SIZE OF THE VELA PULSAR’S RADIO EMISSION REGION: 500 KILOMETERS

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ABSTRACT

We use interstellar scattering of the Vela pulsar to determine the size of its emission region. We find that radio-wave scattering in the Vela supernova remnant broadens the source by 3.3 ± 0.2 mas × 2.0 ± 0.1 mas, with the major axis at a position angle of 92° ± 10°. From the modulation of the pulsar’s scintillation, we infer a size of 500 km for the pulsar’s emission region, with an estimated uncertainty of about a factor of 2, including systematic errors. We suggest that radio-wave refraction within the pulsar’s magnetosphere may plausibly explain this size.

Subject headings: pulsars: general — pulsars: individual (Vela pulsar) — techniques: interferometric

1. INTRODUCTION

Although magnetized rotating neutron stars have been observed as pulsars for more than 25 years, the processes by which strong magnetic fields and rapid rotation give rise to emission at radio and other wavelengths are poorly understood. Proposed sites for the emission range from a few meters above the magnetic pole of the neutron star to near the light cylinder, where corotating fields and matter would travel at the speed of light (e.g., Ruderman & Sutherland 1975; Arons & Scharlemann 1979; Cheng, Ho, & Ruderman 1986; Ardavan 1981; Daugherty & Harding 1994). Pulsars’ strong magnetic fields presumably mediate the loss of their spin energy through either magnetic dipole radiation or an electron-positron wind traveling outward along open magnetic field lines. Observational tests of these models are difficult because the light cylinder is far smaller than the resolution limit for Earth-based observations. However, interstellar scattering provides an opportunity to image the emission region.

Because electron density fluctuations in the interstellar plasma scatter radio waves, an observer receives radiation from a range of angles, defining an effective aperture—the “scattering disk.” The diameter of the scattering disk can exceed 1 AU, with a consequent theoretical angular resolution of the order of nanoarcseconds, which is sufficient to resolve the light cylinder. Observers have sought to exploit this potentially extremely high resolution by comparing the diffraction pattern at different points in the pulsar pulse (Baeker 1975; Cordes, Weisberg, & Boriakoff 1983). Such studies rely on the hypothesis that the apparent structure of the emission region changes over each pulse as the pulsar rotates. Uncommon episodes of very strong refraction show evidence for a shift in the diffraction pattern over the pulse (Wolszczan & Cordes 1987). Because the location of refracting material along the line of sight is unknown, the corresponding shift of the emission region at the pulsar is not known.

2. THEORETICAL BACKGROUND

Fluctuations in the electron density in the interstellar plasma refract radio waves. Radiation traversing different paths from a point source thus interfere to produce a random diffraction pattern in the plane of the observer. The scattering is “strong” if paths differ by more than 2π in phase, as is the case for the Vela pulsar. In strong scattering, both the amplitude and the phase of the electric field vary with location; the diffraction pattern is complex. The spatial scale of the diffraction pattern is λ/θ, where θ is the angular broadening and λ is the observing wavelength. The observer sees the source scintillate on a timescale tISS = λ/θν, as he moves with transverse velocity Vt with respect to the diffraction pattern. The diffraction pattern also changes with the observing wavelength, with characteristic bandwidth Δν = 1/2πτ, where τ is the temporal broadening of a single pulse. Observations of the diffraction pattern require averaging by less than tISS in time and Δν in frequency, and such observations are said to be in the speckle limit of interstellar scattering.

The Vela pulsar is the brightest pulsar at decimeter wavelengths. Careful studies of its temporal broadening indicate that its scattering takes place in a thin screen rather than in an extended medium (Williamson 1972; Lee & Jokipii 1976). By comparing angular scattering and temporal broadening, Desai et al. (1992) found that the scattering material lies in the Vela supernova remnant enclosing the pulsar. The diffraction pattern at the Earth has spatial scale λ/θ ≈ 4000 km; treated as a lens, the scattering disk has a spatial resolution at the pulsar of about 1000 km. The scattering disk thus resolves the 8500 km diameter of the light cylinder.

