a large proper motion directed away from the center of Vela X. Alternatively, if the pulsar was formed at the center of the Vela SNR as a whole and the estimated distance and age of the pulsar are accurate, then the velocity of the Vela pulsar would be ~ 800 km s^{-1}, making it the highest known of any radio pulsar by a factor of 2 (see Lyne, Anderson, and Salter 1982). Such a velocity could not be produced solely from the break-up of a close binary (Radhakrishnan and Shukre 1985), and some other acceleration mechanism would need to be invoked. A large proper motion directed toward, say, the center of the remnant would cast doubt on the pulsar–SNR association. An accurate determination of the proper motion is therefore of great interest.

Unlike most pulsars, the Vela pulsar has been identified optically, and thus its proper motion can be determined by comparing the optical position over a range of epochs. Using the original discovery plate of Lasker (1976) and a more recent CCD image of the pulsar field, Bignami and Caraveo (1988) placed an upper limit on the proper motion of the Vela pulsar of 60 mas yr^{-1}. Timing data on the pulsar have been unable to yield a proper motion as the Vela pulsar exhibits a large amount of timing noise and is subject to "glitch" behavior (Cordes, Downs, and Krause-Polstroff 1988). Radio interferometry is much more suitable for the determination of pulsar proper motions as it is capable of determining proper motions to a few mas yr^{-1} over relatively short times (see Lyne, Anderson, and Salter 1982). In this *Letter* we report the results of radio interferometric observations of the Vela pulsar which, for the first time, accurately determine the proper motion of the pulsar.

II. RADIO OBSERVATIONS AND RESULTS

In order to determine accurate proper motions for pulsars with a radio interferometer, one measures the relative interferometric phase between the pulsar and a nearby unresolved extragalactic source at various epochs. A secular change in phase indicates a proper motion. The Parkes Tidbinbilla Interferometer (PTI) is a microwave-linked radio interferometer of baseline 275 km which can operate at an observing frequency of 1.6 GHz (Norris *et al.* 1988). In 1986 September we began a proper motion survey of several southern hemisphere radio pulsars using the PTI.

To search for suitable reference sources near the Vela pulsar we used the PTI to examine sources detected on a Molonglo Observatory Synthesis Telescope map of the field. The nearest suitable source was about 40′ from the pulsar and of flux density 0.15 Jy. Observations at 2.3 and 8.4 GHz show the source to have a spectral index of -0.3, consistent with an extragalactic origin. The pulsar's flux density (average over pulse phase) varied between epochs, but was typically ~ 1.0 Jy. The reference and the pulsar were observed at eight different epochs over a 2 yr period (Table 1). Since the separation of the pulsar and the reference is more than the primary beamwidth of the interferometer (12′), it was necessary to beam-switch the antennas. A 4 minute cycle, 2 minutes on the pulsar and 2 minutes on the reference, was adopted. The observed visibilities were fringe-stopped in turn at assumed positions (J2000) for the pulsar, R.A. $08^h35^m20\overset{s}{.}60$, decl. $-45°10'35\overset{''}{.}8$ and reference, R.A. $08^h33^m22\overset{s}{.}247$, decl. $-44°41'38\overset{''}{.}92$, and phases differenced after interpolation. The differential phases, averaged over 10 minute intervals, are shown in Figure 1 with the different symbols representing the different epochs shown in Table 1. As can be seen from the figure, there is a clear systematic change in the phase curves with epoch indicating a proper motion. A least-squares fit of a proper motion model to the entire data set is also plotted on the figure.

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TABLE 1

OBSERVATIONS

Epoch (MJD)	Symbol
46799.........	□
46825.........	*
47127.........	▲
47140.........	⊙
47239.........	△
47273.........	●
47489.........	+
47491.........	×

Although the quality of the fit is extremely good (rms phase residual 17°), giving us confidence in the derived proper motion, there are some deviations from the fitted curves, especially for the later sessions. For the 1988 November session, we have plotted observations made 2 days apart with different symbols showing the systematic differences over the 2 days. We attribute these differences, which were much less evident in earlier sessions, to small-scale ionospheric fluctuations producing differential refraction between the pulsar and reference source. Such fluctuations might be expected to be worse in later sessions as we approach the solar activity maximum. The absence of large systematic effects in the earlier sessions also shows that large-scale diurnal and seasonal changes in the ionosphere had little effect on our data.

