SOLAR BRIGHTNESS DISTRIBUTION AT A WAVELENGTH OF 60 CENTIMETRES

II. LOCALIZED RADIO BRIGHT REGIONS

By G. SWARUP* and R. PARTHASARATHY†

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Summary

The localized radio bright regions on the Sun which give rise to a slowly varying component of the solar radiation were studied at a wavelength of 60 cm, using a 32-aerial interferometer with a beamwidth of 8·7 min of arc. The observations were undertaken during July 1954 to March 1955 and were limited in number due to this being a minimum period of the solar cycle. The low activity, however, provided the advantage of simple interpretation as often only one region was present on the solar disk.

The characteristics of the observed bright regions are described; their occurrence is closely correlated with regions of chromospheric faculae, the emission polar diagram has a half-power width of 6 days, the estimated size of the sources varied from less than 3 to 6 min of arc, the largest value of the derived brightness temperature was 10^7 °K, and for two groups of localized regions the height of the source was derived to be $35,000 \pm 15,000$ km above the photosphere. Sometimes the slowly varying component showed marked intensity fluctuations in periods of nearly half an hour. The presence of apparently associated fluctuations suggests that at least a part of the slowly varying component at 60 cm has a non-thermal origin.

I. INTRODUCTION

Measurements of solar radiation at decimetre wavelengths by several workers identified a component which has been called the slowly varying component. It varies slowly from day to day, and was distinguished from the rapid variations that were observed occasionally for a duration of seconds or minutes. Pawsey and Yabsley (1949) found it to be superimposed upon a basic steady level attributed to thermal radiation from the " quiet Sun ". The component was found by Covington (1948) and Lehany and Yabsley (1949) to have good correlation with the sunspot area. Eclipse observations made by Covington (1947) at a wavelength of 10 cm, and by Christiansen, Yabsley, and Mills (1949) at 50 cm showed that the component originated in localized regions on the solar disk. These radio bright regions were observed close to positions where sunspots were visible or had occurred during previous rotations. One was found close to a stable prominence well off the limb.

To investigate the characteristics of bright regions in detail, it was necessary to isolate them from the background radiation of the quiet Sun by using aerials of

* Division of Radiophysics, C.S.I.R.O., University Grounds, Chippendale, N.S.W.; present address: Stanford University, Stanford, California.

† Division of Radiophysics, C.S.I.R.O., University Grounds, Chippendale, N.S.W.; present address: Radio Propagation Unit, National Physical Laboratory of India, New Delhi.

narrow beamwidth. Christiansen, Warburton, and Davies (1957) studied the regions at a wavelength of 21 cm during the years 1952-53, using a 32-aerial interferometer of beamwidth 3 min of arc. Covington and Broten (1954) and Dodson (1954) made a study at 10 cm using a wave-guide array with a beamwidth of $7 \cdot 5$ min of arc. Kakinuma (1956) made observations at $7 \cdot 5$ cm using an 8-element interferometer with quarter-wavelength plates that had a beamwidth of $4 \cdot 5$ min of arc. It was shown that the occurrence of bright regions on the Sun at 10 and 21 cm is closely correlated with regions of chromospheric faculae, seen in calcium or hydrogen line emission. The study at $7 \cdot 5$ cm confirmed the presence of a small degree of circularly polarized component.

We have now employed Christiansen's 32-aerial interferometer to study the solar radiation at a wavelength of 60 cm. The results concerning the brightness distribution across the quiet Sun have been reported in Part I of this series (Swarup and Parthasarathy 1955). The study of the localized bright regions which give rise to the slowly varying component is described here.

The observations were undertaken during July 1954 to March 1955, which was during the minimum period of the solar cycle. The radio emission from the disturbed Sun was low for most of the period, which is consistent with the low level of optical activity. Only a small number of localized regions that gave strong radio emission were observed. This limited our study of the regions. Because of this, it should be emphasized that the results obtained here are more of an exploratory nature. The low level of activity has had the advantage, however, that often only one bright region was present on the solar disk at any one time. This simplified the interpretation of observations made with an interferometer which had a limited resolving power.

