UNUSUALLY LOW CORONAL RADIO EMISSION AT THE SOLAR MINIMUM

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Abstract. We present two-dimensional observations of the quiet Sun at 73.8, 50.0, and 38.5 MHz obtained with the Clark Lake Radioheliograph during the sunspot minimum period of September 1986. The observed peak brightness temperatures during the entire period of sunspot minimum are found to be extremely low, lying in the range (0.6×10^5 K–2.5×10^5 K). It is shown that these low values cannot be explained by the generally adopted models for N_e and T_e in a homogeneous corona. The effect of scattering by random density fluctuations is introduced in order to decrease the values of predicted T_b. The value of peak T_b is computed as a function of relative r.m.s. density fluctuations $\varepsilon = \langle \Delta N_e \rangle / N_e$; and it is found that ε should be in the range from 0.07 to 0.19, 0.1 to 0.25, and 0.15 to 0.35, respectively, at 38.5, 50.0, and 73.8 MHz, respectively, to explain the observed low brightness temperatures.

1. Introduction

Since the first radioastronomical observations, the topic of thermal radio emission from the quiet Sun has attracted the attention of many radio astronomers (for details, see Kundu, 1965; Zheleznyakov, 1970; Pawsey and Smerd, 1954; Sheridan and McLean, 1985). The 'quiet Sun' is often pictured as an idealized Sun with a static atmosphere which behaves in a very simple fashion, radiating energy thermally over a wide range of frequencies in a steady manner. It is ideal to observe the Sun during the minimum phase of the solar cycle when all the gross, disturbing features of its atmosphere are absent for a sufficiently long duration, so that the effects of part or future disturbances are assumed not to affect the quiet-Sun radio emission. Even though in recent years our knowledge of these disturbing features, like active regions, flares, filaments, prominences, streamers, coronal holes, etc., has grown considerably, it is still not easy to calculate all their effects on the quiet-Sun radiation. Therefore, the thermal emission from the quiet Sun remains one of the most intriguing and challenging problems for solar radio astronomers.

Interferometer aerials of variable aperture were used to obtain the Sun's disk brightness distribution at meter–decameter wavelengths by earlier works (e.g., Machin, 1951; O'Brien, 1953; Hewish, 1959; and Firor, 1959). Most of the above observations showed that the peak brightness temperature $T_b \simeq 10^6$ K. However, the observations of Hewish (1959) at 50 MHz, which were carried out during an extended period of exceptionally low solar activity in 1954, indicated T_b as low as 2×10^5 K at the disk center (see Moriyama, 1961). Aubier, Leblanc, and Boischot (1971) used the large

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Arecibo radio telescope to observe the quiet Sun at 60.0, 36.9, and 29.3 MHz for a period of one month, from July 15 to August 15, 1970 during the solar maximum. The values for T_b obtained by them were 6×10^5 K, 5×10^5 K, and 3.8×10^5 K at 60.0, 36.9, and 29.3 MHz, respectively.

Sheridan (1970) using the Culgoora radioheliograph imaged the quiet Sun at 80 MHz during September 1969, again near the solar maximum and estimated the brightness temperature at the disk center to be 8.7×10^5 K. Using the Clark Lake instrument with the same spatial resolution as that of Culgoora but with better sensitivity, Erickson *et al.* (1977) measured the brightness temperatures at a number of frequencies from 109 to 25.8 MHz during the solar minimum of 1976. The lowest values were 2.3×10^5 K and 2.1×10^5 K at 30.9 and 25.8 MHz, respectively. The 'official' solar-cycle minimum of sunspot number occurred in June 1976 whereas the observations of Erickson *et al.* (1977) were carried out between July 16 and July 23, 1976 and between August 18 and August 21, 1976 when the new cycle regions already predominated over the occurrence of old cycle regions. Kundu, Gergely, and Erickson (1977) measured the diameters and brightness distribution of the quiet Sun at various frequencies, as low as 25.8 MHz. Using the Clark Lake radioheliograph two-dimensional images, several aspects of the quiet Sun at 73.8, 50.0, and 30.9 MHz were studied by several authors (see Kundu *et al.*, 1987, 1989; Gergely, Gross, and Kundu, 1985; Wang, Schmahl, and Kundu, 1987; Lantos *et al.*, 1987; Kundu, 1987). The lowest value of $(1.5\text{–}2.0) \times 10^5$ K for the quiet-Sun radio emission at 30.9 MHz was reported by Wang, Schmahl, and Kundu (1987), who carried out their observations in October 1984, when the Sun was near its sunspot minimum. Sastry *et al.* (1981) and Sastry, Shevgaonkar, and Ramanuja (1983) reported that during their observations of the quiet Sun at 34.5 MHz form July 1980 to December 1981 (solar maximum), the brightness temperature at the center of the disk was as low as 2×10^5 K.

In the present paper, we report the Clark Lake observations of the quiet Sun during the sunspot minimum of September 1986, when the observed brightness temperatures were as low as 60000 K. We compute the brightness temperature distribution in a spherically-symmetric corona for various density and temperature models and compare them with observations. We also trace the rays in an inhomogeneous corona where the scattering of electromagnetic waves by density inhomogeneities plays the dominant role and calculate the brightness temperature as a function of the level of relative density fluctuations. It is surprising to note that either the temperature and density would have to be very low without the presence of inhomogeneities or the r.m.s. fluctuation level of electron density large compared with that during solar maximum, in order to explain the observed low brightness temperatures.

2. Observations

The observations discussed in the present paper were obtained using the Clark Lake radioheliograph during September 9 to 28, 1986 when the Sun was spotless for almost a month, which was ideal for quiet-Sun studies. The details of the Clark Lake radio telescope and its use as a solar instrument are given, respectively, by Erickson, Mahoney, and Erb (1983) and Kundu *et al.* (1983). The spatial resolution of the telescope at 73.8, 50.0, and 38.5 MHz was 4.6, 6.7, and 8.8 arc min, respectively. The time resolution was 1.28 s on some days and 2.56 s on others; thus yielding a large number of snapshot pictures of the Sun during each observing session.

In Figures 1(a) and 1(b) we give typical snapshot maps of the quiet Sun of September 28, 1986 at 73.8 and 50.0 MHz, respectively. The two-dimensional contour maps are in terms of brightness temperatures and are believed to be accurate to about 20%. On the side of each map, we give the time of observations, the peak brightness temperature, and the levels of the brightness contours. The circle inside each map corresponds to the photosphere, the top being north. Usually the noise level at 38.5 MHz is large. The noise levels at 73.8 and 50.0 MHz are also usually high, but fortunately they were small during our observations. Here we preferred to show only snap shot maps since they give a good account of all the emission features. The observations typically started at 17 : 20 UT and ended at 21 : 45 UT on most of the days. In Figure 2, we give measured peak brightness temperature as a function of time for September 28, 1986 observations at 50.0 MHz. Each point represents the peak brightness temperature T_b as given in the shap shot picture. In this figure, we have not included the data with low signal-to-noise ratio. The gap in the figure is due to such poor maps. Since the trend is the same at all frequencies, we have confined ourselves only to 50.0 MHz. The two points at the top of Figure 2 believed to be due to microbursts. Thus it is easy to remove the enhancements due to microbursts from the quiet-Sun data. One can also notice from Figure 2 that the peak brightness temperature remains steady for several hours of observations.

