THE DISTRIBUTION OF RADIO BRIGHTNESS OVER THE SOLAR DISK AT A WAVELENGTH OF 21 CENTIMETRES

IV. THE SLOWLY VARYING COMPONENT

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Summary

A large number of highly emitting regions on the Sun have been studied individually by means of a 32-element interferometer which produces fringes 3 min of arc wide at a wavelength of 21 cm. These regions are responsible for the slowly varying component of the solar radiation at decimetre wavelengths.

The radio sources appear always to be associated with plages faculaires and, during the years 1952–53, were found to lie about 22,000 km above them. The observations showed that the sources, when resolved, appeared to have the same size as the associated plages.

The angular distribution of flux from radio sources was found to follow approximately a cosine law, which suggests that a source has the form of a thin sheet, lying parallel to the surface of the Sun.

The observations throw light on conclusions reached from the statistics of whole-Sun observations. A high correlation exists between radio flux and sunspot area in an active region in the period when both are near their peak. In the period of decay, however, the radio flux decreases more slowly than the sunspot area.

I. Introduction

One of the early discoveries in radio astronomy was that there is a relatively steady emission of radiation at decimetre wavelengths which is associated with sunspots. Two clues led to this discovery. During a partial eclipse of the Sun in 1946, Covington (1947) found that there was a sharp decrease in the radio flux received from the Sun when a large sunspot group was occulted. He also found (1948) that his daily measurements of the solar radiation at a wavelength of 10·8 cm showed a variation which was closely related to the total visible sunspot area on the solar disk. Lehany and Yabsley (1949) showed independently that this variation also existed at wavelengths of 25 and 50 cm.

From a statistical study of these observations, Denisse (1949) and Pawsey and Yabsley (1949) showed that, in the steady radiation from the Sun at decimetre wavelengths, there are two distinct components, one of which is constant over long periods and can be attributed to thermal radiation from the quiet Sun, while the other varies from day to day and shows a high correlation with the total area of visible sunspots. The second component is called the slowly varying component of the solar radio-frequency emission.

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The very close correlation between the slowly varying component and sunspot area is unexpected, since it is most unlikely that the source of radio emission can lie close to the photosphere. The first indication of another possibility was found by Christiansen, Yabsley, and Mills (1949) during the eclipse of November 1948. These observations showed that regions of high radio emission were present not only in the vicinity of sunspot groups but also near places previously occupied by sunspot groups.

The persistence of radio emission from sunspot regions has recently been confirmed in a statistical study of solar emission by Vauquois (1955*b*), and was used by Piddington and Davies (1953) in a new analysis of the relation between radio emission and sunspot area.

A search for persistent solar features associated with sunspot groups and sufficiently high above them to make the escape of radio waves likely, led Waldmeier and Müller (1950) to suggest that coronal condensations might be the source of the slowly varying component of the solar emission. The only coronal observation which has been related to decimetre wavelength emission was that of Laffineur *et al.* (1954) during a solar eclipse. They found that the radio brightness distribution over the solar disk at a wavelength of 54 cm appeared to be similar to a weighted function of the estimated brightness of the green coronal line over the disk.

While high resolution studies were limited to eclipse observations there was no possibility of deriving much information about individual regions of high emission on the Sun. The construction of aerial systems of high resolving power—the line array of Covington and Broten (1954) and the 32-element interferometer of Christiansen and Warburton (1953*a*, 1953*b*, 1955) provided the possibility of studying individual regions over a period of many days. The first new observation with these systems was that there appeared to be a close relation between radio emission and areas of plage faculaire on the solar disk. This was noted by Helen Dodson (1954) when comparing spectroheliograms in calcium K emission with the records (8 min of arc resolution) of Covington. A similar conclusion was reached independently by the present authors from a comparison of high-resolution observations at a wavelength of 21 cm and spectrohelioscopic observations in Hα.

The present paper is based on observations of a large number of individual regions of high radio emission with the 32-element interferometer to which reference was made earlier. During the period of the observations (1952–1953) it was the only instrument available which had sufficient resolving power (3 min of arc) to resolve any of the radio sources on the Sun. The observations substantiate in general what was deduced from total flux and eclipse observations, but go well beyond that. They provide the basis for estimating the position in the solar atmosphere of the regions responsible for the slowly varying component. They also give the approximate shape, dimensions, and directivity of emission of the bright regions. A study of the life histories of these sources of radio emission has been possible and the statistical and physical relationships with other solar phenomena are discussed.

II. Observations

The 32-element interferometer (Christiansen and Warburton 1953*a*), which was used for the observations described here, produces a series of fan-shaped beams, each 3 min of arc wide and separated by about 1°·7 from neighbouring beams. The rotation of the Earth causes these beams to pass across the solar disk, one at a time, so that the Sun is repeatedly strip-scanned. The interfero-

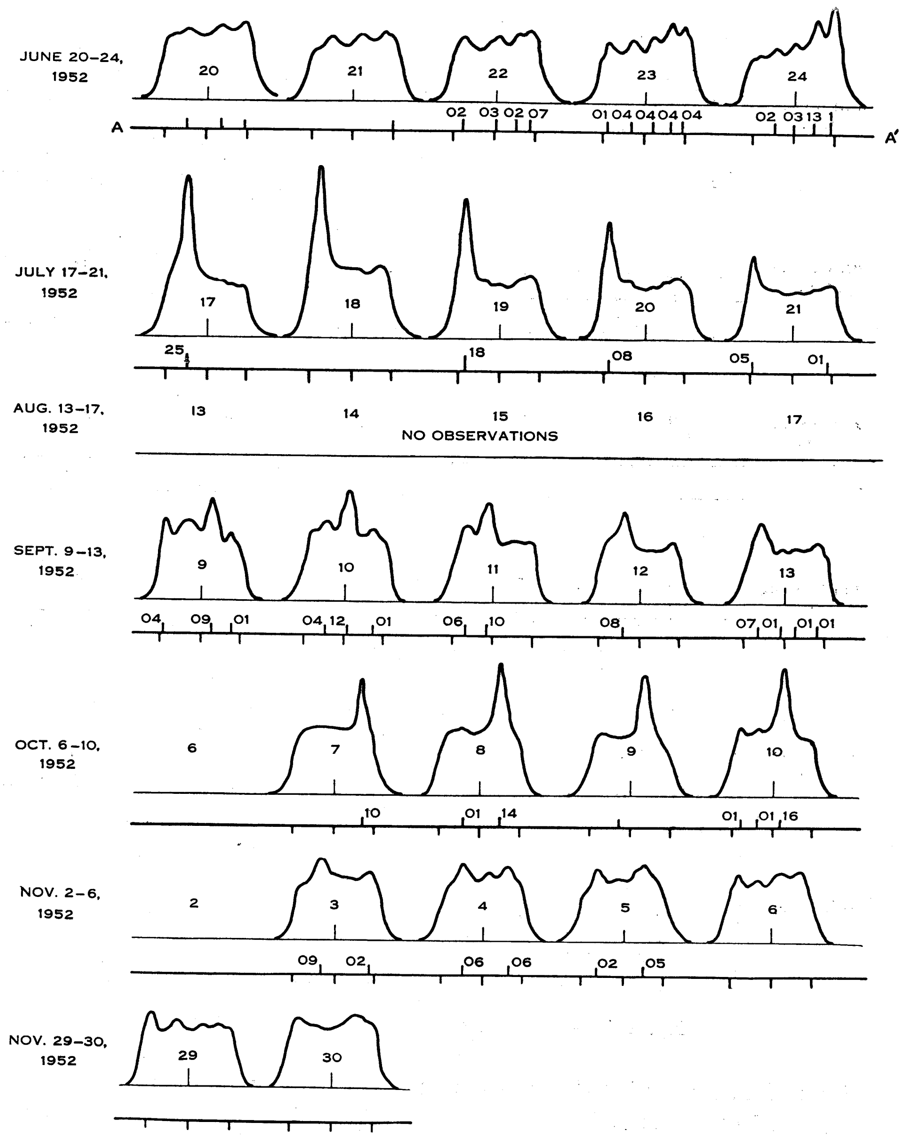

Fig. 1 (*a*).—Daily records obtained with the 32-element interferometer during 1952. The positions of centre and limbs of the solar disk are indicated below the line AA'. The directions of scan are given in Table 1. In some cases the estimated position and radio flux from a bright region (in terms of quiet-Sun flux) is also shown above the line AA'.

meter is connected to a radio-frequency amplifier and recording milliammeter, and the records obtained give the one-dimensional distribution of radio flux across the solar disk.

