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MEASUREMENTS OF KILOMETER COSMIC RADIOEMISSION IN INTERPLANETARY SPACE

by

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by V. I. Slysh

SUMMARY

Data have been obtained on the intensity of low-frequency radioemission in interplanetary space according to measurements of that emission from interplanetary probes (AIS) Zond-2, Zond-3 and Venera-2 in the 20 to 2200 kc/sec frequency band.

The intensities measured in the frequencies of 985, 2000 and 2200 kc/sec are in agreement with the measurements of the galactic background performed by other authors.

In the 210-220 kc/sec band the spectrum increases steeply toward the side of low frequencies; the variation of intensity with distance, the observation of interference lobes and, possibly, that of occultation by the Moon, point to Jupiter as being an emission source, at least in the frequency of 200 kc/sec.

The occultation by the Moon took place in the presence of differential refraction in the upper ionosphere. In the very lowest frequencies of 20 and 30 kc/sec the observed radioemission may also be conditioned by the schrot effect of interplanetary electrons.

The radioemission spectrum of Jupiter in kilometer waves agrees well with Jupiter's spectrum of decameter radioemission.

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During measurements of cosmic radioemission on the AIS Zond-2 it was revealed that in case of reception on a short dipole antenna, the radioemission flux in interplanetary space constitutes about $3 \cdot 10^{-18}$ w/m^2·cps in the frequency of 210 kc/sec, which exceeds by about 100 times the anticipated radioemission flux of the Galaxy in the same frequency [1]. The existence of comparatively powerful radioemission in interplanetary space in the longwave band was confirmed in a new series of measurements aboard AIS Zond-3 and Venera-2 in 1965-1966.

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* IZMERENIYA KILOMETROVOGO KOSMICHESKOGO RADIOIZLUCHENIYA V MEZHPLANETNOM PROSTRANSTVE.

A more circumstantial character of last measurements and certain favorable conditions allowed us to investigate a series of properties of the source of that emission. Evidence is presented in the current work that Jupiter may be that source.

MEASUREMENTS ON AIS ZOND-3

AIS Zond-3 was launched on 18 July 1965 toward the orbit of Mars. A three-channel measurement radioreceiver with frequencies of 20, 210 and 2000 kc/sec was installed on board the station. As in the case of Zond-2 the dipole, formed by the station's frame and a 3.75m long metallic rod served as the antenna (Fig.1). The amplification factor control was conducted by set noises.

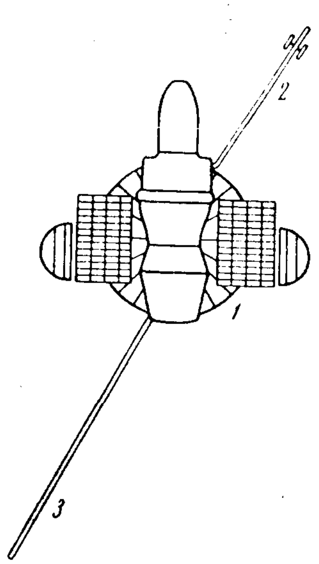

Fig.1.

Antenna system for the measurement of low-frequency radioemission aboard interplanetary stations

The results of measurements conducted at distances from Earth in tens of millions of kilometers show that in the frequency of 2000 kc/sec the emission flux is in agreement with the radioemission flux of the Galaxy, while at lower frequencies a rapid increase in the flux with frequency decrease is observed. The striking property of this radioemission is its relative constancy in time: in the frequency of 210 kc/sec the variations do not exceed 5 to 10 percent.More significant variations were observed in the frequency of 20 kc/sec. Separate bursts are superimposed to that constant level, of which a part could be identified with radiobursts of the Sun [2].

Despite the absence of short-lived variations (with the exception of separate bursts) a slow and constant rise of radioemission flux was observed in the frequency of 210 kc/sec for the first six months of flight of AMS Zond-3 along a heliocentrical orbit.(Fig.2).