During the period of our observations, the day-to-day variation of the peak brightness temperature was significant. In Figures 3(a–c) we give the histograms of the peak brightness temperature of the quiet Sun as observed in the snap shot mode at 73.8, 50.0, and 38.5 MHz on three different days, i.e., on September 9, 16, and 28, 1986. The peak T_b on September 9 was very low, lying between 50 000 K and 100 000 K at 38.5 MHz, 50 000 K and 70 000 K at 50.0 MHz, and 50 000 K and 110 000 K at 73.8 MHz. The upper limit of the peak T_b at 38.5 MHz is larger than that at 50.0 MHz because of the increased level of noise at low frequencies. The September 28 observations show similar brightness variations as those of September 9 whereas the peak T_b on September 16 was twice that of September 9 or September 28. In Table I we give the mean values of the peak brightness temperatures of the quiet Sun during the days of our observations at all three frequencies. From Table I, it is clear that the mean T_b fluctuated between 60 000 K and 250 000 K at 73.8 MHz, 60 000 K and 130 000 K at 50.0 MHz, and 70 000 K and 150 000 K at 38.5 MHz. These are the lowest peak brightness temperatures ever reported for the quiet Sun at meter–decameter wavelengths. To make sure that the low observed values for peak brightness temperatures were not due to an error in the calibration, we checked the calibration carefully. The solar images were calibrated in terms of brightness temperatures using the sidereal sources: namely, Tau A, Hydra A, Virgo A, Her A, Cygnus A, and Cas A. The details of calibration procedure adopted at Clark Lake is described in Erickson *et al.* (1977). We also made maps of the point

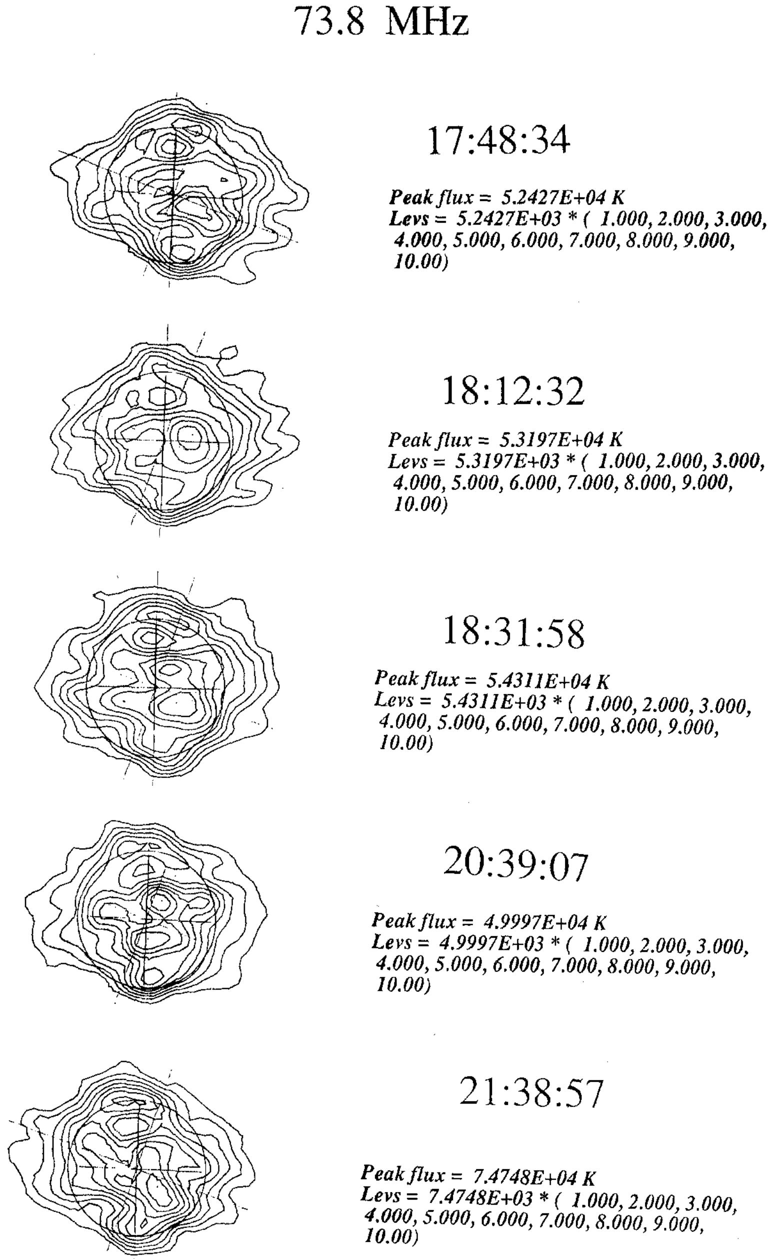


Fig. 1a.

Fig. 1. Typical snapshot pictures of the quiet Sun at 73.8 and 50.0 MHz. Next to each map the time of observation, the peak brightness temperature, and the levels of brightness contours are given. The circle inside each map represents the optical disk. The solar north is directed to the top.

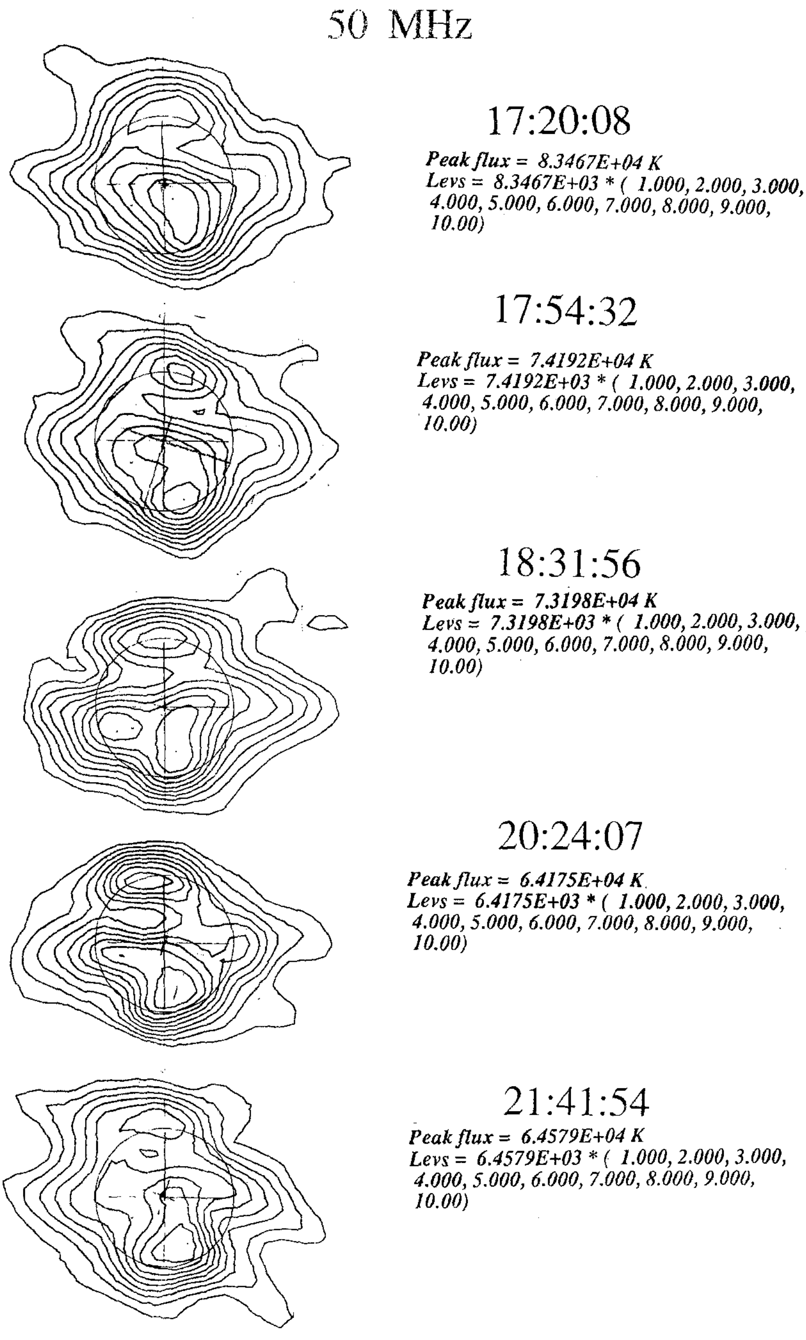

50 MHz
17:20:08
Peak flux = 8.3467E+04 K
Levs = 8.3467E+03 * (1.000, 2.000, 3.000, 4.000, 5.000, 6.000, 7.000, 8.000, 9.000, 10.00)
17:54:32
Peak flux = 7.4192E+04 K
Levs = 7.4192E+03 * (1.000, 2.000, 3.000, 4.000, 5.000, 6.000, 7.000, 8.000, 9.000, 10.00)
18:31:56
Peak flux = 7.3198E+04 K
Levs = 7.3198E+03 * (1.000, 2.000, 3.000, 4.000, 5.000, 6.000, 7.000, 8.000, 9.000, 10.00)
20:24:07
Peak flux = 6.4175E+04 K
Levs = 6.4175E+03 * (1.000, 2.000, 3.000, 4.000, 5.000, 6.000, 7.000, 8.000, 9.000, 10.00)
21:41:54
Peak flux = 6.4579E+04 K
Levs = 6.4579E+03 * (1.000, 2.000, 3.000, 4.000, 5.000, 6.000, 7.000, 8.000, 9.000, 10.00)

Fig. 1b.

