Solar radiation at radio frequencies and its relation to sunspots

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Experimental studies of solar radiation on a frequency of 200 Mcy.c./sec. are described. This radiation has characteristics similar to those of thermal radiation but is always hundreds of times greater than the thermal radiation anticipated from the photosphere and sometimes greater by a factor of $10^4$.

The day-to-day intensity variations over a period of 6 months confirm a correlation with sunspots. The received intensity of radiation is subject to rapid fluctuations; sudden increases, or 'bursts', of duration from a fraction of a second to a minute are characteristic. These rapid fluctuations are similar at widely-spaced receiving points, and it is concluded that most of them are extraterrestrial, and presumably solar, in origin.

Directional observations, based on the interference phenomenon as the sun rises over the sea, indicate that the radiation originates not uniformly over the sun's disk but in restricted areas in the immediate vicinity of a sunspot group.

Values of received intensity are at times too great to be accounted for in terms of thermal radiation, so that another mechanism producing radiation must exist. Radiation from gross electrical discharges is suggested.

INTRODUCTION

The discovery of radio-frequency radiation, with the characteristics of fluctuation noise, arriving at the earth from the direction of the Milky Way, was announced by Jansky (1933). This discovery is potentially of fundamental importance to astrophysics, since it provides a source of information concerning extraterrestrial phenomena other than that obtained through the use of light. Up to the present, however, the interpretation of such observations has contributed little to astrophysics, and it appears that more complete observational data are necessary.

Jansky's original work on cosmic noise was confirmed and extended by himself and others to cover the frequency range 15 to 160 Mcy.c./sec., but, at first, no measurable radiation was observed from the sun. It was therefore suggested that the radiation originates not in the stars but in collision processes in the residual ionized matter in interstellar space.

The development of microwave radar suggested the possibility of detecting at these wave-lengths the black-body radiation from the sun to be expected on Planck's law, assuming the optical temperature of 6000° K. The intensity of this radiation per unit frequency range is proportional to the square of the frequency at radio frequencies. It is too small to be detected in the ordinary short-wave region but should be detectable at centimetre wave-lengths. In 1942 Southworth detected centimetre radiation from the sun (Southworth 1945) and showed that it was of the order to be expected from the Planck formula.

[ 357 ]
In the period between Southworth's discovery and its delayed publication, Reber (1944) observed solar radiation on 160 Mcyc./sec. Reber did not attempt to explain this radiation, but, had it been of thermal origin, it may be deduced from data given in his paper that a temperature about a hundred times the optical value would be required.

Solar radiation was also observed in 1942 by English radar stations in the frequency range 40 to 200 Mcyc./sec. (Hey 1946). The effect continued for several days and was noted to coincide with the presence of the exceptionally large sunspot of February of that year. Early in 1945 certain New Zealand Air Force radar stations working on 200 Mcyc./sec. observed similar radiation and showed that it varied from day to day (unpublished). Radiation on still longer wave-lengths was reported by Appleton (1945), who described reports on radio noise received in the short-wave communication band at times of marked solar activity during the sunspot maximum about 1936. The observed intensities were greatly in excess of 6000°K black-body radiation, and he concluded that the noise originated in active areas on the sun.

Observations on 200 Mcyc./sec. similar to those of the New Zealand stations were begun by us towards the end of 1945, and the initial results showed that the radiation was associated with sunspots and that it was subject to surprisingly rapid fluctuations (Pawsey, Payne-Scott & McCready 1946). The present paper describes an extension of this work. It includes more detailed observations, almost exclusively on 200 Mcyc./sec., of the variations in intensity of solar radiation, and the use of direction-finding methods to locate its place of origin on the sun.

Observations

Method of observation

In making measurements, a directional aerial is pointed in turn at a 'cold' part of the sky (i.e. a part relatively free from stars) and at the sun. The output of a receiver connected to the aerial is partly due to the noise generated in the receiver itself and partly to radiation received from outside. At the wave-lengths used the external noise is effectively constant over the 'cold' sky but increases appreciably when the aerial is pointed at the sun. The proportional increase in output is taken as a measure of the intensity of the solar radiation.

The intensity of the radiation is specified as the power falling on the earth in watts per square metre normal to the rays per megacycle band width. It is derived from the instrumental constants as in appendix 1. The polarization is assumed random, so that the values quoted are twice those measured on plane-polarized aerials. It is assumed that the intensity of the radiation is constant over the pass band of the receiver (a few megacycles).

