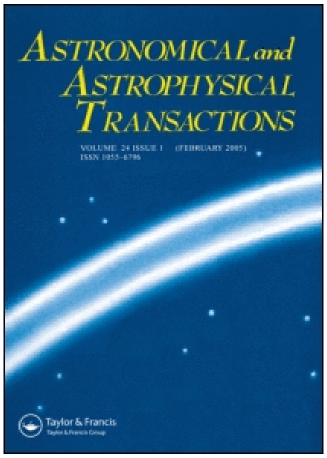

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Interstellar turbulent plasma spectrum from multi-frequency pulsar observations

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We present here our recent results concerning the shape of interstellar plasma spectrum of five pulsars: PSR $0329+54$, $0437-47$, $0809+74$, $0950+08$ and $1642-03$ based on complex analysis of multi-frequency observations of diffractive and refractive scintillation of pulsars. We found that in particular directions, the spectrum differs from the Kolmogorov one. Strong angular refraction was detected in the direction to PSR $0329+54$, $0437-47$ and $0950+08$.

Keywords: ISM; Interstellar spectrum; Pulsar scintillation

1. Introduction

Diffractive and refractive interstellar scintillation of pulsars are caused by electron density fluctuations in interstellar turbulent plasma spectrum (ISM) [1–3] and so pulsars are a very good tool to study ISM. Although data are well described by the Kolmogorov spectrum in a statistical sense [2, 4], in particular directions the spectrum can differ. The study of interstellar scintillation of pulsars observed at many frequencies gives us the possibility to construct a composite structure function (SF) of phase fluctuations in wide range of spatial scales of inhomogeneities. We recently developed [4] a method of constructing the time and frequency SF by converting all scintillation data into one reference frequency. Here, we present our recent results concerning the shape of interstellar plasma spectrum of five pulsars.

2. Construction of the SF based on multi-frequency observations

The spatial spectrum of electron density, $\Phi_{N_e}(q)$, is described by a power law:

$$\Phi_{N_e}(q) = C_N^2 q^{-n}, \tag{1}$$

where C_N^2 characterizes the level of plasma turbulence and q is the space frequency, $n = 11/3$ for the Kolmogorov spectrum.

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The SF of phase fluctuations, D_S, is more related to pulsar observations:

$$D_S(\vec{\rho}) = \langle [S(\vec{\rho}_1 + \vec{\rho}) - S(\vec{\rho}_1)]^2 \rangle,$$
$$S = (\lambda r_e) \int_0^R \mathrm{d}r N_e = \alpha_s \left(\frac{f_0}{f}\right) \mathrm{DM}, \tag{2}$$

where $\alpha_s = 2.526 \times 10^7 \mathrm{pc/cm}^3$, $\vec{\rho}$ is a two-dimensional vector between two points in the plane normal to the line of sight and DM is a dispersion measure. $D_S(\rho)$ for a power law spectrum is described by the equation [5]:

$$D_S(\rho) = \frac{A(n) L (\lambda r_e)^2 C_N^2 \rho^\alpha}{(\alpha + 1)},$$
with
$$A(n) = \frac{2^{4-n} \pi^3}{[\Gamma^2(n/2) \sin(\pi n/2)]}, \quad \alpha = n - 2. \tag{3}$$

Here, λ is the wavelength, r_e is the classical electron radius, and L is the thickness of the turbulent layer. In the case of a statistically homogeneous medium $L = R$, where R is a distance to pulsar. $D_S(\rho)$ describes the turbulence spectrum for the spatial frequency region near $q = 1/\rho$. The coefficient $1/(\alpha + 1)$ corresponds to the spherical wave, which is correct for pulsars.

We have observed intensity variations in frequency and time domain caused by a scattering of signal by inhomogeneities of ISM. For data analysis, we used the correlation function of intensity variations $B_I(t)$, which is given in the saturated scintillation regime by the equation

$$B_I(t) = \langle I \rangle^2 \exp[-D_S(t)]. \tag{4}$$

If Δt_d is the characteristic time scale of intensity variations defined as half of the $1/e$ level of the correlation function width, then $D_S(\Delta t_d) = 1$. $D_s(\Delta t)$ can be obtained [4] for small time lags Δt from:

$$D_s(\Delta t) = \frac{B_I(0) - B_I(\Delta t)}{\langle I \rangle^2} \text{ for } \Delta t \leq t_{\mathrm{ISS}}. \tag{5}$$

We have a similar relation in the frequency domain. We have to convert all observations at different frequencies into a reference frequency, f_0, to construct SF in a wide range of frequency and time scales:

$$D_s(f_0, \Delta t(f_0), \Delta f(f_0)) = D_s(f, \Delta t(f), \Delta f(f)) \left(\frac{f}{f_0}\right)^2. \tag{6}$$

