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RADIOASTRONOMICAL INVESTIGATIONS OF THE INHOMOGENEOUS STRUCTURE OF THE NEAR-SOLAR PLASMA

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I. INTRODUCTION

THE study of the physical properties of interplanetary plasma has been attracting great interest in view of the intense mastery of outer space. The most important characteristics to be studied are the concentration, structure, and dynamics of the interplanetary plasma, and also the structure of the magnetic fields. These characteristics are studied with the aid of rockets and earth-based radioastronomical and other research methods.

Radioastronomical investigations are based on the study of the influence of the interplanetary plasma on the passage of radio waves through it. They therefore make it possible to solve problems of two types: 1) if the true characteristics of the radio emission of the discrete sources are known, then it is possible to obtain from them and from their observable characteristics information concerning the properties of the near-solar plasma; 2) on the other hand, if we do not know the true characteristics of the radio sources (their dimension, structure, radio-brightness distribution), then they can be obtained from the observed characteristics and known properties of the near-solar plasma. Two radioastronomical methods involving different quantities are extensively used at present to solve this group of problems. These are the "transmission" method, based on the use of the eclipses of sources in the radio band, i.e., on transmission of radio waves from discrete sources of radio emission through the near-solar space, and the method of "radio scintillation," which is based on the study of the scintillation of the intensity of sources with very small angular dimensions.

The "transmission" method was proposed and employed for the first time in 1951 by V. V. Vitkevich, who called attention to the fact that one of the most powerful discrete sources of radio emission, the Crab nebula, is located near the ecliptic. This suggested the investigation of the solar corona "by transmission" during periods of visible approach of this source to the sun[1]. To effect these observations, a radio interferometer was proposed and employed, with specially chosen parameters, making it possible to separate the radio emission of the Crab nebula against the background of the much more powerful (by one order of magnitude) radio emission of the sun. Observations carried out in 1951–1953 in the Soviet Union and in 1952–1953 in Cambridge (England) led to unexpected results. It turned out that the near-solar medium exerts an influence on the meter-band radio waves passing through it over tremendous distances (up to 15 $R_\odot$), since a decrease in the amplitude of the interference pattern is observed in this case[1,1a]. However, the nature of the observed effect remained unclear until 1954 because these results could not be interpreted uniquely. They could be due both to absorption of the radio waves in the solar corona and to scattering in it. Observation with an interferometer with bases of different lengths have made it possible to clarify the nature of the observed effect[2-4]. It was established that the increase of the angular dimensions of the Crab nebula is due to scattering of its radiation by inhomogeneities of the electron density, which first observations have shown to extend over tremendous distances, on the order of 15 $R_\odot$. An extension of the solar corona (the supercorona of the sun) could thus be observed.* It was established thereby that the supercorona

*This is usually defined as the region $r < 60R_\odot$. The extension of the supercorona is the interplanetary plasma.

has an essentially inhomogeneous structure, and this is indeed the cause of the observed scattering of the radio waves. Perfection of the radio-interferometric observation procedures has made it possible in subsequent years to observe the supercorona in the region of larger distances, which by now have reached ≈ 1/3 a.u. (i.e., ~ 60 $_{\odot}$)[5-9].

The discovery of quasars (sources with very small angular radio dimensions, ≲ 1″) in 1963[10] has made it possible to extend radioastronomical investigations to more remote regions of interplanetary plasma. This has become possible as a result of the application of a new method—the "radio scintillation" method, which is also based on transmission through the interplanetary plasma, but the measured quantities are in this case the fluctuations of the intensity and the period of the "scintillation" of the radio source. This method was first used in 1964 by Hewish et al.[11] The idea of the method was proposed back in 1956 by V. L. Ginzburg[12] and was considered in detail in 1958 by V. V. Pisareva[13]. However, its practical implementation became possible only after the discovery of the quasars. The principle of this method consists in the following. If a layer in which the electron density is statistically inhomogeneous is located between a point source of radio waves and the earth, then the waves passing through this layer are diffracted. When the inhomogeneities move with velocity v relative to the earth, the diffraction pattern moves over the earth with the same velocity, thus causing fluctuations (scintillations) of the intensity of the radio emission at the point of observation. Such radio scintillations were first observed systematically by Hewish et al. for a large number of sources[11]. Since the intensity oscillations observed in[14-17] had a period τ on the order of several seconds, they could not be due to changes of the intensity of the sources themselves, because τ is much shorter than the time of propagation of the light through the source. One must also reject an ionospheric origin for the observed scintillations, since such a hypothesis leads to the absurd result whereby scattering of radio waves by the ionospheric inhomogeneities should lead to "visible" angular dimensions of the source ≳ 10°. It was therefore concluded that the scintillations of the radio sources are due to diffraction of the radio waves by the inhomogeneities of the interplanetary plasma, which move with the velocity of the solar wind, reaching in accordance with Parker's theory approximately 400 km/sec at a distance on the order of 100 $R_{\odot}$[18]. Observations of radio scintillations have made it possible to study the electronic inhomogeneities of interplanetary plasma in the region (80—260) $R_{\odot}$, i.e., up to record distances exceeding the radius of the earth's orbit. Recently these observations were extended to the region of high frequencies, making it possible to investigate by the "flicker" method regions closer to the sun, and thus encompass a broader region of distances, (20—260) $R_{\odot}$.

The combination of the two radioastronomical methods makes it possible to carry out regular observations of the near-solar plasma in a distance range (4.5—260) $R_{\odot}$ and obtain its most important parameters, namely the form, dimension, and concentration of the electrons in the inhomogeneities, and also their velocity of motion at different distances from the center of the sun. These characteristics of the interplanetary plasma cannot be obtained by any other method.

II. RESULTS OF STUDY OF THE SOLAR SUPERCORONA BY THE "TRANSMISSION" METHOD

1. Characteristics of Inhomogeneities in the Distance Range r = (5—60) $R_{\odot}$.

Observations by the "transmission" method have established that the presence of inhomogeneities is a characteristic and permanent property of the quiescent supercorona and the interplanetary plasma. The inhomogeneities are observed both during the years of the maximum and during the years of the minimum solar activity, in both low and high solar latitudes[1-9,23]. Inhomogeneities of various types were discovered and investigated in the near-solar plasma[2,23]. Thus, rapidly moving large-scale inhomogeneities were observed (with dimension $l \sim 10^6$ km and velocity on the order of several thousand km/sec), leading to short-duration variation of the intensity of the source signal (characteristic time ~ 1—3 min). Stable (without noticeable motion) large inhomogeneities (characteristic dimension about 10^6 km) leading to refraction of radio waves were observed starting in 1956; refraction near 30′ was observed at a wavelength λ = 6 m and a distance (10—20) $R_{\odot}$. These values of the refraction were attributed to the presence of inhomogeneities with an electron density approximately 10 times the average value. Cases of refraction were observed many times later also at larger distances. However, the main result of these investigations was the establishment of the fact that the plasma in the near-solar space always contains small-scale inhomogeneities which scatter radio waves of the meter band[5-9,24,25]. A study of the dependence of the angle of scattering of the radio waves on the minimum distance of the line of sight to the center of the sun $\overline{\Phi}^2(r_0)$ has made it possible to obtain estimates of the characteristics of these inhomogeneities.

