PULSAR INVESTIGATION USING INTERSTELLAR SCINTILLATION

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Abstract. We discuss the resolution of pulsar magnetospheres using interstellar scintillation. The two-dimensional spatial structure of pulsar emission zones can be obtained from analysis of diffractive scintillations at low frequencies. Based on refractive and diffractive scintillation of pulsars we can also reconstruct the distribution of turbulent plasma along the line of sight, and using this analysis a new approach to pulsar distance estimation can be made.

Keywords: pulsar, scintillation

Propagation of radio waves from pulsars is affected by electron density inhomogeneities in the interstellar medium (ISM), and we see variations or scintillation of radio emission in time and frequency. Interstellar scintillation of pulsars includes two components: short-period (minutes or hours), or 'diffractive', and long-period (days or months), or 'refractive'. Diffractive scintillation is caused by the diffraction of radio waves on plasma inhomogeneities with scales ($10^9 \div 10^{11}$) cm. Refractive scintillation is attributed to weak focusing of the radiation by inhomogeneities with scales ($10^{12} \div 10^{15}$) cm.

Studying interstellar scintillation of pulsars allows a unique opportunity for measuring the angular size of sources with an angular resolution of up to 10 nanoarcsec at meter wavelengths. Pulsars have the smallest angular size of all known radio sources: about 0.3 μarcsec. The angular size of the diffraction pattern at the Earth is (Pynzar' and Shishov, 1980): θ_d = b/R = $c/(f\theta_0 R) \sim f^{1.2} \approx 0.1$ μarcsec at meter wavelengths, where θ_0 is the apparent angular size of the source, b is the characteristic size of the diffraction pattern, R – is the pulsar distance. If the space separation between two sources is more than the size of the diffraction pattern at the Earth then we will see decorrelation of intensity variations from these sources.

1. Resolution of Pulsar Magnetospheres by Scintillations

The first attempt to resolve pulsar magnetospheres was made at an observing frequency of 430 MHz by Cordes, Weisberg and Boriakoff (1983) for two pulsars: PSR 1133+16 and 0525+25. They did not see any decorrelation between scintillation spectra of the two distinct components of these pulsars, so they obtained only upper limits on the source space separation. A strong refraction event can split the apparent source image into two or more subimages, causing periodic structure in the resultant dynamic spectrum. An episode of double imaging of PSR 1237+25 was detected by Wolszczan and Cordes (1987) at 430 MHz. Based on the measured

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fringe phase shift across the pulse profile, they estimated the spatial separation of the emission sources: $\Delta r = (7 \cdot 10^7 \div 6 \cdot 10^8)$ cm (assuming the location of the screen, Ds = R/2). For a dipolar magnetic field the height of the emission zone should be about the radius of the light cylinder. Interference patterns of this type are very rare events and the location of the phase screen has to be assumed for emission-zone size definition. This is a limitation of the method.

At meter wavelengths the regime of multiple ray interference from interstellar medium irregularities is realized and we can use diffractive scintillations for resolving pulsar magnetospheres. In this case it is not necessary to make any assumptions about the screen location. As was shown by Shishov *et al.* (1995) for nearby pulsars ($R \leq 1$kpc) we have a statistically uniform medium filling all the space between the source and the observer, and so we can use the corresponding theory. For saturated scintillations, in the case of a statistically uniform medium and when the velocity of the pulsar, v_s, exceeds the velocities of both the observer and the medium, we have the following simplified relation for the Cross-Correlation Function (CCF) of intensity fluctuations of the two sources (the more general formulation is given by Smirnova, Shishov and Malofeev, 1996):

$$B_I(\rho_0, t) = I_1(t) * I_2(t) \cdot exp\{-(\rho_0 - v_s t)^2/b^2\}, \tag{1}$$