The sensitive radar receivers used have output meters measuring second-detector current. Initially ordinary meters were used, but were later replaced by recording milliammeters. The records obtained from these meters read from right to left and have been reproduced without transposition. The time co-ordinates are curved as
Solar radiation at radio frequencies and its relation to sunspots

indicated in the figures. Two types of aerial have been used; large horizontally polarized radar aerials capable of rotation only about a vertical axis, and so able to 'see' the sun only near dawn or sunset, and smaller aerials capable of being tilted in any direction. The first type were situated some hundreds of feet above sea-level and had a clear view over the Pacific Ocean towards the rising sun at dawn but an outlook over irregular land to the west.

Table 1 gives the nominal characteristics of the equipments used on 200 Mcyc./sec., the frequency at which most observations were made. Measured values of intensity may have errors up to 40%.

**Table 1. Location and characteristics of 200 Mcyc./sec. equipment**

<table>
<thead>
<tr>
<th>station</th>
<th>location</th>
<th>aerial area effective (A)</th>
<th>tilttable</th>
<th>receiver noise factor (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collaroy</td>
<td>lat. 33° 43' 45&quot;, long. 10 h. 5 m. 10 s.; hill-top 1/4 mile inland 400 ft. above mean sea-level</td>
<td>18</td>
<td>no</td>
<td>7</td>
</tr>
<tr>
<td>Dover Heights: (1)</td>
<td>lat. 33° 52' 28&quot;, long. 10 h. 5 m. 8 s.; edge of cliff on coast 278 ft. above mean sea-level</td>
<td>9.5</td>
<td>no</td>
<td>11</td>
</tr>
<tr>
<td>(2)</td>
<td>do.</td>
<td></td>
<td>6.5</td>
<td>yes</td>
</tr>
<tr>
<td>Stromlo</td>
<td>lat. 35° 19' 30&quot;, long. 9 h. 56 m. 0 s.; inland</td>
<td>9</td>
<td>yes</td>
<td>13</td>
</tr>
<tr>
<td>North Head</td>
<td>Sydney</td>
<td></td>
<td>7.5</td>
<td>yes</td>
</tr>
</tbody>
</table>

*Note.* Collaroy is approximately 10 miles north of Dover Heights, and Stromlo approximately 160 miles south-west of Dover Heights.

**Characteristics of solar radiation**

During the 6 months since observations began solar radiation has been observed whenever an observation has been made. The radiation appears to have the characteristics of receiver fluctuation noise when observed on headphones or on a cathode-ray oscillograph except that the mean level fluctuates continually. Figures 1 a, b, c and d indicate the kinds of variation believed to be typical. Figure 1 a is a tracing of a record obtained when the intensity was very high and large rapid fluctuations were absent. Figure 1 b1 shows a similar slowly varying signal of much lower amplitude interrupted just before 1614 hr. by a huge burst of radiation lasting about 10 sec. This was the only burst which occurred in several hours of continuous recording if modest ones like that at 1613 hr. are excluded. Figure 1 b2, obtained simultaneously from a different site, is discussed below. Figure 1 c, an earlier part
of the same record, shows a series of intense bursts which are so frequent as to be almost continuous. This condition lasted from the beginning of observations at 1100 to 1400 hr. and then suddenly ceased, the only subsequent large burst on that day being the one shown in figure 1b. Figure 1d shows a graph of average levels over 5 hr. on a day when the variation of intensity was similar to figure 1a, and illustrates a slower type of variation.

Figure 1. Typical records of 200 Mcyc./sec. solar radiation. The upper records show variations over a few minutes, and the lower one over several hours.

Summarizing, there appear to be two distinct types of variation, a relatively slowly varying type with intensity ranging from about $0.5 \times 10^{-15}$ to $100 \times 10^{-15}$ W m. $^{-2}$ (Mycy./sec.)$^{-1}$, and a type consisting of intense bursts of duration between a fraction of a second and a minute, and of widely varying frequency of occurrence. Their intensity may be tens of times greater than the general level on comparatively quiet days. On days of high general level of intensity, bursts gave off-scale deflexions several times greater than the mean level.

