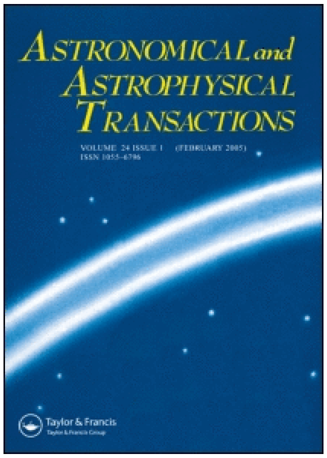


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# INTERSTELLAR SCINTILLATION AND THE INTERSTELLAR TURBULENT PLASMA

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# INTERSTELLAR SCINTILLATION AND THE INTERSTELLAR TURBULENT PLASMA

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Data on interstellar diffractive and refractive scintillation of pulsars are analyzed. The comparison between the theory and the observational data shows that two types of spectra for electron density fluctuations are realized in the interstellar medium: simple power law and piecewise with a break. The distribution of turbulent plasma in the Galaxy has a two component structure. Component A is diffuse and it is distributed outside of the spiral arms of the Galaxy. Component B is cloudy and it is associated with Galactic arms. The origin of the interstellar plasma turbulence is considered. The possible sources of turbulent energy are discussed. The contribution of supernova bursts in the interstellar gas ionization and generation of turbulence are analyzed among other factors.

*Keywords*: Interstellar plasma; Scintillation; Turbulence

## 1 INTRODUCTION

In his pioneer work Scheuer (1968) supposed that pulsar intensity fluctuations with a fine frequency structure and a temporal scale of order of minutes are determined by scintillation on irregularities of the interstellar medium. In the next year Rickett (1969) showed, that the frequency scale of the intensity fluctuations of pulsars decreases with the increasing of dispersion measure *DM*. This result proved the interstellar origin of the small scale intensity variations. In 1982 Sieber revealed, that characteristics of the slow pulsar flux fluctuations with time scales of order of days and months depend on dispersion measure *DM* also. Large sets of data were obtained for 30 years of investigations and we have a lot of information on the interstellar turbulent clouds causing interstellar scintillation. However up to now we don't have universally adopted model of the interstellar plasma turbulence.

## 2 DATA ON SCATTERING AND SCINTILLATION

The modulation of radio waves propagating through interstellar medium is caused by inhomogeneities of the refractive index. For a plasma, the refractive index at frequencies much higher than the plasma frequency $\omega_p$ is (Ginzburg, 1967; Salpeter, 1967)

$$n \cong 1 - \left(\frac{1}{2}\right)\left(\frac{\omega}{\omega_p}\right) = \left(\frac{1}{4\pi}\right) r_e \lambda^2 N_e, \tag{1}$$

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where $\omega$ is the cyclic frequency, $\lambda$ is the wavelength, $r_e$ is the classical electron radius, and $N_e$ is the electron number density. We can see that the refractive index depends only on the electron density. The basic parameter of the interstellar plasma that is used in pulsar investigations is dispersion measure

$$DM = \int \mathrm{d}r\, N_e \tag{2}$$

where path length is measured in parsecs and electron density in $\mathrm{cm}^{-3}$. The dispersion measure determines a time delay due to the interstellar plasma

$$t = 2.2 \times 10^{-6} \lambda^2 DM[\mathrm{sec}] \tag{3}$$

and total phase of wave

$$S = 4.2 \times 10^5 \lambda DM[\mathrm{rad}] \tag{4}$$

Small scale variations of electron density are described by a turbulent spectrum

$$\Phi_{N_e}(\mathbf{q}) = \left\langle \left[ \int \mathrm{d}^3\mathbf{q} \exp(-i\mathbf{qr}) N_e(\mathbf{r}) \right]^2 \right\rangle, \tag{5}$$

where $\mathbf{q}$ is spatial frequency and angular brackets denote ensemble average over the medium fluctuations. These inhomogeneities can be described by a structure function of phase or dispersion measure variations

$$D_S(\rho) = \langle [S(\rho_1 + \rho) - S(\rho_1)]^2 \rangle = 1.8 \times 10^{11} \lambda^2 D_{DM}(\rho), \tag{6}$$

where $\rho$ is distance between two points in the plane normal to the line of sight. For the case of spherical wave one can obtain

$$D_S(\rho) = \int_0^R D\left[\left(\frac{r}{R}\right)\rho\right] \mathrm{d}r \tag{7}$$

$$D(\rho) = 4\pi(\lambda r_e)^2 \int \mathrm{d}^2\mathbf{q}_\perp [1 - \cos(\mathbf{q}_\perp \rho)] \Phi_{N_e}(\mathbf{q}_\perp, q_l = 0), \tag{8}$$

where the gradient of the phase structure function $D(\rho)$ is a principal value in the theory of scintillation. The following effects of radio wave modulation by the interstellar turbulent plasma are observed:

I. Scattering effects
  - (a) The angular scattering. Characteristic scale is $\Theta_{\mathrm{scat}}$.
  - (b) The pulse broadening. Characteristic scale is $\tau$.