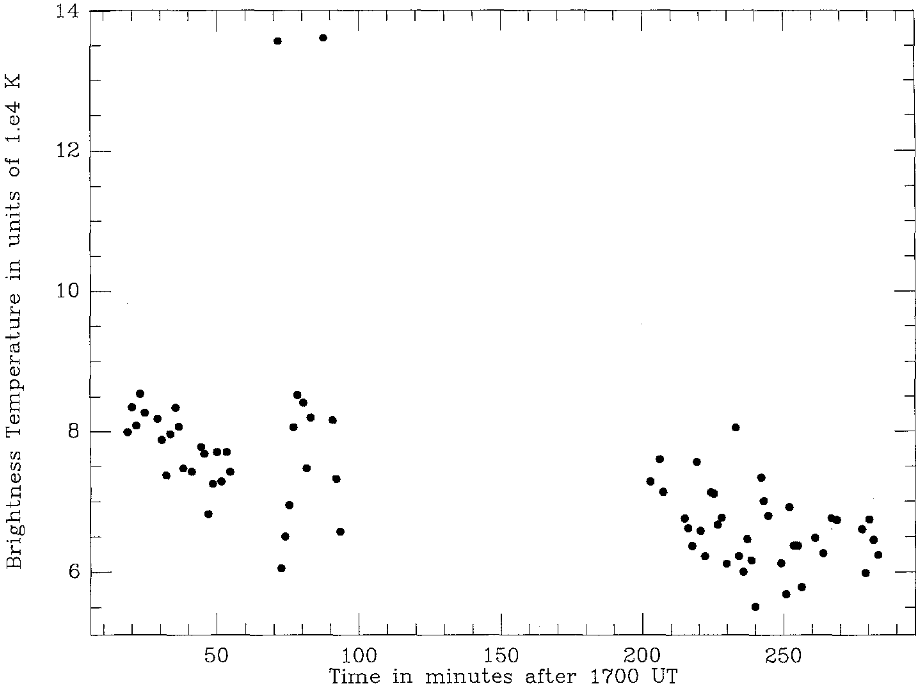


Fig. 2. The variation of the peak brightness temperature of the quiet Sun with time at 50.0 MHz on September 28, 1986.

sources that were used for calibration and found that the contribution from the sidelobes is negligible. We compared the observed peak flux values of the sidereal sources during the periods of low brightness temperatures and during those periods when peak brightness temperatures were greater than 10^5 K and found to be comparable. We also found that the observed peak brightness temperatures were in the same range from 60000 K to 100000 K at all three frequencies during another period of spotless minimum which was in June 1986, the results of which we will present elsewhere. We have also noticed that the observed peak brightness temperatures of the quiet Sun were greater than 10^5 K whenever there was some activity on the Sun, even though it was free from any transient disturbances. Therefore, we believe that the observed low peak brightness temperatures are not likely due to calibration errors, but rather they are intrinsic to the lack of activity on the Sun.

We have measured the east–west and north–south diameters of the quiet Sun from half-power contour levels. The average values of E–W and N–S diameters are, 42, 52, and 64 arc min and 35, 47, and 53 arc min, respectively, at 73.8, 50.0, and 38.5 MHz. These values agree well with those reported by Gergely, Gross, and Kundu (1985).

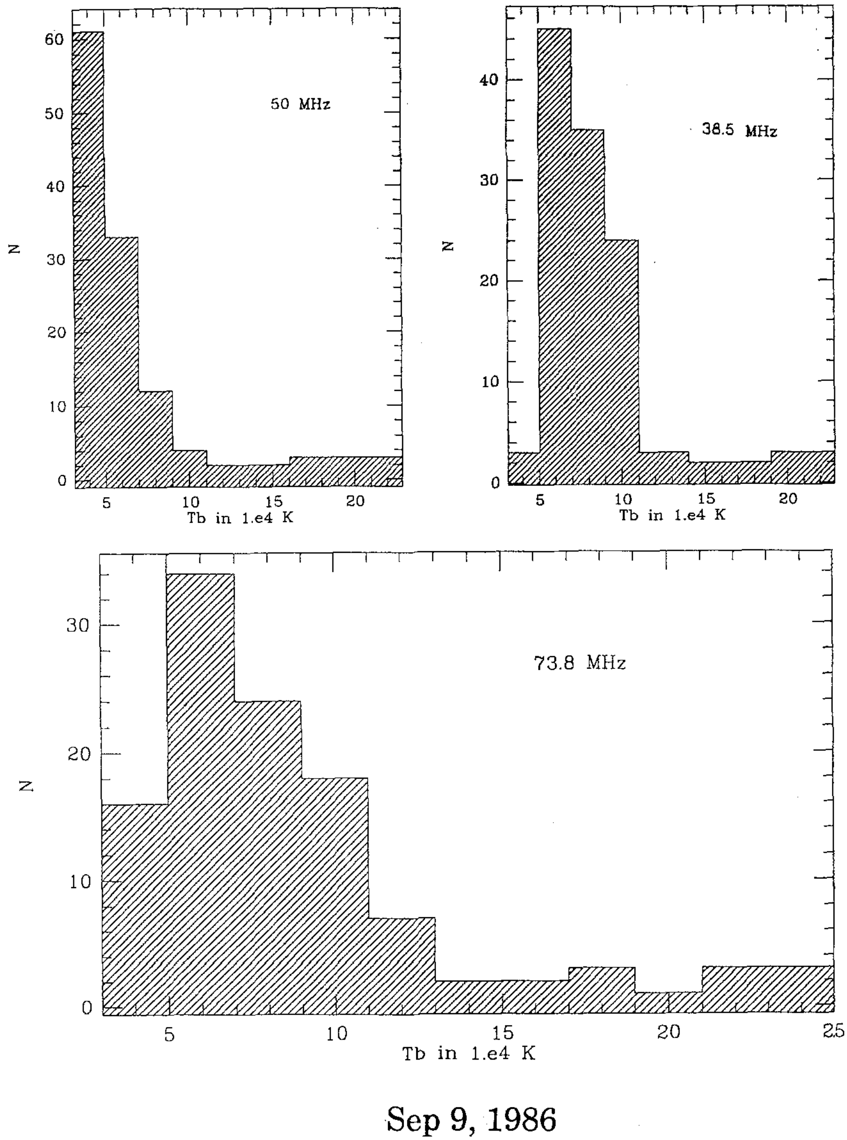
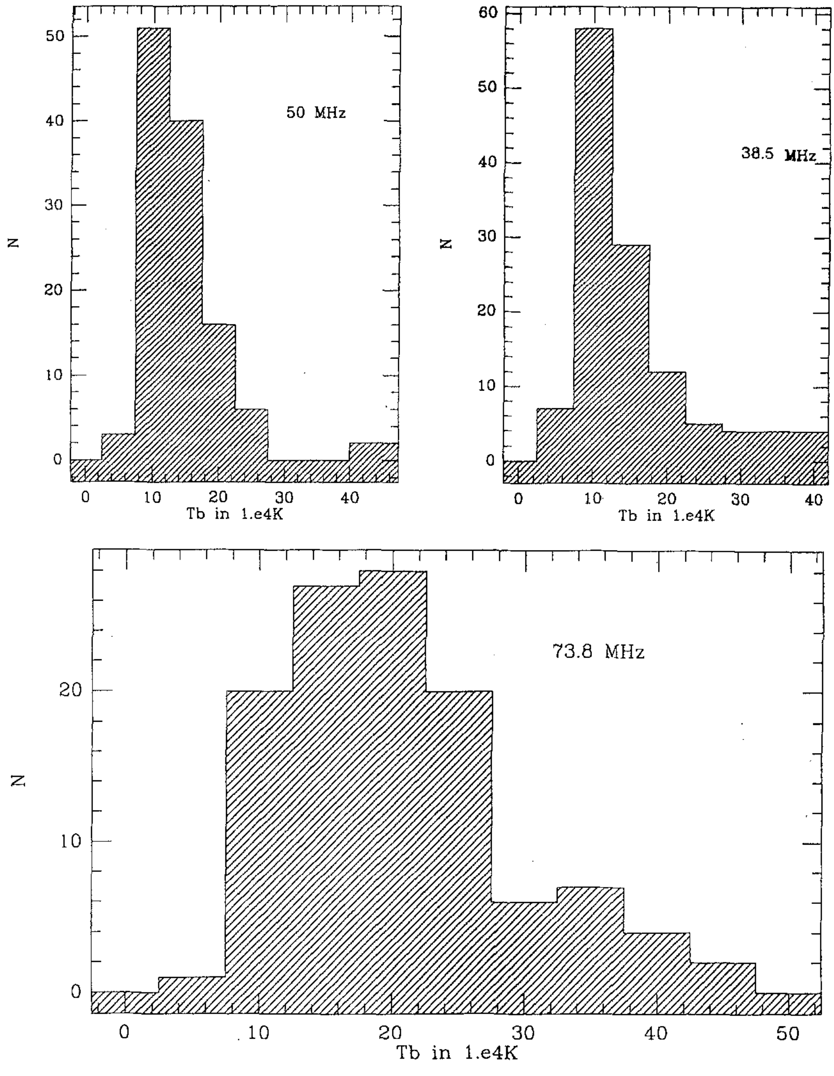


