1983SoPh...87..391S

OBSERVATIONS ON THE SLOWLY VARYING COMPONENT OF SOLAR RADIO EMISSION AT DECAMETER WAVELENGTHS

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(Received 14 September, 1982)

Abstract. We have made two-dimensional maps of the slowly varying component (SVC) of solar radio emission at a frequency of 34.5 MHz with half power beam width of 26′/40′. It is found that a majority of SVC sources have brightness temperatures of the order of 0.5×10^6 K and half power widths of about $4\,R_\odot$. The shifts in the positions of the centroids of the SVC sources from the center of the Sun were in the range 1.5 to $2\,R_\odot$. These observations can be explained in terms of thermal emission from coronal regions of enhanced density and temperature located at distances of 1.5 to $2\,R_\odot$ from the center of the Sun.

1. Introduction

We have been observing the Sun with a large decameter wave antenna system during the last three years. Among other things, we have detected very weak continuum radiation from the Sun where there is no burst activity at long wavelengths. The brightness temperature of this radiation was usually in the range 0.3×10^6 to 1.5×10^6 K. We believe that this radiation is the extension of the 'Slowly Varying Component' (SVC) to decameter wavelengths. We have already reported our one-dimensional measurements and results on this radiation, Sastry *et al.* (1981). Since July 1980 we have been making two-dimensional maps of the sources of SVC at decameter wavelengths, whenever possible. In this paper we present the results of these observations and discuss some of the implications.

2. Equipment and Observations

The observations reported here are made with the low frequency radio telescope at Gauribidanur (Lat. 13° 36′ 12″ N and Long. 77° 26′ 07″ E). The telescope can be operated in the frequency range 25 to 35 MHz and the present observations were made at a frequency of 34.5 MHz. The antenna system of the telescope consists of two broad-band arrays arranged in the form of a '*T*'. The half-power beam widths of 34.5 MHz are 26′ and 40′ s (δ–14°.1) in the EW and NS directions, respectively. The collecting area is approximately $250\,\lambda^2$. The telescope is of the transit type and the beam can be pointed anywhere along the meridian in the zenith angle range ±45° using remotely controlled diode phase shifters. A time multiplexing system is used to cycle the beam through eight different declinations sequentially, the beam being changed from one

Solar Physics **87** (1983) 391–399. 0038–0938/83/0872–0391$01.35.

direction to another in a few milliseconds. The receiving system extracts the in-phase (cos) and the quadrature (sin) correlations between the two arms for each one of the eight beam positions. Pre-detection bandwidths of 30 and 200 kHz and post-detection time constants ranging from 1 to 30 s are available. The output of the receiving system is recorded in both analog and digital forms. Full details of the telescope will be published elsewhere.

The observations on the Sun were made with a 200 kHz band width and 10 s time constant. Drift scans were taken daily in hour angle for about 15 min on either side of transit of the center of the Sun. The declination range was 3°.2 centered on the Sun and is covered in steps of 24′. On most days the Sun was active and a variety of transient bursts were recorded. However, on some days when there was no burst activity we were able to make two-dimensional maps of the weak continuum radiation. Out of a total of 520 days of continuous observing during the period July 1980 to December 1981, only 60 days were suitable for making the maps of the SVC sources.

These observations were calibrated mainly using the radio sources 3C123, 3C274, 3C348, and 3C218. The assumed flux densities of these sources are 616, 3853, 1860, and 1750 Jy, respectively. The errors in these values are about 5% of the quoted values. The peak brightness temperatures, T_b, is equal to

