THE ORIGIN OF THE 10.7 CM FLUX

K. F. TAPPING and B. DeTRACEY*
Herzberg Institute of Astrophysics, Ottawa, K1A 0R6, Canada

(Received 15 May, 1989; in revised form 19 July, 1989)

Abstract. We propose that when all sources on the solar disc are taken into account, the S component at 10.7 cm wavelength is dominated by thermal free-free (bremsstrahlung) emission. It is not produced only in the vicinity of sunspots; more than 60% of the total flux may be due to a widely-distributed emission associated with the hot complexes of activity. Using a model for the solar atmosphere based upon an assumption of weak (or vertical) magnetic fields, the spectrum of the S-component is calculated and its sensitivity to changes in the model parameters investigated. Variation of the thicknesses of the chromosphere, transition region and mixed zone cause only small changes in the S-component spectrum; there is a much stronger dependence upon the plasma density, particularly at the base of the corona. The behaviour of the S-component at 10.7 cm wavelength is examined in more detail. We find that the largest contribution to the 10.7 cm flux originates in the low corona, that structural changes affect it only slightly, but that it is strongly density-related. This dependence upon few quantities, together with its relative localization in the low corona, contributes to the usefulness of the 10.7 cm flux as an index of solar activity.

1. Introduction

The integrated emission at centimetric wavelengths from the whole solar disc can be separated on the basis of characteristic time-scales into 3 components: (i) transient events associated with flare and similar activity, having durations less than an hour; (ii) slow variations in intensity over hours to years, following the evolution of active regions and cycles in solar activity; (iii) a minimum level below which the emission intensity never falls. The latter is termed the 'Quiet Sun Level'. Component (ii) is designated as the S-component. It is discussed at length in Kundu (1965) and Krüger (1979).

The S-component was discovered independently by Covington (1947, 1948) at 10.7 cm wavelength, and by Lehaney and Yabsley (1949) at 25 and 50 cm. The 10.7 cm measurements have been continued by the National Research Council of Canada, and now form a data base covering more than 40 years. The continuity and consistency of calibration of these measurements of the '10 cm flux' (also referred to as $F_{10.7}$) have helped establish it as an internationally-accepted index of solar activity. It is used both as an index in its own right and as a proxy for other parameters. A discussion of the 10.7 cm flux in the light of recent studies of active region emissions at centimeter wavelengths is given by Tapping (1987a).

The strong correspondence between the S-component and sunspots was identified by Covington (1947, 1948), Denisse (1948), and Pawsey and Yabsley (1949). The excellent correlation of the S-component at 10.7 cm wavelength with the full-disc flux in Ca II and Mg II is discussed by Donnelly *et al.* (1983). The 10.7 cm flux resembles the

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* Summer Student Worker, 1988.

Solar Physics **127**: 321–332, 1990.

integrated fluxes in UV and EUV well enough to be used as their proxy (Chapman and Neupert, 1974; Bossy, 1983; Donnelly *et al.*, 1983; Oster, 1983a, b; Hedin, 1984; Nicolet and Bossy, 1985; Lean, 1987).

Another striking correspondence is between the 10.7 cm flux and the full-disc X-ray flux. When activity is high, they are well-correlated; however, when activity is low, the X-rays are too weak to be detected, while some 10.7 cm emission in excess of the quiet-Sun level is almost always present (Krüger, 1979). The intensities of the Ca II and Mg II spectral lines are primarily functions of chromospheric density and temperature, while the soft X-rays are produced in the corona. The high degree of correlation of the 10.7 cm flux with all these quantities suggests some dependence upon common (or related) plasma parameters and that their sources are spatially close.

Many different models for the *S*-component have been studied. The earlier ones assumed that it was purely thermal free-free (bremsstrahlung) from variously-defined density enhancements in the solar atmosphere overlying active regions (Waldmeier and Müller, 1950; Newkirk, 1961). The existence of strong magnetic fields in the vicinity of sunspots led to the suggestion that gyroresonance might be an important contributor to the *S*-component (Zheleznyakov, 1962; Kakinuma and Swarup, 1962). Models incorporating both processes together with the propagation properties of the ambient magnetoplasmas have been developed (e.g., Lantos, 1968; Krüger, Hildebrandt, and Fürstenberg, 1985).

