RADIO ASTRONOMICAL INVESTIGATIONS WITH THE AID OF ARTIFICIAL SATELLITES

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THE use of satellites for optical astronomy is known to promise a possible increase in the spectrum of the received waves. Specifically, a satellite can receive the near and far ultraviolet, x-ray, and far infrared rays absorbed by the atmosphere before they reach the earth's surface. The situation is analogous in radio astronomy, since the range of wavelengths employed is also limited on one end by absorption in the troposphere and is limited on the other, long-wave end by refraction and absorption in the ionosphere.

Molecular (tropospheric) absorption begins to manifest itself at wavelengths shorter than 2 cm, and is particularly substantial at wavelengths of approximately 1.3 cm (water vapor) and approximately 5 mm (molecular oxygen). Consequently, reception of extraterrestrial millimeter waves without the special complications connected with the need for allowing for substantial absorption is possible only in the transparency region i.e., at wavelengths of approximately 8 mm (for more details on absorption in the atmosphere see reference 1, sections 84 and 120; radio astronomical measurements in the millimeter range are discussed in references 2, 3, and 4). An example of the difficulties encountered when going to shorter waves is that at wavelengths from 1 to 33 mm absorption in the atmosphere reduces the effective temperature of the solar radio waves by a factor of approximately 15.

Disregarding the use of very large mirrors, millimeter radiation can be received at the present time, even in the absence of absorption, only from the sun (effective temperature $T_{eff} \approx 6{,}000°$) and from the moon ($T_{eff} \approx 200°K$). Although an investigation of such radio waves is indeed of interest, it can hardly be considered as particularly important to the physics of the sun and the moon. On the other hand, the performance of such measurements with a satellite is difficult for many reasons (complexity of apparatus, need for orienting the receiving mirror on the sun or on the moon with an accuracy of several angular minutes).

The ionosphere begins to affect noticeably the reception of extraterrestrial radio waves at wavelengths on the order of 30 meters. It is enough to state that in daylight the critical wavelengths for the F_2 layer reach even 20 meters, meaning that longer waves, with the exception of some feeble effects, cannot reach the earth at all. At night the critical wavelength increases by a factor of several times. In addition, owing to the presence of a latitude dependence and to the seasonal and 11-year variations in the critical frequencies, it is possible to find conditions under which the ionosphere transmits waves up to 200 or 300 meters. Finally, the ionosphere sometimes lets longer waves pass, but these are generally greatly attenuated. Another factor complicating the earthside reception of long-wave cosmic radio waves is the high level of noise of terrestrial origin. By virtue of all these complications, the information available on cosmic radio waves in the region with $\lambda > 30$ m is quite meager.[5,6] This pertains in particular to wavelengths with $\lambda \gtrsim 100$ m, at which only a few individual measurements have been made;[7] the data obtained permit merely to state that there is strong radiation up to $\lambda \cong 600$ m, but the intensity of this radiation has not yet been established. Yet an investigation of cosmic radio waves with $\lambda > 30$ m is of primary importance. The point is that the radio waves represent magnetic bremsstrahlung of cosmic (relativistic) electrons moving in interstellar magnetic fields of intensity $\sim 10^{-5}$ oersteds. The frequency spectrum of the radio waves is determined here by the energy spectrum of the radiating particles. Consequently radio-astronomical measurements provide valuable data on the electronic component of cosmic rays in the galaxy (for more details see references 8 and 9). We note in particular that it is indeed in the wavelength region with $\lambda > 30$ m that a kink[5,6] appears in the spectrum of the cosmic radio waves. This circumstance, which requires further verification and refinement, is quite important since the location of the kink, which is evidence of the need for allowing for ionization losses, can be used to estimate the density of the interstellar gas.[8]

There is no doubt therefore that an investigation of the long-wave cosmic radio waves is in order. The use of artificial satellites for this purpose can solve the problem, since the interfering effect of the ionosphere is substantially removed and the necessary apparatus is quite simple.*