The records show a number of narrow peaks superimposed on a broad source. These can be seen in Figures 1 and 2. The peaks, which change both in

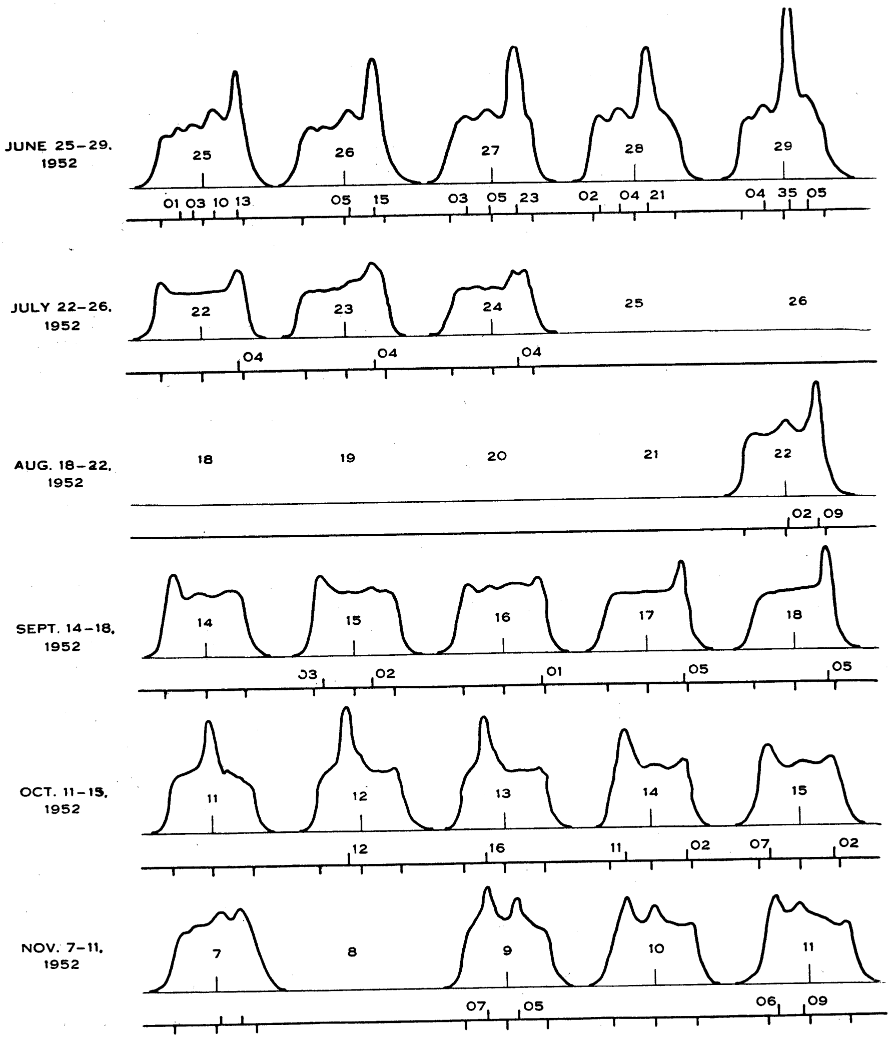

Fig. 1 (*b*).—Daily records during 1952 (*Continued*).

position and in size as the Sun rotates on its axis, show the presence on the solar disk of localized areas of intense radio emission. These areas are the source of the slowly varying component of the solar radio emission. The broad source, which represents the thermal emission from the quiet Sun, can be delineated by finding the lower envelope of a large number of daily records, as was shown in Part II of this series of papers (Christiansen and Warburton 1953*b*). If this quiet-Sun contribution is subtracted from the curves of Figures 1 and 2 we are left with the contribution from the localized areas of intense emission. The width of a region can be estimated from the width of the corresponding peak on the record, provided it is greater than the beamwidth of the aerial, while the area between the curve and the quiet-Sun baseline, for each peak, gives a measure of the radio flux being emitted by that region. A determination of the position

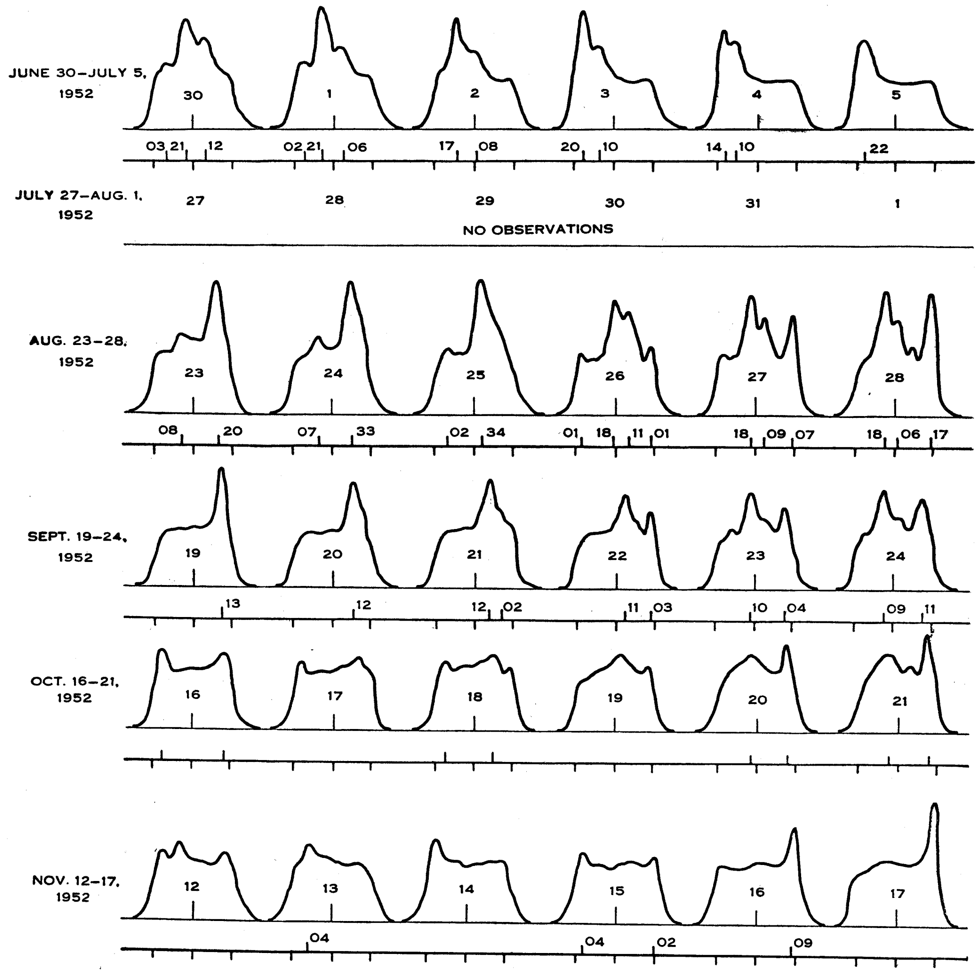

Fig. 1 (*c*).—Daily records during 1952 (*Continued*).

on the solar disk of one of these regions requires the time at which the peak appears on the record to be known accurately. Since the position of the aerial beams is known from the geometry of the system, the position of a source must lie in one of the aerial beams at the time at which a peak appears on the record. To locate the source on the solar disk, one may use astronomical tables to find the position, size, and orientation of the solar disk at the time when the peak appeared. The source is then located along a strip across the solar disk.

A simplified procedure could often be used. This was possible because on many of the records the position of the quiet Sun could be recognized accurately. Hence the position of the peak with respect to the centre of the quiet Sun could be measured directly and all that was then required was the compilation and use

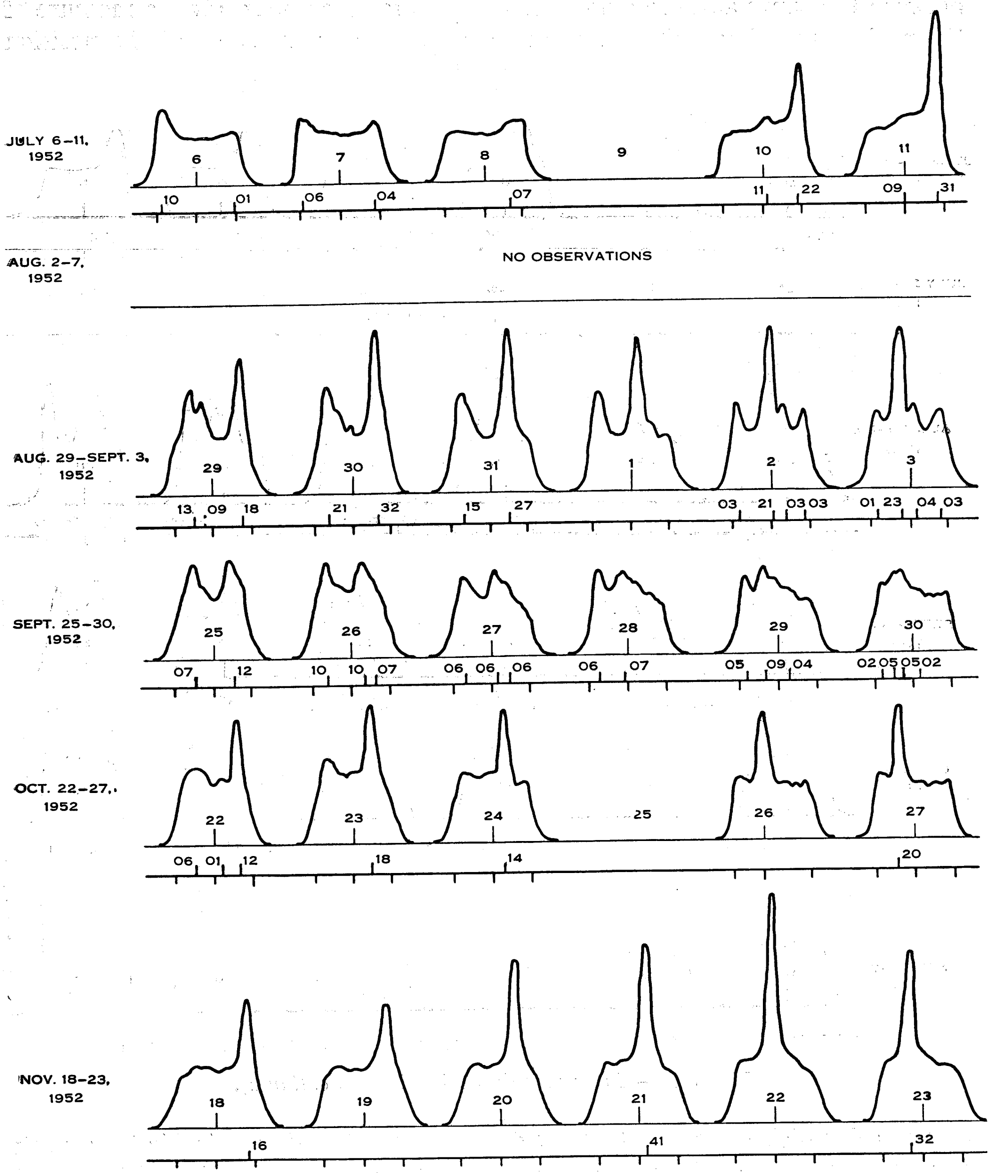

Fig. 1 (*d*).—Daily records during 1952 (*Continued*).

of a table which gives the scanning angle of the aerial beam with respect to the Sun's axis of rotation for any day—see Table 1. A comparison on a number of days of the position as determined by the two different methods showed no systematic difference.