$$T_b = \frac{9.24 \times 10^5 \alpha S}{\theta \phi} ,$$

where α is the ratio of antenna temperatures due to the Sun and the calibrator. S is the flux density of the calibrator (janskys): θ and ϕ are the east–west and north–south half power beam widths of the antenna system in minutes of arc. The errors in the estimation of the brightness temperature are mainly due to: (1) the variations in the antenna gain with zenith angle; (2) the uncertainty in the flux densities of the calibrators; and (3) the variable attenuation due to the ionosphere. We believe that the observed brightness temperatures are accurate to within ±20%. The errors in the position of the centroids are difficult to estimate. These errors are essentially due to the regular and irregular refraction in the ionosphere. On the basis of a series of measurements on point sources we find that the regular refraction at noon time is usually around 10 to 15 arc min in declination although in rare cases it can be as high as 30 arc min or more. Taking into account these effects the total uncertainty in the position of the centroids will be of the order of ±10 arc min. The peak brightness temperature, the brightness temperature at the center of the Sun, the half power widths, and the angular distance of the peak of the brightness temperature distribution from the center of the Sun were obtained for each day, for which data was available.

3. Results

The observed brightness distribution maps for six days are shown in Figures 1a, b, c, d, e, f. The measured values of peak temperatures, temperatures at the centre of the Sun,

