THE RADIO BRIGHTNESS OF THE QUIET SUN AT 21 CM WAVELENGTH NEAR SUNSPOT MAXIMUM

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Summary

An investigation has been made of the radio emission from the quiet Sun at 21·2 cm wavelength in 1958 (near sunspot maximum). Two different methods have been used, both involving observations with very high angular resolution, to distinguish between the quiet-Sun component and the radiation from localized active regions. In one method, the Sun was scanned with a narrow pencil-beam ; in the other, a fan-shaped aerial beam was used to give one-dimensional strip scans. In both cases it was necessary, when analysing the data, to take into account the residual effects of the very intense radiation from the localized sources. The two independent measurements gave results which agree within the limits of error. The apparent disk temperature was found to be approximately 140 000 °K, or twice the value for the same wavelength at sunspot minimum.

The fan-beam observations also provide some evidence on the distribution of quiet-Sun brightness with respect to heliographic latitude. There is limb darkening at the poles, and the distribution does not appear to have changed in shape between sunspot minimum (1953) and the time of the present series of observations.

I. Introduction

The Sun's radio emission at wavelengths of the order of 20 cm is made up of two main components. One of these varies slowly in intensity from day to day and originates in localized active regions in the solar atmosphere. These emitting regions may conveniently be termed " radio plages ", by analogy with the optical plage areas with which they are closely associated. The second component consists of thermal radiation from the undisturbed or " quiet " Sun, and remains at a constant level for periods of months or years. Radio measurements of the quiet Sun are of considerable importance, since they can provide information on temperatures and electron densities in layers of the solar atmosphere which are difficult to observe optically.

The existence of a quiet-Sun component is inferred from the fact that, at a particular wavelength, a constant base level can be recognized in the varying intensity of the solar radiation. For an experimental investigation of the quiet Sun, it is necessary to find a method of separating the fixed component from the slowly varying plage radiation. This may be done by statistical analysis of a large number of daily observations of the total power received from the whole Sun at a chosen wavelength. An alternative is to use an aerial system with sufficient angular resolution to distinguish the active regions on the solar disk from each other and from the quiet-Sun background. Pawsey and Yabsley (1949) used a statistical method. A series of daily values of the apparent disk

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temperature (at 50 cm wavelength) was plotted against the corresponding projected sunspot areas. The distribution of the points on this diagram showed that the two quantities were closely correlated, and that the radiation consisted of a constant base level (quiet Sun) and a component proportional to sunspot area. The quiet-Sun temperature was estimated by drawing the line of best fit and extrapolating back to zero sunspot area.

Many quiet-Sun determinations of this kind have since been made. Taken over a period of years, they show that the temperature at a given wavelength appears to increase towards the time of sunspot maximum (Christiansen and Hindman 1951). The technique is, however, open to objections because of the underlying assumption of a linear relationship between sunspot area and radio emission. There is evidence that individual radio plages generally have a considerably longer life than the corresponding sunspot groups. The method therefore tends, especially at sunspot maximum, to ascribe to the quiet Sun some radiation from active regions which no longer contain visible sunspots.

Piddington and Davies (1953) and Dodson (1957) used alternative methods of analysis in attempts to overcome this difficulty. In each case it was found that, with the particular sets of data used, there was no clear indication of any change in quiet-Sun temperature over the sunspot cycle. On the other hand, Allen (1957) made a somewhat more elaborate analysis of the available observations and concluded that a real variation does occur. His results indicate that the greatest change (about 2 : 1 during the cycle) takes place at wavelengths near 25 cm. Christiansen, Warburton, and Davies (1957) independently confirmed Allen's conclusions. In view of these conflicting results, it is obviously desirable to make quiet-Sun observations by high resolution methods, and so avoid dependence on assumptions of correlation between radio emission and visible solar phenomena.

II. High Resolution Techniques

This paper describes two separate determinations of the quiet-Sun temperature at a wavelength of 21·2 cm (frequency=1423 Mc/s) in 1958, shortly after sunspot maximum. Both use the high resolution Christiansen crossed grating interferometer at Fleurs, N.S.W. (see Christiansen, Mathewson, and Pawsey 1957).