II. Observations

The 32-aerial interferometer described in Part I (Swarup and Parthasarathy 1955) produces a family of fan-shaped beams like those of a diffraction grating. The angular spacing of the beams is $4 \cdot 9°$, which is much larger than the diameter of the solar disk. The half-power beamwidth is $8 \cdot 7$ min of arc. The aerial pattern was derived by measuring the response of the radio source Cygnus-A and that of a strong, localized, bright region on the solar disk. The fan-shaped beams of the interferometer scan the solar disk in a stripwise manner producing a series of records of the one-dimensional radio brightness distribution across the solar disk each day. The daily records exhibit peaks which change in position with solar rotation. This shows the presence of localized bright regions on the solar disk. As described in Part I, the response curves of the localized bright regions for any day are obtained by subtracting the background component due to the quiet Sun from the record of the one-dimensional distribution for the day. The derived curves give both the position and intensity of the radio bright regions. The location is given along a line corresponding to the position of the fan-shaped aerial beam on the solar disk when the peak appears on the record.

Taking the flux density of the quiet Sun as 2×10^{-21} W m^{-2} (c/s)$^{-1}$ on two polarizations, the error in derivation of flux densities of bright regions was estimated to be 3×10^{-23} W m^{-2} (c/s)$^{-1}$. The error was small, as the calibration of records was checked in terms of power received from adjacent parts of the quiet Sun. Receiver fluctuations were negligible. The total effective area of the 32 parabolic aerials was nearly 35 m^2, and the measured transmission line loss was 3 dB. The receiver had a noise factor of 10 dB, bandwidth of 4 Mc/s, and time constant of 2 sec.

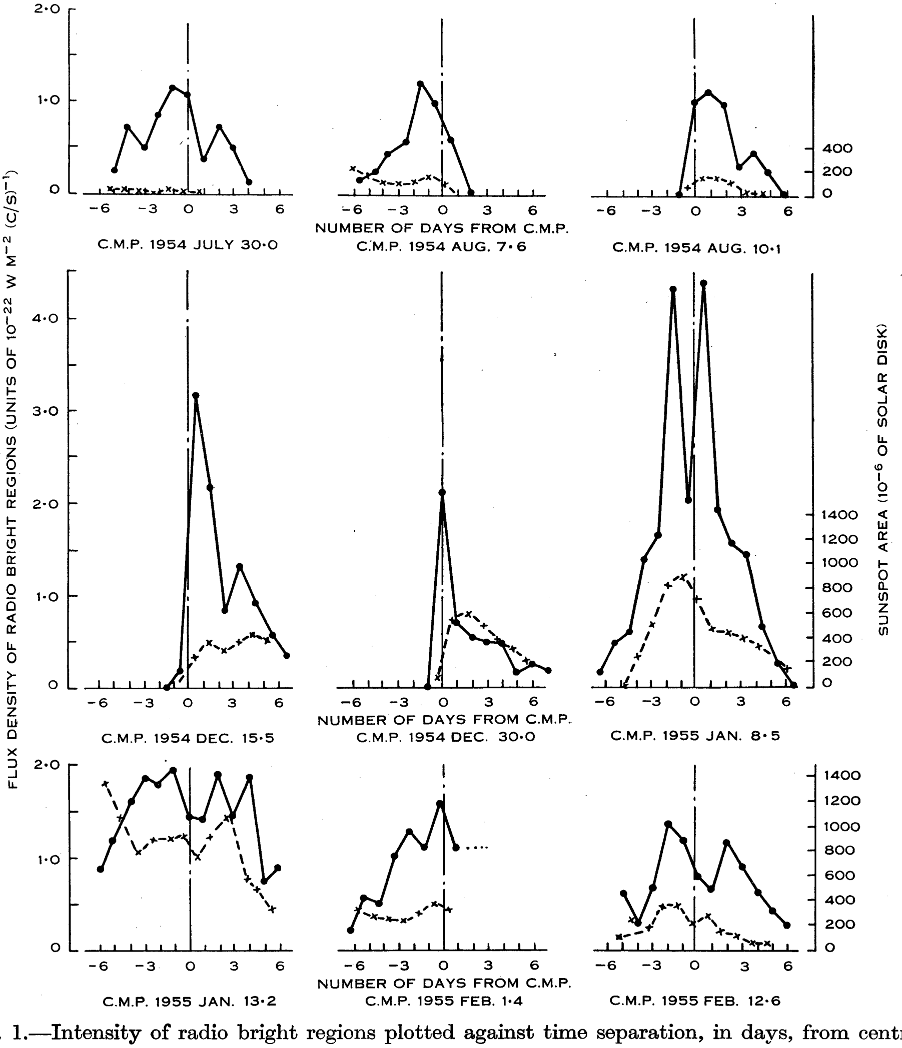

Fig. 1.—Intensity of radio bright regions plotted against time separation, in days, from central meridian passage (full line). Area of the associated sunspots is also plotted (broken line).