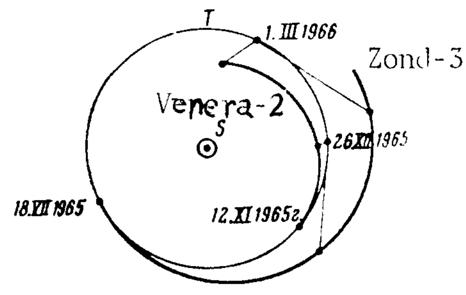

Fig.2
Trajectories of AIS Zond-3 and Venera-2

The mean values (24-hr) of the flux in the frequency of 210 kc/sec in the course of about half a year are plotted in Fig.3. It may be seen from that diagram that the radioemission flux in that frequency increased nearly two-fold by comparison with the measurements immediately upon start. This smooth rise could have been caused by various circumstances, for example, by gradual increase of the amplification factor. However, the readings of the measurement channel of set noises of the receiver are evidence of the absence of notable drift of the amplification factor. With the view of searching for a possible explanation of this rise, we plotted in the same figure the variation of the quantity $1/R_{♃}^2$ in time, where $R_{♃}$ is the distance from AIS Zond-3 to Jupiter. The trajectory of Zond-3 thus ran in such a fashion that at the outset the distance between the station and Jupiter differed little from Jupiter's geocentrical distance, and then became considerably smaller owing to station's drifting from the Sun. Fig.3 shows that the shape of the curve for the dependence of radioemission flux in the frequency of 210 kc/sec resembles that of the curve for $1/R_{♃}^2$, which may be the case if Jupiter actually is the basic source of radioemission. At the same time, the radioemission flux in the frequency of 2000 kc/s remained constant over that entire period. The flux in the frequency of 20 kc/sec was registered only during the first quarter of the flight, the channel being saturated during the remainder of time.

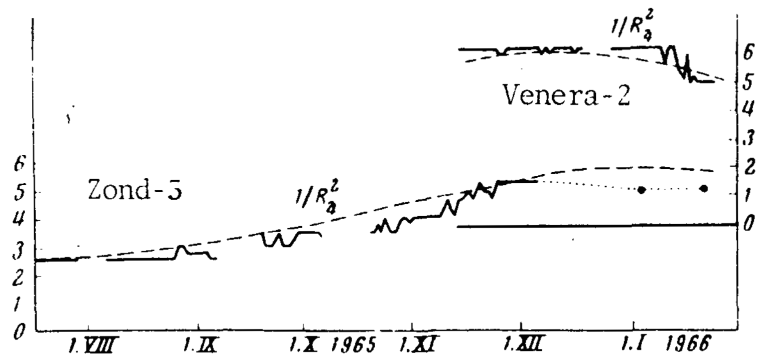

Fig.3. Average daily values of signal intensity in the frequency of 200 kc/sec during the flight.

The lower diagram corresponds to Zond-3, and the upper one to Venera-2. The dashed line represents the variation of the inverse square of the distance between the station and Jupiter

If we consider that Fig.3 reflects the variation of the received flux at the expense of distance variation between the AIS and Jupiter, then at least 80% of the entire flux arrives from Jupiter. In this case there would exist only one source of radioemission in the sky in the frequency of 210 kc/sec. In principle, such a situation might even be detected with the aid of a short-dipole-type littledirectional antenna. A special experiment was carried out aboard Zond-3, which consisted in that the entire station was set into spin about an axis, approximately perpendicular to the axis of the antenna in such a fashion that the assumed "zeros" of radiation pattern should periodically pass by Jupiter. If Jupiter is the main source of emission, the modulation depth should reach 100% at a sufficiently precise orientation. In reality, the modulation observed in the experiment had a depth of no more than 5 ÷ 10 percent, which is comparable with the measurement error. However, this circumstance may be not in contradiction with the assumption that Jupiter is the basic source of radioemission, and this because of the following reasons:

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1) the source may have sufficiently large angular dimensions on account of scattering on the irregularities of the interplanetary medium, which could reach at such low frequencies a significant value;

2) inasmuch as the exact position of radiation pattern "zeros" is not known, they may by-pass Jupiter;

3) owing to its complex configutation (see Fig.1), the antenna may be altogether lacking the radiation pattern "zeros". In this case even those directional properties, with which a dipole antenna is endowed, may be absent.

