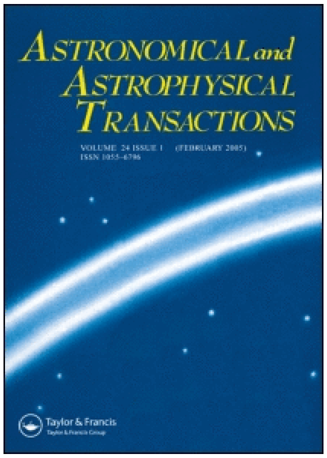

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Measurements of the scattering of pulsars radio emission. Statistical uniformity of large-scale plasma turbulence in the near Galaxy

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We report the low frequency measurements of the scatter pulse broadening τ_{sc} for a large sample of 100 pulsars in a vast Galaxy region of galactic longitudes from 6° to 311° and distances up to 3 kpc. Analysis of τ_{sc} dependencies on the frequency, dispersion measure, distance and Galactic longitude have been done. The scatter to frequency dependence can be presented by the power-low relation $\tau_{sc}(\nu) \propto \nu^{-\gamma}$ with $\gamma = 4.1 \pm 0.3$. Up to a distance of 3 kpc the scatter to dispersion measure dependence can be presented by the power-low relation $\tau_{sc}(\mathrm{DM}) \propto \mathrm{DM}^{2.2\pm0.1}$. The turbulence level C_n^2 is nearly identical in various directions and distances of the near Galaxy, testifying to the statistical homogeneity of a large-scale plasma turbulence in this Galaxy region.

Keywords: Interstellar matter; Scatter; Pulsars: general; Interstellar matter

1. Introduction

Pulsars as the point sources of a pulsed radio emission, distributed over the whole Galaxy, are a good instrument for investigating the scatter and turbulent plasma properties in our Galaxy.

There is a great deal of scatter of pulsar radio emission measurements. However these data are not uniform and their analyses are not unambiguous. Measurements of the frequency dependence $\tau_{sc} \propto \nu^{\gamma}$ demonstrate a large spread of a power index γ between 3.1 and 5.0 [1–9]. Such as wide scatter of the frequency dependence data may be due to the measurement error over a small range of frequencies. One needs measurements in a wide frequency range. The dispersion measure dependence $\tau_{sc}(\mathrm{DM}) \propto \mathrm{DM}^{-\alpha}$ also demonstrate a significant spread of the α value.

The most complete and widely used set of the pulse scatter data, tabulated in the “Catalog of 706 Pulsars” [10] contains scatter data for 143 pulsars. However, these data are not based on direct measurements and represent a collection of non-uniform measurements by various

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observers obtained using different parameters (decorrelation bandwidth $\Delta\nu$ or pulse time broadening τ_{sc}) at various frequencies recalculated to the frequency of 1 GHz.

Uniform measurements of scatter parameters were performed only for a small number of pulsars. Most of these are measurements of 15 pulsars at 160 MHz [11], 56 pulsars at 102 MHz [5], 21 pulsars at 430 MHz, 29 pulsars at 1175 MHz, and 14 pulsars at 1474 MHz [9].

We report the low-frequency direct homogeneous measurements of a single scatter parameter—pulse scatter broadening τ_{sc} for the most complete set of 100 pulsars in the vast Galaxy region of Galactic for longitudes of 6° to 311° and distances up to 3 kpc at the same frequency, 111 MHz, using a single reduction method. Low frequency expands a frequency interval of τ_{sc} data and provides a more precise determination of the frequency dependence $\tau_{sc} \propto \nu^{\gamma}$. A large sample of pulsars and uniform measurements and reduction processes provide more precise determination of a dispersion measure dependence τ_{sc} (DM). The vast scope of the Galaxy provides a study of the inhomogeneity of a Galactic scattering medium.

2. Observations and data reduction

The measurements were performed from 2003 to 2005. The major part of the observations were carried out at 111 and 102 MHz with the Large Phase Array Radio Telescope (BSA) at Pushchino Radio Astronomy Observatory. Additional observations were performed at 44 and 63 MHz with the DKR Radio Telescope. One linear polarization was received. The 128-channel receiver with channel bandwidth 20 or 1.25 kHz was used.