III. Observed Characteristics of Radio Bright Regions

(a) *Emission Polar Diagram*

During the period July 1954 to March 1955 several isolated radio bright regions were studied during their passage across the solar disk. Figure 1 shows the radio flux densities for nine of the most active regions observed during the period. The projected area of the associated sunspots is also plotted in the figure for comparison.

It is clear from Figure 1 that, apart from variations due to growth or decay of a radio bright region, its radiation flux density is greater when it is located closer to the central meridian of the Sun. An attempt was, therefore, made to calculate the directivity or the emission polar diagram of an average radio bright region at a wavelength of 60 cm. It was assumed that the emission polar diagram was symmetrical with respect to the central meridian, and that for the nine regions observed any variations due to growth or decay occurred randomly with respect to their location on the solar disk. The latter assumption was considered to be justified on an examination of the associated sunspot areas. Only those observations were considered for this study for which the radio bright regions were seen near their central meridian passage (C.M.P.) and for the adjoining 5 days on the eastern or western side of the solar disk. A mean was taken of the flux densities of each region measured for the above 6 days. The mean values were used to normalize the curves shown in Figure 1. The normalized values are plotted in Figure 2 against the time separation, in days, from C.M.P. of the regions. The values of days are approximated to the nearest integer. The curve passing through the mean of the points shown in Figure 2 is the derived emission polar diagram. The variation with position for the radio regions at 60 cm is steeper than the cosine variation known to occur for the visible area of sunspots.

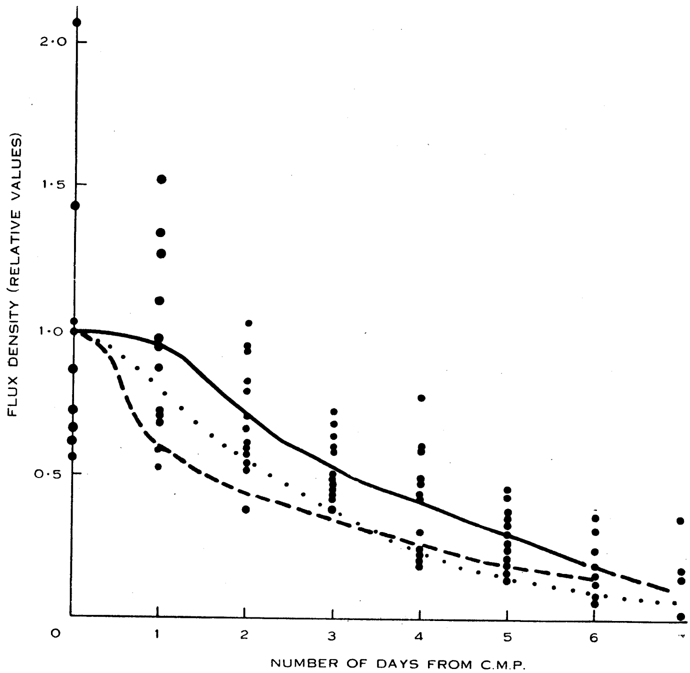

Fig. 2.—Emission polar diagram derived by us (full line), by Machin and O'Brien (broken line), and by Müller (dotted line). The values of flux density measured by us, after being normalized, are shown by dots.

Machin and O'Brien (1954) calculated the emission polar diagram for a wavelength of 60 cm by a statistical analysis of the daily apparent disk temperature of the Sun measured during 1953. Müller (1956) deduced the polar diagram at 50 cm from a study of the apparent disk temperature during the passage of eight large sunspot groups in the years 1949-1952. The curves derived by them are also shown in Figure 2 and are reasonably similar to ours. However, we would like to point out again that the present observations, though limited in number, had small errors and were free from confusion as the radio bright regions were isolated from the background.