As is well known, a series of methods were proposed in order to obtain directional properties for long-wave antennas installed on satellites. It was proposed, in particular, to utilize the focusing and reflecting properties of the Earth's ionosphere [3]. Possible also is the utilization of heavenly bodies as screens. Below we shall present the results of measurements in which attempts were made to apply both methods.

As was shown in our preceding work [1], during the first two hours of their flight AIS cross a region where the critical frequency of the ionosphere is equal to 210 kc/sec. In the case of Zond-2 this region was situated at the distance of $4R_E$. The registration of signal intensity at 210 kc/sec, brought out in [1], has been obtained with an interval of about 2 minutes between separate measurements. If there is only one source of radioemission in the sky, interference lobes, occurring owing to the combination of the direct ray with that reflected by the ionosphere, must be observed immediately upon the egress from the ionosphere. The width of these lobes depends on the zenithal distance of the source, on the shape of the ionosphere and on the motion speed of the station. The results of registration of the power of the signal received aboard Zond-3 in the frequency of 210 kc/sec in the course of the first two hours of station's flight are plotted in Fig.4. Two measurements were performed every 1.8 minutes with an interval of about 10 seconds; this allowed us to determine the variation rate in case of rapid variations. The character of signal variation in Fig.4 is qualitatively the same as during the flight of Zond-2. The peak, corresponding to the plasma frequency is this time situated somewhat nearer the Earth, at a distance of about $3R_E$. The gaps in information, seen in Fig.4, are caused by interferences from the electrical devices on board the station.

The most interesting peculiarity of Fig.4 is constituted by the periodical signal level oscillations after a "peak" corresponding to plasma frequency. At least three periods of such oscillations may be traced. Shown by a dashed line is the possible shape of these oscillations, rediced by their derivative (measured by its variation in the course of 10 seconds). This patterns suggests the interference lobes linked with the reflection from the ionosphere. The AIS passed for 1 period of these lobes a distance R = 1700 km. The first minimum was observed at the distance from the center of the Earth R = 16,900 km, i.e., $\Delta R / R = 0.1$. If these lobes are caused by interference of the radiation arriving from one discrete source, their relative width may be estimated with the aid of formulas given by Budden [4]. In the assumption of spherically-symmetrical ionosphere with radial distribution of electron concentration of the form $R^{-\gamma}$ by formulas given in [4], the relative width of the first lobe is

$$\frac{\Delta R}{R} \simeq \frac{3 \sin^{5/4} \varphi}{n} \sqrt[3]{\frac{\lambda}{2\pi\gamma R_E}}, \qquad (1)$$

where ϕ is the zenithal distance of the source, n is the index of refraction, λ is the wavelength in vacuum, R_E is the radius of the Earth. During the flight of Zond-3, the zenithal distance of Jupiter constituted approximately 80°.

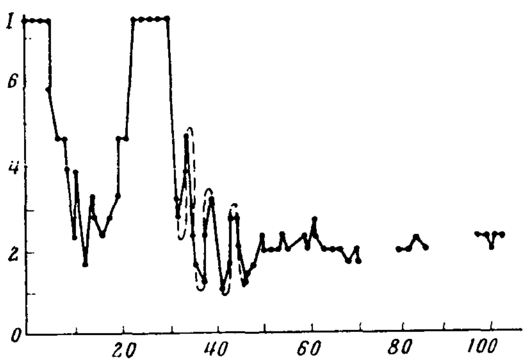

Fig.4. Registration of signal intensity in the frequency of 210 kc for the first two hours of flight of Zond-3 on 18 July 1965. Shown by dashed line is the possible shape of interference lobes, reduced by measurements of accretions for a time period Δt = 10 sec.

On the basis of the results obtained by us in [1], we shall assume γ = 4. Substituting these values into (1) and assuming n = 0.5, we shall obtain

$$\Delta R / R = 0.12,$$

which coincides sufficiently well with Fig.4.