The observations displayed in Figures 1 and 2 were all made with an interferometer which was aligned in an approximately east-west direction. Near midday therefore, when observations were made, the interference fringes or aerial beams lay roughly along the meridian. Because of this, the scanning

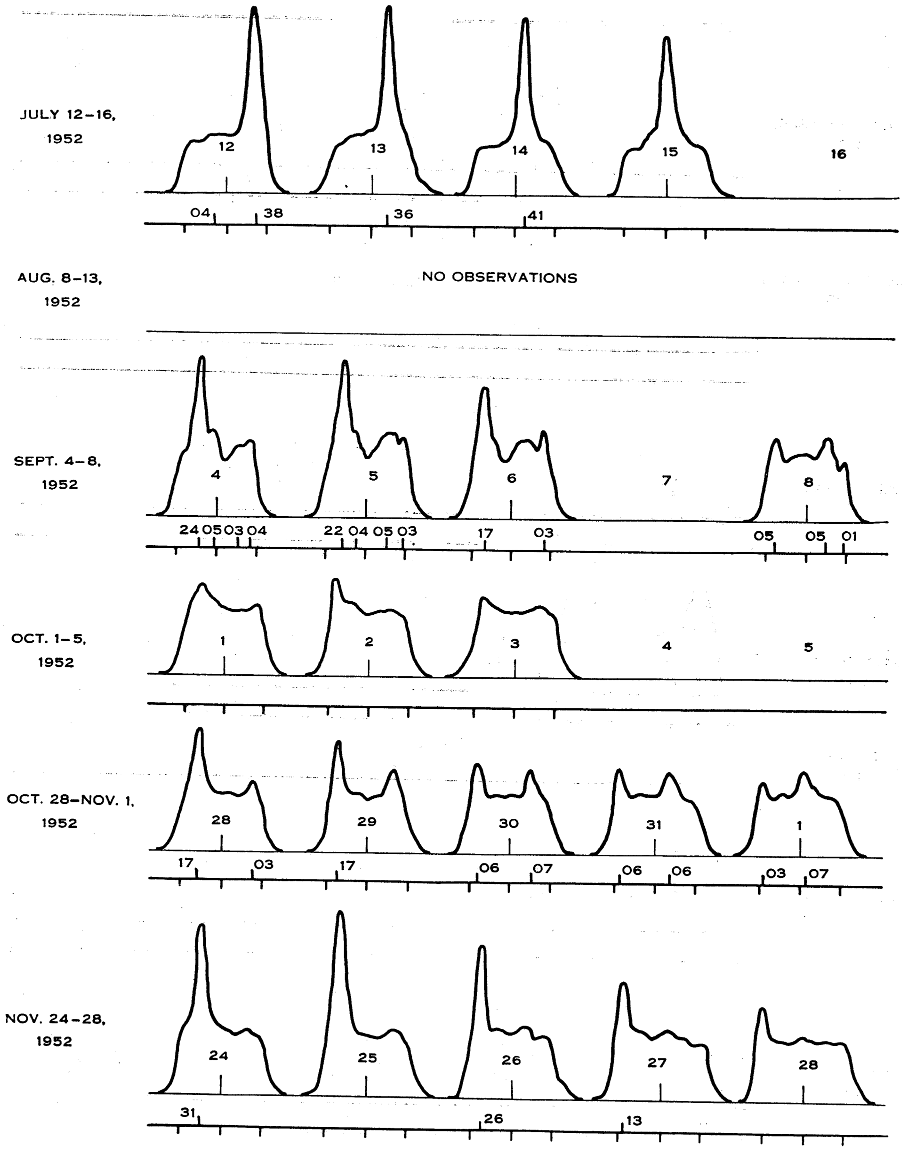

Fig. 1 (*e*).—Daily records during 1952 (*Continued*).

strip on the solar disk was, in general, nearly at right angles to the equatorial line on the solar disk, and the observations of the intensely emitting areas established, at least near the centre of the disk, the heliographic longitude of the areas.

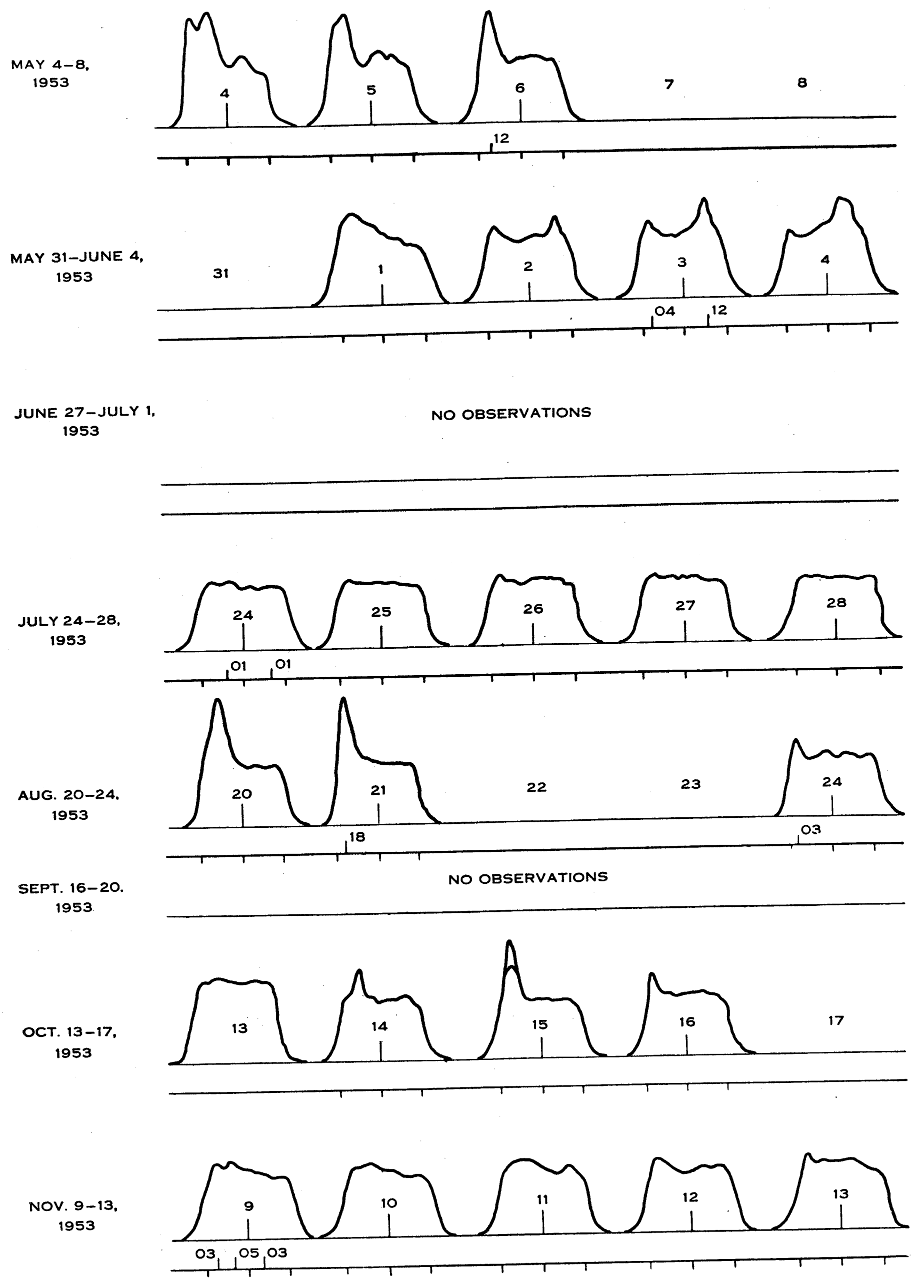

Fig. 2 (*a*).—Daily records during 1953.