In "transmission" experiments, the quantity measured directly is the radio-wave scattering angle Φ, with the aid of which one calculates the combination of quantities[26,27]

$$\frac{(\Delta N)^2}{l}, \tag{1}$$

where ΔN—excess of the electron concentration in the inhomogeneities above the mean value and l—effective dimension of the inhomogeneities. To determine the parameters ΔN and l separately, estimates were made of l by starting from indirect considerations, and then the values of ΔN were obtained from the known values of Φ using (1). An estimate of the upper limit of l was obtained from the conditions of applicability of the geometrical-optics approximation to the problem of radio-wave scattering in a statistically inhomogeneous medium containing inhomogeneities of the electron density[28]

$$l \gg \lambda, \tag{2}$$

$$D = \frac{\sqrt{\lambda R}}{l} \ll 1, \tag{3}$$

where λ—radiation wavelength, R—distance from the observation source to the effectively scattered region, and D—wave parameters. As shown in[28], it is necessary in this case to consider two possibilities. The first occurs when the angular dimension of the inhomogeneities satisfies the relation

$$\sqrt{\overline{\Phi^2}} < \frac{2l}{R}, \qquad (4)$$

at which rays from only one inhomogeneity of the phase of the wave front reach the observation point. In this case only refraction phenomena can be observed, without an increase of the source dimensions. When the inverse relation

$$\Phi > \frac{2l}{R} \qquad (5)$$

is satisfied, the radiation arrives at the point of observation from several inhomogeneities of the wave-front phase, and the effect of radio-wave scattering leads to an observable increase of the angular dimensions of the radio source. In this case the observable quantity Φ can be regarded as the upper limit of the angular dimension of the inhomogeneities:

$$2l_{\max} = R\Phi. \qquad (6)$$

Estimates based on formula (6) have shown that[24] $l_{\max} \simeq 5 \times 10^3$ km at $r/R_\odot = 60$. To estimate the lower limit $l_{\min}$, the diffraction-theory approximation was used for the case when the wave parameter D satisfies the condition

$$D \gg 1. \qquad (7)$$

In this case, the deviation of the incident-wave energy flux from the unperturbed direction (i.e., the increase of the "visible" angular dimensions of the radio source) is due to statistical diffraction of the radio waves. The expression for the radio-wave scattering angle has in this case the form[29]

$$\overline{\Phi^2} = \frac{\lambda^2}{\pi^2 l^2} \overline{(\Delta\varphi)^2}, \qquad (8)$$

where $\overline{(\Delta\varphi)^2}$ is the mean square phase shift of the wave in the layer as a result of the inhomogeneities. Substituting in (8) the value of $\overline{(\Delta\varphi)^2} = 1$, corresponding to the maximum possible value of the scattering angle (an apparent increase of the dimensions of the source will be observed only for the case of strong perturbation of the wave front, when $\overline{(\Delta\varphi)^2} \gg 1$[24]), we get

$$l_{\min} = \frac{\lambda}{\pi\Phi}. \qquad (9)$$

Application of formula (9) to the values of Φ obtained in experiments by "transmission," lead to the value[24] $l_{\min} \sim 50$ km at $r/R_\odot = 90$. The values of the scattering angles were recalculated in terms of electron densities with the aid of the obtained values of l[5,24,25,30].

From the values of $l_{\max}$ and $l_{\min}$ we get

$$50\ \text{km} \leqslant l \leqslant 5000\ \text{km}. \qquad (10)$$

The plasma characteristics l and ΔN estimated with the aid of the "transmission" method are subject to a considerable uncertainty, due to the inaccurate value of the characteristic dimension of the inhomogeneities. Nonetheless, this method has yielded many new data on the near-solar plasma, which heretofore could not be investigated at all. First, it was established that the dimensions of the supercorona depend on the phase of the eleven-year cycle of solar activity: during the period of the maximum, the dimension of the supercorona is on the average twice as large, but the laws governing the variation are different for different regions of the corona[5,24,23]; second, it was established that the supercorona is asymmetric (is elongated in the equatorial plane) in different years (on the average the dimension of the equatorial region is approximately double the polar dimension)[31]; finally, these measurements served as a basis for the creation of models of the inhomogeneities themselves[32,33].

2. Influence of the Scattering of Radio Waves in the Solar Supercorona on the Observable Dimensions and Shape of the Discrete Sources of Radio Emission

A study of the solar supercorona by the "transmission" method has led to the discovery of anisotropy of its scattering properties[34-38]. It was established[34] in 1957 that the scattering of radio waves in a direction radial with respect to the center of the sun is much smaller than scattering at an angle perpendicular to it. This anisotropic scattering effect can be attributed to the fact that the inhomogeneities have an elongated form and are oriented principally in directions close to radial. The form and the orientation of the inhomogeneities are due in all probability to the influence of the quasiradial magnetic field of the sun, which makes the diffusion of the charge particles across the force lines difficult. It has therefore become customary to consider the scattering properties of the supercorona by starting from the existence of radially-elongated inhomogeneities.

Simultaneous observations of the Crab nebula during the periods of its approach to the sun, with interferometers having three differently oriented bases, have made it possible to ascertain that the form of the scattered source in the picture plane is close to elliptic, with an axis ratio equal to approximately unity at $r/R_\odot \lesssim 10$, becoming equal to about 1/2 at $r/R_\odot > 10$, and remaining constant at this value in a wide range of distances (up to $40 R_\odot$)[39]. These averaged results make it possible to draw some conclusions concerning the form of the scattering inhomogeneities and to propose the existence of isotropic inhomogeneities in the distance region $r/R_\odot \lesssim 10$ and radially-elongated the inhomogeneities in the region $r/R_\odot > 10$. The results of these investigations served as the basis for the development of a supercorona model using two types of inhomogeneities: isotropic and radially-elongated[33]. Extensive calculations made within the framework of this model have made it possible to take into account the influence of the solar supercorona and of the interplanetary plasma on the observable dimensions and shapes of the discrete sources of radio emission located at various distances from the sun, when observed from different points of the solar system[40].

The problem consisted of relating the observable scattering of the radio waves with the properties of the near-solar plasma. An integral equation was derived, in which the scattering properties of the medium at each point of space are characterized by a scattering function

$$\Psi(r) = 2\sqrt[4]{\pi}\cdot 4.47\cdot 10^{-10}\lambda_m^2 \frac{\Delta N}{\sqrt{l}}. \quad (11)$$

When applied to the case of the isotropic inhomogeneities, this equation takes the form[55]

$$\overline{\Phi_{is}^2}(r_0) = 2\int_{r_0}^{\infty} \Psi_{is}^2(r)\frac{r\,dr}{\sqrt{r^2 - r_0^2}}. \quad (12)$$

In the case of the radially-elongated inhomogeneity[33] we have

$$\overline{\Phi_{rad}^2}(r_0) = \frac{2}{r_0}\int_{r_0}^{\infty} \Psi_{rad}^2(r)\frac{r^2\,dr}{\sqrt{r^2 - r_0^2}}. \quad (13)$$

In experiments with "transmission" it was established that the dependence of the radio-wave scattering angle on the minimum distance of the line of sight to the center of the sun r_0 in the distance range

$$4.5 < \frac{r}{R_\odot} < 90$$

can be well approximated by the power-law function

$$\overline{\Phi^2}(r_0) = \frac{k^2}{r_0^{2m}}, \quad (14)$$

in which the parameter m depends on the phase of the solar activity: according to Vitkevich, for the major axis of the scattering ellipse m = 1.11, during the years of minimum solar activity (1959–1963) and m = 1.72 in the years of maximum activity (1956–1958)[5,31]; according to data by foreign authors, the corresponding values are m = 1.38 and m = 2.33[23,24]. A power-law dependence of the type (14) makes it possible to solve the integral equations of scattering (12) and (13) by the Abel method, and to find an expression for the scattering function Ψ in terms of the values of the parameters k and m, which are known from experiment[33]:

$$\Psi_{is}^2(r, m_{is}) = \frac{k_{is}^2 m_{is}\Gamma\left(m_{is} + \frac{1}{2}\right)}{\sqrt{\pi}\,\Gamma(m_{is} + 1)\, r^{2m_{is}+1}}, \quad (15)$$

$$\Psi_{rad}^2(r, m_{rad}) = \frac{k_{rad}^2 (2m_{rad} - 1)\Gamma(m_{rad})}{2\sqrt{\pi}\,\Gamma\left(m_{rad} + \frac{1}{2}\right) r^{2m_{rad}+1}}, \quad (16)$$

where Γ(m) is the gamma function.

Knowledge of the scattering functions for the radially elongated and isotropic inhomogeneities makes it possible to calculate the radio-wave scattering angles for a source located both "infinitely" far (for example, in the galaxy),* and at any finite distance from the sun. The latter problem is quite timely in connection with the study of the influence of the near-solar plasma on the intrinsic radiation of the "quiet" sun and its active formations. We encounter a similar problem also when the supercorona is viewed by transmitted light from Jupiter and other planets, and in problems involved in rocket investigations. The inhomogeneities of the near-solar plasma influence the observable distribution of the radio brightness of the "quiet" sun, the observable dimensions and shape of the individual local sources. This influence, at wavelengths near 10 meters, becomes quite noticeable and it must be taken into account in the interpretation of the experimental data.

