RADIO ASTRONOMY

BY

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INTRODUCTION

Since 1945 there has been much work done in the measurement and interpretation of cosmic or extra-terrestrial radio waves.[2] The first evidence of the existence of such waves was obtained twenty years ago by Jansky (1)[3] who observed, at short wavelengths, "random" noise signals whose intensity was a maximum when the antennas were directed at the center of the galaxy. In spite of this very remarkable astrophysical discovery, it was not until 1942 that scientists realized the great importance of cosmic noise, when it became evident that the sun is also a source of high-frequency radiation in the region of meter- and centimeter wavelengths. In recent years techniques of radio astronomy have been developed to enable investigators to obtain information about the positions of stellar bodies and matter in interstellar space that could never have been seen with an optical telescope. It is the aim of this paper to review the most important progress made in this new science of Radio Astronomy during recent years.

PRINCIPLES OF TECHNIQUES USED IN RADIO ASTRONOMY

To detect the very weak radio signals coming to the Earth from extra-terrestrial sources, a directive antenna and a highly sensitive radio receiver must be used. Figure 1 shows a typical receiving system.

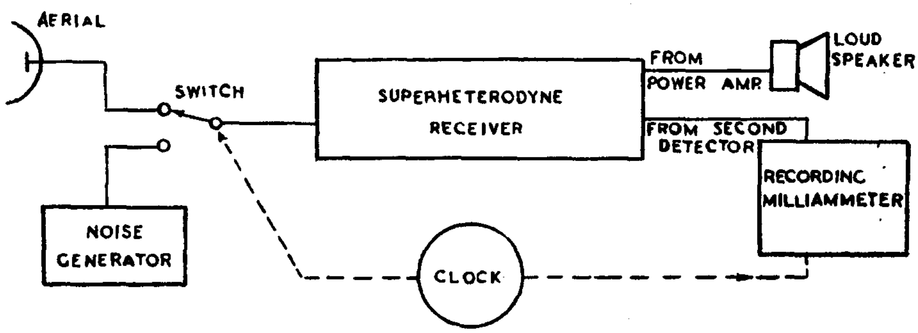

FIG. 1. A typical cosmic noise receiving system.

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[2] The term "cosmic radio waves" or "cosmic radio noise" includes solar radio noise, galactic and extra-galactic noise.

[3] The boldface numbers in parentheses refer to the references appended to this paper.

Energy intercepted by the aerial is fed through a transmission line to the input of a superheterodyne receiver, where it is amplified linearly about a millionfold before rectification in the second detector, which is usually a diode. The d-c. output current actuates a recording milliammeter, which is calibrated in terms of input noise-power. At suitable intervals the receiver calibration is checked by being switched automatically to the noise generator, which is as a rule a diode operating under controlled temperature conditions. A clock provides electrical impulses both to the control mechanism of the switch and to the chronograph pen, providing charts of intensity *versus* time for various frequencies.