The *S*-component comprises the integrated emission from all sources on the solar disc. It contains contributions from free-free and gyroresonant processes, and perhaps some non-thermal emission (Webb *et al.*, 1983; Akhmedov *et al.*, 1986; Gaizauskas and Tapping, 1988). There is considerable uncertainty about the relative importance of these processes, which probably varies from region to region, and with time. Felli, Lang, and Willson (1981) suggest that the bulk of the *S*-component at 6 cm is due to free-free emission; Schmahl *et al.* (1982) reject this process, proposing that gyroresonance is the prime contributor.

The relative magnitude of these processes is also a function of observing wavelength. Observations of emission from active regions over the wavelength range 21–2 cm suggest that at 21 cm, free-free emission is dominant, whereas at 6 cm, the contribution from gyroresonance is larger. At a wavelength of 10 cm, the two processes are roughly equal in importance. At a wavelength of 2–3 cm, the emission is again mainly free-free, possibly with a non-thermal component (Chiuderi Drago *et al.*, 1982; Lang, Willson, and Gaizauskas, 1983; Shevgaonkar and Kundu, 1985; Gary and Hurford, 1987; Gaizauskas and Tapping, 1988).

The spatial distributions of the two thermal processes are different; the gyroresonant emission originates chiefly in the vicinity of sunspots, where the magnetic fields are strong enough, while the free-free emission is more widely-distributed over the host region or complex (Akhmedov *et al.*, 1986; Gary and Hurford, 1987). A model for the widely-distributed emission at 10.7 cm is discussed by Tapping (1987b).

In this paper we discuss the relative importances of these processes as contributors to the 10.7 cm flux. We propose that the total free-free contribution from widely-distributed emission is larger than that by gyroresonance. A model for the 10.7 cm flux is discussed which is based upon free-free emission from areas where the magnetic fields are too weak for gyroresonance, and where, for reasons discussed below, they play no important part in the solar atmosphere's vertical pressure balance. We then use the model to identify the parameters most strongly affecting the 10.7 cm flux, and where it chiefly originates.

2. Contributions to the 10.7 cm Flux

The correlation of the 10.7 cm flux with sunspot number points to a connection with strong magnetic fields, while other strong correspondences (Ca II, Mg II, UV, EUV, X-rays) suggest a relationship with widely-distributed phenomena. There is not necessarily any strong inference to be drawn from this, except that these indices are related to the same underlying, activity-related processes.

At 10.7 cm wavelength, gyroresonance requires ambient magnetic field strengths of more than 300 G. In the corona, the required field strengths are unlikely to occur other than in the immediate vicinity of sunspots, although, they may also occur at low levels in the chromosphere at other locations. To be important here, the structure containing these fields would have to extend above the level where the refractive index at 10.7 cm becomes real and larger than zero. Free-free emission takes place all over the solar disc (producing the quiet-Sun level), with enhanced emission being produced where the densities in the chromosphere and corona are enhanced above their usual values.

There is evidence of a significant contribution to the *S*-component at 10.7 cm originating outside the main active areas, where the chromospheric and coronal magnetic fields are too weak (<300 G) for gyroresonance to be important. Such emission would be almost completely free-free in origin. Erskine, Lang, and Willson (1982) report the observation at 6 cm wavelength of enhanced emission originating in the vicinity of elements of the active network.

Further proof of a widely-distributed contribution to the 10.7 cm flux is seen in the daily, one-dimensional scans of the solar disc made using the 32-element solar interferometer at the Algonquin Radio Observatory. Figure 1 shows a selection of these data. The numbers accompanying each scan are the date, the 10.7 cm flux value for that day, and the local transit time in U.T. The upper 8 records show scans recorded when solar activity was low, near the minimum of activity between Cycles 21 and 22. The lower 8 scans were obtained when activity was much higher, during the rise of Cycle 22.

The level indicated on the central meridian mark shows the quiet-Sun level (64 s.f.u.*). There is some enhancement of the background disc level above this value, even when activity is low, corresponding to an excess over the quiet-Sun level of several flux units. This enhanced background is much larger when the Sun is more active. Along with the emission peaks due to the localized sources in active regions, there is a bacground level which contributes about half of the total increase over the quiet-Sun flux value.

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* A solar flux unit (s.f.u.) = 10^{-22} W m^{-2} Hz^{-1}.

