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

II. THE QUIET SUN—ONE-DIMENSIONAL OBSERVATIONS

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Summary

Daily records of one-dimensional distribution of radio brightness over the Sun are obtained in the way described in Part I of this series (Christiansen and Warburton 1953). When superimposed, these records show a well-marked lower envelope which remains substantially the same, in shape and size, over a period of months. This envelope gives the brightness distribution over the "quiet" Sun. The direction of scan, with respect to the position of the solar axis, changes during a year by more than 50°. The very small change in shape of the envelope during this period suggests that for purposes of preliminary calculation the brightness distribution may be assumed to be circularly symmetrical. The radial distribution of brightness, calculated on this basis, is found to show marked limb-brightening and to be consistent with the calculated brightness distribution for a simple solar model in which the assumed values of temperature and density are close to those commonly accepted.

I. INTRODUCTION

The Sun is known to show limb-darkening when viewed optically. This is attributed to the negative temperature gradient outwards in the photosphere. What might be expected at radio frequencies cannot be determined from temperature gradients alone, because one cannot assume that all rays reach effectively infinite optical depth (Smerd 1950). However, the high temperature of the corona relative to the inner atmosphere of the Sun, derived from optical evidence and confirmed by radio observation (Pawsey 1946 ; Pawsey and Yabsley 1949), is likely to lead to limb-brightening at some radio frequencies. This was first suggested by Martyn (1946, 1948). More detailed calculations by Unsöld (1947), Waldmeier and Müller (1948), Smerd (1950), Denisse (1950), and Reule (1952) have shown the magnitude of limb-brightening to be expected from various "models" of the Sun. All have indicated marked limb-brightening at some part of the centimetre-decimetre range of wavelengths.

Much information on electron temperatures and densities in the chromosphere and corona, and particularly in the relatively unknown transition region between these, could be gained from observed brightness distributions at different radio frequencies. Many attempts have been made to derive the brightness distribution, usually during solar eclipses. Results to date have been disappointing, mainly because of the difficulty of separating the effects of small

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areas of enhanced radio brightness (usually associated with sunspots) from the background or " quiet-Sun " radiation. This difficulty arises because in a single set of observations, such as that obtained during a solar eclipse, variable and constant components cannot be distinguished from each other. In addition, the reduction of eclipse observations to a one-dimensional or a radial brightness distribution presents considerable, if not insurmountable, difficulties. It is clearly desirable to obtain a brightness distribution of simple geometry and high resolution and capable of being separated into steady background and short-lived components.

In an attempt to measure the brightness distribution over the solar disk in the absence of variable components, Stanier (1950) recorded the radiation from the Sun during periods when the Sun was relatively free from areas of enhanced radio brightness. A two-aerial interferometer was used and the amplitude of the interference pattern was determined for different spacings between the aerials. From these a one-dimensional brightness distribution over the solar disk was derived and, by an assumption of circular symmetry, the radial brightness distribution was determined. Stanier found no sign of the expected limb-brightening at a wavelength of 60 cm.

The results obtained, however, must be treated with some reserve since the relative phases of the Fourier components were not determined and it was necessary therefore to assume that the one-dimensional brightness distribution was symmetrical. The published experimental curves show the presence of localized bright areas, which are probably situated asymmetrically with respect to the centre, and these could cause an error in the final result.

A more direct way of determining the one-dimensional brightness distribution is obviously to be preferred. The 32-element interferometer described in Part I of this series (Christiansen and Warburton 1953), which has a beam width in an east-west direction of only 3′ of arc, has been employed for this purpose at a wavelength of 21 cm.

II. Observations

As described in Part I, daily records of the one-dimensional brightness distribution across the solar disk are obtained. These daily records normally show peaks of intensity which change in position from day to day and indicate the effects of areas of enhanced radio brightness on the disk. The change, with time, in the shape of the brightness records makes possible an investigation of the existence of a steady base-level component of the solar radiation and a determination of its brightness distribution.

The method adopted was to superimpose a number of daily records and investigate the lower boundary of these curves. Before this could be done, however, it was necessary to ensure that the curves were all on the same scale and to find reference axes by means of which the curves could be superimposed. Changes in the gain of the system from one day to the next were detected, as stated in Part I, by a daily measurement of the area of the interferometer record produced by the Sun's passage through the aerial beam and a comparison of this with the reading of an instrument which registered the magnitude of the radio energy received from the whole solar disk. The result could be checked by comparison of suitable parts of the interferometer records on successive days. Hence short-term changes in the vertical scale of the records could be detected and corrected.

