*MILLIMETER-WAVE OPTICS AND RADIO ASTRONOMY**

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IN the history of physics the name Petr Nikolaevich Lebedev is always associated with the experimental discovery of the ponderomotive effect of light—the Lebedev light pressure. The name of Lebedev is no less important in the development of the optics of millimeter radio waves. After the remarkable experimental discovery of Heinrich Hertz "it was necessary to repeat his experiments on a small scale," so wrote Lebedev in his work "On the Birefringence of Electrical Force Rays."[1] What he actually had in mind was going on from the radio waves discovered by Hertz (decimeter waves in present-day language) to thermal waves, that is to say, infrared waves. In 1895 Lebedev became the first one in the world to successfully build a set of experimental devices required for the generation and detection of waves shorter than 1 cm, in contemporary terminology, millimeter waves. Furthermore, he was able to devise a number of devices by means of which he could direct, focus, and analyze "electrical force rays," making it possible to demonstrate their wave nature, and to investigate the interaction of these waves with matter. It was the possibility of carrying out this kind of research that Lebedev saw as the chief advantage of using such short waves. He was the first to carry out experiments on birefringence of radio waves in crystals. It required the mastery of a clever general experimentalist such as Lebedev to carry out the program of research he envisaged. The P. N. Lebedev Institute of Physics has the original devices used by Lebedev for carrying out the Hertz experiments at a wavelength of 6 mm. These are shown in Fig. 1.

A brief examination of these devices emphasizes the virtuosity of Lebedev. It should be remembered that only damped electromagnetic waves could be generated at that time; these were generated by means of spark discharges. In order to produce oscillations at wavelengths of several millimeters Lebedev used a radiator a few millimeters in size that was located in a kerosene bath at the focus of a cylindrical mirror with a 12 mm aperture and a focal distance of 6 mm. The detector was a dipole tuned to a wavelength of 6 mm and located at the focus of a similar mirror. The indicator used to show the presence of electromagnetic waves consisted of an iron-constantan thermocouple and a sensitive galvanometer.

*Talk at the Physics Institute, Academy of Sciences U.S.S.R., at a meeting on March 12, 1962, commemorating the fiftieth anniversary of the death of P. N. Lebedev.

Among the devices one finds a polarizer in the form of a wire lattice with an area of 4 cm^2, a mirror for investigating interference and for exact measurements of wavelength, and a prism fabricated from ebonite (dimensions 1.8 cm × 1.2 cm) with which it was possible to determine the refractive index of the ebonite by finding the angle of minimum deviation. The interaction of electromagnetic waves with a crystal lattice was studied by means of birefringent rhombic crystals from which Lebedev fabricated a prism, a Nicol prism, and a quarter-wave plate. The plate thickness required to produce a phase shift of 90° between waves polarized in mutually perpendicular planes was 0.6 cm.

Using these devices Lebedev carried out a number of brilliant experiments that demonstrated the "identity of the effects of electrical and optical waves in this more complicated case."

One great difficulty in these experiments was the fact that the damped oscillations were highly nonmonochromatic.

Lebedev could not obtain more than two interference maxima and could not do experiments in thick crystal plates with highly different properties be-

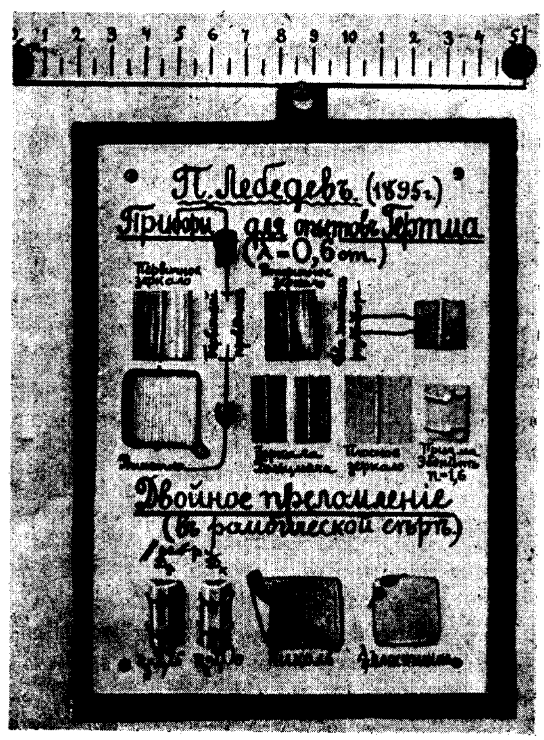

FIG. 1. Devices used by Lebedev for Hertz experiments at 6 mm wavelengths (preserved at the P. N. Lebedev Physics Institute, Academy of Sciences, U. S. S. R.).

