RADIO-FREQUENCY INVESTIGATIONS OF ASTRONOMICAL INTEREST.

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ELECTROMAGNETIC energy is emitted at radio frequencies by various astronomical sources. Advances in the study of such energy have been rapid. In this review we will attempt to summarize briefly the present (1946 Sept. 15)* status of investigation in this rapidly expanding field. We include a fairly complete bibliography, since many original papers appeared in non-astronomical journals. We are indebted to several investigators for permission to describe unpublished work. Phenomena connected with meteors have been omitted from this discussion.

The name "cosmic static" has been applied to long-wave radiation of extra-terrestrial origin which is observable over extended regions of the Milky Way. Cosmic static is set apart from the energy in the visible spectrum by the nature of the equipment used in its detection. Absolute calibration of the intensity received still affords considerable difficulty. A signal generator of known intensity may be used by substitution, or by actual flight before the antenna. The thermal fluctuation noise in the first circuit of the receiver (determined by the ambient temperature) affords calibration if all other sources of receiver noise are absent. The angular aperture of the acceptance cone of the antenna must be known if we are to interpret the received signal in terms of the surface brightness of the emitting source, since the acceptance cones may be large compared to the source. The intensity of the emitting source is sometimes given in units such as watts per unit area per unit solid angle per receiver band width. It is also possible to define the apparent temperature of a black body which, on substitution, would produce the same fluctuation noise in the receiver as does the observed source. The relative narrowness of the Milky Way and its variations of surface brightness also lead to difficulty in absolute calibration, since an observed intensity distribution must be corrected for the "instrumental" blurring of small features. Determination of this instrumental correction is difficult and leads to uncertainties also in the absolute calibration of the received intensities. At present, we can expect absolute calibration of the work of different investigators to show only order-of-magnitude agreement. Relative intensities by one investigator at a given frequency are of higher accuracy; even here the uncertainty of the receiver-noise level, and of terrestrial or man-made noises, affects the ratio of maximum to minimum cosmic signal.

Cosmic static was discovered by K. G. Jansky of the Bell Telephone Laboratory, at Holmdel, New Jersey, during experiments on the direction of arrival of terrestrial atmospherics. When other noises were at a minimum, his apparatus showed small residual disturbances when the antenna pointed in certain directions. The discovery was made at a frequency of 20·6 megacycles per sec. (Mc.) In December 1931, the maxima occurred at noon when the antenna pointed south. Thus, in his first paper[1], Jansky attributed the disturbance to the Sun. In later papers[2, 3, 4], he demonstrated that the noise was received whenever the

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* [An addendum by Dr. Greenstein following this article brings it to 1947 Jan. 10—ED.]

antenna pointed to the Milky Way. The maximum disturbance was received from a point near R.A. $18^{h} \pm 30^{m}$, Dec. $-10° \pm 30°$. Later work[4] at 18 Mc. showed closely the same intensity of received noise. No radiation was detected from the Sun.

In Jansky's experiments the antenna was rotatable in azimuth and fixed in altitude. The acceptance cone (conventionally defined by the width at which the power received has dropped to one-half its maximum value), was about 30° in width and 37° in height. In 1935 a large fixed antenna was used at Holmdel for reception of signals from England. The direction in altitude toward which it pointed was varied by electrical means. When terrestrial electrical noise was at a minimum, Friis and Feldman[5] noted that the received noise varied with antenna direction, at 18·6 Mc. and at 9·5 Mc. The maximum variation of angle obtainable was 20°. At 18·6 Mc. a variation of intensity of 2·5 : 1 was observed; the acceptance cone was 3° high and 11° wide. At 9·5 Mc. the variation was 4 : 1 and the acceptance cone 4° high and 16° wide. Reber computed the position in the sky at which the antenna pointed during the observations of Friis and Feldman, and found it to be in Cygnus. No accurate calibration is available, although recent estimates indicate the intensity is high. Two new conclusions appear in the work of Friis and Feldman. Cosmic static arrives from Cygnus as well as from the galactic centre in Sagittarius, and it has considerable concentration to the galactic plane. If we correct the variation of received intensity with angle for the finite resolving power of the antenna, the emitting region of the Milky Way is small.