These rapid variations are a very striking feature for a solar phenomenon, and it is desirable to check that they actually originate in the sun and not in some atmo-
Solar radiation at radio frequencies and its relation to sunspots

Spheric effect analogous, perhaps, to the twinkling of stars. No systematic difference in the variations as the sun rose from zero elevation towards the zenith had been detected and the somewhat subjective conclusion had been reached that the variations consisted of increases above a datum level. Both observations suggest a solar origin. Further confirmation was obtained by taking simultaneous records at different places and comparing the variations. Figure 2a shows, superposed, two records taken 10 miles apart on a north-south line. The two records were taken with different and arbitrary sensitivities and have two different interference patterns, discussed fully in a succeeding section, so that it is only possible to look for the correspondence of sharp dips and peaks. Nearly all agree to within a second, the limit of timing accuracy. Figure 2b shows simultaneous recordings at Mt Stromlo and Dover Heights, Stromlo being 160 miles south-west of Dover Heights. The variations are smaller, but again generally agree in timing and shape on the two records. Figures 1b1 and b2 show another recording at the latter two stations when an isolated burst was recorded simultaneously. It is highly improbable that variations having such a high degree of correlation at widely separated sites should be due to any effect in the atmosphere, and it seems certain that most of them are extraterrestrial, and presumably solar, in origin. The evidence does not exclude residual variations due to the atmosphere.

A few measurements have been carried out on other frequencies between 3000 and 75 Mcyc./sec. The intensity observed on 3000 and 1200 Mcyc./sec. was of the order of $5 \times 10^{-10}$ W m.$^{-2}$ (Mycy./sec.)$^{-1}$, which is consistent with Southworth’s results and is a little higher than the usual quiet-day 200 Mcyc./sec. intensity. An increase during the great sunspot of February was observed on 3000 Mcyc./sec., but was trivial compared with those on 200 and 75 Mcyc./sec. Observations on 75 Mcyc./sec. during disturbed periods have shown intensities considerably higher than the corresponding 200 Mcyc./sec. ones and with similar variations.

Day-to-day variations of intensity

Observations of mean intensity based on dawn observations at Collaroy began on 3 October 1945, and were carried through with few gaps to 15 February 1946. Most of the observations were carried out by Royal Australian Air Force personnel. It is now clear that, because of the violent changes in intensity which can occur, these observations, each of about a half-hour in duration, give an inadequate estimate of the daily value. Consequently in figure 3, 3-day running averages have been used in plotting the daily intensity over this period. Figure 3 also includes provisional Wolf sunspot numbers and integrated areas based on pencil sketches.* The great sunspot of February 1946 was associated with very high intensities, and both intensities and sunspot areas went off the scale of the graph. The data for this period are replotted on one-fifth scale on the right.

* The solar data throughout this paper were supplied by Dr C. W. Allen of the Commonwealth Observatory, Mt Stromlo, Canberra.
Figure 2. Simultaneous records of 200 Mcyc./sec. solar radiation from different places. (a) Dover Heights—Collaroy, separation 10 miles, sunrise interference patterns superimposed on solar variations. (b) Dover Heights—Stromlo, separation 160 miles, aerials pointed to sun near noon so interference pattern absent.
Solar radiation at radio frequencies and its relation to sunspots

These data confirm a connexion between sunspots and radiation intensity. In this series of observations the correlation with areas is somewhat closer than with sunspot number but neither is exact.

![Graph showing sunspot number, intensity of 200 Mcy/sec radiation from sun, and sunspot area over time.](http://rspa.royalsocietypublishing.org/downloaded from June 15, 2017)

**Figure 3.** Day-to-day intensity variations (200 Mcy/sec.), neglecting isolated bursts, together with provisional Wolf sunspot numbers and integrated areas (3-day running averages).

Figure 4 shows sketches of the sun on four typical days with corresponding values of intensity, sunspot area and sunspot number. The days chosen are:

(a) 5 October—two large groups of spots on meridian—intense 200 Mcy/sec. radiation.

(b) 11 November—a typical day of few sunspots and little radiation.

(c) 26 January—the first day on which it was demonstrated that the radiation was coming from only a small part of the sun.

(d) 7 February—the great sunspot near the meridian—extremely intense radiation from a limited area.