cause of this reason. The sensitivity of his detector was extremely low. Nevertheless, Lebedev's skill as an experimenter allowed him to carry out all the experiments he had envisaged. It is interesting to note that Lebedev was able to demonstrate the rectilinear propagation of a wave with an accuracy of 3°. It is easy to show that the diffraction effects in the reflector used by Lebedev allowed a resolution of approximately 20° (in present-day language, the directivity pattern). Thus, he was able to detect a galvanometer deflection of approximately 10% of the maximum value, corresponding to 0.1 of the pattern width.

Radio engineering has made great strides in the decades that have passed since the pioneering experiments of Lebedev. In the words of Academician L. I. Mandel'shtam, it has been one of the miracles of the modern world. [2]

Powerful generators of undamped radio frequency oscillations have been built, as have sensitive detection and amplification devices. These devices derive from developments in electronics, primarily the vacuum tube. Hence it is not surprising that developments tended to push radio-frequency usage into the long-wave region. Gradually, however, radio engineering moved toward shorter and shorter wavelengths; at short wavelengths the size of the generators and detectors is smaller and the physical principles used as a basis for their operation are different. In the Thirties and thereafter main emphasis was shifted toward ultrahigh frequencies, reaching decimeter, centimeter, and finally millimeter waves.

Radiophysics and radio engineering, which started with the work of Hertz, Lodge, Riga, Lebedev, and Glagoleva-Arkad'eva in the decimeter, centimeter, and millimeter ranges returned, albeit on a much more advanced level, to these same short wavelengths.

It is difficult to exaggerate the value of microwave frequencies, including millimeter waves. The value of these waves lies with the nature of the wave effect itself. The possibility of obtaining a highly directional beam of radio waves is limited by diffraction; because of diffraction effects the angular spread of a beam φ is characterized by the familiar relation $\varphi \approx \lambda/D$, where λ is the wavelength while D is the dimension of the exit aperture of the device. To fix ideas we may recall that ultrashort radiowaves, say 5 m, are at least 10,000,000 times larger than light waves. In the meter range the analog of a relatively small optical telescope, with a mirror of diameter 10 cm, would require the mirror of a radio telescope to have a cross section of thousands of kilometers.

By using short wavelength radio waves it has been possible to obtain relatively sharp beams with devices whose dimensions are comparable with human dimensions. It was precisely the need for improving the ratio λ/D, which arises in connection with the requirements of radar, that led to the second period of development of centimeter and then millimeter radio waves.

Any detailed description of the role of centimeter and millimeter waves in physics and engineering would be beyond the scope of this paper; however, we wish to point out their value in one of the relatively new fields of science, radioastronomy.

As long as man looked out at the universe from the surface of the earth he had at his disposal only the relatively narrow window corresponding to visible light. The ultraviolet and a large part of the infrared regions of the spectrum were practically unusable because of losses in the earth's atmosphere. The development of radio engineering in the meter and centimeter wavelength ranges has made available a second and wider window. On the meter wavelength side this window is limited by the reflection properties of the ionosphere; on the millimeter wavelength side it is limited by the molecular absorption in the atmosphere due to water vapor and oxygen.

There are at least two good reasons why centimeter and millimeter waves are important in radioastronomy. On the one hand, as we have indicated above, as the wavelength becomes shorter one can use relatively narrow beams of radio waves, thus making it possible to increase the resolving power. On the other hand, in certain important cases, the reduction in wavelength of the radio waves makes it possible to work with relatively higher radiation fluxes.