where ρ_0 is the spatial separation of the sources in the plane perpendicular to the line of sight, t is the time shift between fluctuations of the intensities of sources separated in space by $b=\lambda/(2\pi\theta_0)$. The shift of the maximum of the temporal CCF is $t_{max} = (\bar{v}_s \cdot \bar{\delta}_0) / v_s^2$. The characteristic scintillation time and frequency scales are $t_0 = b/v_s$, and $\Delta f_d = 2c(k \cdot b)^2/R$. From the value of t_{max} and using equation (1) we can determine the projection of the vector ρ_0 on the velocity vector of the pulsar $\rho_{0,||} = (\bar{v}_s \cdot \bar{\delta}_0)/|v_s|$ as a function of the longitude of the source l. If we have two sources with a transverse separation ρ_0 and the width of emission diagram is much less than the distance between sources we see interstellar scintillations (ISS) that are decorrelated. The CCF is:

$$S_I(\rho_0, f) = I_1(f) \cdot I_2(f) exp[-(\rho_0/b)^2] \tag{2}$$

So measuring the decorrelation of spectra from separated sources we can determine the absolute value of the transverse separation between sources, and measuring the time shift of the CCF from temporal intensity variations we can determine the projection of the vector ρ_0 on the velocity vector of the pulsar.

In the papers of Smirnova and Shishov (1989) and Smirnova (1992) the spatial structure of the emission zones of 5 pulsars: PSR 0823+26, 0834+06, 1133+16, 1237+25 and PSR 1919+21 were studied at 102 MHz with the Big Sinphaze Antenna (BSA) of Lebedev Physical Institute located in Pushchino. A 32 channel receiver with a 5 kHz bandwidth per channel was used for observations. Individual pulses in all channels were recorded with a sampling rate of 2.4 ms. Measuring the shift of the temporal CCF of the intensity variations on the leading part of the mean pulse profile (used as a reference), and all following longitudes, we obtained the projection of the transverse separation of emission regions on the velocity vector of the pulsar. We found an increasing temporal shift of the CCF with increasing longitude separation. The phase curves for all pulsars had the same behaviour: a non-monotonic increase with growth of the longitude separation and a flattening near the central part of the mean profile. For four observed pulsars we obtained $\rho_{0,||} = (0.3 \div 1) \cdot 10^3$ km. To improve the frequency resolution, and to study the two-dimensional structure of emission zone, we observed four pulsars in 1994 – PSR 0834+06, PSR 1133+16, and PSR 1237+25 and PSR 1919+21 – at 102 MHz with a new 128 channel receiver of 1.25 kHz channel width. We saw obvious decorrelation of the spectra at remote longitudes. The strongest differences between spectra were for PSR 1919+21. From the falling CCF between spectra with increasing longitude shift we obtained the absolute value of the baseline ρ_0 between sources. From the shift of the center of the temporal CCF relative to zero delay we calculated the projection of ρ_0 on the velocity vector of the pulsar $\rho_{0,||} = t_{max} \cdot v_s$, as a function of the longitude of the source. The analysis has shown that, first of all, $\rho_{0,||} \ll \rho_0$. The typical value of ρ_0 is approximately equal to b, which is $(4 \div 8) \cdot 10^3$ km, while the typical value of $\rho_{0,||} \approx (0.1 \div 0.2)b$ (Smirnova, Shishov and Malofeev, 1996). This means that the apparent distribution of sources is close to a straight line, and that the velocity vector of the movement of the pulsar in space is close to the orientation of the rotation axis of the pulsar. Theoretical foundations for a pulsar velocity aligned with the rotation axis were presented in the work of Bisnovatyi-Kogan (1993).

Secondly, the dependence of the space separation between sources on longitude is obviously non-linear. In the central longitudes of the mean profile a plateau is observed in the dependences of $\rho_{0,||}$ and ρ_0 on l. The data can be naturally explained by a model with a non-dipole magnetic field. Close to the edges of the radiating region the magnetic field lines are close to dipolar, and we observe here a linear dependence of ρ_0 on l. In the central regions the magnetic field lines are close to radial, and here ρ_0 does not depend on l. Using the relations obtained for the dipole magnetic field we can estimate the height of the radiating region as $r_{em} = 3\rho_0/\Delta l$, where Δl is the difference in longitudes of the edges of the averaged pulse profile. The values of r_{em} are of the order of the radius of the velocity of light cylinder RLC. In this case we should expect a substantial deviation of the magnetic field structure from a dipole one. As was shown in other papers from observations at low frequencies (Shitov, Malofeev and Izvekova, 1988; Smirnova, 1991), we have evidence for non-dipolar structure of the magnetic field in the emission zone.