The derived proper motion of the pulsar with respect to the extragalactic reference is $\mu_\alpha = -48 \pm 4$ mas yr^{-1} and $\mu_\delta = +34 \pm 2$ mas yr^{-1}. After correction for the peculiar motion of the Sun with respect to the local stars, and for rotation of the Galaxy, the derived proper motion for the pulsar in the local rest frame is $\mu_\alpha = -40 \pm 4$ mas yr^{-1} and $\mu_\delta = +28 \pm 2$ mas yr^{-1}. A distance to the pulsar of 500 pc, a Galactic rotation of 5.88 mas yr^{-1}, and a peculiar velocity of the Sun of 16.5 km s^{-1} in the direction $l = 53°$, $b = 25°$, were assumed when computing the corrections. The quoted errors are twice the formal standard errors from the fit to allow for unknown systematic effects. The total proper motion is 49 mas yr^{-1} at a position angle of 305°. This is less than the upper limit of 60 mas yr^{-1} quoted by Bignami and Caraveo (1988).

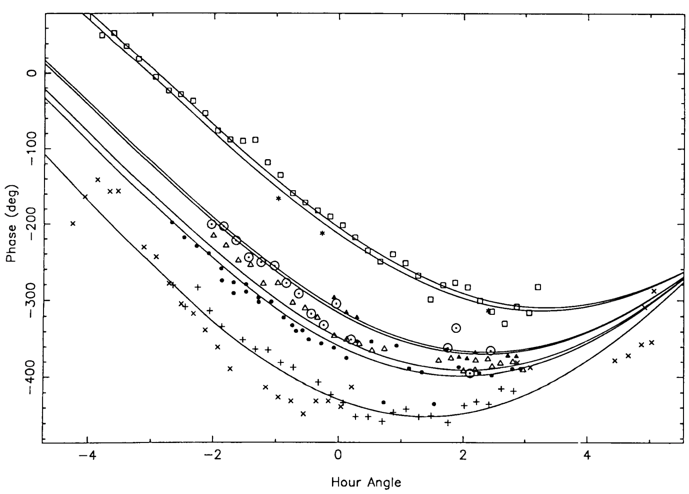

FIG. 1.—A plot of the differential interferometric phase vs. hour angle (at Parkes) for the Vela pulsar and a nearby reference source at several epochs. The symbols each represent the phase at a different epoch and are tabulated in Table 1. The sinusoids plotted on the figure are from the best-fitting proper motion solution to the whole data set and represent the expected phase at each epoch. The uppermost sinusoid is from the first epoch of observation with the sinusoid for each subsequent epoch plotted below that of the preceding epoch.

III. DISCUSSION

The proper motion vector, together with age estimates of the remnant and pulsar, yield the probable birthplace of the pulsar and remnant. For an assumed age of 12,000 yr, Figure 2 (Plate L2) shows this position on the radio map of Day, Caswell, and Cooke (1972), and an Hα image of the remnant, together with the proper motion vector. Clearly, it is very unlikely that the pulsar originated in the center of the strong emission in Vela-X. We conclude, therefore, that Vela X is not directly pulsar-driven or plerionic, but rather an enhanced region of shell emission as suggested by Milne and Manchester (1986) and Manchester (1987).

Bignami and Caraveo (1988) raised doubts about the association of the pulsar and remnant based on their limit on the proper motion. They argued that the birthplace of the pulsar and remnant could be coincident only if the estimated ages of the pulsar and remnant were greatly in error, or if the expansion of the remnant was highly asymmetric, both of which they deemed unlikely.

Our data reveal that the pulsar is in fact moving out of the remnant, but not from the geometric center (insofar as this can be defined). We must attribute this offset from the center to asymmetric expansion of the remnant since the orientation of the proper motion vector makes the age uncertainty almost irrelevant. Such asymmetries are not uncommon in Galactic SNR (Caswell 1988). Perhaps the best analogy is with PSR 1509−58 and G320.4−1.2 (Manchester 1987). In both this case and for Vela, the pulsar location is offset toward the brighter part of the remnant. Asymmetric expansion could be due to denser interstellar gas on the bright side of the remnant or a cavity on the fainter side. There is no suggestion of enhanced densities to the southwest of Vela in the CO map of Dame *et al.* (1987) or in *IRAS* HCON1 images (Beichman *et al.* 1988). We therefore suggest that the Vela SNR has expanded at a faster than average speed toward the northeast.

