OBSERVATIONS OF THE CONTINUUM RADIO EMISSION FROM THE UNDISTURBED SUN AT A WAVELENGTH OF 8.7 METERS

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Abstract. We have mapped the continuum emission from the undisturbed Sun at a wavelength of 8.7 m during 1981–1985 using the large decameter-wave radiotelescope at Gauribidanur, India with a resolution of 26 × 38 arc min. During the period August 6–30, 1983, the Sun was exceptionally quiet at meter and decameter wavelengths, and we were able to make maps on several consecutive days. On these days the position of the centroid of the radio Sun agreed quite closely with the center of the optical Sun indicating that there is very little or no contribution from active regions. But the observed peak brightness temperature varied from 100 000 to 700 000 K. The half-power widths of the brightness distribution were in the range of 3 to 4 $R_\odot$. The variations of the brightness temperature and the half-power widths are not correlated. It is therefore suggested that the variations of the brightness temperature are not caused by uniform density variations or due to scattering by an irregular corona.

1. Introduction

The continuum emission from the undisturbed Sun and active regions was studied in great detail at centimetric wavelengths for several decades. There are very few measurements of the brightness distribution of the continuum emission from the undisturbed Sun at meter and decameter wavelengths. The main reason for this is the lack of radiotelescopes with sufficient resolution and sensitivity at low frequencies. In addition the intermittent radio burst emission from the Sun and terrestrial radio interference make it very difficult to map the quiet Sun, especially with transit instruments like ours. Low-frequency measurements are important for our understanding of the physical processes in the outer corona. A comparison of the white-light coronographic and radio observations of the outer corona are necessary in view of a possible discrepancy in the derived densities by the two methods reported by Jackson, Sheridan, and Dulk (1979) and others. Kundu, Gergeley, and Erickson (1977) used the Clark Lake radiotelescope to obtain low-frequency (26.3 MHz) one-dimensional E–W scans of the Sun. We have made a series of observations of the continuum emission from the undisturbed Sun at 34.5 MHz during the period 1979–1985 whenever it was possible. An analysis of the E–W scans obtained during the period July 1979 to March 1980 revealed (Sastry *et al.*, 1981) that (1) the brightness temperature could be less than 0.2×10^6 K, (2) the shift in the position of the peak of radio emission from the center of the optical Sun can be as much as 2 $R_\odot$, and (3) the half-power width of the brightness distribution varies between 2 to 4 $R_\odot$. The first low-frequency (34.5 MHz) two-dimensional maps of the undisturbed Sun were published by Sastry, Shevgaonkar, and Ramanuja (1983)

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which confirmed all the above results. In addition it was pointed out that these observations can be explained only in terms of enhanced density and temperature of coronal regions located at distances up to 2 $R_\odot$ from the center of the optical Sun. A similar conclusion was reached by Dulk and Sheridan (1974) in the case of coronal holes for which they suggested decreases in density and temperature. We present here the results of our observations during a quiet period in August 1983.

2. The Radiotelescope

These observations were made with the decameter-wave radiotelescope at Gauribidanur (latitude: 13°36′ N and longitude: 05 hr 10 min E). The beamwidths of the radiotelescope at $\lambda = 8.9$ m are 26 × 38 arc min in the EW and NS directions, respectively. The collecting area is approximately $250\lambda^2$. The telescope was used in the transit type and the beam can be pointed anywhere along the meridian in the zenith angle range ±45° using remotely controlled phase shifters. A time-multiplexing system was used to cycle the beam through eight different declinations sequentially, the beam being changed from one declination to another in 10 ms. We made drift scans in hour angle for about 15 min of time on either side of the transit of the Sun. The solar records were calibrated mainly using the radio sources 3C 123, 218, 274, and 348. The assumed flux densities of these sources are 616, 1750, 3853, and 1750 Jy, respectively. The errors in these values are about 5% of the quoted values. The peak brightness temperature, T_0, is computed using the relation

$$T_0 = \frac{9.24 \times 10^5 \, \alpha S}{\theta \phi} \, ,$$

where α is the ratio of the 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 beamwidths of the antenna system in minutes of arc. The errors in the estimation of brightness temperatures are mainly due to: (1) variation of the antenna gain with zenith angle, (2) variable attenuation of the ionosphere, and (3) uncertainties in the flux densities of the calibrators. We believe that the observed brightness temperatures are accurate to within ±20%. The errors in the positions of the centroid are due to the regular and irregular refraction in the ionosphere and pointing errors of the radiotelescope. On the basis of a series of measurements on point sources we find that the regular refraction at noon time can be of the order of 10 min of arc although in rare cases it can be much higher.