R. M. Langer has kindly informed Reber (in private correspondence) that during 1936 Potapenko and Folland of the California Institute of Technology made some simple measurements at 20 Mc. which in a general way confirmed Jansky's work.

Reber undertook an investigation of cosmic static with specially designed apparatus. The main piece of equipment consisted of a mirror, 31 feet in diameter, fixed in azimuth and movable in altitude. The signal was picked up by a dipole at the focus. First results were obtained at 160 Mc., at which frequency the acceptance cone is about 6° by 8°. The centre of the maximum disturbance was definitely fixed to be near the galactic nucleus in Sagittarius[6, 7], and a provisional estimate made of the maximum absolute intensity as $4{\cdot}5 \times 10^{-22}$ watt per cm.^{2} from a circle one degree in diameter within a band-width of one megacycle. (We will abbreviate this unit as watts/cm.^{2} cir. deg. Mc. bd.). In this and in other quantitative data published it has been assumed that the ionosphere does not attenuate cosmic radiation at frequencies higher than 20 Mc. Actually, sporadic attenuation is observed up to 60 Mc., and only above 100 Mc. can the attenuation be safely ignored. Reber later published[8] a more comprehensive investigation with automatic recording equipment. It was found that the cosmic static arrived from a very narrow plane in space which is closely associated with the Milky Way. While the maximum energy is in Sagittarius, there are other minor sources along the galactic equator not yet completely resolved.

In 1942, Franz published[9] results of experiments at 30 Mc. His antenna was fixed in altitude and azimuth and had an acceptance cone about 13° wide in azimuth and 40° in altitude. The Earth's rotation swept the antenna across Sagittarius. The apparent width of the cosmic static disturbance was about 24°, and allowance for the instrumental resolving power gives a width of the source in Sagittarius near 11°. Three reviews of the investigations of cosmic static [10, 11, 12, 13] have appeared in the European literature.

In 1943 Reber secured data with improved electronic equipment at 160 Mc. From measures of drift-curves at various declinations he constructed constant-intensity lines[14] giving the observed strength of cosmic static over the Milky Way. Several maxima of intensity were found in the galactic plane. Relative energies are accurate to within a few per cent since all data are obtained with the same apparatus. The absolute intensity is subject to considerable uncertainty, and errors of a factor of two are not excluded; it is improbable that errors as large as a factor of ten exist. The maximum intensity in Sagittarius is measured as $11{\cdot}2 \times 10^{-22}$ watts/cm.^{2} cir. deg. Mc. band. It is interesting to note that the Rift in the Milky Way, conspicuous at optical frequencies, is not detectable at radio frequencies. The concentration to the galactic plane, in Sagittarius, is such that the intensity received drops by a factor of ten within 15°, without correction for instrumental resolution. Work has recently been started with the same antenna but with apparatus operating on 480 Mc. Preliminary results indicate that the intensity at 480 Mc. is of the same order as that at 160 Mc.; a provisional calibration gives the intensity from the Sagittarius region as 6×10^{-22} watts/cm.^{2} cir. deg. Mc. band.

During 1945, Hey, Phillips and Parsons[15] modified English radar apparatus to measure cosmic static at 64 Mc. A diagram showing constant intensity lines is given in their brief report. It reveals a maximum disturbance in Sagittarius and a minor one in Cygnus. After correction for the instrumental resolving power the peak value of the energy received is $3{\cdot}2 \times 10^{-22}$ watts/cm.^{2} cir. deg. Mc. bd. The observed concentration of the energy to the Milky Way seems rather low; the antenna was movable only in azimuth and had an acceptance cone 30° wide and 12° high. The acceptance pattern of the radar antenna was calibrated by a signal generator flown in front of the apparatus. The absolute value of the energy received at 64 Mc. agrees well with that found by Reber at 160 Mc.; it is particularly valuable as representing an independent type of calibration.