(b) *Source Height above Photosphere*

As mentioned earlier, the interferometer gives the position of a radio bright region on the solar disk along a line. Its location, however, can be determined unambiguously by a method described by Christiansen and Warburton (1953) if it is observed for several days during its rotation on the solar disk. On a Mercator's projection of the Sun, an arc is drawn for each day corresponding to the heliographic coordinates of the line that passes through the bright region on the solar disk. The arcs intersect at a point only if the bright region lies on the photosphere. Several similar graphs are drawn, assuming different values of effective solar radius corresponding to distance of the source from centre of the Sun. The best intersection gives heliographic coordinates as well as height of the bright region. The method has only one assumption, that the heliographic coordinates of the region remain the same from day to day; this implies a rotational velocity of the region of $13 \cdot 2°$ per day. However, a correction can be made for a different rotational velocity of the region, if it is known.

During December 1954 and January 1955 two bright regions were observed on the solar disk over several days and gave sufficiently strong radio emission for their positions to be located within $\pm \frac{1}{4}$ min of arc. The mean rotational velocity of the associated sunspot groups was $12 \cdot 5°$ per day for each group. For derivation of height, it was assumed that the bright regions had the same rotational velocity. The height above the photosphere was determined to be $35{,}000 \pm 15{,}000$ km for both the regions. There were two main sources of error, uncertainty in measurements of the positions of the radio source, and change of heliographic coordinates of the source in an uncertain manner due to its proper motion or due to any absorption effects taking place as the source approached the limb.

(c) *Size and Equivalent Brightness Temperature*

For an extended source the response pattern of the aerial is wider than that for a point source. The approximate size of the source can be deduced from this widening if an assumption is made as to its shape. We assumed the bright regions on the solar disk to be circularly uniform. The only cases analysed were those where the radio bright regions were completely isolated and there was only a single area of optical activity within the region of response of the aerial beam.

The radio bright regions observed at 60 cm produced only a small amount of broadening. This was reliably determined only when the sources were sufficiently strong, and the study was limited to these. The largest calculated size was 6 min of arc, which was obtained for the radio source observed on January 15 and 17, 1955. Some strong sources did not show any detectable widening, for which an upper limit to their diameters was calculated to be 3 min of arc.

The equivalent temperature of a bright region was calculated using the measured value of its flux density and its estimated size. The largest value obtained was 10^7 °K which occurred on December 16, 1954 at 0144 U.T. It should be noted that the radio source, which was probably not uniform, was not fully resolved and the peak value of brightness temperature could be higher. The deduced value of size, average daily flux density, and the corresponding equivalent temperature for the various days are listed in Table 1. Values of the associated

Table 1

SIZE AND EQUIVALENT BRIGHTNESS TEMPERATURE OF RADIO BRIGHT REGIONS

Date	C.M.P. of the Region	Projected Sunspot Area (10^{-6} disk units)	Diameter (min of arc)	Average Flux (10^{-22} W m^{-2} (c/s)$^{-1}$)	Brightness Temperature (10^6 °K)
1954, Dec. 16	Dec. 15·5	240	<3	3·2	>7·4
Dec. 17	Dec. 15·5	310	<3	2·2	>5·1
Dec. 19	Dec. 15·5	415	<3	1·3	>2·1
Dec. 30	Dec. 30·0	240	<3	2·1	>4·9
1955, Jan. 5	Jan. 8·5	260	<3	1·4	>3·1
Jan. 14	Jan. 13·2	830	5	1·4	1·2
Jan. 15	Jan. 13·2	820	6	1·9	1·1
Jan. 17	Jan. 13·2	530	6	1·9	1·1
Jan. 18	Jan. 13·2	415	4	0·8	1·0
Jan. 19	Jan. 13·2	300	4	0·9	1·1
Average		440	<4	1·7	>2·8

sunspot areas are also given in the table for comparison. It is interesting to note that the values obtained for the size and equivalent temperature of the sources at 60 cm are similar to those derived at 50 cm by Christiansen, Yabsley, and Mills (1949) from observation of an eclipse in 1948. The total sunspot area was 850×10^{-6} of the solar disk on the day of the eclipse. Eight sources were identified whose estimated sizes varied between 2 and 4 min of arc. The average equivalent temperature was 5×10^6 °K, the most intense being at least 10^7 °K.

