Current ideas concerning the spectrum of the irregularities in the interplanetary plasma

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The introduction contains a brief review of the study of interplanetary plasma by the "transillumination" method, with a summary of the development of the method and the results obtained with it during various stages. Principal attention is paid to the inhomogeneity spectrum, which plays an important role in the understanding of the physical processes that occur in solar wind. To this end, the experimental data obtained by the "scintillation" method are considered in detail. This is followed by an analysis of the theoretical conclusions that follow for two different models of the inhomogeneity spectrum, and by tests with which it is possible to choose between the two hypotheses. The results of the latest experiments and the difficulties connected with the available observed facts are discussed from this point of view.

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I. INTRODUCTION. INTERPLANETARY SCINTILLATION OF RADIO SOURCES

Study of the physical properties of the interplanetary medium by the methods of radio astronomy involves the use of the "transmission" method. The different stages in the development of this method are closely connected with the discovery and use of new types of radio sources.

The "transmission" method is based on the use of the occultation of discrete radio sources, i.e., on the passage of radio waves from discrete sources through circumsolar space. At first, sources of comparatively large angular dimensions were used, such, for example, as the Crab Nebula. When the radio emission from such sources traverses a medium containing electron-concentration irregularities, it is scattered by those irregularities. As the source in its motion approaches the sun, the radio waves are more and more strongly scattered and the angular dimensions of the sources appear to increase (Fig. 1). The quantity measured in the transmission method is the scattering angle θ_{sc} of the radio waves as a function of the angular separation of the source from the sun (the elongation ϵ of the source) (Fig. 1).

The studies in 1952–1953 of the circumsolar plasma via "transillumination" by the radio emission from the Crab Nebula[1-4] are regarded as the origin of the "transmission" method. In subsequent years (1954–1967) this method was successfully employed to investigate the interplanetary medium at distances up to several tens of solar radii from the sun (in the region $(5–60)R_{\odot}$, $\epsilon \lesssim 15°$)[5-16]. These studies led to the discovery that the

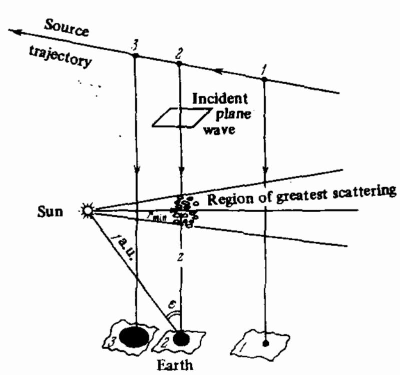

FIG. 1. Geometry of the "transmission" method.

plasma near the sun has a nonuniform structure consisting of small scale irregularities in the electron concentration with a characteristic size a_{eff} of some 50–5000 km[11, 14-16]. And although the "transmission" method involved considerable uncertainty in estimating the characteristics of the plasma–the effective size a_{eff} of the irregularities and the rms value ΔN_e of the electron-concentration fluctuations[14, 15]–it provided considerable new information on the circumsolar plasma, which had previously been quite inaccessable to study. A relationship was established between the activity of the irregular component of the medium and the phase of the 11-year solar activity cycle (the supercorona is about twice as large on the average during a period of maximum activity)[5, 10, 11], and the irregular component was found to depend on the heliographic latitude (the supercorona is about twice as large in the equatorial plane as in the polar direction)[17]. Simultaneous measurements of the scattering angle with interferometers having differently oriented bases led to the discovery of the anisotropy of the scattering properties of the medium and of the presence of a magnetic field in interplanetary space[18-22]. The anisotropy of the scattering can be accounted for on the assumption that the irregularities have a prolate shape and are mainly oriented in directions close to that of the radius vector from the sun. The shapes and orientations of the irregularities are due to the quasiradial magnetic field of the sun. All these results provided a basis for the development of various models of the circumsolar medium[15, 23-27].

The next stage in the development of the "transmission" method was the "scintillation" method. This method involves the transmission through the medium of the radiation from discrete radio sources having very small angular dimensions and is based on the study of the intensity fluctuations (scintillation) of such sources.

The discovery in 1963 of quasars–radio sources with angular dimensions[28] of the order of 1″ or less–made it possible to extend the "transmission" method to the study of more remote regions of interplanetary space, thanks to the "scintillation" of the radio emission from the quasars as a result of scattering of the radio waves by the irregularities of the interplanetary medium that they traverse on their way to the observer. The scintillation of quasars as a result of scattering by the interplanetary plasma ("interplanetary scintillation") was discovered in 1964[29].

In principle the scintillation method works as follows[30, 31]: If there is a layer containing random electron-concentration irregularities between a point source of radio waves and the earth, the waves will be diffracted on crossing the layer (Fig. 2). If the irregularities move with velocity v with respect to the earth the diffraction pattern will move along the ground with that same velocity. Then the spatial intensity modulation pattern will be observed at a fixed point on the earth as temporal fluctuations of intensity ("scintillation"), whose period T will be

$$T = \frac{l}{v}, \tag{1}$$

where l is the scale of the diffraction pattern at the earth and v is the relative velocity of the irregularities.

What one measures in the scintillation method is the intensity fluctuations $\delta I(t) = I(t) - \langle I(t)\rangle$, which are characterized by the parameter m, the relative rms deviation of the intensity, the so called magnitude of the scintillations or the scintillation index[32, 33]:

$$m^2 = \frac{\overline{I^2} - \langle I\rangle^2}{\langle I^2\rangle}. \tag{2}$$

In investigating interplanetary scintillation one measures the scintillation index m and scintillation period T as functions of the elongation ϵ and the wavelength λ[15, 21, 34-44]. It was found that T is independent of λ and remains almost constant over a wide range of elongations ($\epsilon > 20°$)[29, 34-44]. Typical $m(\epsilon)$ curves showing the scintillation index as a function of elongation are presented in Fig. 3. The $m(\epsilon)$ curves behave similarly over the entire investigated wavelength range. Figure 3 shows that the scintillation index reaches a maximum value m_{max} at a certain value of ϵ, which depends on λ.