Kirchhoff diffraction relates the electric field at the source to that at the observer via propagation integrals (Born & Wolf 1980; Goodman 1985; Cornwell & Napier 1988; Cornwell, Anantharamaih, & Narayan 1989). The phase-structure function Dϕ(b) is the mean square difference in phase between two points on the screen with lateral separation b: Dϕ(b) = ⟨(φ(u + b) − φ(u))²⟩ (e.g., Rickett 1977). The angle brackets denote an average over an ensemble of possible scattering screens, as well as over position on the screen u. The interferometric visibility CAB(b) is the product of electric fields at two antennas separated by baseline b. For short baselines (Gwinn et al. 1997),

\[ Dϕ(b) = 2 \frac{⟨|\text{Im}(C_{AB}(b))|^2⟩}{ ⟨|\text{Re}(C_{AB}(b))|^2⟩} . \]
Observations averaged over many scintillation timescales or frequency bandwidths yield an average scattering disk with full width at half-maximum intensity $\theta_M$:

$$D_\omega(b) = \left( \frac{\pi}{\sqrt{2 \ln 2}} \frac{\theta_M}{\lambda} \right)^2. \quad (2)$$

A generalization of this expression describes elongated scattering disks (Gwinn et al. 1988).

Interstellar scattering acts like an imperfect optical system in that the diffraction pattern in the plane of the observer is the convolution of the response to a point source (the point-spread function) with an image of the source. In principle, a diffraction-limited image of the source and the phase variations induced by the scattering screen can both be extracted from the diffraction pattern (Cornwell et al. 1989; Narayan & Cornell 1993). More simply, the modulation index of scintillation, $m$, provides a measure of source size: stars twinkle, planets do not. The modulation index is the fractional rms variation of intensity on the Parkes-Tidbinbilla baseline. This 275 km baseline is so short that the diffraction pattern is nearly a point source with the difference between the two sharply declining exponentials subtracted from it. The relative normalizations of these three exponentials are set by the requirements that at $I = 0$, $P(I) = 0$ and $dP/dI = 0$.

3. OBSERVATIONS AND ANALYSIS

We observed the diffraction pattern of the Vela pulsar interferometrically in 1992 October–November. For this southern sky object we used antennas at Tidbinbilla (70 m diameter), Parkes (64 m), and Hobart (25 m) in Australia, Hartebeesthoek (25 m) in South Africa, and the seven antennas of the Very Long Base Array of the US National Radio Astronomy Observatory* that could usefully observe the source. Each antenna recorded right-circular polarized radiation in 14 bands, each 2 MHz wide (between 2.273 and 2.801 GHz), using the Mark III recording system. We analyzed the data with the Haystack Observatory’s very long baseline interferometer (VLBI) correlator, forming both autocorrelation spectra to sample the diffraction pattern at individual antennas, and cross-power spectra to measure the relative phase and spatial coherence between antennas. To study possible variation in the structure of the emission region across the pulse, we made all measurements in three different gates, each covering a different range of phases of the pulse profile. Because of limits on correlator throughput, we have analyzed only a fraction of the potentially useful data to date.

In this paper we concentrate on three of the many observables calculable from the diffraction pattern: the mean square variation of phase due to scintillation $D_\omega(b)$, the decorrelation bandwidth $\Delta \nu$, and the modulation index $m$. Phase variations on short baselines yield the size and shape of the scattering disk. Comparison with decorrelation bandwidth yields the location of scattering material along the line of sight. The modulation index then yields the size of the pulsar’s emission region.

