SOLAR BRIGHTNESS DISTRIBUTION AT A WAVELENGTH OF 60 CENTIMETRES

I. THE QUIET SUN

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Summary

A multiple-element interferometer has been employed to determine one-dimensional distributions of radio brightness over the quiet Sun at a wavelength of 60 cm for scanning directions varying from 90° to 60° with respect to the central meridian of the Sun. These observations have been compared with measurements by other workers at the same, or nearly the same, wavelength. The present observations are reasonably consistent with the two-dimensional brightness distribution derived recently by O'Brien and Tandberg-Hanssen with a two-aerial interferometer, but do not agree with the earlier results of Stanier at the same wavelength. The disagreement, largely the absence of the theoretically predicted limb-brightening in Stanier's results, may reflect actual changes in the Sun over the solar cycle. However, the possibility of localized disturbed regions affecting Stanier's results for the quiet Sun cannot be eliminated.

I. INTRODUCTION

Solar radiation at decimetre wavelengths is known to consist of a steady background, attributed to the quiet Sun, and variable components that are emitted by localized disturbed regions on the Sun.

The brightness distribution of the quiet Sun is of considerable interest because of the information it may give on conditions in the solar chromosphere and corona. On the basis of model solar atmospheres derived from optical observations several workers have suggested that the Sun should show limb-brightening at decimetre wavelengths.

The first attempts to investigate this were made using eclipse observations. Christiansen, Yabsley, and Mills (1949) made detailed observations of an eclipse in 1948 to investigate the radio brightness distribution over the solar disk at a wavelength of 50 cm. But their results were not conclusive as it was found difficult to isolate completely the " quiet " component of solar radiation. In addition, the eclipse curve was insensitive to widely different, assumed distributions. Stanier (1950) used a two-aerial interferometer to derive a distribution across the quiet Sun at a wavelength of 60 cm. This showed no limb-brightening. On the other hand, limb-brightening at shorter wavelengths has been deduced from the recent observations at 3 cm by Alon, Arsac, and Steinberg (1953,

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1955), at 10 cm by Covington and Broten (1954), and at 21 cm by Christiansen and Warburton (1953*b*; 1955).

It has been found difficult to explain Stanier's distribution on the basis of currently accepted solar models. With the technique employed by him, however, there was no direct way of eliminating with certainty the slowly varying component of solar radiation. The observations were taken near the maximum phase of the solar cycle and it was likely that a number of localized, disturbed regions may have existed on the Sun. The possibility of unsuspected, localized radio-bright regions on the Sun affecting Stanier's result prompted us to use an independent technique to explore the brightness distribution across the quiet Sun at the same wavelength, by means of a 32-element interferometer. The usefulness of a multiple-element interferometer of high resolving power for a study of the different components of the solar radiation in the range of decimetre wavelengths has been shown by the results of Christiansen and Warburton (1953*a*, 1953*b*) at 21 cm.

The preliminary results of our observations of the quiet component of solar radiation, which showed considerable limb-brightening, were reported at the XIth General Assembly of U.R.S.I. At the same time it was reported from Cambridge that a recent experiment with a two-aerial interferometer also demonstrated limb-brightening at a wavelength of 60 cm. Brief reports of the results with these two independent techniques have been published recently (O'Brien and Tandberg-Hanssen 1955; Swarup and Parthasarathy 1955). The two results are compared here.

The results emerging from our observations of radiation from localized disturbed regions on the Sun will be submitted in another paper.

II. Equipment

The 32-element interferometer has been described in detail by Christiansen and Warburton (1953*a*). It consists of 32 paraboloidal aerials, each 66 in. in diameter, arranged at intervals of 23 ft in a straight line lying approximately in an east-west direction. The aerials are joined to a sensitive radio receiver by a branching system of two-wire open-transmission lines. For the present study, the aerial system was converted to operate at a wavelength of 60 cm.

The interferometer gives a number of fan-shaped beams which, at a wavelength of 60 cm, are separated by $4\cdot 9°$. The calculated half-power width of the central beam in an east-west direction is $8\cdot 2$ min of arc. Owing to rotation of the Earth, each fan-shaped beam scans the solar disk stripwise, producing a number of one-dimensional distributions across the solar disk every day. Some of the daily records are shown in Figure 1.