We should point out that radio observations of the Milky Way at high frequencies are difficult for two reasons. For an antenna of fixed size, the acceptance cone becomes smaller as the frequency increases, so that the signal arriving at the receiver is weakened. Furthermore, galactic space becomes more transparent as the frequency increases, so that the thermal emission by electrons in space falls below that of a black body at the electron temperature of space. At optical frequencies, the radiation from the Milky Way is far smaller than that of a black-body at 10,000° (the approximate electron temperature in space); stellar radiation is very highly diluted. The 9·5 to 64 Mc. radio-frequency observations, however, indicate radiation even greater than that of a black body at 10,000°. Obviously, at some intermediate frequency, space is transparent and the microwave radiation becomes relatively weak. Reber, at 160 Mc., finds cosmic static of intensity 11×10^{-22} watts/cm.^{2} cir. deg. Mc. bd. G. C. Southworth, of the Bell Telephone Laboratory, informs us that George

Mueller of that laboratory failed to detect cosmic static at 9400 Mc. An estimate of the sensitivity of Mueller's apparatus reveals that he would have detected radiation only if the intensity had been greater than 5×10^{-20} watts/cm.^{2} cir. deg. Mc. bd. at 9400 Mc. If the radiation in space is that of a black body, which varies as the square of the frequency, the negative observation by Mueller proves that the optical thickness of the Galaxy is small at 9400 Mc.

If the radiation is assumed to be of thermal origin, the most serious observational problem is the quantitative measurement of intensities in the 10 to 30 Mc. range. Observations of Jansky, Friis and Feldman, and Franz should be repeated with particular attention to the absolute calibration, and to the correction for the low instrumental resolution encountered at long wave-lengths. Reber estimates that Jansky's 20·6 Mc. observations require an intensity of 14×10^{-22} watts/cm.^{2} cir. deg. Mc. bd. Very approximate calibrations of the work of Friis and Feldman and of Franz seem also to indicate the same order of intensity. In an as yet unpublished discussion, C. H. Townes of the Bell Telephone Laboratory has independently estimated the absolute intensities found by these workers and also concludes that they require an unexpectedly high temperature. In fact, over a range of frequency 9·5 to 480 Mc., the available observations indicate an intensity constant within less than a factor of ten.

A recent observation by Hey, Parsons and Phillips[16] seems of great theoretical importance. They found a small region 2° in diameter in Cygnus, in which the intensity received at 64 Mc. was a rapidly fluctuating function of time. A cycle of variation occurred within less than one minute and had an amplitude of 15 per cent in the received power. Since the emitting region was small compared to the acceptance cone, the intrinsic variations in the region must be very large. If cosmic static had its origin over a long path in space, such fluctuations would appear improbable. If the emission observed found its origin in a relatively small diffuse nebula, erratic changes in the ionizing radiation of an illuminating star might produce rapid increases of ionization. However, at the low electron densities of a nebula, the collision or recombination time is long and fluctuations of emitted intensity seem improbable. For the same reason, quick erratic refraction or absorption of cosmic static passing through an electron cloud seems improbable. The region observed was near R.A. 20^h, Dec. $+ 43°$; this lies near the bright star cloud in Cygnus which is rich in B stars, but in a region of dark nebulosity. The North America nebula and the small nebulae near γ Cyg are not far distant. The electrostatic and magnetic phenomena in space are unexplored as yet. In the Milky Way, regions of ionized hydrogen gas surrounding hot B stars may be in motion through neutral gas; an unpublished theoretical treatment by Spitzer established the existence of large temperature differences in different regions of space. Large-scale electromagnetic interaction of moving and circulating charged particles must be included as a possible source of radiation.