From scintillation measurements one can determine the parameters m, l, T, and v_{eff}, of the diffraction pattern at the earth. In order to find the characteristics of the medium one must decipher the diffraction pattern, i.e., one must establish the relation between the parameters of the diffraction pattern and those of the medium. This relation is established by analyzing the dependence of the diffraction pattern on the structure of the phase fluctuations $\sqrt{\overline{\Delta\psi^2}}$ of the wave, which are related to the electron-concentration fluctuations in the medium[102].

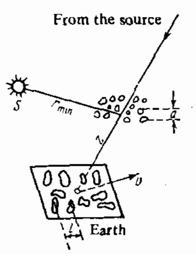

FIG. 2. Diagram illustrating scintillation.

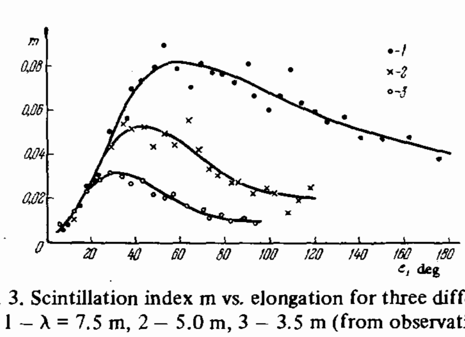

FIG. 3. Scintillation index m vs. elongation for three different wavelengths: 1 – λ = 7.5 m, 2 – 5.0 m, 3 – 3.5 m (from observations of the source 3C 144).

The effects of scattering and scintillation of the radio waves are usually described in terms of the "thin phase screen" model[36, 44-48, 123]. In this model it is assumed that the screen, lying at the distance z from the observer (see Fig. 2), acts as a thin scattering layer and produces the same phase changes in the incident plane wave as does the action of the actual medium, which is extended along the line of sight. All the basic relationships connecting the parameters observed on the ground (the scattering angle θ_{sc}, the scintillation index m, the scintillation period T, and the scale l of the diffraction pattern at the ground) with the parameters describing the irregularities of the medium (the size a_{eff} of the irregularities, the rms value $\Delta N_{e\,eff}$ of the electron-concentration fluctuations in the irregularities, and the velocity v_{eff} of the irregularities) are derived from the theory of the scattering of waves by a thin phase screen[36, 44-48].

Examination of the $m(\epsilon)$ curves (Fig. 3) showed that two basic types of interplanetary scintillation can be distinguished[44, 49]. The elongation ϵ at which the scintillation index reaches its maximum separates the interplanetary medium into two regions that differ as regards scattering conditions[50]: At large elongations ($\epsilon > 20°$ for the decimeter and meter waves), where $m \ll 1$ and $|\Delta\psi| < 1$, the scintillations are produced under conditions of weak scattering, while in the region of small elongations ($\epsilon < 10°$ for decimeter and meter waves), where $m \approx 1$ and $|\Delta\psi| > 1$, the scintillations are produced under conditions of strong scattering. We note that all the basic information about the interplanetary medium obtained by the scintillation method relate to the region $\epsilon < 20°$ ($r > 70R_\odot$) in which the irregularities of the interplanetary plasma constitute a weakly scattering medium.

At large elongations ($\epsilon > 20°$), where the interplanetary medium acts as a weak scatterer, the scattering angle is given by the formula[45-47, 51, 52, 60]

$$\theta_{sc} = \frac{\lambda}{\pi a_{eff}} \tag{3}$$

and is small compared with the angular size of the irregularities:

$$\theta_{sc} < \frac{a_{eff}}{z}. \tag{4}$$

In this case the diffraction pattern at the ground has the same scale as the irregularities in the medium: $l \sim a_{eff}$[32, 33, 48, 53]; also, the wave parameter $D = \lambda z/\pi a_{eff}^2$ is small compared with unity, so that $a_{eff} > \sqrt{\lambda z}$, i.e., the irregularities are larger than the width of the Fresnel zone or $z < z_f = \pi a_{eff}^2/\lambda$, where z_f is the Fresnel distance. The last inequality means that the distance z of the effective screen from the observer is shorter than the Fresnel distance and the diffraction pattern is formed in the near zone. In this case the scintillations observed at the earth are a product of Fresnel diffraction.

In the region of small elongations ($\epsilon < 10°$) under strong-scattering conditions ($|\Delta\psi| \gtrsim 1$) the expression for the scattering angle has the form[50-53, 60]

$$\theta_{sc} = \frac{\lambda|\Delta\psi|}{\pi a_{eff}} \text{ and } \theta_{sc} \gg \frac{a_{eff}}{z}. \tag{5}$$

Then for the scale of the diffraction pattern measured at the earth we have $l = a_{eff}/|\Delta\psi|$, and for the wave parameter, $D \gtrsim 1$; i.e., $a_{eff} < \sqrt{\lambda z}$, or $z > z_f$. In this case the distance z from the screen to the observer is greater than the Fresnel distance, the diffraction pattern is formed in the distant zone, and the scintillations observed at the earth are a product of Fraunhofer diffraction.

All that was said above refers to the case of a point source. As the angular dimensions θ_{source} of the source increase, the diffraction pattern begins to smooth out when

$$\theta_{source} \sim \frac{a_{eff}}{z}. \tag{6}$$

Thus, we can recognize sources with dimensions $\theta_{source} < a_{eff}/z$ from the presence of scintillation. Condition (6) also explains why scintillation at decimeter and meter wavelengths disappears near the sun in the region $r \sim (5\text{–}40)R_\odot$ ($\epsilon \lesssim 12°$) and only the "transmission" method works there.