The aerial pattern was experimentally determined by observing the response of the radio source of Cygnus whose width at this frequency is much smaller than that of the aerial beam. The half-power width of the interferometer beam thus determined was found to be $8\cdot 7$ min of arc, instead of the calculated value of $8\cdot 2$ min of arc. The beam width was also measured by determining the excess radiation of a strong, localized, bright region (see Fig. 1 (*c*)) over that of the steady background due to the quiet Sun. This also gave the half-

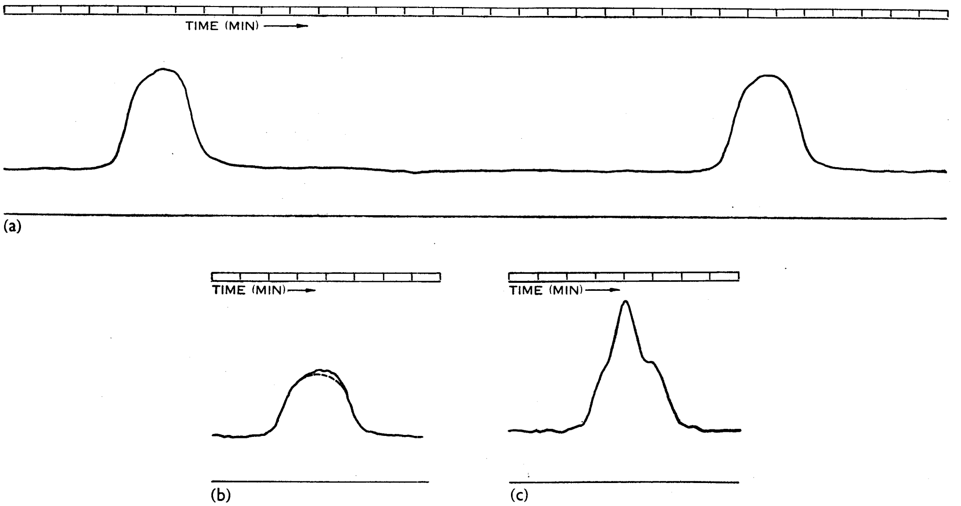


Fig. 1 (*a*).—A typical record of the passage of the Sun through successive aerial beams.
Fig. 1 (*b*).—A record for July 6, 1954 showing a small localized bright region. The dotted line indicates the quiet Sun.
Fig. 1 (*c*).—A record for December 12, 1954 showing a large bright region.

power width as 8·7 min of arc. The aerial pattern thus determined is shown in Figure 2, together with the theoretical curve for a beam of 8·2 min of arc

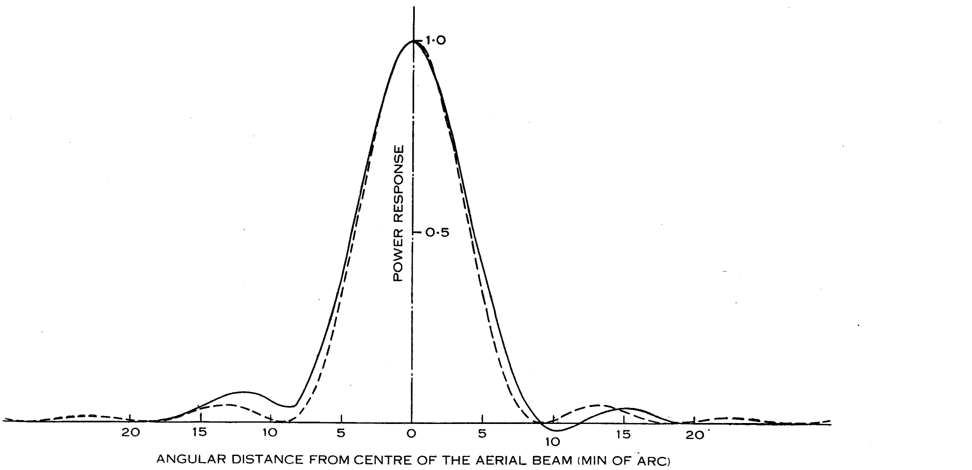


Fig. 2.—Theoretical aerial pattern (broken line) compared with the derived response of a localized bright region on the solar disk (full line).

width. The two are reasonably similar. Differences in the value of side lobes could be due to small experimental errors.

