THEORETICAL MODELS OF FREE-FREE MICROWAVE EMISSION FROM SOLAR MAGNETIC LOOPS

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We calculate the free-free microwave emission from a series of model magnetic loops. The loops are surrounded by a cooler external plasma, as required by recent simultaneous X-ray and microwave observations, and a narrow transition zone separating the loops from the external plasma. To be consistent with the observational results, upper limits on the density and temperature scale lengths in the transition zone are found to be 360 km and 250 km, respectively. The models which best produce agreement with X-ray and microwave observations also yield emission measure curves which agree well with observational emission measure curves for solar active regions.

As discussed by Holman (previous paper in these Proceedings), coronal loops are often optically thick to free-free emission at observational frequencies around 1 GHz. We deal primarily with a frequency of 1.45 GHz (20 cm), and include only thermal bremsstrahlung as the source of emission. In the present discussion we will expand on the thermal bremsstrahlung model of the previous paper--that of a semi-circular loop surrounded by a cooler, absorbing, external plasma--and consider the effects of a temperature/density "transition zone" (boundary layer) separating the loop and the external medium. We choose density and temperature functions which yield a smooth transition from the loop values ($N_L=1.5 \times 10^{10}$ cm^{-3}, $T_L=2.5 \times 10^6$ K) to the external medium limiting values ($N_0=0$ at infinity, $T_0=5 \times 10^4$), and we incorporate the full Appleton-Hartree expression for the index of refraction in the evaluation of the optical depth and brightness temperature integrals. The density and temperature of the external plasma are taken to vary as

$$N = (N_s)\exp(-y/L_g) + \exp[-(r-r_0)/L_N][(N_L)-(N_s)\exp(-y/L_g)]$$

$$T = (T_0) + (T_L-T_0)\exp[-(r-r_0)/L_T],$$

where $N_s=2 \times 10^{13}$ is the base density, y is the vertical height, $L_g=3000$ km is the gravitational scale length, r is the radial position (the center of curvature of the loop is at r=0), r_0 is the outer radius of the loop (3×10^4 km), L_N is the density scale length in the transition zone, and L_T is the temperature scale length in the transition zone. The inner radius of the loop is 2.5×10^4 km.

To begin, we show a naked loop, i.e., one with no external absorbing plasma (Fig. 1). Since the loop is optically thick, the observer sees an essentially constant brightness temperature (equal to the loop temperature) as

the loop is scanned. When an external, cool plasma is provided (with a temperature/density discontinuity at the outer edge of the loop, i.e., $L_N = L_T = 0$), a significant amount of the loop emission is absorbed (Fig. 2). The result is that one obtains a model which conforms to the recent observations of Webb et al. (1986), in which the microwave source covers about 1/3 the physical extent of the X-ray loop and is found to have a peak brightness temperature of $\sim 1.0 \times 10^6$ K.
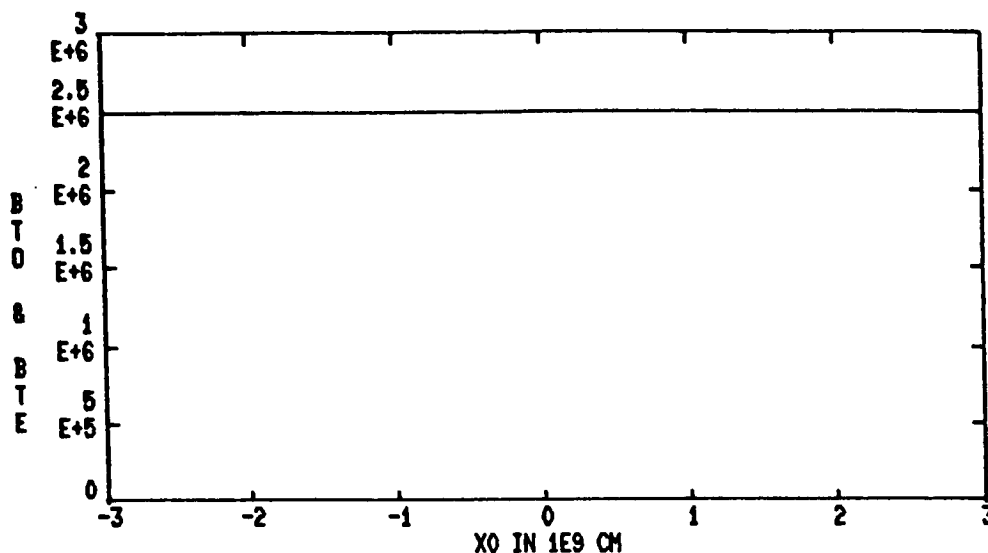