This aerial system consists of two long arrays, each made up of 32 steerable paraboloid elements, 6 m in diameter and spaced 12·2 m apart on a 380 m base line. The base lines are aligned north-south and east-west respectively. The arrays can be combined in the same way as in the Mills Cross (Mills *et al.* 1958), to give a multiple response pattern of pencil beams about 3′ in half-power width and 1° apart. The separation between adjacent beams is sufficient to ensure that no more than one of them can lie on the Sun at any one time ; thus the multiple-beam response does not introduce any ambiguities in solar observations. Alternatively, either array can be used alone, to give a multiple fan-beam pattern with high resolution in only one direction. The system is thus suitable for either pencil-beam scanning over the solar disk (with the complete cross), or one-dimensional strip-scanning (with a single array).

At sunspot maximum, a large part of the quiet Sun is at any time obscured by intense radio plages. Because of this, it has not been possible to observe details of the brightness distribution of the quiet-Sun component by either of these scanning methods. Both, however, were used to determine the quiet-Sun temperature; the two independent results are in satisfactory agreement with each other. The fan-beam observations have also provided some information on the distribution of quiet-Sun radiation in heliographic latitude.

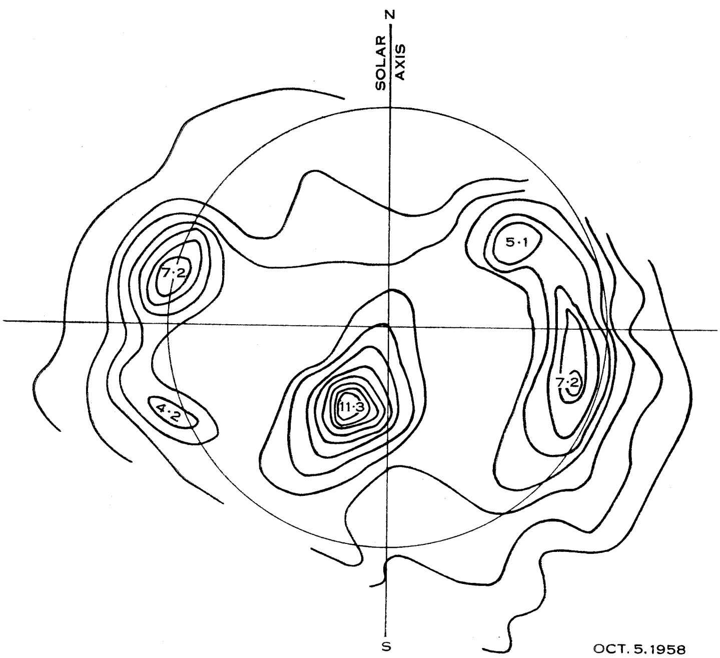

Fig. 1.—A typical contour map of the 21 cm solar brightness distribution, based on pencil-beam observations. Contour interval = 100 000 degK.

III. Pencil-beam Measurements

The solar data obtained with the crossed interferometer are summarized in daily contour maps of the radio brightness of the Sun; Figure 1 shows a typical example. It might be supposed that quiet-Sun temperatures could be read directly from each of these maps at points which on that day happened to be clear of plage areas, and that in this way a complete map of the quiet-Sun brightness distribution could be built up. The situation is, however, complicated by the presence of spurious responses to the radiation from plage areas. Like all aerials of the Mills Cross type, the crossed interferometer has rather large side lobes. The latter may be either positive or negative, and occur when a source is in a main lobe of the fan-beam pattern of one of the arrays. Their positions and magnitudes cannot be accurately predicted, as they are largely due to small accidental maladjustments in the aerial system.

Examination of the records showed that, on most days in 1958, the largest side lobes were about 4 per cent. of the main response (in terms of received power). From this, the effect of side lobes on the accuracy of quiet-Sun measurements was estimated for each of the records made between May and November 1958. It was found that in most cases the range of uncertainty was at least