To estimate the requirements that must be met by the receiving apparatus we recognize that in the wavelength region 10 cm < λ < 10 m the effective temperature of the non-thermal radiation is $T_{eff} = a\lambda^{2.8}$ (the intensity, $I_\nu = (2kT_{eff})/\lambda^2$, is proportional to $\lambda^{0.8}$). At a wavelength of approximately 3 m, T_{eff} is on the order of several thousand degrees. According to references 5 and 6, $I_\nu \cong$ const and $T_{eff} \sim 10^6$ or 10^7 at 30 m < λ < 100 m. At even longer wavelengths, λ > 100 m, no quantitative determination was made of the intensity of the radio waves that reach the top of the ionosphere. However, there are grounds for assuming[6] that $T_{eff} \gtrsim 10^7$ deg at λ > 100 m. At the same time at wavelengths greater than approximately 100 meters, the absorption in the interstellar medium already becomes substantial, and consequently upon further increase in λ the effective temperature of the cosmic radio waves will approach the temperature of the interstellar or interplanetary matter.

What apparatus should be used for the reception of such radio waves? Modern superheterodyne receivers with rf amplifier stages with extremely low noise factors, $S_n \sim 2$, can be built for wavelengths longer than 100 meters. The internal noise should originate mostly in the input circuits of the receiver. If the antenna is ideally matched to the receiver the ratio of the useful received signal to the internal noise should be T_a/T_{in}, where T_a is the antenna temperature, determined by the intensity of the received radio waves,† and T_{in} the temperature of the receiver input circuits. Naturally, it is impossible to obtain perfect matching between the antenna and the receiver. For a receiver designed for wavelengths longer than 100 meters, and for an antenna with a radiation resistances on the order of several tens of ohms, signal power gain on the order of 0.1 can be readily obtained.

Thus, the real signal-to-noise ratio at the grid of the first tube of the receiver should be on the order of $0.1\,T_a/T_{in}$. Assuming $F_nT_{in} \cong 10^3$ and $T_a \cong 10^7$, we have $0.1\,T_a/T_{in} \cong 10^3$, i.e., the internal noise is much smaller than the received signal. Under such conditions the relative error $\Delta T_a/T_a$ in the measurement of the intensity of a continuous-spectrum signal is determined, in the case of a sufficiently good receiver, only by the receiver bandwidth, Δf, and the averaging "time constant" of the receiver input circuits, τ. Here

$$\frac{\Delta T_a}{T_a} \sim \frac{1}{2}\frac{1}{\sqrt{\Delta f \tau}}.$$

Putting, somewhat arbitrarily, Δf = 5 kcs and τ = 1 second, we get $\Delta T_a/T_a \cong 2\%$, i.e., the relative measurement error is small.

If the antenna-to-receiver signal transfer is not too small the radiation resistance R_Σ of the antenna, as already noted, must be on the order of 20 or 30 ohms. If a wire antenna (elementary dipole) is used we get, with $R_\Sigma = 80\pi^2(l/\lambda)^2 =$ 20 ohms, $l/\lambda \gtrsim 1/6$, where l is the length of the dipole. Thus, for example, $l \gtrsim 50$ m if λ = 300 m.

It is not convenient to use a wire antenna several tens of meters long on a satellite. A loop antenna with a ferrite core is structurally more suitable. Such an antenna has a relatively larger radiation resistance with small size and weight (length ~ 10 cm, weight ~ 300 g). The axis of the loop must be parallel to the metallic surface of the satellite. Naturally, the receiver must be calibrated after installation before launching.

Speaking of the installation of the apparatus on the satellite, the weight becomes an important parameter. A five-tube miniaturized superheterodyne receiver with the necessary gain at wavelengths greater than 100 meters and with provision for band switching (for example, tuned to several fixed frequencies) can be made relatively small. If one is interested only in the intensity of the cosmic radio waves, the apparatus must operate only for several revolutions of the satellite around the earth. The weight of the power supply will then be relatively small.