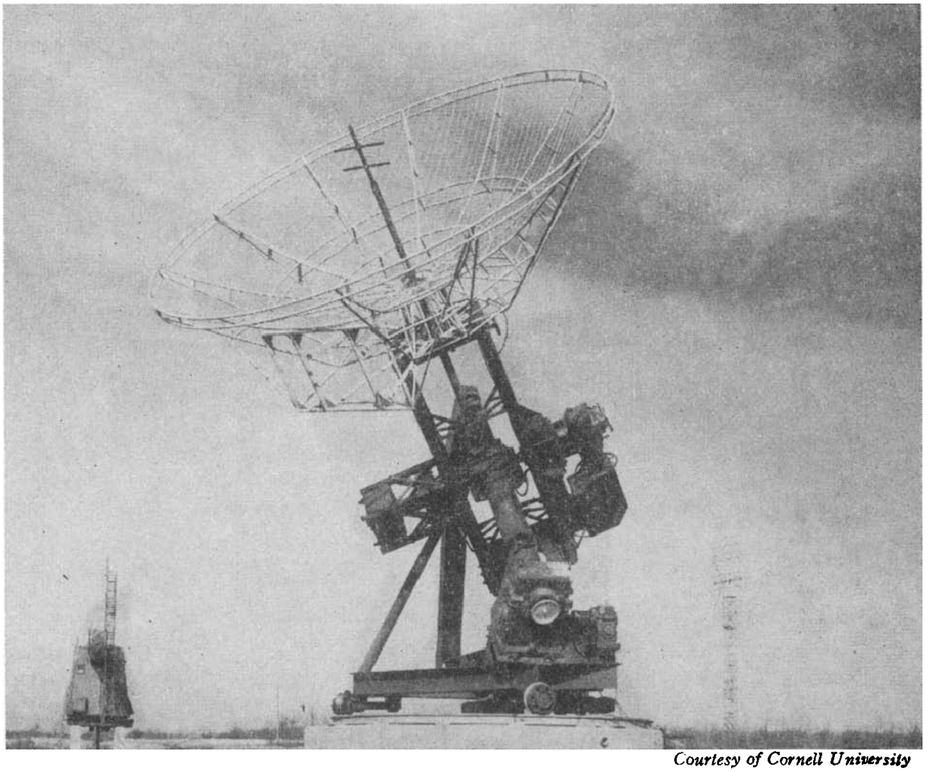
The basic physical quantity to be measured is the noise flux intensity S, defined as the total power per unit frequency interval falling on a unit area normal to the direction of the power flow. Using the M.K.S. system of units, it is expressed in watts per square meter per cycle per second. The noise flux intensity is related to the equivalent black-body temperature of the source by the relation

$$S = \frac{2kT}{\lambda^2} \Omega_s$$

which follows directly from the Rayleigh-Jeans approximation to Planck's radiation law for radio waves. In the equation above, T is the equivalent temperature (absolute) of the extra-terrestrial noise source, λ is the wavelength observed (meters), k is Boltzmann's Constant (1.37×10^{-28} Joule per degree) and Ω_s is the solid angle subtended by the source at the earth. For the case of the sun, $\Omega_s = 6.8 \times 10^{-5}$ steradian.

In measuring the intensity of the emission from extra-terrestrial sources, and hence their equivalent temperature, three different cases must be distinguished. In the first and ideal case the radiation pattern of the directive antenna is sufficiently narrow so that the entire beam is smaller in diameter than the source. In this case the effective temperature of the antenna is the same as the equivalent temperature of the source. The second case is that in which the antenna pattern is so broad that the gain of the antenna does not vary within the angle subtended by the source. In this case, while the effective antenna temperature will be less than the equivalent temperature of the source by an amount determined by the gain of the antenna, nevertheless the equivalent temperature of the source can be calculated by well known and rigorous expressions. The third case is that the beamwidth of the antenna lies between the two previous cases and is commensurate with the angular diameter of the source. Here, when the axis of the beam is directed at the center of the source, such as the sun, the gain varies across the disc of the sun, and therefore to compute the equivalent temperature of the sun from the measured intensity of the emission, an integration involving a detailed knowledge of the pattern of the directive antenna is necessary.

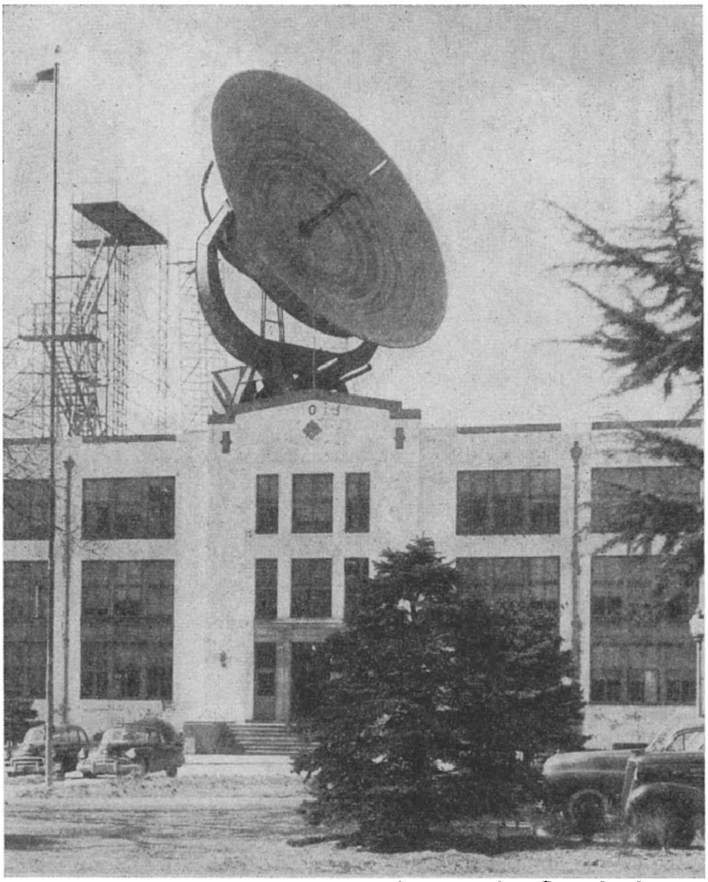
In Radio Astronomy it is common practice to use a parabolic mirror with a dipole antenna at the focus as a directive antenna. Such a "radio telescope," consisting of a parabolic wire mesh mirror, used at Cornell University for investigations of solar radio waves, is shown in Fig. 2. The accuracy θ with which the direction of arrival of cosmic