3. Observations

During the period August 6–30 the Sun was very quiet at meter and decameter wavelengths. No strong radio bursts from the Sun at decameter wavelengths were

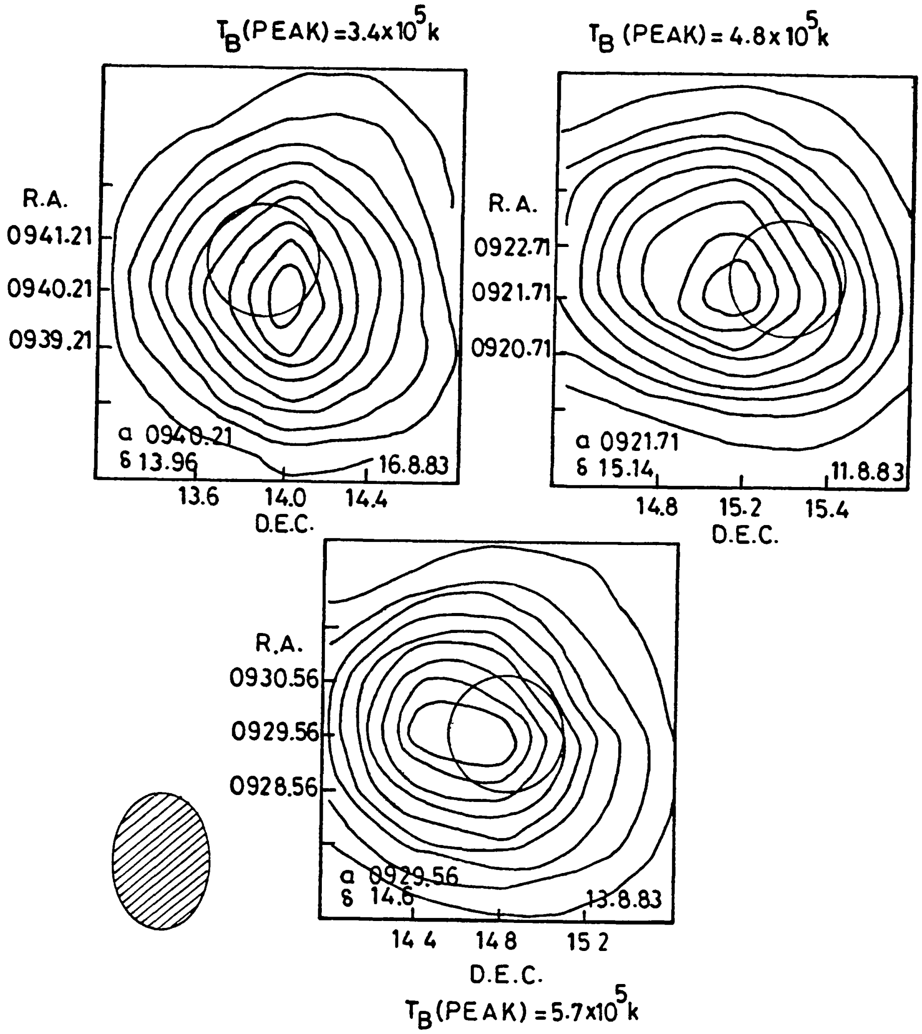

Fig. 1. Radio maps of the Sun at 34.5 MHz on August 11, 13, and 16, 1983, obtained with the decameter wave radiotelescope at Gauribidanur, India. The optical Sun is shown as a full circle, the beam size is indicated as a shaded ellipsoid. The contour interval is 0.1 × peak T_B.