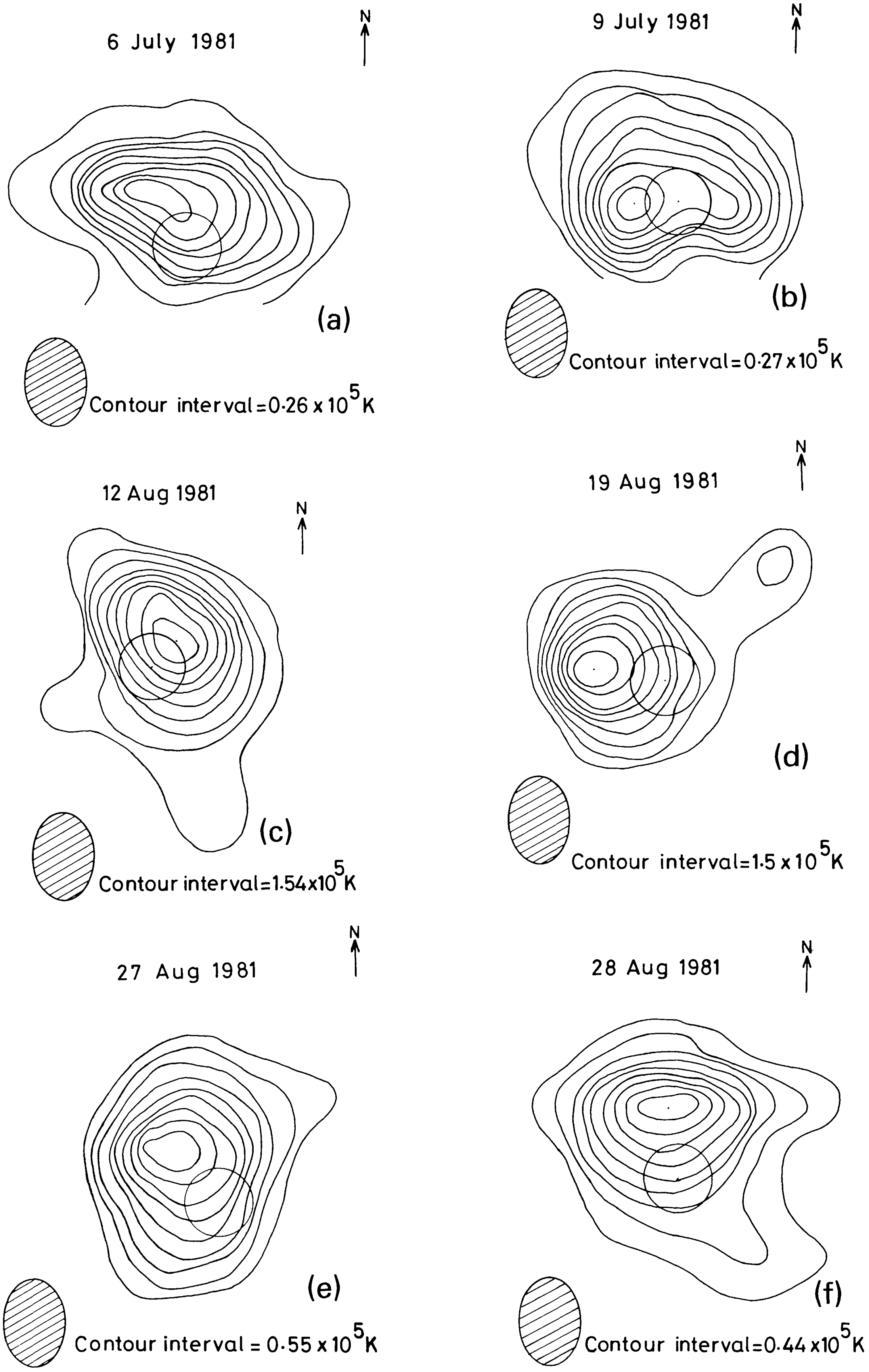

Fig. 1. Brightness temperature distribution across the Sun for various days.

TABLE I

Date	Position angle	Peak brightness temperature (× 10^6 K)	Brightness temperature at the center of the Sun (× 10^6 K)	Half power width of brightness distribution: Major axis ($R_\odot$)	Half power width of brightness distribution: Minor axis ($R_\odot$)	Shift of the centroid from the center of the Sun ($R_\odot$)
July 6, 1981	25°	0.26	0.20	6.1	3.0	1.54
July 9, 1981	90°	0.27	0.20	5.3	4.0	1.40
August 12, 1981	315°	1.54	1.15	4.4	3.2	1.2
August 19, 1981	78°	1.48	0.81	3.5	3.1	2.1
August 27, 1981	40°	0.55	0.35	4.2	4.2	2.0
August 28, 1981	05°	0.44	0.22	4.8	3.3	2.1

the half-power widths and the shifts of the centroid from the centre of the Sun are given in Table I. These represent typical samples of the maps we obtained on all other days. It can be seen that there is only a single peak of emission in all the maps. This is probably not a convolution effect, due to our beam size since the angular size of the SVC sources