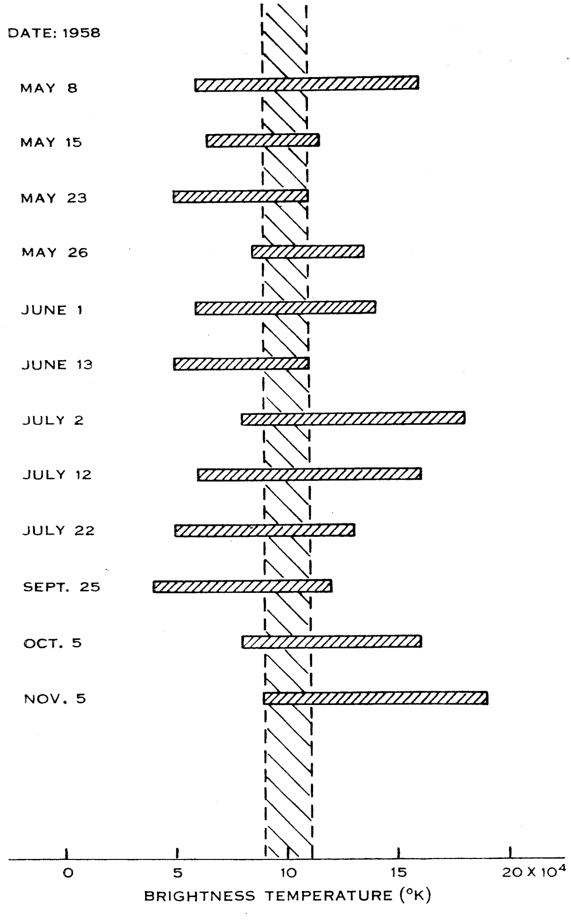

Fig. 2.—Estimation of quiet-Sun brightness temperature (at centre of visible disk) from selected pencil-beam records. The horizontal strips show the limits of error for individual records ; the vertical shaded band indicates the range of temperatures which is consistent with all the observations in the group.

$\pm$100 000 degK, which is of the same order as the expected quiet-Sun temperatures. Under these conditions, it was impossible to derive any significant information on the distribution of quiet-Sun brightness ; however, in a number of particularly favourable occasions there were points near the centre of the solar disk at which the quiet-Sun temperature could be determined within $\pm$50 000 degK. These selected observations were used in making an estimate of the central brightness temperature of the quiet Sun.

The temperatures were read from the original records, since the contour interval on the maps was inconveniently large for this purpose. The results are summarized in Figure 2. The mean value of the quiet-Sun temperature at the centre of the disk is 102 000 °K, and all the individual measurements are consistent with any value between 90 000 and 110 000 °K.

IV. Fan-beam Measurements

For the one-dimensional strip scans, one of the interferometer arrays was used alone, giving a multiple fan-beam response. The method is a modification of that used by Christiansen and Warburton (1953*a*, 1953*b*, 1955), who obtained sets of daily strip scans across the Sun in chosen directions and found the lower envelope of each set. These envelopes were the corresponding quiet-Sun profiles; the area under any one of them was a measure of the flux density of the quiet-Sun component.

The plage radiation is so intense at sunspot maximum that it becomes impossible to isolate the quiet-Sun component by this simple lower-envelope technique. The active regions are, however, mainly confined to narrow bands of heliographic latitude; it will be shown that, because of this feature of the distribution, a quiet-Sun profile can be derived even at sunspot maximum, provided that the scans are taken in a direction parallel to the solar axis.

The use of strip scans is a less direct approach to the problem than is the pencil-beam method described above. However, it avoids appreciable errors due to side-lobe responses; in the fan-beam pattern these are always very small (less than 0·2 per cent. in received power).

(*a*) *Observations*

The aerial used was the north-south array of the crossed interferometer. In directions normal to the array, where the angular resolution is greatest, the width of the fan beams (to half-power points) is 2′ arc; in the oblique directions in which the Sun was observed during this work, the beamwidth is about 3′. The directions of maximum response, when projected upon the celestial sphere, appear as small circles centred on the line of aerials. In Figure 3, a typical aerial beam is plotted in coordinates of declination and hour angle, together with the apparent diurnal path of the Sun across the sky. As each beam crosses the Sun, the receiver output records a one-dimensional strip scan. The direction of this scan, relative to the celestial meridian, depends on the solar hour angle and the declination, whilst the angle between this meridian and the Sun's axis varies annually over a range of $\pm 26°$. The scanning angle θ measured from the central meridian of the Sun (see Fig. 3) therefore depends on the time of day and year; by a proper choice of observing time, scans parallel to the solar axis ($\theta = 0°$) can be obtained.

The records used for this work were made between September and November 1958. They consist of 20 strip scans taken on different days; the scanning directions are all within $\pm 5°$ of the Sun's central meridian.

(b) *Method of Reduction*

(i) *Positions of Scans.*—The most precise method of locating a scan in relation to the Sun is to calculate the time at which the centre of the appropriate aerial beam crosses the centre of the solar disk. It was found to be sufficiently accurate, however, simply to determine this time by measurement on the record to the mid point of the scan. In all cases where comparisons were made, the times so estimated were within 5 sec of the calculated values.