As was expected for that part of the solar cycle during which observations were made, the optically active regions (centres of activity), which were not numerous, lay close to the equator of the Sun. It was noticed that the strip in which a radio source was located invariably fell close to one of these regions (see Fig. 3). It was natural to assume, therefore, that, since the heliographic longitude of a solar region which was optically active coincided, more or less, with that of an area of intense radio emission, the latitudes of the two should also coincide. In the present paper such an assumption will be made, but it is

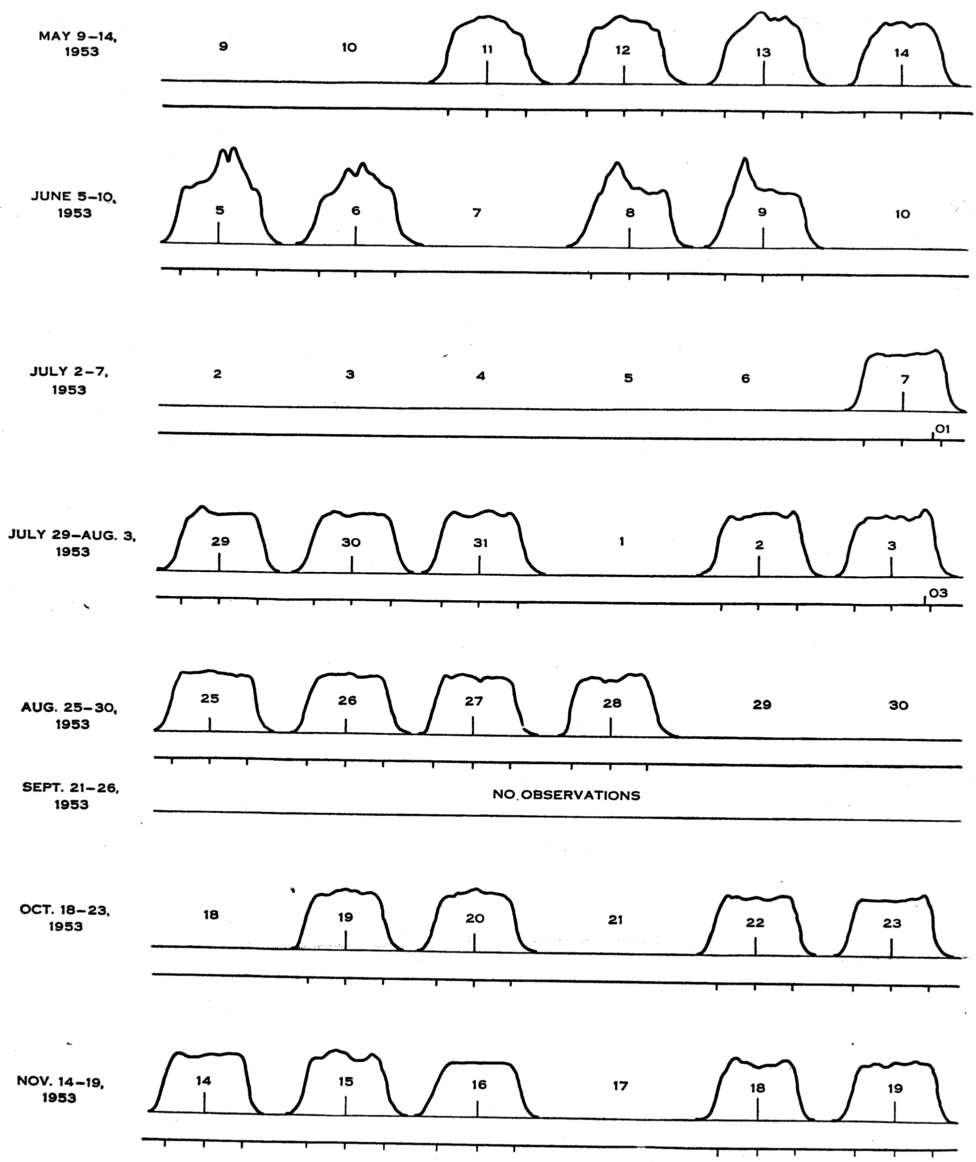

Fig. 2 (*b*).—Daily records during 1953 (*Continued*).

necessary to assume only that this is approximately true. A test of the assumption was possible towards the end of the observations when a second interferometer of 16 elements, aligned at right angles to the first, became available for use. A typical " fix " on an active region, when the two interferometers were used, is shown in Figure 4. It will be seen that the result is in good agreement with our assumption. The position on the solar disk of active regions—nearly along the equator—which made the observations with the east-west

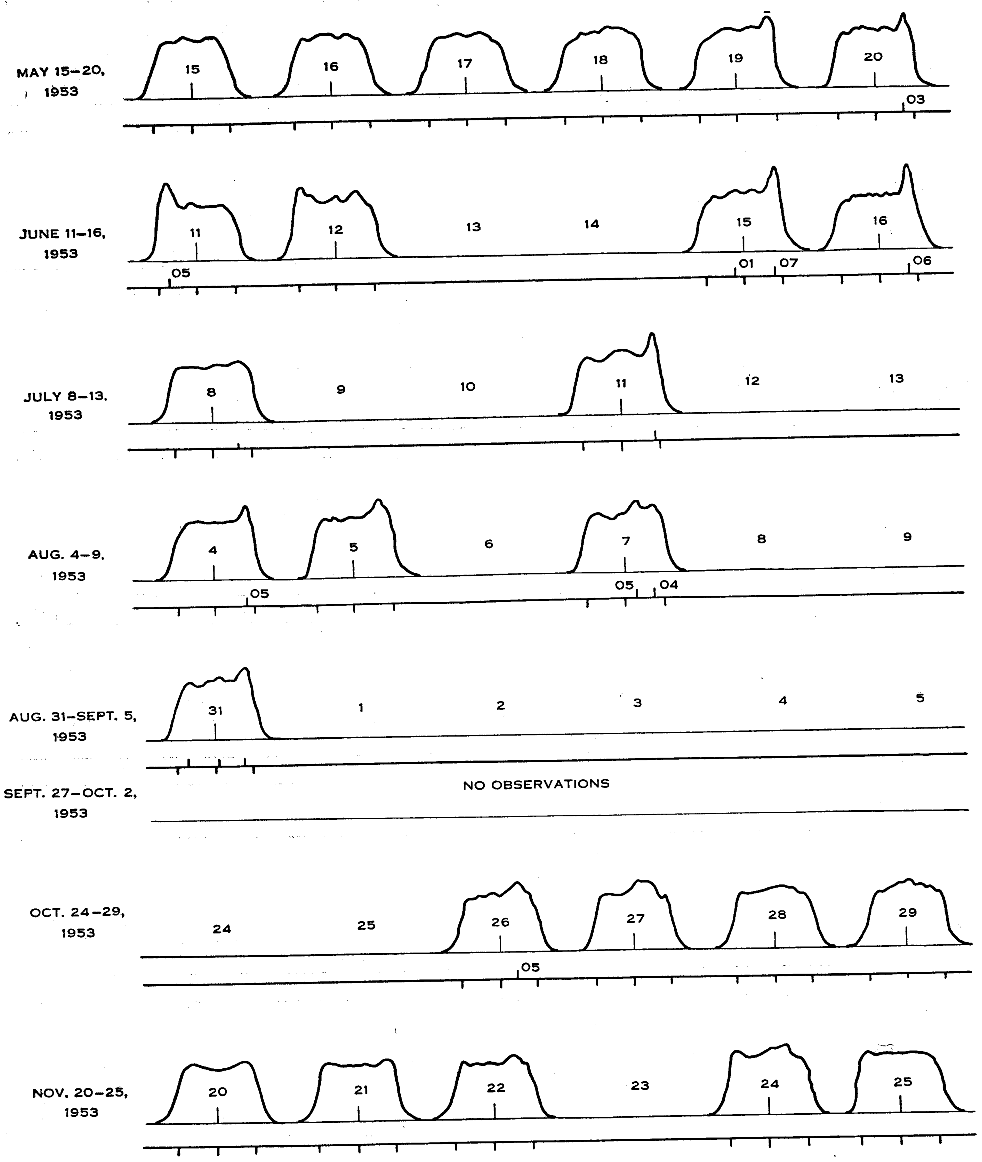

Fig. 2 (*c*).—Daily records during 1953 (*Continued*).

interferometer normally unambiguous, made those with the north-south interferometer usually completely ambiguous; all sources on the Sun tended to fall in the beam of the north-south interferometer at nearly the same time. Not much use of these observations will be made, therefore, in the present paper.