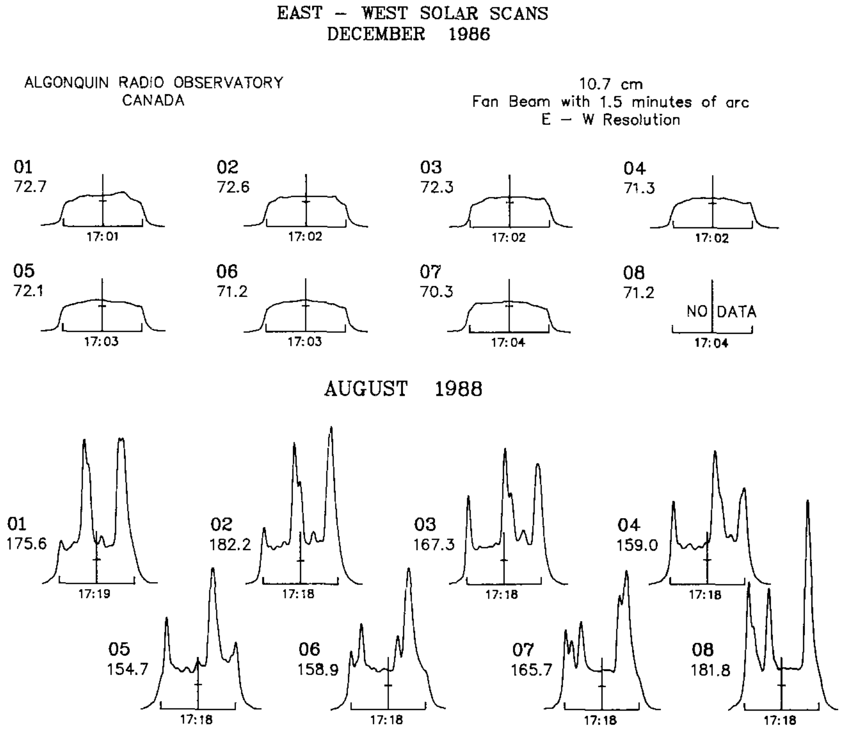

Fig. 1. Scans of the solar disc observed using the 32-Element Solar Interferometer at the Algonquin Radio Observatory. The upper 8 scans were obtained close to solar minimum, when activity was low, and the lower 8 during the rising phase of the current cycle, when activity was high. On each scan, the upper number is the date it was recorded, and the lower one the corresponding value of the 10.7 cm flux.

Using the interferometer records and the cotemporally-measured values of the 10.7 cm flux, a modified version of the 10.7 cm flux has been derived where the relative contribution by the bright, localized sources is strongly reduced*. The results suggest that, on the average, about 60% of the 10.7 cm flux is due to the widely-distributed emission, so at least that much of the 10.7 cm flux is due to free-free emission.

This conclusion is not at variance with observations. A study by Gaizauskas *et al.* (1983) indicates that active regions are not distributed randomly over the solar disc; they cluster in *complexes of activity*,which persist for up to a dozen solar rotations, with active regions forming and decaying within them. Besides active regions, these complexes contain other magnetic structures, such as new plage, shreds of magnetic flux left from the decay of old active regions, and scattered small ephemeral regions. Thermal emission from density enhancements associated with these structures (which are well-visible in Ca II) would contribute to the *S*-component. This conclusion cerves as a basis for the model discussed below.

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* Starting on 1 January, 1989, this modified 10.7 cm flux, designated $F_{10.7}$(m), has been included in the monthly reports distributed by the National Research Council of Canada. Values have also been calculated for all of 1988.

3. The Atmospheric Model

Almost everywhere in the solar chromosphere and corona the contribution to the total pressure by ambient magnetic fields far exceeds the kinetic pressure of the plasma. In formulating an atmospheric model, the magnetic field must, therefore, be considered. To calculate the *S*-component emission in the vicinity of major concentrations of magnetic flux, as done by Lantos (1968) and Krüger, Hildebrandt, and Fürstenberg (1985), a dipole-like magnetic field structure is usually assumed. It is then possible to model thermal free-free mission and gyroresonance, together with the propagation of the emission through the ambient magnetoplasmas.

Here we consider the emission from locations remote from sunspots, where the above approaches are inapplicable. Even over 'quiet' areas, Hα photographs show the chromosphere to be filled with complex systems of magnetic loops, ranging from small ones at the limit of visibility, to large ones extending high into the corona. The 'average' atmosphere for calculating *S*-component emission is difficult to describe meaningfully. We assume that everywhere (remote from sunspots) the ambient magnetic field strengths at or above the appropriate plasma level (where the refractive index is zero) are smaller than about 300 G and, therefore, too small for gyro-resonance to be important. Free-free emission is, therefore, the dominant process.

