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Small-scale solar wind density turbulence spectrum from interplanetary scintillation observations

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The method of determining the angular sizes of compact radio sources and parameters of the plasma turbulence using temporal scintillation power spectra is described and tested. The observations were carried out with the radio telescope BSA of Lebedev Physical Institute at the frequency 111 MHz. Estimates of the angular size and the turbulence parameters are obtained for the strong scintillating source 3C 48 observed during April–May of 2007-2009. During these periods the interplanetary plasma was comparatively quiet.

Key words: solar wind, interplanetary scintillation

INTRODUCTION

Solar wind is the plasma flow continuously emanating from the Sun. One of the main properties of the solar wind plasma is turbulence: all the plasma parameters, magnetic field, density, speed etc., are fluctuating at all measurable temporal and spatial scales. The remote sensing technique for solar wind density irregularities study is based on analysis of radio waves phase and amplitude fluctuations multipoint measurements. Interplanetary scintillations (IPS) are temporal fluctuations of radio waves amplitude (or flux density) caused by diffraction of waves on irregularities with the scales of about Fresnel scale (several hundred kilometres for metric waves). Hereafter we use the term "small-scale irregularities" for this spectral range. Compact ($< 1''$) radio sources, such as active galactic nuclei (AGN), are used in IPS observations. The IPS characteristics are dependent only on source/observer geometry relative to the solar wind, and on the level of the small-scale density turbulence as well as on the solar wind speed in the case of a point radio source. Angular sizes of the sources influence the IPS level and power spectra if they are finite. The effect of source angular size on IPS temporal power spectra was investigated in [11]. The possibility to estimate the solar wind speed using IPS temporal spectra was demonstrated in [9] . In the present paper we describe the method and the first results on turbulence spectral index, source angular sizes and solar wind speed from the IPS observations at the Big Scanning Array radio telescope of Lebedev Physical Institute (BSA LPI) during the period close to the 23rd solar activity minimum. We concentrate mainly on the results concerning the spectral index of the turbulence spatial spectrum.

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OBSERVATIONS

IPS observations were carried out using the BSA LPI radio telescope in April–May of 2007-2009. Radio telescope operating frequency was 111 MHz. Temporal fluctuations of the flux density of the strongly scintillating radio source 3C 48 were measured at 600 kHz with sampling rate 0.1 s. During the observation series the angular distance between the line of sight and the direction to the Sun (elongation) was within the range $20° - 40°$. Only the records of a good quality with signal-to-noise ratio SNR>30 were used for analysis. The whole number of such records is 157. Temporal IPS power spectra were firstly calculated using the initial records and then analysed.

IPS TEMPORAL POWER SPECTRA

The IPS temporal power spectrum $P(f)$ is the Fourier transform of the correlation function $B(\tau)$:

$$P(f) = \int B_I(\tau) \exp(2\pi i f \tau) \mathrm{d}\tau, \qquad (1)$$

$$B_I(\tau) = \langle \delta I(t) \delta I(t+\tau) \rangle, \qquad (2)$$

where $I(t)$ is the measured flux density and $\delta I(t) = I(t) - \langle I \rangle$ is its temporal fluctuation. According to [9, 11] in the weak scintillation regime the IPS temporal power spectrum is defined by the following equation

$$P(f) = 4\lambda^2 \int \frac{A(z)}{v_\perp(z)} dz \int \mathrm{d}q_\perp \Phi_e(q) \times \times \sin^2\left(\frac{q^2 z}{2k}\right) F^2(qz)\Big|_{q_\parallel = \frac{2\pi f}{v_\perp(z)}}, \qquad (3)$$