detected except for an occasional Type III burst reported by Culgoora (*Solar-Geophysical Data*, 1983). The daily values of the total flux at 200 MHz measured at Hiraiso and 100 MHz at Gorky remained constant at levels of 8 to 9 s.f.u. and 3 s.f.u. respectively (*Quarterly Bulletin of Solar Activity*, 1983). The radio maps, at 34.5 MHz, made at Gauribidanur shown in Figure 1 are reasonably symmetric and the positions of radio and optical centroids were within 10′ of each other on most days. This is in contrast to our previous observations during active periods where the positions of the radio peaks are shifted by 1.5 to 2 $R_\odot$ from the center of the optical Sun. The positional differences between the radio centroid and the center of the optical Sun on various days during August 1983 are plotted in Figure 2. On most days the difference in R.A. and Dec. is less than ≈10′ (0.6 $R_\odot$). These differences can be accounted for by the refraction effects in the terrestrial ionosphere and pointing errors of the radio telescope. We, therefore, conclude that

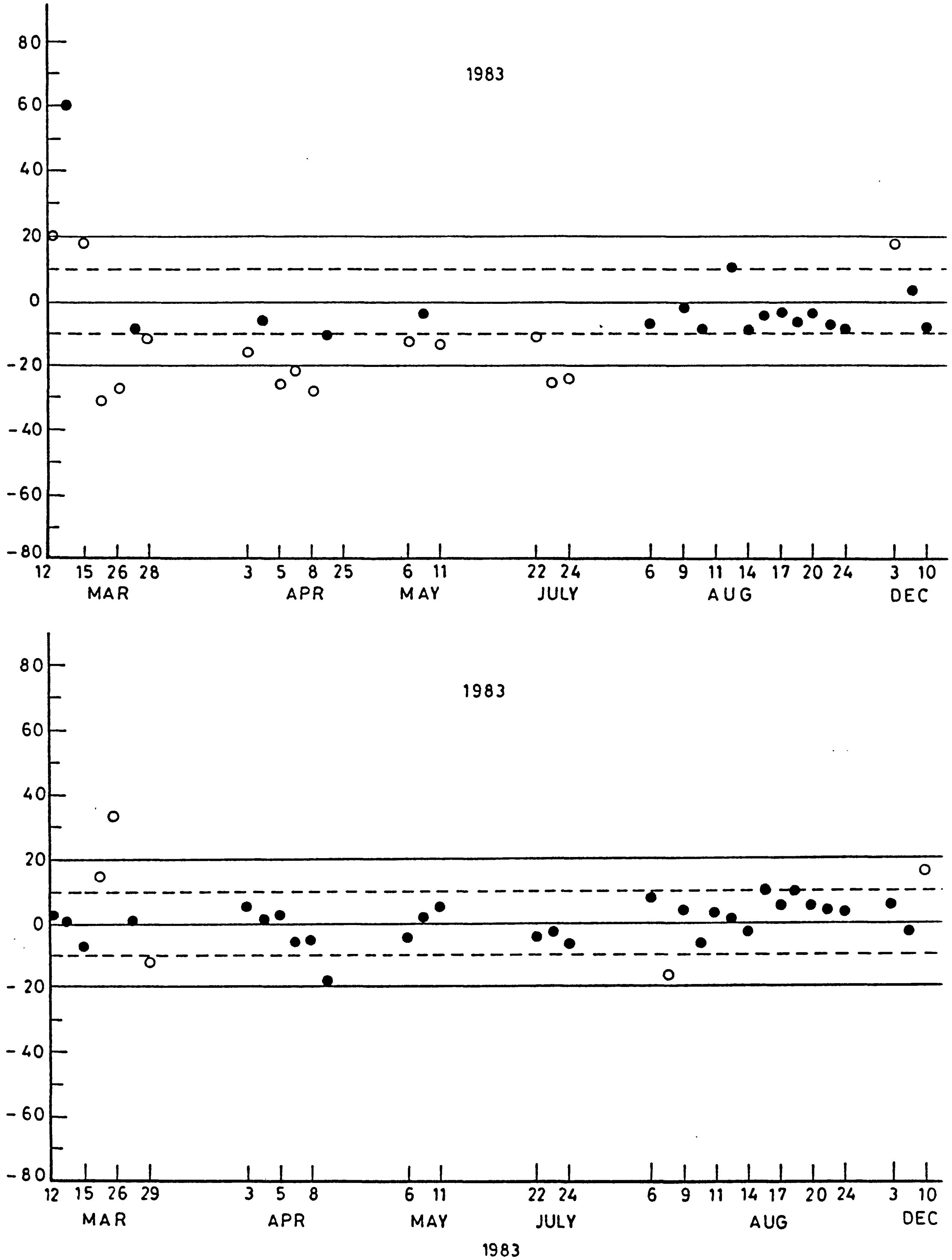

Fig. 2. Positional differences between the radio centroids and the centers of the optical Sun during August 1983. The vertical axis shows the positional differences in minutes of arc in declination, $\delta_{\odot}$ (*upper plot*) and right ascension, $\alpha_{\odot}$ (*bottom plot*). The dashed lines are drawn at ±10′. Days for which the positional difference is $<10'$ are represented by solid circles.

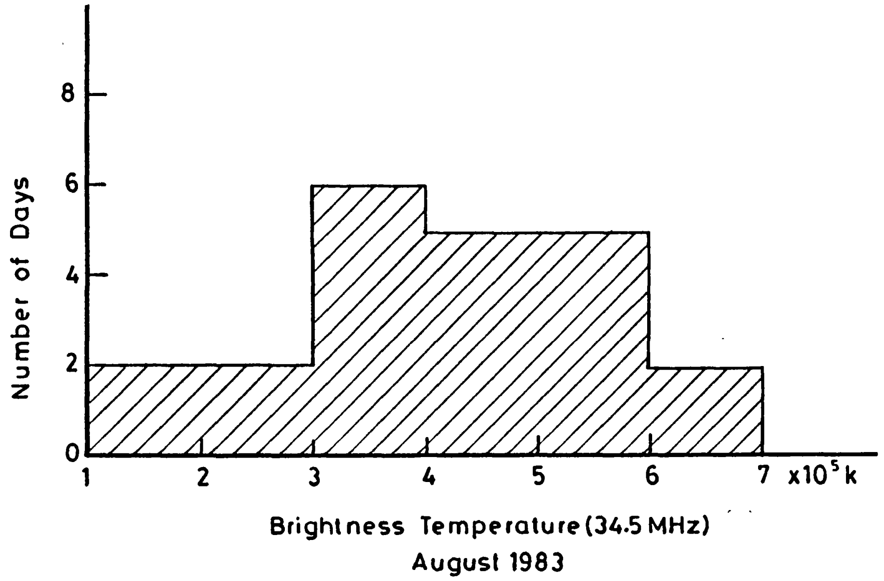

Fig. 3. Distribution of the observed peak brightness temperatures at 34.5 MHz during August 1983.