The rate at which the aerial beam moved across the Sun was calculated for each observation. The scale of time in the original record was then converted into one giving the perpendicular distance from the centre of the scanning strip to that of the solar disk. To compensate for the small annual variation in the angular diameter of the Sun, all positions were expressed in terms of the apparent diameter of the visible disk at the time of observation.

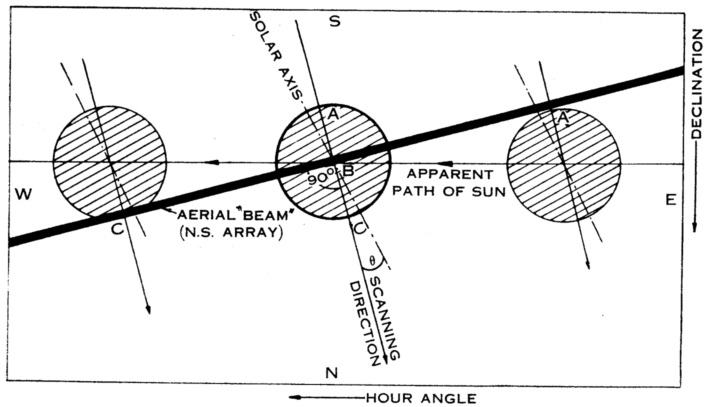

Fig. 3.—Strip-scanning across the Sun with a fan beam. The shaded circles are successive apparent positions of the Sun, at approximately 4-min intervals. θ is the scanning angle, as defined in the text.

(ii) *Intensity Calibration.*—The overall sensitivity of the equipment inevitably varied somewhat from day to day. A complete daily calibration was impracticable, owing to the difficulty in measuring losses in the complicated aerial and feeder system. Instead, a relative measure of the total energy received from the whole Sun was found for each day by integrating the strip-scan record; this was then compared with an absolute value of the total flux density obtained from an independent direct measurement. In this way a multiplying factor was found, to bring each of the scans to a common intensity scale.

The Sydney 1420 Mc/s radiometer was unfortunately not operating continuously over the required period; however, daily flux records at 1500 Mc/s were available from the Heinrich Hertz Institute, Berlin, Germany. These were adjusted to 1423 Mc/s on the assumption that the flux density is proportional to frequency. An examination of published data at frequencies from 1000 to 2000 Mc/s indicates that, for the small frequency change involved in this case, this procedure is unlikely to lead to errors of more than 1 per cent. in the derived values.

(iii) *The Quiet-Sun Profile.*—A typical scan with $\theta=0°$ is shown in Figure 4, while 20 such scans have been superimposed in Figure 5. These diagrams show clearly the characteristics of the distribution of plage areas with heliographic latitude. At sunspot maximum, practically all the major radio plages are centred in the middle latitudes; strong sources are unusual within $\pm 10°$ of the equator and very rare in latitudes higher than $\pm 40°$.

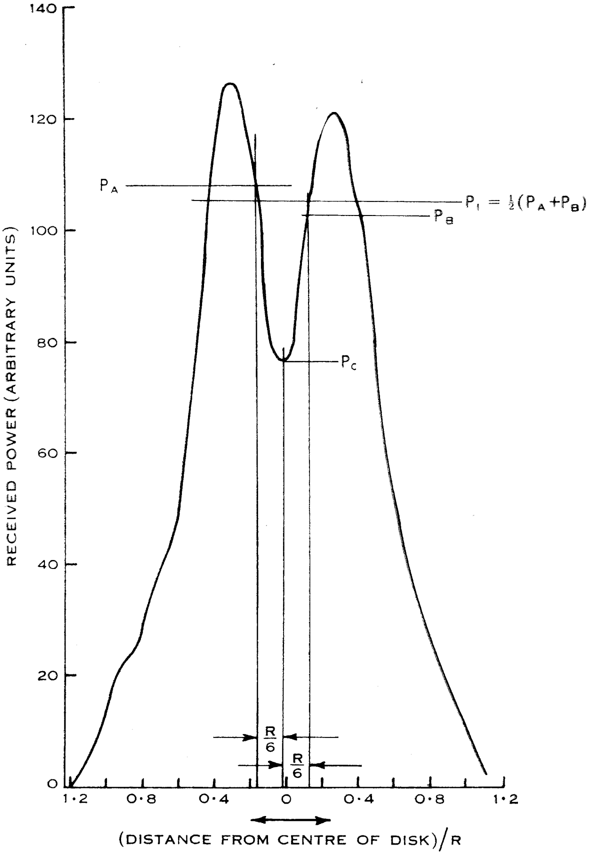

Fig. 4.—A typical strip scan, with scanning direction parallel to the central meridian ($\theta=0°$). R is the radius of the photosphere.