Fig. 3a.

Fig. 3a–c. Histograms of the observed peak brightness temperature of the quiet Sun at 73.8, 50.0, and 38.5 MHz on September 9, 16, and 28, 1986, respectively.

3. Models of Quiet-Sun Emission

It is clear that the observations of the quiet Sun at long decameter wavelengths showed very low brightness temperatures during the sunspot minimum of September 1986; the T_b varied from 60 000 to 250 000 K. The brightness temperature distribution over the solar disk is usually calculated by raytracing at various frequencies either in a spherically-



Sep 16, 1986

Fig. 3b.

symmetric, homogeneous coronal plasma (see, for example, Burkhardt and Schluter, 1949; Ginzburg. 1946; Martyn, 1946, 1948; Waldmeier and Muller, 1948; Smerd, 1950; Bracewell and Preston, 1955) or in an inhomogeneous coronal plasma (see, for example, Scheffler, 1958; Fokker, 1966; Aubier, Leblanc, and Boischot, 1971; Riddle, 1974b). In this paper we consider both cases. In the first case we calculate the distribution of brightness temperature for various models of electron temperature and density in the corona and compare them with observations; in the second case we trace the rays in an inhomogeneous corona by including the effects of scattering and compute the peak

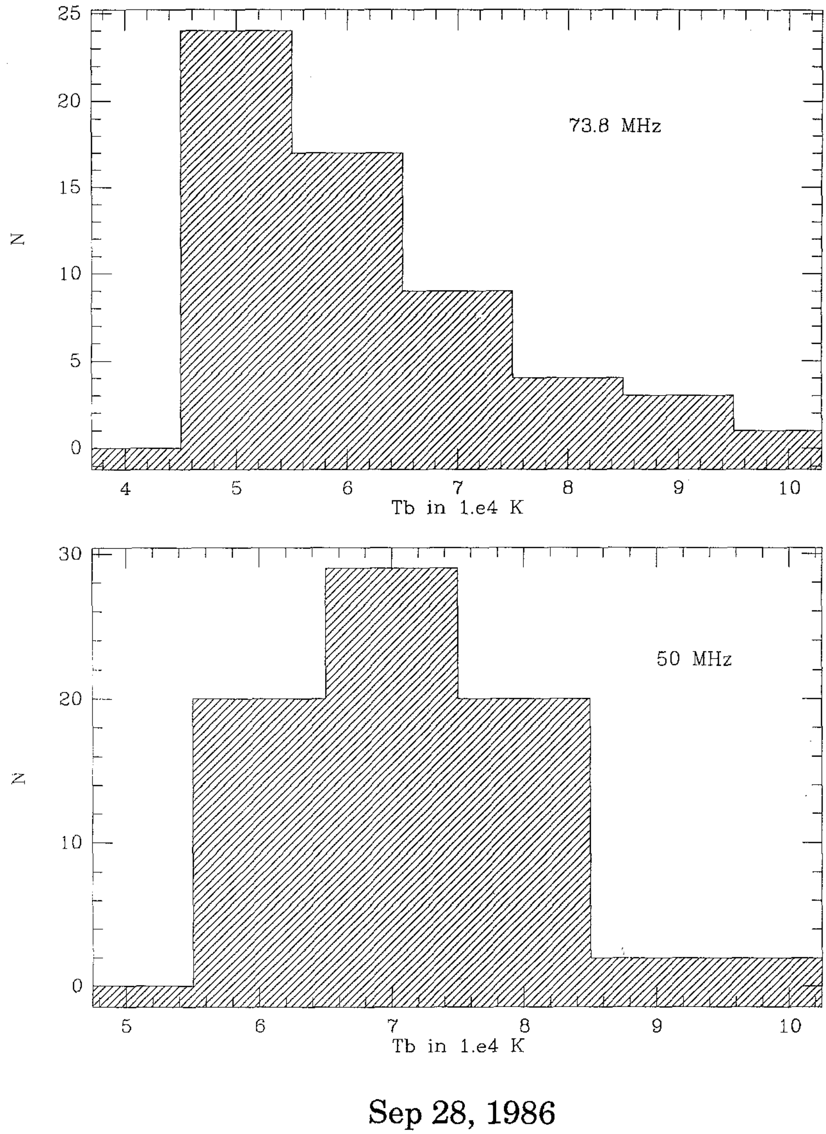


Fig. 3c.

brightness temperature at the disk center as a function of the r.m.s. relative density fluctuation level, ε.