All observations were time-referenced to the Observatory's rubidium master clock, which in turn was monitored against the National Time standard via TV timing signals. During the off-line data reduction, the signal records were cleaned of radio interferences. Subsequently, the inter-channel dispersion delays imposed by an interstellar medium were removed.

The scatter of Grab pulsar PSR B0531 + 21 is variable. Therefore for this pulsar we used "quit" scatter period MJD 53000 − 53173.

The scatter broadening value was determined by the last square approximation of the observed pulse and the convolution of a template pulse with a truncated exponent

$$G(t) = \{ \begin{array}{l} \exp\left(\frac{-t}{\tau_{sc}}\right) \text{ for } t \geq 0 \\ 0 \text{ for } t < 0 \end{array}$$

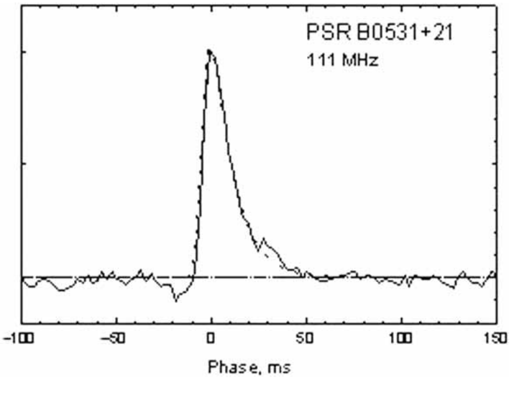

Figure 1. An example of a pulse scatter measurement for pulsar PSR B0531 + 21.

that corresponds to the scatter of the delta function pulse on a thin screen. The values of the pulsar pulse scatter broadening $\tau_{\rm sc}$ were determined as the fitting result. An example of this procedure is shown in figure 1. The solid line shows the observed pulse, and doted line the model convolution of the template pulse with the thin screen scattering function.

3. Results and analysis

Results of the measurements of the pulse scatter broadening $\tau_{\rm sc}$ are listed in table 1.

The columns are: (1) PSR, pulsar name, (2) ν, frequency of observations (MHz), (3) $\tau_{\rm sc}$, the pulse scatter broadening (ms), (4) $\delta\tau_{\rm sc}$, the error of $\tau_{\rm sc}$ (ms) and (5) the logarithm of $\tau_{\rm sc}$(s) at the frequency of 100 MHz.

Analyses of the pulse scatter broadening $\tau_{\rm sc}$ dependencies on frequency, dispersion measure, distance and Galactic longitude have been done.

3.1 *Scatter to the frequency dependence*

Our low frequency measurements appreciably extend the frequency interval available for determining the frequency dependence, enhancing the accuracy of this quantity. Analysis of this dependence has been done for 18 pulsars (PSR $B0329+54$, $B0355+54$, $B0525=21$, $B0531+21, B0540+23, B0740-28, B0823+26, B0919+06, B0950+08, B1133+16, B1508+55, B1612+07, B1642-03, B1919+21, B1933+16, B1937+47, B2303+30$) for which our data, along with scatter measurements from other published works [3, 5, 11–30] provide scatter data at no fewer then five frequencies spanning no less than 10:1. To recalculate the literature data for the decorrelation bandwidth $\Delta\nu$ to the scatter broadening $\tau_{\rm sc}$ we adopted the relation $2\pi\tau_{\rm sc}\Delta\nu=1$.

The resulting frequency dependence $\tau_{\rm sc}\propto\nu^{\gamma}$ is shown in figure 2 as the distribution of the frequency dependent indexes γ.

The mean value for these 18 pulsars is $\gamma=4.1\pm0.3$ that is in favour of the Gaussian turbulence spectra of density irregularities ($\gamma=4.0$) rather then the Kolmogorov one ($\gamma=4.4$).

3.2 *Scatter to the dispersion measure dependence*

The measured scatter to dispersion measure dependence from a sample of 100 pulsars reduced to the frequency of 100 MHz is shown in figure 3.