III. Observations

The contribution of radiation from the localized bright regions on the solar disk can be separated from the steady base-level component due to the quiet Sun by superimposing a number of daily records, using the method described by Christiansen and Warburton (1953*b*). The lower envelope of the records is taken to be the one-dimensional distribution across the quiet Sun. The daily

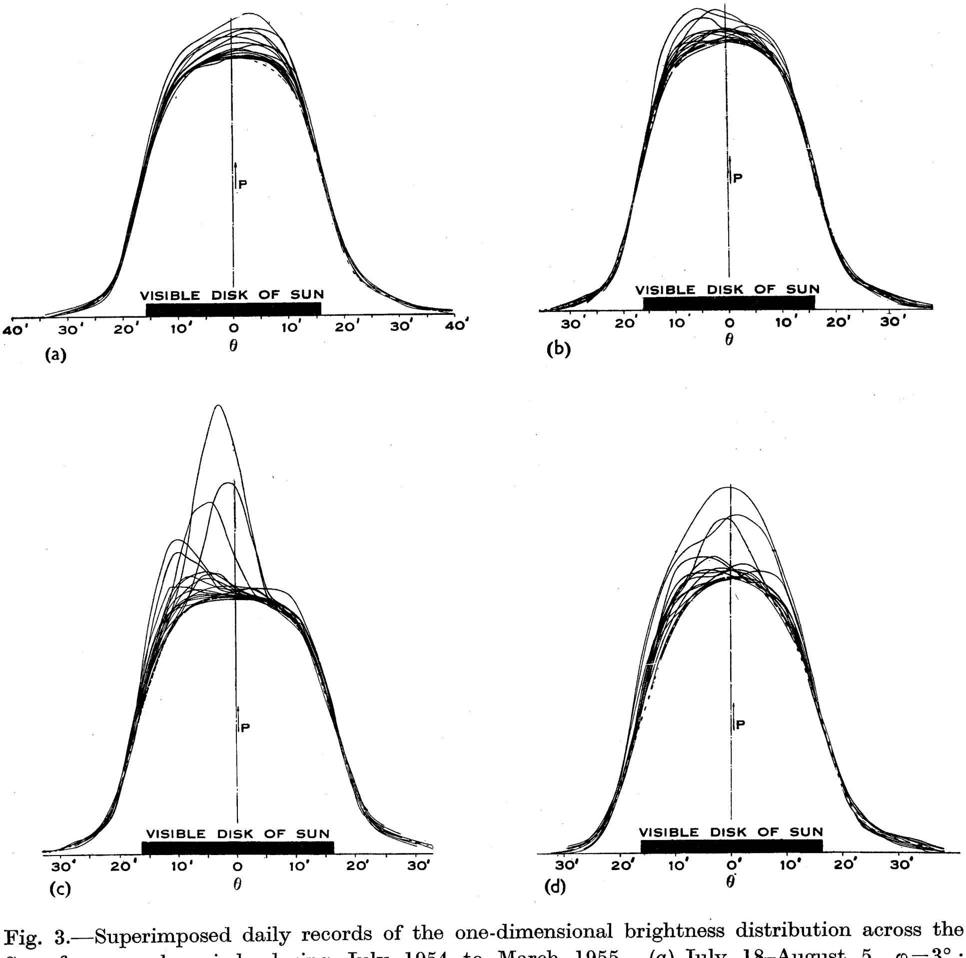


Fig. 3.—Superimposed daily records of the one-dimensional brightness distribution across the Sun for several periods during July 1954 to March 1955. (*a*) July 18–August 5, $\varphi=3°$; (*b*) August 9–September 1, $\varphi=11\cdot5°$; (*c*) December 15–January 3, $\varphi=-3°$; (*d*) February 7–March 4, $\varphi=26°$. φ is the mean angle between the scanning direction and the central meridian of the Sun; it changed by about 6° in each observing period. P is the power received in arbitrary units. θ is the angle in minutes of arc between the centre of the visible disk and the centre of the aerial beam.

records were superimposed in groups of about 20 for several periods during July 1954 to March 1955. The superimposed records are shown in Figure 3. The estimated base level is indicated by a dotted line. On several days during this period the observed records coincided with this estimated base level. At such times optical observations showed that there was no sign of sunspots or chromospheric faculae on the Sun. Hence we may conclude that the lower envelope of the superimposed records does, in fact, refer to the quiet Sun.