**Accurate location of the source of radiation using the interference pattern at dawn**

An attempt was next made to elucidate the connexion between sunspots and the radiation by means of accurate directional measurements. Because an aerial of about a mile in aperture would be required to produce a beam narrow compared with the half-degree angular diameter of the sun, the direct-scanning method is not feasible. An alternative is a method involving the use of a steerable minimum. In practice, such a method may be realized rather simply by recording the intensity variations as the sun rises over the sea. Interference occurs between the direct and reflected rays, leading to a series of maxima and minima familiar in radar as ‘lobes’, or in optics as ‘Lloyd’s mirror’ interference fringes. Since the angular separation of the lobes on our equipment is about equal to the sun’s diameter, clearly defined maxima and minima will not be expected unless the radiating source is considerably smaller than the sun itself.

In initial observations early in October no interference pattern was observed; figure 4a shows that at this time there was a wide distribution of spots over the sun’s
Figure 4. Sketches of sunspots on typical days, with values of 200 Mc/sec. radiation and sunspot number and area.
Solar radiation at radio frequencies and its relation to sunspots

surface. Towards the end of January a compact sunspot group dominated the sun (figure 4c), and for this reason an attempt was made to detect a lobe pattern on the morning of 26 January. A regular series of maxima and minima was observed, with the expected period and with very deep minima which were less than the limit of detection (3% of the maxima).

An ideal opportunity to extend these observations came a few days later with the appearance of the great sunspot of February 1946. Figure 5a shows the record obtained at dawn at Dover Heights on 7 February. The record is unmistakably an interference pattern with deep minima, complicated by the short-period variations already discussed. The section between 0553 and 0602 hr. shows the beginning of a remarkable series of bursts, an isolated one at 0554 hr., followed by an almost continuous sequence lasting beyond the end of the record. These bursts show interference maxima substantially in phase with the steadier radiation. (This is further evidence that these bursts are not due to terrestrial interference.) The received amplitude decreased towards the end of the record as the sun rose out of the beam of the aerial. Figure 5b shows the pattern obtained from Collaroy on the succeeding day. The period of the oscillation is shorter corresponding to the greater height of the Collaroy aerial, 400 compared with 278 ft. above mean sea-level. Figure 5c shows the record obtained on a day on which the minima were shallow, corresponding to a distributed source of radiation.

Let us examine the significance of the shape of the interference pattern, assuming tentatively a plane earth of reflexion coefficient $-1$. At a point of height $h$, the phase difference $\Delta$ between direct and reflected rays from a distant point source at a small angle of elevation $\theta$ is $4\pi h\theta/\lambda$, where $\lambda$ is the wave-length. Consequently $\Delta$ is a linear measure of angle of elevation. The received power, $p$, is related to that due to either ray, $p_0$, by

$$p = p_0(2\sin \frac{\Delta}{2})^2 = 2p_0(1 - \cos \Delta).$$

(1)

Suppose the source is a uniform strip, parallel to the horizon, of width $2W$ and located with angles of elevation as indicated in figure 6a. Let $\alpha_1, \beta_1, W_1$ represent respective phase differences so that

$$\alpha_1 = \frac{4\pi h}{\lambda} \alpha, \text{ etc.}$$

(2)

Then, if the power contribution per unit angle of elevation is constant over the strip and zero outside, the total received power $P$ is given by

$$P = \frac{P_0}{2W_1} \int_{\alpha_1 + \beta_1 - W_1}^{\alpha_1 + \beta_1 + W_1} 2(1 - \cos \Delta) d\Delta,$$

where $P_0$ is the total power in the absence of a reflected ray. This reduces to

$$P = 2P_0 - 2P_0 \sin \frac{W_1}{W_1} \cos \alpha_1 \beta_1.$$

(3)
Figure 5. Interference patterns at dawn, aerial looking out to sea. (a) Great sunspot of February 1946. Intense radiation with deep minima, indicating small source. Series of large bursts about 6 a.m. (aerial height 278 ft.). (b) Following day at another station; aerial height 400 ft., period of interference pattern correspondingly shorter. (c) Record obtained on normal day. Shallow minima indicate extended source (aerial height 278 ft.). See figure 7 for appearance of sun on these days.
Solar radiation at radio frequencies and its relation to sunspots

As the sun rises, $\alpha_1$ alone varies and $P$ fluctuates sinusoidally about twice the free-space value $P_0$ as shown in figure 6b. The record will show maxima and minima at the times for which $(\alpha_1 + \beta_1)$ is equal to an odd or even multiple of $\pi$, and a ratio, $R$, of minimum to maximum power given by

$$R = \frac{1 - (\sin W_1/W_1)}{1 + (\sin W_1/W_1)}.$$  \hspace{1cm} (4)

For small values of $W_1$ this becomes $\frac{1}{2} W_1^2$ and the actual width, $2W$, of the equivalent radiating strip is given by

$$2W = \frac{\lambda}{\pi h} \sqrt{(3R)}.$$  \hspace{1cm} (5)

Figure 6. (a) Angles of elevation of strip source and sun. (b) Predicted interference pattern from strip source abscissae measured in units of phase difference, upper scale relating to centre of strip, lower to centre of sun.