Therefore, the oscillations of the received power after egress from the ionosphere, observed on AIS Zond-3, may be the consequence of interference, whereupon the width of interference lobes is in agreement with the zenithal distance of Jupiter. The angular width of intereference lobes is of the order of a degree. Thus, at least half of the power received in the frequency of 210 kc/sec originates from a single discrete radiosource with angular dimension less than a few decrees, and with a zenithal distance close to that of Jupiter. The power variation of the received signal with the variation of distance between AIS Zond-3 and Jupiter (Fig.3) is in agreement with such a conclusion.

Note that during the flight of Zond-2, no interference phenomena of any kind were observed in the same frequency after egress from the ionosphere, despite the fact that the zenithal distance of Jupiter was 63° relative to the direction to the center of the Earth. However, in this case the trajectory passed on the night side of the Earth, while Jupiter was located in a direction opposite to the Sun. The critical density of electrons over the trajectory of AIS Zond-2, which was 550 electrons/cm^3, was intersected at the distance of $4R_E$, contrary to Zond-3 ($3R_E$) and Venera-2 ($2R_E$), of which the trajectories passed at great illumination by the Sun. This means that the Earth's ionosphere is elongated analogously to the "tail" of the Earth's magnetosphere. This is why it is quite probable that during measurements from Zond-2 Jupiter was located above the local ionosphere ho horizon (at calculations by formula (1) the notion of vertical implied the local direction of electron density gradient).

MEASUREMENTS ON AIS "VENERA-2"

AIS Venera-2 was alunched on 12 November 1965. The three-channel measurement receiver aboard the station had frequencies of 30, 200 and 985 kc/sec. The antenna was similar to antennas applied in preceding experiments. A somewhat different method of measurements was utilized here, that would allow to increase the sensitivity. Because of that, the readings of the 200 kc frequency channel reached most of the time the upper limit of the measurement scale, considerably lowering the value of measurements. In this experiment the antenna capacitance in the 270 kc frequency was measured simultaneously with cosmic radioemission (corresponding to electron concentration of 900 electrons/cm). This provided the possibility of accounting for the influence of the Earth's ionosphere on the measurements in the near-terrestrial space.

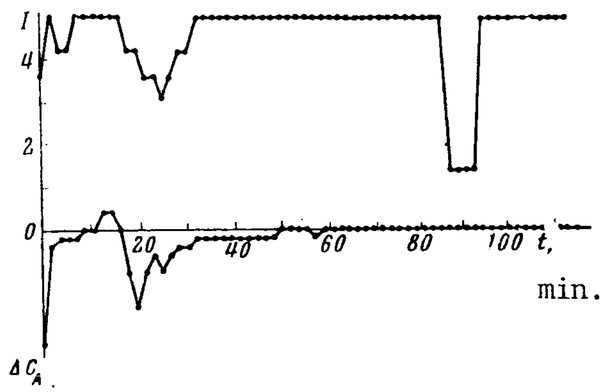

Fig.5. Registration of signal intensity in the frequency of 200 kc/sec and variation of antenna capacitance in the frequency of 270 kc/sec for the first two hours of flight of AIS Venera-2 on 12 Dec.1965.

The trough (gap) near t = 90 min.is a possible occultation of Jupiter by the Moon

As may be seen from Fig.2, the trajectory of AMS Venera-2 passed in such a fashion that the distance between the AIS and Jupiter slowly increased. No noticeable signal level variation was observed during that time in the frequency of 985 kc/sec, but at 30 kc/sec the power of the signal increased by about 50%. At the same time, despite the above-noted effect, one could notice in the 200 kc channel a certain signal attenuation, which corresponds, within the bounds of measurement precision, to the increase of distance between the AIS and Jupiter (Fig.3).