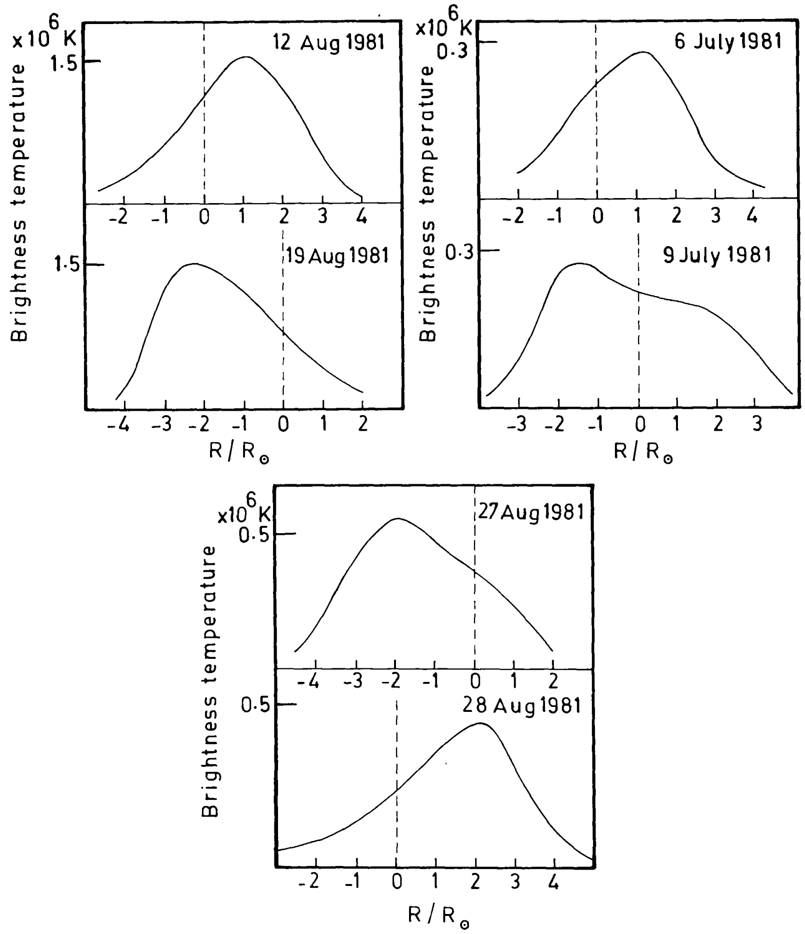

Fig. 2. Brightness temperature distribution along the line passing through the centroid and the center of the Sun for various days.

is known to increase with decreasing frequency. In general the intensity rises steeply on the side away from the Sun and decreases gradually towards the center of the Sun. Sometimes one can see a plateau in the region of the center of the Sun. These characteristics are clearly brought out in Figures 2a, b, c, d, e, f, where the brightness distributions along a line passing through the centroid of emission and the center of the Sun are shown. The presence of this type of asymmetry is independent of the peak brightness temperature. Note the relatively large plateau in Figure 2b. On this day the centroid is shifted by about $1.4 R_\odot$ in an easterly direction. An analysis of the distribution of values of the measured half power widths revealed that it is usually around $4 R_\odot$. The maximum and minimum values of the half-power widths we observed are $5.5 R_\odot$ and $2.0 R_\odot$, respectively.

A histogram showing the distribution of peak brightness temperatures is shown in Figure 3. It is clear that on most days the maximum brightness temperature was between 0.3×10^6 K and 0.5×10^6 K. In general the variations in brightness temperature from day to day are slow and gradual. We have rarely observed abrupt and large changes in the brightness temperature. In Figure 4 we have plotted the positions of the centroids of emission for all the available data. It can be seen that most of the centroids lie within a circle of $2 R_\odot$ from the center of the Sun. We also found that the day to day variations in the positions of the centroids are irregular in nature for periods when continuous data is available. During the days when the centroid position was away from the center of the Sun the brightness temperature at the center of the Sun is about 0.5 to 0.7 times that of the peak temperature. The least value of the observed brightness temperature at the center of the Sun is $\approx 0.2 \times 10^6$ K.

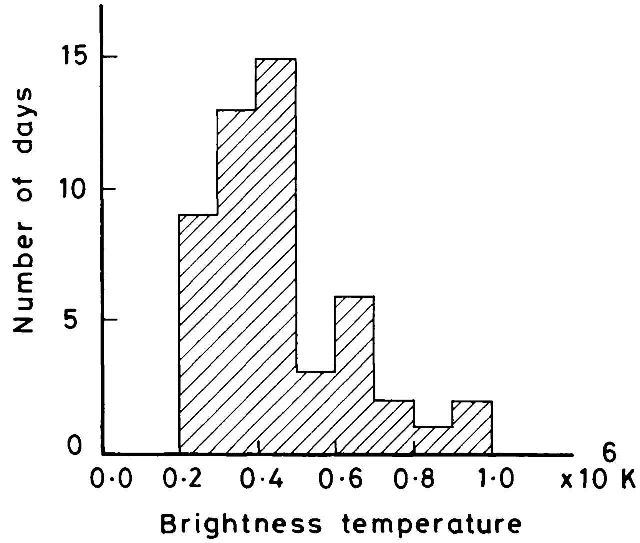

Fig. 3. Distribution of the peak values of brightness temperatures.