Fig. 1. Brightness temperature versus line-of-sight distance from loop center (in units of 10^9 cm) for a loop with no transition zone and no external plasma.
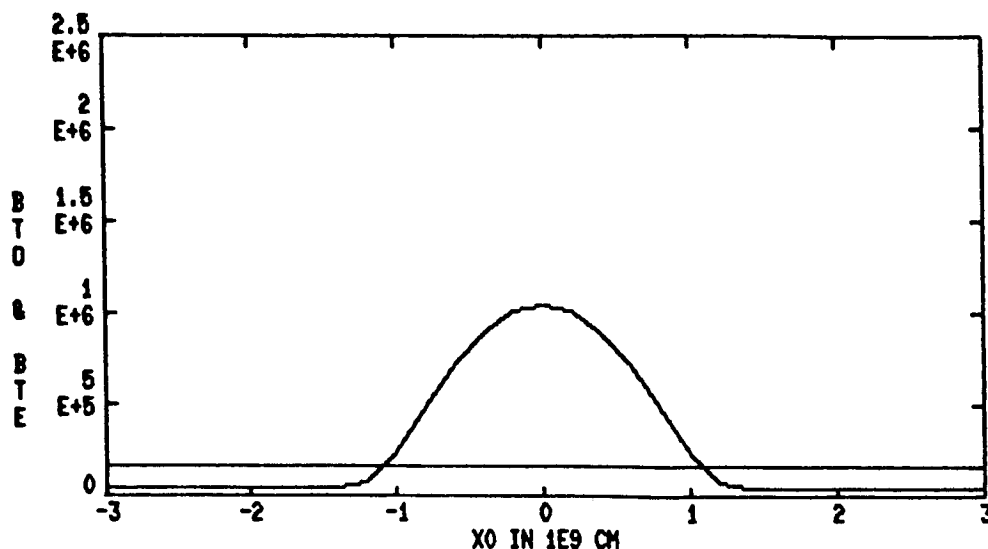

Fig. 2. Same as above for a loop surrounded by an external plasma and thin transition zone ($L_N = L_T = 0$).

The presence of cool, external material in the corona is suggested by recent observational and theoretical work (Webb et al., 1986; Kanno and Suematsu, 1982; Schmahl and Orrall, 1979). In particular, Schmahl and Orrall find continuum absorption in EUV spectra from everywhere on the sun, whether in coronal holes, active regions, prominences, or elsewhere. They propose a "cloud" model to account for this neutral hydrogen absorption shortward of 912 Å, and this model is later confirmed by Kanno and Suematsu. Thus a cloud of cool (neutral) hydrogen is believed to overlie material at transition region temperatures. Kanno and Suematsu (1982) suggest that such clouds are the remnants of cool, chromospheric material jetted into the corona. In the present context, we suggest that cool ($T \lesssim 10^5$ K), plasma overlies hot, magnetic structures associated with the solar corona.

At the interface between the hot, dense loop and the cool, less dense external plasma, we introduce a "transition zone" boundary layer. This is reasonable primarily because a smooth transition is physically more appealing than a sharp discontinuity. Thus we have an essentially inverted solar atmosphere above magnetic loops, in which the coolest material overlies the narrow transition layer material, which overlies the hot, coronal plasma.

Now that we have argued for the presence of the cool external plasma and seen its effects, let us consider the effects of the density/temperature "transition zone" boundary layer separating the hot loop from this cool plasma.

The base density of the external plasma and the gravitational scale height (which depends upon T_0) both have a strong effect on the absorption by the external medium. For present purposes, therefore, it is advantageous to keep these parameters fixed and to allow only the "transition zone" density and temperature scale lengths, L_N and L_T, to vary. For a given base density and external temperature, one may estimate the density and temperature scale lengths which yield a peak brightness temperature of 1×10^6 K. A loop model may then be calculated for this set of parameters, and appropriate adjustments on the density and temperature scale lengths made until either (a) the peak brightness and loop width are made to conform to the simultaneous X-ray and microwave observations, or (b) it be shown that the brightness and width could not be made to conform to the simultaneous X-ray and microwave observations.

