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The Low-Frequency Radio Spectrum of the Continuum Emission from the undisturbed Sun

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Abstract. The low-frequency radio spectrum of the continuum emission from the undisturbed Sun is determined for 24 days during the period 1985 May–September. It is found that the spectral index varied from +1.6 to +3.6 during this period. It is suggested that the large positive spectral indices are due to the existence of temperature gradients in the outer corona.

Key words: Sun, low-frequency radio observations—Sun, corona

1. Introduction

Very few measurements of the flux densities and spectra of the low frequency ($\leqslant 100$ MHz) radio emission from the undisturbed Sun have been made, on a synoptic basis. The difficulties in making such measurements were pointed out by Aubier Leblanc & Boischot (1971) and Erickson *et al.* (1977). Briefly, the problems deal with accurate calibration, and base-line determination due to the low contrast between the solar brightness and the sky background temperature. The only measurements available, are due to (1) Aubier, Leblanc & Boischot (1971) who published only one set of flux densities at three low frequencies in the range 60 to 29 MHz and (2) Erickson *et al.* (1977) who reported two sets of flux densities in the frequency range 109 to 19 MHz, and computed the spectral index. The variations of the spectral index were not investigated.

We have used a broad-band antenna system to measure the flux densities of the undisturbed Sun at four low frequencies in the range 64 to 36 MHz. We report here on a series of measurements made, during the solar minimum period 1985 May–September, when the transient burst activity of the Sun was absent.

2. Observations

The antenna system consists of 64 bi-conical dipoles placed in corner reflectors. The dipoles are designed for operation in the frequency range 70 to 30 MHz, with a VSWR $\leqslant 2$. The antenna is divided into two groups of 32 elements in the NS direction. Diode delay shifters are used to steer the beam of each group to ±45° in zenith angle instantaneously. The EW and NS beamwidths of the array at various frequencies are listed in Table 1. The collecting area is approximately 2500 m^2. The signals collected

Table 1. Antenna parameters and measured maximum, minimum and average flux densities of the Sun at various frequencies during the period 1985 May–September.

Frequency MHz	Flux Density (Jy) Maximum	Minimum	Average	HPBW (Degrees) E−W	N−S
36.25	4212	1011	2436	12.27	7.60
45.70	6135	2402	3615	9.55	5.96
55.50	10616	3598	5878	7.80	4.88
64.25	18686	5513	11784	6.61	4.13

by the two groups are split into four frequency channels and the corresponding channels are correlated in four separate receivers. The bandwidth and time constant used were 1 MHz and 1 s respectively. The sensitivity of the system is better than 100 Jy at 64 MHz and $\leqslant 200$ Jy at 36 MHz and so it is possible to detect extremely weak radio bursts from the Sun. We have monitored the Sun continuously during the period 1985 May–September and selected about 24 days on which there was no transient burst activity on the Sun. The radio sources Tau A, and Virgo A, were used as calibrators since their spectra are accurately known (Viner 1973) and their positions were close to the Sun during the above period. The following corrections were applied to the measured flux densities of the Sun at various frequencies:

(1) During the entire observing period the Sun's declination was within 5 degrees of the calibrating radio source, and on a majority of days the difference in declination was less than 2 degrees. Corrections ($\simeq$ 1 per cent) were applied for the change in the gain of the antenna with declination.

(2) Due to the incremental nature of the delay shifters there was in general a difference between the setting of the beam and the actual position of the source in the sky. The maximum difference was about 0.25 degrees and the correction due to this effect is $\leqslant 2$ per cent.

(3) The distance between the two phase centres of the antennas in the NS direction is 32 metres. Therefore the visibility is slightly less than unity at all the four frequencies. The correction factors were calculated on the basis of uniform brightness distribution of the Sun.

(4) The major factor contributing to the error in the flux density measurement is the baseline determination. In our case the uncertainity due to this amounts to about 5 per cent at 65 MHz and 10 per cent at 35 MHz.

After taking into account all the above individual errors the total error in the measurement of flux densities is estimated to be about ± 15 per cent. The maximum and minimum values of the measured flux densities at various frequencies are listed in Table 1. The minimum values agree well with the spectrum given by Erickson *et al.* (1977).