With the scanning direction parallel to the central meridian, therefore, the quiet-Sun profile is seriously obscured only in positions corresponding to the middle latitudes. The complete profile can be estimated by determining the equatorial and polar sections and drawing a smooth curve through the intervening unobservable region. The lower envelope is clearly defined in the polar regions; at the centre of the disk, however, there is a large scatter between individual scans, and a more elaborate method is necessary to determine the quiet-Sun value. Sources centred near the solar equator occur so infrequently that their contribution is likely to be unimportant; any excess over the quiet-Sun flux at the central minima in the scan must be due mainly to radiation from the outer parts of the intense active regions centred in middle latitudes. The influence of these is accentuated by the smoothing effect of the finite aerial beam. The problem is, therefore, to subtract the component due to these strong sources from the observed " central " values.

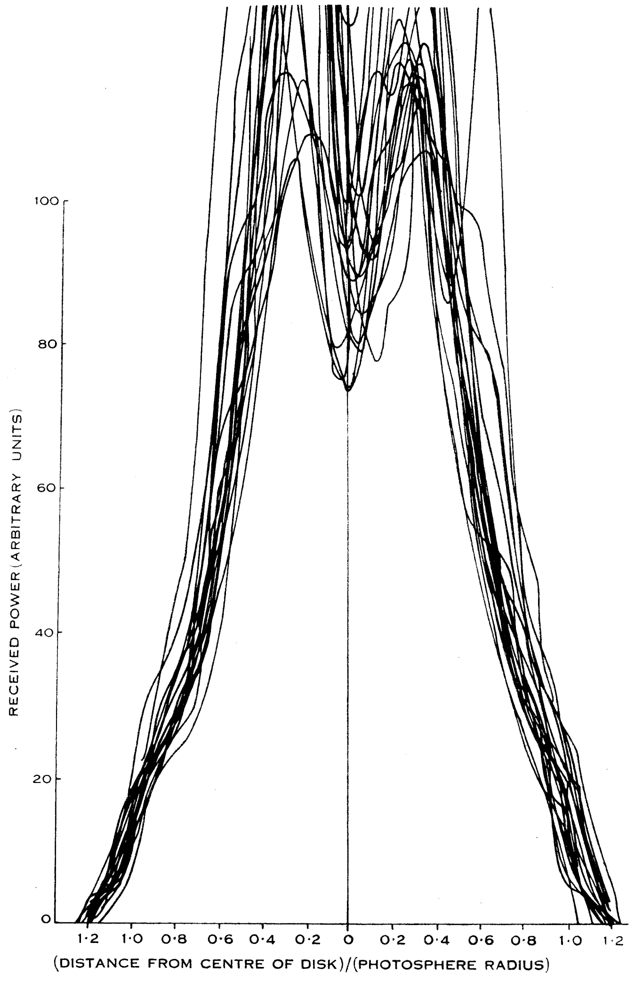

Fig. 5.—A set of 20 scans at $\theta=0°$ (Sept.–Nov. 1958).

This has been done by correlating the observed minimum value, p_c, of the flux near the centre of each record with a parameter p_1, which is used as a measure of the combined effect of the middle latitude sources. The choice of p_1 is somewhat arbitrary. An obvious possibility is to use the average of the two maximum flux values on the record. The positions of these maxima, however, vary somewhat from day to day, and it appeared preferable to take p_1 as the average of the two values at equal fixed distances on either side of the minimum position. A suitable spacing was found to be one-sixth of the solar radius, which was in all cases rather less than the distance between the positions of maximum and minimum flux density, as indicated in Figure 4.

In Figure 6, p_c is plotted against p_1. The coefficient of correlation between the two quantities is 0·80, and the points in the diagram have a clearly defined lower envelope—the straight line AB. The slope of this line is interpreted as representing the contribution of the middle latitude sources to p_c; the upward displacement from it of individual points corresponds to the occasional presence of weak sources close to the solar equator.