Study of the scintillation of quasars revealed the presence of an irregular structure of the interplanetary plasma at very large distances from the sun—out to $\sim 260R_\odot$, which considerably exceeds an astronomical unit (1 a.u. = $213R_\odot$). It also proved possible unambiguously to determine the characteristic dimensions and electron concentrations of the irregularities[44,45]. Further, it proved possible to derive information not only on the dimensions and concentrations of the irregularities, but also on their shape and motion, from simultaneous observations of scintillations at three points (the velocity vectors of irregularities have been measured)[55-61]. The results of studies of the interplanetary scintillation during the period 1966–1970 showed that not only the activity of the sun, but also that of the interplanetary medium surrounding it—the solar wind—varies with time[55,62].

The study of interplanetary scintillation developed during the period 1964–1970 mainly along the line of measuring the parameters m, a_{eff}, and v_{eff} as functions of ϵ, and the principal effort was directed toward evaluating the parameters a_{eff}, $\Delta N_{e\,eff}$, and v_{eff} at various distances from the sun. The following characteristic values were found at a solar distance of ~1 a.u.: for the size of the irregularities, $a_{eff} \simeq 200$ km; for the excess electron concentration in the irregularities, $\Delta N_{e\,eff} \simeq 10^{-2}$ electron/cm^3; for the relative excess electron concentration, $\Delta N_e/\langle N_e\rangle \approx 0.5\%$; for the scintillariot period, $T \approx 3$ sec; and for the velocity of the irregularities, ~300 km/sec[44]. Basic successes were achieved in the problems of deciphering the relationships between the parameters describing the diffraction pattern observed at the earth and those describing the irregularities of the medium[63-75].

A beginning has recently been made in the study of new problems concerning the interplanetary medium. In this connection we may mention the study of the sectorial structure of the interplanetary plasma by detecting fast solar-wind streams, which have a marked tendency to give rise to scintillations. It was found that the effective parameters describing the irregularities in the fast streams differ from the corresponding parameters for the quiescent solar wind[76-81].

The features of the irregular structure of the solar wind came to be intensively studied in their dependence on distance from the sun and on heliographic latitude[82-86], and the transition began from the study of the integral effective parameters of the irregularities to the analysis of their variations, of the fine structure along the line of sight. The assumption of the rigidity of the diffraction pattern observed simultaneously at two or three points was renounced and a beginning was made in the study of several cases of the reorganization of the pattern and in the analysis of the fine structure of the solar wind[87-95].

The successes achieved in the study of interplanetary scintillation revealed the possibilities of the method, and recent years have seen an intensive development of experimental studies. Whereas at first studies of the interplanetary scintillation of quasars were undertaken in only two or three countries (England, the USSR, the USA) and attracted the attention of only a few specialists, the greatest observatories are now involved in such work (Table I). Scintillation caused by the interplanetary plasma come to be more and more frequently invoked to solve the most diverse astrophysical problems, frequently having nothing to do with questions of the structure of the interplanetary medium. As such applications we may mention the use of interplanetary scintillation to investigate the intrinsic sizes of radio sources[96-99], to investigate the distribution of the ionized component in the galaxy[100], and to assist in the cosmological interpretation of the red shift[101]. Under discussion at present are the use of interplanetary scintillation to investigate changes in the angular sizes of quasars associated with their variability, and the detection of sources emitting discrete radio-frequency lines by their scintillation caused by the interplanetary plasma with the purpose of investigating the sizes of such sources and their motions in the interstellar medium (from the absorption line).

Despite the great popularity of the scintillation method, however, and the successes achieved in applying it to the study of the structure and physical properties of the interplanetary medium, the physics of the irregularities themselves is still but poorly investigated. The nature of the irregularities remains obscure. In this connection the form of the spectrum of the irregularities in the interplanetary plasma is of especial interest, and we now turn to the discussion of that problem.

II. THE FORM OF THE SPECTRUM OF THE IRREGULARITIES IN THE INTERPLANETARY PLASMA

1. Basic relationships. The quantity directly measured in scintillation observations is the intensity of the source at a specific instant: I(t). In terms of this we define the intensity fluctuations $\delta I(t) = I(t) - \langle I\rangle$. From many such measurements made at a single point one can determine the temporal autocorrelation function $B(0, \tau)$ of the intensity fluctuations and the scintillation index m^2 [32,33]:

$$B(0, \tau) = \langle \delta I(\mathbf{r}, t)\, \delta I(\mathbf{r}, t+\tau)\rangle, \tag{7}$$

$$m^2 = \frac{\langle \delta I^2(t)\rangle}{\langle I\rangle^2}. \tag{8}$$

From intensity measurements made simultaneously at two or more points one can obtain the spatial-temporal

TABLE I

Country, observatory	Working frequency (wavelength)	No. of observation points
France, Nancy	1420 MHz (0.21 cm)	1
India, Ootacamund	326 MHz (0.92 cm)	1
USSR, FIAN	102 MHz (2.94 m) 86 MHz (3.5 m)	1
England, Cambridge	81.5 MHz (3.7 m)	1
USA, University of California at San Diego	74 MHz (4 m)	4
Japan, Nagoya University	69.8 MHz (4.3 m)	3
USA, Colorado	34 MHz (8.8 m)	1

crosscorrelation function $B(\rho, \tau)$ of the intensity fluctuations:

$$B(\rho, \tau) = \langle \delta I(\mathbf{r}, t)\, \delta I(\mathbf{r}+\rho, t+\tau) \rangle. \tag{9}$$

Further, using the known autocorrelation and crosscorrelation functions $B(0, \tau)$ and $B(\rho, 0)$ of the intensity fluctuations, we can calculate the temporal and (two-dimensional) spatial spectral densities of the intensity fluctuations, $M_I(\nu)$ and $M_{2I}(q)$, respectively. Expanding the temporal and spatial autocorrelation functions $B(0, \tau)$ and $B(\rho, 0)$, respectively, in Fourier integrals, we obtain[32, 33]

$$B(0, \tau) = \int M_I(\nu)\, e^{i2\pi\nu\tau}\, d\nu, \tag{10}$$

$$B(\rho, 0) = \int\int M_{2I}(\mathbf{q})\, e^{i2\pi\rho\mathbf{q}}\, d\mathbf{q}, \tag{11}$$

where ν and q are the temporal and spatial frequencies, respectively.