The spectral index α (defined as in the expression $S \propto \nu^{\alpha}$) is calculated for each day using the observed flux densities at the four frequencies. It is found that the spectral index varied from $+1.6 \pm 0.4$ to 3.9 ± 0.7. Out of a total number of 24 days for which spectral index measurements are available, on 18 days its value was >2.5 and on 6

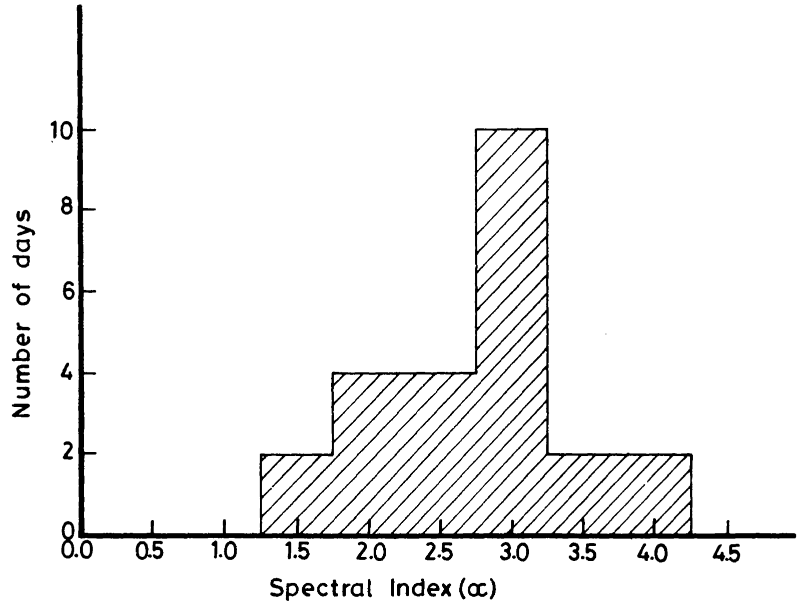

Figure 1. Distribution of spectral indices of the solar radio flux in the frequency range 64 to 36 MHz during the period 1985 May–September.

days value was <2.3. Fig. 1 shows the distribution of spectral indexes during the period 1985 May–September.

3. Discussion

The solar radio emission in the frequency range 65 to 35 MHz originates entirely in the corona. The total flux density of the undisturbed Sun is the sum of the flux densities due to quiet Sun and the contributions due to bright regions. Kundu, Gergeley & Erickson (1977) measured the peak brightness temperatures of the quiet Sun and some sources of slowly varying component (SVC). According to Sastry, Shevgaonkar & Ramanuja (1981) the continuum emission from bright regions, identified as SVC at 34.5 MHz, can be explained on the basis of thermal emission from regions of enhanced density and temperature. Erickson *et al.* (1977) derived a spectral index of $+2.3$ based on observed flux densities of the quiet Sun in the range 109 to 19 MHz. We have computed the total flux of the quiet Sun at several frequencies in the range 65 to 35 MHz by determining the brightness temperature (T_B) distribution using the equation:

$$T_B(\nu) = T_e(1 - e^{-\tau(\nu)})$$

and integrating over the solid angle subtended by the Sun at each frequency. Here $\tau(\nu)$ is the optical depth at any frequency ν. A spherically symmetric corona with an uniform temperature (T_e) of 10^6K and density distribution of Newkirk (1961) is assumed. The derived spectral index is $\simeq +2.3$ in good agreement with the observed value of Erickson *et al.* (1977). We found that it is not possible to increase the spectral index to values $\geqslant +3$ either by varying the density gradient or uniformly increasing the temperature and density over the entire corona. The possibility of nonthermal contribution to the observed flux densities is then considered. This contribution at any frequency must originate at or above the corresponding plasma level. If it originates at the plasma level then one can consider, to a first approximation, that the thermal and nonthermal contributions are mixed along the line of sight. This is because the major contribution to the optical depth comes from a thin region located near the plasma level. The solution of the transfer equation in this case is:

$$T_B(\nu)=\left[T_e+\frac{T_N\,\nu^{\beta}}{\tau(\nu)}\right][1-e^{-\tau(\nu)}].$$