where f is the temporal frequency, axis OZ is directed along the line of sight with $z = 0$ at the observation point, $A(z) = \frac{A_0}{(z^2 + r_0^2)^2} \sim \frac{1}{r_0^4}$, $A_0 = 2\pi r_e^2 \simeq 5 \cdot 10^{-25}\mathrm{cm}^2$, r_e is the classical radius of electron, $r_0 = \sin\varepsilon \cdot 1\,\mathrm{AU}$, $v_\perp(z) = v\cos\varphi = v\frac{r_0}{\sqrt{r_0^2 + z^2}}$ is the projection of the solar wind speed on the pattern plane at the point z, v is the solar wind speed, q is the spatial frequency, $q_\parallel$ is a component of the spatial frequency along the solar wind velocity projection on the plane, $q_\perp$ is the spatial frequency component of the perpendicular projection of the solar wind velocity on the plane, $q = \sqrt{q_\perp^2 + q_\parallel^2}$, $\Phi_e(q) = Cq^{-n}$ is the spatial spectrum of the electron density fluctuations in the interplanetary plasma, n is the exponent of the 3D turbulence power spectrum, $k = \frac{2\pi}{\lambda}$ is radio the wavenumber, $F(q) = \left(\frac{1}{2\pi}\right)^2 \iint \mathrm{d}^2\theta \exp\left[-ikq\theta\right] I(\theta)$ is spatial spectrum of the radio source and $I(\theta)$ is brightness distribution of the source.

Numerical simulations of the temporal IPS spectra (3) is performed with the following assumptions:

1) the 3D spatial turbulence spectrum is isotropic power-law, $\Phi_e(q, q_z = 0) = Cq^{-n}$ with the structure constant C;

2) the density turbulence level depends on heliocentric distance r as $C \sim r^{-4}$, $C = C_0\left(\frac{1\mathrm{AU}}{r}\right)^4$;

3) the solar wind speed v is constant, radial and uniform;

4) the source brightness distribution over the source is a symmetric Gaussian $I(\theta) = \exp\left(-\frac{\theta^2}{2\theta_0^2}\right)$ with the angular radius θ_0 at the $(1/e)^{1/2}$ level.

The model used in simulations has four free parameters: the absolute turbulence level C_0, the solar wind speed v, the turbulence spectral index n and the radio source size θ_0. The first three of them can vary from day to day, and the last one is assumed to be constant. We define free parameters from the best fit of the spectrum obtained from IPS measurements by the calculated spectrum $P(f)$.

SIMULATION RESULTS

Fitting procedure is illustrated in Fig. 1. The measured IPS temporal power spectrum shown in Fig. 1 has a typical shape with approximately constant level at low frequency $f < F_0$ and decreases with increasing f at higher frequency range $f > F_0$. Constant level at the highest frequencies corresponds to the noise. The distribution of the source angular sizes Θ_0 is shown in Fig. 2. Using this distribution one can find the mean value $\theta = 0.33'' \pm 0.06''$. According to published data obtained by the scintillation method at 81.5 MHz the angular size of 3C 48 is $0.5''$, according to the analysis of the VLBI and VLA observations given in [1], the angular size of 3C 48 is $0.1'' \times 0.4''$ and is approximately $0.3''$ at the observed elongation. Hence the source size was assumed to be constant and equal to $\theta_0 = 0.33''$ and other free parameters were determined for each IPS record. The distribution of the turbulence spectral index n is presented in Fig. 3. From this distribution we found the mean value of n to be 3.7 ± 0.2. The observed values of n lie within the range of $3.1 - 4.0$.

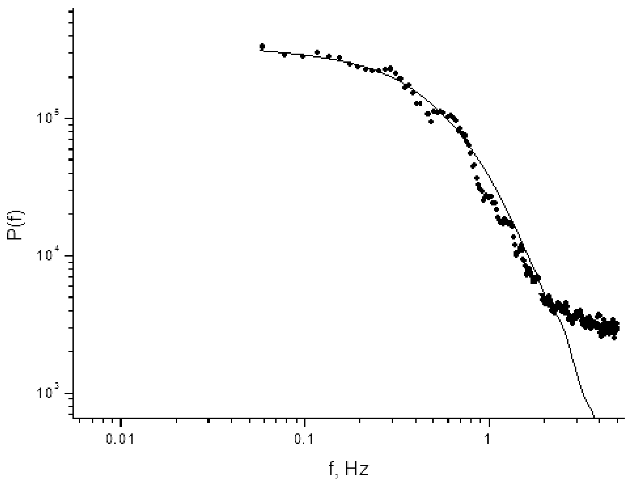

Fig. 1: An example of the power spectrum of the source 3C 48 (dots) and the theoretical power spectrum (solid line), $n = 3.7$, $v = 520\,\mathrm{km/s}$.