Where magnetic field lines are vertical, they play no part in defining the vertical pressure variation. If the magnetic field lines are inclined, they help support the atmospheric plasma. However, when the loops are small, the mean-free path for thermal electrons is comparable with, or much larger than the size of loops. Under these conditions the electrical conductivity is not easily defined and may not be infinite (Alfvén, 1981). In addition, if the ambient gas is not completely ionized (as is the case in the chromosphere), there is an atmospheric component which is not supported by the magnetic fields.

Our model comprises two main components; an isothermal chromosphere of temperature 10^4 K, overlain by a homogeneous corona of temperature 10^6 K. They are separated by a thin transition region forming a skin between them. A linear temperature variation is assumed, ranging from the chromospheric temperature at the bottom, to the coronal value at the top. This interface is not simply planar in structure; observations show intrusions of chromospheric structures into the corona and vice versa.

This inhomogeneous zone containing magnetized chromospheric or coronal plasma is termed the 'mixed zone'. The relative fraction of chromospheric versus coronal plasma is assumed to vary linearly in composition with height, being completely chromospheric at its base and completely coronal at the top. It is approximated here by a sawtooth-like perturbation of the chromosphere/corona interface, as shown in Figure 2.

The model is specified in terms of the thickness of the chromosphere, mixed zone, and transition region, and a reference value for the density at a given height above the photosphere. If vertical pressure equilibrium is assumed, these parameters completely specify the atmosphere model. The mixed zone is assumed to be symmetrically-

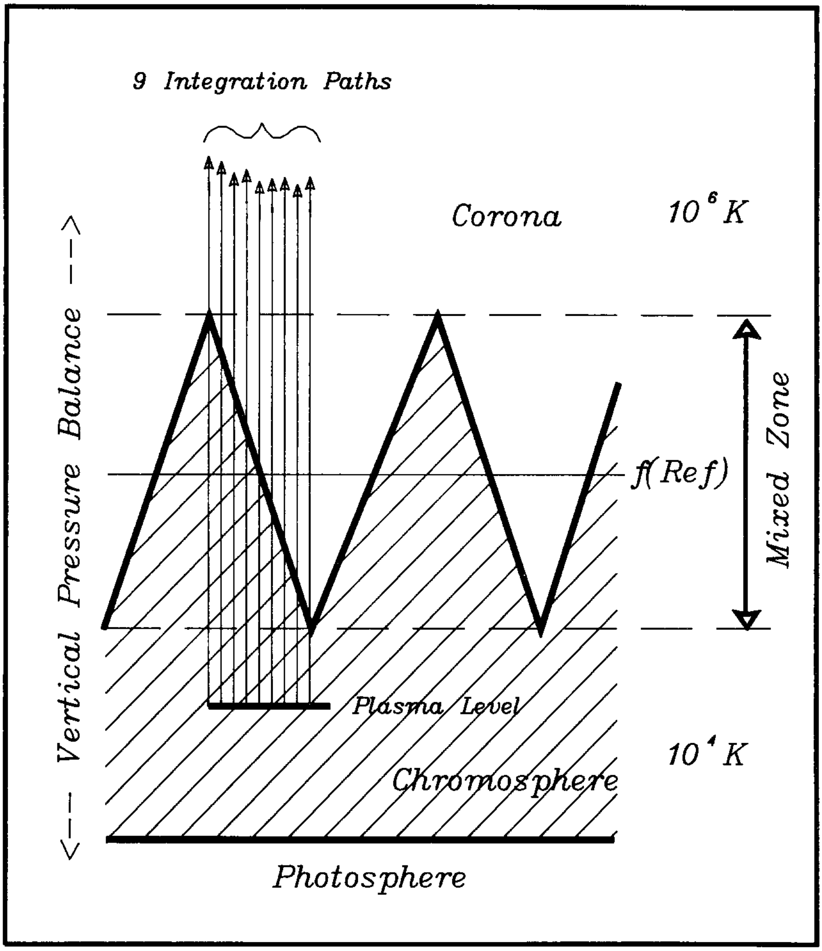

Fig. 2. The structure of the model solar atmosphere used for the calculations. The effect of the mixed zone is estimated by averaging the emission integrated along the 9 integration paths shown.

distributed about the mean surface between the chromosphere and corona. The reference density used is the value at the centre of the mixed zone. Since a major consideration in the analysis is the relationship of observing wavelength to ambient plasma frequency, the reference density is expressed in terms of a reference plasma frequency, as defined in Equation (5).