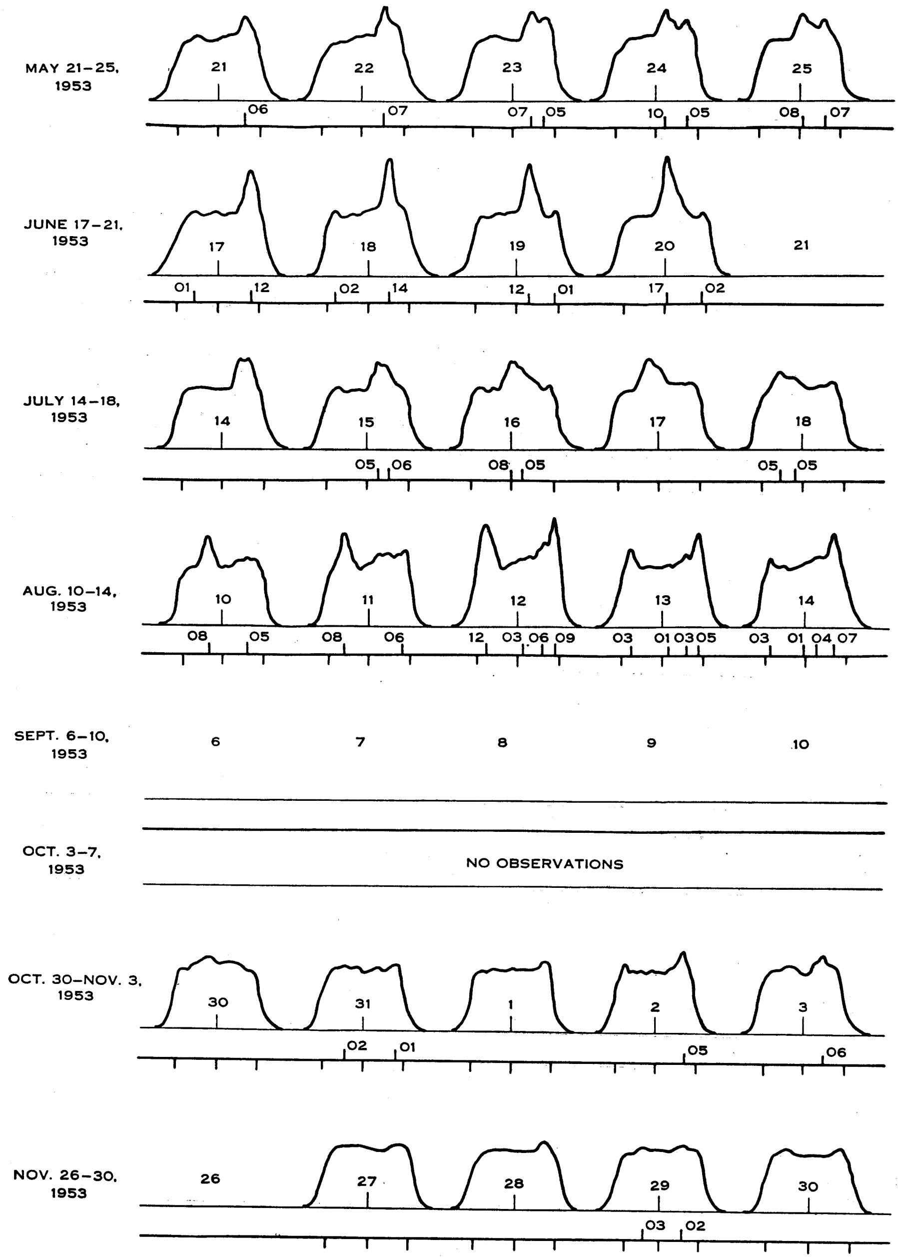

Fig. 2 (*d*).—Daily records during 1953 (*Continued*).

The visual observations of the Sun which were required for comparison with the radio observations were in most cases obtained from observatories at great distances from Sydney. It was thus necessary to allow for the solar rotation during the time that elapsed between radio and optical observations. Stonyhurst disks were found very useful for making any necessary changes.

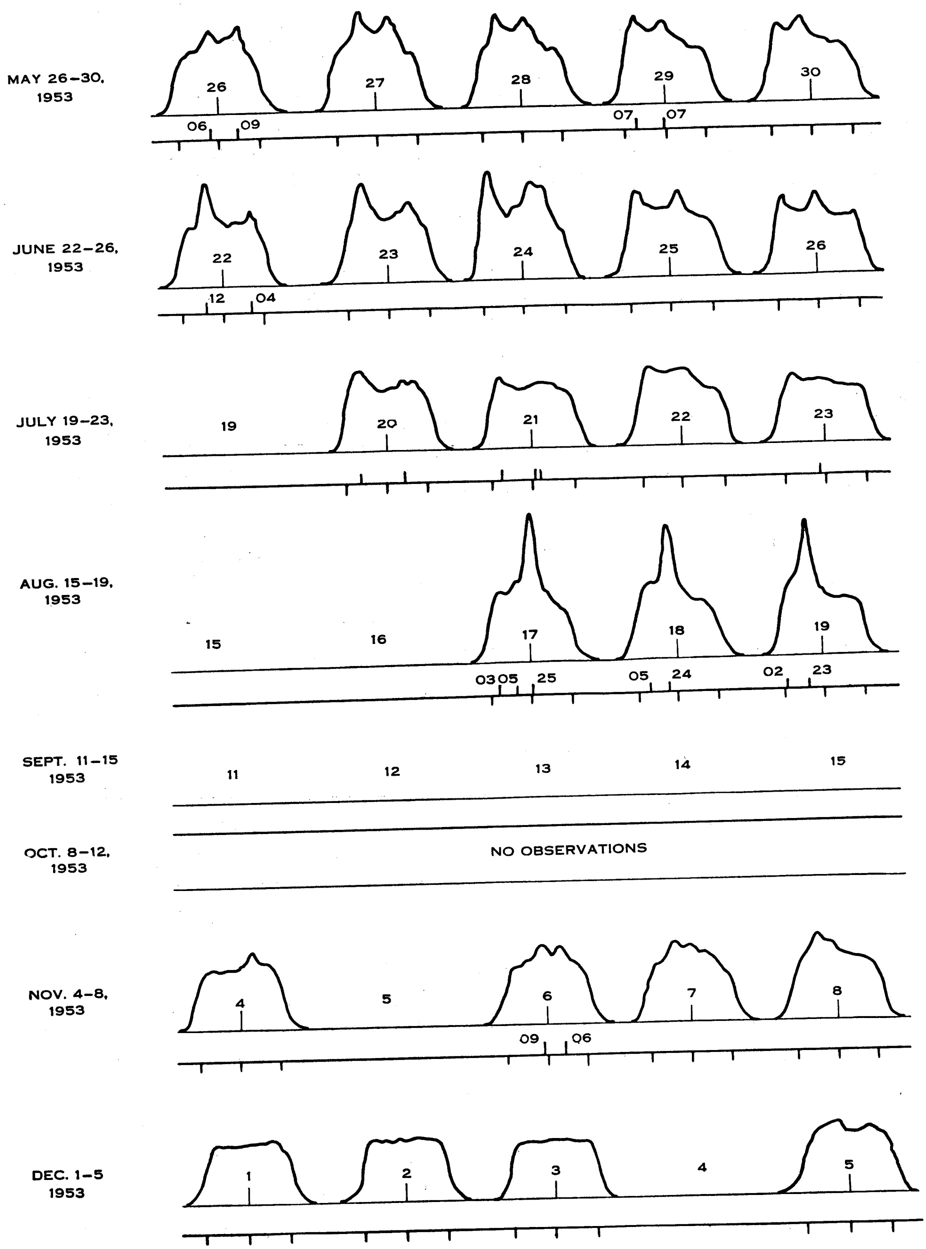

Fig. 2 (*e*).—Daily records during 1953 (*Continued*).

III. Results

The sample results shown in Figure 3 are typical for the whole period of observations. It was found that the position-line of a radio source invariably passed through, or very close to, the position of an active region on the Sun. Active regions are characterized by the appearance of photospheric and chromospheric facules (plage faculaire) in which sunspot groups grow and decay, by strong localized magnetic fields, and by enhanced emission in the corona. It is in these regions that short-term disturbances such as flares occur from time to time. There is a close correlation between the intensities of the various features of an active region, but there are marked differences in rate of decay. Sunspots appear to be the shortest lived feature (apart from temporary disturbances); chromospheric faculae and bright coronal regions have a longer life and the longest lived feature of all appears to be the associated prominences (filaments) which are visible after all the other features of an active region have disappeared.

It is of interest to discover which of the optical features of an active region are related most closely to the radio emission. This involves accurate position-finding of the source of radio emission, its change in position with time, the size of the radio source, and the radio flux from a given source and its change with time. These characteristics of the radio source may then be compared, where this is possible, with those of the various optical features of an active region.

In the present paper the radio information will be given, and a very incomplete comparison made with some optical features for which published information is available.

(a) *Location of Radio Sources with Respect to Optical Features*

It is highly probable that the sources of the radio emission, at a wavelength of about 2 dm, lie in the lower part of the corona. This region is not, at present, available for optical observations, except at the limb, and a comparison in position of optical and radio features must refer therefore to optical observations of features which presumably exist much lower in the solar atmosphere.

A comparison between the positions on the disk of a radio source and an optical feature must take into account the difference in heights in the solar atmosphere. This means that comparisons in longitude must be made near the central-meridian passage (C.M.P.) of the radio source. With the solar rotation, a source moves away from the centre of the disk, and it is to be expected that, because of the height difference, it will also move relatively to the comparison optical feature. Measurement of this relative movement provides a means of determining the height of the radio source in the solar atmosphere.

(i) *Location in Longitude*.—In comparing the longitudes of a radio source and an area of plage faculaire, the position of the peak of the radio flux defined the position of the radio source. Had information on brightness distribution been available, the centre of brightness of the plage would have been taken as the position of the plage; for lack of this, the position was taken as the centre of apparent area of the plage.