II. Scintillation effects
  - (c) Weak scintillation. Parameters are: $m_{\mathrm{weak}}$ – scintillation index, $t_{\mathrm{weak}}$ – characteristic temporal scale.
  - (d) Strong or saturated scintillation
    - (d1) Diffractive scintillation. Parameters are: $m_{\mathrm{dif}} \cong 1$ – scintillation index, $t_{\mathrm{dif}}$ – temporal scale, $\Delta f_{\mathrm{dif}} \cong 1/2\pi\tau$ – frequency scale
    - (d2) Refractive scintillation. Parameters are: $m_{\mathrm{ref}}$ – scintillation index, $T_{\mathrm{ref}}$ – temporal scale.

Theory of wave propagation in random media is well developed now (see, for example, Prokhorov *et al.*, 1975; Martin and Flatte, 1988; Shishov, 1992; Smirnova *et al.*, 1998). Modulation effects caused by plasma depend only on power spectrum of electron density fluctuations. Theory shows that wave evolution is essentially different for three types of a turbulent spectrum (Shishov, 1993): 1) Kolmogorov type

$$\Phi_{N_e}(\mathbf{q}) = C^2_{N_e} q^{-n}, \quad 1/L < q < 1/l, \; 3 < n < 4, \tag{9}$$

here $L$ is outer and 1 is inner scales of turbulence, $C^2_{N_e}$ is a coefficient that is proportional to the square of the electron density fluctuations variance; 2) Steep power law type, that determined by Eq. (1) with $4 < n < 6$; and 3) one scale (Gaussian) type. Kolmogorov type spectrum leads to two scales scintillation pattern in strong or saturated regime: small scale or diffractive and large scale or refractive. Refractive scintillation index decreases with increasing distance. Steep power law spectrum gives the similar picture for strong scintillation. But the scintillation index of the large scale component is constant. A strong angle refraction exists for this case. The Gaussian type spectrum gives only the diffractive scintillation component in the saturated regime.

Rickett *et al.* (1984) supposed, that refractive and diffractive interstellar scintillation are caused by effects of wave propagation through medium with a single power law (Kolmogorov) spectrum of electron density irregularities. For this spectrum and for the case of saturated scintillation one can obtain the next equations (Smirnova *et al.*, 1998)

$$\begin{aligned} T_{\text{ref}} &\propto \left(\frac{R\Theta_{\text{scat}}}{V}\right) \\ t_{\text{dif}} &\propto \left(\frac{1}{k\Theta_{\text{scat}}V}\right) \\ \Delta f_{\text{dif}} &\propto \left(\frac{c}{\pi R\Theta^2_{\text{scat}}}\right), \end{aligned} \tag{10}$$

here $k$ is wave number, $V$ is the pulsar velocity, $c$ is the speed of light, $R$ is distance. It follows from the Eq. (10), that one can expect the correlation between variations of the parameters of diffractive and refractive scintillation. Analysing the observational data for 21 pulsars at 610 MHz, Smirnova *et al.* (1998) showed, that the ratio of the characteristic time scales for diffractive and refractive scintillation is proportional to the decorrelation bandwidth

$$\left(\frac{T_{\text{ref}}}{t_{\text{dif}}}\right) \propto \Delta f_{\text{dif}} \tag{11}$$

This relation is evidence for Kolmogorov type spectrum because this dependence follows from the Eq. (10). The power law index $n$ can be determined by using the dependence of the refractive scintillation modulation index on the decorrelation bandwidth $\Delta f_{\text{dif}}$.

## 3 TURBULENCE IN THE NEARBY INTERSTELLAR MEDIUM

Cordes *et al.* (1985) established, that turbulent interstellar plasma is concentrated in compact clouds and the distribution of clouds in the Galaxy has a two component structure. Component A is diffuse, localized in interarm regions and has a distribution that is nearly statistically uniform. Component B has essentially nonuniform distribution in the Galaxy and is associated with the galactic arms. It was shown in (Smirnova *et al.*, 1998) that component B can, in turn, be separated into two subcomponents. Sub-component BI is characterized by a Kolmogorov turbulent spectrum and is distributed more uniformly in Galactic space. The spectrum of subcomponent BII can be described by a power law with inner scale $l \approx 3 \times 10^{10}$ cm, and this subcomponent is concentrated in compact regions adjacent to pulsars.