One of the fundamental assumptions on which the analysis of the scintillation pattern is based is that the diffraction pattern is rigid, i.e., that the entire pattern moves through space with a single velocity u. In this case the temporal intensity fluctuations can be attributed to the motion of the spatial fluctuations with velocity u with respect to the fixed line of sight. Then, writing $\tau = \rho/u$, we can pass from temporal correlations to spatial ones and transform the crosscorrelation function $B(\rho, \tau)$ to a type of spatial correlation function:

$$B_I(\rho, \tau) = B_I(\rho - \mathbf{u}\tau, 0), \tag{12}$$

in which, according to (11),

$$B_I(\rho - \mathbf{u}\tau, 0) = \int M_{2I}(\mathbf{q})\, e^{i2\pi\mathbf{q}(\rho - \mathbf{u}\tau)}\, d\mathbf{q}. \tag{13}$$

Now writing $B_I(0, \tau) = B_I(\rho - u\tau, 0)$ we obtain the following relation between the temporal and spatial spectral densities $M_I(\nu)$ and $M_{2I}(\mathbf{q})$:[102]

$$M_I(\nu) = \frac{2\pi}{u} \int M_{2I}(q_x, q_y)\, dq_y, \tag{14}$$

where

$$q_x = \frac{2\pi\nu}{u}. \tag{15}$$

Now using the spectral densities $M_I(\nu)$ and $M_{2I}(\mathbf{q})$ we can write the following formulas for the basic scintillation parameters—the scintillation index m^2 and the second moments ν_2 and q_2 of the temporal and spatial intensity fluctuation spectra, respectively:[32, 33, 102]

$$m^2 = \frac{1}{\langle I \rangle^2} \int\int M_{2I}(\mathbf{q})\, d\mathbf{q} = \frac{1}{\langle I \rangle^2} \int M_I(\nu)\, d\nu, \tag{16}$$

$$\nu_2^2 = \frac{\int \nu^2 M_I(\nu)\, d\nu}{\int M_I(\nu)\, d\nu}, \quad q_2^2 = \frac{\int \mathbf{q}^2 M_{2I}(\mathbf{q})\, d\mathbf{q}}{\int M_{2I}(\mathbf{q})\, d\mathbf{q}}, \tag{17}$$

where $\nu_2^2 = (u/2\pi)^2 q_2^2$. Here ν_2 and q_2 characterize the spectral width of the correlations or the scintillation period $T = \nu_2^{-1}$ and the scale of the scintillations $a \approx q_2^{-1}$.

2. Formulation of the problem. One of the most sharply posed problems in the theory of interplanetary scintillation is that of the form of the spatial spectrum $M_{3N}(q)$ of the density irregularities. At first the observed scintillations were interpreted on the assumption that the medium contains irregularities with a characteristic scale of ~100 km at a distance of about 1 a.u. This approach was based on the assumption that the spectrum $M_{3N}(q)$ was Gaussian with the characteristic scale q_0^{-1} [34, 44, 60, 61, 103]. Doubt has been recently cast on the idea that there is a scale such as q_0^{-1} inherent in the medium, however, in connection with the hypothesis that the irregularities in the interplanetary plasma have the power-law spatial spectrum

$$M_{3N}(q) \propto q^{-\beta} \tag{18}$$

(over a wide frequency range)[104] and the corresponding temporal spectrum

$$M_I(\nu) \propto \nu^{-(\beta-1)} = \nu^{-\alpha} \tag{19}$$

with the correlation scale $q^{-1} \gtrsim 10^6$ km. In the case of a power law spectrum one cannot speak of a characteristic size of the irregularities, and in this case the scale derived from the scintillation measurements cannot represent the physical size of the irregularities, but must rather represent the so-called "inner scale," which is of the order of the first Fresnel zone for the wavelength at which the observations are made.

Thus, the problem of the form of the spectrum of the density irregularities is connected with the answer to a very important question: Does the length q_2^{-1} derived from the scintillation data represent the true physical size of the irregularities, coinciding with the size of the first Fresnel zone only in order of magnitude, or does it have nothing to do with a physical scale inherent in the medium, being rather associated with the limit imposed by diffraction theory, i.e., with the "inner scale" of the irregularities? We note that in the case of the power law spectrum (18) the observed size q_2^{-1} of the diffraction pattern as given by Eq. (17) is determined by the length in spectrum (18) that coincides with the size of the first Fresnel zone. In this case the length a derived from the observations does not correspond to the physical size of the irregularities.

The problem of the shape of the spectrum $M_{3N}(q)$ of the irregularities is also connected with the answer to another question: Do the large-scale ($\gtrsim 10^6$ km) density and magnetic-field fluctuations observed with satellites and the small-scale (~100 km) electron-concentration fluctuations revealed by scintillation measurements belong to the same power-law spectrum (18), and hence to a single plasma regime, or are they associated with different regimes, thus differing in nature?

At present there are two hypotheses concerning the form of the spatial spectrum of the irregularities. According to the first of these hypotheses (Fig. 4,a) there is a Gaussian spectrum in the small-scale region with the characteristic length $q_0^{-1} \sim 100$ km, which agrees with the scale q_2^{-1} of the diffraction pattern observed at the ground[105]. This would mean that the irregularities in the interplanetary medium are generated by two different mechanisms—the large-scale irregularities by one mechanism and the small-scale ones by another. According to the second hypothesis, all the irregularities of the medium belong to the single power-law spectrum (18) (Fig. 4,b)[104, 106].