Here we have in mind those cases in which the radio emission from cosmic sources, studied in

FIG. 2. The RT-22 radio telescope of the P. N. Lebedev Physics Institute. (The diameter of the parabolic reflector is 22 m.).

radio astronomy, is the long wavelength portion of the quantum thermal radiation. In this part of the Rayleigh-Jeans spectral curve the intensity is in inverse proportion to the square of the wavelength. This is the case for example, in the radio radiation from the moon and certain planets in the solar system, in particular Mars, and perhaps Venus. Reflector radio telescopes with extremely high resolution can be achieved with centimeter and millimeter waves. For example, the reflector radio telescope of the P. N. Lebedev Physics Institute (Fig. 2) has an angular resolution of approximately 2 minutes at a wavelength of 8 mm. The diameter of the aluminum parabolic reflector used in this telescope is 22 m.

If we recall that good reflectivity can be obtained from a surface (in accordance with the usual requirements of optics) only when the deviations from the paraboloid are smaller than 0.1 wavelength we get a good idea of the difficulty involved in building such a mirror.

This radio telescope has made it possible for workers at the Radio-astronomy Laboratory of the Physics Institute to study the temperature distribution in the layer above the surface of the moon as a function of its phase. In Fig. 3 we show radio isophots of the natural radiation of the moon close to its first and third quarters obtained at a wavelength of 8 mm; we also show the brightness temperature at the center of the disc as a function of phase. Such measurements

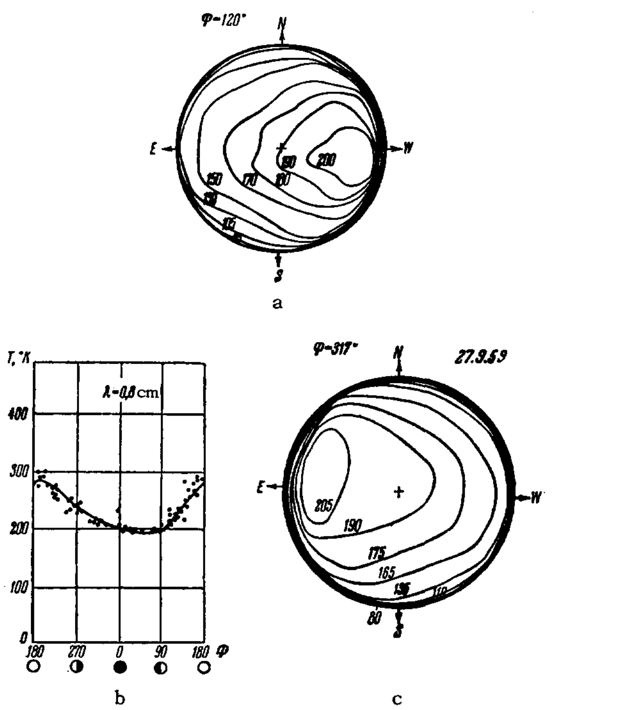

FIG. 3. Isophots of the radio emission from the moon at a wavelength of 8 mm as measured with the RT-22 radio telescope close to the first (a) and last (c) quarters and also the change in brightness temperature at the center of the lunar disc as its phase changes (b).

yield information about the physical properties of the material in the lunar crust.

This same radio telescope has been used to investigate radio emission from the planet Venus at 8 mm [3] and even 4 mm [4].* In Fig. 4 we show typical recordings of the passage of the planet through the directivity cone in which the mirror picks up radiation. The maximum signal is obtained when the axis of the parabolic reflector is aimed directly at the planet.

These recordings were obtained at wavelengths of 8 and 4 mm in 1961 close to the lower conjunction of Venus and allow us to determine the brightness temperature on the dark side of the planet, which is found to be approximately 400°K. The radio emission from the planet Jupiter has also been investigated at a 8 mm. In Fig. 4 we give the results of analysis of several recordings of the passage of this planet.