Courtesy of Cornell University

FIG. 2. Telescope for solar radio waves

radio waves can be determined with such a telescope is, however, limited by the ratio between the width W of the mirror and the wavelength λ of the waves received. The angle θ, measured in radians, is of the order λ/W, and is usually spoken of as representing the "resolving power" of the telescope. It is of interest to compare the resolving power available with optical telescopes, using light waves of about $\lambda = 5 \times 10^{-5}$ cm. wavelengths, and a radio telescope using wavelengths of about $\lambda = 5$ m. An optical telescope with an aperture of 10 cm. would have the same resolving power as a radio telescope with an aperture of 1000 km. It is obvious that, with radio telescopes, we cannot hope to approach the resolving power possible with light waves. In an attempt, however, to get the best possible resolving power, large mirrors have been constructed. One of the largest radio telescopes used at present in Radio Astronomy is that of the Naval Research Laboratory, shown in Fig. 3, which consists of a parabolic mirror with an aperture



Courtesy of Naval Research Laboratory

FIG. 3. Giant telescope for cosmic radio waves.

of 60 ft. A much larger mirror, having an aperture of about 80 meters, is now in use at the University of Manchester. This telescope, when used on a wavelength of $\lambda = 2$ m., has a resolving power of about 1/40 radian, or 1.5°. Its importance in Radio Astronomy may be similar to that of the great 200-in. telescope used at Mt. Palomar in visual astronomy.

THE RADIOFREQUENCY RADIATION FROM THE QUIET SUN [4]

According to our present knowledge there are three types of solar radiofrequency radiation. First, there is a component which remains

[4] The term "quiet" sun means a sun which is free from sunspots, flares and other solar activities.

fairly constant in intensity and is randomly polarized. This component is due to thermal radiation or black-body radiation of the sun's atmosphere, which is a highly ionized hydrogen gas with a slight mixture of other elements—principally helium in the corona, and heavier elements in the chromosphere. In the Coulomb field of the positive protons, the free electrons approaching the protons are deflected and leave on hyperbolic orbits of lower energy. The difference in energy of these "free-free" transitions between adjacent orbits is transformed to electromagnetic radiation. The spectrum radiated is similar to the "Bremsstrahlung" of Röntgen-rays and consists of a continuum of wavelengths, whose longest wavelength region is that of radio waves. The intensity of this radiation however depends in a characteristic manner on the frequency. This is due to the fact that the emission and absorption of a black body, such as the corona, depends on the "optical depth"

$$\tau = \int_0^h k dh$$

which is the product of the absorption coefficient k and the length dh along the path transversed by the rays. The absorption coefficient of a proton-electron gas is a function of the electron density N, the wavelength λ, the temperature T and the refractive index n according to the relation

$$k = \frac{2\sqrt{2}\,\lambda^2 N^2 e^6}{3\sqrt{\pi}\, nc^3(mkT)^{\frac{3}{2}}} \log_e\left(\frac{4kT}{e^2\sqrt[3]{2N}}\right)^2,$$

where e and m are, respectively, the charge and the mass of the electron, k is Boltzmann's constant and c the velocity of light. From this equation, it is seen that the absorption coefficient of the corona is proportional to the square of the wavelength λ and the electron density N,

TABLE I.