In the (isothermal) chromosphere and corona, the gravitational acceleration varies significantly over the applicable height range. If there is vertical pressure equilibrium, the density as a function of height is given by

$$N = N_0 \exp\{-zR(mg_0/kT)/(z+R)\}, \tag{1}$$

where N = particle number density at height z above the photosphere; N_0 = particle number density per cm^3 at base of layer; g_0 = gravitational acceleration at the base of the layer; m = particle mass; R = distance from solar centre to base of layer; T = ambient plasma temperature.

The transition region is assumed to be thin, but it cannot be ignored. If the plasma density is sufficiently high for the refractive index to approach zero within the wavelength range of interest, its contribution to the brightness temperature of the thermal emission could be significant. In such a thin layer, the gravitational acceleration can be assumed constant across it. If the temperature variation is linear with height, then the density variation with across the transition region is then given by

$$N = N_0\{b/(az + b)\}^{(1 + mg/ka)}, \tag{2}$$

where

$$a = (T_C - T_c)/d, \tag{3}$$

$$b = T_c \tag{4}$$

and T_C = temperature of the corona; T_c = temperature of the chromosphere; d = thickness of the 'transition region'; z = distance measured from the bottom of the layer; N_0 = particle number density per cm^3 at the chromosphere side of the layer.

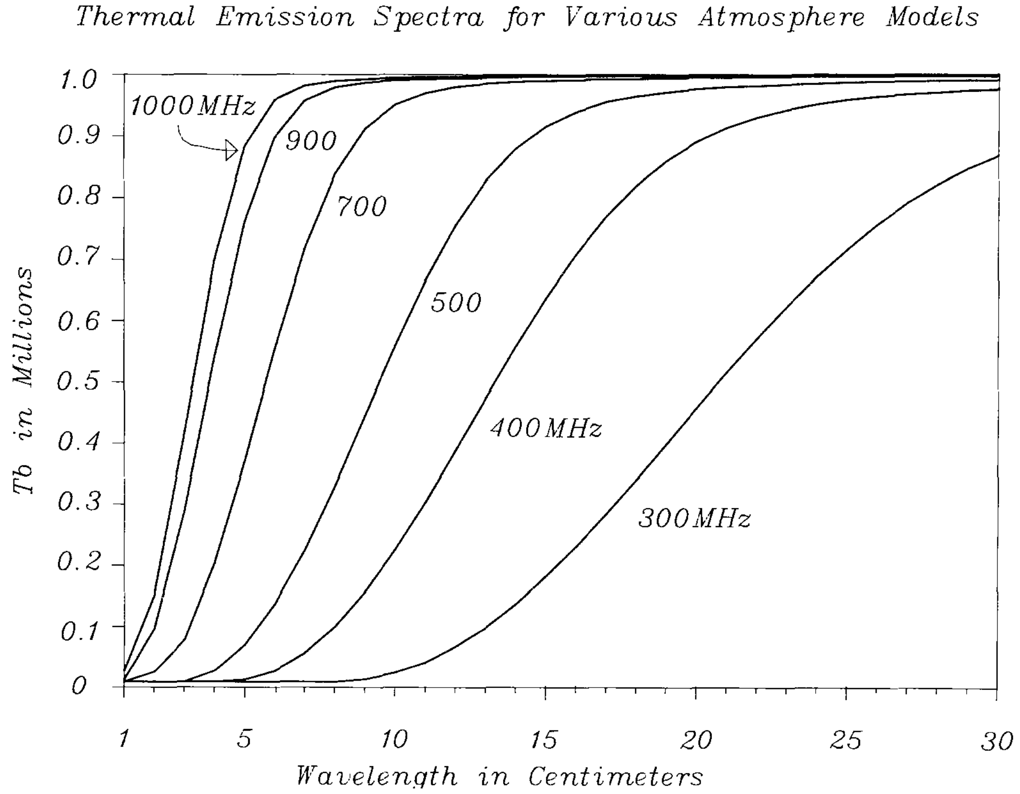

Fig. 3. Spectra of free-free (bremsstrahlung) thermal emission from the model solar atmosphere as a function of electron density (expressed as a plasma frequency).

4. The *S*-Component Model

This calculation follows broadly the lines of previous models. The absorption coefficient for free-free emission in the solar atmosphere is given by Kundu (1965):

$$K = (aN^2)/(nf^2T^{3/2}), \quad (5)$$

where $a = 0.11$ in the chromosphere and 0.16 in the corona; f = observing frequency in Hz; T = ambient temperature in K.