Several preliminary theoretical interpretations of the observations on cosmic static have been made. Whipple and Greenstein showed[17] that even under exceptional conditions the intensity of thermal emission from small dust particles radiating as black-bodies was insufficient to account for Jansky's observations. The black-body equilibrium temperature rises from 3°K to 30°K in the galactic centre where the energy density is highest. Selectively absorbing and radiating substances may reach higher temperatures[18], perhaps attaining 500°K in the galactic centre. It can be shown that the absorption of radio waves by small dust particles is negligible in general. Henyey and Keenan[19] considered the radiation arising from free-free transitions of electrons in the ionized interstellar hydrogen gas. Without specifying the physical mechanism of interchange of thermal motion and radiative energy, a simple theoretical picture of the type of energy distribution can be obtained. The electron temperature of the gas, where ionized, corresponds roughly to the colour temperature of the integrated star light in the ultraviolet region; electron temperatures of 5000° to 15,000° may be expected and are confirmed by the nature of the emission spectra observed in the interstellar gas. The intensity received from an extended interstellar medium would be equal to $B_\nu(T_e)$, the black-body emission at the electron temperature, T_e, if the medium were opaque. At frequencies such that the medium has a small optical thickness $\tau_\nu < 1$, the radiation would be $\tau_\nu B_\nu (T_e)$. According to Henyey and Keenan, free-free transitions are of importance at frequencies below 60 Mc., where $\tau_\nu > 1$. Thus at $\nu > 60$ Mc., the emission from space will be $B_\nu (T_e)$. When $\tau_\nu < 1$ the emission falls increasingly below $B_\nu (T_e)$, but actually remains roughly constant up to quite high frequencies. Van de Hulst's computations[13] of the variation of the opacity with frequency agree with those of Henyey and Keenan.

It is possible that line absorption and emission phenomena would be involved in cosmic static. At higher frequencies, where the line absorption coefficient exceeds the free-free opacity, the emission will approximate $l_\nu B_\nu (T_e)$, or even $B_\nu (T_e)$ if l_ν is large. In the hydrogen spectrum there exist such fine-structure permitted transitions as $4^2P^\circ - 4^2D$ (near 5 metres) and high-level transitions of the type $n^2(L) - (n - 1)\,{}^2(L - 1)$ (which correspond to n about 340). It can be shown that these have small intensity. Van de Hulst[13] has suggested the hyperfine-structure transition of the ground state of hydrogen, located near 1410 Mc. Since nearly all neutral hydrogen is in the ground state, the hyperfine-structure transition may be the strongest of the discrete transitions. Unless the upper hyperfine state has a life-time exceeding 10^8 years, this magnetic-dipole transition might yield an appreciable emission within the relatively small Doppler-broadening band width (about 0·1 Mc.).

Another investigation of the energy distribution to be expected from free-free transitions in space has been made by C. H. Townes[20]. He has attempted a classical calculation of the absorption by free-free transitions. Essentially his results agree with those of Henyey and Keenan. At frequencies below 60 Mc., $B_\nu (T_e)$ is proportional to $\nu^2 T_e$. The apparent temperature of space, T_a, required to explain an intensity larger than that given by B_ν (10,000°) varies as ν^{-2}. All theoretical investigators point out that the large energies observed by Jansky and Friis and Feldman are difficult to explain unless the electron temperature in space is of the order of 100,000°.

The large temporary enhancements of solar radiation discussed below lead to the suggestion that the cosmic static is the integrated effect of such outbursts in stars in the Milky Way. Since increases up to a factor of 10^5 times greater than solar black-body radiation have been observed, it might be thought that the time-average of radiation from highly disturbed stars might become appreciable. Greenstein, Henyey and Keenan[21] point out the enormous dilution of stellar radiation; since stars like the Sun cover only about 10^{-14} of the celestial sphere, the radiation received at the Earth from all stars is only about 10^{-14} of the mean radiation emitted. A mean enhancement of stellar radiation by a factor of 10^{14} would be required before the observed cosmic intensity would equal that of a black-body at 6000°. It is, however, suggestive that the excess cosmic radiation occurs at low frequencies, and that the solar enhancements (probably of electromagnetic origin) also seem most conspicuous at low frequencies. Since rapid stellar rotation and instability are characteristic of the infrequent but more luminous early-type stars, possible enhancements of electromagnetic origin may become important in such objects.