The possibility that the spread in the positions of the centroids is entirely due to refraction effects, and the emission is due to quiet Sun, must be considered. If this is

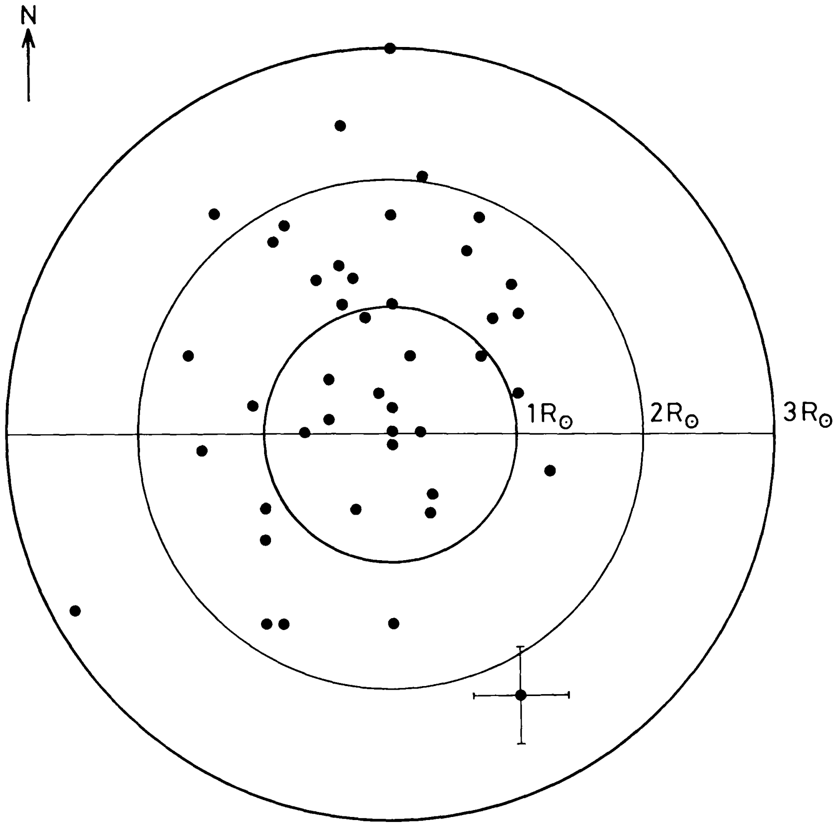

Fig. 4. A plot of the position of the centroids of SVC sources for all the available data.

the case then one would expect a symmetric distribution of the brightness around the centroid irrespective of its position. But as already pointed out, the observations show that most of the brightness distributions are asymmetric in nature. Therefore, it would appear that the shifts in the positions of the centroids with respect to the center of the Sun are mostly real, and are not entirely due to refraction effects.

4. Discussion

It was shown by Sastry *et al.* (1981) that the observed brightness temperatures are due to thermal radiation from the corona. According to them, the normal corona becomes optically thick at 34.5 MHz for temperatures in the range 0.1×10^6 to 0.8×10^6 K and so the measured temperatures are the same as the electron kinetic temperatures, in the corona. In order to simulate the observed brightness distribution of an SVC source whose centroid lies at about 1.5 to 2 $R_\odot$ from the center of the Sun, we have calculated the brightness distribution expected from a corona with various types of electron density and temperature distributions. The coronal model used is based on the one determined by Newkirk (1961) for a streamer in an otherwise symmetric corona. The electron density N at any point in the corona is given by

$$N = 4.2 \times 10 \; \frac{4.32}{\rho} \; (1 + C_N e^{-(\beta^2/2\sigma^2)}) ,$$

