THE RADIO BRIGHTNESS OF THE UNDISTURBED OUTER SOLAR CORONA IN THE PRESENCE OF A RADIAL MAGNETIC FIELD

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Abstract. The radio brightness of the quiet outer solar corona at a frequency of 35 MHz in the presence of a radial magnetic field is computed. It is found that the brightness temperature of the ordinary radiation increases significantly. It is also found that in the presence of a radial magnetic field, coronal holes will appear as bright emission regions on the disk and as depressions at the limb.

1. Introduction

The brightness distribution of the quiet Sun was computed theoretically from centimeter to meter wavelengths for the first time by Smerd (1950). These calculations were extended to decameter wavelengths by Bracewell and Preston (1956). At decameter wavelengths the radiation originates purely in the outer corona. These authors assumed a spherically symmetric corona to derive the solution by numerical integration of the radiative transfer equation for an ionized medium. The existence of density enhancements or coronal condensations in some regions makes the corona asymmetric and one has to take recourse in a more involved ray-tracing techniques to derive the brightness distribution. Such calculations were carried out by Newkirk (1961) who derived the brightness profiles at short wavelengths. Sastry, Shevgaonkar, and Ramanuja (1983) used a ray-tracing technique similar to that of Newkirk (1961) and showed that the peak brightness temperatures observed by them at decametric wavelengths cannot be explained on the basis of density enhancements alone. In all these calculations the effect of the magnetic field on the propagation of radio waves in the outer corona is neglected. It is well known that in the presence of a magnetic field the corona becomes anisotropic and the energy associated with electromagnetic waves does not, in general, travel in the direction of wave normal. Also, in an inhomogeneous anisotropic medium the energy follows a curved path known as the ray path. Ionosphere physicists have derived a set of differential equations which determine the ray path in a magneto-ionic medium. We have attempted here to calculate the radio brightness distribution of the undisturbed outer corona in the presence of a radial magnetic field, using such equations. The brightness distribution is also computed when a coronal hole is present, since these

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are believed to be associated with open field lines. These computations were made at a frequency of 35 MHz for comparison with the observations of the Gauribidanur Radio Telescope.

2. Magnetic Field in the Outer Corona

Although there are no direct measurements of the magnetic field in the outer corona, its existence is inferred from the observations of radio bursts. Dulk and McLean (1978) derived an equation of the form $B(R/R_\odot) = 0.5[(R/R_\odot) - 1]^{-1.5}$ in the range $1.02 \leq R/R_\odot \leq 10$ for the magnetic field strength, using the available observational evidence. Gopalswamy *et al.* (1986), using data on Type I noise storms, only derived a similar radial dependence of the magnetic field, and estimated a strength in the range 0.5 to 1 G at heights of $\simeq 1.5\ R_\odot$. At these heights the field is drawn out by the solar wind into open field lines. In the present work we have assumed a field variation of the form $B(\rho) = B_\odot \rho^{-1.5}$ G, where $B_\odot$ is the field strength at $\rho = R/R_\odot = 1$.

3. Ray-Tracing in a Magnetized Corona

The flow of electromagnetic energy in a coronal model including radial magnetic field was calculated by tracing ray paths, using the equations derived by Haselgrove (1955). Since the magnetic field is assumed to be radial in the outer corona, rays were traced in two dimensions. The Haselgrove equations in their two-dimensional form are

$$\frac{dr}{dt} = \frac{1}{\mu^2}\left(\mu \cos\chi + \frac{\partial \mu}{\partial \chi}\sin\chi\right) ,$$

$$\frac{d\theta}{dt} = \frac{1}{r\mu^2}\left(\mu \sin\chi - \frac{\partial \mu}{\partial \chi}\cos\chi\right) ,$$

$$\frac{d\chi}{dt} = \frac{1}{r\mu^2}\left\{\frac{\partial \mu}{\partial \theta}\cos\chi - \left(r\frac{\partial \mu}{\partial r} + \mu\right)\sin\chi\right\} ,$$