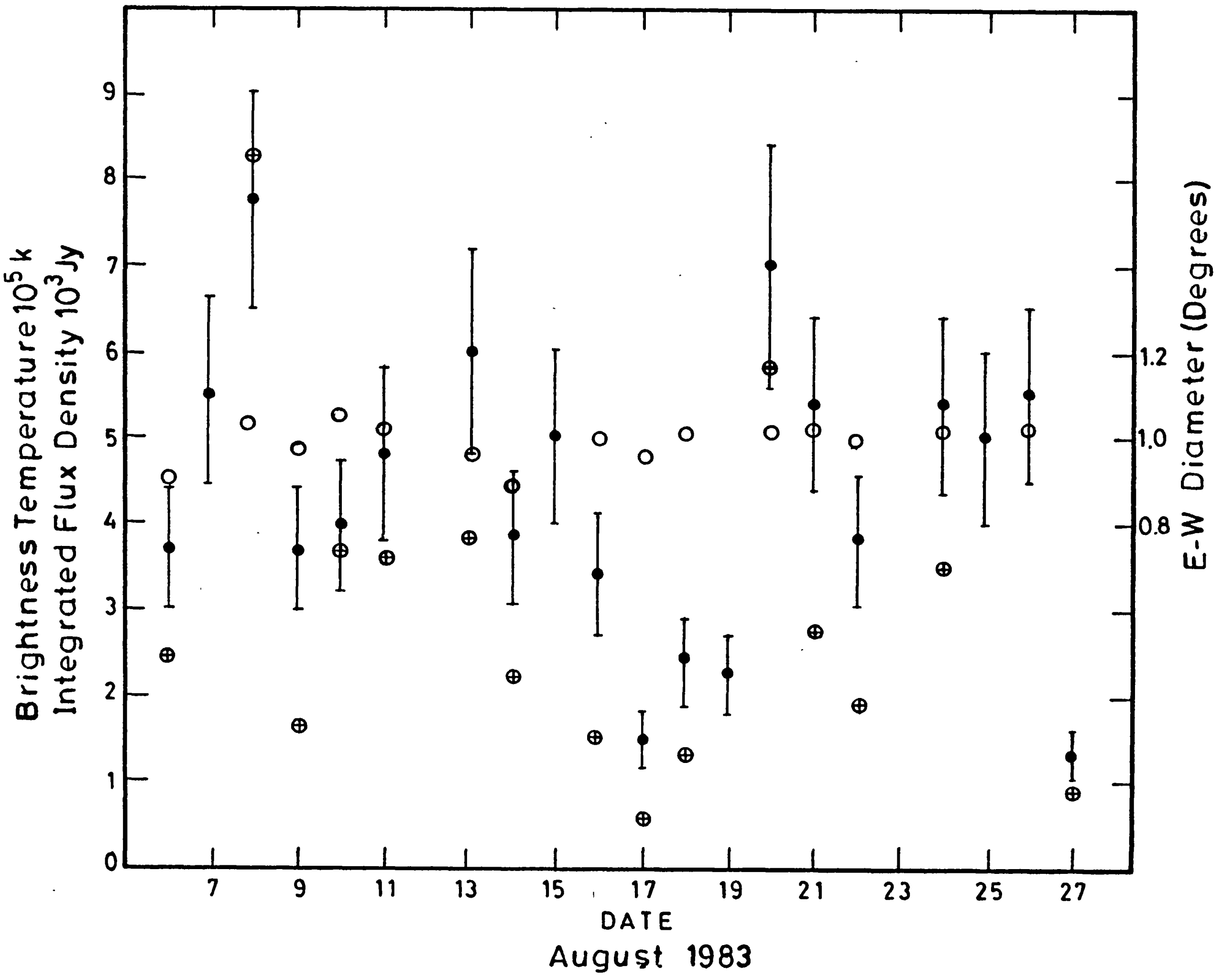

Fig. 4. A plot of the daily variation of the peak brightness temperature (filled circles), integrated flux density (circles with crosses) and E–W diameter (open circles) during August 1983.

the contribution from active regions to the brightness temperature, if any, is not significant. The distribution of the observed peak brightness temperatures given in Figure 3 shows that they range from 100 000 to 700 000 K at long wavelengths although the Sun was very quiet during this period. These values are within the range of previous low-frequency brightness temperatures measured by various workers and compiled by Sheridan and McLean (1985). The daily values of the peak brightness temperature plotted in Figure 4 show that it can change by a factor of two on consecutive days and the ratio of maximum to minimum values is about six for the entire period. We have also determined the daily values of the total flux density and the E–W diameter of the Sun and these are also plotted in Figure 4. The integrated flux density varied from about 1000 to 8000 jy and half-power width of the radio brightness distribution lies in the range 3.2 to 4.5 $R_\odot$. The integrated flux densities measured by us agree reasonably well with the total flux densities compiled by Sheridan and McLean (1985) at low frequencies. It should however be pointed out that no measurements of integrated flux density of the Sun based on two-dimensional brightness distribution maps were reported previously The E–W diameters measured by us and those of Gergeley, Gross, and Kundu (1985) are in close agreement There is no correlation between the half-power widths and peak brightness temperatures.