where ρ is the distance from the center of Sun, β is the distance from the axis of the region of enhanced density, and σ is the width of the enhanced region. All distances are in units of solar radii. The constant C_N determines the density of the enhanced region and is equal to four for a density enhancement factor of five. To determine the brightness temperature at some point in the solar corona, rays initially directed towards that point, are traced (using the technique of Newkirk (1961)) from the Earth towards the Sun, until the ray is moving away from the Sun and is atleast 4 $R_\odot$ from the Sun. The brightness distributions were computed for various angles, ranging from 0° to 70°, between the axis of the region of enhanced density and the Sun–Earth line. Figure 5 shows a plot of the angular distance between the peak of emission and the center of the Sun vs the orientation of the axis of the density enhancement. It is clear that for sources whose centroid lies at about 1.5 $R_\odot$ from the center of the Sun, the orientation of the axis of the enhanced region should be about 45° to the line of sight. In these calculations the density enhancement factor is equal to five and the angular size of the enhanced region is 1.0 or 1.5 $R_\odot$. As already stated, the angular size of SVC sources increases with decreasing frequency. It is about 10′ at 169 MHz (Leblanc, 1970) and $\geq 20'$ at 26 MHz (Kundu *et al.*, 1977). Therefore, we assumed values in the range 1 to 1.5 $R_\odot$ for the width, of the enhanced regions. We found that while the curve in Figure 5 is sensitive to the density enhancement factor, it is not very much dependent on the electron temperature assumed. We have computed the brightness distributions only for an orientation angle of 45° to the line of sight. The computed brightness distributions were convolved with our beam. The results are shown in Figure 6. Figure 6a shows the derived brightness distribution for an isothermal corona with a temperature of 0.5×10^6 K and a density enhancement (× 5) oriented at 45° to Sun–Earth line. It can be seen that there is no significant difference in the brightness temperature between the centroid and the center of the Sun. Since this model is not adequate to explain the

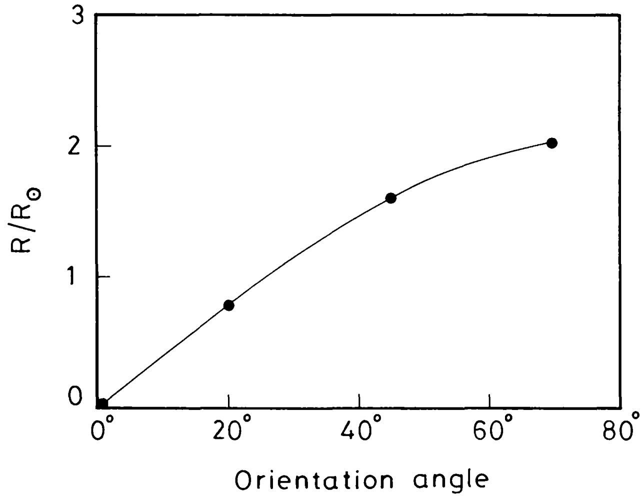

Fig. 5. A plot of the computed distance between the peak of emission and the center of Sun vs the orientation of the axis of the density enhancement.