The direction of scanning of the solar disk by the aerial beam changed during the period of recording as a result of a variation in the position angle P of the solar axis. On normalizing the one-dimensional distributions across the quiet Sun, shown in Figure 3, to the same reference axes, it is noted that the diagrams become narrower in width when the scanning direction changes from 90° to 60° with respect to the central meridian of the Sun. This is demonstrated in Figure 4 and implies that at a wavelength of 60 cm the solar disk is not circular, but has a maximum width in the equatorial region. This is consistent with the findings of Christiansen and Warburton (1955) at 21 cm wavelength and of O'Brien (1953) at 1·5 m wavelength. Recent two-dimensional results of O'Brien and Tandberg-Hanssen (1955) at 60 cm confirm this.

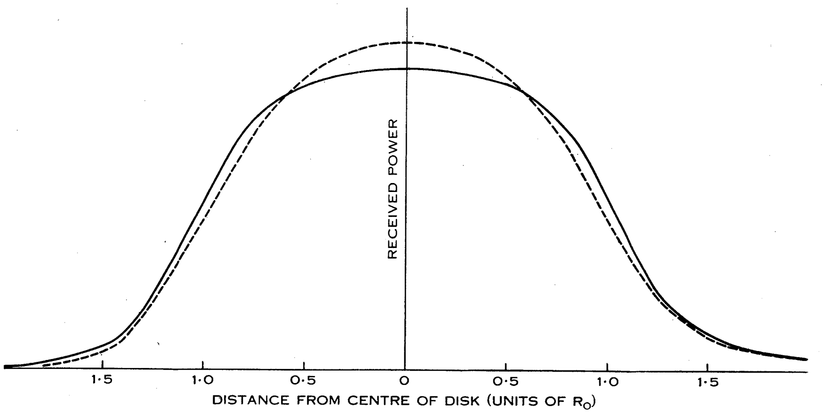


Fig. 4.—One-dimensional distributions over the quiet Sun (normalized to the same area) for scanning directions of 90° (full line) and 64° (broken line) with respect to the Sun's central meridian.

IV. Comparisons and Discussion

The present observations covered only a limited range of scanning directions. It was, therefore, not possible to derive a two-dimensional picture of the Sun without making assumptions about the Sun's shape. However, we can compare our one-dimensional distributions with the results derived by other workers at the same or nearly the same wavelength.

The comparisons to be made are with the results of Stanier (1950) and O'Brien and Tandberg-Hanssen (1955) and with the eclipse observations by various workers. These other measurements were made at different phases of the solar cycle, and this must be taken into account in any comparison. It may be mentioned here that in the present investigations the base level for the apparent disk temperature of the Sun at 60 cm was estimated to be $3 \cdot 8 \times 10^5$ °K, whereas at the time of Stanier's measurements it was estimated to be $5 \cdot 4 \times 10^5$ °K.

(a) Comparison with the Results of Stanier

Stanier used a variable-spacing two-aerial interferometer to derive the solar brightness distribution at a wavelength of 60 cm. He scanned the solar disk in the equatorial direction. To compare his results with ours, it was necessary to allow for a difference in the response for the received Fourier components in the two aerial systems. The overall spacing of Stanier's and our aerial systems is similar. That means the same range of Fourier components was measured in the two observations. However, the weighting of the Fourier components differs in the two aerial systems. The variable-spacing two-aerial interferometer attaches equal weights to all components, while the multiple-