If the nonthermal radiation originates in front of the region of origin of thermal radiation then the equation describing the frequency dependence of the brightness temperature is

$$T_B(\nu)=T_e[1-e^{-\tau(\nu)}]+T_N\,\nu^{\beta}.$$

Here T_N is the nonthermal brightness temperature and β is its spectral index. In the direction of the centre of the Sun the corona is optically thick ($\tau \geqslant 1$) in the frequency range 65 to 35 MHz for an uniform temperature of 10^6 K and Newkirk (1961) density distribution. Therefore the factor $(1-e^{-\tau(\nu)})$ is approximately equal to unity in the above equations. Generally, the nonthermal spectral index, β, is <0 and can be <-3 for some processes like the plasma emission (Kaplan & Tsytovitch 1968). It is therefore clear from the above equations that the observed flux density should increase with decreasing frequency in the presence of nonthermal emission, for both cases discussed above. The spectral index is not likely to attain large ($>+2.3$) positive values. This will not be the case if the nonthermal emission is confined to frequencies around 65 MHz only either due to the bandwidth of the emission process or the radial extent of the source. However, such a situation is most unlikely since the measured sizes of bright regions are $\simeq 20$ arcmin and the bandwidth of the emission $\geqslant 100$ MHz (Kundu, Gergeley & Erickson 1977). Another possibility is the existence of temperature gradients in the corona. We have assumed a temperature of 10^6 K at the 65 MHz plasma level and decreasing to 0.5×10^6 K at the 35 MHz plasma level, and computed the expected flux densities from the quiet Sun. In this case the spectral index turns out to be $\simeq +3$ and will further increase if the density gradient is steeper than that given by Newkirk (1961). The existence of such gradients in the coronal temperature distribution can be inferred from arguements based on the constancy of the conducted energy flux. According to Athay (1976) the gradient would be about -0.4 K km^{-1} at 1.5 $R_\odot$ in the case of a hydrostatic conduction model and -0.8 K km^{-1} if coronal expansion is taken into account. It should also be pointed out here that Aubier, Leblanc & Boischot (1971) measured brightness temperatures of 0.60, 0.50 and 0.36 ($\times 10^6$ K) at 60, 37 and 29 MHz respectively and Erickson *et al.* (1977) measured brightness temperatures of 0.7 and 0.2 ($\times 10^6$ K) at 74 and 26 MHz. Sastry, Shevgaonkar & Ramanuja (1983) measured peak brightness temperatures in the range 0.2 to 0.5 ($\times 10^6$ K) at 34.5 MHz. These measurements also imply the existence of temperature gradients since the corona is optically thick at these frequencies and so the measured brightness temperatures are equal to the electron kinetic temperatures. It is therefore possible that temperature gradients of the order of -1 K km^{-1} do exist at distances of the order of 1.5 $R_\odot$ in the solar corona, on some occasions.

It should however be pointed out that the density models of Newkirk (1961) and others may not be applicable to the corona on some occassions. If the densities in the height range 1 to 2 $R_\odot$ are reduced by more than an order of magnitude then the corona might become optically thin at lower frequencies leading to steeper positive spectral indexes. Another possibility is the scattering of radiation by density inhomogeneities in the corona, (Aubier, Leblanc & Boischot 1971). The effect of scattering, if it exists, is to raise the level of reflection above the plasma level leading to smaller optical depths at lower frequencies. The resulting decrease in the brightness temperature, of the order of twenty to thirty per cent, is not sufficient to explain temperatures of about 0.2×10^6 K sometimes observed at 34.5 MHz by us (Sastry, Shevgaonkar & Ramanuja 1983). Also, according to McLean & Melrose (1985) the scattering hypothesis fails to account for the observed sizes and directivity of Type I solar radio bursts although it should offer a plausible explanation for these features. On this basis, the effect of scattering to explain coronal phenomena, is not favoured by many authors.

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