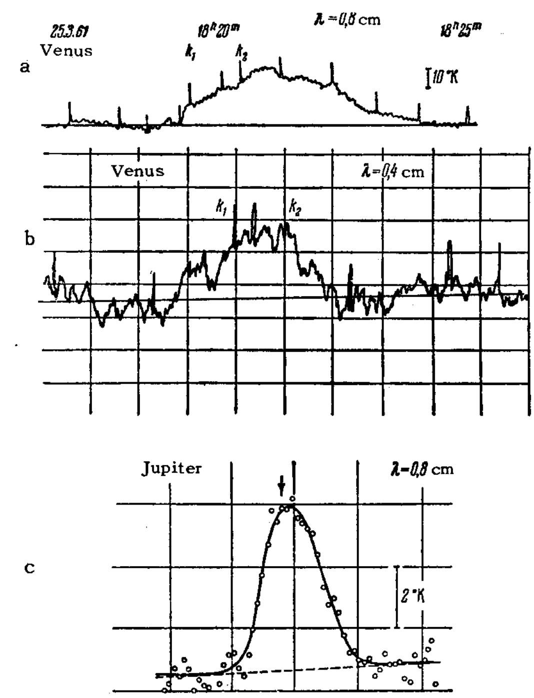

FIG. 4. Typical recordings of the radio emission from Venus at 8 mm (a) and 4 mm (b) and Jupiter at a wavelength of 8 mm (c) obtained in 1961 with the RT-22 telescope.

Important information as to the physical nature of radio sources can be obtained if one studies the polarization as well as the intensity of the radiation. In his classical polarization experiments Lebedev built and used polarizers, analyzers, and quarter-wave plates. Elements of this kind are now widely used in radio astronomy.

The roles of analyzers and polarizers are frequently played by the radio waves by which the high-frequency energy is carried. Quarter-wave plates are made by

*Interesting radio astronomic observations of the sun and the moon at 4 mm have been carried out at the Radiophysics Research Institute by A. G. Kislyakov using a small radio telescope [Izv. vuzov (Radiofizika) No. 1, (1961)].

placing thin dielectric slabs along the axis of a circular waveguide; with this arrangement it is possible to reduce the velocity of propagation of a wave polarized in the plane of the plate as compared with a wave polarized perpendicularly to the plate. As a result a plane polarized wave can be transformed into a circularly polarized wave and vice versa. The propagation velocity can also be changed by deforming a circular waveguide into elliptical shape. The idea of using the birefringent properties of matter, first realized in the experiments of Lebedev, also finds wide application in radio astronomy. For instance, one can exploit the well-known properties of ferrites: these are polycrystalline materials which, in a remarkable way, combine the magnetic properties of ferromagnets and the low electrical losses of semiconductors. As a consequence of the interaction between the spins of electrons of atoms in the material and the electromagnetic waves in the presence of an external magnetic field the velocity of propagation in a ferrite material varies as a function of polarization, depending on whether the wave is right-hand or left-hand circularly polarized. Radio astronomy makes use of the Faraday rotation of the plane of polarization that arises as a consequence of this effect.

Ferrite modulators and quarter-wave plates for the 8 mm region have been developed and used successfully at the Radio-astronomy Laboratory of the Physics Institute of the Academy of Sciences.

In Fig. 5a we show an assembly of such devices comprising the high-frequency head of a polarization radiometer.

The polarization characteristics of the radio radiation from the sun are of special interest.

The high resolving power of radio telescopes in the centimeter and millimeter regions has made it possible to obtain radio isophots of different portions of the solar disc; these include radio isophots obtained with polarized radiation. In particular, it is found that the radio emission from the brighter local sources on the sun is associated with groups of spots where the local magnetic field is large and that this radiation is partially circularly polarized. Measurements of this radiation yield information as to the solar atmosphere above the groups of spots and the magnetic field environment. The first observations of the polarization of the radiation from the sun in the centimeter region were carried out at the Pulkovo Observatory.[6] In Fig. 5b we show a typical radio-isophot plot of the sun obtained with a 22 m radio telescope at a wavelength of 8 mm. Similar radio isophots at a wavelength of 3 cm have been obtained earlier with a 30 m radio telescope of the Physics Institute, Academy of Sciences, in Crimea.[7] Recently, radio isophots of the