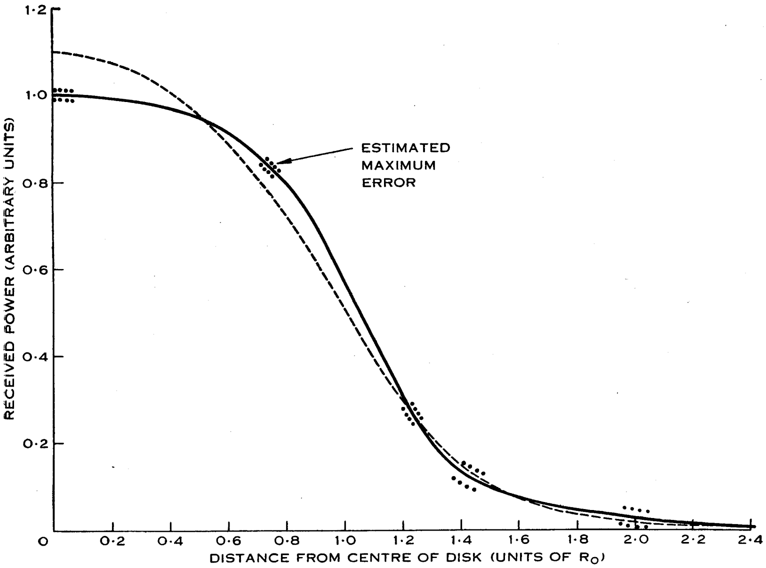


Fig. 5.—Comparison of our one-dimensional distribution over the quiet Sun for equatorial scanning direction (full line) with that derived on smoothing Stanier's distribution with our aerial beam (broken line).

element interferometer attaches weights which decrease steadily towards the cut-off frequency. Allowing for this difference, the comparison was made in two different ways.

First, the one-dimensional distribution obtained by us for the equatorial scanning direction was compared with that of Stanier's. The latter was not published in his paper. It was here derived by smoothing the published radial brightness distribution, which was derived on the assumption of circular symmetry, by our aerial pattern. This is an equivalent process to reducing the weights of the Fourier components in Stanier's distribution to those of ours. The two curves are shown in Figure 5 ; they differ by amounts which considerably exceed our estimated error.

The effect of this disagreement shows out more clearly when the corresponding radial brightness distributions are compared. For the purpose of this comparison we derived the radial brightness distribution from our equatorial scan by assuming, like Stanier, a circularly symmetrical Sun. The different response of the two aerial systems was here allowed for by restoring the Fourier components of our one-dimensional distribution. This was done by an approximate method described by Bracewell (1955). Our radial brightness distribution shows considerable limb-brightening (Fig. 6) whereas Stanier's results show limb-darkening.

(*b*) *Comparison with the Results of O'Brien and Tandberg-Hanssen*

Recently O'Brien and Tandberg-Hanssen (1955) obtained a two-dimensional distribution across the Sun at 60 cm by a series of measurements with a variable-spacing two-aerial interferometer in which the Sun was scanned in several directions. Their distribution, which is non-circular, exhibits limb-brightening. In order to compare our one-dimensional distributions with their two-dimensional

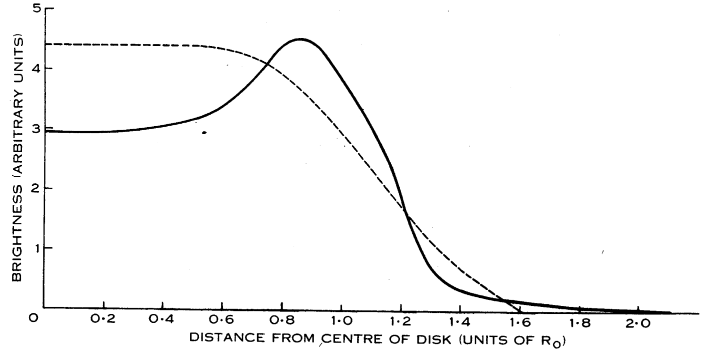


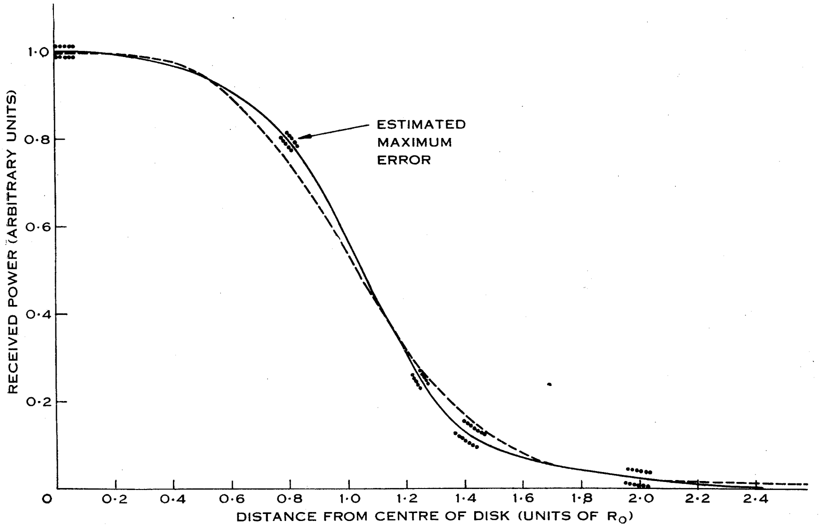
Fig. 6.—Radial brightness distribution across the solar disk at 60 cm derived on assumption of circular symmetry. The full line is the one derived by us and the broken line that by Stanier. Both are normalized for the same apparent disk temperature of the Sun.