The time difference, Δt, characterizes the same spatial scale independent of the observing frequency, $\Delta t(f_0) = \Delta t(f)$. For diffractive scintillation, one obtains:

$$\Delta f_d(f_0) = \left(\frac{f_0}{f}\right)^2 \Delta f(f). \tag{7}$$

In the presence of a strong angular refraction with a refractive angle which is much more than the scattering angle, $\theta_{\mathrm{ref}} \gg \theta_{\mathrm{sc}} = 1/(k\rho)$, we have the following equation

$$\Delta f_r(f_0) = \left(\frac{f_0}{f}\right)^3 \Delta f(f). \tag{8}$$

This different frequency dependence of frequency shift for two models (diffractive and refractive) can be used to detect strong angular refraction. The spatial scale of diffractive scintillation in a statistically homogeneous medium is connected with a time scale, Δt, by the relation $\rho = V_\perp \Delta t$, where $V_\perp$ is a transverse velocity of the line of sight relative to diffractive pattern.

3. Results

In figure 1, we show the composite SFs obtained for pulsars PSR B1642-03 and B0329 + 54 presented in more narrow range of time lags than in [4, 6]. For PSR B1642-03, the SF is based on observations at 102 MHz (stars), 340 MHz (open circles), 800 MHz (filled squares), 4.85 GHz (triangles), and refractive scintillations at 610 MHz (crust). All data for all figures were converted into the same reference frequency $f_0 = 1000$ MHz. Solid lines correspond to the best fit in log–log scale to data. We do not show here the points obtained from timing of these pulsars to see better small scales. We know the transverse pulsar angular velocity, Ω, for PSR 1642-03, which is 30 mas/year [7], but we do not know the distance. We believe that PSR B1642-03 is a nearby pulsar, and we used $R = 160$ pc and $V = 20$ km/s for conversion of the temporal scale into the spatial scale (top axis in figure 1). For this pulsar, SF consists of two components: the small-scale component (scales 10^7–10^9 cm) corresponds to the flat spectrum of turbulence with $n_1 = 3.35 \pm 0.03$ ($n = \alpha + 2$) and the large-scale component corresponds to the Kolmogorov spectrum: we obtained $n_2 = 3.7 \pm 0.02$.

We used the transverse pulsar velocity $V = 95$ km/s and the distance $R = 1$ kpc for PSR 0329 + 54 (right side, figure 1) from parallax measurement of this pulsar [8]. These values

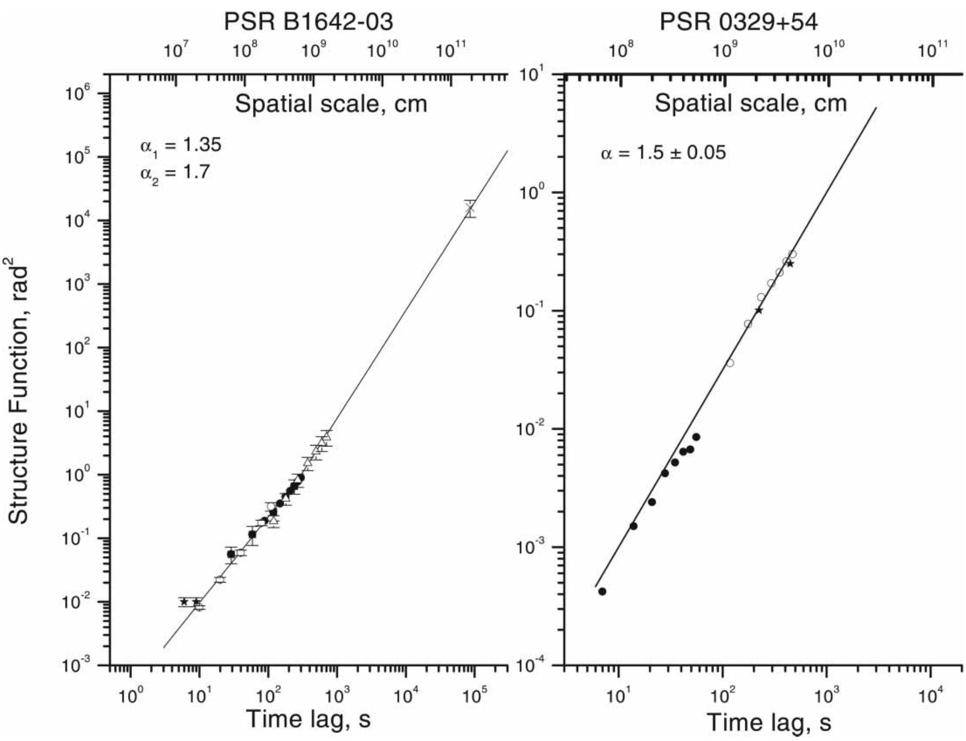

Figure 1. The composite Sfs versus time lag (top axis is the spatial scale) for PSR B1642 − 03 and B0329 + 54. All data were converted into the reference frequency $f_0 = 1000$ MHz. Solid lines correspond to the best fitting power law to points.