Calculations have shown that allowance for the finite distance from the source to the scattering medium leads to a weakening of the radio-wave scattering effect[40]. The influence of different factors (shape of the inhomogeneity, values of the parameters m and r_0) on the attenuation of the scattering effect was investigated. It was shown that the weakening of the scattering is less pronounced for radially-elongated inhomogeneities. The influence of the scattering of radio waves on the observed shape of the discrete sources was also investigated, and the "visible" elliptical form of the radio source was found to depend on its distance from the center of the sun: when the source approached the observer, a noticeable elongation of the elliptic form took place in a direction perpendicular to the radial direction to the source[33]. The influence of the inhomogeneities of the near-solar plasma on the observed shape and dimensions of the source situated at a finite distance from the sun were investigated by observation from points that were likewise located at a finite distance from the sun. It was shown that the presence of the supercorona leads to scattering of the radio emission from the active regions of the sun by amounts on the order of 3′–20′ (at 8 meter wavelength)[40]. Observations of such effects can be used to obtain regular information on the near-solar plasma.

3. Model of Two-component Structure of the Solar Supercorona

The concept of the supercorona as a two-component medium was developed in[25,41]. This concept follows from a comparison of the optical measurements of the electron density with the radioastronomic measurements, which were described in Sec. I above. The optical investigations of the supercorona are based on the fact that the light flux from these regions is due to scattering of the radiation of the photosphere (in the continuous spectrum) by free electrons and by the dust component of the supercorona. It is assumed here that the polarized emission is connected with the scattering by electrons. The photometric polarization measurements made it possible to determine the dependence of the average concentration of the electrons on the distance to the center of the sun. Such measurements were performed by Blackwell during the time of the solar eclipses of 1954 and 1963[42,43]; they encompassed the distance range $5 \le r/R_\odot \le 20$. Taking into account the earlier observation by Michard[44] ($3 \le r/R_\odot \le 10$), it can be stated that optical data obtained in the distance region $3 \le r/R_\odot \le 20$ indicate that $\overline{N}_e \simeq 3.4\times 10^5$ el/cm³ (at $r/R_\odot = 3$), 10^4 el/cm³ (at $r/R_\odot = 10$), and 2.6×10^3 el/cm³ (at $r/R_\odot = 20$). We note once more that the optical investigations yield the average electron density, whereas the radio observations by the "transmission" method make it possible to obtain the excess ΔN of the electron density in the inhomogeneities over the average concentration $\overline{N}$ in the supercorona. The rates of decrease of the electron density with increasing distance from the center of the sun, as obtained from optical and radio data, were compared in[41]. For both electronic components, the exponent of the decrease was calculated in[41] as a function of the distance to the center of the sun. It was established that for distances $(5–10)\,R_\odot$ the exponent obtained from optical data is much higher

*This case is realized when the supercorona is viewed by transmitted radiation from the Crab nebula and from other galactic radio sources.

than that obtained from radio data, but the two exponents are approximately equal in the region (12–15) $R_\odot$. Starting from these results, Vitkevich reached the conclusion that the supercorona of the sun has a two-component structure. One is a regular component, with uniform distribution of the electron density. Radio waves propagating through it are not scattered. The second component is statistical and consists of inhomogeneities of the electron density, which cause scattering of the radio waves.

In the investigation of the solar supercorona by the "transmission" method, using radio sources such as the Crab nebula, it is natural to assume that the statistical component is responsible for the scattering of the radio waves and leads to an increase of the observable angular dimensions of the radio source, whereas the regular component is responsible for the refraction of the radio waves. Since the regular component is characterized by a relatively rapid decrease of the electron density with increasing distance from the sun, it can be assumed that at large distances ($r > 10 R_\odot$) the effect of scattering of radio waves will prevail, and the refraction of the waves can be neglected. However, at distances (3–10) $R_\odot$, when both effects are significant, it is essential to solve the problem of the simultaneous influence of the scattering and refraction of the radio waves. The problem of the influence of a two-component medium on the observable position and shape of the penetrating radio sources was considered qualitatively in[23] and in detail in[45]. It was found that allowance for the simultaneous influence of refraction and scattering of the radio waves at distances up to $10 R_\odot$ leads to a shift of the effective radiation center of the source and to a distortion of its observed form. It has been shown that by measuring the shift of the effective center of the radiation of the transmitting radio sources it is possible to investigate the distribution of the average electron density by a radioastronomical method, a fact which is of certain interest.

III. STUDY OF INTERPLANETARY PLASMA BY THE "RADIO SCINTILLATION" METHOD[1]

1. Observations of Interplanetary Scintillations

The first observation of interplanetary scintillations of radio sources were made (by Hewish et al.) at a wavelength $\lambda = 1.7$ m and at an angular distance $\theta = 80°$ from the source to the sun[11]. The use of longer wavelengths, $\lambda = 3.5$ and 7.9 m (Vitkevich et al.) has made it possible to observe scintillations up to $\theta = 160°$, i.e., much farther[15,20]. At the present time, such observations are carried out successfully in a number of countries, and we have data for the wavelengths $\lambda = 7.9$ and 3.5 m (Vitkevich; sources 3C144, 3C48, 3C147)[15,19,20], $\lambda = 3.7$ and 1.7 m (Hewish; sources 3C144, 3C48, 3C138, 3C237, 3C208, 3C225)[11,14,16,46], $\lambda = 0.74$ m (Sinigaglia; source 3C273)[47], $\lambda = 1.5$, 0.70, 0.49 m (Cohen; sources CTA21, 3C138, 3C273, 3C287, 3C286, 3C298)[17,21,66], and $\lambda = 0.21$ (Hogg and Menon; sources 3C273 and 3C279)[22]. In each case, very complicated plots were obtained. These were used to calculate the period of the scintillations (the reciprocal of the number of maxima per unit time)

$$\tau = \frac{L}{v}, \tag{17}$$

where L is the scale of the diffraction pattern on earth, v is the velocity of the inhomogeneities relative to the earth, and the measure of the scintillation F is the relative mean square deviation of the intensity

$$F = \frac{\overline{I^2} - (\overline{I})^2}{(\overline{I})^2}. \tag{18}$$

The dependence of τ and F on the angular distance θ and on the employed wavelength λ was investigated.

Comparison of the data obtained by different authors has made it possible to draw the important conclusion that the period of the scintillations τ does not depend on the wavelength λ and remains approximately constant in a wide range of angular distances from the source to the sun. Data at the shorter wavelengths, 0.75–0.21 m, are used at closer distances ($\theta < 35°$), and data at the longer wavelength, 7.9 m, are used for larger angles ($\theta \simeq 80$–$160°$). These conclusions were obtained in[15], where it was shown that the histograms of the periods of the scintillations at 3.5 m (Vitkevich et al.) have a spectrum similar to the spectrum obtained by Hewish at 1.7 m.