Short-term changes in the horizontal (time) scale of the records were small and could be detected by measuring the distance between successive time marks on the records. Longer-term changes will be mentioned later.

In superimposing records for different days, the horizontal and vertical registration lines are respectively the line drawn by the receiver when the aerial beams are directed away from the Sun and a line drawn at the instant when the centre of the solar disk passes through an aerial beam. The position of this second line on the record can be found from calculations of the directions of the aerial beams and from astronomical data relating to the Sun.

Calculations of the relative positions of the Sun and aerial beams were carried out for several weeks and lines were drawn on the interferometer records corresponding to the times of passage of the centre of the solar disk through the aerial beams. It soon became apparent that these lines always fell very close to the centre of the patterns on the interferometer records, the maximum difference corresponding to a time interval of less than 4 sec. This indicated that the central lines of the optical and radio disks could be considered identical for the purposes of this investigation. The central lines could be determined therefore with sufficient accuracy by simple measurements on the records rather than by tedious calculation. This practice was followed for a large number of the records displayed in this paper.

The sets of superimposed records were each confined to convenient periods of about one solar rotation. This was adequate to establish a lower envelope and in addition gave the possibility of investigating longer-term changes in brightness distribution. Before a comparison could be made between different sets of records, however, further corrections had to be made to allow for annual effects.

The first annual effect is the changing declination of the Sun. The time of passage of the Sun through an aerial beam varies with the secant of the Sun's declination. This causes a change in the width of the record of the Sun's passage through the aerial beam, and this must be taken into account before a comparison is made between records separated in time by many days.

A second annual effect is the change in apparent size of the Sun during the year. Unlike the effect of declination changes, this does not affect the gain calibration procedure but it has simply the effect of increasing the size of the record in height and width. The changes are small, being less than 4 per cent.

A third annual effect is the change in the inclination of the Sun's axis relative to that of the Earth (and hence the aerial system) during the course of the year. This may result in changes in the recorded apparent width of the disk if this is non-circular.

III. Results

In Figure 1 are shown five sets of records obtained over a period of 9 months. A well-defined lower envelope is seen on these records and its position has been indicated for each set of observations. The areas of enhanced brightness are seen above a constant base level.

This lower envelope has the same height (within a few parts in 100) for all sets of observations. After the corrections have been applied it is found that the shapes of the curves are similar. Hence the results provide good evidence for the existence of a " quiet " component of the radio-frequency emission from the Sun.

It may be noted that the lower envelope is occasionally approached when there is little sunspot or other activity on the solar disk. We infer from this that during the present part of the solar cycle the emission sometimes falls to the base level at this wavelength, which corresponds to an apparent disk temperature of approximately 7×10^4 °K.

Although the distribution of brightness appears to remain constant during the period of the measurements, a careful comparison shows a very small systematic change in the apparent angular width of the Sun over this period. In Figure 2 the measured angular width of the solar disk, as derived from the five determinations of quiet-Sun brightness distribution, is plotted against the inclination of the Sun's axis (projected on the disk) relative to the direction on the disk of the strip which is being scanned at any instant by the aerial. Very little change in the apparent width of the solar disk is found as the direction of scanning changes. The small change that is present appears to indicate that the Sun is widest in the equatorial region. This latter conclusion was reached also by Blum, Denisse, and Steinberg (1952) who found that the solar disk had a markedly elliptical shape at metre wavelengths. Our results, however, are not conclusive, and further work over a much larger range of angles will be necessary before definite conclusions can be reached.

The effect found at 21 cm wavelength is small enough to justify the assumption of circular symmetry for the purposes of a preliminary analysis. On the basis of this assumption it is possible to determine the radial distribution of brightness over the disk. In Figure 3 is shown the radial brightness distribution over the solar disk as calculated from the five separate one-dimensional distributions of Figure 1 by means of an approximate method. It will be noted that the shapes of the curves are strikingly similar.

