DIFFRACTIVE SCINTILLATION OF THE PULSAR PSR B1259−63

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ABSTRACT

PSR B1259−63 is in a highly eccentric 3.4 yr orbit around the Be star SS 2883. The system is located in the direction of the Sagittarius-Carina spiral arm at a distance of ~1.5 kpc. We have made scintillation observations of the pulsar far from periastron at 4.8 and 8.4 GHz, determining the diffractive bandwidth, \( \Delta \nu_d \), and timescale, \( \Delta \tau_d \), at both frequencies. We find no dependence on orbital phase until within 30 days of periastron. The data indicate that the scintillation is caused not by the circumstellar environment but by an H \( \alpha \) region within the Sagittarius-Carina spiral arm located at least three-quarters of the way to the pulsar. Close to periastron, when the line of sight to the pulsar intersects the disk of the Be star, the electron densities within the disk are sufficient to overcome the “lever-arm effect” and produce a reduction in the scintillation bandwidth by 6 orders of magnitude.

Subject headings: ISM: structure — pulsars: individual (PSR B1259−63)

1. INTRODUCTION

Scintillation studies provide us with a powerful tool for determining conditions along the line of sight to a particular pulsar. They have the potential to determine both the strength of the scattering process and the location of the dominant scattering screen and have been extremely successful in determining some properties of the interstellar medium (Cordes et al. 1991; Gupta 1995). In binary pulsars that are interacting with their companion stars, such as the ablating millisecond pulsars, scintillation studies provide us with a vital clue in understanding the eclipse mechanisms (Luo & Melrose 1995). We present observations and interpretation of the scintillation parameters for the binary pulsar PSR B1259−63, the only known radio pulsar with a Be star companion.

PSR B1259−63 was identified as a pulsar in a highly eccentric \( (e \sim 0.87) \), 3.4 yr orbit with the 10 \( M_\odot \) Be star, SS 2883 (Johnston et al. 1992). Optical observations determined that SS 2883 is of spectral type B2e and also suggested that the system is at a distance of \( D \sim 1.5 \) kpc, placing the pulsar in or just beyond the Sagittarius-Carina spiral arm (Johnston et al. 1994). Be stars are characterized by a circumstellar disk of cool, dense material, which extends outward from the equator to a few tens of stellar radii, and a hot, low-density polar wind.

Observations of the pulsar have shown that dispersion measure (DM) variations around the orbit are \( \leq 0.2 \) cm\(^{-3}\) pc, except close to periastron, where the DM increases by \( \sim 15 \) cm\(^{-3}\) pc. At this time the pulsar undergoes extreme scatter broadening at frequencies up to at least 5 GHz (Johnston et al. 1996). The increased DM and the scatter broadening can be explained by the line of sight to the pulsar traversing the Be star’s wind and disk (Melatos, Johnston, & Melrose 1995). PSR B1259−63 thus potentially provides us with a probe of the wind structure of a Be star (far from periastron) and the disk structure (close to periastron).

A priori, one can think of four potential locations for the scattering material: the general interstellar medium, dense material within the spiral arm, an H \( \alpha \) bubble around the hot star, or the wind/disk of the Be star. In this Letter we examine each of these possibilities in turn.

2. OBSERVATIONS AND RESULTS

We made a total of 46 independent observations of PSR B1259−63 between 1993 August and 1997 February using the Parkes 64 m radio telescope. This excludes data taken in 1993 December and 1994 January during the periastron passage of the pulsar (Johnston et al. 1996). The observations were made at 4.8 and 8.4 GHz using dual channel, cryogenically cooled systems sensitive to two orthogonal linear polarizations. The signals from the receivers were down converted to an intermediate frequency and then passed into a back-end filter bank that consisted of a number of contiguous frequency channels. Prior to 1996 October the filter bank consisted of 64 channels, each 5 MHz wide, for a total bandwidth of 320 MHz. Since 1996 October we have used an alternative back-end system consisting of 128 channels, each 3 MHz wide (total bandwidth of 384 MHz). The signal was detected, high- and low-pass filtered, and sampled at 0.6 ms. The observations were typically between 30 and 100 minutes in duration.