2. Pulsar Distance Estimation using Scintillations

The interstellar medium is strongly irregular for different directions in the Galaxy. Using simultaneous analysis of data on refractive and diffractive scintillations we can reconstruct the distribution of the turbulent plasma along the line of sight. Measuring such parameters as characteristic temporal scale of the refractive scintillation, T_{ref}, and characteristic frequency scale, Δf_d, of the diffractive scintillation we can determine a parameter $\varphi = r_0/(R - r_0)$, where r_0 is a distance from a source to an effective layer of the turbulent plasma, R is the distance from a source to an observer. In the paper of Smirnova, Shishov and Stinebring (1998) a theory of refractive scintillation for different models of the turbulent plasma distribution along the line of sight was developed. Using the results of this paper we carried out the analysis of observational data for the purpose of distance determination for 15 pulsars for which the flux variations were measured during 5 years (Stinebring *et al.*, 1996).

We considered 4 models of the distribution of the turbulent medium on the line of sight. Model 1: the medium occupies all space between a source and an observer. Model 2: the medium is located in the layer between a source and its boundary $r_0 \ll R$. Model 3: the medium occupies the layer between an observer and the boundary $R - r_0 \ll R$. Model 4: the medium is concentrated in thin layer with the thickness Δr_0 at a distance r_0 from the source, $\Delta r_0 \ll r_0$, R (phase screen model). For all models we assumed that the medium is statistically homogeneous. We considered two types of spectra in the turbulent medium: a pure Kolmogorov spectrum, and a piecewise power spectrum with a break at the inner scale l. We supposed also that the temporal structure of scintillations is determined by the source motion. We can determine the parameter $\varphi = (T_{ref}\Omega)^2 \Delta f_d R(\pi/cGC^2)$, where Ω is the angular velocity of the proper motion of the source, which we obtained from the Taylor, Manchester and Lyne (1993: TML) catalogue. The numerical coefficients G and C depend on the medium model. The value φ characterizes the medium distribution on the line of sight. For model 1 this value is $\varphi = 1$, for models 2, 3 and 4: $\varphi = (r_0/R)^2(R/r_{eff}) = r_0/(R - r_0)$. For model 2 it should be $\varphi \ll 1$ and for model 3: $\varphi \gg 1$. For models 2, 3 and 4 only the value $R/\varphi = R^2/r_0$ or $R(R - r_0)/r_0$ can be obtained. The distance R is uniquely determined for model 1 only. We can obtain:

$$R_0[kpc] = 6.67 \cdot 10^6/\{[(T_{ref}[days]\Omega[mas/year])^2 \Delta_{fd}[KHz]\} \qquad (3)$$

Assuming a statistically homogeneous medium we calculated the distance, R_0, using eq. (3) and then compared it with the distance, R_{cat}, from the TML catalogue. Values of T_{ref} and Δf_d were taken from Smirnova *et al.* (1998). The estimate, R_{cat}, based on the TML model gives us the right evaluation of the distance in a statistical sense. For those pulsars where we have a statistically homogeneous medium in the line of sight, the calculated values of R_0 are about or equal to R_{cat}, and φ is about 1. But if we have some strong peculiarities in the electron density distribution in the line of sight to a pulsar then we have a large difference between R_0 and R_{cat}. When the calculated distance, R_0, differed greatly (more than a factor of two) from the catalogue values we conclude that we don't have the model 1 case. We have the case of turbulent layer near the source (model 2) when $R_0 \gg R_{cat}$ (PSR 0531+21, PSR 0833-45, 1911-04) or the layer near an observer (model 3) when $R_0 \ll R_{cat}$ (PSR 0329+54, 0818-13). Then, if we know the distance to the pulsar from an independent method, we can obtain the distance to the turbulent layer and its thickness.

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