Pynzar' and Shishov (1997; 1999) investigated more detaily statistical relations between scattering and scintillation parameters on the one hand, and dispersion measure *DM* and emission measure *EM*, on the other hand. The most of observation data were obtained for the pulse broadening time $\tau$ and for the decorrelation width, $\Delta f_{\rm dif}$, that can be reduced to $\tau \approx 1/2\pi\Delta f_{\rm dif}$. These data were reduced to frequency $f = 300$ MHz. For small values of *DM* observations can be described by a single power law

$$\tau \propto DM^2, \quad DM < 50\,{\rm pc/cm^3} \tag{12}$$

The relation (12) is consistent with the distribution of the turbulent plasma in a statistically uniform model and corresponds to component A of the distribution of the turbulent clouds in the Galaxy.

It could be shown that for the different kinds of pulsar observations connected with the propagation through the interstellar plasma a composite 3-dimensional spatial spectrum of the electron density can be constructed and that this spectrum follows a power law over a very wide range of scales ($10^6$ to $10^{15}$ m). This spectrum fits the experimental data quite well for the nearby ISM ($\leq$1 kpc) (Armstrong *et al.*, 1995; Shishov and Smirnova, 2002). The 3-dimensional spatial spectrum of the electron density can be described by a Kolmogorov spectrum with a power law index $n = 11/3$.

Although the Kolmogorov spectrum describes the data sufficiently well in a statistical sense, the dispersion of the points is large and the spectrum may differ from a Kolmogorov one in specific directions to given sources. In general, there are two types of power law spectra known for turbulent plasma: the Kolmogorov spectrum with $n_K = 11/3$ (Tu *et al.*, 1984) and the spectrum of weak plasma turbulence with $n_{\rm wpt} = 3.5$ (Iroshnikov, 1963; Kraichnan, 1965). The difference between $n_K$ and $n_{\rm wpt}$ is unfortunate small, about 5%, whereas the accuracy of the measurements of the value of $n$ is not better than 10%. New measurements with much higher accuracy are therefore urgently needed. More detail this problem is discussed in paper (Shishov *et al.*, 2002).

Using data on the turbulent spectrum and the outer scale one can estimate the value of the electron density fluctuations $\Delta N_{\rm e} \cong 4 \times 10^{-4}\,{\rm cm^{-3}}$. The relative level of the energy of the plasma turbulence is order of $\delta \cong (\Delta N_{\rm e}/N_{\rm e})^2 \approx 10^{-2}$. Therefore the plasma turbulence in the region between the Galaxy arms is week. However this turbulence can be important in the energy balance in the interstellar plasma because the energy source due to the turbulence dissipation is compared with the energy losses due to plasma radiation.

The problem of the origin of turbulence in the nearby interstellar plasma is open up to now. The solution of this problem is difficult for reason of the statistically uniform distribution of the turbulent inhomogeneities in the nearby Sun region.

## 4 TURBULENCE IN THE SPIRAL ARMS OF THE GALAXY

For large values of dispersion measure (Pynzar' and Shishov, 1999)

$$\tau \propto DM^{4.5}, \quad DM > 50\,{\rm pc/cm^3} \tag{13}$$

This dependence can be explained if electron density variations is the main factor for variations of *DM* and $\tau$. The region of large values of *DM* corresponds to the component B of the distribution of turbulent clouds. Observational refraction scintillation data for 21 pulsars at 610 MHz show two groups of points for large value of *DM* (Smirnova *et al.*, 1998). Group I corresponds to a medium with a piecewise power law spectrum with the value $n \cong 11/3$ and inner scale $l \cong 3 \times 10^{10}$ cm. Group II corresponds to the pure power law spectrum with the value $n \cong 11/3$. This means that the spectrum shape is different for different regions of the interstellar medium. Unfortunately data on outer scale of the turbulent spectra are absent.

Analysis of the turbulent clouds distribution along the line of sight showed that the turbulent plasma is frequently located near pulsars (Smirnova *et al.*, 1998). Therefore one can expect the association between pulsars and the turbulent plasma with the density enhancement. To check this assumption we investigated the dependence of pulsar number density on the sky, $N/S$, on emission measure, *EM*. Here $N$ is the pulsar number in the spatial angle, $S$. The statistical data show that the pulsar number density increases with increasing *EM* up to the value of order of $EM_0 = 1000\,\text{pc}/\text{cm}^6$ (Pynzar' and Shishov, 2001). The characteristic angular scale the HII region corresponded $EM_0$ is of order of $3^\circ$.