where μ is the refractive index. The origin of the (r, θ) coordinate system is at the center of the Sun. The equations are differential equations in the ray position $(r,\ \theta)$ and the angle χ between the wave vector and the direction of the magnetic field. The partial derivatives $\partial\mu/\partial\chi$, $\partial\mu/\partial r$, $\partial\mu/\partial\theta$ are derived using the Appleton–Hartree equation and the electron density models of Baumbach and Allen (1947), or Newkirk (1961). The corona is assumed to be isothermal at a temperature of 10^6 K. The equations were solved using the fourth-order Runge–Kutta method. The step used to extend the ray from one point to another in the corona is made dependent on the refractive index, since the absorption coefficient tends to grow very fast as the refractive index becomes smaller. This procedure ensures that the change in absorption coefficient is small over the step. The absorption coefficient is calculated at the end of each step and the average of two successive values is used to calculate the increase in optical depth over each step. To determine the brightness temperature at some point in the corona, rays initially directed towards that point are traced from the Earth towards the Sun until the ray is moving away from the Sun and is at least 4 $R_\odot$ from the Sun.

4. Results

The brightness distribution of the quiet Sun without any magnetic field and Baumbach and Allen (1947) type density distribution is shown in Figure 1(a). The distribution is symmetric, with a broad maximum in brightness temperature of about 0.70×10^6 K. The distribution and the maximum temperature are about the same for Newkirk's (1961) density model. The brightness distributions for the ordinary and extraordinary rays, when a radial magnetic field of 1 G at $\rho = 1.5$ is permeating the whole corona, are shown in Figures 1(b) and 1(c). In this case, the peak brightness temperature of the ordinary radiation increased to almost 10^6 K, while that for extraordinary radiation is $\simeq 0.7 \times 10^6$ K, with an average of $\simeq 0.85 \times 10^6$ K. Note that these and other profiles presented below should be convolved with the actual beam used, for comparison with observations. These calculations were repeated for the case where the magnetic field is present only in a small region of the corona with a distribution of the form $B(\rho, \theta) = B_\odot/\rho^{1.5}(1 + C_1 \exp[C_2(\theta - \theta_c)])$. The constants C_1 and C_2 determine the variation of the field strength and the angular extent of the region. In the present case the constants were chosen such that the peak field strength on the axis of the region is 1 G at $\rho = 1.5$, and its angular extent is about 20°. The angle between the axis of the region with a magnetic field and the Sun–Earth line is varied from 0 to 45°. The brightness temperature profiles when the axis of the region containing magnetic field coincides with the Sun–Earth line are similar to those in Figure 1(b), where the magnetic field is assumed to be permeating the whole corona. The peak brightness temperature of the ordinary radiation becomes almost 10^6 K, while that of the extraordinary radiation remains at 0.7×10^6 K. Figure 2 shows the profiles when the axis of the region with a magnetic field is inclined at an angle of 40° to the Sun–Earth line. In this case the effect of the magnetic field is very small and there is no significant change in the brightness temperatures. The variation of the peak brightness temperature of the ordinary radiation with the strength of the magnetic field for the case where the Sun–Earth line and the axis of the enhancement are coincident is shown in Figure 3. The brightness temperature of the radiation starts to increase for field strengths of $\simeq 0.05$ G at $\rho = 1.5\ R_\odot$ and reaches a maximum of 10^6 K for a field strength of 2 G.