Solar Radiation

In spite of its great visual luminosity the Sun proved to be a difficult object to observe with radio techniques. In 1944 Reber observed[14] solar radiation at 160 Mc. in an amount about 300 times larger than was expected from a black body at 6000°K. The wide acceptance cone prevented an accurate determination of the apparent diameter of the solar emitting disk. (In problems of solar radiation a possible origin of emission in the corona must not be excluded.) In 1945 Southworth reported[22, 23] a comprehensive set of measures of the Sun at about 3,000, 10,000 and 25,000 Mc. He considers that within observational error the observed intensity corresponds to that of a black body at 6000°. At his highest frequency, evidence exists for sporadic refraction in the Earth's atmosphere, probably connected with the water-vapour absorption bands at 1·25 cm.

Dicke and Beringer[24] observed solar thermal radiation with a radiometer at 24,000 Mc. The technique of calibration of the radiometer is more direct than that of the radio devices hitherto discussed, permitting accurate measures of absolute intensity to be made by the substitution of an artificial black body of known temperature before the first detector. The most important result of the work of Dicke and Beringer is that the solar radiation corresponds to that expected from a black body at 10,000° ± 1000°. Further, by observation of a partial solar eclipse they established that the solar disk showed approximately its optical diameter and that the observed intensity varied without time lag in proportion to the optical intensity. At these high radio frequencies, therefore, the Sun is an approximately uniformly illuminated disk; the energy detected travelled with the speed of light.

At lower frequencies there have been a series of observations indicating variable strong enhancements of solar radiation. Appleton was the first to remark on this phenomenon[25] and Hey and Stratton[26] found that at 60 Mc. the solar intensity reached about 10^5 times the expected black-body value during the interval Feb. 26-28, 1942. Stratton pointed out the presence of a large sunspot group near the centre of the solar disk. At 200 Mc. variable enhancements of solar radiation were detected[27] by Pawsey, Payne-Scott and McCready. They find an excellent correlation of the visible sunspot area and the radiation received. The maximum enhancement reached 2×10^3 on October 4-5. Because of insufficient sensitivity no radiation was found at 600 Mc. on those dates, but if an enhancement by a factor of 7 had existed, it would have been detected. At 1200 Mc. the radiation had the expected black-body value. A brief report on "Project Diana" mentions[28] that the solar intensity at 111 Mc. varied with time. At the time of the radio fade-out on August 17, 1945, a hissing disturbance of great intensity was observed at various stations in the southern hemisphere at frequencies in the range 10 to 16 Mc. According to J. M. Watts[29] the signal was of unusual character and resembled fluctuation noise. Because of the disturbed condition and high absorption of the ionosphere under fade-out conditions, the solar origin of this type of noise remains to be established, possibly by highly directional antennae. This phenomenon seems to have been first observed by the Japanese[30] during radio fade-outs. More recently, in February 1946, it has been found[31] at 44·9 Mc. Unpublished measurements by Reber in August to October 1946, at 480 Mc., show that the solar radiation is about two hundred times the expected value from a black body at 6000°K. Small variations with an amplitude of about 20 per cent have been observed to be well correlated with sunspot activity.

The enormous temporary solar enhancements are obviously not due to thermal emission, since they correspond to temperatures higher than the central temperature of the Sun. Within the radio-frequency band they have been found between 10 and 200 Mc.; the lack of evidence for such disturbances in the earlier work of Reber, Southworth and Dicke and Beringer may arise from the low level of sunspot activity. The spectral distribution of the enhanced radiation, while not accurately known, seems to be rather narrow. If regions of the frequency spectrum exist where the enhancements are negligible, radio measurements provide data on the variation of the continuous absorption coefficient, κ_ν, in the solar atmosphere. For example, the accurate work of Dicke and Beringer[24] indicates an emission near that expected at 10,000°. Since the apparent temperature of the emission varies as $(\bar{\kappa}/\kappa_\nu)^{1/4}$, their observations require $\bar{\kappa}/\kappa_\nu$ near 10. If so high a value should prove theoretically impossible, there may be some enhancement of solar radiation even at high frequencies. The theoretical evaluation of the expected continuous absorption coefficient may be difficult, because of the small energies involved in the transitions.