The arguments in favor of the first hypothesis are based on the fact that a number of theories of the small-scale irregularities predict that the medium will exhibit a scale of magnitude $a \approx r_{HI}$, where r_{Hi} is the Larmor radius of the ions, which, at a distance of ~1 a.u., corresponds to the observed scale ~100 km[76]. The second hypothesis is favored by the fact that the measured scale q_2^{-1} of the diffraction pattern (Eq. (17)) agrees in order of magnitude with q_f^{-1}, the size of the first Fresnel zone. Corresponding estimates of q_2 and q_f are presented in Table II; it will be seen that q_2 and q_f differ by only a factor of the order of two[106].

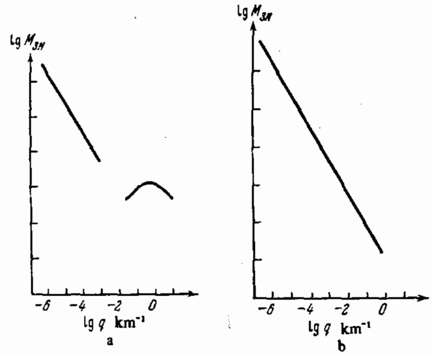

FIG. 4. Form of the spatial spectrum of the irregularities in the interplanetary plasma according to two different models: a—spectrum with a Gaussian hump, b—power-law spectrum.

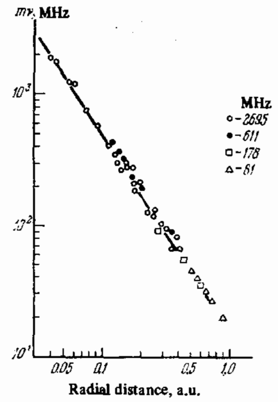

FIG. 5

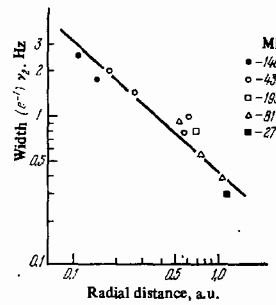

FIG. 6

FIG. 5. Dependence of the scintillation index m on the solar distance from observations at different frequencies ν (the product $m\nu$ is plotted on the vertical axis for convenience).

FIG. 6. Width ν_2 of the temporal scintillation spectrum vs. solar distance from observations at various frequencies ν.

TABLE II

r, a.u.	λ, m	ν_2	ν_f	Ref.
0.06—0.14	0.11	2.2—1.3	1.5	121
0.04—0.14	0.21	2.5—1.2	1.1	121
0.14—0.60	0.70	1.2—0.7	0.6	121
>0.34	1.54	0.6	0.4	38
>0.55	3.70	0.5	0.3	122

TABLE III

Solar-distance dependence of the effective size of the irregularities

Solar distance range	Accuracy of the a_{eff} measurements	Value of a_{eff}	r Dependence of a_{eff}	Method of Measurement	Ref.
$0.1 \leqslant r \leqslant 1$ a.u.	±25%	200 km $r=1$ a.u.	Rising power law	From the size of the diffraction pattern (one source) and from scattering	60
$0.03 \leqslant r \leqslant 0.8$ a.u.	±15%	240 km $r=0.8$ a.u.	$a \propto r^{0.9\pm0.2}$	From the size of the diffraction pattern and from scattering	108
$0.35 \leqslant r \leqslant 1$ a.u.	±10%	150 km $r=1$ a.u.	$a \propto r^{0.5}$	From the size of the diffraction pattern (one source)	55, 109
$0.2 \leqslant r \leqslant 0.8$ a.u.	±10%	200 km $r=0.8$ a.u.	$a \propto r^{1,5}$	Calculated theoretically with allowance for the extent of the medium	90
$0.35 \leqslant r \leqslant 1$ a.u.	±10%	200 km $r=1$ a.u.	Weak dependence a от r	From the size of the diffraction pattern (one source)	110
$0.3 \leqslant r \leqslant 0.7$ a.u.	±25%	100 km $r=0.7$ a.u.	$a=\text{const}$	From ν_2 measurements (six sources)	111
$0.1 \leqslant r \leqslant 1$ a.u.		200 km $r=1$ a.u.	$a \propto r^{1,1\pm0,1}$	From the size of the temporal spectrum (five sources)	112

To analyze the problem further we need a criterion to distinguish between the two models. The wavelength dependences of the scintillation parameters m and ν_2 can serve as such a criterion, for the dependences predicted by the two models differ from one another. Then by comparing the theoretical predictions with the observational results we can reach a conclusion concerning the shape of the spectrum of the irregularities in the interplanetary medium.

3. Observational results. Scintillation observations made by various investigators over a wide frequency range provide the data for determining the dependence of the scintillation index m on the distance from the sun (see Fig. 5, in which we have plotted the quantity $m\nu$ on the vertical axis for convenience)[107]. The data presented in Fig. 5 pertain to the region of elongations exceeding the critical value of r at which the m(r) curve exhibits a bend which is associated with the finite angular diameter of the source and is due to scattering of the radiation from the source by the irregularities of the interplanetary medium. From Fig. 5 we can conclude that

$$m \propto \lambda^{1.0\pm0.05}. \qquad (20)$$

Figure 6 shows the values of the width ν_2 of the temporal spectrum of the scintillations derived from the observations at various frequencies[107]. This figure shows that ν_2 depends as follows on the distance r from the sun:

$$\nu_2 \propto r^{-1}. \qquad (21)$$

Moreover, ν_2 is independent of the observation frequency. Values obtained for ν_2 by other methods are listed in Table III[55, 40, 60, 108-112].

Now we must attempt to account for the relationships (20) and (21) on the basis of each of the model spectra adduced to describe the distribution of the irregularities.

We note that relations (20) and (21) characterize the spectrum $M_{3N}(q)$ in the region of low spatial frequencies q. The spectrum has been measured at low frequencies with satellites. These measurements show that at low frequencies the spatial density fluctuation spectrum $M_{3N}(q)$ follows a power law with the exponent $\beta_3 = 3.3$[113].