It is generally accepted that coronal holes are low-density areas with open field

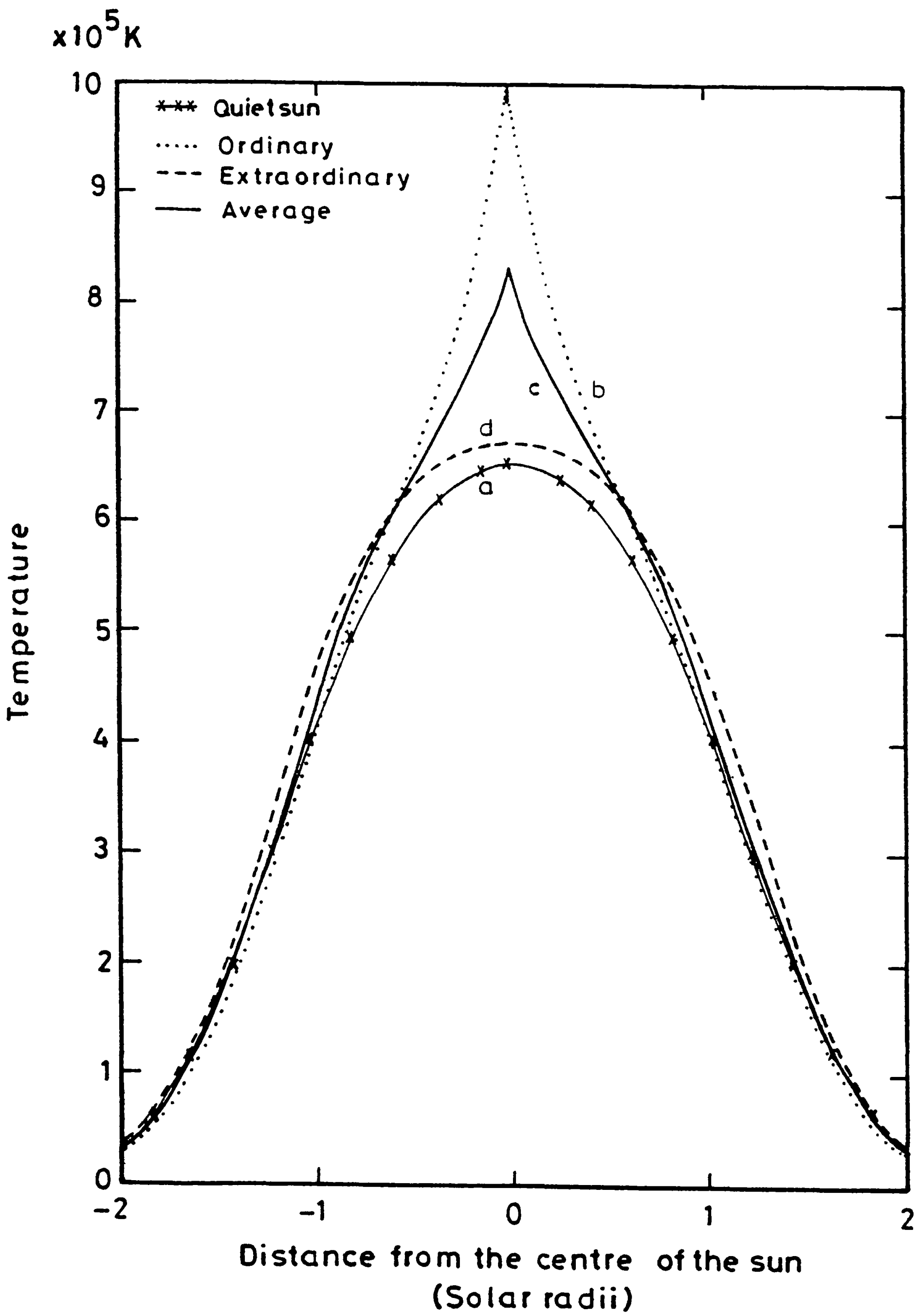

Fig. 1. Brightness temperature profiles of (a) undisturbed Sun, (b) and (c) ordinary and extraordinary radiations when a radial magnetic field of 1 G at 1.5 $R_\odot$ is permeating the whole corona, and (d) average of (b) and (c).

lines. The brightness temperature profiles are computed for a hole characterized by density distribution of the form $N(\rho, \theta) = N_0(1 + C_1 \exp[C_2(\theta - \theta_c)])$. The constants C_1 and C_2 were chosen so that the density on the axis of the hole is one-fourth that of the ambient corona and the angular width is 20°. The magnetic field is assumed to be 1 G on the axis of the hole and very small outside the hole. The brightness distributions are computed for a hole at the disk center and also