All of the diagrams shown in Figures 1, 2, and 3 are smoothed by the effect of the finite width of the aerial beam. Various methods are available to reduce this effect, although it is not possible to resolve features which have an angular width which is much less than that of the aerial beam. In Figure 4 (full line) the effect of the aerial has been partly removed from the curve of Figure 3 (*c*) by use of a simple iterative process described by Bolton and Westfold (1950). As a check, the effect of passing the aerial beam over the distribution of Figure 4 has been calculated and the one-dimensional brightness distribution found. This is shown in Figure 5 together with the experimental curve which was the starting point of the analysis.

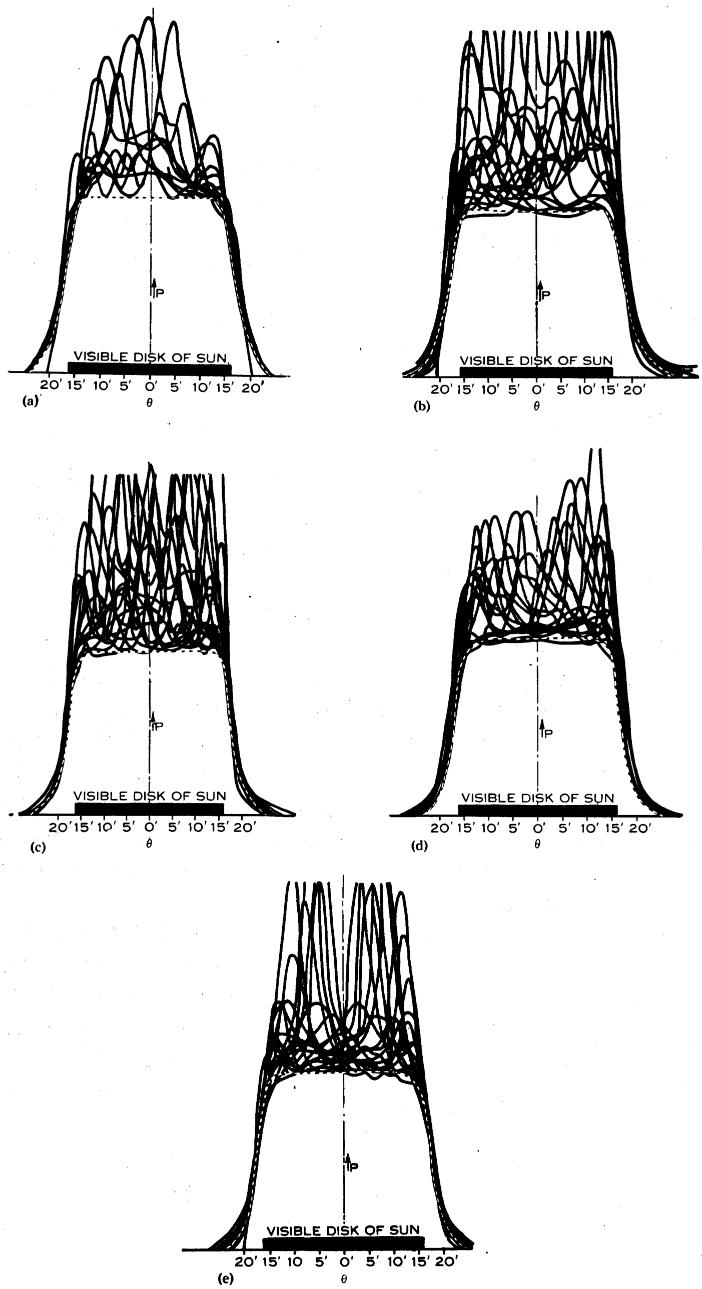

Fig. 1.—Superimposed daily records of the one-dimensional radio brightness distribution across the Sun during 1952. (*a*) March 15 to April 9, (*b*) June 20 to July 10, (*c*) August 22 to September 12, (*d*) September 13 to October 3, (*e*) October 7 to October 28. The dotted lines show the estimated base levels. P is the power received, in arbitrary units. θ is the angular separation between the centre of the aerial beam (scanning strip) and the centre of the optical disk of the Sun in minutes of arc.

The curve of Figure 4 is consistent with observations but these could equally well be satisfied if the bright ring round the edge of the solar disk were considerably sharper than is shown in Figure 4. The amount of energy in this bright ring can be calculated from this curve, but only the outer limit of its width can be derived. In Figure 4 a dotted line has been drawn to indicate one of an infinite number of distributions that could not be distinguished from that obtained from the measurements. Marked limb-brightening, of course, is a feature of all of these distributions.