4. Theoretical results. Let us first consider how requirements (20) and (21) are fulfilled in the model in which the power-law spectrum (18) is assumed. Assuming that the scattering takes place in a comparatively thin layer lying close to the point on the line of sight nearest the sun (because of the relation $N_e(r) \propto r^{-2}$) (see Fig. 1), we shall use the "thin screen" model to describe the scattering effects. For observations at elongations of ~60° and smaller this layer lies at a distance of ~1 a.u. from the observer on the earth.

The equations that relate the nonuniform three-dimensional structure of the electron concentration $\Delta N_e\rho(\mathbf{r})$, which is described with the aid of the three-dimensional spatial wave-number spectrum $M_{3N}(q_x, q_y, q_z)$, to the two-dimensional spectrum $M_{2\,Ph}(q_x, q_y)$ (which describes the phase screen and also to the two-dimensional spectrum $M_{2I}(q_x, q_y)$ of the intensity fluctuations in the plane of observation, have the form[106]

$$M_{2\Phi}(q_x, q_y) = 2\pi r_e^2 \lambda^2 M_{3N}(q_x, q_y, 0), \qquad (22)$$

$$M_{2I}(q_x, q_y) = F(q_x, q_y)\, M_{2\mathrm{ph}}(q_x, q_y), \tag{23}$$

where $M_{2I}(q)$ is related to the temporal intensity-fluctuation spectrum $M_I(\nu)$ by Eq. (14). Here $F(q_x, q_y)$ is a factor describing the "fresnel filter":

$$F(q_x, q_y) = 4\sin^2\left(\frac{q_x^2+q_y^2}{q_f^2}\right); \tag{24}$$

where q_f is the spatial Fresnel number $(q_f = \sqrt{4\pi/\lambda z}$ $\approx (110\ \mathrm{km})^{-1}\lambda^{-1/2}$ for $z \approx 1$ a.u.) corresponding to the temporal Fresnel frequency $\nu_f = (1/2)(u/350\ \mathrm{km} \times \mathrm{sec}^{-1})\lambda^{-1/2}$ Expression (24) has the following asymptotic forms in the high- and low-frequency regions:

$$F \approx \left(\sqrt{2}\,\frac{\sqrt{q_x^2+q_y^2}}{q_f}\right)^4 \quad \text{for} \quad q < q_f, \tag{25}$$

and

$$F \approx 2 \quad \text{for} \quad q > q_f. \tag{26}$$

Expressions (25) and (26) together with (16) and (17) can be used to calculate m and ν_2 for a given form of the spectrum $M_N(q)$ of the irregularities. For the power-law spectrum (18) with an upper limit q_{max} that exceeds q_f,

$$q_{min} \ll q_f \ll q_{max}, \tag{27}$$

we can determine the form of the spectrum $M_I(\nu)$: the low frequencies $(q < q_f)$ in the spectrum $M_{3N}(q)$ will be suppressed by the filter F and we must expect the spectrum $M_I(\nu)$ to be nearly flat in this region. At frequencies above ν_f, $M_I(\nu)$ will be described by a power law: $M_I(\nu) \propto \nu^{-(\beta-1)}$ (Fig. 7, a)[54].

Using Eq. (16) for the scintillation index and noting that the high frequencies $(\nu > \nu_f)$ are not so important in generating scintillations (owing to the weakness of the spectrum $M_N(q)$ they will produce only small phase change, so that the scintillations will predominate at wave numbers q of the order of $\sqrt{4\pi/\lambda z}$, somewhat exceeding the Fresnel break in the spectrum $M_I(q)$), we obtain

$$m^2 \propto \lambda^2 q_f^{-\beta_1} \propto \lambda^{(\beta_1+4)/2}, \quad m \propto \lambda^{(\beta_1+4)/4} = \lambda^{(\beta_3+2)/4}; \tag{28}$$

$$q_f^2, \quad \nu_2 = \frac{u}{2\pi} q_f, \tag{29}$$

where β_1 is the exponent in the one-dimensional spectrum $M_N()$, and $\beta_3 = \beta_1 + 2$ is the exponent in the three-dimensional spectrum $M_{3N}(q)$.

Thus, if the upper limit of the spectrum is large compared with q_f $(q_{max} \gg q_f)$, the theory gives (28) for the form of the wavelength dependence of the scintillation index, and this agrees with the observed relation (20)

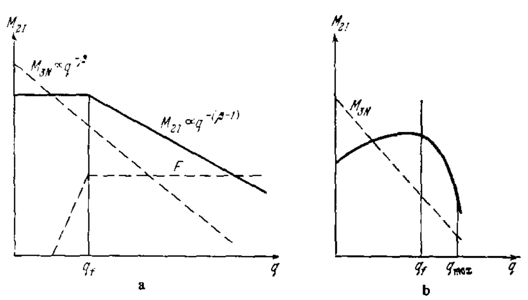

FIG. 7. Theoretical shape of the spatial spectrum of the intensity fluctuations calculated on the assumption of a power-law spectrum for the irregularities, whose upper limit q_{max} satisfies the condition $q_{max} \gg q_f$ (plot a) or $q_{max} \lesssim q_f$ (plot b).

with $\beta_3 = 2$. In this case, however, the width q_2^{-1} of the diffraction pattern will be determined by the size of the first Fresnel zone, which does not depend on the elongation, and this is inconsistent with the result (21)[54].