The results of the observations[11,14-17,19-22] have made it possible to conclude that the scintillations can be subdivided into two main types: scintillations produced under conditions of weak scattering ($\theta > 20°$), and those produced under conditions of strong scattering ($\theta < 10°$). All the principal data pertain to the region of radial distances $\theta > 20°$, when the interplanetary inhomogeneities form a weakly scattering medium, i.e., when the total phase shift of the wave $\Delta\varphi$ due to the inhomogeneities of the interplanetary medium along the line of sight is smaller than 1 rad. In this case it is well known that the dimension of the diffraction pattern L observed on earth can be assumed equal to the dimension l of the inhomogeneities themselves[48]. Indeed, in the case when the dimension of the inhomogeneities greatly exceeds the wavelength (~1 m), as is the case under the conditions of the near-solar plasma, the conditions of geometrical optics are well satisfied, so that the scattering action of the layer of inhomogeneities in the case of weak deflection of the rays reduces to a distortion of the phase of the wave $\Delta\varphi$.* When $\sqrt{\overline{(\Delta\varphi)^2}} \ll 1$ (as is known from the theory of scattering or radio waves by a thin phase screen), the scale of the diffraction pattern in the observation plane coincides with the characteristic dimension of the inhomogeneities, $L = l$; on the other hand, if $\sqrt{\overline{(\Delta\varphi)^2}} \gg 1$, then the observed dimension of the diffraction pattern L depends on the ratio of the dimension of the inhomogeneities l to the first Fresnel zone $\sqrt{\lambda R}$[48,49]. When $D > 1$ (i.e., when $l < \sqrt{\lambda R}$; see (7)) we have

$$L = \frac{l}{\sqrt{\overline{(\Delta\varphi)^2}}}, \tag{19}$$

whereas when $D < 1$ (when $l > \sqrt{\lambda R}$) the diffraction pat-

*Satisfaction of the conditions of geometrical-optics and of small amplitude modulation of the wave after emergence from the layer makes it possible to replace the layer with inhomogeneities by a phase screen.

tern contains characteristic dimensions of the order of l and $l/\sqrt{\overline{(\Delta\varphi)^2}}$. The presence of the scale l is connected with the focusing action of the inhomogeneities, which takes place when $l \gg \sqrt{\lambda R}$. All these considerations pertain to a pointlike source. With increasing angular dimensions Φ of the source, the diffraction picture begins to smear out when

$$\Phi \sim \frac{l}{R}, \tag{20}$$

where R is the distance from the layer containing the inhomogeneity to the earth. This makes it possible to detect sources with $\Phi < l/R$ (quasars) by the presence of scintillations, and since in this case $\Phi \propto \lambda^2$, (11)–(13), it follows that for each wavelength λ there is a certain limiting value of Φ, determined from the condition (20), beyond which the approach of the source to the sun leads to a decrease in the scintillation measure F. On the other hand, in the case of very large θ, the increase of the angular distance will also lead to a decrease of F, this being connected with the decrease in the density of the medium (i.e., with the decrease of the phase shift $\sqrt{\overline{(\Delta\varphi)^2}}$). Therefore, for each wavelength λ there is a separate region of values of θ where the fluctuations of the intensity are particularly strongly pronounced. Observation of the intensity fluctuations at different wavelengths makes it possible to separate different regions of the near-solar plasma.

2. Method of Calculating the Electron Densities From Radio-scintillation Data

The experimentally known values of τ and F make it possible to calculate the plasma parameters l and ΔN. Relation (17) allows us to obtain the value of l if we know the velocity of the inhomogeneities relative to the earth, v. The value of ΔN is calculated from the known values of F and l. In the case when $\overline{(\Delta\varphi)^2} \ll 1$, the expression for F takes the form[13,19]

$$F = 2\overline{(\Delta\varphi)^2}\left[1 - \frac{1}{1 + 4\lambda^2R^2/\pi^2l^4}\right]. \tag{21}$$

The mean-square phase shift of the inhomogeneities $\sqrt{\overline{(\Delta\varphi)^2}}$ is determined in terms of the phase shift from one inhomogeneity $\sqrt{\overline{(\Delta\varphi_0)^2}}$ and the number of the inhomogeneities m: $\overline{(\Delta\varphi)^2} \sim m\,\overline{(\Delta\varphi_0)^2}$; more accurate calculations give an additional factor $\sqrt{\pi}$, so that

$$\overline{(\Delta\varphi)^2} = 1.8\,\overline{(\Delta\varphi_0)^2}\,m. \tag{22}$$

Expression (21) for F was obtained under the assumption that the phase screen is produced by the inhomogeneities located in a layer having a small thickness ΔR compared with the distance R, i.e., $\Delta R \ll R$. When scintillations of the radio sources are observed, this inequality is not satisfied, and for most cases $\Delta R \sim R$. No rigorous theory has yet been developed for this relation, so that we shall take R to mean a certain mean distance from the earth to the layer with the inhomogeneities, and ΔR to mean a certain effective thickness of the scattering layer. R and ΔR, were calculated numerically in[19].

Let us see how F changes with changing R along the line of sight at a specified θ. When the condition $\Delta R \ll R$ is satisfied, the scintillation measure F depends strongly on the distance R. When $2\lambda R \ll \pi l^2$ (observation in the near zone) the quantity in the square brackets of (21) is much smaller than unity, and F is also small. Thus, at close distances from the scattering layer, the efficiency of the inhomogeneous screen is small. With increasing R, the number of scintillations from the same layer increases; when $\lambda R = l^2$ we have

$$F = 0.6\,\overline{(\Delta\varphi)^2}. \tag{23}$$

Finally, at $2\lambda R \gg \pi l^2$, when we are in the far zone, the quantity in the square bracket can be assumed equal to unity. In this case the action of the inhomogeneous screen is most effective. As to the dependence of the phase shift per unit length (along the line of sight) on the distance, it is obvious that at sufficiently large distances this quantity always decreases. Therefore, if we represent F in the form of a sum, breaking up the entire layer into thin layers δR_i of equal thickness with phase shift $\overline{(\Delta\varphi_i)^2}$ and with corresponding distance to the observer R_i, namely

$$F = 2\sum_{i=1}^{n}\overline{(\Delta\varphi_i)^2}\left[1 - \frac{1}{1 + \frac{4\lambda^2R_i^2}{\pi^2l^4}}\right], \tag{24}$$

then the terms for small values of i will be small because the second factor is small, and at large i the first factor will always be small, starting with a certain value i = k. For a certain value i = m, the corresponding term of (24) will have a maximum, i.e., this layer will make the largest contribution to the scattering. The distance to this layer will be denoted R_m, i.e., R_m is a certain effective distance from the observer to the scattering inhomogeneities. It is further possible to find a certain effective layer thickness ΔR, which we define as the thickness at which F decreases to 0.5 of the maximum on both on the side of smaller distances (R_1) from the observer, and on the side of the larger distances (R_2)

$$\Delta R = R_2 - R_1.$$

The corresponding calculations were performed in[19], and the values of R_m and ΔR were obtained for different θ.

Since ΔR is the path in the inhomogeneous medium and $2l$ is the dimension of the inhomogeneities, we rewrite (22) in the form

$$\overline{(\Delta\varphi)^2} = 1.8\,\overline{(\Delta\varphi_0)^2}\,\frac{\Delta R}{2l}. \tag{25}$$

using the well known relation[19]

$$\sqrt{\overline{(\Delta\varphi_0)^2}} = \frac{4\pi}{\lambda_{km}}\ 4.5\cdot10^{-10}\lambda_m\sqrt{\overline{(\Delta N)^2}\,l_{km}^2}, \tag{26}$$

we find the expression of interest to us for the electron density of the inhomogeneities

$$\overline{(\Delta N)^2} = 3.5\cdot10^{10}\frac{\overline{(\Delta\varphi)^2}}{\lambda_m^2 l_{km}\Delta R_{km}},$$

where $\overline{\Delta\varphi^2} = F/2$ from (21).

Figure 1 shows an example of the values of R_m, R_1, and R_2 as functions of the angle θ for $\lambda = 7.9$ m. We see that at $\theta = 180°$ the region of the more effective scattering comes closer to the earth, $\Delta R \sim 0.45$ a.e. When θ decreases, ΔR first increases, but it decreases noticeably on approaching the sun.

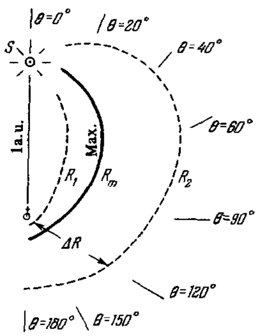

FIG. 1. Location of that layer of inhomogeneities of interplanetary plasma which makes the main contribution to the radio scintillations. R_1 and R_2 – internal and external boundaries; ΔR – thickness of layer along the given direction θ. In the calculations it was assumed that λ = 7.9 m, l = 600 km, and 2m = 3.5.