If the power distribution is not rectangular but arbitrary given by $f(\beta_1)$, where $\beta_1$ measures the difference in elevation relative to the centre of the sun in terms of phase difference as before, then, substituting $\Delta - \alpha_1$ for $\beta_1$, the total power $P$ is given by

$$P = 2 \int f(\Delta - \alpha_1) (1 - \cos \Delta) \, d\Delta$$

$$= 2 \int f(\Delta - \alpha_1) \, d\Delta - 2 \int f(\Delta - \alpha_1) \cos \Delta \, d\Delta,$$  \hspace{1cm} (6)

where the integration is taken over the significant range of $\Delta$. The first term is twice the free-space power as in (3). The second term is in the form of a Fourier cosine transform. A little consideration indicates that, as $\alpha_1$ varies, this term varies sinusoidally with an amplitude given by the modulus of the component of the Fourier transform of $f(\beta_1)$ at unit angular frequency.

Since an indefinite number of distributions have identical Fourier components at one frequency, measurement of the phase and amplitude of the variation of intensity at one place at dawn cannot in general be used to determine the distribution
over the sun without further information. It is possible in principle to determine
the actual form of the distribution in a complex case by Fourier synthesis using
information derived from a large number of components. In the interference method
suggested here $\Delta$ is a function of $h$ and $\lambda$, and different Fourier components may be
obtained by varying $h$ or $\lambda$. Variation of $\lambda$ is inadvisable, as over the necessary wide
range the distribution of radiation may be a function of wave-length. Variation of
$h$ would be feasible but clumsy. A different interference method may be more
practicable.

We now return to the special case in which the minima are very deep, i.e. the power
is concentrated in a small range of angles, so that we feel justified in quoting the
position and width of an equivalent rectangular strip. These quantities have been
calculated as indicated in figure $6b$. The width is derived from the ratio $R$, using
equation (5), while the position relative to the centre of the sun (i.e. $\beta$) is calculated
from the times of occurrence of minima, measured from the time when the
centre of the sun has zero elevation. The calculations are complicated by
certain factors discussed in appendix 2 and by the variable nature of the signal;
errors due to the latter are reduced by taking the average value over a large
number of lobes.

Such calculations have been made for some mornings on which deep minima
occurred and the results are shown in figure 7. In each case the estimated accuracy
of the position of the strip is a few minutes of arc. The widths given are upper limits
and may be too wide by a few minutes (see appendix 2). The upper row shows sketches
of the sun for each morning from 6 to 9 February with the equivalent radiating strips
calculated from the observations at Collaroy. The next two sketches show corre-
sponding results from Dover Heights on two of these days, and are in satisfactory
agreement. In each case the radiating strip has a width considerably less than that
of the sun’s disk, being of the order of the size of the sunspot group, and passes
through the group. It moves across the sun with the spots as the sun rotates.
Although this method gives no information about the distribution parallel to the
horizon, there seems no reasonable doubt that the source was localized in a small
region in the vicinity of the spots. The observations do not provide any information
as to the detailed structure of the source within this region. The great series of
bursts about 0600 hr. on 7 February (figure 5a) have their maxima at the same
times as the steady radiation and hence originate in the same vicinity.

The bottom row of figure 7 shows a similar series of sketches for 29 to 31 March.
There was at this time a predominant sunspot group, but it did not completely
overshadow the other spots as in the February series. The equivalent position of the
source is in the vicinity of this group but moved towards the ‘centre of gravity’ of
the spots. The width is much greater than previously, corresponding to the dispersal
of spots. This series is again consistent with the assumption that energy originates
in the vicinity of sunspots.
Figure 7. Sketches of sun with position and width of equivalent radiating strip. (Widths are upper limits only, position uncertain to a few minutes of arc.) 1st row: great sunspot, Collaroy observations. 2nd row: great sunspot, Dover Heights observations. 3rd row: sources of radiation scattered, though radiation mainly from one group, Dover Heights observations.
INTERPRETATION OF OBSERVATIONS

The previous sections have included accounts of observations and direct inferences from them. Before discussing more speculative deductions this material is summarized as follows. The statements refer to 200 Mcyc./sec. radiation unless stated otherwise:

1. Solar radio-frequency energy of intensity varying between observed limits of 0.5 \times 10^{-15} and more than 100 \times 10^{-15} \text{ W m}^{-2} \text{ (Mcyc./sec.)}^{-1} is incident on the earth.