3.1. Without scattering

The observed brightness temperature for any ray path is

$$T_b = \int_0^{\tau} T_e(\tau) \exp(-\tau)\, d\tau, \qquad (1)$$

TABLE I

Mean peak brightness temperature of the quiet Sun in units of 10^4 K during September 9–28, 1986

Date Sept. 1986	Frequency in MHz		
	73.8	50	38.5
9	8.92	5.96	7.94
10	14.58	6.91	9.35
11	8.53	6.4	9.41
12	16.01	7.32	7.27
15	17.66	14.70	14.64
16	20.78	13.56	13.11
17	25.78	13.85	14.03
18	17.03	9.75	9.56
19	10.61	10.03	18.84
20	18.39	15.50	16.38
21	21.75	18.83	19.31
22	20.21	11.57	13.28
23	8.21	6.29	5.87
24	8.91	6.37	6.12
25	6.97	5.78	5.97
26	18.42	11.71	15.85
27	13.15	10.17	14.25
28	6.14	7.3	11.95

where the optical depth

$$\tau = \int_{s_1}^{s_2} k \, \mathrm{d}s \,, \tag{2}$$

and the absorption coefficient per cm of path length is approximately (Bracewell and Preston, 1955)

$$k = \frac{0.16 N_e^2}{f^2 \mu T_e^{3/2}} \,. \tag{3}$$

Here T_e is the electron temperature, s is the path length along a ray, f is the frequency of the radio radiation, μ is the refractive index of the medium, and N_e is the electron density. The basic equation for calculating the optical thickness of the corona taken along a ray path (see, Bracewell and Preston, 1955) is

$$\tau = \frac{2 \times 10^{-11} R_\odot}{f^2 T_e^{3/2}} \int_{\rho_a}^{\infty} \frac{N_e^2 \rho \, \mathrm{d}\rho}{(\mu^2 \rho^2 - a^2)^{1/2}} \,, \tag{4}$$

where ρ is the radial distance from the Sun's center in units of solar radii $R_\odot$, a is the distance of the asymptote of the ray from the parallel line through the disk center, also in units of $R_\odot$. The radial distance ρ_a of the turning point, i.e., the point where the direction of propagation changes from that of decreasing μ to that of increasing μ, is determined from Snell's law of refraction. In other words we have to find the root of the equation, obtained by equating the denominator of the integrand in Equation (4) to zero. We used Newton–Raphson method to find the roots. The integral (4) is an improper integral with an integrable singularity at its lower limit. The basic trick to evaluate the improper integrals is to make the change of variables to eliminate the singularity or to map an infinite range of integration to a finite one (see, e.g., Press *et al.*, 1986). By using such a trick, we could eliminate the singularities encountered at turning points. We have assumed Newkirk's density model for the corona (see Newkirk, 1961), $N_e = 4.2 \times 10^4 De^{Q/\rho}\ \mathrm{cm}^{-3}$, where $D \approx 0.1$ to 0.5 for a coronal hole, $D = 2$ for an active region, $D \approx 10$ for a dense streamer, and $D = 1$ for quiet corona. The value for Q is taken as 10. For three different sets of D and T_e, we traced the rays and computed the radial distance of the turning points (ρ_a), optical depths (τ), and brightness temperatures (T_b) for various values of the distance from the disk center a for 73.8, 50.0, and 38.5 MHz. We present the results in Figures 4(a–c), 5(a–c), and 6(a–c) for 38.5, 50.0, and 73.8 MHz for three sets of parameters: (1) $D = 1$, $Q = 10$, and $T_e = 10^6$ K; (2) $D = 0.1$, $Q = 10$, and $T_e = 2 \times 10^6$ K; and (3) $D = 0.1$, $Q = 10$, and $T_e = 10^5$ K, respectively.

From Figures 4(a–c), which represent the generally accepted coronal model, i.e., $D = 1$ and $T_e = 10^6$ K, the following facts emerge for 38.5, 50.0, and 73.8 MHz frequencies, respectively: (1) the radial distance to the turning point for the central rays is $1.64\ R_\odot$, $1.5\ R_\odot$, and $1.35\ R_\odot$, (2) the optical thickness (τ) for the central rays is approximately 1.02, 1.45, and 2.5 giving brightness temperatures of 8.71×10^5 K, 9.45×10^5 K, and 9.9×10^5 K, and (3) the half-power E–W diameters are approximately 49′, 46′, and 45′. Since T_b decreases very slowly as the distance from the disk center increases, limb darkening may not be an observable effect.

In Figures 5(a–c) and 6(a–c) the corona is assumed to be rarefied (i.e., by assuming $D = 0.1$ corresponding to a coronal hole) while T_e is taken as 2×10^6 K and 10^5 K, respectively. One notices the following for 38.5, 50.0, and 73.8 MHz frequencies: (1) ρ_a is $1.19\ R_\odot$, $1.12\ R_\odot$, and $1.03\ R_\odot$, (2) the optical thickness for the central rays is 0.18, 0.27, and 0.5 giving T_b equal to 6.15×10^5 K, 8.42×10^5 K, and 1.26×10^6 K for $T_e = 2 \times 10^6$ K whereas for $T_e = 10^5\ K$, $\tau \gg 1$ giving $T_b \approx T_e$, (3) the brightness temperature T_b decreases rapidly as a increases for $T_e = 2 \times 10^6$ K (see Figure 5(c)) whereas T_b remains constant up to $a = 1.3\ R_\odot$ with a sharp decline beyond that value for $T_e = 10^5$ K (see Figure 6(c)), and (4) the half-power E–W diameters are approximately 27′, 26′, and 25′ for $T_e = 2 \times 10^6$ K whereas they are 53′, 50′, and 47′ for $T_e = 10^5$ K.

Thus for larger values of T_e, the brightness temperature falls off more rapidly as the distance from the center of the disk increases contrary to observed brightness temperature distribution. The optical thickness for the central rays is not small even for the assumed high values of T_e and, therefore, the observed low brightness temperatures can never be attained at the center of the disk. At low values of coronal temperatures, the

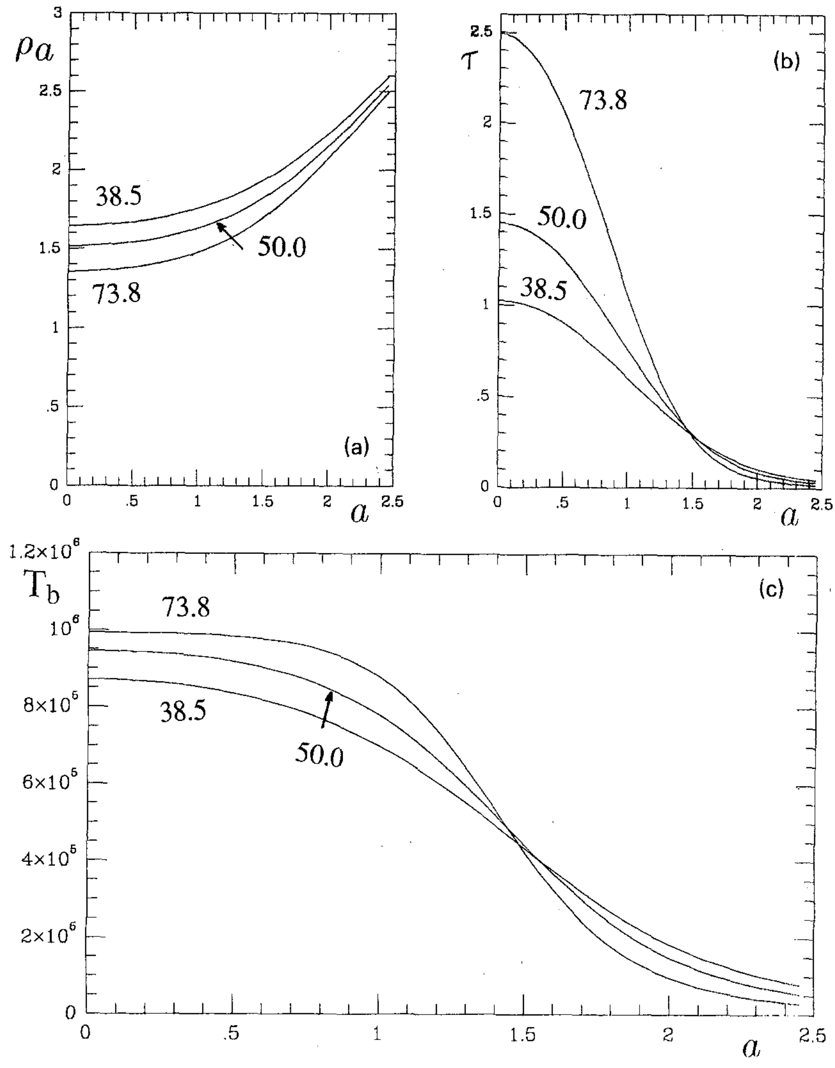


Fig. 4a–c. The variation of the radial distance of the turning point (ρ_a), the optical thickness (τ), and the brightness temperature (T_b), respectively, with distance from the disk center (a) for $T_e = 10^6\,K$ and $D = 1$.

corona is optically thick over a wide range of a values, making a large uniform radio disk which again contradicts the observed variation of T_b with a. The diameter of the radio disk increases as the temperature decreases. Although the predicted values for the half-power diameters of the radio Sun at $T_e = 10^5$ K seem to fit the observed diameters better in comparison with other models, the predicted change of diameter with frequency does not agree with observations. The observed E–W diameters at 73.8, 50.0, and 38.5 MHz are approximately 42, 52, and 64 arc min whereas the computed diameters at half-power level at $T_e = 10^5$ K are 47′, 50′, and 53′, respectively, even when the density is decreased by an order of magnitude (see Figure 6(c)).