The observation of the enhancements in solar radiation are subject to a difficulty of instrumental character, if fixed radar antennae pointed at low altitudes are used. There exist sporadic diffracting centres in the ionosphere and with the large "air-mass" involved there may be sporadic variations in the received signal, especially if the emitting course is small. These would be analogous to the twinkling of the stars, and would be less significant if radiation is observed from an extended source such as the Milky Way. A similar difficulty occurs in the observations of polarization of the enhanced solar radiation; such short-period variations may possibly also affect the Milky Way observations if the emitting source is small.

Circular polarization of the enhanced solar radiation was detected by Martyn[32] at 200 Mc. He found a reversal of the direction of polarization after the spot crossed the meridian. Appleton and Hey[33] found circular polarization at 85 Mc. Ryle and Vonberg observed[34] at 175 Mc.; they used an ingenious antenna array which effectively provided high angular resolution. They show that the enhanced solar radiation originates in an area smaller than the solar disk and probably in an active sunspot region. Reversal of the direction of circular polarization also was observed. It would be interesting to determine whether the polarization becomes linear when an active sunspot region approaches the limb of the Sun. A preliminary theoretical interpretation of the enhanced solar radiation is offered by Kiepenheuer[35], who suggests that electrons rotate about the nearly radial lines of magnetic force associated with the sunspots. Kiepenheuer assumes that the thermal velocities of the electrons correspond to about 1,000,000°K, i.e. to the temperature of the corona. His brief account of the theory also predicts that the enhancement is independent of frequency. No re-absorption or diffraction and polarization phenomena in the upper corona are considered.

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Addendum

The rapid growth of the subject requires further brief review of observations and theory to date (1947 Jan 10.). I am indebted to H. van de Hulst for discussion of some of the new theoretical problems.

The increase in solar activity makes it probable that solar outbursts of radio noise will also increase. Short-period variability of the enhanced solar radiation at 75 Mc. was observed by Williams and Hand[36]; changes by a factor of 100 in received intensity occurred within a few seconds. Some correlation with flares and prominences was suggested. Lovell and Banwell[37] also found rapid fluctuation at 72·6 Mc.; changes by a factor of 1000 occurred within a few seconds. The maximum energy received attained 10^8 times the black-body value on 1946 July 25, $16^h\ 24^m$ U.T.; an intense solar flare began at $16^h\ 00^m$ and reached its peak at $16^h\ 27^m$. Enhancements by a factor of 10^5 were observed for several days subsequently. The rapidity of the observed changes should help to limit the possible physical mechanisms invoked to explain the solar radio emission. Mass motions of gas are relatively slow; relaxation times for atomic and electromagnetic phenomena in the corona may be relatively long. If solar outbursts occur within the corona, time lags of several seconds might exist between radio phenomena originating at the solar limb, and those produced by a secondary mechanism at the coronal limb. If the coronal absorption depends on frequency, time lags may occur between radio outbursts as observed at different frequencies. Unpublished work at the Radio Physics Laboratory at Sydney, Australia, was reported on by E. G. Bowen in a talk at the RCA Laboratory at Princeton, N.J., on Dec. 9. He stated that the time of arrival at the Earth of bursts of solar energy is a function of frequency. Bowen also reported that the direction of circular polarization behaves rather erratically with time during solar outbursts and is not directly correlated with meridian passage of a sunspot group.