3. Description of Radio Wave Scattering with the Aid of the Theory of the Phase Screen

As already noted above, to describe the scattering of transmitted radio waves by a medium, extensive use is made of the theory of the phase screen, in which the action of the medium is replaced by a phase screen which produces the observed scattering. A recently published paper by Salpeter[50] is devoted to an extension of the result of the theory of the phase screen to the study of the intensity and measure of the scintillations in the picture plane as a function of the distance z from the screen to the observer at different values of $\overline{(\Delta\varphi)^2}$ [13,51,53]. We consider the cases $z < z_0$ and $z > z_0$, where z_0 is the distance from the scattering screen at which the angular dimension of the inhomogeneities of the refractive index coincides with the angular dimension of the first Fresnel zone. When $z = z_0$, the wave parameter (3) is D = 1 and

$$z_0 = \frac{2\pi l^2}{\lambda}. \tag{28}$$

The case $z < z_0$ ($D < 1$) corresponds to the region of the near field, when effects of focusing can play a major role in the distribution of the intensity in the observation plane, together with the diffraction effects (this is the case if $\overline{(\Delta\varphi)^2} > 1$). In this case, the intensity distribution contains both large inhomogeneities, with dimension on the order of l, as well as smaller ones, on the order of $l/\sqrt{\overline{(\Delta\varphi)^2}}$, which are superimposed on the large-scale inhomogeneities. The presence of large inhomogeneities when $\overline{(\Delta\varphi)^2} > 1$ is connected with the focusing action of the inhomogeneities of the refractive index, which have a characteristic dimension $l \gg \sqrt{\lambda z}$ [13]. The case $z > z_0$ ($D > 1$) corresponds to the region of the far field, when only diffraction effects are observed and the average dimension of the inhomogeneities in the observation plane is of the order of $l/\sqrt{\overline{(\Delta\varphi)^2}}$.

Salpeter[50] has shown that the character of the flicker of a point source depends on two parameters: $\overline{(\Delta\varphi)^2}$ and z/z_0. In this case it is possible to distinguish four different regimes:

Region 1, where $z \ll z_0$ when $\sqrt{\overline{(\Delta\varphi)^2}} < 1$ (weak scattering) and $z \ll l \equiv z_0/\sqrt{\overline{(\Delta\varphi)^2}}$ when $\sqrt{\overline{(\Delta\varphi)^2}} > 1$ (strong scattering). In this region, the spectrum M(q) (the Fourier transform of the intensity correlation function I(x) (one-dimensional screen)) takes the form

$$M(q) \approx I_0^2 \left(\frac{z}{z_0}\right)^2 (ql)^4 \varphi^2(q). \tag{29}$$

The measure of the scintillations is

$$F \approx \sqrt{\overline{(\Delta\varphi)^2}}\,\frac{z}{z_0}; \tag{30}$$

$\varphi(x)$—random change of the phase along the screen, $\overline{(\Delta\varphi)^2}$—mean square phase deviation, $\overline{(\Delta\varphi)^2}\,\rho(r)$—autocorrelation function of $\varphi(x)$, and $\varphi(q)$—Fourier transform of the autocorrelation function of the phase of $\varphi(x)$. The correlation length l is defined as the reciprocal of the second moment of $\varphi^2(q)$, for example, for a Gaussian screen

$$\left.\begin{aligned} &\rho(r) = e^{-\frac{1}{2}\left(\frac{r}{l}\right)^2},\\ &\varphi^2(q) = \sqrt{2\pi}\, l\, \overline{(\Delta\varphi)^2}\, e^{-\frac{1}{2}(ql)^2},\\ &l^2 = q_0^2, \end{aligned}\right\} \tag{31}$$

where q_0^2—second moment of $\varphi^2(q)$. The spectrum (29) has a maximum at $q = l^{-1}$, and the scintillation measure F is proportional to λ^2. The frequency spectrum of the intensity is Gaussian and there exists a high cross-correlation between the scintillations observed at different frequencies.

In region 2 we have $z \gg z_0$ and $\overline{(\Delta\varphi)^2} \ll 1$ (weak scattering). The spectrum is

$$M(q) \approx 2I^2\varphi^2(q), \tag{32}$$

$$F \approx 1. \tag{33}$$

In this case the spectrum (32) observed on earth is the same as the spectrum of the phase fluctuations on the screen. The scintillation measure F is proportional to λ. There is a Gaussian distribution of the intensity and a high cross correlation under the condition

$$\frac{\Delta\nu}{\nu} \equiv \frac{1}{2}\,\frac{\nu_2-\nu_1}{\nu_2+\nu_1} < \frac{z_0}{z}. \tag{34}$$

In region 3 we have $z \gg l = z_0/\sqrt{\overline{(\Delta\varphi)^2}}$ and $\overline{(\Delta\varphi)^2} \gg 1$,

$$M(q) \approx \exp\left[-\left(\frac{ql}{2\sqrt{\overline{(\Delta\varphi)^2}}}\right)^2\right], \tag{35}$$

$$F \approx 1. \tag{36}$$

The spectrum has a Gaussian form, and its width $\sqrt{2}\sqrt{\overline{(\Delta\varphi)^2}}/l$ is proportional to λ. The scintillation measure is of the order of unity, and the cross correlation is small if

$$\frac{\Delta\nu}{\nu} < \left(\frac{z_0}{z}\right)\left(\sqrt{\overline{(\Delta\varphi)^2}}\right)^{-2}. \tag{37}$$

Region 4 is the boundary between regions 1 and 3, $z \sim l \ll z_0$. Scintillations with sharp maxima prevail, and there is a weak correlation between the scintillations at different frequencies if

$$\frac{\Delta\nu}{\nu} < \left(\sqrt{\overline{(\Delta\varphi)^2}}\right)^{-1/3}. \tag{38}$$

The width of the spectrum depends strongly on λ, increasing from l^{-1} in the region 1 to $\sqrt{2}\sqrt{\overline{(\Delta\varphi)^2}}\,l^{-1}$ in region 3. The scintillation measure exceeds unity. The theory of the phase screen makes it possible to separate the four principal regimes of the scintillations (intensity fluctuations), depending on the values of the parameters $\sqrt{\overline{(\Delta\varphi)^2}}$ and z/z_0. Knowledge of these regimes (29)—(38) makes it possible to determine from the available experimental data the region of the scattering, and accordingly to obtain the parameters of the phase screen: its distance, the characteristic scale l, and the electron densities ΔN. This work was performed in[21], where the results of observations at wavelengths 1.5 m, 70 cm, and 49 cm are compared with the theory presented above. It is shown that the observations are in sufficiently good agreement with the theory and it is possible to determine the corresponding scattering regime. The characteristic dimension l has been determined (l = 110 km), as well as the mean-square fluctuations of the electron density, which amount to approximately 2% of the surrounding density:

$$\frac{\Delta N}{N} \simeq 2\%. \tag{39}$$

4. Radio Astronomical Observations of Solar Wind

A study of the interplanetary plasma by an indirect method, from observations of comets, has shown that there always exists a plasma stream flowing in all directions away from the sun. The plasma flows in first approximation radially, with an average velocity 400–500 km/sec. This makes it possible to regard the interplanetary plasma as a solar wind, i.e., we can state that the interplanetary plasma is of solar origin and is connected with the hydrodynamics of the external layers of the solar atmosphere[53]. In the region of the earth's orbit, the velocity of the solar wind was measured with the aid of rockets, and values v = 270–800 km/sec were obtained[54].

The question of the direction and velocity of the motion of the inhomogeneities is one of the fundamental ones in the physics of the interplanetary plasma. For radioastronomical calculations, it is very important to know the velocity of the inhomogeneities, for this makes it possible to calculate the dimensions l of the inhomogeneities (17) and the electron concentration ΔN (27). Until recently, however, the velocity of the inhomogeneities remained undetermined. To be sure, in estimates of l and ΔN use was made of values v taken from rocket data, but in this case it was implicitly assumed that the inhomogeneities are frozen into the interplanetary plasma, and that their velocities coincide with the mean velocities of the total flow of the interplanetary plasma.