(*d*) *Association with the Optically Active Regions on the Sun*

The bright regions observed at a wavelength of 60 cm were compared with the optical features on the Sun. It was found that radio bright regions were always associated with regions of chromospheric faculae or plages. Except for some weak regions, sunspots appeared in these active regions for at least some part of their lifetime. The radio bright regions often preceded sunspots by a few days and succeeded them for a much longer period. The activity of bright regions usually increased with the appearance of sunspots.

The relationship between the flux densities of radio bright regions and the areas of the associated sunspots can be investigated using the curves shown in Figure 1. It has been shown in Section III (*a*) that the observed radio emission decreases as the region rotates from the centre to the limb. Also the visible sunspot area has a cosine variation. It has been pointed out by Christiansen, Warburton, and Davies (1957) that this common dependence on position might give a fictitiously high correlation between radio emission and sunspot area. The dependence on position was, therefore, eliminated for the radio regions by using suitable correction factors obtained from the emission polar diagram shown in Figure 2. Correspondingly, in the case of sunspots, values of projected area were used. As it was undesirable for the correction factors to become too large, only

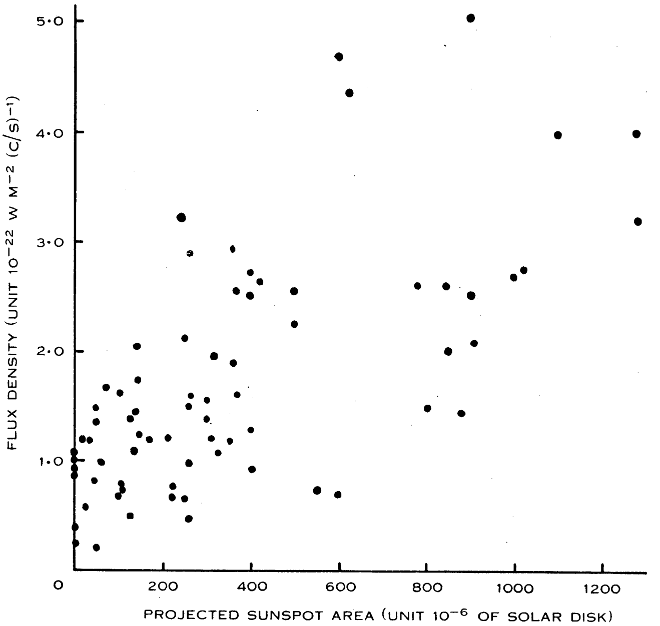

Fig. 3.—Scatter diagram showing flux of a radio bright region versus projected sunspot area. The radio flux has been corrected for directivity of the source (see Fig. 2).

those regions were considered which were situated within 5 days of the C.M.P. The corrected values of radio emission are plotted in a scatter diagram, Figure 3, against projected area of the associated sunspots. The correlation coefficient between the two was found to be 0·62.

(e) *Variation of Brightness in a Short Period*

Previous observations of the total radio emission from the Sun at decimetre wavelengths have shown that the slowly varying component remains noticeably steady for a period of a few hours and usually varies slowly from day to day. Our measurements, however, occasionally gave evidence of marked fluctuations in the brightness of the localized regions which gave rise to the slowly varying component, in periods of half an hour.

Records of the one-dimensional distribution across the solar disk were obtained by the interferometer over a period of about 2 hr around midday. Five records separated by nearly 20 min were obtained in this period as the successive interferometer beams scanned the solar disk. Any variations in the brightness of a localized region could be detected quite accurately in the successive records as any gain change of the receiver could be checked by comparing in the two records power received from adjacent parts of the quiet Sun. From December 15, 1954 to January 19, 1955, when four large sunspot groups moved across the solar disk, the flux density of the associated radio bright regions was more than 5 per cent of the quiet Sun flux density for 22 cases; in such cases it was thought that a relative change of 15 per cent or more in brightness of the regions was detectable, being outside the limits of experimental errors. Variations were noted only in five cases for which the values of flux density for the five patterns are given in Table 2. Two successive records obtained on December 16, 1954, are shown in Figure 4 (a). The records are superimposed in Figure 4 (b), which illustrates the

TABLE 2

FLUX DENSITIES OF FLUCTUATING BRIGHT REGIONS

(10^{-22} W m^{-2} (c/s)$^{-1}$)