Since the satellite will have a rotation of its own and the orientation of the loop antenna will vary, the intensity of the received cosmic radio waves may vary somewhat. Therefore, generally speaking, it is necessary to know the orientation of the antenna loop at every instant of time. However, inasmuch as the cosmic radio waves are approximately isotropic in the range of interest to us, we can restrict use the maximum readings of the output meter. An important advantage of the observation of cosmic radio waves longer than 100 m from an artificial satellite is the great reduction in the atmospheric in other noise, since the receiver on the satellite is so to speak shielded

*We have in mind here the so-called "general" galactic radio waves. Long-wave radio waves from individual discrete sources can be observed only with very large antennas or interference apparatus. We consider here only the reception of "general" radiation.

†For equilibrium radiation with a temperature T_{eff}, the antenna temperature is naturally $T_a = T_{eff}$. This conclusion is true for any medium with a real dielectric constant ε > 0. In the ionosphere $T_a \sim T_{eff}$; a more exact connection between these quantities depends on many conditions ($T_a \cong T_{eff}$ above the F layer for waves reflected from this layer at any angle; for waves passing through the layer, $T_a \cong \frac{1}{2} T_{eff}$).

from the earth's surface when the satellite moves above the maximum of the F_2 layer.*

In conclusion we remark that data obtained with a satellite concerning the frequency spectrum of intensity of cosmic radio waves with wavelengths $\lambda \gtrsim 100$ m lead to certain conclusions regarding the electron concentration at the corresponding levels of the ionosphere above the maximum of the F_2 layer, not accessible to radio sounding from the surface of the earth. In fact, the antenna cannot receive waves for which $\epsilon(f, N) \cong 0$ at the point of reception. Neglecting the effect of the earth's magnetic field, we have

$$\varepsilon(f) = 1 - \frac{4\pi e^2 N}{m(2\pi f)^2} = 1 - 8\cdot 10^7 \frac{N}{f^2},$$

where N is the electron concentration and f is the frequency of the received radiation. Even at very high altitudes, in interplanetary space, $N \sim 1$ to 5×10^2, i.e., $\epsilon(f) > 0$ when $f > f_0 = 9 \times 10^4$ to 2×10^5, or $c/f < \lambda_0 = 1.5$ to 3 km; when $N \sim 10^4$ the radiation propagates only if its wavelength in vacuum is $\lambda < \lambda_0 = 300$ m.

By measuring the frequency f_0 for which $\epsilon(f_0) = 0$ and reception ceases, it is possible to determine the concentration N.* The effect of the earth's magnetic field complicates the picture. However, for sufficiently high satellites this effect is small (owing to the reduced intensity of the earth's field). It can be accounted for even for lower satellites. For sufficiently long waves, longer than 200 to 300 meters, the influence of the field causes only one of the two normal waves propagating in the magnetoactive medium to be received. In this connection it is advisable to install two antennas and thus be able to measure the polarization.

*On the other hand, one could receive on the satellite not only cosmic radio waves but also waves due to the motion of fast electrons (of cosmic or solar origin) in the earth's magnetic field.[10]

An estimate given in reference 10, which can be readily refined and generalized, indicates that the presently known currents of fast electrons near the earth should produce magnetic bremsstrahlung radio waves that are considerably weaker than the cosmic radio waves, at least for wavelengths less than several kilometers. However, such long waves are particularly affected by the surrounding medium, i.e., by the magnetoactive plasma (in other words, it is necessary to reckon with the fact that the index of refraction of the medium differs from unity). This may give rise, in particular, to Cerenkov radiation. Such radiation, which is due to streams of particles of solar origin and produces auroras, has already been discussed in reference 11. It is very important that Cerenkov radiation, unlike magnetic bremsstrahlung radiation, is generated with equal efficiency by electrons and protons of a given velocity. E. A. Benediktov has called attention to the fact that the use of a satellite for the study of such radio waves may be very fruitful.

*The index of refraction of the ionosphere near the satellite influences, naturally, the input resistance of the antenna borne by it. To match the input resistance of the antenna to the receiver during the measurement of the radio waves, it is necessary to vary automatically the input resistance of the receiver by changing, for example, the capacitance of the tank circuit. On the other hand, if the satellite is provided with an instrument that measures the input impedance of the antenna, it is possible to measure directly the index of refraction in that region of the ionosphere where the satellite is located.

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