Table 1. Pulsar parameters.

PSR	R(pc)	V km/s	n	Refraction
B0329 + 54	1000	95	3.5 ± 0.05	+
B0437 − 47	150	30	3.46 ± 0.2	+
B0809 + 74	433	102	3.7 ± 0.1	−
B0950 + 08	262	36.6	3 ± 0.05	+
B1642 − 03	160	20	3.35 ± 0.03; 3.7 ± 0.02	−

differ from the ones used in [4] ($V = 139$ km/s). In this figure, the SF is based on the observations at 102 MHz (filled circles), 610 MHz (open circles), and 5 GHz (stars). The slope of the composite SF is flatter than it should be for the Kolmogorov spectrum: $\alpha = 1.5 \pm 0.05$. As was shown in [4], we have a strong angular refraction in the direction to this pulsar. This conclusion was based on the analysis of the frequency SF for two models: diffractive and refractive. The velocity, distance, and the power of spectrum, n, are presented in table 1 for all analyzed pulsars. Existing angular refraction in the direction to each pulsar were marked by signs '+' or '−', and we put them in the corresponding column of table 1.

The composite SF of phase fluctuations for pulsars PSR B0437 − 47, B0809 + 74, and 0950 + 08 are shown in figure 2 and 3. The SF for PSR B0437-47 is based on analysis of scintillation data for this pulsar [9] at 327 MHz (close circles), 328 MHz (squares and stars), and 436 MHz (open circle). All data were reduced to the reference frequency $f_0 = 1000$ MHz. The solid line indicates the best-fit to all points ($\alpha = 1.46 \pm 0.2$). The distance to this pulsar is known from parallax measurement [8]: $R = 150$ pc. We suggested in [9] that the scattering of

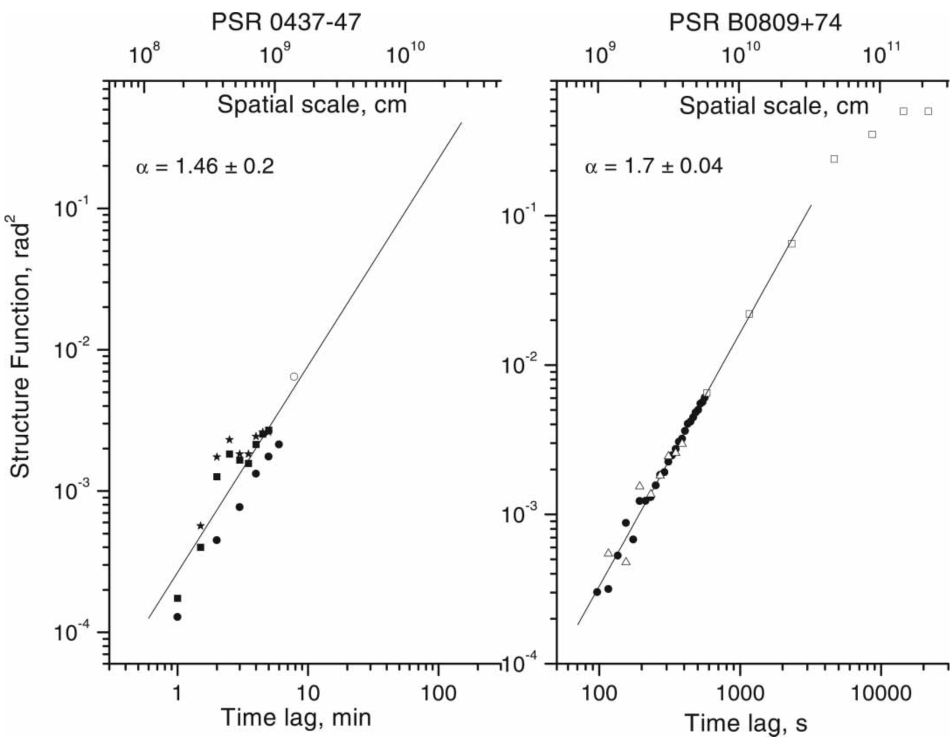

Figure 2. The composite SFs versus time lag (top axis is the spatial scale) for PSR B0437 − 47 and B0809 + 74. Solid lines correspond to the best-fit to data.