The refractive index, n, is

$$n = (1 - (f_0/f)^2)^{1/2}, \quad (6)$$

where f_0 is the ambient plasma frequency

$$f_0 = 9 \times 10^3 N^{1/2} \quad (7)$$

and N is the ambient electron density.

Starting at the height where the refractive index for the observing wavelength is zero, the brightness temperature is integrated numerically along a vertical ray-path to the Earth. The inhomogeneous 'mixed zone' is accommodated by integrating over 9 ray-paths uniformly distributed over the interval extending from the bottom to the top of the zone, as depicted in Figure 2.

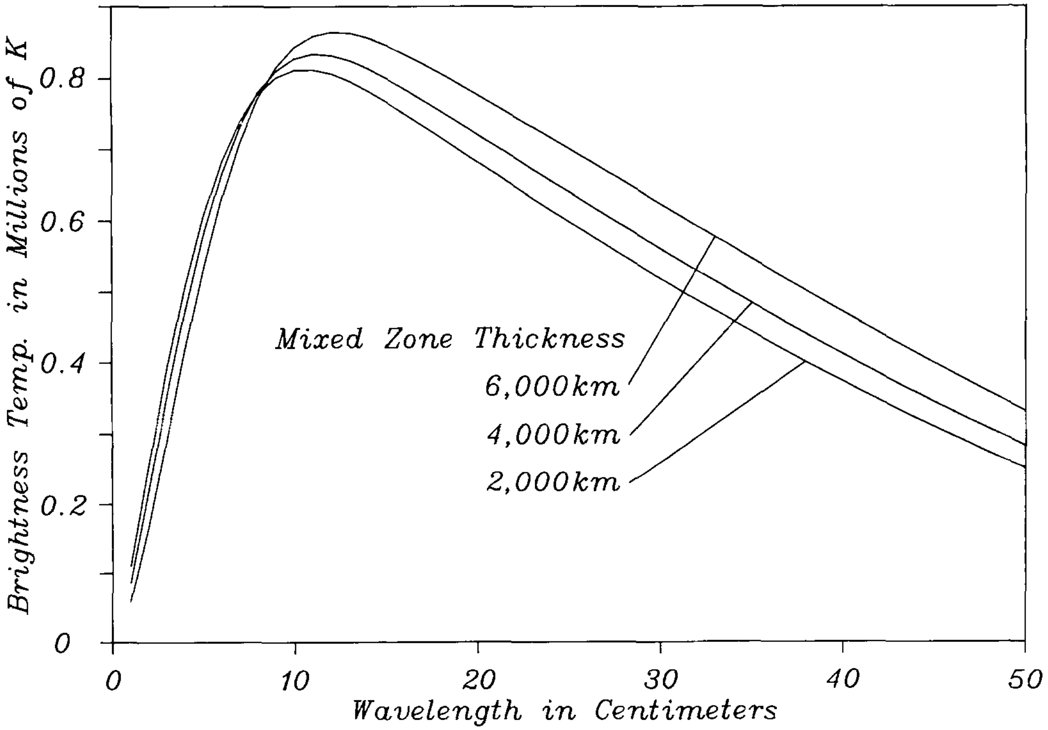

Fig. 4. Calculated *S*- component spectra for different thicknesses of the mixed zone.

5. The Spectrum of the *S*-Component

The spectrum of the *S*-component is the difference between the active and quiet solar atmosphere, in the range 1–50 cm. For the calculation discussed here, it is necessary to define the appropriate active and quiet spectra. The minimum flux density observed at 10.7 cm wavelength is 64 solar flux units. This flux density is obtained for a reference plasma frequency of 300 MHz ($N_0 = 10^9$ cm^{-3}) in our model when no active regions are present.

The upper limit is not so easily selected. The active Sun is highly inhomogeneous, and any value would have to be a spatial average. Observations of the Sun at wavelengths of about 1 cm do not show widely-distributed emission more than a few thousand degrees in excess of the background (quiet) solar disc. If this is taken as an upper limit, the highest reference frequency cannot be much more than 900 MHz, corresponding to an average electron density over the whole disc of 10^{10} cm^{-3}. A model *S*-component spectrum is given by the difference in these two spectra. Figures 4 and 5 show spectra for a range of thicknesses of the transition region and mixed zone. They all appear similar to observed *S*-component spectra (Krüger, 1979).