Date	Relative Time				
	0^m	$21 \cdot 5^m$	43^m	$1^h\ 4 \cdot 5^m$	$1^h\ 26^m$
1954, Dec. 16	3·0	3·0	3·0	4·2	2·8
Dec. 19	0·7	0·7	1·5	1·9	1·5
Dec. 30	2·3	2·0	2·4	1·9	1·9
1955, Jan. 7	4·0	4·6	4·8	4·1	4·1
Jan. 15	1·6	1·6	1·8	2·6	
Jan. 17	2·2		2·2	1·6	1·6

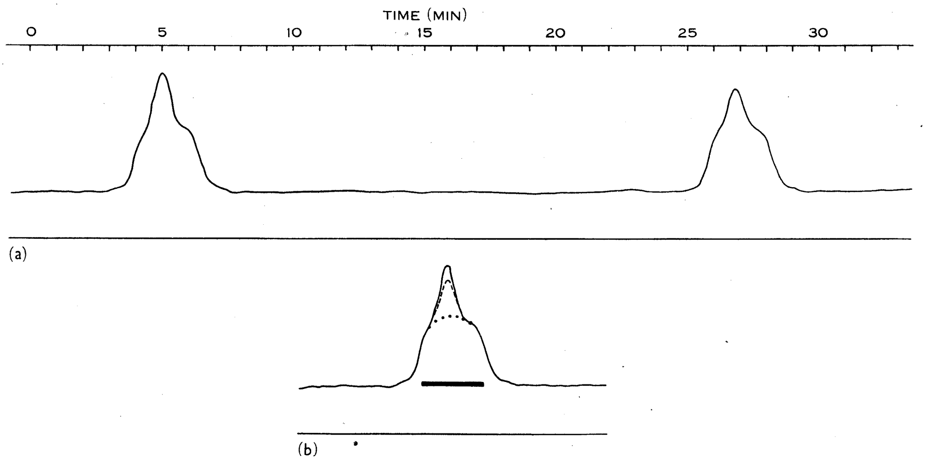

Fig. 4 (a).—Two successive records obtained on December 16, 1954.

Fig. 4 (b).—The two records shown in (a) are superimposed upon each other. The background radiation is shown by the dotted line and the size of the visible solar disk by the thick line.

observed change. Though the brightness of the localized regions changed, the shape of the response curves obtained on subtracting the background component remained the same in all five cases. This implies that the variations are slow, as it takes about 1·25 min for the interferometer beams to scan the bright regions. The changes are slower than that occurring at the time when bursts are observed in solar radiation. Moreover, no bursts were observed on the above occasions at frequencies of 200 and 600 Mc/s. Only in one case (January 15, 1955) a noise storm occurred at a frequency of 200 Mc/s. At two other times when a noise storm occurred at a frequency of 200 Mc/s no detectable variation was observed in our records at 500 Mc/s. The changes observed in the present observations are considered to have been caused by comparatively rapid variations of the slowly varying component.

It can be seen from Table 2 that on two occasions a variation of more than 40 per cent. and on one occasion a variation of more than 100 per cent. in the brightness have been noted in a period of nearly 20 min.

IV. Comparison with Characteristics derived at Other Wavelengths

Some of the characteristics of radio bright regions determined by various high resolution observations at decimetre wavelengths are summarized in Table 3. The differences in the characteristics with respect to the wavelength are in the proper direction to fit qualitatively in the existing ideas about the radio bright regions.

The emission polar diagram of the radio source becomes narrower as the wavelength increases. This result is the same as derived by Müller (1956) and others from statistical analysis of observations of the whole Sun. However, the emission polar diagram calculated from observations of the whole Sun is narrower for each wavelength than that derived from high resolution observations.

It should be noted that the heights of the radio source at the three wavelengths were derived for different bright regions. Moreover, experimental errors were large. It is therefore difficult to make a comparison. It is likely that the height of the radio source above the photosphere increases with the wavelength, although the possibility of origin from nearly the same level cannot be excluded.

Observations at decimetre wavelengths show that the size of the radio bright regions corresponds approximately to that of the chromospheric faculae (Ca or Hα plages). Also, Dodson (1954) found good correlation between intensities of the radio regions at 10 cm with those of calcium plages. Recently it was shown by Hatanaka *et al.* (1955*a*) that the brightness isophotes of a radio region at 8 cm agreed well in shape with a calcium plage. All these observations suggest that there is a very close relation between the origins of the radio emission and line emission from chromospheric faculae.