In the summer of 1966, at Vitkevich's initiative[55], an experiment was set up at the FIAN radioastronomical station for the purpose of directly measuring the projection of the velocity of the inhomogeneities on the earth. The velocity was measured by determining the relative time shift of a similar picture of scintillations between three observation points. Observations were made of the scintillations of the sources 3C144, 3C48, and 3C147 at a wavelength λ = 3.5 m and at angular distances between the source and sun θ = 35–45° [56]. We note that the values θ = 35–45° correspond to a location of the effectively scattering layer r ~ 150 $R_\odot$ from the center of the sun, i.e., to a distance approximately equal to the orbit of Venus. We recall that according to Parker's theory the velocity of the solar wind in the section from Venus to the earth remains practically constant[18]. The measured velocity of the inhomogeneities responsible for the "scintillations" of the discrete sources was approximately equal to 350–250 km/sec, and its direction was close to the radial direction from the sun[56]. Thus, it was established experimentally that the velocity of the solar wind is on the average close to the velocity of the inhomogeneities of the interplanetary plasma. This makes it possible to assume that the inhomogeneities of the interplanetary plasma are among the components of the solar wind. Analogous results were obtained by Hewish for measurements of the delay of the scintillations between two points[16]. A somewhat underestimated value of the velocity v compared with rocket data is connected apparently with the fact that the scintillations are really used to measure the projection of the velocity vector.

The described method of measuring the velocity of solar wind from the radio scintillations can in principle be extended to smaller wavelengths λ, making it possible to measure the velocity of the solar wind at small distances from the sun ~ (20–40) $R_\odot$ and to verify experimentally Parker's theory in those regions in which direct rocket measurements are impossible.

5. Interpretation of the Experimental Data

Measurements of the fluctuations of the intensity of radio sources at different wavelengths λ have shown that the period of the scintillations τ does not depend on the average on λ[20-22,11]. As applied to formulas (17) and (19), this means that the obtained data can be referred to the case of a thin screen, when $\sqrt{(\Delta\varphi)^2} < 1$. As already mentioned in Sec. III, the period τ of the scintillations remains practically constant in a wide region of angular distances from the source to the sun[15]. Taking (17) into account, this allows us to conclude that in a wide region of distances from the sun (60–260 $R_\odot$) the dimension of the electron inhomogeneities remains constant (provided their velocity remains unchanged). Knowledge of the velocity of the inhomogeneities makes it possible to determine uniquely the scale of the diffraction picture on earth, which in the case of weak scattering ($\sqrt{(\Delta\varphi)^2} < 1$) coincides with the scale of the inhomogeneities. Thus, data on the period of the scintillations and on the velocity of motion of the inhomogeneities gives a unique determination of l, which makes it possible to decrease the uncertainty of the initial estimate (10). Comparison with data obtained by the "transmission" method shows that the spectrum of the scattering inhomogeneities, at distances $4.5 \leq r/R_\odot \leq 260$ lies mainly in the interval

$$100\,\text{km} \leqslant l \leqslant 1000\ \text{km} \tag{40}$$

with a characteristic dimension l at distances ≃ 100 R. amounting to ≈ 800 km in accordance with the Vitkevich estimates[15,56], and ~ 200–300 km according to the data of Hewish[16]. Knowledge of l makes it possible in turn to calculate ΔN with the aid of (11), (21), and (27). In[19] they used radio-wave scattering observational data obtained from the scintillations, and the values of ΔN were determined for different distances from the sun (Fig. 2). The electron concentration near the earth's orbit turned out to be 0.1–0.5 el/cm³. Comparison of these values of ΔN with the existing data on the average electron concentration, obtained from Blackwell's optical measurements[43], shows that the relative values of the electron concentration of the small-scale inhomogeneities (40) is approximately 1.5–4% (this agrees with the estimate (39) given in[21]). Thus, the param-

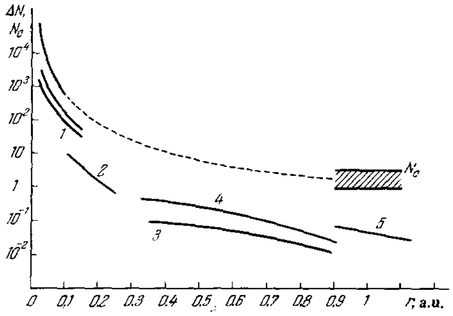

FIG. 2. Electron concentrations of the solar supercorona and of interplanetary plasma. N_0 – mean values (upper curve), ΔN – inhomogeneity concentrations. 1 – Data on radio-wave scattering (Vitkevich); the upper and lower curves were obtained for inhomogeneity dimensions $l = 600$ and 200 km, respectively; 2 – data on radio scintillation observations (Sinigaglia), 0.74 m wave; 3 – data on radio scintillations (Vitkevich), 3.5 m wave; 4 – the same (Hewish), 1.74 m wave; 5 – the same (Vitkevich), 7.9 m wave.

eters of the inhomogeneities were uniquely determined and a unified picture of the inhomogeneous structure of the solar supercorona and of the interplanetary plasma was constructed.*

IV. NATURE OF THE INHOMOGENEOUS STRUCTURE OF THE NEAR-SOLAR PLASMA

Radioastronomical investigations make it possible to assume the existence of an inhomogeneous structure of the near-solar plasma as reliably established. Additional very important information on the properties of the interplanetary plasma were obtained in 1966 by rocket measurements. As a result of measurements performed with the rocket "Pioneer-VI" it was established that there exists an appreciable anisotropy in the distribution of the plasma particles by velocity near the earth's orbit (the trajectory of Pioneer-VI is close to the earth's orbit): the temperature $T_{\parallel}$ in the direction of the magnetic field turns out to be approximately five times larger than the temperature $T_{\perp}$ in the perpendicular direction, and $T_{\parallel} \sim 10^5\,^{\circ}\mathrm{K}$ near the earth's orbit[57].

A possible mechanism for the occurrence of the temperature anisotropy is discussed in[58]. Thus, for example, it is shown in this paper that in the region of distances $\lesssim 1$ a.u. from the sun the inertial cooling of the solar wind with increasing distance from the sun leads to a slower decrease of the thermal component $v_{\parallel}$ than of the component $v_{\perp}$, the decrease of which occurs by virtue of the conservation of the first adiabatic invariant. The difference between the changes of $v_{\parallel}$ and $v_{\perp}$ leads to the appearance of the temperature anisotropy.

The occurrence and development of instabilities in the plasma as a result of the anisotropic temperature distribution was regarded in[59] as one of the possible causes of the formation of the inhomogeneous structure of the near-solar plasma. The present section is devoted to an examination of this mechanism.

The instability of a plasma with anisotropic temperature has been investigated in the literature in sufficient detail[60–63]. It is known from these investigations that the plasma is unstable at arbitrarily small anisotropy $T_{\perp} \neq T_{\parallel}$. The instability is manifest in an excitation of long-wave (low-frequency) oscillations in the plasma. Thus, in a collisionless plasma in the absence of a magnetic field (more accurately, when $\beta = 8\pi N T_{\parallel}/B_0^2 \gg 1$) at $T_{\parallel} > T_{\perp}$, there occurs an aperiodic buildup of the oscillations propagating almost perpendicular to the magnetic field (the direction of the maximum temperature). This means that the perturbations corresponding to such oscillations should be elongated in a longitudinal direction at least by a factor 2–3. The increment of the development of the instability is of the order of[60]

$$\gamma \approx \frac{\omega_{Le} k v_{T\parallel}}{\sqrt{k^2c^2 + \omega_{Le}^2}}, \tag{41}$$

where k is the wave number (or the reciprocal dimension of the perturbation, $k \sim \pi/l$), $v_{T_{\parallel}} = \sqrt{T_{\parallel}/m}$—thermal velocity of the plasma electrons, and $\omega_{Le} = \sqrt{4\pi N e^2/m}$—the Langmuir frequency. The conditions for the applicability of formula (41), $\gamma \gg k v_{T_{\perp}}$, ν_e determine the dimensions of the perturbations that can develop in the plasma:

$$\sqrt{\frac{T_{\perp}}{T_{\parallel}}}\frac{\pi c}{\omega_{Le}} < l < \frac{\pi v_{T_{\parallel}}}{\nu_e}. \tag{42}$$

Here ν_e—frequency of the electron collisions.

