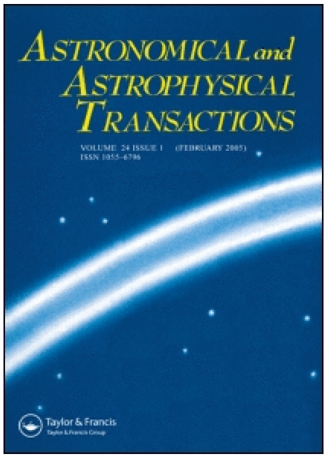

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SPECTRUM OF ELECTRON DENSITY FLUCTUATIONS IN THE INTERSTELLAR MEDIUM FROM PULSAR OBSERVATIONS

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We present here our new results about the shape of the turbulent spectrum based on pulsar observations.

KEY WORDS scintillations, interstellar medium, pulsars

Refractive scintillations of pulsar radioemission provide a powerful method for studying of the spectrum of electron density fluctuations in the interstellar plasma. Refractive scintillations are attributed to weak focusing of the radiation by inhomogeneities in the interstellar medium with scales 10^{12}–10^{15} cm. As a result we see long time scale flux variations, fringe-like patterns in the pulsar spectrum, and an angular shift of the image.

Recently we developed the theory of refractive scintillation of pulsar radioemission (Smirnova, Shishov, Stinebring, 1998 (SSS in this paper)) which is very useful for extracting information about the electron density fluctuation spectrum from observational data. We studied two types of spectra of the fluctuation of the electron density in interstellar matter. The spectrum of the first type is a power spectrum:

$$\Phi_{\mathrm{Ne,I}}(q) = C_{\mathrm{Ne,I}}q^{-n} , \tag{1}$$

where $C_{\mathrm{Ne,I}}$ characterizes the level of turbulence. The spectrum of the second type is a piecewise power spectrum:

$$\Phi_{\mathrm{Ne,II}}(q) = \begin{cases} C_{\mathrm{Ne,II}}q^{-n}, & q < 1/l, \quad 3 < n < 4 \\ C_{\mathrm{Ne,II}}l^{n_1-n}q^{-n_1}, & q > 1/l, \quad n_1 > 4, \end{cases} \tag{2}$$

where l is the spatial scale at the break of the spectrum, that is, where the exponent changes. We obtained an expression for the structure function, index of modulation of the pulsar flux, m_{ref}, refractive time scale, T_{ref}, and characteristic scales for the frequency and time decorrelation, f_{dif} and t_{dif}, of the emission for both spectra for four different distributions of the turbulent medium between the source and the observer: (1) a uniform medium; (2) a phase screen, where the turbulent medium is concentrated in a layer of thickness Δr_0 located at a distance r_0 from the source ($\Delta r_0 \ll r_0$); (3) a layer near the source, that is $r_0 \ll R$; (4) a layer near the observer, $R - r_0 \ll R$.

Basically the results obtained are as follows: the dependence of the modulation index on the characteristic scale of the decorrelation in frequency, $m_{\rm ref}(\Delta f_{\rm dif})$, is defined only by the type of spectrum, and does not depend on the distribution of the medium along the line of sight. For example for the power spectrum: $m_{\rm ref} \propto (\Delta f_{\rm dif}/f)^{(4-n)/2}$, and for the piecewise power spectrum: $m_{\rm ref} \propto (\Delta f_{\rm dif}/f)^{(4-n)/4} l^{(4-n)/2}$. The exponents differ by a factor of 2. On the other hand the structure function, $D_{\rm I}(t)$, does not depend on the type of spectrum when $t \leq T_{\rm ref}$ and is defined by the distribution of the scattering material along the line of sight. That is, $D_{\rm I}(t) = 1/2(t/T_{\rm ref})^{n-3}$ for a uniform medium and a layer near the source. For a phase screen and a layer close to the observer: $D_{\rm I}(t) = 1/2(t/T_{\rm ref})^2$.