We compared our 60 cm observations with the 7·5 cm observations (simultaneous in time) undertaken by Kakinuma (1956), who employed an 8-element interferometer with beam of 4·5 min of arc. It was found that the ratio of the radio flux at 7·5 cm to that at 60 cm, when the regions were near

C.M.P., varied between 3 and 10 for different regions. If we assume nearly the same size of the source, it is seen that the brightness temperature of the radio region is appreciably higher at the longer wavelength. The values of the bright-

TABLE 3

CHARACTERISTICS OF BRIGHT REGIONS DETERMINED BY HIGH RESOLUTION OBSERVATIONS AT DM-CM WAVELENGTHS

Technique	Multiple-element Interferometer Observations			Eclipse Observations	
Period of observations	1954	1952–53	1955	Nov. 1, 1948	June 20, 1955
Observers	Authors	Christiansen, Warburton, and Davies (1957)	Kakinuma (1956)	Christiansen, Yabsley, and Mills (1949)	Hatanaka *et al.* (1955*b*)
Characteristics	Wavelength (cm)				
	60	21	7·5	50	8
1. Emission polar diagram	Steeper than cosine variation	Cosine variation			
Half-power width ..	6 days	9 days			
2. Height above photosphere (km)	35,000 ±15,000	24,000 ±3,000	35,000		
3. Observed sizes (min. of arc)	<3 to 6	<3 to 10	3 to 5	2 to 4	4
4. Brightness temperature of a strong region (10^6 °K)	5	2	0·7	5	1
5. Flux density near C.M.P. for an associated sunspot area of 10^{-3} of the Solar disk (in units of 10^{-22} W m^{-2} (c/s)$^{-1}$)	3·5	10	18*		
Flux density of quiet Sun (10^{-22} W m^{-2} (c/s)$^{-1}$)	20	30	80		

* This information was evaluated by the authors from the drift curves of the interferometer published by the observers (*Proc. Res. Inst. Atmosph., Nagoya University* (1955) **3**: 149).

ness temperature for the radio regions that are given in Table 3 agree broadly with the hypothesis of thermal origin of the radio emission (Waldmeier and Müller 1950; Piddington and Minnett 1951).

It was shown by Christiansen, Warburton, and Davies (1957) that at 21 cm the slowly varying emission corresponding to the same sunspot area decreases to nearly half from the maximum (1947) to the minimum (1952-53) of a solar cycle, and so does the quiet Sun flux. The study made at 60 cm gives a similar indication though the effect is less pronounced. At 60 cm both of the components decreased by a factor of 0·7 approximately.

V. Conclusions

The observations, made with an aerial of high resolving power operating at a wavelength of 60 cm, enabled us to study several highly emitting regions on the solar disk which give rise to the slowly varying component. It was found that the radio regions always occurred in association with Ca or Hα plages. It was possible to detect radio emission even from a very faint plage region. Except for some weak radio regions, sunspots appeared in these for some part of their lifetime. A correlation coefficient of 0·62 was found between the flux from the radio regions and the area of the sunspots.

The study gave information about the emission polar diagram, the height above the photosphere, the size, and the equivalent brightness temperature of the regions at 60 cm. The results are summarized in Table 3. A comparison was made with the results derived at shorter decimetre wavelengths by different workers. The characteristics change with wavelength in the proper direction to fit qualitatively the existing ideas about the origin of radio emission from these active regions on the solar disk. The simplest explanation is that the radio emission originates in thermal radiation from regions of very high electron density and temperature such as "coronal condensations" (Waldmeier and Müller 1950) which tend to occur in the corona over sunspot groups. In order to make quantitative deductions it is desirable to make simultaneous optical and radio observations of the same region.

Christiansen, Warburton, and Davies (1957) pointed out that no evidence appeared against the hypothesis of thermal origin in their investigation at 21 cm. However, the present observations give some evidence that at least part of the slowly varying component at 60 cm has a non-thermal origin. On six occasions, there were marked fluctuations in the brightness of the radio regions in periods of half an hour. It is difficult to visualize these fluctuations on the hypothesis of thermal origin as it takes time to change the temperature of a large volume of gas (70,000 km in extent). As a further indication of the non-thermal origin, it should be noted that, whereas radio brightness temperatures over 10^7 °K have been measured, such high optical temperatures have not.

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