Observer	Wavelength in cm.	Effective Temperature in degrees K.
Hagen	0.85	6,740
Dicke and Beringer	1.25	11,000
Southworth	3.2	16,000
Sander	3.2	22,000
McGready, Pawsey and Payne-Scott	10	25,000
Covington	10.6	58,000
McGready, Pawsey and Payne-Scott	25	150,000
Lehany and Yabsley	50	500,000
Reber	62.5	590,000
Pawsey	150	600,000
Ryle and Vonberg	172	ca. 1,000,000
Ryle and Vonberg	375	ca. 1,000,000
Machin	670	ca. 2,000,000

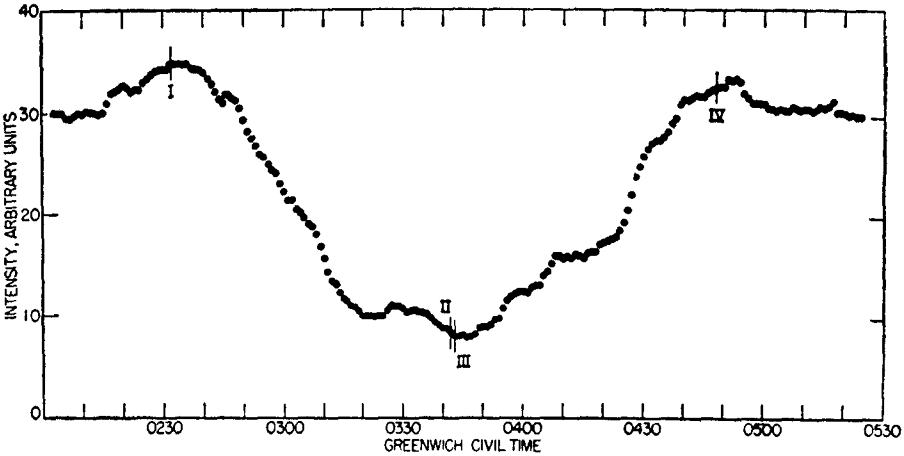


FIG. 4. Chart of intensity *versus* time for 65 cm. radiation received from the sun during its eclipse by the moon on September 11, 1950. Roman numerals indicate instants of first, second, third and fourth contact.

and inversely proportional to the 3/2 power of the temperature T. For light waves the corona is transparent. At meter wavelengths, however, the absorption of the corona—and hence according to Kirchhoff's black-body law also the emission—is such that a radio telescope receives approximately black-body radiation as determined by the electron temperature of the corona, a temperature on the order of a million degrees. For shorter radio waves the corona becomes more and more transparent. At 10-centimeter wavelengths radiation is partially emitted from the corona and the cooler chromosphere and at centimeter wavelengths or microwaves, radiation is emitted principally from the chromosphere, which acts as a black body for wavelengths of this magnitude. Hence the longer radio waves originate in the corona and the shorter radio waves in the chromosphere. In Table I the equivalent temperature of the quiet sun observed at various radio wavelengths is shown. From these measurements it is seen that, over the wavelength range observed, the equivalent temperature of the quiet sun varies from 7000 deg. Kelvin at the short wavelengths to the order of 10^6 deg. Kelvin at the longer wavelengths. These results are in accordance with the theories of black-body radiation of the sun developed by Martyn (2), Waldmeier (3) and Unsöld (4).

Because of the radio waves emitted by the sun's ionized atmosphere, the apparent diameter of the sun observed at radio frequencies is always appreciably greater than at visual wavelengths. Consequently, all solar eclipses viewed by a radio telescope appear to be annular rather than total. Results obtained from measurements at wavelengths of $\lambda = 3$, 10 and 65 cm. during the sun's eclipse by the moon (Fig. 4) indicate that the apparent diameter of the sun exceeds that of the moon by 3, 7 and 11 per cent, respectively (5). At a wavelength of about $\lambda = 5$ m., the apparent diameter of the sun equals nearly twice the diameter of the visible sun.