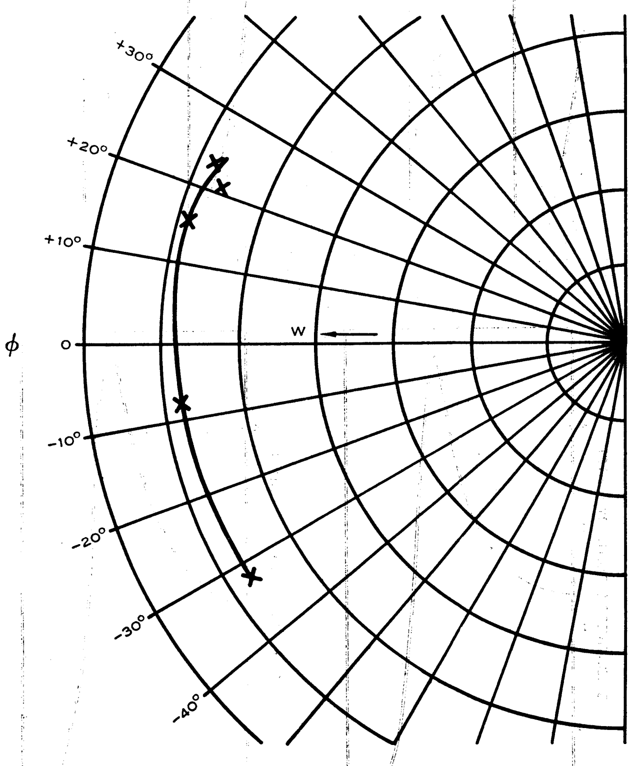

Fig. 2.—Apparent width W of the solar disk, between half-amplitude points on the curves of one-dimensional brightness distribution.
φ is the angle that the scanning strip on the disk makes with the projection on the disk of the Sun's axis.

From the brightness distribution at only one frequency it is not possible to derive the physical characteristics of the solar atmosphere. It is possible, however, to eliminate various possibilities by comparing the experimental curve with those derived theoretically from various solar models. A comparison has been made with some curves published by Smerd (1950) who assumed chromospheric and coronal densities derived from Cillié and Menzel (1935) and from Baumbach's formula as modified by Allen (1947) together with an isothermal corona and an isothermal chromosphere with several assumed values of electron