If the upper limit of the irregularity spectrum (18) lies in the region

$$q_{max} \leqslant q_f, \tag{30}$$

the spectrum $M_I(q)$ will have a form involving the characteristic length q_{max}^{-1} (Fig. 7,b). In this case we shall have

$$M_{2I}(q) \propto \frac{q_{max}^4}{q_f^4} \lambda^2 q_{max}^{-\beta} \propto \lambda^4, \qquad m \propto \lambda^2, \tag{31}$$

and this is inconsistent with the observed relation (20). Here, however, $\nu_2 = uq_{max}$, and ν_2 is determined by the minimum size in the spectrum, which depends on the elongation, so that here $\nu_2 \propto r^{-1}$. Relations (28), (29), and (31) show that the conclusions derived from the theory based on the power-law irregularity spectrum do not agree with observation[54].

Now let us consider the second model for the irregularity spectrum M_{3N} (Fig. 4,a), in which it is assumed that $q_0 \gtrsim q_f$. In this case the maximum contribution to the scintillation will come from irregularities with the scale of q_0 and the phase shift will not depend on the size distribution. Hence we have

$$m^2 \propto F\left(\frac{q_0}{q_f}\right) M_{2\,\mathrm{ph}} \propto \lambda^2 q_0^{-1/2} \Delta N(q_0), \qquad m \propto \lambda \tag{32}$$

and

$$\nu_2 = uq_0 \qquad (\nu_2 \propto r^{-1}). \tag{33}$$

Thus, comparison of the observational relationships (20) and (21) with the calculated wavelength dependences of the scintillation parameters m and ν_2, for which the two models under consideration yield different predictions, confirms the assumption that the irregularity spectrum has a complex shape and that "weak" scattering takes place from irregularities having a Gaussian spectrum in the region of sizes of the order of 100 km.

It is important to note that the main objection to the model with the power-law spectrum (18) is that the scintillation data indicate (via the λ dependence of m) that the spatial fluctuation-density spectrum $M_{3N}(q)$ should be proportional to q^{-2} in the region of high frequencies q[107], whereas data from satellite measurements indicate that the medium has a steeper power-law spectrum $(M_{3N}(q) \propto q^{-3.3})$ in the low-frequency region[113]. In other words, the scintillation data lead to a spatial spectrum of the intensity fluctuations which, measured in the high-frequency region, is less steep than the spectrum obtained by extrapolating the satellite data to the corresponding frequency region.

5. Temporal spectra of the scintillations. Not only have the functions $m(\nu)$ and $\nu_2(\lambda)$ been investigated, but an attempt has been made to obtain the spatial spectrum $M_{3N}(q)$ of the irregularities in the high-frequency region by another radio-astronomical method: from measurements of the temporal scintillation spectrum $M_I(\nu)$[107].

At present, such measurements have been made at four observatories[43, 112, 114, 115]; the results are presented in Table IV. The table shows that the values of α (the exponent in the temporal scintillation spectrum (19)) obtained by different investigators differ widely.

TABLE IV. Comparative data on temporal scintillation spectra

ν, MHz	Elongation	ν_b, Hz	ν_{max}, Hz	α	v, km/sec	Year	Source	Ref.
69.3	60°	0.3	1.0		400	c 1971	3C 48	114
81.5	30—90°	0.2—0.3	1.0	1.4	330	1971	3C 48, 237, 241, 287	112
86	30—50° 50—90°	0.5	2.5	3—4 2—3	300	1973	3C 48	115
430	11—36°	1.0	3—12	3—5	400	1967	CTA-21	43

We note that the values of α reported in[43, 115] agree with the calculations reported in[113] and that the values reported in[112, 114] agree with the radio-astronomical values derived from the λ dependence of m[107]. In order to understand how such widely different values of α might be obtained we must recall the limitations of the theory that relates the measured temporal scintillation spectrum $M_I(\nu)$ to the spectrum $M_{3N}(q)$ of the irregularities.

The relation between the temporal and spatial scintillation spectra (22), (23) was derived on the assumption that the diffraction pattern is stationary (that all the irregularities move with the same velocity) and that the observed scintillations are those of a point source[108]. Recent observations have shown, however, that the measured velocity of the diffraction pattern constantly exhibits a fine structure which is associated with the presence of different velocities among the irregularities on the line of sight[78, 82]. Moreover, it was found that the sizes of the scintillating sources in the meter wavelength region are due to scattering by the interstellar medium[116].

The intrinsic size of the source and the fine structure of the solar-wind velocity lead to a difference between the observed temporal scintillation spectrum $M_I(\nu)$ and the spectrum due to irregularities of the medium. Attempts were made in[112] and[114] to take the effect of the angular sizes of the sources on the observed spectrum $M_I(\nu)$ into account, and the values of α reported in those papers are for the corrected spectrum $M_I(\nu)$. On the other hand, no such correction was made in[43] and[115].

Much of the difficulty in comparing the results presented in Table IV stems from the fact that the several studies are based on observations of different sources, which have different intrinsic sizes and different heliographic latitudes (α may depend on the latitude).

Since there is no reliable way to correct the measured temporal spectra $M_I(\nu)$, the conclusions concerning the shape of the spatial spectrum $M_{3N}(q)$ of the irregularities are not reliable and lead to contradictory assertions. Thus, in[112] the presence of a bend in the temporal spectrum $M_I(\nu)$ is regarded as a manifestation of a characteristic length q_b^{-1} inherent in the medium, whereas in[115] the same bend is attributed to the operation of a Fresnel filter.

To obtain more reliable information about the form of the spatial spectrum $M_{3N}(q)$ it will be necessary to combine measurements of the temporal spectra of the scintillations with measurements of the velocity and fine structure of the irregularities.

6. Discussion of new results. In 1972 the first direct measurements of the temporal spectra $M_N(\nu)$ of the electron concentration fluctuations in the solar wind were made in the high-frequency region $4.8 \times 10^{-3} \le \nu \le 1.33 \times 10^{1}$ Hz[117]. The frequency range covered by these measurements adjoins frequency regions that have now been measured by different methods. For comparison we note that the correlation length of the magnetic field, which is $\sim 2 \times 10^6$ km, corresponds to a frequency ν in the range $\sim 10^{-6}$–10^{-5} Hz. Previous results of measurements in outer space relate to the region $10^{-5} \le \nu \le 10^{-3}$ Hz. The power-law spectrum flattens out at frequencies below 10^{-5} Hz. The correlation scale derived from scintillation measurements ($\sim$100 km) corresponds to the region 10^{-1}–10^{1} Hz.