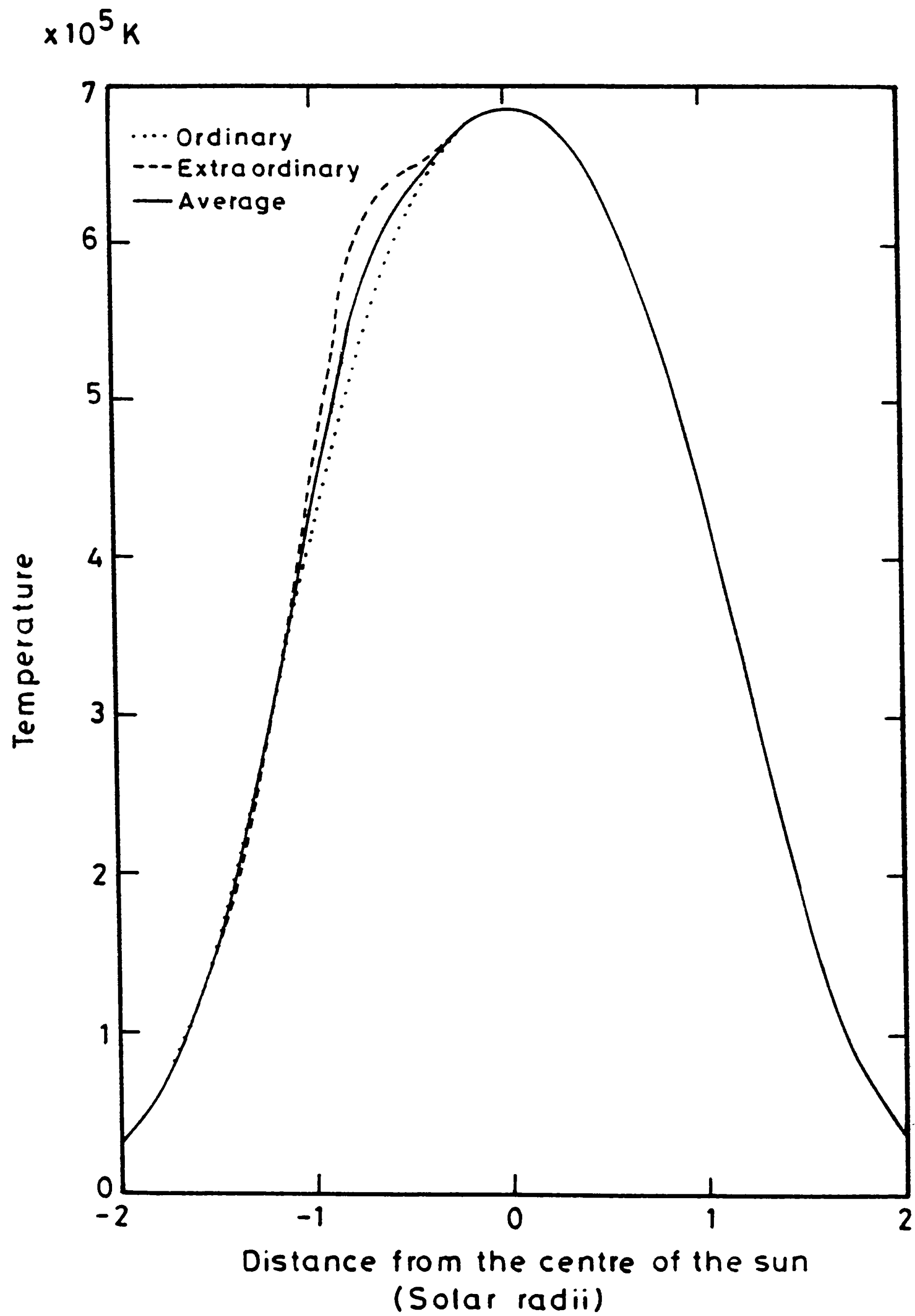

Fig. 2. Brightness temperature profiles of ordinary and extraordinary radiations in the presence of a region of angular extent 20° with a magnetic field of 1 G on its axis, which is inclined at an angle of 40° to the Sun–Earth line.

for one whose axis is inclined to the Sun–Earth line by 30°. Figures 4(a) and 4(b) show that when the hole is near the disk center it would appear brighter than the surrounding region. On the other hand it will appear as a depression when it is close to the limb.