distribution, the latter was smoothed by the aerial pattern of the 32-element interferometer. The smoothed curves for scanning directions of 90° and 64° with respect to the central meridian of the Sun are in fair agreement with our one-dimensional distributions when the Sun was scanned in the same directions. The results are shown in Figure 7.

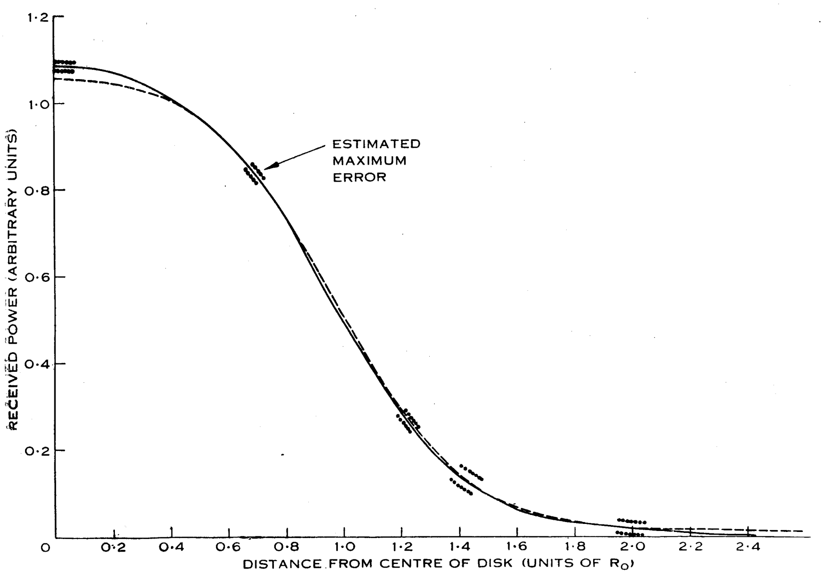
The remaining discrepancy we believe to be greater than our errors of observation. Since both series of observations are subject to limitations of resolving power associated with the aerial aperture or spacings employed, we examined the distribution of the Fourier components of the two distributions. The distribution for the equatorial scanning direction was used in each case. Our distribution shows significant components nearly to the cut-off frequency corresponding to the size of our aerial system (aperture 350 wavelengths). O'Brien and Tandberg-Hanssen used spacings up to 260 wavelengths, but were unable to detect any components greater than that corresponding to a spacing of 200 wavelengths. In addition, on July 6 and 7 when O'Brien and Tandberg-Hanssen obtained one of the records, there was a localized bright region of low intensity (see Fig. 1 (*b*)) which would not be detected in their experiment and would have produced a small error in the results.

(c) *Comparison with Eclipse Results*

We have shown above that Stanier's observations do not agree with the present ones. This may merely reflect actual changes in the quiet Sun, as seen at a wavelength of 60 cm, between the two observing periods. To examine



(a)



(b)

Fig. 7.—Comparison of our one-dimensional distributions (full line) with those derived on smoothing the two-dimensional distribution of O'Brien and Tandberg-Hanssen with our aerial beam (broken line). (*a*) Scanning direction 90°, (*b*) scanning direction 64°.

this possibility various brightness distributions were compared with eclipse results.

O'Brien (1953) found reasonable agreement of Stanier's distribution with the 1948 eclipse results of Christiansen, Yabsley, and Mills (1949). But agreement with an eclipse curve is not very significant, though a disagreement is, because the eclipse curves are insensitive to widely different brightness distributions ; for instance, Blum (1953) showed that an elliptical model of the Sun could also explain the eclipse results of Christiansen, Yabsley, and Mills.