ENHANCED SOLAR RADIATION

Besides thermal radiation from the quiet sun, during periods of sunspot activity there is an additional component, referred to as "enhanced radiation" associated with sunspots. This component is as a rule circularly polarized. There are, however, two different types of enhanced radiation associated with the wavelengths observed. At wavelengths below $\lambda = 50$ cm. the intensity of enhanced radiation appears to be closely related to the sunspot area, as shown for a wavelength of $\lambda = 10.7$ cm. in Fig. 5 (6). The intensity of this sunspot

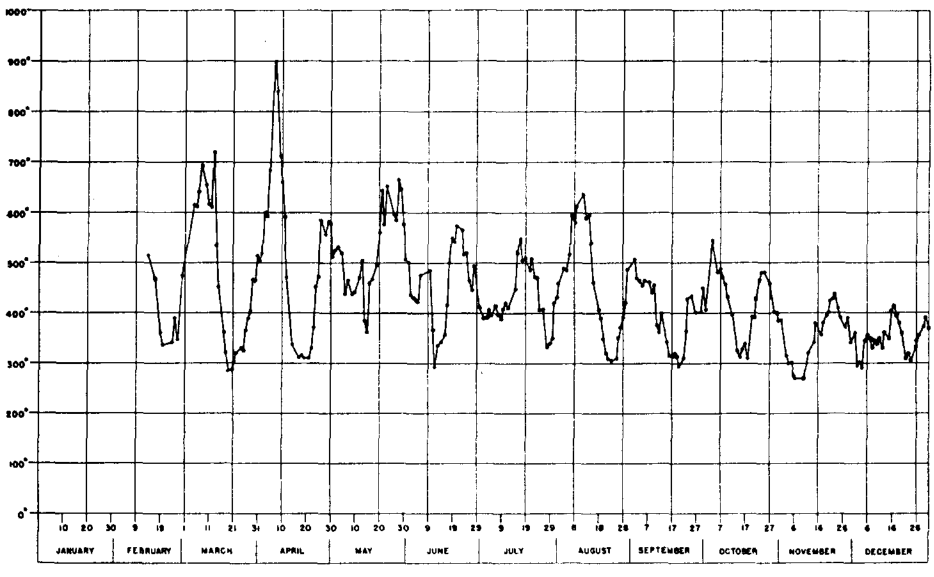


FIG. 5. The daily variation of solar intensity at 10.7 cm. wavelength for the year 1947. The antenna temperature is ordinate.

radiation exceeds the thermal component of the quiet sun only twice or three times. It is believed that this component originates in regions of coronal condensations, where the electron density and hence the optical depth is much greater than in the undisturbed corona of the quiet sun (7). As a consequence of this, regions of coronal condensations behave as a black-body for centimeter wavelengths. This hypothesis on the origin of enhanced radiation at microwaves seems to be more likely than those which consider it as radiation emitted by rotating electrons or protons in the magnetic fields associated with sunspots. The correlation between the intensity of enhanced radiation and sunspot area is observed down to shortest wavelengths of about $\lambda = 3$ cm. and may be of considerable practical importance in conjunction with meteorological aspects.

At meter wavelengths another type of enhanced radiation is observed. This component is characterized by very rapid fluctuations of intensity. The intensity may be as much as 100 times greater than the basic thermal component at wavelengths of about $\lambda = 1$–2