For the comparison, observations of 18 radio sources and plages during times when they were within 3 days of C.M.P. were used. It was found, after correction for time differences, and taking the average of 80 observations, that the radio source lay $0 \cdot 2 \pm 0 \cdot 1$ min of arc behind the centre of the associated plage. Since the average angle subtended by a typical isolated plage is about

Table 1

SCANNING ANGLE φ DEFINED AS THE ANGLE BETWEEN THE SUN'S CENTRAL MERIDIAN AND THE NORMAL TO THE AERIAL BEAM

Date	φ (deg.)	Date	φ (deg.)	Date	φ (deg.)	Date	φ (deg.)	Date	φ (deg.)	Date	φ (deg.)
Jan.		Mar.		May		July		Sept.		Nov.	
1	— 96·4	1	—119·4	1	—120·0	1	—97·5	1	75·4	1	73·6
2	— 96·9	2	—119·6	2	—119·7	2	—97·0	2	75·1	2	73·8
3	— 97·4	3	—119·9	3	—119·5	3	—96·5	3	74·9	3	74·0
4	— 97·9	4	—120·0	4	—119·3	4	—96·2	4	74·7	4	74·2
5	— 98·4	5	—120·2	5	—119·0	5	—95·7	5	74·4	5	74·4
6	— 98·8	6	—120·5	6	—118·8	6	—95·3	6	74·3	6	74·6
7	— 99·4	7	—120·6	7	—118·5	7	—94·8	7	74·1	7	74·8
8	— 99·8	8	—120·8	8	—118·3	8	—94·3	8	73·9	8	75·1
9	—100·3	9	—121·0	9	—118·1	9	—93·9	9	73·6	9	75·3
10	—100·8	10	—121·1	10	—117·8	10	—93·5	10	73·4	10	75·6
11	—101·2	11	—121·3	11	—117·5	11	—93·1	11	73·3	11	75·8
12	—101·7	12	—121·5	12	—117·3	12	—92·7	12	73·2	12	76·1
13	—102·2	13	—121·6	13	—117·0	13	—92·2	13	73·1	13	76·3
14	—102·7	14	—121·8	14	—116·7	14	—91·7	14	73·0	14	76·6
15	—103·1	15	—121·9	15	—116·4	15	—91·4	15	72·9	15	77·0
16	—103·6	16	—122·0	16	—116·0	16	—90·9	16	72·7	16	77·2
17	—104·1	17	—122·2	17	—115·7	17	—90·5	17	72·5	17	77·5
18	—104·5	18	—122·3	18	—115·4	18	—90·0	18	72·4	18	77·8
19	—105·0	19	—122·4	19	—115·1	19	+89·7	19	72·3	19	78·1
20	—105·5	20	—122·5	20	—114·8	20	+89·3	20	72·2	20	78·4
21	—105·8	21	—122·6	21	—114·4	21	+88·9	21	72·1	21	78·8
22	—106·3	22	—122·7	22	—114·1	22	+88·4	22	72·0	22	79·0
23	—106·7	23	—122·7	23	—113·7	23	+88·1	23	71·9	23	79·4
24	—107·2	24	—122·8	24	—113·4	24	+87·7	24	71·8	24	79·7
25	—107·6	25	—122·9	25	—113·1	25	+87·3	25	71·7	25	80·0
26	—108·0	26	—122·9	26	—112·6	26	+86·8	26	71·7	26	80·5
27	—108·5	27	—123·0	27	—112·3	27	+86·5	27	71·6	27	80·9
28	—108·9	28	—123·0	28	—112·0	28	+86·1	28	71·6	28	81·2
29	—109·3	29	—123·0	29	—111·6	29	+85·7	29	71·5	29	81·6
30	—109·7	30	—123·0	30	—111·2	30	+85·3	30	71·4	30	82·0
31	—110·2	31	—123·1	31	—110·8	31	+85·0				

Feb.		Apr.		June		Aug.		Oct.		Dec.	
1	—110·5	1	—123·1	1	—110·4	1	+84·6	1	71·4	1	82·3
2	—110·9	2	—123·1	2	—110·0	2	+84·2	2	71·4	2	82·8
3	—111·3	3	—123·1	3	—109·7	3	+83·8	3	71·4	3	83·1
4	—111·7	4	—123·0	4	—109·2	4	+83·5	4	71·4	4	83·5
5	—112·1	5	—123·0	5	—108·8	5	+83·1	5	71·3	5	83·9
6	—112·5	6	—123·0	6	—108·4	6	+82·7	6	71·3	6	84·3
7	—112·8	7	—123·0	7	—108·0	7	+82·5	7	71·3	7	84·8
8	—113·2	8	—123·0	8	—107·6	8	+82·1	8	71·3	8	85·2
9	—113·5	9	—122·9	9	—107·2	9	+81·7	9	71·3	9	85·6
10	—113·9	10	—122·9	10	—106·7	10	+81·4	10	71·4	10	86·0
11	—114·3	11	—122·8	11	—106·3	11	+81·1	11	71·4	11	86·5
12	—114·6	12	—122·7	12	—105·9	12	+80·7	12	71·5	12	86·9
13	—114·9	13	—122·6	13	—105·4	13	+80·4	13	71·5	13	87·3
14	—115·2	14	—122·5	14	—105·0	14	+80·1	14	71·5	14	87·8
15	—115·6	15	—122·4	15	—104·6	15	+79·9	15	71·5	15	88·2
16	—115·9	16	—122·3	16	—104·2	16	+79·5	16	71·6	16	88·7
17	—116·2	17	—122·2	17	—103·7	17	+79·2	17	71·7	17	89·1
18	—116·5	18	—122·1	18	—103·3	18	+78·9	18	71·8	18	89·6
19	—116·8	19	—122·0	19	—102·9	19	+78·6	19	71·9	19	90·1
20	—117·1	20	—121·8	20	—102·4	20	+78·3	20	72·0	20	90·6
21	—117·4	21	—121·7	21	—102·0	21	+78·1	21	72·1	21	91·1
22	—117·6	22	—121·5	22	—102·0	22	+77·7	22	72·1	22	91·4
23	—117·9	23	—121·4	23	—101·1	23	+77·5	23	72·2	23	91·9
24	—118·2	24	—121·3	24	—100·6	24	+77·2	24	72·4	24	92·4
25	—118·4	25	—121·1	25	—100·2	25	+77·0	25	72·5	25	92·9
26	—118·7	26	—121·6	26	— 99·7	26	+76·7	26	72·6	26	93·4
27	—118·9	27	—120·7	27	— 99·3	27	+76·5	27	72·7	27	93·9
28	—119·2	28	—120·6	28	— 98·8	28	+76·2	28	73·0	28	94·4
		29	—120·4	29	— 98·1	29	+76·0	29	73·1	29	94·8
		30	—120·2	30	— 97·9	30	+75·8	30	73·3	30	95·3
						31	+75·6	31	73·4	31	95·8

3 min of arc, the results are consistent with a location of the radio source on the same heliographic longitude as the centroid of the plage.

No such coincidence was found when a similar comparison was made between the positions of a radio source and the largest sunspot in an active region. The radio source showed a significant lag of $1 \cdot 2 \pm 0 \cdot 1$ min of arc behind the largest sunspot. This result suggests that the radio source probably lies radially above the plage rather than above any particular sunspot.

(ii) *Determination of Height of Radio Source.*—The comparison in position just described was extended to observations out to the limb, and the differences between the positions of the radio source and centroid of plage faculaire plotted with respect to time from C.M.P. of the source. The results are shown in Figure 5. Observations on both sides of C.M.P. were plotted on this one-sided diagram and

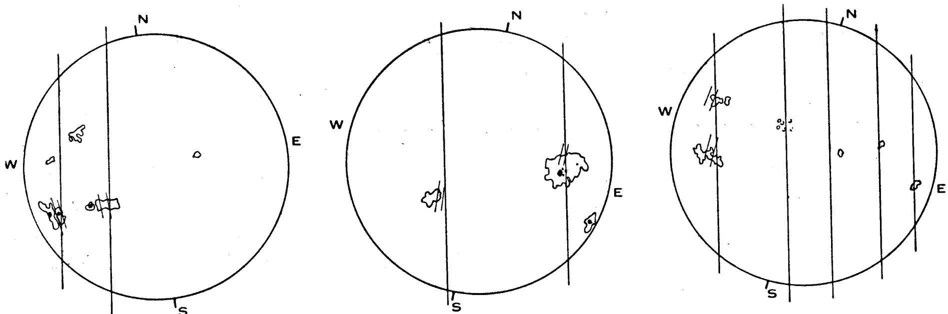

Fig. 3.—Position-lines of peaks in the radio records with respect to the optical disk of the Sun. The positions are shown also of sunspots and plages faculaire (Ca K). The optical and radio observations were made on the same day, but not at the same hour. The amount of correction at the point of interest is indicated on each diagram.

the mean relative position on each day is shown with its probable error. This figure shows that the radio source moves more rapidly than the associated plage faculaire over the central part of the solar disk, but then appears to slow down until the two are nearly coincident near the limb. Some assumptions are required if one is to deduce the height of the radio source above the plage from these results. To determine the height we assume that the relative movement results from the sources having the same angular velocity, but different heights in the solar atmosphere. We have to assume, also, that the peculiar form of the curve near the limb is the result of some absorption or other effect and that the significant part of the curve, for height determination, is that near the centre of the disk. A final assumption is that the two sources are either small or comparable in size, since the apparent centroid of a large section of spherical shell will change as it rotates with respect to some point on the shell. This last assumption is not as important as the others since if it were false the error produced in the results would not be a major one.

The slope of the curve in the central region of Figure 5 gives the height of the radio source as 22,000 km above the chromospheric plage (K_2 line of calcium), or about 24,000 km above the photosphere. This is the result of combining the

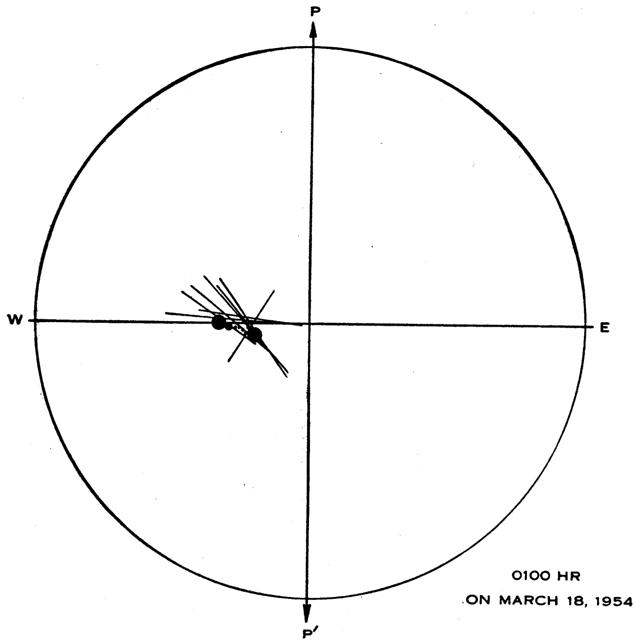

Fig. 4.—Location on the solar disk of a radio source by means of scans in several directions. The 32-element east-west interferometer and the 16-element north-south interferometer were used for these observations.