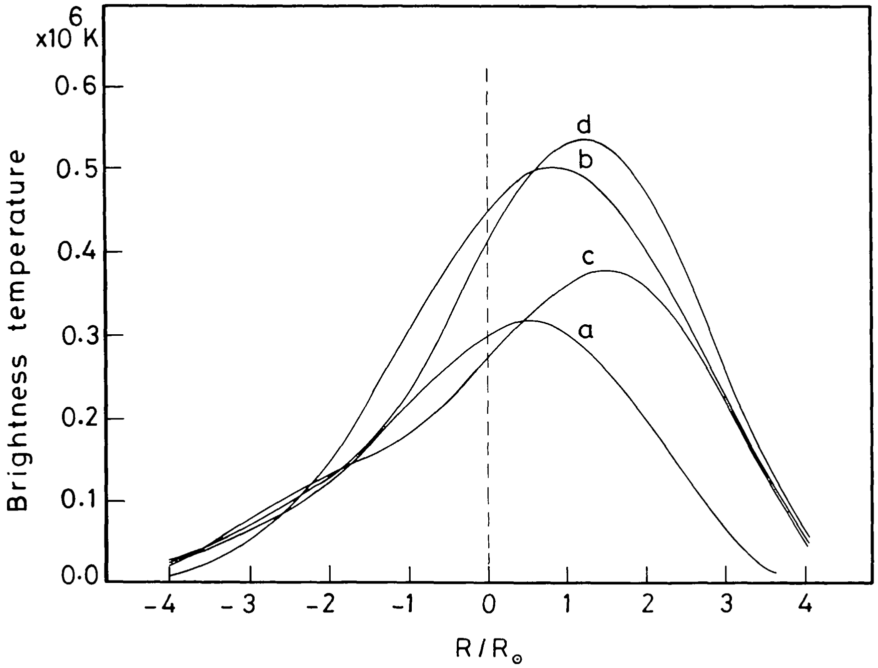

Fig. 6. The computed brightness distribution for various combinations of density and temperature enhancements.

observed decrease of brightness temperature towards the center of the Sun, we introduced a temperature enhancement in the region of the density enhancement. We assume that the electron temperature, T, at any point in the corona is given by

$$T = T_Q(1 + C_T e^{-(\beta^2/2\sigma^2)}),$$

where C_T is temperature enhancement factor and T_Q is the temperature of the ambient corona. The brightness distributions were calculated for various combinations of density (C_N) and temperature enhancement (C_T) factors and for a orientation angle of 45°. Figure 6b shows the computed temperature distribution for only a temperature enhancement by a factor of 2.5 with no accompanying increase in density. Here again there is no variation of temperature between the centroid and the centre of the Sun. Figures 6c and 6d show the computed temperature distributions for temperature enhancement factors of 1.5 and 2.5, respectively. The density enhancement factor in both the cases is five. In this case the temperature at the center of the Sun is 0.6 to 0.7 times that of the centroid and the computed distribution agrees quite well with the observed brightness temperature distribution.

It is interesting to note that during the height of solar activity there are days when the Sun is absolutely free of transient burst emission and the electron temperatures at heights of about 2 $R_\odot$ can be as low as 0.2×10^6 K. Aubier *et al.* (1971) measured brightness temperatures of the order of 0.36×10^6 K during 1970 for the quiet Sun at a frequency of 30 MHz. The measurements of Erickson *et al.* (1977) during July and August 1976 indicate brightness temperatures of about 0.2×10^6 K at frequencies around 30 MHz. Cavallini and Righini (1975) showed from an analysis of the coronal spectrum taken during the eclipse of July 20, 1963 that cold regions ($\approx 2 \times 10^5$ K) can exist at heights of about 2 $R_\odot$ from the center of the Sun.

The random changes in the position of the centroids we observed are similar to the variations in the white light corona reported by Sheeley *et al.* (1980). They detected major changes in the daily positions of bright coronal structures in the region 2.6 to 10 $R_\odot$ using the Solwind satellite coronagraph data.

5. Summary

Two-dimensional maps of the sources of SVC for some days during the period July 1980–December 1981 have been made.

The observed brightness temperatures of the SVC sources were in the range 0.3 to 0.5×10^6 K.

The average half power width of the SVC sources is about 4 $R_\odot$.

There can be a shift of about 1.5 to 2 $R_\odot$ in the position of the centroid of the SVC source from the center of the Sun.

During the days when the SVC centroid was away from the center of the Sun the brightness temperature at the center of the Sun is 0.5 to 0.7 times the peak temperature.

These observations can be explained in terms of thermal emission from regions of enhanced density ($\times$ 5) and temperature ($\times$ 2.5) located at distances of 1.5 to 2.0 $R_\odot$ from the center of Sun.

Acknowledgements

We would like to thank M. K. V. Bappu† and V. Radhakrishnan for their interest and support of the Low-Frequency Radio Astronomy Project at Gauribidanur. Our thanks are also due to Messrs G. N. Rajasekhar and C. Nanjegowda for their help in obtaining the data.

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