The off-line data analysis was performed in two stages. First, a dynamic spectrum was constructed by forming pulse profiles for each frequency channel over a small length of time, typically 10 s. In order to maximize the signal-to-noise ratio, we often summed consecutive frequency channels and time intervals, making sure that we retained adequate resolution across individual scintillation maxima. Subsequently, a two-dimensional autocorrelation was formed of the summed dynamic spectrum, and one-dimensional Gaussians were fitted to the zero lag in time and frequency to find the diffractive bandwidth, \( \Delta \nu_d \), and diffractive timescale, \( \Delta \tau_d \), respectively. No significant tilt of the autocorrelation function was observed, and we computed fractional uncertainties of the values on the basis of the number of scintles present in the dynamic spectrum following Cordes (1986). The scintillation parameters for each observation and their associated errors are plotted as a function of days from periastron in Figure 1.

The main finding from these observations is that there is little or no change in the scintillation parameters with orbital phase from 25 days after periastron until 100 days before periastron. The apparent decrease in the scintillation bandwidth at 4.8 GHz in late 1996 and early 1997 is most likely due to the improved spectral resolution. The standard deviation of the
values throughout the orbit is $\sim 30\%$, consistent with the individual uncertainties at both 4.8 and 8.4 GHz. Averaging all data at 4.8 GHz, we find that $\Delta \nu_d = 8.5 \pm 0.9$ MHz and $\Delta t_d = 190 \pm 10$ s. At 8.4 GHz, we find that $\Delta \nu_d = 70 \pm 20$ MHz and $\Delta t_d = 360 \pm 100$ s. The contrast of these values far from periastron with the $\sim 20$ Hz scintillation bandwidth at 4.8 GHz just prior to periastron is startling.

3. DISCUSSION

Scattering in the interstellar medium (ISM) is due to electron density inhomogeneities that are thought to be distributed as a power law, $P_N = C_N^2 q^{-\beta}$. $P_N$ is the three-dimensional electron density power spectrum, $C_N^2$ gives the averaged level of turbulence along a particular line of sight, $q$ is the spatial wave number, and $\beta$ is the spectral index of the power spectrum (see, e.g., Kaspi & Stinebring 1992). In the discussion below we assume Kolmogorov turbulence such that $\beta = 11/3$.

Using the definition for $C_N^2$ given in Cordes (1986) and the parameters for PSR B1259$-$63, we find that $C_N^2 = 10^{-1.3}$ m$^{-20/3}$. This value places PSR B1259$-$63 in the top five pulsars ranked by $C_N^2$ and is more than 2 orders of magnitude greater than the “canonical” value of $10^{-3.5}$ m$^{-20/3}$ for the warm, ionized ISM. Further evidence for the enhanced density toward the pulsar comes from the pulsar’s DM. At a distance of 1.5 kpc, the Taylor & Cordes (1993) model yields an expected DM of $\sim 50$ pc cm$^{-3}$, in contrast to the measured value of 147 pc cm$^{-3}$.

The scintillation velocity, $V_{\text{iss}}$, can be computed from

$$V_{\text{iss}} = 3.85 \times 10^4 \frac{\sqrt{\Delta \nu_{\text{MHz}} \Delta D_{\text{unc}}}}{\nu_{\text{GHz}} \Delta t_d} \text{ km s}^{-1},$$

where $\nu$ is the observing frequency and $x$ is the ratio between the screen-observer distance and the screen-pulsar distance (Gupta, Rickett, & Lyne 1994; Gupta 1995). Assuming a midplaced ($x = 1$) scattering screen, we derive a scintillation velocity of $\sim 150$ km s$^{-1}$. We note that the scintillation velocity,
as a function of orbital phase, is constant within the errors. The small and slowly changing component of the pulsar’s orbital velocity cannot be detected in the data. The proper motion of PSR B1259–63 has not been measured, although Johnston et al. (1994) estimate a recessional velocity of 80 km s⁻¹ based on the shift of the Ha line. Theoretical considerations of the evolution of systems like PSR B1259–63 give an upper limit of 90 km s⁻¹ for the space velocity (Brandt & Podsiadlowski 1995). To reconcile this with the measured scintillation velocity implies that \( x \approx 3 \), placing the screen closer to the pulsar than the observer.

Evidently, then, there is good evidence for enhanced-density scattering material located significantly closer to the pulsar than midway from the observer. In the following discussion we derive an expression linking the scintillation bandwidth with the total electron density variance along the line of sight, \( \delta n_e^2 \), the outer scale of density inhomogeneities, \( l_r \), and the thickness of the scattering screen, \( \Delta L \). We then consider three possible locations of the scattering screen: the wind of the Be star, a possible Strömgren sphere surrounding the system, and the Sagittarius-Carina spiral arm, all three of which satisfy the condition on \( x \).