The peak brightness temperatures of the Sun at three low frequencies (73.8, 50.0, and 38.5 MHz) for the quiet period September 9–28 were published by Thejappa and Kundu (1992). It is clear from their data also that the brightness temperature can vary by more than a factor of three on consecutive days although the Sun is free of spots during this period. The ratio of maximum to minimum brightness temperatures is about four at all the three frequencies.

4. Discussion

At decameter wavelengths, the radio emission originates purely in the outer corona. The observed brightness temperature, T_o, is related to the kinetic temperature, T_e, of the corona through the standard relation $T_o = T_e(1 - \exp(-\gamma))$, where γ is the optical depth. Due to the radial and azimuthal variations of electron density (consequently the radio refractive index) ray trajectories have to be computed to obtain the integrated optical depth in any direction (Smerd, 1950; Bracewell and Preston, 1956). The computed optical depth in the direction of the center of the Sun at 34.5 MHz is >0.8 for any generally accepted density model (e.g., Newkirk, 1961) and for a uniform temperature of 1 to 1.5×10^6 K (Sastry *et al.*, 1981; Sastry, Shevgaonkar, and Ramanuja, 1983; Thejappa and Kundu, 1992). Therefore the observed brightness temperatures should be of the order of 0.8 to 1.0×10^6 K. In order for the brightness temperature to be 0.2×10^6 K the optical depth should decrease by a factor of nearly ten. The optical depth depends on refraction and scattering in the corona which determine the path length and electron density and coronal temperature along the ray path. The present observations indicate that the variations in the optical depth are probably not confined to any specific region by to the entire corona above 1.5 $R_\odot$. It is therefore reasonable to expect that the variations in the optical depth should be accompanied by variations in the size of the radio Sun at these wavelengths. We have computed the effect of uniform variations of the density on the optical depth using the model of Newkirk (1961) for a spherically-symmetric corona multiplied by a factor D, i.e.,

$$N_e(R) = 4.2 \times 10^4 \, D e^{Q/R} \,,$$

where

$$Q = (GM_\odot \mu m_\mathrm{H})/RkT \,.$$

Here G is the gravitational constant, $M_\odot$ is the solar mass, μ is the mean mass of the coronal material, m_H is the mass of the hydrogen atom, and k is the Boltzmann constant, and R is the radial distance in solar radii. We found that the optical depth is a very slowly varying function of D. It is possible to understand this on the basis of the fact that a variation in D affects the optical depth through the change of the height of the plasma level which in turn will vary the scale height $H = R^2/Q$. Therefore the effective path length which contributes most to the optical depth varies slightly (Dulk and Sheridan, 1974). We found that the value of D should change by a factor of nearly 50, i.e., from 0.1 to 5 in order for the brightness temperature to increase from 200 000 to 800 000 K. The half-power width of the brightness distribution (radio diameter of the Sun) would be approximately 1.5 to 2.0 $R_\odot$ when $D = 0.1$ and increases to 3 to 4 $R_\odot$ when $D = 5.0$. As already pointed out the present observations do not support this type of correlation. Another possibility is to change the density gradient Q. If hydrostatic equilibrium prevails, this essentially means changing the temperature of the whole corona. Newkirk's (1961) value of $Q = 10$ implies a uniform coronal temperature of 1.4×10^6 K. The value of Q has to be about 70 for a coronal temperature of 200 000 K but more importantly the size of the radio Sun would become larger by an order of magnitude than the observed value in such a case. It is also well known that optical and other observations do not support such low values for the entire corona.