2. The intensity varies grossly with time. Comparatively slow variations have superposed on them bursts of duration of the order of a second. These bursts may be isolated, or appear in slow or rapid succession. A large proportion of the rapid changes are extraterrestrial, and presumably solar, in origin.

3. On days of great solar activity high levels of intensity have been observed on 75, 200 and 3000 Mcyc./sec., the relative increases being large on 75 and 200 Mcyc./sec. but small on 3000 Mcyc./sec. Observations over 6 months on 200 Mcyc./sec. showed correlation with both sunspot numbers and areas, the correlation with areas being better.

4. The region from which energy is received varies, but at times of a single dominant sunspot or group this region is of the same order of size as, and is situated in the immediate vicinity of, the spot or group.

A consideration of intensity values yields evidence as to the mode of origin of the radiation. If it is thermal in origin, its intensity will not be greater than that given by the Planck formula for the appropriate temperature. At radio-frequencies the Planck formula reduces to the Rayleigh-Jeans form which, for constant frequency increments, is

\[ S = \frac{2kT}{\lambda^3} \Omega_s \times 10^6 \text{ W m}^{-2} \text{ (Mcyc./sec.)}^{-1}, \]  

where

- \( S \) = intensity on the earth (W m\(^{-2}\) (Mcyc./sec.)\(^{-1}\)),
- \( k \) = Boltzmann's constant (1.38 \times 10^{-23} \text{ joule/degree}),
- \( \lambda \) = wave-length (m.),
- \( T \) = temperature of source (degrees Kelvin),
- \( \Omega_s \) = solid angle subtended by source (steradians).

If the whole disk of the sun radiates uniformly the intensities observed by Southworth (1945) on 3000 and 10,000 Mcyc./sec. correspond to temperatures of about 20,000° K,\(^*\) which is three times the optical temperature. On the other hand, the present 200 Mcyc./sec. results would require temperatures of from 0.5 to 100 millions of degrees for the general level with still higher values for bursts. In addition, it has been shown that the radiation does not originate uniformly over the surface but in small regions, so that even higher temperatures are required. For example, on 7 February the intensity was 100 \times 10^{-15} \text{ W m}^{-2} \text{ (Mcyc./sec.)}^{-1} and the area of

\(^*\) The original paper gave a temperature of about 6000° K, owing to an error subsequently corrected.
Solar radiation at radio frequencies and its relation to sunspots

origin apparently less than \((6.5'/32')^2\) or \(\frac{1}{25}\) of the sun’s disk (see figure 7). This would mean a black-body temperature of about 3000 million degrees, which is impossibly high compared with any known temperatures on the sun. The known temperatures range from 6000° at the visible surface to about a million degrees in the corona and a few tens of millions at the centre. Consequently, though thermal radiation will be present, it is overshadowed at 200 Mcyc./sec. by radiation due to some other mechanism, probably gross electrical disturbances as suggested in our previous communication (Pawsey et al. 1946). The occurrence of short-duration bursts favours this hypothesis. It must be borne in mind that the detailed mechanism in the partially conducting ionized atmosphere of the sun will be different from the sudden breakdown occurring in lightning flashes. An analogous terrestrial phenomenon on a much smaller scale is the generation of noise in radio valves containing gas. The appearance of bursts superposed on a more slowly varying background suggests that there may be two separate mechanisms, though it is possible that the background may consist of a large number of overlapping bursts.

The connexion between this radiation and sunspots is established by two independent lines of evidence, the correlation of intensity with sunspot area and the coincidence of direction of origin with that of sunspot groups. No evidence is yet available as to a particular visible solar phenomenon, associated with sunspots, which gives rise to the radiation.