Up to distances of about 3 kpc it can be presented by the power-law relation $\tau_{\rm sc}({\rm DM})\propto{\rm DM}^{2.2\pm0.1}$, close to the theoretical dependence $\tau_{\rm sc}$ (DM)$\propto$DM^2 expected for a uniform ratio of $\Delta n_{\rm e}/n_{\rm e}$.

3.3 *Turbulence level*

The degree of inhomogeneity of the interstellar plasma $\Delta n_{\rm e}/n_{\rm e}$ are characterized by a turbulence level C_n^2. According to [4]

$$C_n^2=2\times10^{-3}\nu^{\mu}d^{-\mu/2}\Delta\nu^{-(\mu-2)/2}$$

where ν is the frequency (in GHz), d is the distance (in kpc), $\Delta\nu$ is the decorrelation bandwidth (in MHz), $\mu=2\beta(\beta-2)$, β is the spectral index for the electron density power spectrum and the dimension C_n^2 is $m^{-20/3}$. For a Gaussian spectrum $\beta=4$ and $C_n^2=2\times10^{-3}\nu^4d^{-2}\Delta\nu^{-1}$.

Table 1. Pulse scatter broadening.

PSR	ν	τ	$\delta\tau$	$\log\tau^{100}$	PSR	ν	τ	$\delta\tau$	$\log\tau^{100}$
B0011 + 47	111	4	1	−2.22	B1633 + 24	111	2.5	1.0	−2.42
B0031 − 07	44	3	1	−4.25	B1639 + 36A	102	3.0	1	−2.52
J0034 − 0534	111	1	0.5	−3.0	B1642 − 03	111	1.5	0.5	−2.64
						63	7.2	1.2	
B0045 + 33	111	3	1	−2.34	J1652 + 2651	111	4	1	−2.20
B0052 + 51	111	7	3	−2.00	B1706 − 16	102	1.8	1.0	−2.74
B0105 + 65	111	2.5	1	−2.70	J1713 + 0747	102	0.3	0.15	−3.52
B0114 + 58	111	15	3	−1.70	B1737 + 13	111	10	2	−1.82
B0136 + 57	102	25	6	−1.60	B1745 − 12	111	55	24	−1.10
B0138 + 59	111	4	2	−2.22	J1752 + 2359	111	3	1.5	−2.35
B0144 + 59	102	4.7	2	−2.33	B1758 − 03	111	55	30	−1.10
B0154 + 61	111	3.2	1.8	−2.30	J1758 + 30	111	8.4	4	−1.90
B0226 + 70	111	13	2	−1.71	B1802 + 03	102	33	10	−1.48
B0301 + 19	111	0.4	0.2	−3.21	B1818 − 04	102	60	40	−1.22
B0320 + 39	40	130	40	−2.81	B1821 + 05	102	5.5	1	−2.26
B0329 + 54	63	4.9	0.7	−3.38	B1831 − 04	102	50	25	−1.30
	44	15.5	5						
B0331 + 45	102	3.5	2	−2.45	B1839 + 56	111	2.9	1.3	−2.40
B0339 + 53	111	25	5	−1.42	B1839 − 04	111	150	15	−0.65
B0353 + 52	111	45	10	−1.15	B1846 − 06	111	100	40	−0.82
B0355 + 54	111	5.4	1.5	−2.30	B1853 + 01	111	26	10	−1.40
B0402 + 61	111	28	6	−1.38	B1907 + 02	111	140	50	−0.70
B0450 − 18	111	5.5	3	−2.06	B1911 − 04	102	35	15	−1.45
B0450 + 55	111	1.0	0.4	−3.15	B1914 + 09	111	13	10	−1.70
B0523 + 11	111	20	10	−1.50	B1915 + 13	102	40	20	−1.40
B0525 + 21	111	10	5	−2.40	B1919 + 21	111	0.6	0.4	−3.10
						63	4.6	3.2	
						44	14.9	3.6	
B0531 + 21	111	10	3	−1.78	B1933 + 16	111	50	15	−1.10
	63	100	20						
	44	300	80						
J0533 + 04	102	70	30	−1.15	B1937 + 21	111	5	3	−2.10
B0540 + 23	111	15	5	−1.61	B1946 + 35	111	45	10	−1.15
B0559 − 05	111	28	10	−1.36	B1953 + 50	111	2.0	1.3	−2.52
B0609 + 37	102	4	2	−2.38	B1957 + 20	111	4.0	1.0	−2.22
B0611 + 22	111	40	10	−1.32	B2016 + 28	111	1.2	0.2	−2.74
B0621 − 04	111	45	4	−1.20	J2019 + 2425	102	0.6	0.3	−3.22
B0626 + 24	111	55	30	−1.12	B2020 + 28	111	0.5	0.3	−3.12
						63	2.3	1.0	
J0631 + 10	111	60	25	−1.02	B2021 + 51	111	1.3	0.7	−2.70
B0656 + 14	111	1	0.5	−2.82					
B0740 − 28	102	22	5.3	−1.65	B2027 + 37	111	132	10	−0.70
B0751 + 32	111	6	3	−2.05	J2043 + 2740	111	2	1.2	−2.52
B0809 + 74	63	0.6	0.2	−4.39	B2053 + 21	111	4.3	0.8	−2.20
	44	3.9	1						
B0818 − 13	102	6	3	−2.22	B2053 + 36	111	74	25	−0.95
B0823 + 26	63	4	2	−3.68	B2110 + 27	111	1	0.5	−2.82
	44	12	3						
B0919 + 06	111	1.5	0.8	−3.00	B2111 + 46	111	120	40	−0.75
	63	9	5						
	44	25	15						
B0943 + 10	111	1.6	1.1	−2.62	B2113 + 14	102	25	10	−1.60
B0950 + 08	40	0.4	0.3	−4.57	B2154 + 40	111	26	5	−1.40
J1012 + 5307	102	0.5	0.2	−3.30	B2217 + 47	111	3.2	0.3	−2.50
						63	12	9	
						44	70	20	
J1022 + 10	102	0.7	0.3	−3.15	B2224 + 65	102	6	3	−2.22
J1025 − 0709	102	0.3	0.1	−3.52	B2303 + 30	111	13	3	−1.70
			5			63	110	20	
						44	300	100	

