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# Nanoarcsecond Single-Dish Imaging of the Vela Pulsar

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**Abstract.** We have measured the properties of the diffractive scintillation toward the Vela pulsar under the extremely strong scattering conditions encountered at 660 MHz. We obtain a decorrelation bandwidth of $\nu_d = 244 \pm 4$ Hz and diffractive decorrelation timescale of $t_{\rm diff} = 3.3 \pm 0.3$ s. Our measurement of the modulation indices $m = 0.87 \pm 0.003 \pm 0.05$ and $m = 0.93 \pm 0.03 \pm 0.05$ (one for each polarization stream), are at variance with the modulation index of the Vela pulsar obtained at 2.3 GHz by Gwinn et al. (1997) *if* the deviation from a modulation index of unity is ascribed to a source size effect.

## 1. Introduction

Under sufficiently strong scattering conditions, a point source whose radiation propagates through the Interstellar Medium (ISM) exhibits diffractive scintillation, whereby the fluctuations in the intensity, $I$, are fully modulated: $\langle (I - \langle I \rangle)^2 \rangle / \langle I \rangle^2 = 1$. If $r_{\rm diff}$ is the length scale on the scattering screen for which the root-mean-square phase difference is one radian, the angular size of the diffractive pattern is $\theta_d = r_{\rm diff}/D$, where $D$ is distance between the observer and the scattering screen. The amplitude of the intensity fluctuations is suppressed if the angular size of a scintillating object, $\theta_s$, is comparable to $\theta_d$.

Finite source size effects are more pronounced at low frequency. Since the phase delay caused by the density inhomogeneities in the ISM is linearly proportional to frequency, the scatttering effect of density inhomogeneities is greater at lower frequency. The diffractive scale, which is a measure of the amplitude of the turbulent phase fluctuations, therefore decreases with frequency. Pulsar scattering data shows that the spectrum of turbulent density fluctuations in the ISM, $\Phi(\mathbf{q})$, is consistent with a power law: $\Phi(\mathbf{q}) \propto q^{-\beta}$ over $\sim 5$ decades in wavenumber (Armstrong, Rickett & Spangler 1995). For such behaviour, the diffractive scale varies as $r_{\rm diff} \propto \nu^{2/(\beta-2)}$, with evidence for both $\beta \approx 11/3$ and $\beta \approx 4$ for the Vela pulsar (Johnston et al. 1998).

Gwinn et al. (1997) (see also these proceedings) measured $m = 0.87$ for the Vela pulsar at 2.3 GHz and, attributing the deviation from $m = 1$ to a source size effect, used the theory of diffractive scintillation to derive a source size of

$\sim$ 500 km. However, as $\theta_d/\theta_s$ decreases for the stronger scattering encountered at lower frequencies the modulation index is also expected to decrease. For the source size stated by Gwinn et al. (1997), scintillation theory predicts that the modulation index is no larger than 0.45 if $\beta = 4$ ($m < 0.35$ if $\beta = 11/3$) at 660 MHz, assuming that the size of the emission region does not decrease with frequency.

Conversely, source-size effects at higher frequencies are expected to be negligible, with the intensity probability distribution following a negative exponential distribution $p(I) = 1/I_0 \exp(-I/I_0)$ with mean intensity $I_0$ (e.g. Gwinn et al. 1998).

## 2. Results

We observed the Vela pulsar for 3 minutes with the Parkes telescope and the CPSR (Caltech-Parkes-Swinburne Recorder) backend to analyse the diffractive scintillation of Vela at 660 MHz, thereby testing the source-size assertion of Gwinn et al. (1997). We describe the data reduction procedure here briefly; full details of the analysis will be presented elsewhere (Macquart et al. 2000).

The CPSR system recorded a two-bit complex sampled data stream in each of two linear polarizations at a rate of 20 MHz. Each polarization stream was analysed separately. For each stream, the mean pulsar power was determined by subtracting the average off-pulse spectrum (obtained by FFTing the data stream) from the on-pulse spectrum. Although the variation of the pulsar flux density is negligible over the 20 MHz bandwidth, Faraday rotation across the band is not, as it causes the detected power in each (linear) polarization stream to vary as a function of frequency.

The spectra then were combined in groups of 10 pulses – equivalent to a third of the scintillation timescale – and normalized by the pulsar's mean power at that frequency and by the instrumental bandpass. The mean signal across the normalised band was subtracted to leave only the fluctuations in $I(\nu)$ across the band. The outer eighths of the band were clipped due to the tapering of the bandpass at the edges. These normalised pulsar spectra were then autocorrelated and cross-correlated to find the normalised covariance

$$\Gamma(\Delta\nu, \Delta t) = \frac{\langle [I(\nu + \Delta\nu, t + \Delta t) - \langle I(\nu, t)\rangle]^2\rangle}{\langle I(\nu, t)\rangle^2}. \tag{1}$$