When $\beta \sim 1$, the influence of the magnetic field on the character of the anisotropic instability becomes appreciable. The development of the instability is possible in this case if

$$\frac{T_{\parallel}}{T_{\perp}} > \frac{1}{2}\left(1 + \frac{v_A^2}{v_{\perp i}^2}\right), \tag{43}$$

where $v_A = \sqrt{B_0^2/4\pi N M}$—Alfven velocity, the increment of its development being of the order of[61,62]

$$\gamma \leqslant \sqrt{2}\,k\sqrt{\frac{T_{\parallel}}{M}}. \tag{44}$$

Perturbations connected with the development of such an instability are also elongated in a longitudinal direction, although to a lesser degree than those considered (when $\beta \gg 1$). From the condition of the applicability of (44), namely $\Omega_i = eB_0/Mc \gg \gamma \gg \nu_i$, we get the dimensions of the instability of the perturbations in the plasma:

$$\frac{\pi}{\Omega_i}\sqrt{\frac{2T_{\parallel}}{M}} < l < \frac{\pi}{\nu_i}\sqrt{\frac{2T_{\parallel}}{M}}. \tag{45}$$

Finally, when $\beta \ll 1$, a slow cyclotron anisotropic instability can develop, with a maximum increment[63]

*After this review was already in press, an article by Douglas and Smith appeared [65], reporting results of a study of the fast temporal fluctuations of the dekameter radio emission from Jupiter ($\lambda = 13.5$ m). Observations with the aid of four receivers located at different points have made it possible to establish the existence of a one-second component in the temporal structure of the decimeter radiation of Jupiter. Using the inhomogeneous structure of the solar wind as presented in the present paper, and extending it to the region of larger distances from the sun, approximately to 2 a. e., the authors of [65] have concluded that sources with small angular dimensions exist on Jupiter. The existence of decimeter flashes of radio emission from Jupiter are identified by them with interplanetary scintillations of the emission of these sources. The scale of the inhomogeneities of the interplanetary plasma (assumed equal to approximately several hundred–several thousand kilometers) makes it possible to obtain an estimate of <5″ for the upper limit of the intrinsic angular dimensions of these sources.

$$\gamma \simeq \frac{\sqrt{\pi}\,\omega_{Li}T_{\perp}}{\sqrt{2T_{\parallel}Mc^2}}\,e^{-\frac{B_0^2}{8\pi NT_{\parallel}}\frac{T_{\parallel}^2}{(T_{\perp}-T_{\parallel})^2}}. \quad (46)$$

The wavelength of the most rapidly increasing oscillations

$$k \simeq \frac{\Omega_i}{v_A}\left(1-\frac{T_{\perp}}{T_{\parallel}}\right)$$

corresponds to perturbations with dimension

$$l \approx \frac{\pi v_A}{\Omega_i}\left(1-\frac{T_{\perp}}{T_{\parallel}}\right)^{-1}. \quad (47)$$

Let us attempt to connect the anisotropic instability of the plasma with the observable inhomogeneities. We note first that the anisotropy of the interplanetary plasma can be regarded as experimentally established only in the region of the earth's orbit (the trajectory of Pioneer-VI). According to[58], it is precisely in the region of the earth's orbit where the plasma anisotropy should be maximal. Therefore we shall consider primarily the region of the earth's orbit. In this region we have $\beta \sim 1$ and $T_{\parallel}/T_{\perp} \sim 5$, thus ensuring satisfaction of the instability condition (43). From the inequalities of (45) (recognizing that in the region of the earth's orbit we have $N \sim 1\ \text{cm}^{-3}$, $\Omega_i \sim 2 \times 10^{-1}\ \text{sec}^{-1}$, and $\Omega_i \sim 10^{-6}\ \text{sec}^{-1}$), it follows that the dimensions of the observable inhomogeneities should lie in the range

$$300\,\text{km} < l < 10^8\ \text{km}. \quad (48)$$

Since the instability growth increment (44) increases in this region with increasing k, the most probable are small-scale inhomogeneities with $l \sim 300$ km, in agreement with experiment (see above).

In the region behind the earth's orbit $\beta \gg 1$, and if a temperature anisotropy $T_{\parallel} > T_{\perp}$ exists there, then we should use the inequalities (42) to estimate the dimensions of the inhomogeneities. Recognizing that in this region $N \lesssim 1\ \text{cm}^{-3}$, $T \sim 10^{-5}\,^{\circ}\text{K}$, and $\nu_e \sim 4 \times 10^{-5}\ \text{sec}^{-1}$, we have

$$20\,\text{km} < l < 10^8\text{km}. \quad (49)$$

Here, too, the most probable are the small-scale inhomogeneities. However, inhomogeneities of very small scale, owing to their rapid oscillations ($\omega \sim \gamma \sim \omega_{Le}(v_{Te}/c) \sim 10^1-10^2\ \text{sec}^{-1}$) may not be observed in the experiment if the period of their oscillations is much smaller than the observation time $\tau \sim 0.5-0.9$ sec. In order for the inhomogeneities to be observable, it is necessary to have $\tau < 1/\gamma$. This inequality is satisfied for inhomogeneities with $l > v_{Te}/2\pi \sim 100$ km. It should be noted that when the observation time is decreased there should appear in the region behind the earth's orbit also inhomogeneities of smaller scale, as predicted by the theory, if the anisotropy of the temperature in the plasma is appreciable, $T_{\parallel} > 2T_{\perp}$. Therefore an experimental investigation of this region of the interplanetary plasma can serve as a criterion for the correctness of our hypothesis concerning the nature of the inhomogeneities.

Finally, in the region up to the earth's orbit, where $\beta \ll 1$, the observed inhomogeneities can also be connected with the anisotropic instability of the plasma. The most probable dimension of such inhomogeneities, determined from (47), is $l \sim 100-300$ km (we note that in this region Ω_i/v_A change quite little with distance), and is also in good agreement with experiment.

In conclusion let us discuss the question of the values of the fluctuations of the density $\Delta N/N$ upon development of anisotropic instability in a plasma. This topic is dealt with in the nonlinear theory of plasma oscillations. At the present time, such a theory is far from complete and an answer to this problem can be obtained only in the case of weak anisotropy, when $|T_{\parallel} - T_{\perp}| \ll T_{\parallel}$. In weak magnetic fields, the theory then yields[64] $\Delta N/N \sim v_{Te}^2/c^2 \sim 10^{-5}$, and in strong fields ($\beta \ll 1$) we get $\Delta N/N \sim v_A^2/c^2 \sim 10^{-7}-10^{-4}$. These are much lower than the experimentally observed values (we recall that $(\Delta N/N)_{exp} \sim 10^{-2}$), but this is not at all surprising, since the theory considers only the case of small anisotropy $|T_{\perp} - T_{\parallel}| \ll T$. In the case of large plasma anisotropy, $\Delta N/N$ can be much larger, at least by $T_{\parallel}^2/T_{\perp}^2 \sim 25$ times. These estimates likewise do not contradict the experimental data.

CONCLUSION

A systematic study of the inhomogeneous structure of the near-solar plasma by radio astronomy methods has been under way since 1951. As a result of these investigations, it was possible to observe the supercorona and the interplanetary plasma. The inhomogeneities of the electron density were observed and investigated, and this led to a unified picture of the inhomogeneous structure of the near-solar plasma.

The rapid advances in radioastronomic research in recent years, both in our country and abroad, are connected primarily with the need for mastering outer space. In this connection, we note that knowledge of the properties of the near-solar space and its influence on the radio waves propagating in it is important for the extraction of scientific information and for the establishment of radio communication with cosmic rockets sent to the planets and to the space beyond the sun. Knowledge of the properties of the space near the sun is important also for the study of the physics of the sun, since the supercorona and the interplanetary plasma are continuations of the structure of the corona and of the sun itself, concerning which we know little as yet. Knowledge of the characteristics of the near-solar plasma is important for the study of the physical nature of certain cosmic radio-emission sources, since it makes it possible to investigate, by "transmission" through the interplanetary plasma, the fine structure of the sources, and to determine the radio dimensions and the structure of quasars (new astrophysical objects).

In conclusion we wish to point out those problems which are of interest from the point of view of further investigations of the near-solar space. It seems to us that such problems are connected with extension of the "scintillation" method to the region of angular source distances smaller than 20° and larger than 160°, with the study of scintillations at large distances exceeding 1 a.u., with a small time constant (in order to observe small-scale inhomogeneities and to study the temperature anisotropy). It is advantageous to extend the method of "transmission" to the region of distances less than

$5\,R_\odot$. Mention should be made of the fact that radio-astronomical investigations of the near-solar plasma in the indicated regions are the most effective, and in many cases they are also the only ones possible.