As was shown in our paper (Stinebring and Smirnova *et al.*, 1996) flux variations of pulsars with a time scale from 1 day up to several years are defined only by refractive scintillations on interstellar plasma inhomogeneities. The experimental data obtained at Green Bank Observatory at 610 MHz were fluxes of 21 pulsars observed over 5 years practically every day(Stinebring, Smirnova *et al.*, 2000). As a result we had a long time series of fluxes. The analysis of $T_{\rm ref}$, $m_{\rm ref}$, and the logarithmic slope of the structure function, γ, gives us information about the spectrum of electron density fluctuations.

We showed, from the analysis of these data, that for $DM > 30$ pc cm^{-3} the interstellar medium is highly non-uniform and the variations of the scintillation parameters are basically determined by variations of the electron density in different directions. The high correlation of $t_{\rm dif}/T_{\rm ref}$ with $\Delta f_{\rm dif}$ of these parameters proves that both diffractive and refractive scintillation are produced in irregularities that belong to a single turbulence spectrum.

Examination of the dependence of $m_{\rm ref}$ on $\Delta f_{\rm dif}$ normalized to the observing frequency f, (Figure 6 of SSS paper) has shown that the data fall into two groups with different slopes for these branches. The exponent of the power is different by a factor of 2 between the two groups, which agrees with theoretical predictions. The best agreement with observations of group I pulsars (the slope is twice less), is for the spectrum model with a brake and a medium close to the source. The scale of the break is defined by the condition that the two branches of this dependence, $m_{\rm ref}(\Delta f_{\rm dif}/f)$, coincide at $\Delta f_{\rm dif}/f = 10^{-3}$. This corresponds to the field coherence scale, r_c, and the scale of inhomogeneities causing diffractive scintillations at 610 MHz are about (10^{10}–3×10^{10}) cm. Refractive scintillations are defined by inhomogeneities with a scale about the size of the scattering disk, $R\Theta_{\rm sc}$. If the scale of the breaking point in the spectrum is $l < r_c$ these dependences will have the same slope because in this case the scattering angle will be defined by the scale of diffractive scintillations for both types of spectra ($\Theta_{\rm sc} = 1/kb_{\rm dif}$). If $l > r_c$ then the scattering angle will defined by l and these dependences will separate from each other: for a pure power spectrum it will be twice as steep. For the second group the best agreement of the theory and observations is given for a model of the turbulent medium uniformly distributed between the source and the observer and having a Kolmogorov type spectrum with $n = 11/3$. The corresponding theoretical prediction well describes the experimental data.

In general the results of analysis of the dependence of $m_{\rm ref}$ on $\Delta f_{\rm dif}/f$ can be set in the following manner. In the interstellar medium there are two types of turbulent medium. The medium of the first type is characterized by a piecewise power spectrum of turbulent fluctuations of Kolmogorov type with a characteristic scale $l \cong 3 \times 10^{10}$ cm, and is concentrated in compact regions with an increased concentration of electrons. The medium of the second type is characterized by a pure power spectrum of turbulence of Kolmogorov type that is distributed in a diffuse uniform manner in galactic space. We can put a strong limit on the slope of the pure power spectrum by fitting the theoretical curves with different slopes to the experimental data. The resulting value of n is in the range $3.5 \leq n \leq 3.7$.

The average value of the slope of the structure function for the pulsars we investigated is 0.7. For most pulsars we have the case of the turbulent layer close to the source or a statistically uniform medium which corresponds to the theory with $\gamma = n - 3$, which is $\gamma = 0.67$ for $n = 11/3$. For six pulsars the analysis of the structure function has shown a break which corresponds to characteristic scales 5×10^{12}–2×10^{13} cm (Stinebring *et al.*, 2000). The break in the structure function is determined either by the inhomogeneity of the interstellar medium along the line of sight in the direction of these pulsars, or by having another break at these scale sizes. From a summary of different studies Armstrong *et al.* (1995) present evidence for a roughly power spectrum extending over 12 orders of magnitude on the size scale (10^{18} cm to 10^{20} cm) for density fluctuations of the nearby ISM ($R \leq$ 1kpc). Now we have concluded that 2 types of interstellar medium with 2 different spectra are realized in the interstellar medium.

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