The derived SNR age of 12,000 yr was obtained by Clark and Caswell (1975) on the assumption that the geometric center of the remnant was the origin. From our argument above, the remnant has expanded at a normal rate to the southwest. This reduces the diameter which should be used to determine the age of the remnant by a factor of ~ 1.5 and the age of the remnant by a factor of between 1.5 and $1.5^{2.5}$ depending on whether the expansion has been primarily free or in the Sedov phase. The corresponding age range is between 4500 and 8000 yr. If the pulsar has had a braking index of 3.0 since birth, the initial period for the pulsar would then be between 43 and 68 ms.

Bignami and Caraveo (1988) suggest that the probability of a pulsar lying along the line of sight to the Vela SNR is not small. Our proper motion data yield a transverse velocity of 120 km s^{-1} for an assumed distance of 500 pc. Although the scintillation speed measurement for this pulsar yields a velocity of only 53 km s^{-1} (Cordes 1986), the factor of ~ 2 discrepancy is not unusual for pulsars with a large degree of scattering. We can place a limit on the pulsar distance by restricting the pulsar to have a velocity less than that of the highest known pulsar velocity of ~ 350 km s^{-1}. This means that the pulsar is almost definitely within 1.5 kpc of the Sun.

Here we estimate the probability that the Vela pulsar is a chance superposition on the Vela SNR. The local birthrate of