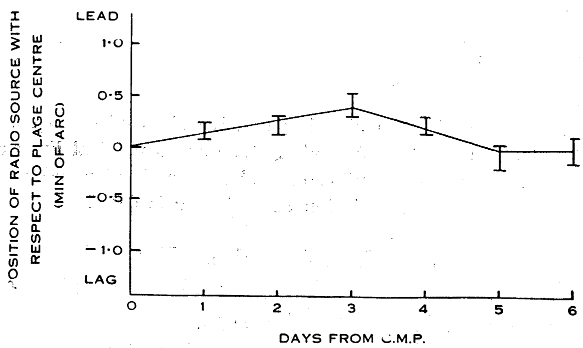

Fig. 5.—The relative movement of a radio source and of an area of plage faculaire when viewed from the Earth. The radio source moves faster than the plage in the central region of the solar disk, and from this, its height in the solar atmosphere may be deduced.

useful observations of 1952 and 1953. If the 1952 and 1953 results are used separately the average heights of the radio sources above the plage are found to be 18,000 and 25,000 km respectively.

(b) *Source-width Measurement and Source Brightness*

The resolving power (3 min of arc) of the instrument used was adequate to resolve some of the sources at least partially, and it was possible to calculate the size of a source if the shape were assumed. When the measured source-width approaches the width of the aerial beam the error, of course, increases sharply.

Some very broad sources were measured; these corresponded to broad and diffuse areas of plage faculaire, in a few cases free from sunspots. In the scatter diagram of Figure 6 are shown the estimated diameters of those of the radio sources which were sufficiently large to be resolved, plotted against the diameter

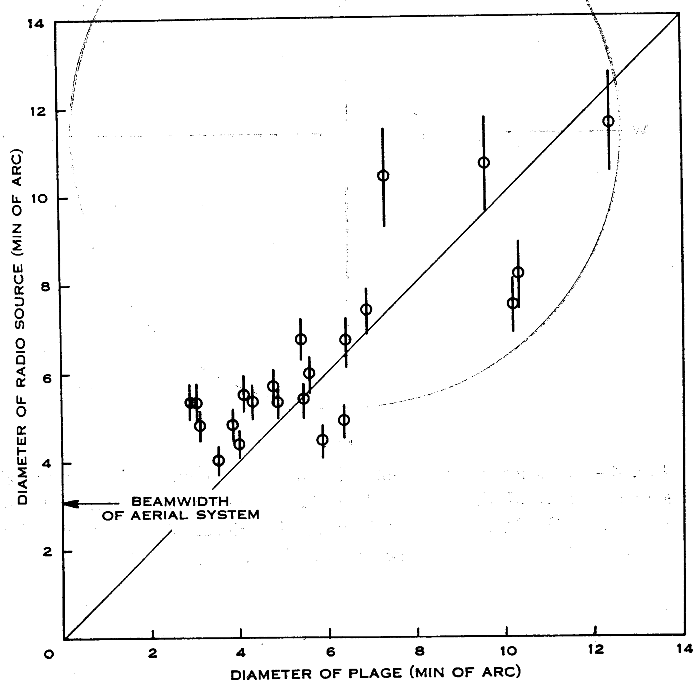

Fig. 6.—Scatter diagram showing relative sizes of radio sources and associated areas of plage faculaire. The short vertical lines represent a range of shapes for the radio sources between circular and rectangular. The correlation coefficient r is 0·85.

of the corresponding areas of plage faculaire. Each observation is represented by a line which covers a range of source shapes between circular and rectangular. The correlation coefficient is found to be 0·85. Although the possibility cannot be excluded that the broad sources may consist of a number of small sources, the results suggest that the radio sources cover an area comparable with that occupied by the plage faculaire. If this is correct we can estimate the brightness of a source. The measured flux from the radio sources varies from very small values up to values of 10^{-21} W m^{-2} (c/s)$^{-1}$. The latter, with an assumed source size of 10 sq. min of arc, corresponds to a brightness temperature of approximately 2×10^{6} °K. It should be stressed, however, that if the source were not fully resolved, parts of it could have brightness temperatures higher than this.

(*c*) *Directivity of a Source*

The directivity of the emission from a radio source can be determined from a study of the radio flux from a large number of sources during their passage from the eastern to the western limb of the Sun. It is necessary to average the effect of a number of sources, since individual ones may be growing or decaying during the days of observation.

There have been previous attempts, at other wavelengths, to determine the directivity of a source from a statistical treatment of whole-Sun observations. Takakura (1953) found the observations at $\lambda=25$ cm insufficiently accurate to give useful results. Waldmeier (1953) and Vauquois (1955*a*) used the more accurate observations of Covington to determine the directivity of the radio sources on the Sun at $\lambda=10 \cdot 8$ cm.

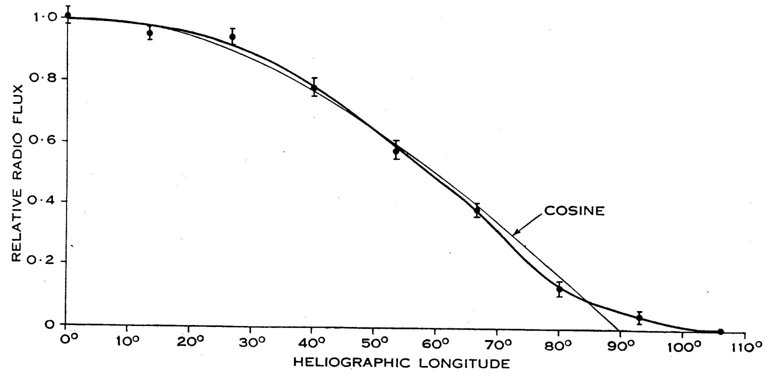

Fig. 7.—Diagram showing the average directivity of a radio source, i.e. the change in relative flux received at the Earth from a radio source as the latter moves across the solar disk. For comparison, a cosine curve, characteristic of the directivity of a plane source, is shown.

There is some difficulty in employing the whole-Sun observations, since it has to be assumed that there is an invariable connexion between visible sunspots and radio emission. The present observations at $\lambda=21$ cm do not suffer from this difficulty.

It was found that 16 observed sources were sufficiently well separated and of sufficient intensity to be easily measurable. The radio flux from each source was taken as unity at C.M.P. and the relative flux plotted on days each side of C.M.P. No significant asymmetry was found, and the observations on the two sides were plotted together. The means, with probable errors, and the normalized smoothed curve through the means are shown in Figure 7. For comparison, a cosine curve is shown in this figure ; except near the limb, the curves are practically identical. This suggests that the source has the form of a thin sheet lying parallel to the photospheric surface. The significance of this result will be discussed in a paper being prepared by S. F. Smerd and one of the authors of the present paper.

(*d*) *Rate of Decay of Radio Sources*

It was possible to follow the course of a few active regions during several rotations of the Sun. The number was adequate to give a rough quantitative measure of the rate of decay of a radio source after it had passed its maximum activity. In Figure 8 (*a*) the radio flux for a few sources is shown plotted against the number of solar rotations. In each case the zero time and unit flux density refer to the time and magnitude of maximum flux. A similar diagram, Figure 8 (*b*), is drawn for the sunspot areas of the groups which are associated with these radio sources ; the zero of time is the same on the two diagrams.

It is apparent that for these groups the radio emission falls off less rapidly than the sunspot area. After two rotations the radio emission has fallen to about 1/6 of the maximum, while the sunspot area has fallen to about 1/30. The mean rate of fall over this period is roughly exponential and the time taken to fall by a factor of 1/e is approximately 23 days for the radio flux and 16 days for sunspot area.

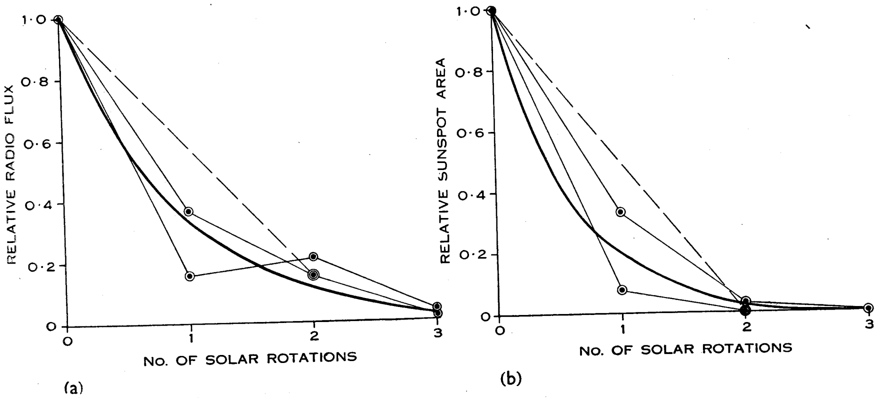

Fig. 8.—Decay curves for three active regions which were observed on four successive rotations of the Sun. Curve (*a*) shows the relative radio flux from the region and curve (*b*) the total sunspot area in the region relative to the value at the peak of activity.

(*e*) *The Relation between Radio Flux and Sunspot Area*

From the previous discussion it appears that the slowly varying component of the solar radiation originates in active regions on the Sun, and is most closely related to optical features of such regions which have longer life than sunspots, e.g. bright coronal regions and plage faculaire. It is known, however, that the radio emissions show statistically an unexpectedly high correlation with visible sunspot area and with sunspot number.