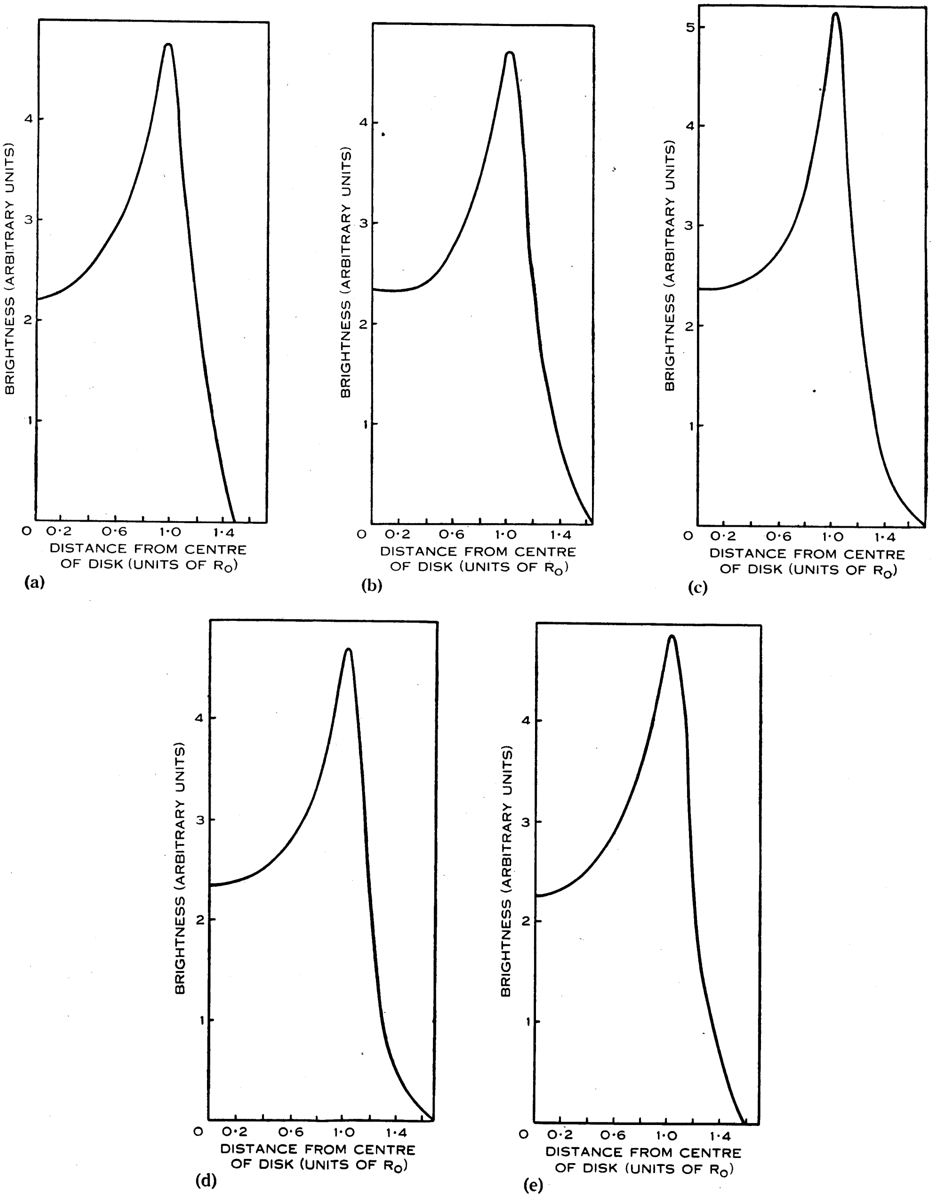

Fig. 3.—Radial distributions of radio brightness across the solar disk, derived from the one-dimensional distributions shown by dotted lines in Figure 1. R_0 is the radius of the visible disk.

temperatures. Smerd* (personal communication) has recently extended his calculations to include a greater range of temperatures and densities.

The curves published by Smerd for wavelengths close to 21 cm show the limb-brightening feature of the experimental distribution but show differences in

* The writers are indebted to Mr. Smerd for the use of these unpublished calculations.

detail. A comparison of the experimental distribution and the unpublished curves calculated for a wavelength of 21 cm reveals a reasonably good agreement, in the region from the centre of the Sun to a little beyond the optical limb, for a model in which the chromospheric temperature is 10^4 °K, the coronal temperature