Then for investigation of possible temporal evolution of the pulsar and gas complexes we analyzed the dependence of the emission measure in the direction to the given pulsar, *EM*, on the pulsar age, $T$. The distribution of points on the plane $\log EM$–$\log T$ shows well defined lower boundary $EM_{\min}$, that decreases with increasing $T$ for $10^3$ years $< T < 10^6$ years. This means that pulsar in this boundary region and plasma in the nearby pulsar HII region are burnt at the same time – the time of the supernovae burst. Using these values of $EM_{\min}$ and data for *DM* one can obtain dimensions $D$ of HII regions nearby pulsars with ages $T$ of order of $10^3$ years in the boundary region and electron densities $N_e$ in these regions. If the temperature value is $T_e = 10^6$ K one can obtain (Pynzar' and Shishov, 2002)

$$\begin{aligned} D &\cong 30\,\text{pc} \\ N_e &\cong 7\,\text{cm}^{-3} \end{aligned} \tag{14}$$

For this case the energy of ionization is of order of $E_{\text{ioniz}} \cong 10^{51}$. The problems of the electron temperature in HII regions and energy of the ionization should be investigated more detaily.

Also, the distribution of points on the plane $\log \tau$–$\log T$ shows well defined lower boundary $\tau_{\min}$, that decreases with increasing $T$ for $10^3$ years $< T < 10^6$ years. This boundary $\tau_{\min}$ can be described by the relation (Pynzar' *et al.*, 2002)

$$\tau_{\min} \cong \frac{\tau_0}{(t/1000\,\text{years})^2}, \quad \tau_0 = 20\,\text{sec} \tag{15}$$

It means that turbulent fluctuations are generated during the first one thousand years of an evolution of the Stremgren zones of a supernova.

We see that the supernovae explosion can be important source of the ionization energy of the interstellar plasma. The evolution of the HII region excited by the supernovae burst must be considered with taking into account the instability of the cooling plasma. This instability leads to the fragmentation of the plasma to dense clouds with the size of order of

$$L \approx V_s \cdot T_{\text{rec}} \approx 0.1\text{–}1\,\text{pc} \tag{16}$$

Here $V_s$ is the speed of sound and $T_{\text{rec}}$ is the recombination time. A series of the successive supernovae bursts can generate the strong plasma turbulence with the outer scale $L$ because sudden heating leads to the expanding of the dense clouds and collisions between them.

The data for the main part of pulsars show, on average, decreasing emission measure, *EM*, with increasing pulsar age, *T*. The characteristic time of this decrease is of order $T = 10^6$ years (Pynzar' and Shishov, 2001). It is possible that this time corresponds to the active stage of star formations and supernovae events.

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### *References*

Blanford, M. and Narayan, M. (1985). Month. Not. R. *Astron. Soc.*, **213**, 591.
Cordes, J. M. and Rickett, B. J. (1998). *ApJ*, **502**, 846.
Cordes, J. M., Weisberg, J. M. and Boriakoff, V. (1985). *ApJ*, **288**, 221.
Martin, J. M. and Flatte, S. M. (1988). *Applied Optics*, **27**, 2111.
Prokhorov, A. M., Bunkin, V. F., Gochelashvily, K. S. and Shishov, V. I. (1975). *Proc. IEEE*, **63**, 790.
Pynzar', A. V. and Shishov, V. I. (1997). *Astronomy Reports*, **41**, 663.
Pynzar', A. V. and Shishov, V. I. (1999). *Astronomy Reports*, **43**, 504.
Pynzar', A. V. and Shishov, V. I. (2001). *Galaxy. Astronomy Reports*, **45**, 502.
Pynzar', A. V. and Shishov, V. I. (2002). *A&A Trans.* (this issue).
Pynzar', A. V., Shishov, V. I. and Chashei, I. V. (2002). *A&A Trans.* (this issue).
Smirnova and Shishov, V. I. (2002). *A&A Trans.* (this issue).
Rickett, B. J. (1969). *Nature*, **221**, 158.
Rickett, B. J., Coles, W. A. and Bourgois, G. (1984). *A&A* **134**, 390.
Sheuer, P. A. G. (1968). *Nature*, **218**, 920.
Shishov, V. I. (1992). Theory of wave scintillations. In: Tatarski, V. I., Ishimaru, A. and Zavoronty, V. U. (Eds.), *Waves in Random Media (Scintillation).* Invited papers of a conference held 3–7 August, 1992, Seattle, Washington, pp. 272–290.
Shishov, V. I. (1995). *Waves in Random Media*, **5**,497.
Sieber, W. (1984). *A&A*, **113**, 311.
Smirnova, T. V., Shishov, V. I. and Stinebring, D. (1998). *Astronomy Reports*, **42**, 766.
Stinebring, D. R., Faison, M. D. and McKinnon, M. M. (1996). *ApJ*, **460**, 460.
Shishov, V. I., Smirnova, T. V., Sieber, W., Malofeev, V. M., Potapov, V. A., Stinebring, D., Kramer, M., Jessner, A. and Wielebinski, R. (2002). *A&A* (in press).