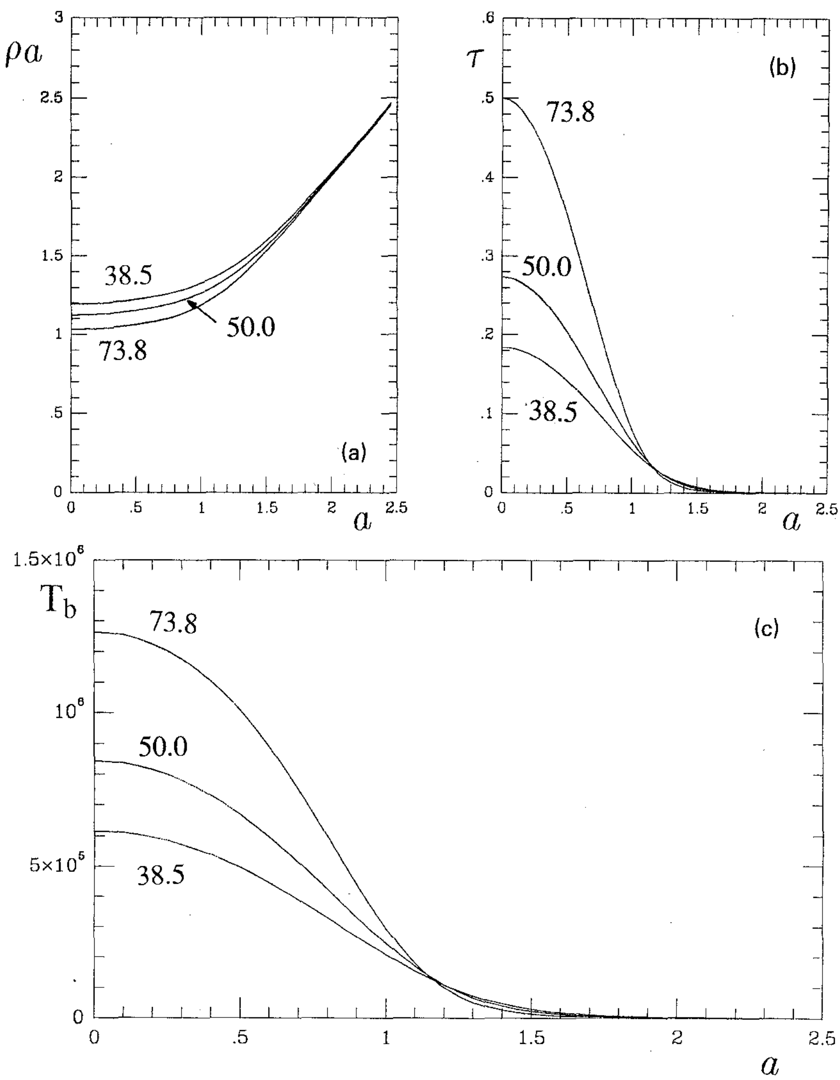


Fig. 5a–c. The same as in Figure 4 but for $T_e = 2 \times 10^6$ K and $D = 0.1$.

3.2. With scattering

Since the beginning of the quiet-Sun radio observations, the importance of scattering of electromagnetic radiation by density inhomogeneities at low frequencies was realized (see Scheffler, 1958; Fokker, 1966; Aubier, Leblanc, and Boischot, 1971; Riddle, 1974a, b). Here one should note that the scattering on density inhomogeneities actually prevents the rays from reaching the turning points where the contribution to optical thickness is maximum thus reducing the observed brightness temperature. A good agreement between the observed and calculated brightness distributions was found by treating the scattering problem analytically (Scheffler, 1958) as well as numerically (see, e.g., Fokker, 1966; Aubier, Leblanc, and Boischot, 1971; McMullin and Helfer, 1977).

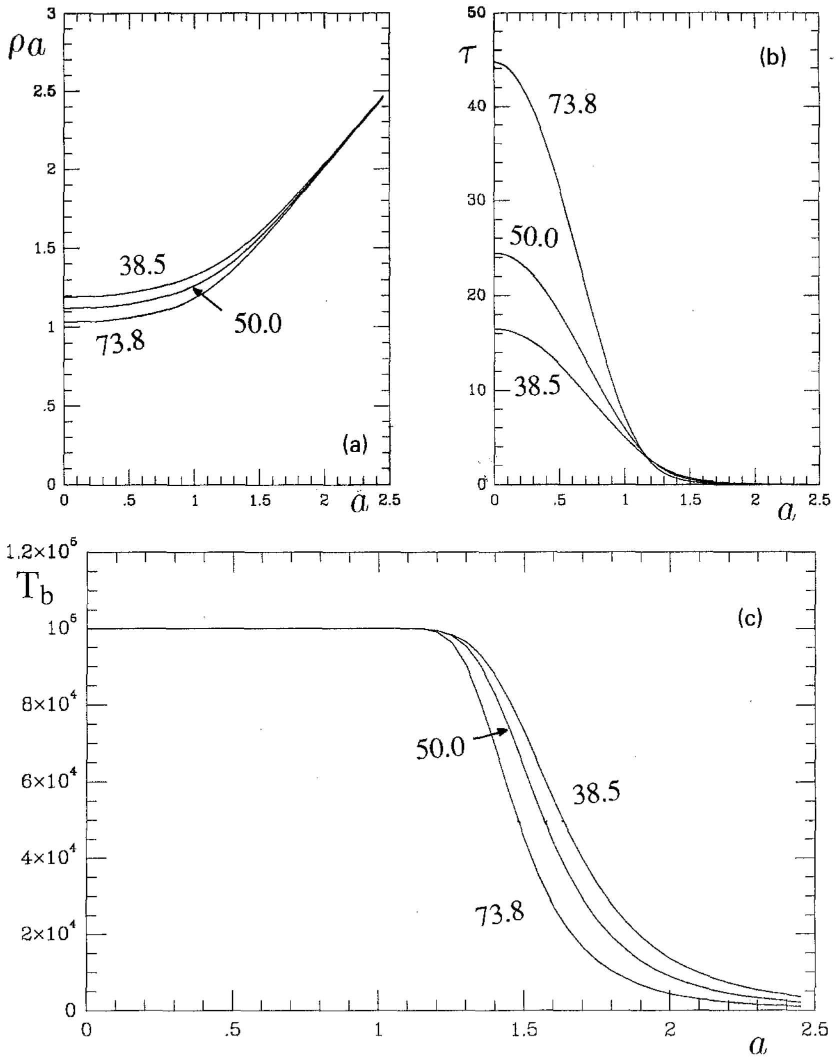


Fig. 6a–c. The same as in Figure 4 but for $T_e = 10^5$ K and $D = 0.1$.