Reber's early work, before the start of the present increased solar activity, showed little solar variability at 160 and 480 Mc. He observed[38] a major disturbance at 480 Mc. on 1946 Nov. 20, with an increase of 10^5 over the black-body value; thermal-agitation noise was audible on the receiver. At the same time Southworth found no unusual enhancement at 24,000 Mc. Pawsey[39] has tried to eliminate the variable solar noise from the emission by a "quiet" sun. At 200 Mc. he observed solar radiation over a period of 140 days; for half this time, when the outbursts were small, the mean solar radiation showed an enhancement of 400 over that expected for a black body at 6000°. On no occasion was the intensity less than 50 times the black-body value. He analyses the frequency distribution of the observed intensities into two components and ascribes one to a quiet coronal source at a temperature near $10^{6\circ}$ and the other to the highly variable enhanced radiation. Appleton and Hey[40] report on continuous recording of solar activity at 64 Mc.; the noise level of their receiver permitted detection of solar radiation when it exceeded 100 times the black-body value. They show a correlation of radio intensity with flares and radio fade-outs; they find that the greatest solar noise did not occur when the large sunspots were centrally located on the disk. On three occasions they measured the spectral energy distribution of the solar noise at six frequencies between 200 Mc. and 25 Mc. The energy rises far above the black-body value as the frequency decreases and shows a maximum enhancement near 64 Mc.; an apparent decrease of energy below 64 Mc. may be due to absorption in the Earth's ionosphere. The energy received at 64 Mc., per unit band-width, reaches 10^{-4} of that at the solar energy maximum. In his Princeton lecture Bowen reported an investigation of the energy distribution in the "quiet" Sun; the apparent temperature is about 18,000° at 30,000 Mc. and rises to $2 \times 10^{6\circ}$ at 60 Mc. In the presence of active sunspots apparent temperatures reach 10^3 times the latter figure.

The escape of radio waves from sunspots or from the chromosphere presents an interesting theoretical problem. Gyromagnetic radiation by electrons in the magnetic field of a sunspot has been suggested by Kiepenheuer[35] as the origin of the enhanced solar radiation; changes of sign of the accompanying circular polarization may be accounted for by the complex absorption and emission processes in the ionized medium, under magnetic forces. Appleton's theory of the Earth's ionosphere has been applied by Saha[41] and Martyn[42] to the Sun. The ionosphere reflects radio waves with a frequency, ν, less than a critical frequency, ν_c; in the absence of magnetic fields the maximum density of ions, N_i, determines the critical frequency:—

$$\nu_c^2 = 8 \times 10^7 N_i.$$

In a magnetic field the bi-refringence of the ionized medium causes the radiation to be propagated in the form of an ordinary and an extraordinary wave, and produces polarization. Saha[41] showed that very strong magnetic fields in sunspots might permit transmission of the extraordinary waves originating in the spot from gyromagnetic radiation. If the field is less than 1000 gauss, radiation of frequency less than 30,000 Mc. cannot escape from the reversing layer. Even the electron density at the base of the corona[43], about $4 \times 10^8/\text{cm.}^3$, prevents radiation escaping at frequencies below 200 Mc. Solar conditions are quite unlike those in the ionosphere, and caution must be exercised in detailed computation of critical frequencies.

Martyn[42] computed the energy distribution of the coronal emission at radio frequencies on the assumption that the emission occurs under conditions of local thermodynamic equilibrium at a temperature of 10⁶°. The opacity of the corona is ascribed to electron collisions; the theoretical basis of the computation has not yet been published. The opacity, τ_ν, is small at high frequencies, so that only photospheric emission is observed; at about 30 Mc. the opacity becomes large, and the quiet coronal emission approaches that of a black body at 10⁶°. At still lower frequencies Martyn suggests that the reflection by the overlying ionized gas (as in the Earth's ionosphere) again reduces the coronal emission; it is not clear theoretically why such a decline should occur.