Departing now from solar phenomena, two other aspects of this work are of interest. In the direction-finding procedures leading to the identification of the area of origin of the radiation, variable refraction effects due to the earth’s atmosphere entered in as a complication reducing the inherent accuracy. The early lobes often show marked displacements and departures from sinusoidal form, e.g. the first lobe in figure 5a, which appear to be due to abnormal refractive effects. It seems possible to exploit the technique to investigate refraction and perhaps deduce the refractive-index structure of the atmosphere.

Cosmic noise was originally attributed to radiation from interstellar matter, rather than from stars, at a time when similar radiation from the sun had not been detected. The discovery of solar noise raises the question as to whether the cosmic noise is due to similar processes in stars. The basic difficulty remains that the intensity of cosmic noise is vastly greater than it should be if the stars emitted the same ratio of radio-frequency energy to light as does the sun. Nevertheless, the great variability of solar noise suggests the possibility of vastly greater output from stars differing from the sun and it seems that data at present available leave the question completely open.

Appendix 1

Derivation of intensity in terms of instrumental constants

The equipment is adequately described in terms of the ‘effective area’ \(A\) of the aerial and the receiver ‘noise factor’ \(N\) which is specified at an arbitrary ambient temperature \(T_a\). Let the relative increase in power output from the receiver when
the aerial is turned from clear sky to the sun be \( R \), i.e. if \( P_{\text{sky}} \) and \( P_{\text{sun}} \) are respective power outputs, let \( R = (P_{\text{sun}} - P_{\text{sky}})/P_{\text{sky}} \). Then the intensity \( S_1 \) of the component polarized so as to be accepted by the aerial is shown below to be given approximately by

\[
S_1 \approx R \frac{N}{A} kT_a
\]

(8)

where \( k \) is Boltzmann’s constant. Plane-polarized aerials have been used and the total intensity \( S \) taken as twice \( S_1 \).

At the frequencies used, the limit to the smallest signal that can be detected is set by the noise power originating in the receiver itself. The power received from the sun is of the same order as this noise power, so that it is conveniently measured in terms of this power. Since, for small signals which do not overload the receiver, the amplification is constant, ratios are preserved if all signals are referred to the input terminal. The merit of a receiver can be measured by the magnitude of receiver noise power \( P_N \) relative to a standard signal. The standard signal chosen is the fluctuation noise power \( P_R \) available from a resistor of given temperature \( T_a \). This equals \( kT_a \Delta f \), where \( \Delta f \) is the band width accepted, independently of the value of the resistance. The noise factor \( N \) is defined by

\[
N = \frac{P_R + P_N}{P_R}
\]

(9)

The effective area \( A \) of an aerial is defined by \( A = P/I \), where \( P \) is the available power at the output terminals of the aerial due to an energy flux \( I \), of appropriate polarization, incident on the aerial. It is related to the isotropic power gain \( g \) by the equation \( A = \lambda^2 g/4\pi \). For uni-directional broadside arrays, large with respect to the wave-length, \( A \) can be made to approach, but not exceed, the actual area of the array.

If an aerial is pointed to the clear sky, a power \( P_C \) is received due to cosmic noise, and this increases to \( P_C + P_S \) when turned to the sun (\( P_C \) being assumed constant) where

\[
P_S = (S_1 \Delta f) A.
\]

(10)

Consequently

\[
R = \frac{P_S}{P_N + P_C}
\]

or

\[
P_S = R(P_N + P_R) \left( \frac{P_N + P_C}{P_N + P_R} \right) \approx R(P_N + P_R),
\]

(11)

since, on the wave-lengths and equipments used, it has been found that \( P_N \) swamps differences between \( P_C \) and \( P_R \) to within a few per cent. Combining (11) with (9) and (10) and writing \( P_R = kT_a \Delta f \) leads to (8) and to the numerical equation for total intensity

\[
S = 8.2 \times 10^{-15} RN/A \text{ W m.}^{-2} \text{(Meyc./sec.)}^{-1},
\]

(12)

where \( A \) is in square metres and \( T_a \) is taken as 300° K.
Solar radiation at radio frequencies and its relation to sunspots

If a square-law detector is used, the current indicates relative power level directly. Otherwise current values must be interpreted as relative power levels from the known detector law before deducing $R$.

APPENDIX 2

Factors complicating the analysis of the interference pattern

The analysis given in the body of this paper neglected sundry factors. Some of these are calculable while others introduce uncertainties. The factors are stated below, together with notes on the treatment adopted in deriving the results given in figure 7.