CONCLUSIONS

The estimates of the density turbulence spectral index $n = 3.7 \pm 0.2$ found from IPS data are in a good agreement with the similar estimates at much greater turbulence scales found from both, local, in-situ, measurements on board spacecraft [12] and the solar wind radio sounding by coherent signals of the spacecraft [3]. This coincidence confirms the hypothesis presented in [5], that the large-scale and small-scale density irregularities belong to the single power-law spectrum within the very wide range of scales.

The problem of physical processes responsible for formation of the wide power-law spectrum in inertial spectral range and energy cascading from the turbulence outer scale to dissipation spectral range is still unsolved. Three possible mechanisms were considered. The first one suggested by Kolmogorov [7] and later modified in [12] for magnetized plasma the strong turbulence of non-compressible neutral fluid with the spectral index of $n = 11/3$. The second possibility is a strongly anisotropic power spectrum suggested by Goldreich and Sridhar [4] for magnetic

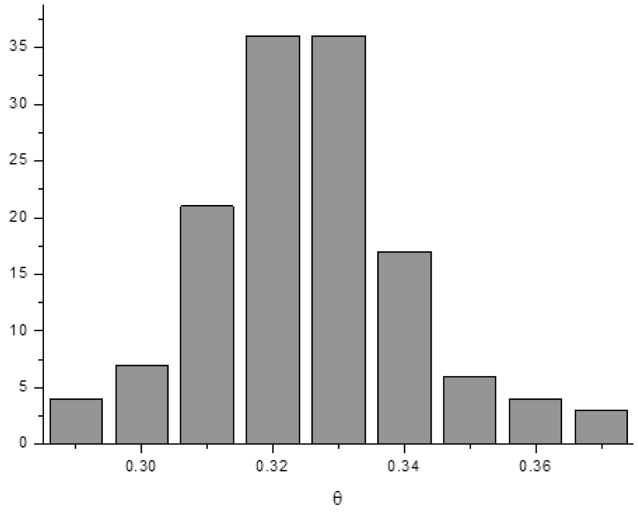

Fig. 2: The distribution of the angular sizes of 3C 48.

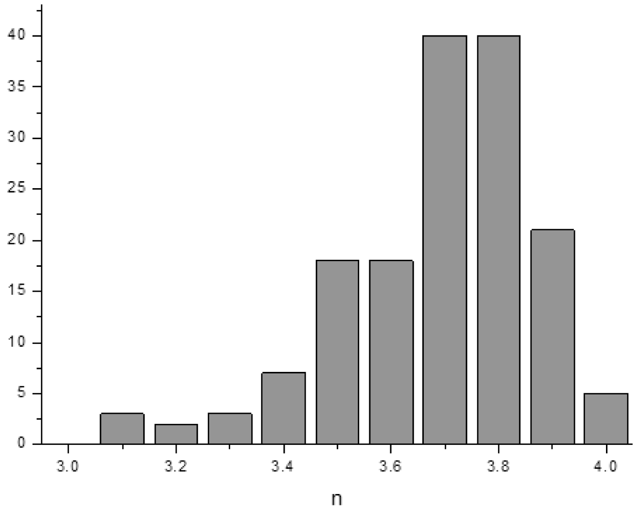

Fig. 3: The distribution of the turbulent plasma indices.

field turbulence. If the same spectrum takes place for density turbulence then the measured spectral index would be $n = 3$, that is in contradiction with our observations. However, strictly speaking, these models are valid for Alfvén turbulence and the mechanisms of the density turbulence generation with similar spectra are not clear. The third turbulence model considers the formation of turbulence spectra in inertial range by the weak decay non-linear interactions suggested in [6, 8]. The value of the spectral index is $n = 7/2$ for Iroshnikov/Kraichnan model [6, 8]. Our data do not allow to distinguish between Kolmogorov and Iroshnikov/Kraichnan spectra because both models are agree with the measurements within the errors. The future studies based on larger statistics with the large- and small-scale data are needed for convincing conclusions. It should be noted in this context that the measured spectra generated by Iroshnikov/Kraichnan mechanism can be steeper than $n = 7/2$ if non-linear partial damping of the spectral energy flux ($n \approx 3.6$) [2] or turbulence intermittency ($n \approx 3.7$) [10] is taken into account.

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