(continued)

Table 1. Continued.

PSR	ν	τ	$\delta\tau$	$\log\tau^{100}$	PSR	ν	τ	$\delta\tau$	$\log\tau^{100}$
B1133 + 16	44	2.8	0.9	−4.46	B2310 + 42	111	0.3	0.2	−3.35
B1257 + 12	102	0.5	0.2	−3.30	B2315 + 21	111	1.9	1.6	−2.54
B1508 + 55	63	6.4	4	−3.00	J2322 + 2057	102	0.5	0.3	−3.30
	44	15	5						
B1530 + 27	111	1	0.5	−2.80	B2334 + 61	111	5	2	−2.10
B1541 + 09	111	8	3.0	−1.92	B2351 + 61	111	35	5	−1.28
B1612 + 07	111	1	0.5	−2.85					

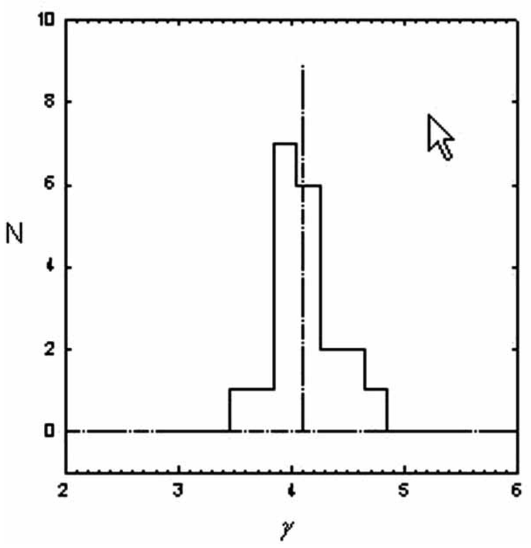

Figure 2. Distribution of the frequency dependent indexes.