Aubier, Leblanc, and Boischot (1971) estimated that the scattering of radiation by density inhomogeneities of 2% relative fluctuation level with scale lengths of the order of $5 \times 10^{-5} R_{\odot}$ can reduce the brightness temperature at the center of the disk by approximately 20%. One can treat the inverse problem, i.e., one can find the level of density inhomogeneities by computing the peak brightness temperature of the inhomogeneous quiet corona and comparing it with the observed value. The angular deflection suffered by a ray travelling in a medium of fluctuating refractive index has been calculated by Chandrasekhar (1952) and successfully adapted by solar radio astronomers in dealing with scattering problems in the solar corona (see, e.g., Fokker, 1965, 1966; Steinberg *et al.*, 1971). The mean-square angular deviation which a ray suffers due to scattering while travelling through a slab of thickness Δs with a random distribution of density inhomogeneities is given by (Steinberg *et al.*, 1971)

$$\langle \Delta \Psi^2 \rangle = \frac{\sqrt{\pi}}{2}\, 6.5 \times 10^{-9}\, \frac{1}{\mu^4}\, \frac{\varepsilon^2 N_e^2}{f^4 h}\, \Delta s\,, \tag{5}$$

where $\varepsilon = \langle \Delta N_e \rangle / N_e$ is the r.m.s. density fluctuation level, h is the size of the isotropic inhomogeneities, and f is the observing frequency.

In the present paper we trace the rays in three dimensions by including the coronal refraction, scattering and absorption in the ray tracing calculations as discussed in detail by Steinberg *et al.* (1971) and Riddle (1974a). In order to obtain a statistically reliable estimate of the peak brightness temperature for each value of ε we compute numerically the paths of 3000 rays. Because of scattering, the paths cover a wide region of the corona. So the observer receives in the direction of the disk center a contribution from

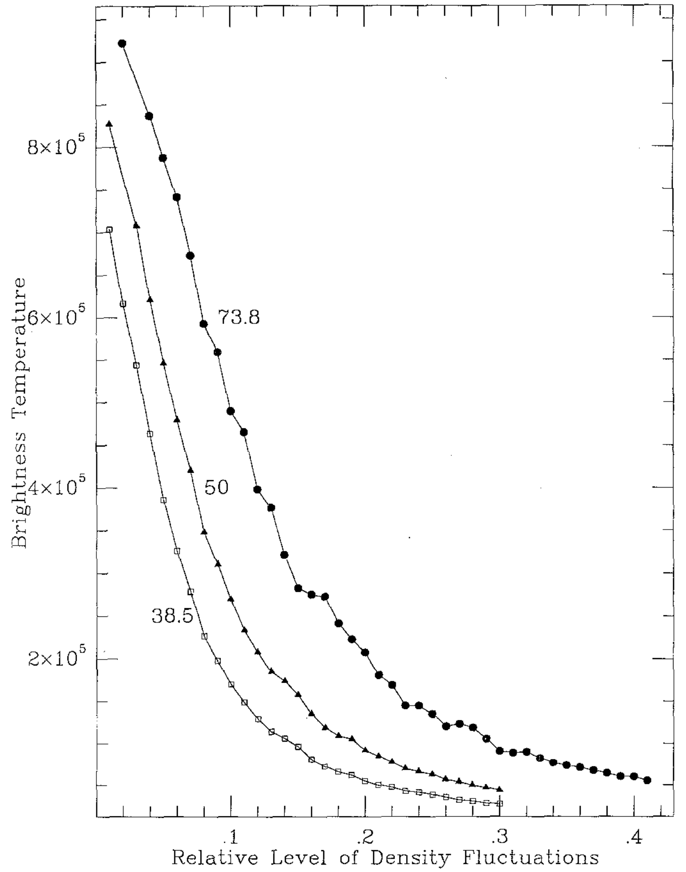


Fig. 7a. The brightness temperature as a function of the relative r.m.s. density fluctuations in the corona (ε) for $D = 0.5$ and $T_e = 10^6$ K at 73.8, 50.0, and 38.5 MHz frequencies.

a large number of elements. For each path, we calculate the total optical depth τ and the corresponding brightness temperature given by $T_b = T_e(1 - e^{-\tau})$. For each value of ε, we obtain 3000 values: we take the mean value as the brightness temperature in the direction of the disk center to take into account the contribution from all the rays. We carried out such computations for various values of ε. Generally the curve T_b versus ε has a gaussian shape. The curve of the predicted brightness temperature as a function of ε is smooth as we increase the number of rays traced for each set of parameters.

In Figure 7(a) we plot the computed peak brightness temperature as a function of ε at 73.8, 50.0, and 38.5 MHz, respectively, by taking the usually adopted density model during solar minimum, i.e., $\frac{1}{2}$ × Newkirk's density model and $T_e = 10^6$ K. The desired values of 2.5×10^5 K to 0.6×10^5 K can be obtained for large values of ε, i.e., ε should lie in the range 0.07 to 0.19; 0.1 to 0.25 and 0.15 to 0.35, respectively, at 38.5, 50.0, and 73.8 MHz, respectively. One should note that as the frequency is increased, the required level of density fluctuations is also increased which confirms the accepted notion that

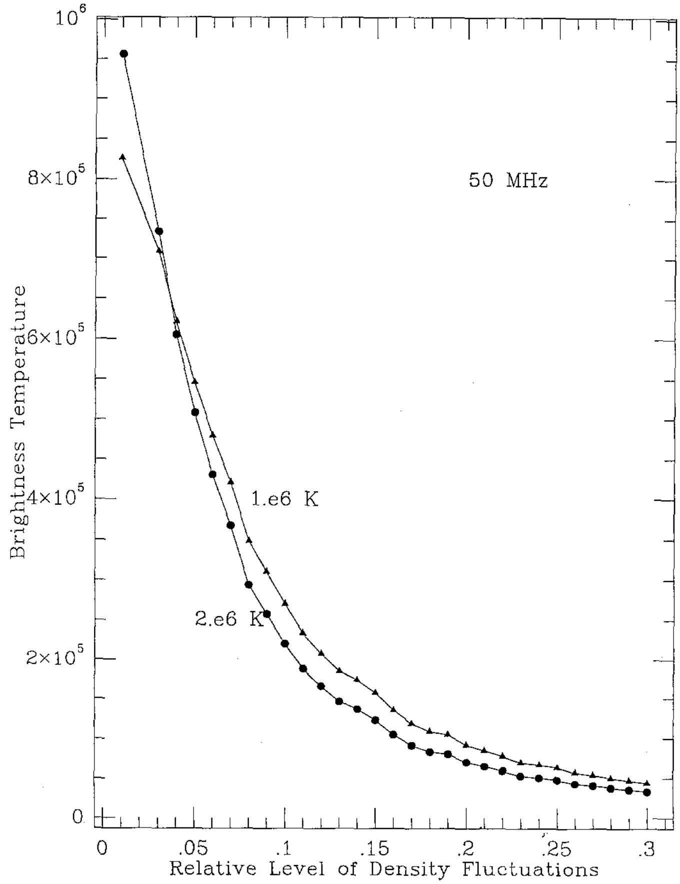


Fig. 7b. The brightness temperature (T_b) at the disk center as a function of the relative r.m.s. density fluctuations in the corona (ε) for (1) $D = 0.5$ and $T_e = 10^6$ K and (2) $D = 0.5$ and $T_e = 2 \times 10^6$ K.

the role of scattering increases as the frequency decreases. Here we have assumed $h = 5 \times 10^{-5} R_{\odot}$. The effect of an increase in h on the brightness temperature is found to be small in comparison with ε. In Figure 7(b) we present the T_b vs ε curves computed for $T_e = 10^6$ K and 2×10^6 K at 50.0 MHz. The values of the resultant peak brightness temperatures are slightly lower for $T_e = 2 \times 10^6$ K than for $T_e = 10^6$ K for $\varepsilon \geq 0.02$, but the functional behavior and the required range of values to explain the observed range of peak brightness temperatures do not change much.