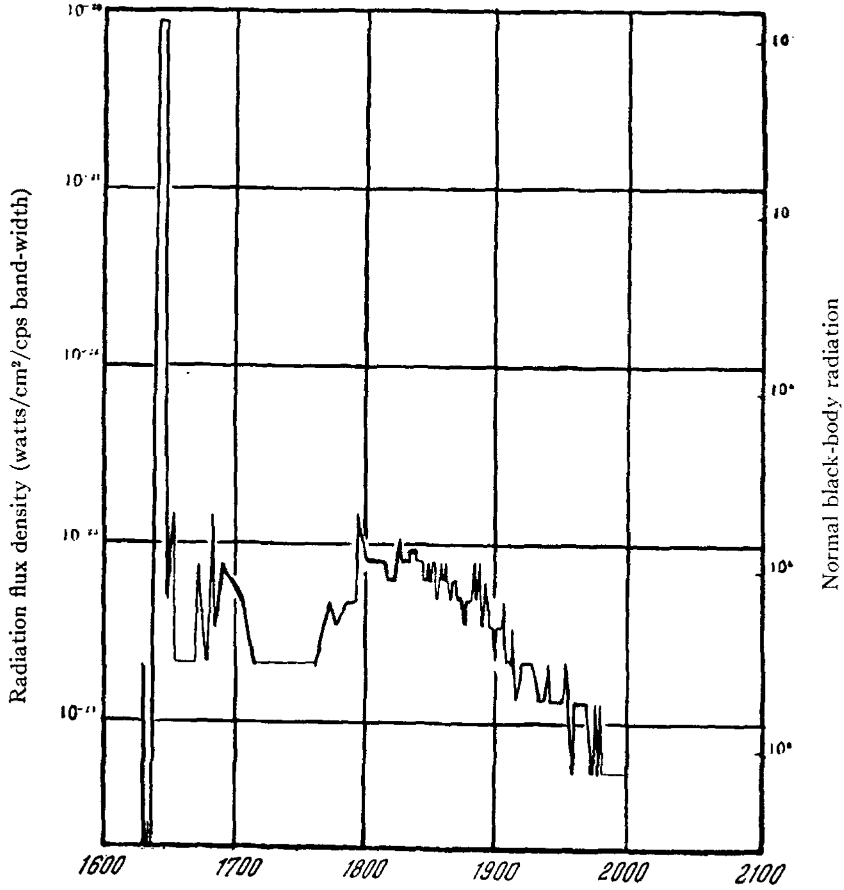


FIG. 6. Abnormal solar radiofrequency radiation (outburst) at $\lambda = 4.2$ m. wavelengths.

meters and 10^4 times greater at the longer wavelengths. This type of enhanced radiation has no correlation to the sunspot area; however, its intensity is usually a maximum when a sunspot is near central meridian passage and it changes the sign of circular polarization if the sunspot observed is passing through the central meridian (8). It is believed that this type of enhanced radiation is not due to thermal radiation as in the case of the short wavelengths. It seems to be much more likely that this component is due to a great number of discrete electrical bursts superposed on a basic thermal component.