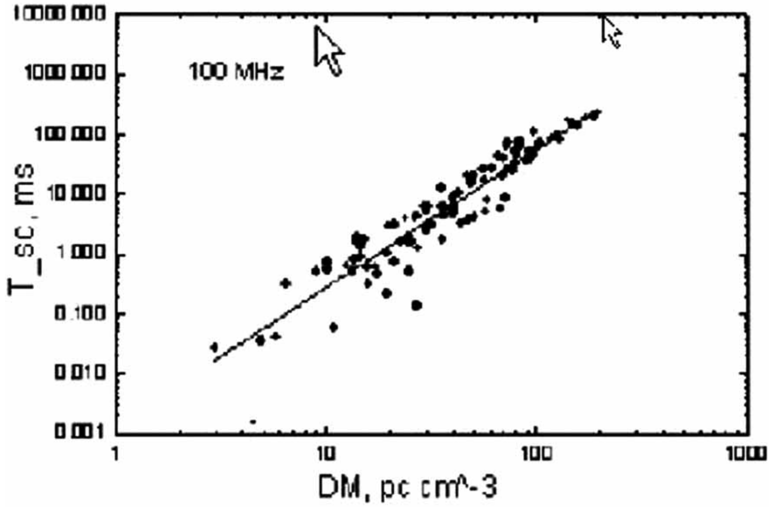

Figure 3. Dependence of the pulse scatter broadening against the dispersion measure. The dotted line shows a power law approximation $\tau_{sc}(\mathrm{DM}) = 60\ (\mathrm{DM}/100)^{2.2}$ ms.

For the frequency of $\nu = 100\,\mathrm{MHz}$ and $\tau_{\mathrm{sc}} = 1/(2\pi\,\Delta\nu)$ the turbulence level is $C_n^2 = 0.00126\tau_{\mathrm{sc}}d^{-2}$.

The distance to the pulsar d was deduced by Cordes-Lazio NE2001 Electron Density Model for the galactic distribution of free electrons and its fluctuations.

The results of calculating the turbulence level C_n^2 are presented in table 2, where l is Galactic longitude and log C_n^2 is the logarithm of the turbulence level.

Table 2. The turbulence level.