I would like to suggest that a theory of the actual physical processes of absorption and re-emission within the corona must combine the macroscopic properties (refractive index and absorptivity) used in the Appleton theory with the atomic properties of the electrons and ions. In view of the great abundance of hydrogen in the Sun, we must assume that the electrons in the corona almost certainly come from the completely ionized hydrogen[44, 45]. It is difficult to see how the enormous negative charge of the electrons could be balanced, otherwise. Helium may contribute some electrons, but protons will far exceed in number the ionized metals that produce the coronal lines. Let us compute, then, the absorption coefficient of an ionized hydrogen gas at 10⁶°. Electron scattering is negligible, but absorption by free-free transition of an electron in the field of a proton is large. Since $h\nu << kT$ the problem is essentially a classical one; however we must include the Gaunt factor (about 10) as evaluated by Menzel and Pekeris[46] and van de Hulst[13]. Since $N_i = N_e$, the opacity of the corona measured above a height r_0 from the solar surface is given by an integration:—

$$\tau_\nu(r_0) = c_\nu \int_{r_0}^{\infty} N_e^2 \, dr,$$

where c_ν is the absorption by an electron-proton pair. The electron densities are given by Baumbach[43] and permit a preliminary integration. The opacity for $r_0 = 0$ is the absorption above the solar photosphere; I find that at 10 Mc., $\tau_\nu(0) = 1500$, at 100 Mc., $\tau_\nu(0) = 14$ and at 1000 Mc., $\tau_\nu(0) = 0{\cdot}12$. Even at a height r_0 equal to one solar radius above the photosphere, the outer corona is still opaque at 10 Mc. The absorption coefficient varies as $\nu^{-2}T^{-3/2}$ approximately. If the kinetic temperature of the corona is 10⁶° the emission will be that of a black body at that temperature for all frequencies below 200 Mc., unless the coronal temperature varies with r_0. When $\tau_\nu(0)$ is small the apparent temperature will be $\tau_\nu(0) \times 10^6$ until the photospheric emission at 6000° dominates.

In view of the large opacity of the corona at low frequencies, it is not clear how gyromagnetic radiation from sunspots could penetrate the corona; absorption and re-emission processes in thermal equilibrium would limit the emission to that corresponding to 10⁶°. Non-equilibrium processes will of course have to be considered separately. It may be suggested that prominences carry ionized gases in sufficient density to heights in the corona such that there is little coronal opacity left above the prominence; strong magnetic fields at great heights are still required to produce the gyromagnetic radiation.

Saha[47] pointed out possible line emissions arising from the existence of nuclear spin and of varying strong magnetic fields. Besides the hyperfine emission of hydrogen there may be many lines of the metals throughout the radio-frequency spectrum. The rarity of the metals and the requirement of strong magnetic fields suggest that the hydrogen emission should be the first object of search.

Cosmic static has been investigated by Moxon[48] using the conventional antennae of wide acceptance pattern; in some cases measures were made from shipboard. The first extension of the cosmic static measures to the southern galactic hemisphere was made at 90 Mc. It would be especially desirable to have narrow acceptance-pattern surveys of the bright Carina region of the Milky Way. From data on a fixed region of the Milky Way obtained at 40, 90 and 200 Mc. in England, Moxon concludes that the apparent temperature, T_a, varies as $\nu^{-2\cdot7}$ approximately. Such a variation is consistent with the hypothesis that the emission is of thermal origin in space at a high temperature—perhaps of the order of $10^{5\circ}$. Since for free-free transitions the optical depth varies more rapidly than ν^{-2} when the opacity is small, T_a should also vary more rapidly than ν^{-2}; however when the opacity approaches unity T_a approaches T_e. In Moxon's data T_a is still increasing at 40 Mc., where it reaches 25,000°. Thus the high apparent temperature suggested by the early work of Jansky *et al* at low frequencies seems to be confirmed. If T_a should continue to rise at still lower frequencies, it may become necessary to ascribe the low-frequency component of cosmic static to some such non-thermal radiation as has been suggested for the solar noise. Rapidly rotating stars of early type have extended and turbulent atmospheres and may possess sunspot, prominence and magnetic phenomena on a grander scale than does the Sun (magnetic phenomena have been observed in one star at the Mount Wilson Observatory). The nearest such objects, however, are at a distance such that we receive from them visually only 10^{-11} the solar radiation. If such a star emits enhanced "solar noise" of perhaps 10^8 the black-body value, it may become observable. Such objects as α Vir, α Leo, the bright Orion stars, the Pleiades and the Orion nebula may be suggested.

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