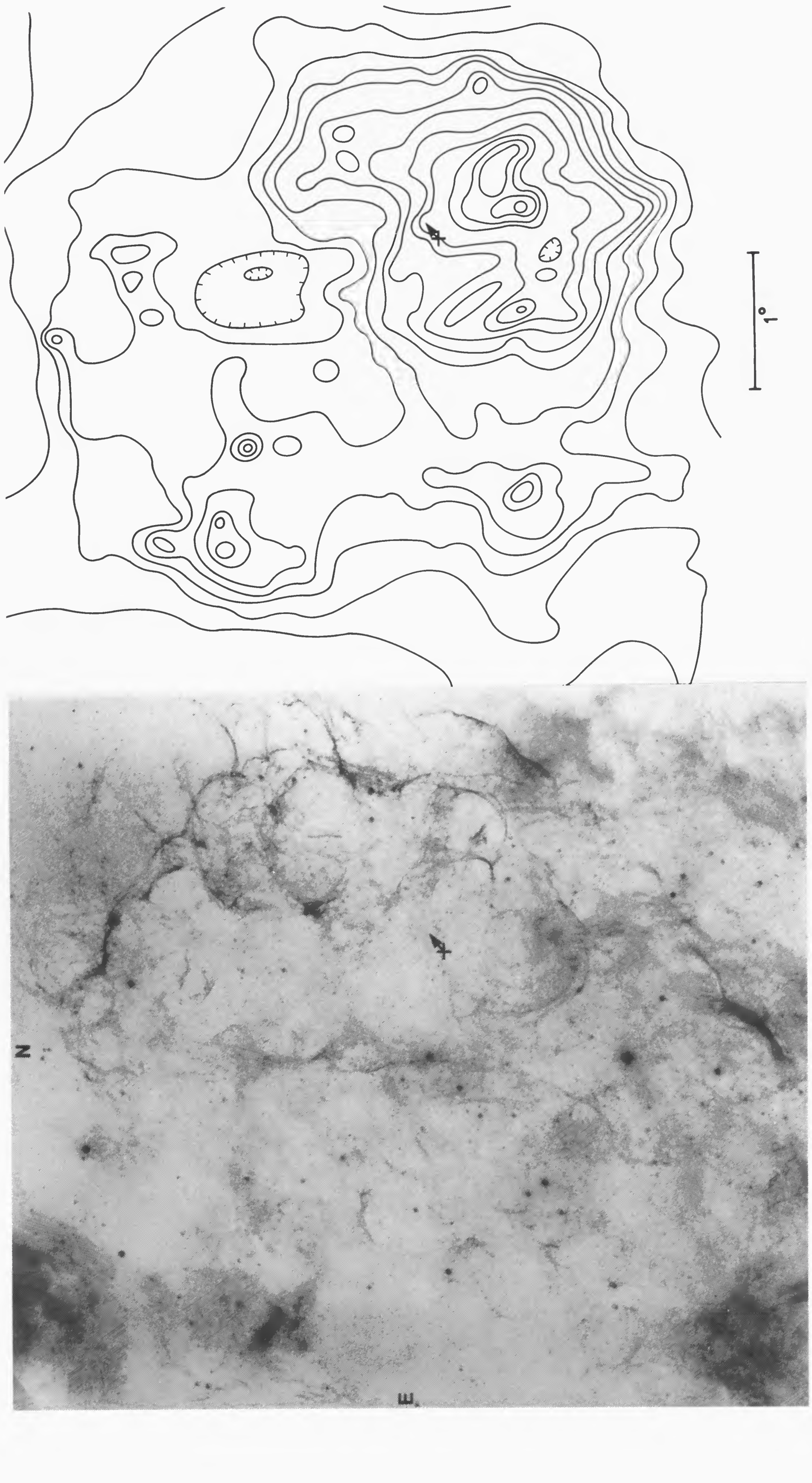

FIG. 2.—The radio map of Day, Caswell, and Cooke (1972) of the Vela SNR together with an Hα image of the region. The cross marks the derived birthplace of the pulsar (assuming an age of 12,000 yr), and the proper motion vector is indicated. The current location of the pulsar is at the tip of the arrowhead.

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pulsars for an assumed beaming fraction of 0.2 is 2.1×10^{-5} kpc^{-2} yr^{-1} (Lyne, Manchester, and Taylor 1985), and hence the number of pulsars that we expect to be born within 1.5 kpc of the Sun and not more than 1° of Galactic longitude from the center of the Vela SNR in the past 12,000 yr is 0.01. The expected fraction of these pulsars within 1° of the Galactic latitude of the center of the SNR is probably less than 0.25. Furthermore, the likelihood that a given pulsar is beamed toward us is probably less than 0.5. Hence the probability that the Vela pulsar is a chance superposition on the SNR is $\sim 10^{-3}$. We therefore conclude that the Vela pulsar and SNR are associated, that both are within 1.5 kpc of the Sun, and that the remnant has expanded asymmetrically.

A velocity of 120 km s^{-1} is typical of pulsars with high magnetic fields (Anderson and Lyne 1983). The origin of this velocity is uncertain. Some authors advocate that an asymmetry in the SN explosion causes the high velocities (Shklovskii 1970; Dewey and Cordes 1986; Bailes 1989), while others have suggested that the velocity arises from the break-up of binaries at the time of the SN explosion (Gott, Gunn, and Ostriker 1970; Radhakrishnan and Shukre 1985). A third mechanism, the "rocket theory" (Helfand and Tademaru 1977), predicts an alignment of the pulsar spin and velocity axes. In the case of the Vela pulsar, the pulsar spin axis is at a position angle of about 55° (Manchester 1987), almost perpendicular to the proper motion vector. This provides further support for the conclusion of Anderson and Lyne (1983) that this theory is not consistent with the observations.

If binary break-up is solely responsible for the velocities of pulsars, then what are the implications of this for the Vela pulsar? One can argue (Radhakrishnan and Shukre 1985) that the companion must have been another (older) neutron star in order for the system to disrupt and that the velocity of the old neutron star must be greater than that of the younger Vela pulsar. The binary would have had to have been very tight with an orbital period of the order a day in order for the Vela pulsar to achieve its current velocity. Old neutron stars in massive binaries with such orbital periods are believed to be spun-up to small spin periods by the accretion of matter from the companion (van den Heuvel 1987). Taking Corbet's diagram (Corbet 1986) as a rough guide, the old pulsar could have a spin period which is of order 100 ms. It would be very difficult to detect such a pulsar even if it was beamed toward us as its present location is unknown.

If radio pulsars receive their velocities from asymmetric explosions then it is not necessary for the Vela pulsar to have had a companion at all. Alternatively, the Vela pulsar's progenitor may have been a member of a wider binary system which was disrupted at the time of the SN. In this case it is possible that the companion is still relatively close to the derived birthplace of the pulsar.

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