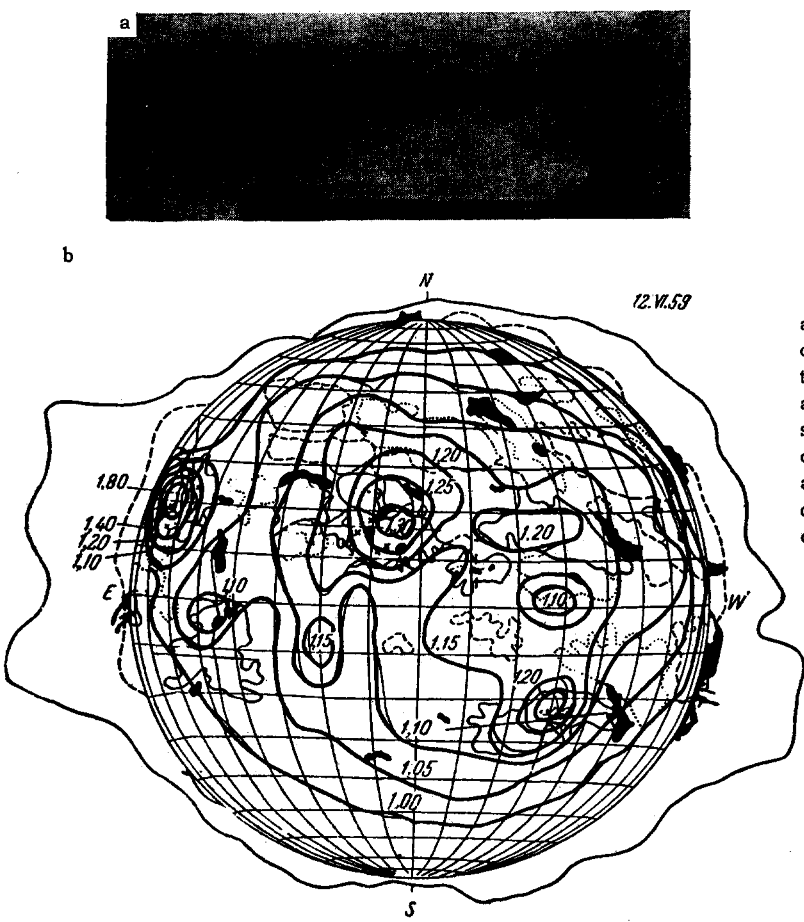

FIG. 5. a) General form of the high-frequency part of a polarization radiometer used in the 8mm region developed by U. V. Khangil'din (Phys. Inst. Acad. Sc.); b) typical isophots of the radio emission from the sun at a wavelength of 8 mm obtained with the RT-22 radio telescope. Visible are the local sources of radio radiation connected with groups of sun spots. The numbers characterize the relative intensity of the radiation. The curve marked 1 indicates the level of radiation of the quiet sun

sun at a wavelength of 4 mm have been obtained with the 22 m radio telescope.

The present stage of development of radio physics is characterized by an unexpected advance in sensitivity of detection devices and monochromaticity and frequency stability of oscillators. Both of these developments are related to the development of quantum electronics, in which the P. N. Lebedev Institute plays a leading role.[8] In turn, the increase of sensitivity of the detection apparatus in the centimeter and millimeter ranges has been of decisive value in the further investigation of astronomical bodies by radio astronomy; in particular it allows a sharp increase in the number of discrete sources of radio emission amenable to measurement.

By going beyond the limits of the earth's atmosphere into the cosmic space we remove the limitations on the choice of electromagnetic waves mentioned above. By carrying radio telescopes beyond the limits of the atmosphere it should be possible to move practically without limit toward shorter wavelengths. In this connection we should mention the important role that will be played by amplifiers and generators of submillimeter, infrared, and optical waves, which will become a reality as quantum electronics develops. And here again we return to the notable experiment connected with the name of P. N. Lebedev concerning light pressure. It is known that one of the important applications of Lebedev pressure is precisely in the region of microwave frequencies. For a number of reasons, in this region it is found very convenient to measure the intensity of radiation by its ponderomotive effect. A number of devices used to measure power at microwave frequencies are based on the use of the Lebedev pressure.[9]

With the creation of optical amplifiers and oscillators it has become possible to extend the techniques of radiophysics into the optical region, just as in Lebedev's time the optical methods helped to explain rays of electrical force. The creation of coherent optical radiators for which the dimensions of a focused spot are limited only by diffraction effects leads to an extraordinary rise in the ponderomotive effect of the light.

Thus, both fields that Lebedev pioneered, light pressure and millimeter waves, have been the subjects of new and varied development some fifty years after his death.

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[3] A. D. Kuz'min and A. E. Salomonovich, Astron. Zh. **38**, 1115 (1961), Soviet Astronomy **5**, 851 (1962).

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Translated by H. Lashinsky