We use observations over a range of orientations of the Tidbinbilla-Hobart baseline to determine the phase-structure function, which from equations (1) and (2) yields the size and shape of the scattering disk. This baseline has a projected length between 500 and 850 km, so it is much shorter than the scale of the diffraction pattern (4000 km). Figure 1 shows a comparison of our measured phase-structure function with the best-fitting models for circular and elliptical Gaussian scattering disks. The elliptical model clearly fits better. This model has axes of 3.3 $\pm$ 0.2 mas and 2.0 $\pm$ 0.1 mas (full width at half-maximum), with the major axis at position angle $92^\circ \pm 10^\circ$. Quoted errors are 1 s standard errors for fits to the data in Figure 1.

We measure a decorrelation bandwidth of $\Delta \nu = 39 \pm 7$ kHz from the cross-power spectrum on the Hartebeesthoek-Tidbinbilla baseline. This 9000 km baseline reduces the effects of source structure on $\Delta \nu$. We find $t_{\text{los}} = 15$ s. Comparison with angular broadening yields a screen distance of 0.73 $\pm$ 0.04 of the way from the Earth to the pulsar (Desai et al. 1992).

We find the modulation index from the distribution of intensity on the Parkes-Tidbinbilla baseline. This 275 km baseline is so short that the diffraction pattern is nearly identical at the two antennas. Figure 2 shows the distribution

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of intensity, observed over a period of 13 minutes starting at 23:40 UT on 1992 October 31. The data in the left panel are from a single pulse gate, comprising the 1.16 ms immediately preceding the peak of the pulse; those in the right panel are from a gate of the same width, but containing no pulsed emission.

Figure 2 also shows the models that best fit the data. For the “empty” gate, this model is Gaussian noise and the fit parameter is its strength. For the gate with pulsed emission, we show the expected distribution for a point source: this is the convolution of Gaussian noise with an exponential, with exponential scale equal to that observed at large amplitudes. We also show the distribution expected for a pulsed emission region of finite size, with full width at half-maximum of \( s_\parallel = s_\perp = 500 \text{ km} \). The size of the emission region is the only free parameter in this panel. The best-fitting model has a size of 460 \pm 110 \text{ km}. The quoted error is dominated by uncertainty in the decorrelation bandwidth and resulting uncertainty in the location of the scattering screen. The modulation index for this best-fitting model, after removing effects of noise, is \( m = 0.86 \).

Averaging over several scintillation times or bandwidths can reduce the modulation index, but our averaging time and bandwidth are well within the speckle limit. Low-level emission from a non-scintillating source would reduce modulation, but we detected no such source in gates outside the pulse. Receiver noise could also reduce modulation, but is well determined from the empty gate for the low-intensity points that show the effect. The pulsar signal itself will increase the noise level at times and frequencies where the pulsar is strongest, but not where it is weakest, as observed. The Van Vleck correction for 1 bit digitization likewise affects only the strongest signals and would not affect our results, even if it were implemented with the wrong sign.

Our model assumes a circular Gaussian distribution of emission. In general, this region could be elongated and could have a non-Gaussian shape. On the basis of long-baseline observations (which probe the two-dimensional structure of the source) and the correlation of scintillations in frequency, we believe that these effects could change our result by no more than a factor of 2, so that the typical dimension of the pulsar's emission region is between 250 and 1000 km.

4. DISCUSSION

The 1.7:1 elongation of the Vela pulsar's scattering disk is not unusual for radio-wave scattering in the interstellar plasma (Wilkinson, Narayan, & Spencer 1994; Frail et al. 1994; Desai, Gwinn, & Diamond 1994; Molnar et al. 1995). Such anisotropic scattering is expected in turbulent plasmas with strong magnetic fields (Higdon 1984; Goldreich & Sridhar 1995). Theory predicts that the major axis of the scattering disk should be perpendicular to the magnetic field. As inferred from the polarization of synchrotron radiation, the magnetic field in the Vela X supernova remnant lies at a position angle of 45° at the line of sight to the pulsar, but runs nearly north-south close by (Milne 1980). Of course, synchrotron emission may not emanate from the scattering screen.