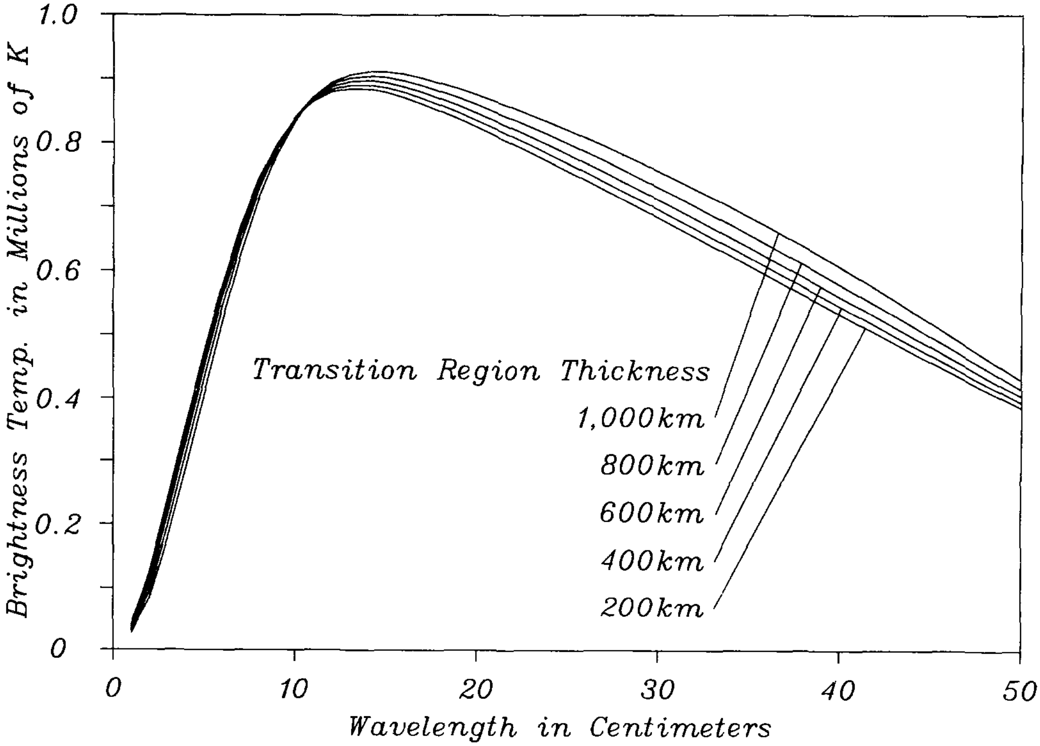

Fig. 5. *S*-component spectra calculated for various transition region thicknesses.