It is now necessary to find what part of p_c corresponds to quiet-Sun radiation. For this purpose, it is tentatively assumed that the central part of the quiet-Sun profile is flat, so that $p_c=p_1$, in the absence of any radiation from plage areas. On this assumption, the quiet-Sun value for p_c is given by the intersection of AB with the line $p_c=p_1$ (Fig. 6).

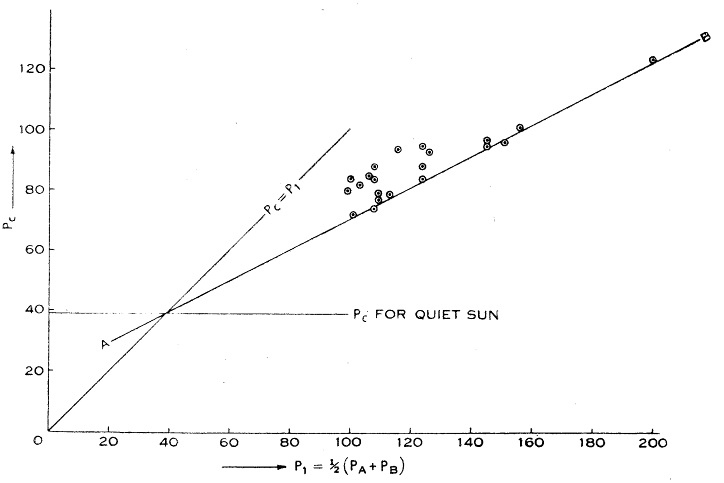

Fig. 6.—Graphical determination of central ordinate on quiet-Sun profile. The units for p_c and p_1 correspond to the vertical scales in Figures 4 and 5.

This value of p_c was combined with the polar sections of the original lower envelope, to give an estimate of the north-south profile of the quiet Sun (Fig. 7). The middle latitude part of the curve is not fixed by this procedure, but is merely interpolated by hand. It appears probable, however, that the true profile lies within the shaded area in the diagram. For any such profile, p_1 does not differ from p_c by more than 3 per cent., so that the initial assumption that $p_c=p_1$ is not invalidated.

A possible source of error in this method is the influence of sources centred near the equator on the measured value of p_1. Pencil-beam records for the dates in question show that any such sources were always too small for an effect of this kind to be appreciable.

(iv) *The Quiet-Sun Flux Density.*—The flux density of radiation from the quiet Sun can now be calculated, since it is proportional to the area under the profile in Figure 7. The constant of proportionality is determined by comparing the area under any one of the individual daily scans (on the same scale) with the corresponding observed flux density. The results range between $5 \cdot 7$ and $6 \cdot 6 \times 10^{-21}$ $\mathrm{Wm^{-2}\,(c/s)^{-1}}$ for the profiles within the shaded area of Figure 7. The corresponding apparent disk temperatures (for a uniform disk equal in size to the photosphere) are 130 000 and 150 000 °K.

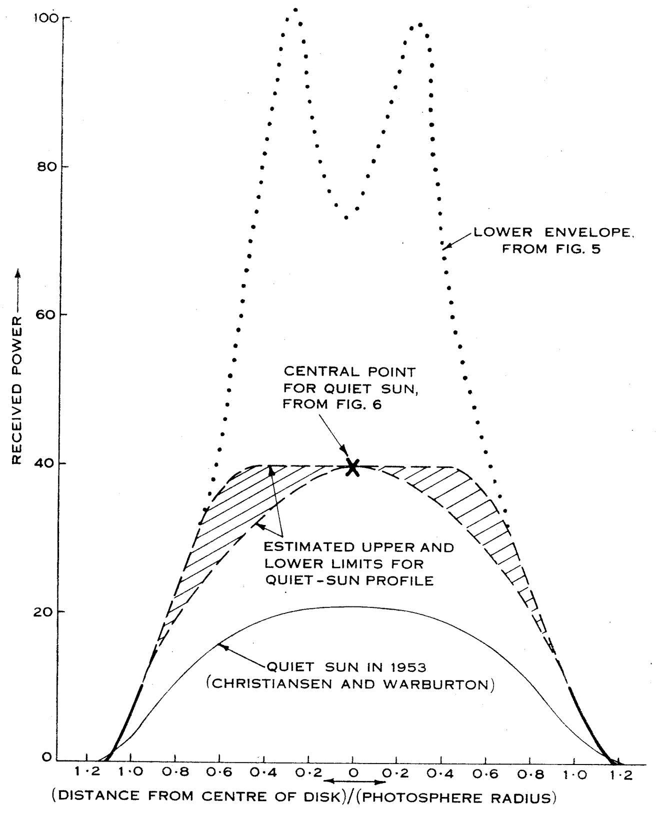

Fig. 7.—The quiet-Sun profile for $\theta = 0°$. For comparison, the corresponding sunspot-minimum profile (Christiansen and Warburton 1955) is drawn on the same scale.