Figure 1 shows the frequency autocorrelation function $\Gamma(\Delta\nu, 0)$. Fits to the covariance function yielded a decorrelation bandwidth $\nu_d = 244 \pm 4$ Hz for poln 0 ($\nu_d = 241 \pm 8$ Hz for poln 1) and a decorrelation timescale $t_{\rm diff} = 3.3 \pm 0.3$ s determined from poln 0 only due to the higher signal to noise available in this channel. The modulation indices are $m = 0.871 \pm 0.003$ (poln 0) and $m = 0.93 \pm 0.03$ (poln 1). The stated errors are obtained from those formally obtained from the data shown in figure 1. However, these measurements are subject to other errors:

- *Intrinsic pulse-to-pulse flux variations* may affect the scaling of the modulation indices. Suppose we receive a pulse $Y$ times stronger than the mean pulse flux density. Then the scintillation signal, which was normalised by

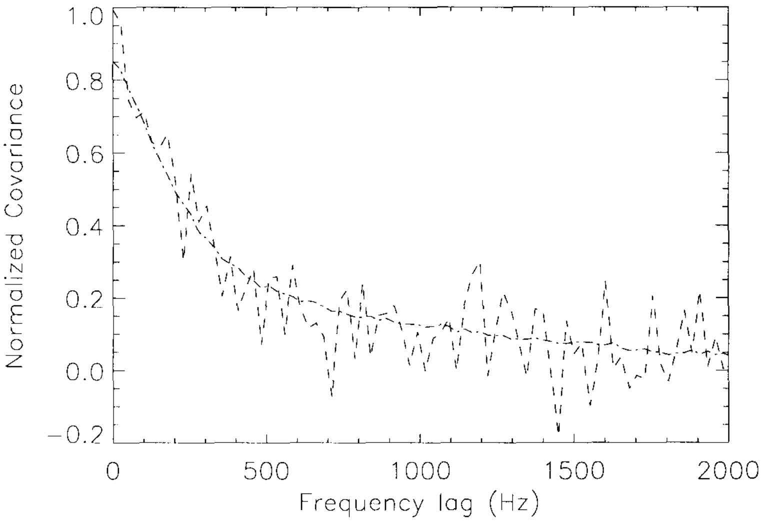

Figure 1. Spectral decorrelation of the signal in the two polarization channels. The zero-lag spikes due to receiver noise are omitted. The dot-dash line represents poln 0 data, the dashed line poln 1 data. Note the difference in signal-to-noise between the two polarization streams. The high (~ 80%) linear polarization of the Vela pulsar at this frequency and the parallactic angle during the observation combined to ensure that little power was collected in the poln 1. Since the signal-to-noise is lower in this polarization, the noise in the autocorrelation function is correspondingly greater.

the mean pulse flux density over one minute, is thus measured to have a modulation index $m_{\rm meas} = Y m_{\rm real}$. The effect of intrinsic pulse variability is reduced by averaging together many independent pulses before calculating the autocorrelation function, and is further reduced by averaging together many such autocorrelation functions. Over the 3 min of data used, intrinsic pulse variations contribute an error $\Delta m \approx 0.01$.

- *Telescope gain variations* play a similar rôle to intrinsic pulsar variability. We estimate their effect on timescales of one minute to be less than a few percent.
- The *finite spectral and temporal resolution* of our observation may *reduce* our measurement of the modulation index due to smearing of the scintillation pattern. However, the spectral and temporal resolution used are sufficiently small compared to the decorrelation bandwidth and timescale that these effects are negligible.

In total, we estimate that the total error in our measured modulation index due to the effects mentioned above is no more than 5%.

In addition to the 660 MHz data, we have also obtained scintillation data at a frequency of 8.4 GHz (Macquart et al. 2000), for which one expects $m = 0.99$ (i.e. negligible source-size effects). However, the observed intensity distribution deviates significantly below the expected negative exponential distribution at high intensity, and the modulation index is $m \approx 0.93$.

## 3. Discussion

Our measured modulation index $m = 0.87 \pm 0.05$ is significantly at variance with the modulation index of $m < 0.45$ expected if the quenching of the diffractive scintillation at 2.3 GHz is a source-size effect. The 660 MHz scintillation data places an upper limit of 50 km on the size of this region.

The two main explanations for the apparent contradiction are:

- The pulsar's emission region is *smaller* at low frequency. The upper limit on the expected modulation index assumes that the emission region retains the same characteristic size between 2.3 GHz and 660 MHz; however, the radius to frequency mapping paradigm leads one to expect the emission region to be larger at low frequency and thus that the diffractive scintillation is quenched even further.
- The reduction in $m$ observed by Gwinn et al. is not related to the apparent source size. This explanation is supported by the 8.4 GHz scintillation data. This data may indicate that the statistics of the phase fluctuations on the scattering screen are not Gaussian, and thus that the expected intensity distribution due to scintillation of a point source is not exactly negative exponential in form.

For a complete discussion of the observing and calibration procedures used and further implications of the results see Macquart et al. (2000).

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