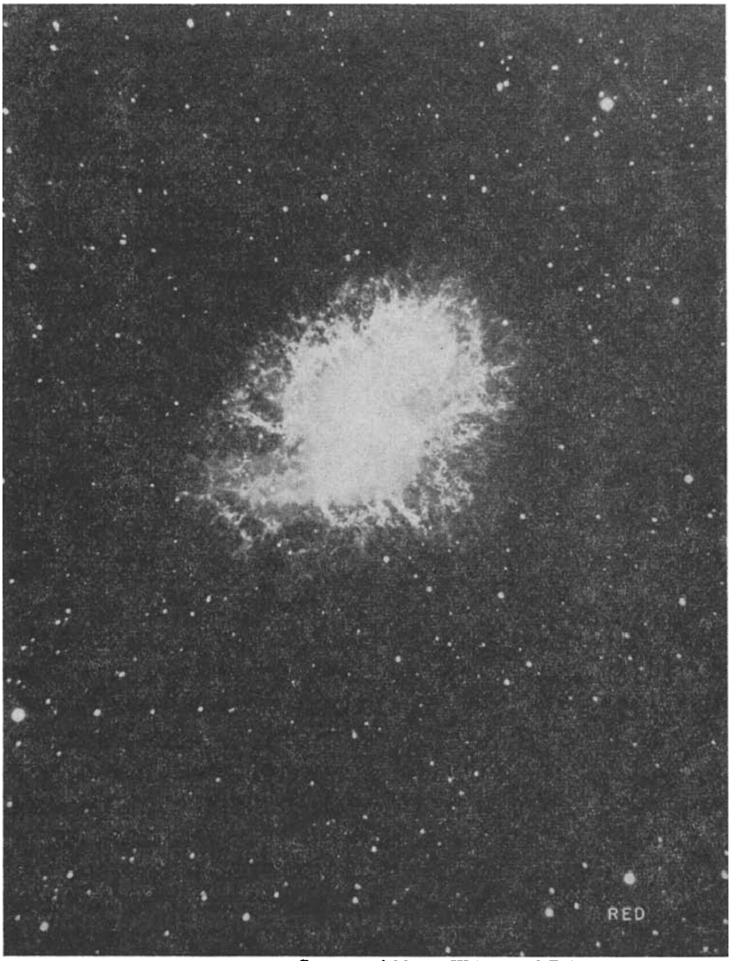
BURSTS AND OUTBURSTS OF SOLAR NOISE

The third type of solar radio noise is characterized by sudden increases of intensity known as "bursts" and "outbursts." The bursts, whose duration does not exceed 30 seconds and may be as short as 2 or 3 seconds, occur at random. The intensity of the bursts decreases as the wavelength of observation decreases, so that in the microwave region they are not observed at all. The "outbursts," on the other hand are characterized by sudden increases of intensity to many times the quiet or background level, then fall exponentially, returning to the quiet noise level in from a few minutes to a few hours. The occurrence of an outburst is frequently coincident with the appearance of a solar flare and with a consequent sudden ionospheric disturbance on the earth, the so-called, "Mögell-Dellinger effect." A large solar outburst observed at a wavelength of $\lambda = 4.2$ m. during a period of great sunspot activity in July 1946 (9) is shown in Fig. 6. The intensity of that outburst exceeds the quiet noise level by a factor of about 10^8. It is very significant that a few hours after the occurrence of that outburst the intensity of cosmic rays at the Earth also became a maximum. It is believed that the large outbursts are caused by corpuscular streams of protons, which move outwards from the flares; it has also been suggested that solar flares, from which large outbursts of radio noise are emitted, are also sources of cosmic rays.

GALACTIC RADIO NOISE AND RADIO STARS

The remarkable observation that radio waves were emitted by the galaxy was made by Jansky (1) and later by Reber (10) and other scientists. Because the intensity distribution of galactic radio noise followed the known features of galactic structure, being greatest in the direction of the galactic center and a minimum at the poles and because there did not appear to be any measurable emission from the brighter stars or other prominent objects in the galaxy, it was generally believed that galactic radio noise originated in the interstellar gas due to the "free-free" transitions of electrons in the fields of protons. This theory was developed more fully by Henyey and Keenan (11). It was found however, that a reasonable fit with experimental observations could be obtained only for the shorter radio wavelengths ($\lambda < 1$ meter) but for the longer wavelengths the theory presented a serious discrepancy (12). It is only possible to explain the high intensities at the longer wavelengths on the theory of Henyey and Keenan by assuming an electron temperature of 100,000 to 200,000 deg. Kelvin, and this is quite in contrast to our knowledge of the electron temperature in the interstellar hydrogen gas concluded from visual observations. On the other hand, it was evident from the early measurements of Jansky and Reber that the intensity of galactic radio noise also could not be explained as being the aggregate black-body radiation from the stars in the galaxy. Even after the discovery of the enhanced radiation from the sun, it was apparent that, if all the stars emitted enhanced radiation like the sun, then there still remained a factor of some 10^{10} to be accounted for in order to explain the intensity of the galactic radio noise.

A significant milestone in radioastronomy was the discovery that a considerable part of the galactic radio noise originates in discrete sources



Courtesy of Mount Wilson and Palomar Observatories

FIG. 7. The Crab Nebula, taken with the 200-in. Hale telescope.

of radiation. At present there are about one hundred known discrete sources in the galaxy, from which radio waves are emitted. The remarkable feature of these "radio stars" is, however, that they do not coincide with visible stars or other prominent objects in the galaxy. Recent experimental evidence indicates that the whole of galactic radiation can be explained if the known radio stars are regarded as the most intense of a large number of radio stars, distributed throughout the galaxy in a manner similar to the distribution of the visual stars (13, 14). We are thus faced with a possibility of the utmost cosmological importance, that the galaxy contains large numbers of stellar objects which are not visible and which only can be seen by radio telescopes.

Courtesy of Mount Wilson and Palomar Observatories

FIG. 8. The great nebula M 31 in Andromeda.