Aside from the above indirect indications on the possibility of the bulk of received radiation in the frequency 200 kc/sec being due to Jupiter, a direct demonstration of this fact was apparently obtained during the flight of Venera-2. The results of registration of signal power in the frequency of 200 kc/sec and the variation of antenna capacitance for the first 110 minutes of Venus-2 flight from the Earth are plotted in Fig.5. Despite the limitation, a typical signal variation can be noted in the 200 kc channel during flight through the ionosphere, and in particular the presence of the "peak" corresponding to the critical electron concentration, between 8 and 16 min, and the subsequent minimum with gradual rise. The interpretation of these measurements as phenomena, attending the egress from the ionosphere, is corroborated by the character of antenna capacitance variation at comparaitively close frequency. This variation takes place in correspondence with the amgneto-ionic theory. The totally unexpected singularity of Fig.5 is the deep trough near 90 minutes. At that time the station was situated at 37,5 thousand km from the center of the Earth, and any local manifestations of plasma at such great distance must not be noticeable. Let us remark that in our preceding experiments nothing similar was observed at such great distances from the Earth.

The character of this trough reminds us very much of the temporal shielding effect of radioemission source. We assumed that it may possibly have been temporarily occulted by the Moon. The projection on the celestial sphere of Moon's motion visible from AIS Venera-2 during its flight is drawn in Fig.6. This drawing, alongside with the calculation show that in its visible motion the Moon passed very near Jupiter indeed. The minimum angular distance between the center of the Moon and Jupiter constituted only about 50' at $t = 50^m$. And at the moment of time when the trough was observed, that is, at $t = 90^m$, the distance between the Moon and Jupiter attained 135'. Therefore, it is found during geometrical consideration that although the Moon did pass close to Jupiter, it actually did not occult it. It should, however, be taken into account that part of the path is covered by radiowaves in the outer part of the ionosphere, with the resulting refraction. We refer here to differential refraction, arising at the expense of the finite distance to the Moon. Though rays from Jupiter and from the Moon are refracted by an identical angle, the visible shift of the Moon on the celestial sphere will be somewhat smaller by comparison with the displacement of Jupiter, which may be considered as remote at infinity. The relative displacement of the Moon and of Jupiter at total refraction θ will be equal to

$$\varepsilon = \theta \frac{R}{L}, \qquad (2)$$

where R is the distance from the AIS to the point of refraction, L is the distance from the AIS to the Earth. In our case L = 12R. If we consider that at $t = 90^m$ occultation of Jupiter by the Moon was really observed, the differential refraction must have been equal to $\theta = 135' \pm 15'$, and the total refraction would have been $\theta = 27° \pm 3°$. The above indicated limits of possible variation correspond to the value of the radius of the Moon.

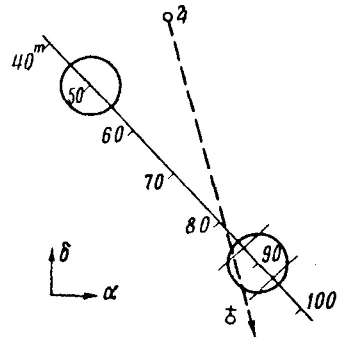

Fig.6. Positions of Jupiter and of the Moon as seen from AIS Venera-2, during flight of the probe near the Earth.

The Moon is shown at the moment of time of greatest rapprochement with Jupiter and occultation in the frequency of 200 kc/sec. The arrow points to the probable direction of refraction at $t = 90^m$ in the upper layers of the Earth's ionosphere, which is toward the center of the Earth

Let us see whether such a refraction could have taken place under flight conditions of AIS Venera-2. In order that the refaction may lead to Jupiter occultation by the Moon, it must take place in the required direction. As is well known, the direction of the refraction is determined by the direction of the refraction index gradient. If we assume the ionosphere to be spherico-symmetrical relative to the Earth,, the refraction will take place in the direction toward the center of the Earth. The line with the arrow in Fig.6, emerging from Jupiter, points to that direction, that is the expected direction of refraction. The circle near $t = 90^m$ shows the position of the Moon at time of occultation. Thus, the assumed refraction took indeed place approximately in a direction which might have led to Jupiter's occultation by the Moon at the moment of time $t = 90^m$. As to the angle of refraction $\theta = 27°$, we shall make use for its estimate the results of measurements of antenna capacitance variation, brought out in Fig.5. The treatment of the curve ΔC_A for distances (1.8 : 4) R_E allowed us to obtain the following profile of electron concentration

$$n_e = 1.6 \cdot 10^4 \left(\frac{R}{R}\right)^{-4,2} \text{electron/cm}^3 \qquad (3)$$

or for a critical density $n_{e\ cr} = 500$ electrons/cm^3

$$\frac{n_e}{n_{e\ cr}} = \left(\frac{r}{2,3}\right)^{-4,2}, \qquad (4)$$

where r is the distance in Earth's radii.