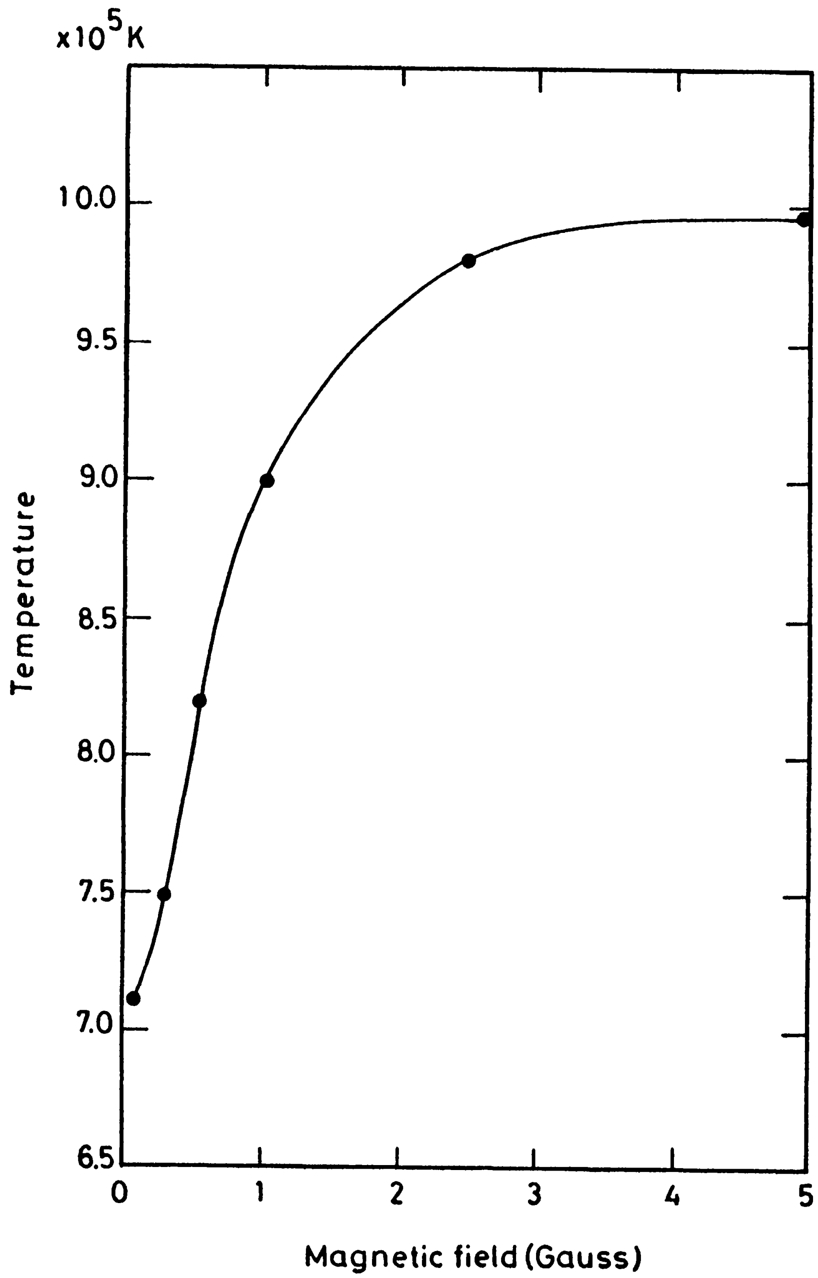

Fig. 3. Variation of the brightness temperature of the ordinary radiation with the strength of the magnetic field.