In half the cases, the measurements reported in[117] lead to the average value $\beta_1 = 1.69$ ($1.12 \le \beta_1 \le 2.17$), which is in agreement with the value $\beta_1 = 1.3$ derived from previous low-frequency measurements. For the other half of the cases, however, the measurements revealed the presence of a hump or a relatively flat place in the $M_N(\nu)$ spectrum. Thus, the results of these measurements are not inconsistent with either of the model spectra $M_N(q)$ for the irregularities, and neither model spectrum can be ruled out.

At the same time, the analysis presented in the preceding section shows that the model with the single power-law spectrum (18) for the irregularities will not do, and that the model with the complex spectrum $M_{3N}(q)$ having a Gaussian hump in the low-frequency region (Fig. 4, a) is to be preferred. However, with the relative positions of the components of the spectrum as shown in Fig. 4, a, it is difficult to account for the bend in the spectrum $M_N(\nu)$ in the low-frequency region ($\nu \sim 10^{-2}$ Hz) observed with satellites. In this connection a new model spectrum $M_N(\nu)$ for the irregularities has been proposed[54], which repeats the shape of the spectrum proposed in the first model (Fig. 4,a) but with the high-frequency part of the spectrum lying below the power-law spectrum as extrapolated from the low-frequency region and having a relatively flat section near the bend (Fig. 8). Then the bend in the power-law spectrum observed in the low-frequency region ($\nu \sim 10^{-2}$ Hz) can be attributed to the "inner scale" of the irregularities with sizes of the order of 10^6 km, while the hump in the low-frequency region ($\nu \sim 10^{-1}$–1 Hz) will mean that a length of the corresponding magnitude ($\sim$100 km), which agrees with the observed size of the diffraction pattern at the earth, predominates in the medium. Such a spectrum enables one to reconcile the satellite data and the scintillation data on the spectrum $M_{3N}(q)$. The presence of a hump in the high-frequency region may indicate that waves of a certain type, for which q_0^{-1} is the characteristic length, predominate in the plasma.

In discussing the physics of this phenomenon under

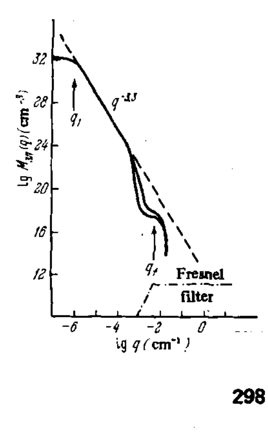

FIG. 8. Spatial spectrum for the irregularities, combining the satellite data at low frequencies with the radio-astronomical data at high frequencies.

various hypotheses concerning the shape of the spatial spectrum of the irregularities, the theory has provided support for the model having a Gaussian spectrum in the small-scale region (Fig. 4,a) in which the basic scale q_0^{-1} of the irregularities in the interplanetary plasma is associated with the basic scale of the plasma instability. Hence the analysis of the instability of the plasma was associated with the search for a type waves for which the basic scale q_0^{-1} of the instability would coincide with the size $a \approx q_2^{-1}$ of the diffraction pattern at the earth.

In[76], the plasma instability mechanism associated with the ionic cyclotron instability of waves, for which the basic scale q^{-1} of the instability is determined by the proton Larmor radius r_{Hi}, was invoked to interpret the scale a of the diffraction pattern:

$$a = \frac{m_i v_i}{eB}. \quad (34)$$

This hypothesis arose because of the fact that at solar distances of about 1 a.u., the observed value of a agrees with estimates of r_{Hi}. In order to analyze this hypothesis, a comparison was undertaken in 1973 between the values of a derived from scintillation observations and calculated values of r_{Hi} for a range of solar distances from $\sim 6R_\odot$ to 1 a.u.[118]. It was found that a and r_{Hi} agree at $r \approx 1$ a.u., but that as the solar distance r decreases, a falls off considerably faster than r_{Hi}, the scale of the irregularities becoming considerably smaller than r_{Hi}.

It has been suggested that the above discrepancy may be due to inaccurate estimation of the phase shift ψ of the wave at the irregularities of the medium, which may prove to be greater than unity ($\psi > 1$) at $r \approx 1.3$ a.u. If this is the case, then at solar distances $r \lesssim 0.3$ a.u. the size of the irregularities (allowing for the "strong scattering" conditions) should be increased by a factor of $\approx \sqrt{2\psi}$:

$$a = \sqrt{2\psi}\, q_0^{-1}, \quad (35)$$

in order to remove the discrepancy between a and r_{Hi}.

We may add that there is a way of testing the above hypothesis that $\psi > 1$ at $r \approx 0.3$ a.u. It has been shown[119] that there should be a sharp decrease in the asymmetry parameter S of the crosscorrelation function $B(r, \tau)$ on passing from the region $\psi < 1$ to the region $\psi > 1$. Analysis of the trend of S as a function of r might lead to proof or disproof of the hypothesis that the small-scale irregularities are associated with the ionic cyclotron instability of the plasma.

Interesting and noteworthy is an attempt to approach the analysis of the hypotheses discussed above concerning the shape of the spectrum of the irregularities from another side–from the physics of the phenomenon. Perkins[120] has shown that if there are two different processes going on in the plasma, in which large-scale density irregularities are associated with the outward propagation of Alfven waves while small-scale irregularities are associated with microturbulent processes in the plasma, the two types of waves will have characteristic features. The phase velocity of the waves responsible for the scintillation of radio sources will be directed opposite to that of the Alfven waves, the electron concentration fluctuations in which can be measured with satellites.

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