PSR	DM	d kπk	l deg	log C_n^2	PSR	DM	d kπk	l deg	log C_n^2
B0011 + 47	31.1	1.57	116	−2.51	B1633 + 24	23.8	1.47	43	−2.65
B0031 − 07	10.8	0.39	110	−3.19	B1639 + 36A	30.3	1.91	59	−3.17
J0034 − 0534	13.7	0.54	111	−2.46	B1642 − 03	35.6	1.12	14.1	−2.90
B0045 + 13	41	2.20	122	−2.92	J1652 + 2651	41	3.70	47.4	−3.23
B0052 + 51	43	1.86	123	−2.44	B1706 − 16	24.8	0.83	5.8	−2.48
B0105 + 65	30.1	1.40	124	−2.79	J1713 + 0747	16	0.89	28.8	−3.32
B0114 + 58	49.4	2.24	126	−2.30	B1737 + 13	48.9	1.48	37.1	−2.06
B0136 + 57	73.7	2.88	129	−2.41	B1745 − 12	100.0	2.47	14	−1.94
B0138 + 59	34.8	2.18	129	−2.80	J1752 + 2359	36	1.95	49.1	−2.83
B0144 + 59	40.1	2.22	130	−2.92	B1758 − 03	117.6	3.50	23	−2.07
B0226 + 70	47	1.86	130	−2.15	J1758 + 30	36	2.04	56	−2.41
B0154 + 61	29.8	1.70	131	−2.66	B1802 + 03	79.4	2.79	30	−2.27
B0301 + 19	15.6	0.62	161	−2.70	B1818 − 04	84.3	1.94	25	−1.69
B0320 + 39	25.8	0.99	152	−2.70	B1821 + 05	67.2	1.85	35	−2.69
B0329 + 54	26.7	0.98	145	−3.26	B1831 − 04	78.8	2.15	27	−1.86
B0331 + 45	47.1	1.63	150	−2.77	B1839 + 56	26.5	1.67	86	−2.75
B0339 + 53	69	2.02	147	−2.21	B1839 − 04	196	4.67	27	−1.88
B0353 + 52	103.6	2.78	149	−1.94	B1846 − 06	147.6	3.40	26	−1.78
B0355 + 54	57.1	1.45	148	−2.52	B1853 + 01	96.7	3.07	34	−2.25
B0402 + 61	65.2	2.12	144	−1.93	B1907 + 02	172.1	4.94	38	−2.02
B0450 − 18	39.9	2.36	217	−2.70	B1911 − 04	89.4	2.78	31	−2.24
B0450 + 55	14.6	0.67	152	−2.60	B1914 + 09	61.4	2.95	44	−2.42
B0523 + 11	79.2	3.10	192	−2.38	B1915 + 13	94.4	3.98	48	−2.50
B0525 + 21	50.8	1.61	183	−2.71	B1919 + 21	12.4	1.08	55	−3.16
B0531 + 21	56.7	1.73	184	−2.16	B1933 + 16	158.5	5.61	52	−2.27
J0533 + 04	83.7	4.47	200	−2.35	B1937 + 21	71.0	3.56	57	−3.06
B0540 + 23	77.7	2.06	184	−2.14	B1946 + 35	129.0	5.78	70	−2.53
B0559 − 05	80.5	3.93	212	−2.45	B1953 + 50	31.8	2.23	84	−3.12
B0609 + 37	26.7	0.85	175	−2.45	B1957 + 20	29.1	2.49	59	−2.91
B0611 + 22	96.7	2.08	188	−1.85	B2016 + 28	14.1	1.22	68	−2.18
B0621 − 04	72.2	2.81	213	−2.00	J2019 + 2425	17.2	1.49	64	−3.47
B0626 + 24	84.2	2.24	188	−1.72	B2020 + 28	24.6	2.10	68	−3.96
J0631 + 10	125.6	3.67	201	−2.05	B2021 + 51	22.5	1.93	87	−3.29
B0656 + 14	14.0	0.67	201	−2.38					
B0740 − 28	73.7	2.07	243	−1.68	B2027 + 37	189	6.3	76	−2.23
B0751 + 32	40.0	1.52	188	−2.51	J2043 + 2740	21.0	1.8	70	−2.93
B0809 + 74	5.75	0.44	140	−3.57	B2053 + 21	35.8	2.4	67	−2.88
B0818 − 13	40.9	1.99	235	−2.72	B2053 + 36	97.5	4.62	79	−2.18
B0823 + 26	19.4	0.34	197	−2.64	B2110 + 27	24.7	2.01	75	−3.32
B0919 + 06	27.3	1.61	225	−3.27	B2111 + 46	141.5	4.53	89	−1.99
B0943 + 10	15.3	0.64	225	−2.29	B2113 + 14	56.3	4.20	64	−2.74
B0950 + 08	2.97	0.25	228	−3.28	B2154 + 40	70.6	3.73	90	−2.45
J1012 + 5307	9	0.41	160	−2.42	B2217 + 47	43.5	2.20	98	−3.08
J1022 + 10	10.2	0.44	231	−2.35	B2224 + 65	36.1	1.86	108	−2.66
J1025 − 0709	6.4	0.38	251	−2.58	B2303 + 30	49.9	3.78	97	−2.75
B1133 + 16	4.87	0.34	241	−3.42	B2310 + 42	17.3	1.25	104	−3.45
B1257 + 12	10.1	0.44	311	−2.47	B2315 + 21	20.5	0.93	95	−2.38
B1508 + 55	19.5	0.99	91	−2.82	J2322 + 2057	13.3	0.80	96	−3.00
B1530 + 27	14.6	0.82	43	−2.63	B2334 + 61	58.3	3.14	114	−2.99
B1541 + 09	35	3.28	17	−2.85	B2351 + 61	94.3	3.45	116	−2.25
B1612 + 07	21.3	0.96	20	−3.00					