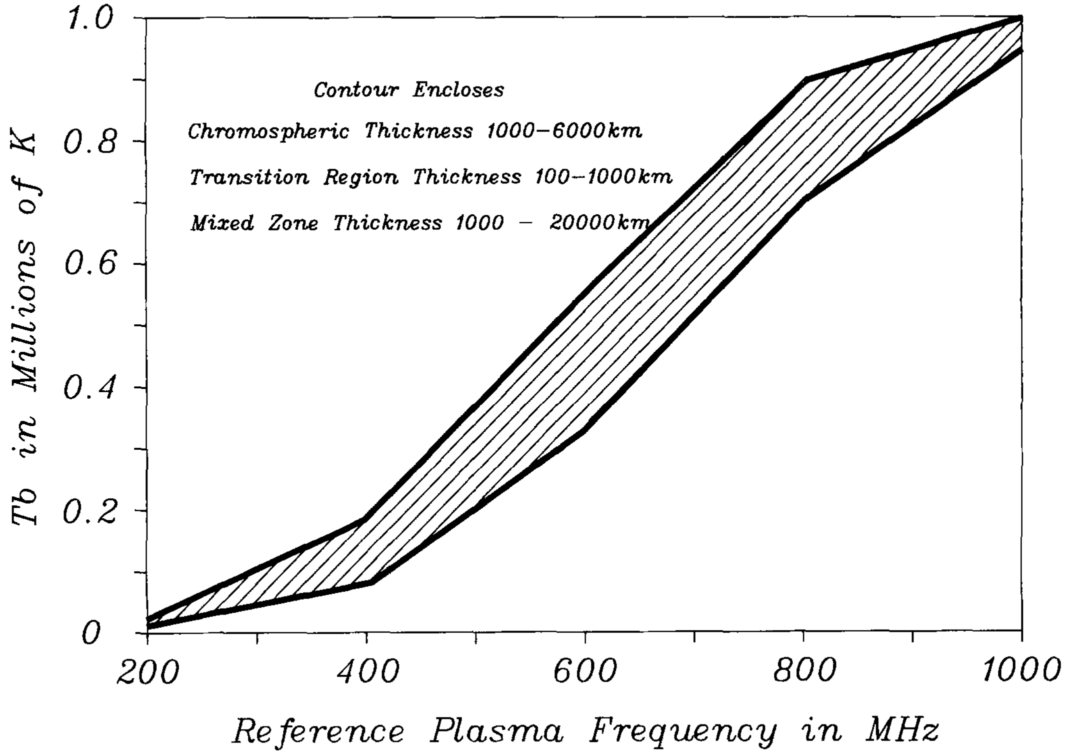

Fig. 6. The sensitivity of the model to variations in reference plasma frequency, and the thicknesses of the transition region and mixed zone.

6. Sensitivity to Parameter Variation

Assuming always the need for vertical pressure equilibrium, the thicknesses of the transition region and mixed zone are varied in order to investigate the sensitivity of the model S-component spectrum to these aspects of atmospheric structure. Figures 4 and 5 show, respectively, the sensitivity of the model S-component to changes in the thicknesses of the mixed zone and transition region. In both cases, the only change in the spectrum is a slight movement of the peak towards longer wavelengths as the thickness of either component is increased.

The curves in Figures 4 and 5 show little sensitivity of the spectrum to fairly large changes in the thicknesses of the chromosphere, transition region and mixed zone. Figure 3 shows that the thermal emission spectra are strongly affected by variations of the reference density value (at the middle of the mixed zone).

7. Sensitivity of the 10.7 cm Flux

For a fixed observing wavelength of 10.7 cm, the brightness temperature of the emission was calculated for the parameter ranges: transition region thickness: 100–1000 km in

100 km increments, mixed zone thickness: 1000–20000 km in 1000 km increments, reference plasma frequency: 200–1000 MHz in 100 MHz increments.

With these three degrees of freedom, a very large number of combinations are possible; it is impossible to show curves for them all. However, all of them lie within the envelope shown in Figure 6. There is little sensitivity to the thicknesses of either the mixed zone or transition region, but there is a strong dependence upon the reference plasma frequency.

8. Discussion and Conclusions

The results of this study suggest why the *S*-component spectrum has previously been explained successfully in terms of a wide range of models for the solar atmosphere. Only plasma density is important, and most of the brightness temperature is accumulated in the low corona and below. Variations in the density higher up in the corona have little effect. It may also account for the value of the 10.7 cm flux as an indicator of solar activity. At 10.7 cm the main contribution to the brightness temperature comes from the low corona, and describes principally the density at those heights. Its excellent correspondence with chromospheric emissions, such as Ca II and Mg II (particularly the latter) can be explained if the main part of the 10.7 cm emission originates spatially close to the sources of the Ca II and Mg II emission.

The small variations in the *S*-component spectrum shown by the model as the atmospheric structure changes are consistent with observation. As solar activity rises, there is more penetration of chromospheric plasma structures into the corona, and *vice versa*, increasing the thickness of the mixed zone. The model indicates that this would be accompanied by a movement of the spectral peak towards longer wavelengths. Such a change is reported in Krüger (1979).

The model can be used to account for observed values of the 10.7 cm flux. When the Sun is active, 3–5% of the surface may be covered with active regions. If that part of the Sun is covered with the 'active model' (density 10^{10} cm^{-3}) and the rest with the 'quiet model' (density 10^9 cm^{-3}), the 10.7 cm flux would be between 120 and 200 solar flux units, which is consistent with observed values.

The atmospheric model used here is an approximation. It would be useful to revise the model including the magnetid field's contribution to the plasma pressure. The resulting calculation of the emission from widely-distributed emission from areas where the magnetic fields are relatively weak, would then need to be combined with the emission models used for the neighbourhoods of sunspots (e.g., Krüger, Hildebrandt, and Fürstenberg, 1985). A composite model, taking into account the number and size of active regions on the solar disc, would be a better approximation for the *S*-component. However, the cruder treatment used here indicates the value of the 10.7 cm flux as an indicator of the density in the low corona, and that this sensitivity to a single parameter is an important part of its value as an index of solar activity.

Acknowledgements

We would like to thank R. Donnelly, V. Gaizauskas, J. Lean, O. White, and C. Zwaan for their comments and advice during the preparation of this paper. Suggestions by the referee have led to significant improvements, and are gratefully acknowledged.

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