From geometric ray optics, we can compute the time delay, \( \tau_c \), of scattered rays and using the “uncertainty relationship,” \( 2\pi \tau_c \Delta \nu_c = 1 \), we have

\[ \Delta \nu_c = \frac{c}{\pi} \frac{(1 + x)^2}{x} \frac{1}{D\theta_{\text{scatt}}^2}, \]

(2)

where \( c \) is the speed of light and \( \theta_{\text{scatt}} \) is the scattering angle at the screen. [Note that for a midplaced screen, \( x = 1 \), the angular broadening, \( \theta_c \), is \( \theta_{\text{scatt}}/2 \) and eq. (2) becomes the familiar \( \Delta \nu_c = c(\pi D\theta_c^2) \).] By relating the electron density inhomogeneities to the coherence length of the electromagnetic phase, \( \theta_{\text{scatt}} \) can be expressed as

\[ \theta_{\text{scatt}} = \frac{c}{2\pi \nu} \left( \frac{A_2 \nu^2}{2 \pi \nu_c c^2 \Delta L C_N^2} \right)^{-3/5} \]

(3)

(Cordes, Weisberg, & Boriakoff 1985), where \( \nu_c \) is the classical electron radius. \( C_N^2 \) is given by

\[ C_N^2 = \frac{\delta n_e^2}{C_{\text{SM}} \frac{2e^2}{\pi c^3} \frac{4}{3}}, \]

(4)

Both \( A_2 \) and \( C_{\text{SM}} \) are dimensionless constants that depend only on \( \beta \) and have values of 2.49 and 0.18, respectively, for \( \beta = 11/3 \) (Cordes et al. 1985, 1991). Combining these equations and putting the parameters in convenient astronomical units, we find that

\[ \delta n_e^2 = 4.0 \text{ cm}^{-6} \Delta \nu_a \cdot D_{\text{pc}}^{5/6} \cdot \frac{\Delta \nu_a}{\nu_a} \cdot \eta_{\text{SM}}^{11/3} \cdot \frac{\nu_a}{\nu_c} \cdot \frac{1}{x} \cdot \frac{1}{\Delta L_{\text{pc}}} \cdot \left[ 1 + \frac{x^2}{3} \right]^{5/6} \]

(5)

The wind of the Be star near apastron is a possible scattering site. However, if this were the case, one would expect a modulation in the scintillation parameters as a function of orbital phase. Our observations cover a period in which the distance of the pulsar from the Be star varies by a factor of 3; assuming a wind profile density that varies as \( \tau_c \), this implies a change in electron density by a factor of \( \approx 10 \). Given that the scintillation bandwidth scales as \( \Delta \nu_a^{-12/5} \) (from eq. [5]), if \( \delta n_e^2 \) and \( \nu_c \) remain constant, we should observe a change in \( \Delta \nu_c \) by a factor of \( \approx 250 \). Furthermore, the wind velocity is as high as \( \approx 1000 \text{ km s}^{-1} \), and this would then be the dominant velocity in the system, causing a diffractive timescale much shorter than observed. Finally, it is unlikely that the electron density within the wind is large enough to cause the observed scintillation until very close to periastron. Assuming that the scattering screen is located only a few hundred light-seconds from the pulsar and that \( l_r = \Delta L \) is also of this order, then \( \delta n_e^2 \approx 10^{11} \text{ cm}^{-6} \). For even a fully modulated wind with \( \delta n_e^2 \approx n_e^2 \), the implied electron densities are encountered only within \( \pm 30 \) days of periastron.

The UV flux from hot, high-mass stars can form an H II bubble (or Strömgren sphere) within the ISM. The interface between these two regions can be a source of turbulence and is a possible site for scattering. We can put limits on the emission measure of the Strömgren sphere from a 12 hr synthesis image of the pulsar made using the Australia Telescope Compact Array. The observations were made at frequencies of 1.4 and 2.4 GHz and were gated into eight bins synchronous with the pulsar period. After removal of the pulsed component from the image, the upper limit on the brightness temperature of any residual emission is \( \approx 1 \text{ K} \). Using standard equations for free-free emission from H II regions and assuming a temperature of \( 10^4 \text{ K} \), the upper limit on the emission measure is 650 cm⁻⁶ pc. The radius of a Strömgren sphere for a B2 star with effective temperature of \( 2 \times 10^4 \text{ K} \) is related to the electron density within the surrounding medium by \( R_e = 13 n_e^{2/3} \text{ pc} \) (Prentice & ter Haar 1969). Hence, we see that \( n_e \leq 20 \text{ cm}^{-3} \) and \( R_e > 1.8 \text{ pc} \) for the Strömgren sphere to be undetectable. Applying equation (5) and assuming that \( x \approx 750 \) and \( l_r = \Delta L \approx 1 \text{ pc} \), we see that \( \delta n_e^2 \) must be larger than \( 3.7 \times 10^{10} \text{ cm}^{-6} \) to yield the observed scintillation bandwidth. Such a large value is inconsistent with the upper limit on the electron density imposed by the lack of radio emission. Thus, the Strömgren sphere cannot be the source of the observed scattering.