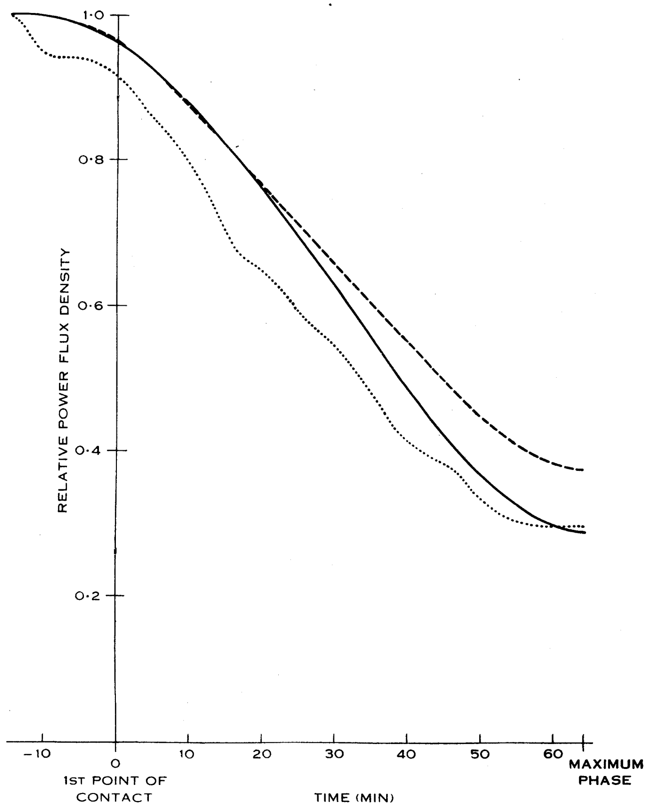


Fig. 8.—Comparison of 1948 eclipse curves at 50 cm with the artificial eclipse curve derived for the brightness distribution of O'Brien and Tandberg-Hanssen at 60 cm.

—— Artificial eclipse curve derived for the distribution of O'Brien and Tandberg-Hanssen.

···· Observed curve for 1948 eclipse.

---- Curve derived for the quiet Sun by Christiansen, Yabsley, and Mills.

However, the 1948 eclipse curve derived for the quiet Sun by Christiansen, Yabsley, and Mills for the observing station, Strahan, does not agree with the curve obtained by artificially eclipsing the distribution of O'Brien and Tandberg-Hanssen (see Fig. 8). It is true that the 1948 quiet Sun curve was derived indirectly and may not be correct. However, at the maximum phase of the eclipse the artificial eclipse curve gives the same residual as the directly observed experimental curve. The former refers to the quiet Sun while the latter clearly exhibits the presence of excess radiation from localized disturbed regions situated in the eclipsed part of the Sun. Only the north polar region of the Sun was not eclipsed. It is difficult to reconcile the presence of the same residual unless the quiet Sun distribution has changed during the period from 1948 to 1954. The alternative explanation is that at the time of the 1948 eclipse the radiation from localized regions in the vicinity of the pole (that is, the uneclipsed part) was equal to or greater than that from these regions in the equatorial zone of the Sun. This would seem most unlikely.

O'Brien and Tandberg-Hanssen (1955) claim that their results conform with 1954 eclipse observations. Their radio brightness distribution also agrees with our observations. Therefore the disagreement with the 1948 eclipse curve suggests that the quiet Sun may have changed during the period. Such a change might be expected, since it is well known that marked changes in the appearance of the solar corona occur during the solar cycle.

V. Conclusions

One-dimensional distributions over the quiet Sun have been obtained for the present minimum phase of the solar cycle. The method employed draws a clear distinction between the quiet Sun radiation and that from temporary and localized disturbed regions. This is not so for the method employed by Stanier who derived the brightness distribution over the quiet Sun at the same wavelength during the last maximum phase of the solar cycle. The measurements described here do not agree with Stanier's results. However, the measurements are in reasonably good agreement with the two-dimensional distribution over the Sun at the same wavelength derived by O'Brien and Tandberg-Hanssen with Stanier's method. Evidence is presented which suggests that the brightness distribution over the quiet Sun may have changed between the last sunspot maximum and the present sunspot minimum. But it is not possible to say whether this change fully accounts for the discrepancy between Stanier's and our results, or whether Stanier's quiet Sun distribution was affected by radiation from disturbed regions which might have been present in the Sun at the time of observations.

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