In Section III (*c*) it was shown that the flux from radio sources and the visible area of sunspots vary with the rotation of the Sun in approximately the same way—a cosine law. Hence there is a possibility that this common factor, which applies approximately also to " sunspot number ", might give a fictitiously high degree of correlation between the two. To test this, the common factor was removed. In Figure 9 sunspot areas corrected for foreshortening (U.S. Naval Observatory) are plotted against corresponding values of radio flux which have also been corrected for centre-limb variation. In order to keep the correction factors from becoming too large, the observations analysed were confined to those within 5 days of C.M.P. The correlation coefficient is high ($r=0 \cdot 89$) showing that the close relationship between sunspot area and radio flux is not affected markedly by the removal of centre-limb and foreshortening variations. A close inspection of Figure 9 shows, however, that, as was expected, the relationship is only a partial one. Three regions typical of old, mature, and new sunspot groups are shown in which the points representing daily observations are joined together by lines. The region which is close to its maximum of area and flux shows a very high correlation between sunspot area and radio flux ; a very new region shows a short delay between the appearance of the new spot group and radio emission ; the old region shows radio emission still present after the sunspot area has fallen to zero. The diagram shows why it is that the correlation is high ; in the most highly emitting regions sunspot area is a good indicator of the radio flux, and these highly emitting regions are the dominating factor in the slowly varying component of the solar radiation.

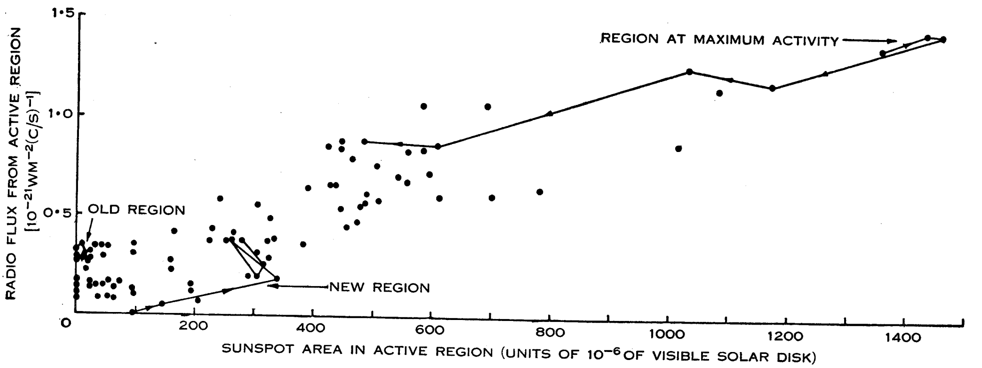

Fig. 9.—Scatter diagram showing radio flux from an active region plotted against the sunspot area in the same region. The radio flux has been corrected for directivity of the source (see Fig. 7) and the sunspot area for foreshortening. The day-by-day development of one new, one mature, and one old region is shown by connecting the points which denote their daily observations by lines.

It is of interest to find whether the results of the present investigation support the use by Pawsey and Yabsley (1949), and others, of correlation between radio flux and sunspot area to determine the radiation from the quiet Sun. We offer new evidence in the form of an estimate, which is much more accurate than previous ones, of the amount of radiation corresponding to a given visible area of sunspots, together with a rough estimate of the effect to be expected from regions from which sunspots have disappeared. We have also from Parts II and III of this series of papers, a more firmly based estimate for the emission from the quiet Sun. This estimate, as for the two listed above, is for the minimum phase of the solar cycle.

For the purposes of comparison with corresponding data at a wavelength of 21 cm for the maximum period of activity of the solar cycle we now refer to Table 2.

In this table we have shown in the first column how a typical total flux value of $11 \cdot 2 \times 10^{-21}$ W m^{-2} (c/s)$^{-1}$ measured near sunspot maximum in 1947 would be distributed into quiet-Sun and slowly varying components after the

Pawsey-Yabsley method. These figures are derived from an interpolation between results at wavelengths of 25 and 10 cm. The slowly varying component is that corresponding to a visible sunspot area of 200×10^{-5} of the area of the visible solar disk, this being an average value for sunspot maximum conditions. In the second column are the corresponding values for the minimum phase of the sunspot cycle as measured by our high resolution aerial in 1952–1953. The quiet-Sun component is that given in Part III of this series of papers, and the probable slowly varying component of the flux is estimated from Figure 9, and corresponds to the same visible sunspot area as for the sunspot maximum condition.

The difference of 6×10^{-21} W m^{-2} (c/s)$^{-1}$ between the values of total flux obtained at the maximum and minimum phases for the same visible sunspot area, we feel, cannot be explained solely in terms of flux from " dead " spots as attempted by Piddington and Davies (1953) ; the present investigation indicates

TABLE 2

COMPARISON OF DATA AT SUNSPOT MAXIMUM AND SUNSPOT MINIMUM

Quantity	Sunspot Maximum 1947 Pawsey-Yabsley Method (10^{-21}W m^{-2} (c/s)$^{-1}$)	Sunspot Minimum 1952–53 High Resolution Observations (10^{-21}W m^{-2} (c/s)$^{-1}$)
Solar flux density at $\lambda = 21$ cm (corresponding to a sunspot area of 200×10^{-5} of the solar disk)	11·2 (measured)	5·0 (extrapolated from measurements)
Quiet-Sun component	6·4 (estimated)	3·0 (measured)
Slowly varying component	4·8 (estimated)	2·0 (extrapolated from measurements)

that the flux from these would certainly be less than from the visible sunspots, viz. 2×10^{-21} W m^{-2} (c/s)$^{-1}$. The difference in total flux, however, can be explained if we suppose that the radio flux corresponding to a given sunspot area is greater at the maximum phase than at the minimum phase of the solar cycle and that the quiet-Sun level is also probably greater at sunspot maximum than at minimum.

Hence we can say, as indicated by the scatter-diagram method, that the slowly varying emission corresponding to a certain sunspot area changes during the sunspot cycle and it would seem very probable that the quiet-Sun flux does so too. It appears therefore that the Pawsey-Yabsley method gives results that are qualitatively correct and are probably not seriously wrong quantitatively.

It will be necessary to observe the Sun during the maximum phase of the solar cycle by means of instruments of high resolving power in order to make clear what is the meaning of " quiet-Sun level " at that time and to evaluate it. However, it appears that the effect of the lag of radio emission in time compared with sunspots is not great enough to produce very serious errors in estimates of quiet-Sun level obtained by the older method.

IV. Conclusions

The observations have shown that the slowly varying radio emission from the Sun is associated with active regions on the solar disk. The emission appears to be invariably associated with plage faculaire rather than with sunspots, since the radio emission continues from the region of the plage after all sunspots have disappeared. In this respect it is similar also to the localized magnetic fields observed by Babcock and Babcock (1955).

A detailed study has shown that the positions of the sources of radio emission coincide, on the average, with the centroids of the corresponding areas of plage. An analysis of the relative rates of rotation of the radio sources and associated optical features has indicated that the radio sources are to be found at heights of about 24,000 km above the photosphere. This also appears to be the height near which maxima in the emission of the coronal green line are found (e.g. Waldmeier and Müller 1950).

The size of the radio sources could not be established with certainty, because of incomplete resolution, but a statistical study showed a correlation coefficient of 0·85 between the size of plage and corresponding radio sources. This suggests that the two are probably identical in size. The correspondence in size does not exclude the possibility that the regions themselves may be non-uniformly bright.

The brightness (averaged over a region of about 10 sq. min of arc) of a strong source which produces a flux density of 10^{-21} W m^{-2} $(c/s)^{-1}$ is 2×10^{6} °K.

The flux received from a radio source has been shown to vary regularly during its change in position from the centre to the limb of the solar disk, in a manner approaching a cosine law ; it behaves as though it were a thin disk lying parallel to the photosphere.

A rough estimate of the persistence of the radio emission compared with that of sunspots has shown that 2 months after the peak which occurs at the same time for radio flux and sunspot area, the radio emission has fallen to about 1/6 of the maximum while the sunspot area has fallen to 1/30. However, near the peak of the emission there is a high degree of correlation between the two. Since emission from the strong sources usually provides the major part of the slowly varying component, the correlation is high between the total visible sunspot area and the total emission which makes up the slowly varying component.

It is noteworthy that the results of this investigation bear a strong resemblance to those which have been concerned with the slowly varying emission of ultraviolet and X-radiation from the Sun. Both the radio emission and the ionizing radiation have been shown to originate in the active regions on the Sun and both show close correlation with sunspot area.

As the result of eclipse observations, it was discovered by Higgs (1942) that the ultraviolet radiation from the Sun, as estimated from ionospheric effects, appeared to originate near areas of plage faculaire. Allen (1946, 1948) found that this emission shows a greater persistence than sunspots and correlates better with indices of facular (photospheric and chromospheric) activity. This conclusion is similar to that found here for the radio emission. It is known also that the coronal green line emission is closely correlated with facular and sunspot indices.

An active region, therefore, shows increases in emission at points in the radio, visible, and ultraviolet (or X-ray) parts of the spectrum, in regions of the solar atmosphere above the photosphere. Against this is a decrease in visible radiation in the photosphere, indicated by the appearance of sunspots. All these features are closely correlated and are apparently invariably associated with a localized magnetic field.

No evidence has appeared against the simplest explanation of the emission, that is, that it results from regions of high density in the solar atmosphere, with the material having temperatures similar to that in the coronal rather than photospheric regions.

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