There have been several speculations as to the mechanism of these radio stars. Some astrophysicists believe that radio stars are young stars being not hot enough to emit light or that radio stars are stars which die. That radio waves are emitted from a dying star has been observed in the case of the Crab-nebula (Fig. 7). The Crab-nebula is a supernova, that is, a star whose explosion had been observed by Chinese astronomers in 1054. Today the Crab-nebula is a great cloud of hot gas expanding daily by 105 million kilometers. The very remarkable feature is, however, that the Crab-nebula is not only a source of intense radio noise but also a source of cosmic rays (15). Here, as in the case of the large solar outbursts, there is a connection between cosmic radio noise and cosmic rays. It has been suggested that the discrete sources of radio noise in the galaxy might be responsible for the primary cosmic rays (**16**, **17**, **18**).

EXTRA-GALACTIC RADIO NOISE

The evidence for the existence of radio waves of extra-galactic origin from the great nebula in Andromeda (M. 31) (Fig. 8) which, at a distance of 750,000 light years, is the nearest of the extra-galactic nebulae, was obtained by Hanbury, Brown and Hazard (**19**). Although the intensity of the radiation received was only 1/150 of that from the intense radio star in the constellation Cygnus in the Milky Way, nevertheless, it is evident from these measurements that the mechanism

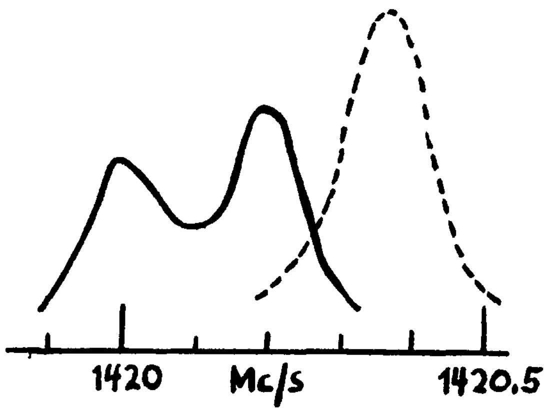


FIG. 9. Line profiles of the 1420 Mc/s emission line.

of the generation of extra-galactic radio noise is very similar to that of our own galaxy. In addition to the Andromeda nebula, several other extra-galactic nebulae have been observed to be sources of cosmic radio waves (**20**). It is estimated that the contribution of extra-galactic nebulae to the cosmic radio noise measured at the Earth is of the order of about 10 per cent.

Although at present the mechanism of cosmic radio noise is not understood, it is evident from recent research that cosmic radio waves are closely related to cosmic rays. Cosmic radio waves are the birth pains of cosmic corpuscular radiation. Therein lies the great importance of cosmic radio noise in astrophysics. It may be expected that the development of Radio Astronomy will help answer the important problem of the origin and genesis of cosmic radiation.

THE 21-CENTIMETER EMISSION LINE FROM INTERSTELLAR HYDROGEN

In addition to the study of radiation from the sun and from the radio stars, there is another important branch in radio astronomy which is related to the study of interstellar matter by monochromatic radio waves emitted by its principal constituent, hydrogen. Such an emission line in the radio spectrum from interstellar hydrogen at 1420 Mc/s (λ = 21-cm) comes from a hyperfine-structure transition in the ground state of atomic hydrogen (21, 22, 23). The discovery of this line, the first to be detected in the spectrum of cosmic radio noise, makes possible for the first time in Radio Astronomy the study of Doppler shifts arising from relative motions of the source-region and the earth. The 1420 Mc/s line is found to be double in some directions (full line in Fig. 9). These directions extend over nearly a full quadrant of galactic longitude. The most interesting effect is a shift in frequency due to the differential rotation of the galaxy and the peculiar velocities of interstellar gas clouds. The radial velocity due to galactic rotation falls to zero towards the galactic center and in the other three cardinal directions. Hence in these directions the observed line-profile is a measure of the peculiar velocities in the line of sight. These velocities are found to be random and of the order of 15 km/sec. In any other direction in the galactic plane, the frequency of the radiation is affected by galactic rotation, and depends on the distance to the source-region. Thus, if the effects of galactic rotation and random motions can be separated, observed frequency shifts can be interpreted as distances.

The observed characteristics of the double line are most simply explained as an effect of galactic rotation. In this case, the source must form two vast elongated masses of hydrogen, possibly delineating two spiral arms of the galaxy. Previously, by far the greater part of interstellar matter was undetectable by any known means. This new development offers a striking example of the important role of radio studies in astronomy.

Acknowledgments

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