5. Discussion

It is well known that the brightness temperature of the undisturbed Sun at decameter wavelengths varies over a wide range (0.2 to 1.0 $\times$ 10^6 K) on time scales of hours to days (Sastry *et al.*, 1981; Sastry, Shevgaonkar, and Ramanuja, 1983; Bazelyan, 1987). It is not possible to explain the variations on the basis of density enhancements alone. It would appear from the present work that at least part of the variations may be due to a magnetic field variations. It is also clear that the

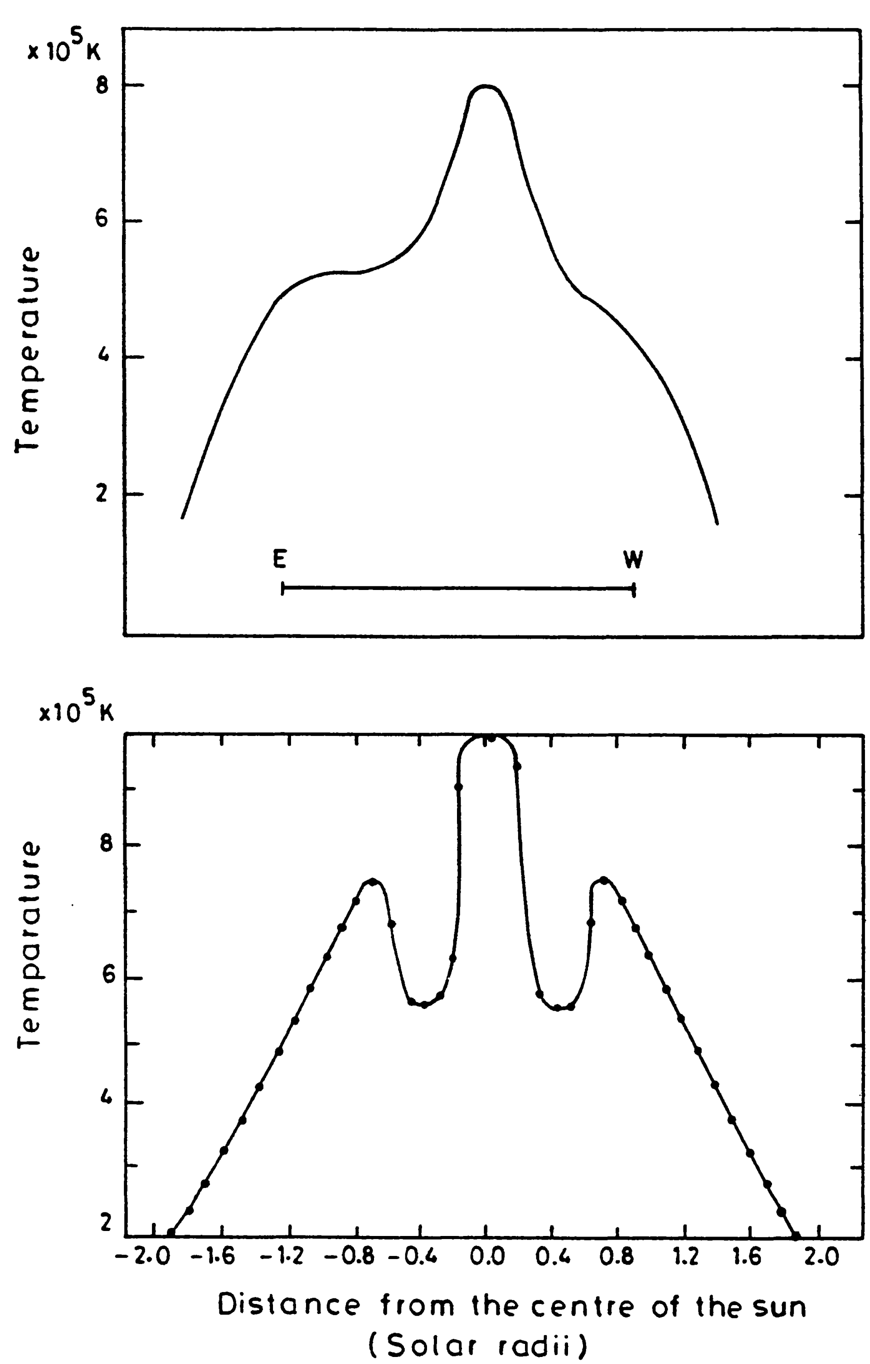

Fig. 4a. Brightness temperature profiles in the presence of a coronal hole. *Top*: observed profile at 80 MHz by Dulk and Sheridan (1980) when the hole is on the disk. *Bottom*: computed profile for a hole at the disk center when a radial magnetic field of 1 G is present.

ambient magnetic field in the outer corona is less than 0.05 G. This is because in the presence of a magnetic field of larger strength the brightness temperature cannot be as low as the usually observed values in the range 0.2 to 0.6×10^6 K at decameter wavelengths (Sastry, Shevgaonkar, and Ramanuja, 1983).

It should be pointed out that at the present time there are no radiotelescopes which are capable of measuring circular polarization of the continuum emission