(1) Earth curvature

For a spherical earth of radius $a$, the phase difference $\Delta$, at height $h$ above the earth, between direct and reflected rays from a very distant point source, is approximately given by

$$\Delta \approx \frac{4\pi x}{\lambda} \left( \frac{h}{x} - \frac{x}{2a} \right)^2,$$

where $x$ is the distance of the point of observation from the point of reflexion. The angle of elevation of the direct ray at the point of observation is given by

$$\theta \approx \frac{h}{x} \left( \frac{3x}{x - 2a} \right).$$

Predicted values of $\theta$ for interference minima were obtained by plotting corresponding values of $\Delta$ and $\theta$ calculated for arbitrary values of $x$ and then reading off values of $\theta$ corresponding to integral values of $\Delta/2\pi$.

The error incurred in using the above approximate formulae becomes appreciable for large values of $\theta$ but is less than 1 min. of arc in $\theta$ up to $7^\circ$ and 3 min. at $10^\circ$.

(2) Inaccurate height data

Corrections for tides were made from Admiralty Tide Tables. No allowance was made for a possible change in effective sea-level due to waves. The estimated uncertainty in $h$ for each station is 1%, giving rise to an uncertainty in $\beta$ (figure 6a) of about 3 min. of arc for $\alpha = 3^\circ$ (sixth lobe at Dover Heights) and 6 min. for $\alpha = 10^\circ$ (twentieth lobe). The width of the equivalent strip is unaffected by height errors.

(3) Refraction

Refraction introduces the major uncertainty in the analysis. It differs from optical refraction owing to the greater refractive index of water vapour at radio frequencies so that known astronomical corrections cannot be used.

An unpublished formula due to T. Pearcey of this laboratory has been used. It is based on a linear variation of refractive index with height and, using the notation of figure 8, is

$$R = \frac{\tau_0}{H[a - \tau_0]}
\sqrt{\left\{2\left(\frac{H}{a} - \tau_0\right) + \theta^2\right\} - \theta},$$
where the refractive index $\mu$ at any height $z$ is given by

$$\mu = 1 + \tau_0 (1 - z/H) \quad \text{for} \quad z < H$$

and

$$\mu = 1 \quad \text{for} \quad z > H.$$

The formula is not in doubt at large values of $\theta$ since it then depends only on $\tau_0$, which is known from ground-level measurements of pressure, temperature and humidity. The validity of the formula for low angles was tested as follows. Taking $H$ as 5 miles (in conformity with the lapse rate of refractive index near the ground) and the value of $\tau_0$ as that at 0600 hr. on the appropriate day (obtained from Sydney Weather Bureau data), the angles of elevation of the lobe minima were calculated from this formula in conjunction with equations (13) and (14). From the times of minima in the experimental record for the day the corresponding elevations of the centre of the sun were computed. For any one day there should be a constant difference between the two sets of angles of elevation, equal to the displacement of the radiating source from the centre of the sun. The actual differences show a certain scatter. Their mean value, neglecting the first few lobes, was taken as giving the true displacement. The deviations from this mean were then plotted as deviations from the theoretical curve for the average value of $\tau_0$ on the days involved (see figure 8).

![Diagram](http://rspa.royalsocietypublishing.org/)
Solar radiation at radio frequencies and its relation to sunspots

The agreement between the curve and the mean distribution of observations down to $\theta = 2^\circ$ is evidence for the validity of the formula in this region. Below $2^\circ$ it is apparent that the amount of refraction varies considerably and that corrections greater than those given by the formula are normally required. This region has not been used in deriving the position of the equivalent radiating strip.

For comparison, figure 8 also shows the correction for refraction used in astronomy (Norton & Inglis 1943).

(4) Imperfect reflection from the sea due to waves

The effect on the reflexion coefficient is believed small, and no allowance has been made for departure from unity. A reduction in the magnitude of the reflexion coefficient to 0.9 would increase the apparent effective width of the radiating strip by less than 2 min. of arc.

(5) Receiver band width

The finite range of frequencies accepted by the receiver leads to a corresponding range of phase differences between the direct and reflected rays. This is equivalent to an increase in angular width of the source, producing a reduction in the ratio of maximum to minimum which increases with elevation of the sun. The apparent increase in width has been allowed for by subtracting $\theta(Af/f)$ from the estimated values of $2W$. The ratio of band width to mid-frequency, $Af/f$, is about 1% for receivers used.

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References

Hey, J. S. 1946 Nature, 157, 47.