The size of 500 km is much smaller than the radius of the light cylinder, but is larger than many theoretical predictions. The extent of the emission region is far larger than expected for the 1/\( \gamma \) opening angle of emission for curvature radiation of electrons and positrons traveling along magnetic field lines with Lorentz factor \( \gamma > 10^5 \). If the emission region lies closer to the pulsar than 35% of the distance to the light cylinder, then its 500 km size exceeds the 5% duty cycle of the pulsar, and radiation from this surface must be beamed into a cone narrower than the size of the emission region as seen from the pulsar. In the context of the Radhakrishnan & Cooke (1969) model, direction of the linearly polarized pulsar emission reflects the magnetic field direction at the emission surface, and the finite size of the emission region would thus lead to greater-than-observed depolarization, even if the emission region lies at the light cylinder.

Krishnamohan & Downs (1983) analyzed extensive observations of the Vela pulsar's pulse shape. They dissected it into four components, each arising from a single location at each pulse phase. From relative longitudes and polarization sweep rates of the components, they infer a spread of \( \approx 400 \text{ km} \) in altitude, close to the size that we measure.
We suggest that the observed size results from magnetospheric refraction. Magnetospheres of pulsars must contain some plasma to cancel the electric fields induced by the strong rotating magnetic field (Goldreich & Julian 1969). Electron-positron winds believed to carry spin-down energy away from the pulsar may reach much greater densities (Ruderman & Sutherland 1975; Arons & Scharlemann 1979). This plasma can scatter the radio emission (Blandford & Scharlemann 1976; Melrose & Stoneham 1977; Arons & Barnard 1986). Magnetospheric refraction can displace waves significantly while maintaining the original wave direction and polarization (Barnard & Arons 1986), and so produce a large, collimated beam with the Radhakrishnan-Cooke polarization. A strong wind carrying spin-down energy outward through the magnetic field (Goldreich & Julian 1969). Electron-positron pairs produced by the $\gamma \approx 10^6$ primary pairs that would be accelerated by a polar cap.

Clearly, speckle VLBI can reveal much about radio emission from pulsars. Observations on long baselines, to be discussed elsewhere, probe the two-dimensional structure of the Vela pulsar. Planned polarimetric VLBI observations of the Vela pulsar, using the VLBI Space Observatory Programme space-based antenna in conjunction with ground radio telescopes, will test the polarization structure of the emission region.

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FIG. 2.—Distribution in amplitude of correlation function for the Vela pulsar and for noise, on the Tidbinbilla-Parkes baseline. Because this baseline is much shorter than the scale of the diffraction pattern, the amplitude is equivalent to intensity at a single location. The 13 minute observation covered 4 bands, each 2 MHz wide, between 2.275 and 2.299 GHz, starting at 23:40 UT on 1992 October 31. The amplitude was sampled with 10 s averaging time and frequency resolution 25 kHz, well within the speckle limit for this pulsar. Left: Distribution of amplitude in a 1.16 ms gate synchronized with the Vela pulsar, but offset from the pulse, so that we expect zero emission. Inset shows average profile of this pulsar, plotted as a function of pulse phase in degrees, and the empty gate. Curve shows best-fitting distribution for Gaussian noise, as expected in this empty gate. The fit includes parameters for the strength of noise and normalization. Right: Distribution of amplitude for a gate including the first 1.16 ms of the pulsar pulse, up to the time of peak emission. Inset again shows pulse profile and gate. At large amplitude, the distribution function follows the expected exponential form, which continues beyond the plot. Dashed curve shows the purely exponential form expected for a point source, convolved with noise as calculated from the upper panel. Solid curve shows the form expected for a circular Gaussian emission region with full width at half-maximum of $s = 500$ km. The size $s$ is the only free parameter in the lower panel: the exponential scale is set by the form of the histogram at large amplitude, and the models are normalized to have the area of the data histogram.