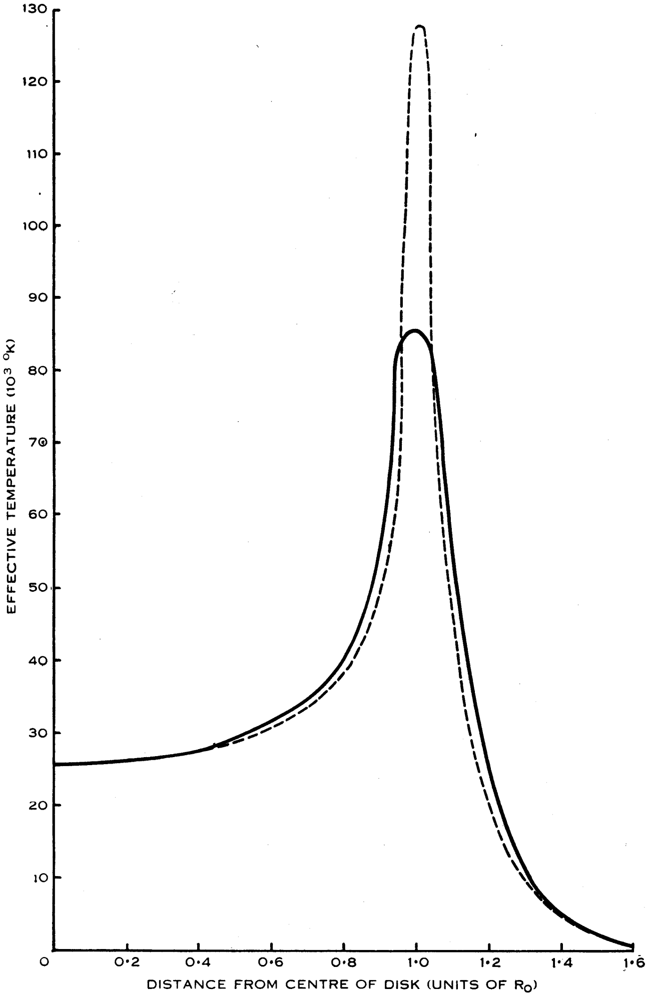

Fig. 4.—Radial brightness distribution across the Sun, derived from (*c*) of Figure 3. The effects of the finite beam width of the aerial have been partly removed (full line). The dotted line shows a typical distribution which would produce an effect on the aerial similar to that shown by the full line.

is 3×10^6 °K, and the coronal densities are as given by the Baumbach-Allen formula.

The agreement is still good if the assumed value of coronal temperature is reduced to 3×10^5 °K provided that the coronal densities are reduced to one-half of the values given by the above formula. Hence the experimental brightness distribution at 21 cm does not lead to unique conclusions with respect to the coronal temperature.

In the region well outside the visible disk all the calculated distributions of brightness, for the ranges of coronal densities and temperatures quoted above, decrease more rapidly with increasing distance from the centre than does the observed distribution. This suggests that the actual rate of decrease in the outer corona is less than that given by the Baumbach-Allen formula.

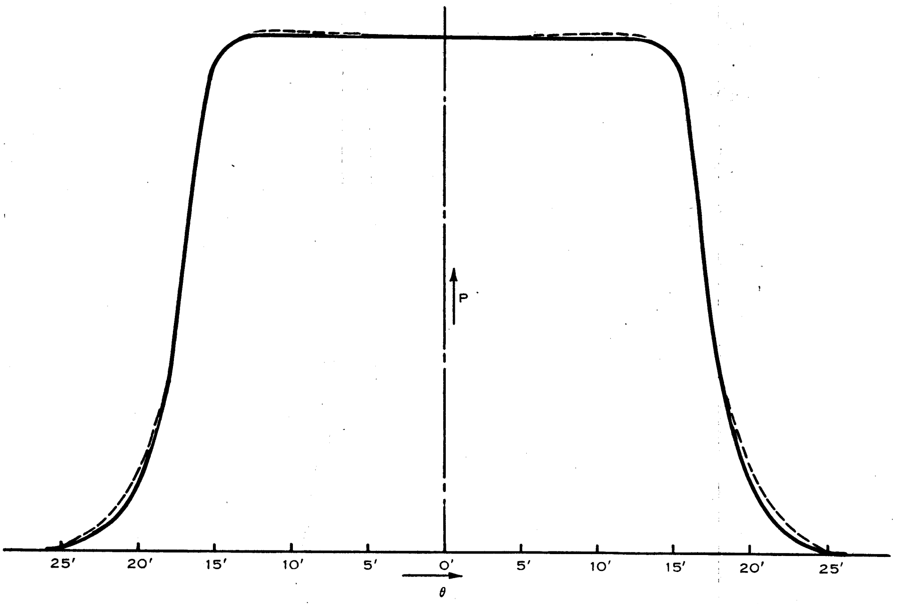

Fig. 5.—Check on Figure 4. The full line shows the experimental one-dimensional brightness distribution from which Figure 4 (full line) was derived. The dotted line shows the calculated effect of scanning the curve of Figure 4 with an aerial of 3′ of arc beam width.

IV. Conclusions

The presence of a clearly defined lower boundary to the daily curves of one-dimensional radio-brightness distribution for the Sun gives conclusive evidence for the existence of a base or quiet level in the radio-frequency emission from the Sun.

The solar disk appears to be nearly circularly symmetrical at a wavelength of 21 cm.

If circular symmetry is assumed, then the derived radial brightness distribution at a wavelength of 21 cm shows marked limb-brightening.

The distribution of radio brightness is in fair agreement with calculations from solar models involving a 10^4 °K chromosphere and a $0 \cdot 3$–$3 \cdot 0 \times 10^6$ °K corona, provided that coronal densities lie between $0 \cdot 5$ and $1 \cdot 0$ times the values usually quoted.

V. Acknowledgments

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