V. Discussion

(a) *Apparent Disk Temperature*

The apparent disk temperature of the quiet Sun in 1958 has now been determined, and an independent estimate has also been made of the brightness temperature at the centre of the disk. In order to compare these two results, it will be assumed that the brightness distribution in 1958 was the same as that found by Christiansen and Warburton (1955) at sunspot minimum. It will be shown later that this is a reasonable assumption. The pencil-beam value of 90 000–110 000 °K for the central temperature then gives a disk temperature of

130 000–160 000 °K. This agrees with the value derived from the fan-beam observations, within the limits of error of the two experiments. For the remainder of this discussion, the apparent disk temperature for the quiet Sun in 1958 will be taken as 140 000 °K. The corresponding flux density is $6 \cdot 2 \times 10^{-21}$ Wm^{-2} (c/s)$^{-1}$.

This result shows that the quiet-Sun temperature increased by a factor of 2 between sunspot minimum and sunspot maximum ; Christiansen and Warburton (1955) give a value of 70 000 °K for the apparent disk temperature in 1953. There is thus good agreement with Allen's (1957) calculations, which indicated a variation of $2 \cdot 0 : 1$ and were based on observations at 25 cm wavelength in the period 1947–1953. The value of the quiet-Sun flux at sunspot maximum also agrees well with an earlier estimate. Christiansen, Warburton, and Davies (1957) found the flux at 21 cm by interpolating between published 10 and 25 cm results for 1947, and obtained a value of $6 \cdot 4 \times 10^{-21}$ Wm^{-2} (c/s)$^{-1}$.

(*b*) *Brightness Distribution*

For sunspot minimum, Christiansen and Warburton (1955) constructed a complete map of the quiet-Sun brightness distribution from a series of profiles at various scanning angles. This was not practicable in 1958, owing to the high level of solar activity. Some inferences can, however, be drawn from a comparison of the north-south profiles for 1953 and 1958. The 1953 curve given by Christiansen and Warburton is shown in Figure 7. The two profiles are similar in shape ; the ratio of corresponding ordinates in both the equatorial and polar sections is approximately 2 : 1. It therefore seems likely that the brightness distribution is much the same at sunspot maximum and minimum. In particular, the pronounced limb darkening at the poles, which was detected from the earlier observations, was also present in 1958. The same conclusion follows from recent eclipse observations at 21 cm wavelength (Krishnan and Labrum, in preparation).

There is no detectable variation over the sunspot cycle in the polar diameter of the radio Sun at this wavelength. The 1953 profile is slightly the broader of the two, but this difference can be explained by the lower angular resolution of the earlier aerial system.

(*c*) *Interpretation of the Results*

The primary purpose of this investigation was to determine whether the observed radio emission from the quiet Sun changes during the sunspot cycle. This has been done by making measurements at a single suitable wavelength. In order to make any detailed deductions regarding the temperature and density in the solar atmosphere, similar data for a range of wavelengths would be necessary. It appears, however, that the present empirical results are consistent with other evidence. In particular, van de Hulst (1949) estimated the coronal electron density from optical measurements and found that the density at any height increases towards sunspot maximum. From this result and assuming that the kinetic temperature of the corona does not vary, he predicted that the brightness temperature of the Sun in the decimetre-wavelength region would show changes of the order of 2 : 1 during the sunspot cycle.

VI. Conclusion

The flux density of radiation from the quiet Sun at $21 \cdot 2$ cm in 1958 was approximately $6 \cdot 2 \times 10^{-21}$ Wm^{-2} $(c/s)^{-1}$; this corresponds to an apparent disk temperature of 140 000 °K. The brightness of the quiet Sun at this wavelength increased by a factor of 2 : 1 from 1953 (sunspot minimum) to 1958 (slightly after sunspot maximum).

The data indicate that the distribution of quiet-Sun brightness with heliographic latitude does not change appreciably during the sunspot cycle. In 1958, as in 1953, there was substantial limb darkening near the poles of the Sun.

VII. Acknowledgments

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