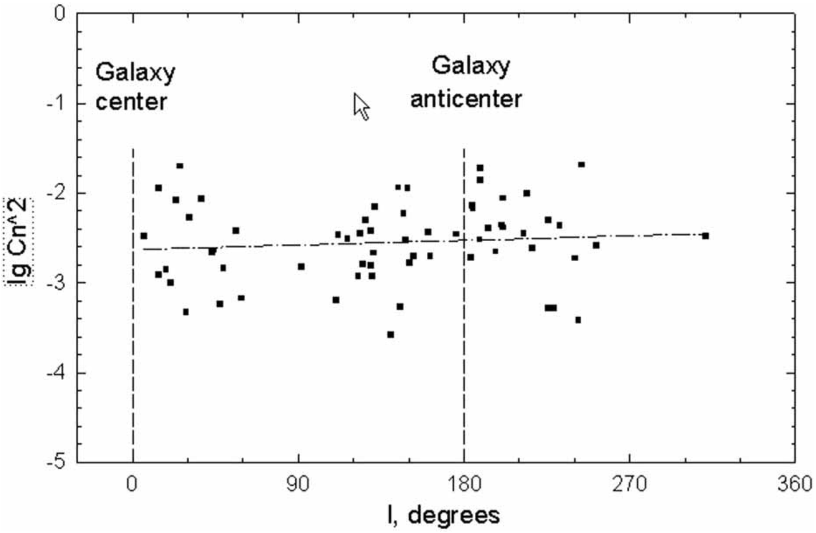

Figure 4. Distribution of C_n^2 along lines of sight.

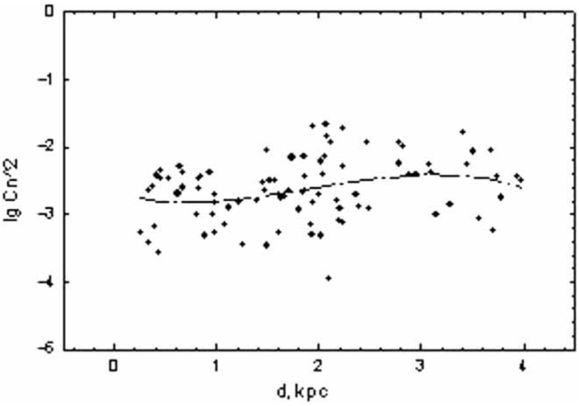

Figure 5. Distribution of C_n^2 along the distances d.

3.4 *Distribution of the turbulence level in the near Galaxy*

Figures 4 and 5 show distributions of the turbulence level C_n^2 over the galactic longitudes l and the distances d.

The turbulence level remains virtually the same throughout the studied region of the Galaxy up to distances of about 3 kpc, testifying to the homogeneity of the large-scale turbulence of the scattered medium in this part of the Galaxy.

4. Summary

Low-frequency measurements of the pulse scatter-broadening of a large sample of 100 pulsars with Galactic longitudes from 6° to 311° and distances up to 3 kpc have been done.

The scatter to frequency dependence in this part of the Galaxy can be presented by the power-law relation $\tau_{\mathrm{sc}}(\mathrm{DM}) \propto \mathrm{DM}^{2.2\pm0.1}$, close to the theoretical dependence $\tau_{\mathrm{sc}}(\mathrm{DM}) \propto \mathrm{DM}^2$ expected for a uniform ratio of $\Delta n_{\mathrm{e}}/n_{\mathrm{e}}$.

The scatter to frequency dependence can be presented by the power-law relation $\tau_{\mathrm{sc}}(\nu) \propto \nu^{-\gamma}$ with $\gamma = 4.1 \pm 0.3$, that is in favour of the Gaussian turbulence spectra of density irregularities ($\gamma = 4.0$) rather than the Kolmogorov one ($\gamma = 4.4$).

The turbulence level C_n^2 is nearly identical in various directions and distances of the near Galaxy that testified to the statistical uniformity of a large-scale plasma turbulence in this Galaxy region.

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