[1] V. V. Vitkevich, Dokl. Akad. Nauk SSSR **77**, 585 (1951).
[2] V. V. Vitkevich, Dokl. Akad. Nauk SSSR **101**, 429 (1955).
[3] V. V. Vitkevich, Astron. zh. **32**, 150 (1955).
[4] A. Hewish, Proc. Roy. Soc. **A228**, 238 (1955).
[5] V. V. Vitkevich, Astron. zh. **35**, 52 (1958) [Sov. Astron. AJ **2**, 45 (1958)].
[6] V. V. Vitkevich, ibid. **37**, 32 (1960) [**4**, 31 (1960)].
[7] A. Hewish, Mont. Not. Roy. Soc. **118**, 534 (1958).
[8] S. Gorgolewski, Bull. Akad. Cracovie **14**, No. 3 (1963).
[9] S. Gorgolewski, Biul. Inform. Kom. N.W.G. **38**, Nr. 3 (1964).
[10] Jesse L. Greenstein, Sci. Amer. **209**, (12) 54 (1963).
[11] A. Hewish, P. F. Scott and D. Wills, Nature **203**, 1214 (1964).
[12] V. L. Ginzburg, Dokl. Akad. Nauk SSSR **109**, 61 (1956) [Sov. Phys.-Dokl. **1**, 403 (1957)].
[13] V. V. Pisareva, Astron. zh. **35**, 112 (1958) [Sov. Astron. AJ **2**, 97 (1958)].
[14] A. Hewish and S. E. Okoye, Nature **207**, 59 (1965).
[15] V. V. Vitkevich, T. D. Antonova, and V. I. Vlasov, Dokl. Akad. Nauk SSSR **168**, 55 (1966) [Sov. Phys.-Dokl. **11**, 369 (1966)].
[16] A. Hewish, P. A. Dennison and J.D.H. Pilkington, Nature **209**, 1188 (1966).
[17] M. H. Cohen, Nature **208**, 277 (1965).
[18] E. N. Parker, Astrophys. J. **128**, 664 (1958).
[19] V. V. Vitkevich, FIAN Preprint, 1966.
[20] T. D. Antonova and V. V. Vitkevich, Astron. Tsirkulyar No. 385 (1966).
[21] M. H. Cohen, E. J. Gundermann, H. E. Hardebeck and L. E. Sharp, Astrophys. J. **147** (2), 449 (1967).
[22] D. E. Hogg and T. K. Menon, Astron. J. **71** (No. 6), 388 (1966).
[23] O. B. Slee, Austral. J. Phys. **12**, 134 (1959).
[24] A. Hewish and J. D. Wyndham, Mont. Not. Roy. Soc. **126**, 469 (1963).
[25] V. V. Vitkevich, Dokl. Akad. Nauk **156**, 1057 (1964) [Sov. Phys.-Dokl. **9**, 405 (1964)].
[26] V. V. Vitkevich, Astron. zh. **33**, 62 (1956).
[27] N. A. Lotova, ibid. **36**, 907 (1959) [Sov. Astron. AJ **3**, 881 (1960)]
[28] V. V. Pisarev, ibid. **36**, 427 (1959) [**3**, 419 (1959)].
[29] J. A. Fejer, Proc. Roy. Soc. **A220**, 455 (1953).
[30] A. Hewish, Paris Symposium on Radio Astronomy, Stanford Univ. Press, 1959.
[31] V. I. Babiĭ, V. V. Vitkevich, V. I. Vlasov, M. V. Gorelova and A. G. Sukhoveĭ, Astron. zh. **42**, 107 (1965) [Sov. Astron. AJ **9**, 81 (1965)].
[32] V. V. Vitkevich and N. A. Lotova, Izv. vuzov (Radiofizika) **4**, 415 (1961).
[33] V. V. Vitkevich and N. A. Lotova, Geomagnetizm i aéronomiya **6**, 650 (1966).
[34] V. V. Vitkevich and B. N. Panovkin, Astron. zh. **36**, 544 (1959) [Sov. Astron. AJ **3**, 529 (1959)].
[35] V. V. Vitkevich, B. N. Panovkin and A. G. Sukhoveĭ, Izv. vuzov (Radiofizika) **2**, 1005 (1959).
[36] V. V. Vitkevich, Paris Symposium on Radio Astronomy, Stanford Univ. Press, 1959.
[37] V. V. Vitkevich, Izv. vuzov (Radiofizika) **3**, 595 (1960).
[38] S. Gorgolewski and A. Hewish, Observatory **80** (916), 99 (1960).
[39] V. F. Bedevkin and V. V. Vitkevich, Trudy FIAN **38**, 96 (1967).
[40] V. V. Vitkevich and N. A. Lotova, Radiotekhnika i élektronika **12** (7), 1157 (1967).
[41] V. V. Vitkevich, Astron. zh. **41**, 684 (1964) [Sov. Astron. AJ **8**, 545 (1965)].
[42] D. E. Blackwell, Mont. Not. Roy. Soc. **116**, 56 (1956).
[43] D. E. Blackwell and A. D. Petford, Mont. Not. Roy. Soc. **131**, 399 (1966).
[44] R. Michard, Ann. d'Astrophys. **17**, 429 (1954).
[45] N. A. Lotova, Izv. vuzov (Radiofizika) **8**, 441 (1965).
[46] L. T. Little and A. Hewish, Mont. Not. Roy. Soc. **134**, 221 (1966).
[47] G. Sinigaglia, Public. Istituto di Fisica "A. Righi", Univ. di Bologna, November 1965.
[48] J. Ratcliffe, Rept. Progr. Phys. **19**, 188 (1956).
[49] N. A. Lotova and V. M. Finkel'berg, Usp. Fiz. Nauk **88**, 399 (1966) [Sov. Phys.-Uspekhi **9**, 180 (1966)].
[50] E. E. Salpeter, Astrophys. J. **147** (2), 433 (1967).
[51] L. M. Erukhimov, Geomagnetizm i aéronomiya **4**, 75 (1964).
[52] R. Mercier, Proc. Cambr. Phil. Soc. **A58**, 382 (1962).
[53] Ludwig Bierman, Sonnenkorona und interplanetarer Raum, Sitzungber, Bayer. Akad. Wiss. **37** (1965).
[54] K. I. Gringauz, Paper at 4th Winter School on Cosmic Physics, Bakuriani, February 1967.
[55] V. V. Vitkevich, Trudy FIAN **38**, 80 (1967).
[56] V. V. Vitkevich and V. I. Vlasov, Preprint FIAN, 1966.
[57] F. L. Scarf, J. H. Wolf and R. W. Silva, Paper at International Conference on the Earth-Sun Problem, Belgrade, 1966.
[58] M. Z. Khokhlov, op. cit.[54].
[59] N. A. Lotova and A. A. Rukhadze, Preprint, FIAN, 1967.
[60] A. E. Stefanovich, Zh. Tekh. Fiz. **32**, 638 (1962) [Sov. Phys.-Tech. Phys. **7**, 462 (1962)].
[61] L. I. Rudakov and R. Z. Sagdeev, in: Fizika plazmy i problema upravlyaemykh termoyadernykh reaktsii (Plasma Physics and the Problem of Controlled Thermonuclear Reactions), v. 3, AN SSSR, 1958, p. 268; A. A. Vedenov and R. Z. Sagdeev, ibid. p. 278.
[62] A. B. Kitsenko and K. N. Stepanov, Zh. Eksp. Teor. Fiz. **38**, 1840 (1960) [Sov. Phys.-JETP **11**, 1323 (1960).
[63] R. Z. Sagdeev and V. D. Shafranov, ibid. **39**, 181 (1969) [**12**, 130 (1961).
[64] V. D. Shapiro and V. I. Shevchenko, ibid. **45**, 1612 (1963) [**18**, 1109 (1964)].
[65] J. N. Douglas and H. J. Smith, Astrophys. J. **148**, 885 (1967).
[66] M. H. Cohen, E. J. Gundermann and D. E. Harris, Astrophys. J. **150**, 767 (1967).

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