The precision of this formula drops with the increase of r, for at $r < 3$ the capacitance variation constitutes only one telemetry stage.

For the distribution (4) the refraction was computed by numerical integration in the assumption of ionosphere's spherical symmetry. It was found that the distribution (4) gives an angle of refraction $\theta > 27°$, i. e., greater than that required for occultation. $\theta = 27°$ is obtained at close distribution

$$\frac{n_e}{n_{e\ cr}} = \left(\frac{r}{2,1}\right)^{-4,2}. \qquad (5)$$

Taking into account the imprecision of capacitance measurement, we may recognize that in the Earth's ionosphere the refraction may have led to such a distoriton of rays, for which the positions of the Moon and of Jupiter, visible from the interplanetary station, coincide.

The trajectory of the rays in the ionosphere for the distribution (5) of electron concentration is drawn in Fig.7.

The steepness of the fronts of the trough indicated that the source is not resolved, that is, its angular dimension is less than 5 to 10'.

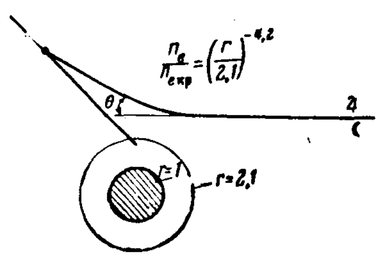

Fig.7. Trajectory of rays from the Moon and Jupiter at $t = 90^m$ for a distribution of electron concentration

$n_e / n_{e\ cr} = (r/2.1)^{-4.2}$

DISCUSSION OF THE RESULTS

Certain indications were obtained aboard AIS Zond-3 and Venera-2 that in the frequency of 200 kc/sec at least 60 to 80 percent of the received radiation originates from Jupiter. In the frequencies below and above 200 kc/sec no indications of any kind, pointing to the Jupiter origin of emission, were obtained.

The values of signal intensity in all frequencies e_ν^2 expressed in units w^2 /cps, are plotted in Fig.8 for all measurements in the three experiments; this corresponds to spectral density of square of voltage induced in the antenna. The intensity of the isotropic background myy be computed by the formula

$$I = \frac{e_\nu^2}{1600\,\ell_{eff}^2}\ \text{w/m}^2\cdot\text{cps}\cdot\text{ster.} \qquad (6)$$

where $_{eff}$ is the effective length of the antenna in meters. The curve representing the "galactic background" is drawn as the average of the large number of measurements of radioemission background in the 0.5 - 5 Mc/sec band from rockets and satellites. $_{eff}$ may be determined from that curve on assuming in 2 Mc/sec frequency, $I = 1.5 \cdot 10^{-20}$ w/m$^2\cdot$cps $\cdot$sterad. Substituting $e_\nu^2 = 2.5 \cdot 10^{-16} w^2$/cps for ν = 2 Mc/sec, we obtain ℓ = 3.2 m, which agrees sufficiently well with the antenna length ℓ = 3.75 m. Consequently,

$$I = 6 \cdot 10^{-5}\, e_\nu^2\ \text{w/m}^2\cdot\text{cps}\cdot\text{sterad.} \qquad (7)$$

Correspondingly, the radioemission flux is linked with e_ν^2 by the relation

$$S = 7.5 \cdot 10^{-4}\, e_\nu^2\ \text{w/m}^2\cdot\text{cps} \qquad (8)$$

Therefore, the radioemission flux of Jupiter constitutes in the frequency of 200 kc/sec $3 \cdot 10^{-18}$w/m^2 cps as an average.