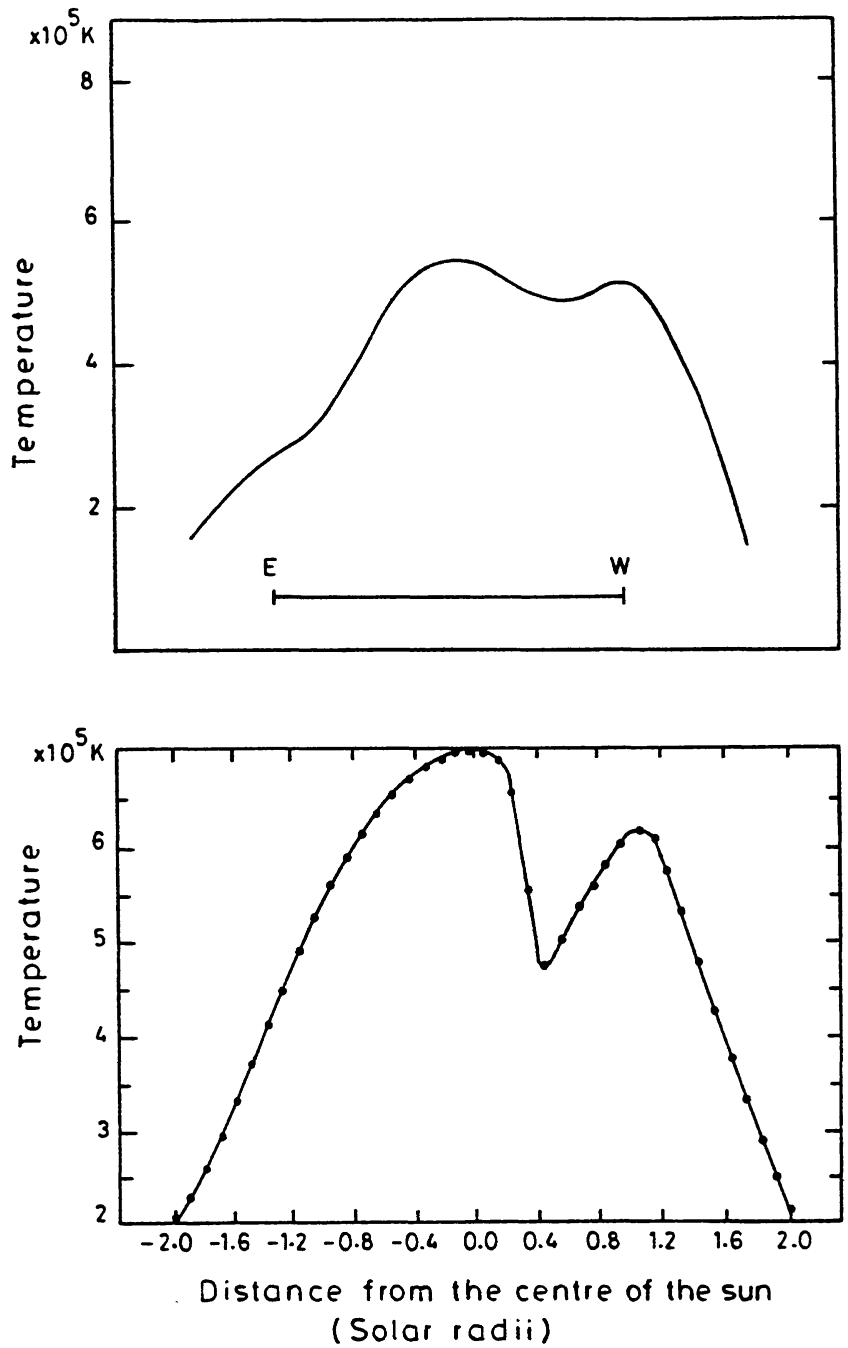

Fig. 4b. Brightness temperature profiles in the presence of a coronal hole. *Top*: observed profile when the hole is at the limb. *Bottom*: computed profile when the axis of the hole is inclined to the Sun–Earth line by 30°.

from the undisturbed Sun at decameter wavelengths. The Gauribidanur radiotelescope is being modified to have such a capability and hopefully we will get some interesting results soon.

The observations of Dulk and Sheridan (1980) at 80 MHz showed that coronal holes may appear as enhancements of the brightness temperature at the center of the disk and as depressions at the limb. Lantos *et al.* (1987) also observed coronal holes as bright emission regions on the disk at decameter wavelengths. There is no explanation for this effect excepting the original suggestion of Dulk and Sheridan (1980) that the electron temperature inside a hole is probably higher than the surrounding regions. It is generally believed that coronal holes are associated with open magnetic field configurations. In this case our results show that they can appear as bright regions, at the center of the disk, depending on the strength of the associated magnetic field. At the limb they will always appear as depressions, irrespective of the magnetic field strength. It would therefore appear that high-resolution observations of coronal holes at meter and decameter wavelengths are capable of yielding valuable information on the magnetic structure of the outer corona.