Aubier, Leblanc, and Boischot (1971) pointed out that the low-frequency brightness temperatures observed by them cannot be explained on the basis of the generally adopted models of density or by changing the gradients of density and temperature in the corona. They therefore introduced the effect of scattering by an irregular corona. This process will essentially raise the height of reflection of the rays above the plasma level. The optical depth is consequently reduced since most of the contribution to it comes from regions very close to the plasma level. It is also obvious that the diameter of the radio Sun should depend on the amount of scattering. The effect of scattering is controlled by the parameter, $\delta = \epsilon^2/h$, where ϵ is the r.m.s. relative fluctuation of electron density ($\Delta N/N$) and h is the radius of correlation of the inhomogeneities. Aubier, Leblanc, and Boischot (1971) have taken the value of $\epsilon = 0.02$ and that of $h = 5 \times 10^{-5}$ in units of solar radii. Subramanian and Sastry (1991) noted that the scattering under these circumstances cannot reduce the brightness temperature to such low values as <200 000 K sometimes observed by them. Thejappa and Kundu (1992) tried to explain the very low brightness temperatures by assuming that the r.m.s. relative fluctuation of electron density is equal to 0.1. McMullin and Helfer (1977) formulated the scattering problem in terms of standard radiative transfer with conservative scattering. They avoided the numerical computations involved in using a ray-tracing approach which incorporates a Monte-Carlo routine for representing scattering. The brightness and the radio diameter of the Sun were calculated for several values of the scattering parameter and electron density. According to their computations increasing the scattering parameter, δ, from 4 ($\Delta N/N = 0.010$) to 12 ($\Delta N/N = 0.024$) will result in an increase of about 75% in the diameter of the radio Sun The value of 0.1 for the r.m.s. fluctuation of the electron density assumed by Thejappa and Kundu (1992) implies a scattering parameter equal to 200 and will lead to a very large increase in the diameter of the Sun and is obviously unrealistic. It is therefore not possible to explain the low brightness temperatures of 200 000 K or less by invoking scattering by density inhomogeneities only. McLean and Melrose (1985) point out that scattering fails to account for the observed sizes and directivity of Type I solar radio bursts although it should offer a plausible explanation.

Melrose and Dulk (1988) pointed out the possibility that the low brightness temperatures could be a consequence of the low emissivity in the source region when $\mu < 1$ and the generalized etendue. This hypothesis would explain the low brightness temperatures provided the observed sources are the scatter images of the true sources. The multifrequency data of Thejappa and Kundu (1992) show that the variations in brightness temperature have a high degree of correlation at all the three frequencies. The measured brightness temperatures at 73.8 MHz are also low, 0.8 to 2.6×10^5 K, and the amplitude of their daily variation is > than that of the two lower frequencies. According to Kundu and Gopalswamy (1990) the effects of scattering on quiet-Sun radiation at frequencies of 78 MHz and above are negligible. In this case it would be difficult to explain the low brightness temperatures on the basis of the Melrose and Dulk (1987) hypothesis. Since the variations are strongly correlated at all the three frequencies they probably have a common origin.

The large variations are also probably not due to rotating structures such as streamers and sector boundaries since the peak of the brightness distribution and the center of the optical Sun are generally coincident during the period of the present observations. For the same reason one can also rule out coronal mass ejections as the cause of the variations. In recent years it has been pointed out by several authors that there are sources of weak noise storms on the Sun whose brightness temperatures are less than or equal to that of the quiet Sun. These sources produce faint continuum without the usually associated Type I noise storm bursts (Alissandrakis, Lantos, and Nicolaidis, 1985). It is also known (Kai, Melrose, and Suzuki, 1985) that storm sources tend to occur on the solar disk. It is therefore possible that the observed brightness temperature variations could be due to these weak noise storm sources.

Observations of the corona by House and Illing (1982), using the coronograph/polarimeter on board the SMM satellite, showed that the corona is neither spherically symmetric nor static. Significant changes are found to occur on time scales ranging from a few hours to a few days. Corresponding spatial variations occur on scales ranging from a few arc min to several solar radii. Under these circumstances it is extremely difficult to construct average density models and the interpretation of radio emission in terms of standard models can be quite deceptive. They also found cool H material out to distances of the order of 6 $R_\odot$. The eclipse observations of Cavallini and Righini (1975) also revealed that cold regions can exist at heights of 2 $R_\odot$ from the center of the Sun. The present observations are probably radio manifestations of such low-temperature regions in the outer corona.

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