The straight line in Fig.8 represents the exprapolation of Jupiter's radioemission spectrum obtained by McCulloch and Ellis [5] in the 4.7 - 20 Mc/sec frequency range. According to [5], the radioemission flux of Jupiter in the frequency of 4.7 Mc is $1.1 \cdot 10^{-21}$ w/m cps, and the spectral index is 2.5. The good agreement of Jupiter's spectrun with the measurements in 200 kc may serve as still another indication on the Jupiterian nature of the radiation in the frequency of 200 kc/sec. Moreover, a tendency is noted in [5] to a decrease in the variations of Jupiter's radioemission with the lowering of frequency. At 200 kc the emission is constant with great precision, except for the slow variations linked with the variation of the distance to Jupiter. No flux variations were noted with characteristic time from several seconds to tens of hours. Coming back to Fig.8, we see that at lowest frequencies of 20 to 30 kc/sec, the emission flux is somewhat smaller than expected from Jupiter's spectrum extrapolation.

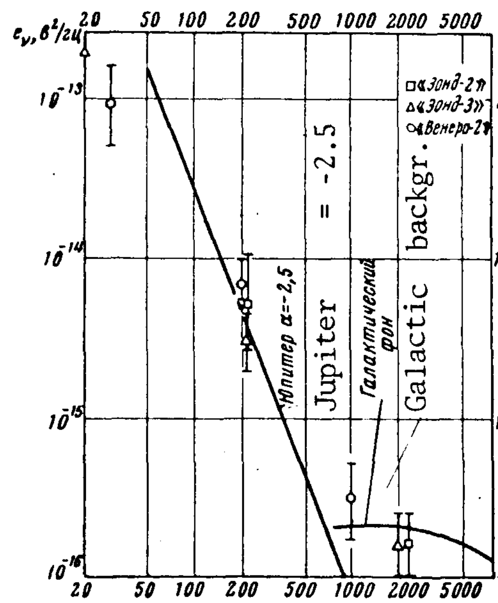

Fig.8. Spectral density of the square of voltage in the antenna according to measurements on □ Zond-2, △ Zond-3, ○ Venera-2 in interplanetary space

However, there is no sufficient foundations for such an extended extrapolation. Moreover, estimates show that the entire signal in the 20 to 30 cps may be explained by the so called shrot effect of interplanetary electrons. This question will be considered at further length elsewhere, and here we shall only point out that the interpretation of large signal level in the very lowest frequencies so far remains uncertain.

The most surprising consequence of observation of Jupiter occultation by the Moon in the 200 kc frequency (if it does indeed take place) is, in our opinion,the smallness of the angular dimension of Jupiter ($\Delta\phi < 5 \div 10'$). In this frequency any remote radioemission source must undergo a strong scattering on the inhomogeneities of the interplanetary medium. Thus, if we take for Jupiter $\Delta\phi = 5 \div 20''$ in the frequency of 19.7 Mc/sec [6] for the angle of scattering, we should have for the quadratic dependence on frequency $\Delta\phi = 15 \div 60°$. The observed angular dimension $\Delta\phi < 5 \div 10'$ may signify that the angle of scattering depends less strongly on frequency, possibly feebler than ν^{-1} in the 0.2 ÷ 20 Mc band.

The Jupiter's radioemission spectrum shown in Fig.8 is evidence of enormous emission power in the low-frequency band. Thus, if we assume that the spectrum stretches to 100 kc frequency, the total low-frequency radioemission power will become of the order of 10^{20} ergs/sec, which is one thousand times greater than the power of decimeter radiation and constitutes 10^{-5} of its total thermal radiation. It is therefore not surprising that in long waves Jupiter is the only bright radiosource in the sky.

It should be noted that to-date Jupiter's radioemission was detected in neither of the rather numerous experiments on satellites and rockets. It may be seen from Fig.8 that the emission flux from Jupiter is compared with the background radioemission, which is nearly 700 kc/sec. It may be that the so-called sporadic radiation, detected aboard AES Elektron-2 [7], partically constitutes Jupiter's radioemission. Further measurements will probably allow us to obtain more specific data.

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