The Sagittarius-Carina arm intersects the line of sight at a distance of \( \approx 1 \text{ kpc} \). The spiral arm likely contains numerous, high-density H II regions that can cause both excess DM and scattering. If we estimate that \( l_r \approx 1 \text{ pc} \) for an H II region and use \( x = 3 \), equation (5) yields \( \delta n_e^2 \Delta L = 600 \text{ cm}^{-6} \text{ pc} \). From the excess DM we have \( n_e \Delta L = 100 \text{ cm}^{-3} \text{ pc} \), and assuming that the condition \( \delta n_e^2 \approx n_e^2 \) holds within the H II region, then we find that \( n_e \approx 6 \text{ cm}^{-3} \) and \( \Delta L \approx 10 \text{ pc} \). The derived electron density is consistent with the values of \( \sim 6 \) and \( \sim 3 \text{ cm}^{-3} \) obtained by Heiles, Reach, & Koo (1996) and McKee & Williams (1997), respectively, for “typical” H II regions. We thus conclude that the source of the enhanced scattering is one (or several) H II regions within the Sagittarius-Carina spiral arm.

A number of other factors point to the Sagittarius-Carina spiral arm as a dominant source of scattering. PSR J1243–6423, only 2'22 distant from PSR B1259–63 on the sky, has very similar scintillation parameters to those of PSR B1259–63 (Johnston, Nicastro, & Koribalski 1998). Its DM-derived distance is 12 kpc, yet indications from H I absorption suggest a distance as low as 2.2 kpc (Fralil & Weisberg 1990). It seems evident that the spiral arm contributes both to its large DM and relatively small scintillation bandwidth. Nicastro & Johnston (1998) recently discovered a pulsar only 7' from PSR B1259–63 with an exceedingly high DM of 875 pc cm⁻³. Such a large DM is not expected in this part of the Galactic plane, and this again points to the spiral arm as a significant source of excess electrons.
Near periastron we conclude that the disk of the Be star must dominate the scattering. Twenty days from periastron, \( \Delta v_c \) is 30 Hz at 1.4 GHz. We assume that the proximity of the scattering screen implies that \( x \approx 5 \times 10^5 \). We take \( \Delta L \approx l_c \sim 100 \) light-seconds and hence obtain \( \delta n_e^2 \) of \( \sim 10^{14} \text{ cm}^{-3} \). Again, assuming that \( \delta n_e^2 \approx n_e^2 \), an electron density of \( \sim 10^5 \text{ cm}^{-3} \) is required. Modeling of the disk of the Be star (Melatos, Johnston, & Melrose 1995) shows that the maximum density encountered along the line of sight through the disk reaches \( 10^7 \text{ cm}^{-3} \) some 25 days prior to periastron and rises by an order of magnitude at periastron itself. Hence, near periastron, there is sufficient density in the Be star’s disk to produce the observed scattering. Because the scattering angle is \( \sim 0.75 \), the angular broadening produces an image size of \( 8 \times 10^{10} \text{ cm} \) on the screen. This value is significantly larger than the diffractive coherence scale of \( \sim 10^7 \text{ cm} \) for scattering in the spiral arm. We thus expect a quenching of the scintillation seen through the spiral arm, which is confirmed by the observations.

4. CONCLUSIONS

We have determined the scintillation parameters of the binary pulsar PSR B1259–63 as a function of orbital phase and conclude that there is no change in these parameters except during a small portion of the orbit around the time of periastron. The scintillation bandwidth is much less than expected if the scintillation were solely due to the background ISM. We have demonstrated that the electron densities are not sufficiently large in either the wind of the Be star far from periastron or a putative Strömgren sphere to produce the observed scattering. The Sagittarius-Carina spiral arm is therefore the most likely origin of the scintillation far from periastron. At periastron, however, the electron density in the Be star disk is sufficiently large to counterbalance the lever-arm effect of having the screen so close to the pulsar. This produces extremely strong scattering, and the resultant broadening of the pulsar image is sufficient to quench further scintillation in the ISM.

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