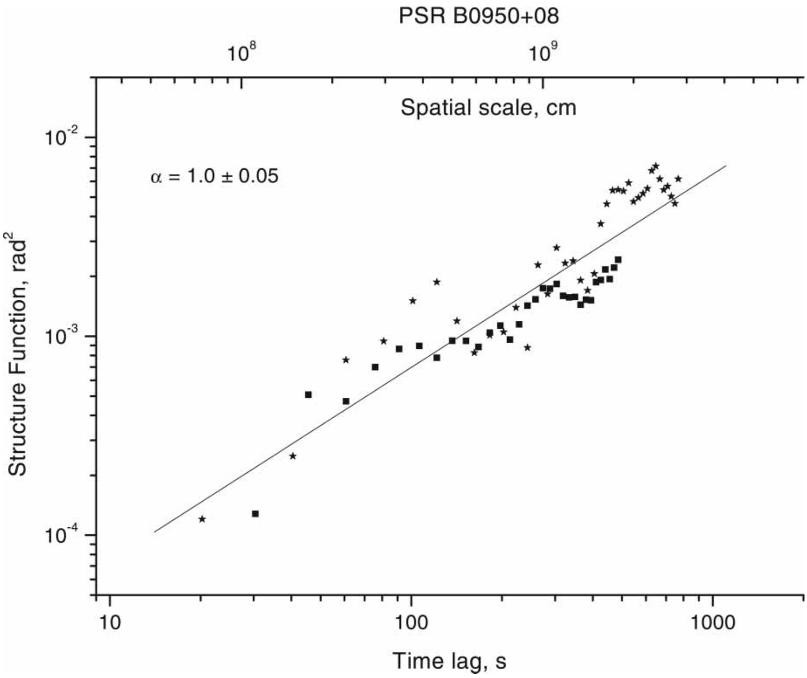

Figure 3. The composite SFs versus time lag (top axis is the spatial scale) for PSR B0950 + 08. Solid line corresponds to the best-fit to data.

this pulsar lies in a layer of enhanced turbulence, which is ~10 pc from the sun. We therefore used the transverse velocity $V = 30\,\mathrm{km/s}$ to convert the time scale into the spatial one. We also obtained a strong angular refraction in this direction [9].

SF analysis for PSR B0809 + 74 and 0950 + 08 was done using our scintillation observations with the Large Phased Array at frequency 112 MHz and Crust telescope of the Pushchino Radioastronomy Observatory at frequencies 62.43 and 88.57 MHz carried out in December–January 2001, 2003, and 2004. A Multi-channel receiver with a bandwidth of 20 KHz or 1.25 KHz (for the lowest frequency) per channel was used for these observations. The time of pulse accumulation ranged from 5 to 51 s at different frequencies. Detailed analysis of these data will be presented in a forthcoming paper and here we show only the resulting temporal composite SF (figure 2 and 3). The distances and transverse velocities for PSR B0809 + 74 and 0950 + 08 are known from parallax measurements [8] and we present them in table 1.

We assumed here that scattering material is homogeneously distributed along the line of sight. All data in figures were reduced to the reference frequency $f_0 = 1000\,\mathrm{MHz}$. In figure 2 (PSR B0809 + 74), data at $f = 112\,\mathrm{MHz}$ are shown by close circles, at $f = 88.57\,\mathrm{MHz}$ by triangles. We also used scintillation data for this pulsar from [10] obtained at $f = 933\,\mathrm{MHz}$ (squares). Fitting gives us the slope of SF: $\alpha = 1.7 \pm 0.04$, which is close to the Kolmogorov value ($\alpha = n - 2$). To constructing the SF for PSR 0950+08 (figure 3), we used data at $f = 88.57\,\mathrm{MHz}$ (stars) and $f = 62.43\,\mathrm{MHz}$ (squares). The slope of SF is $\alpha = 1.0 \pm 0.05$, which is much less than it should be for the Kolmogorov spectrum. We obtained that the slope of the SF function for PSR B0950 + 08 is the same as for the temporal SF. This should be true only in the presence of a strong angular refraction in this direction. The slope of the frequency SF should be half of the temporal SF [4] for the diffractive model, which is not the case.

4. Conclusions

Multi-frequency observations of pulsar interstellar scintillation give us more accurate information about the shape of the turbulent spectrum in definite directions of the sky in a wide range of spatial scales. As we had shown, the interstellar plasma spectrum for four from five nearby pulsars are well described by a power law with n from 3 to 3.5 for scales from 10^7 to 10^{10} cm, which differs from the Kolmogorov one. Although conversion of a temporal scale into spatial depends on distribution of scattering material along the line-of-sight, the shape of the spectrum will be the same.

We detected strong angular refraction of radiation in the direction of three pulsars: 0329 + 54, 0437-47 and 0950+08.

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