4. Discussion

The observations of the coronal emission at wavelengths greater than approximately 2 m are of considerable importance, since they provide information on the kinetic temperature and the shape of the corona. As shown earlier, the optical thickness τ at the center of the disk for generally accepted models of coronal density and temperature is large, making the corona opaque for radio waves at long wavelengths, and rendering the observed peak brightness temperature approximately equal to the kinetic temperature of the corona. By using radio observations, many authors have derived a kinetic temperature of 1 million degrees for the corona. However, the observed peak brightness temperatures during minimum are systematically lower, being 2×10^5 K at 50.0 MHz during the 1954 minimum (see Hewish, 1959; Moriyama, 1961), 2.3×10^5 K and 2.1×10^5 K at 30.9 and 25.8 MHz frequencies, respectively, during the 1976 minimum (see Erickson *et al.*, 1977) and 1.5×10^5 K to 2×10^5 K at 30.9 MHz during 1984 (see Wang, Schmahl, and Kundu, 1987). We present here the lowest values ever reported for the peak brightness temperatures during minimum, i.e., in the range (0.6×10^5 K–2.5×10^5 K). If one believes that the peak brightness temperature directly gives the kinetic temperature by assuming the usual spherically-symmetric formula for the variation of the electron density, the derived low kinetic temperatures for the corona are in contradiction to other observations, as discussed below.

It is well-known that the Fe X and Fe XIV emission lines are good indicators of 1 and 2 million degree corona, respectively. Altrock (1990) reported the Fisher–Smartt Emission Line Coronal Photometer (ELCP) observations of the emission line limb flux variation at 6374 Å (Fe X) and 5303 Å (Fe XIV) over 1.5 solar activity cycles spanning the period from 1973 to 1990. Although the values of limb flux vary by an order of magnitude from maximum to minimum, the mere existence of the emission line flux indicates 1 and 2 million degrees for the kinetic temperatures.

The nonradiative energy that travels outward past the chromosphere in the form of Alfvén and slow-mode MHD waves is believed to be dissipated in the relatively low-density atmosphere above and raise the gas temperature to over 10^6 K. This high temperature is responsible for the great extent of the corona as seen during an eclipse because it produces a large atmospheric scale height. It also greatly enhances the thermal conductivity of the gas, which in turn tends to create a condition of nearly uniform high temperature. The conductive flow of heat varies as $T^{5/2}$ ($\mathrm{d}T/\mathrm{d}h$). Thus the 10^6 K corona transfers heat 10^5 times more efficiently than the chromospheric gas at 10^4 K, resulting in a temperature that is far more uniform than in the atmosphere below. The importance of thermal conduction in determining the large-scale temperature structure of the solar corona was first recognized by Chapman (1957) who pointed out that thermal conduction alone could extend the solar corona to great distances into the interplanetary space. The fact that the slow decline in temperature is inconsistent with hydrostatic equilibrium, combined with the requirement that the gas pressure vanish at large distances, lead Parker (1958) to postulate that the corona must expand, producing the now well-known solar wind. As shown by Cox and Tucker (1969), the energy loss per unit mass by radiation near 10^5 K due to bremsstrahlung, recombination radiation and line emission is much greater than near 10^6 K, where hydrogen is fully ionized, and radiative losses are relatively inefficient. Thus the maintenance of a 10^5 K corona requires more mechanical energy than a 10^6 K corona. In fact, the temperatures from 5×10^4 K to 3×10^5 K lie in the unstable temperature regime, where the radiative losses are so high that the thermal instability sets in and formation of condensations of lower temperature and higher density becomes possible (see, for details, Parker, 1953; Zanstra, 1955; Kleczek, 1958; Field, 1965). Therefore, our observed low value for the peak brightness temperatures are unlikely to represent directly the kinetic temperatures of the corona.

If one assumes that the corona is rarefied with an electron density smaller by an order of magnitude than the usually accepted value and the temperature of the corona is 2 or 1 million degrees, we obtain 6.15×10^5 K, 8.42×10^5 K, and 1.26×10^6 K for the assumed value of $T_e = 2 \times 10^6$ K (see Figure 5(c)) and 6.46×10^5 K, 7.87×10^5 K, and 9.41×10^5 K for $T_e = 1 \times 10^6$ K at 38.5, 50.0, and 73.8 MHz, respectively. Also it is clear from Figure 5(c) that the brightness distribution is peaked at the centre of the disk with a rapid decrease in its value as the distance increases from the center of the disk. However, one does not observe the pronounced limb darkening expected at these frequencies from theoretical computations. The computed half-power E–W diameters at 38.5, 50.0, and 73.8 MHz are approximately 28′, 27′, and 26′ and 27′, 26′, and 25′, respectively, for $T_e = 10^6$ K and $T_e = 2 \times 10^6$ K, which are much smaller than the observed values of 64′, 52′, and 42′. If one assumes that the corona is extremely thin and the transition region from chromosphere to corona is extended to larger distances than the usually adopted values with temperatures as low as 10^5 K, one could explain the anomalously low values of the observed brightness temperatures. However, the transition layer is supposed to be extremely thin and the required coronal densities are unrealistically low to make the central ray at these frequencies to reach the transition layer. And also because of the extremely high radiative energy losses and low thermal conductivity at 10^5 K, it is unlikely that the temperature of the coronal plasma will be of the order of 10^5 K. Moreover the predicted change of half-power diameter with frequency is smaller than what is observed (see Figure 6(c)) and also the predicted constant brightness temperature over a wide range of a values contradicts the slow decline of observed brightness temperature with a. Therefore, the low observed brightness temperatures suggest that the inhomogeneous structure of the decameter corona plays a dominant role in reducing the optical depth.

When scattering is included in the ray-tracing calculations (Figures 7(a) and 7(b)), the peak brightness temperature of 2.5×10^5 K and lower can be explained by assuming large values for the ratio of the mean level of density fluctuations to the ambient electron density, i.e., $\langle \Delta N_e \rangle / N_e \geq 0.1$. Actually minimum corona is known to be highly structured with streamers, coronal holes, spicules, polar plumes, coronal loops, and also with small structures of the order of 2″–10″ where the relative level of density fluctuations can be very large. For example, optical polarization data require the presence of large irregularities in electron density in the corona (Allen, 1975; Orrall and Rottman, 1986; Orrall *et al.*, 1990). And also a variety of length scales, i.e., structures down to scales of order $10^{-6} R_\odot$, are detected in the solar wind near the Sun by spacecraft radio transmissions when they are occulted by the Sun (Woo and Armstrong, 1979; Yakovlev *et al.*, 1980; Bird, 1982; Kolosov *et al.*, 1982; Armand, Efimov, and Yakovlev, 1987; Yakovlev, Efimov, and Rubtsov, 1987, 1988; Rubtsov, Yakovlev, and Efimov, 1987). But Aubier, Leblanc, and Boischot (1971) used $\varepsilon = 0.02$ in their calculations and obtained an excellent agreement with the observations carried out during the period of solar maximum with relatively large T_b values. Therefore, one can speculate that the relative level of density fluctuations during solar minimum is larger than that during solar maximum. Such a peculiarity may be due either to an increase in $\langle \Delta N_e \rangle$ or a decrease in N_e. Actually the coronal magnetic fields are extremely small during spotless minimum, which can shield embryonic condensations arising in such locations where the plasma is thermally unstable. Although a local temperature perturbation may be quickly smoothed out due to thermal conductivity, the appearance of random short-lived coronal condensations which act like enhanced density inhomogeneities is more likely during spotless minimum than otherwise. It is clear that a good knowledge of the inhomogeneities may be very important for understanding the structure and heating of the corona.

5. Conclusions

(1) The peak brightness temperture of the quiet Sun at long decameter wavelengths during the solar minimum of September 1986 is much smaller than what is observed during solar maximum; it ranges from 0.6×10^5 K to 2.5×10^5 K.

(2) If the scattering of radio emission is neglected, the observed low brightness temperatures at decameter wavelengths cannot be explained.

(3) The required values for the relative r.m.s. density fluctuations to reduce the observed T_b to $< 2.5 \times 10^5$ K are $\langle \Delta N_e \rangle / N_e \geq 0.1$.

(4) The values of $\langle \Delta N_e \rangle / N_e$ in the solar corona during solar minimum may be larger than those present during maximum.

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