We have not included the effects of scattering (Aubier, Leblanc, and Boischot, 1971) in our computation. The effect of scattering, if it exists, is to raise the height of reflection above the plasma level. This will lead to a decrease in the optical depth and therefore lower the brightness temperature and to an increase in the radio diameter of the Sun. The amount of scattering is specified 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. It was pointed out by Subramanian and Sastry (1988) that this amount of scattering is not sufficient to explain the very low brightness temperatures, $<0.2 \times 10^6$ K, observed by Sastry, Shevgaonkar, and Ramanuja (1983) and later by Wang, Schmahl, and Kundu (1987). Thejappa and Kundu (1992) assumed r.m.s. relative fluctuation in electron density, $\Delta N/N$, equal to 0.1 to explain brightness temperatures of the order of 100 000 K, on the basis of scattering. The scattering parameter under these conditions will be >200. According to McMullin and Helfer (1977) this amount of scattering will lead to a radio diameter more than an order of magnitude larger than that is usually observed. Melrose and Dulk (1988) pointed out that the implications of scattering models are in conflict with the constancy of the generalized etendue, $\mu^2\, \mathrm{d}r\, \mathrm{d}^2A$, along the ray path. McLean and Melrose (1985) argue that the scattering hypothesis fails to account for the observed sizes and directivity of Type I solar radio bursts. The scattering models require additional mechanisms like ducting, propagation through fibrous medium, etc., to make the radiation more directive. It is therefore clear that the consequences of scattering in the corona are not well understood at the present time. However, we are planning to include scattering effects in a three-dimensional ray-tracing calculation in a magnetized corona, and the results will be published separately.

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