It was found that for temperature scale lengths greater than 250 km, no density scale length could be found which would satisfy both the loop width and peak brightness temperature conditions simultaneously. Furthermore, for this upper limit on the temperature scale length, 360 km was established as an upper limit on the density scale length. See Fig. 3.

We now briefly discuss some of our results.

There are two contributions overall to the observed brightness temperature: (a) the contribution from the loop, as seen through the external medium, and (b) the contribution from the boundary layer/external plasma itself. Varying the scale lengths performs two functions: (a) it varies the optical depth between the observer and the top edge of the loop, thus varying the contribution to the observed brightness temperature from the loop, and (b)

it varies the contribution to the observed brightness temperature from the boundary layer/external plasma itself. The percentage contribution to the total brightness temperature from each of these two regions ranges from 0% to 100%, depending on the optical depth of the external medium.
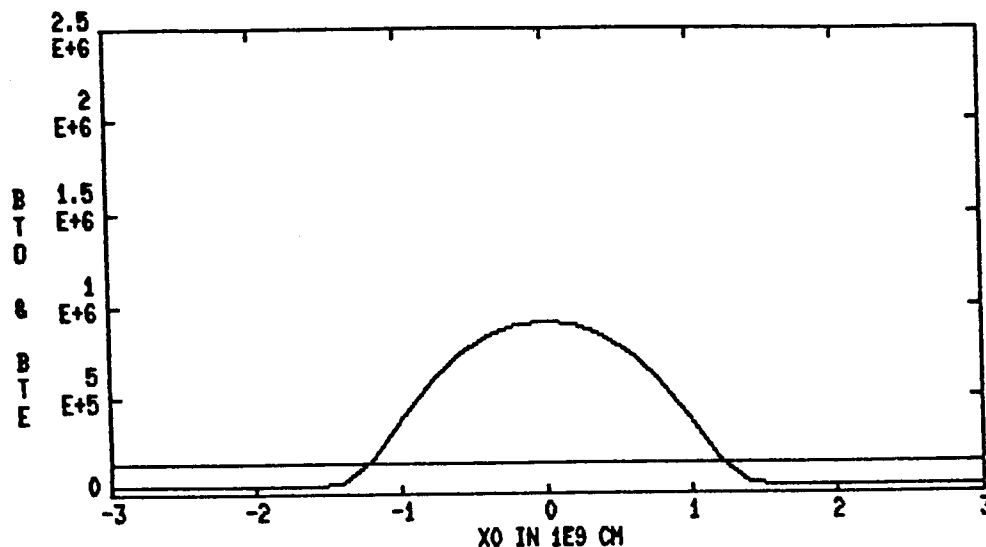

Fig. 3. Brightness temperature versus line-of-sight distance from loop center (in units of 10^9 cm) for a loop surrounded by an external plasma and transition zone with L_N=360 km, L_T=250 km.

For "base densities" less than that used here (2×10^{13}) the external plasma is insufficiently thick to absorb the required amounts of loop emission. Furthermore, for lower temperatures the gravitational scale length is smaller, so that the density drops off faster, also making the external medium less thick and less capable of absorbing the necessary loop emissions. Also, while raising the external temperature would tend to offset this, it should not be raised above the level of instrumental sensitivity (1.7×10^5 K), as the whole loop would then be visible at a temperature of 1.7×10^5 K, which it is not. (This last statement is true only if the external medium is optically thick. We know, however, that it must be at least partially thick, as it must absorb sufficient quantities of loop emission from the loop center.) Finally, for a magnetic field strength of 100 gauss or greater, the plasma at the "base" is field-dominated. If, however, the density were much larger, the gas pressure would exceed the field pressure, and the resulting pressure imbalance would be unrealistic.

Finally, we calculated the emission measure distribution, $EM=N^2T/(dT/dY)$, for the boundary layer/external plasma for several combinations of the density and temperature scale lengths (Fig. 4), and found that the model which best fits the recent simultaneous X-ray and microwave observations produces an emission measure curve which agrees well with recent observationally obtained emission measure curves for solar active regions (Noyes et al., 1985; Vernazza and Reeves, 1978). Notice that for the first time a theoretical emission

measure curve for a <u>single</u> active region loop has been found which rises
sharply to both the cool and the hot side of the emission measure minimum (cf.
Antiochos and Noci, 1986).

We are currently engaged in making theoretical predictions which will
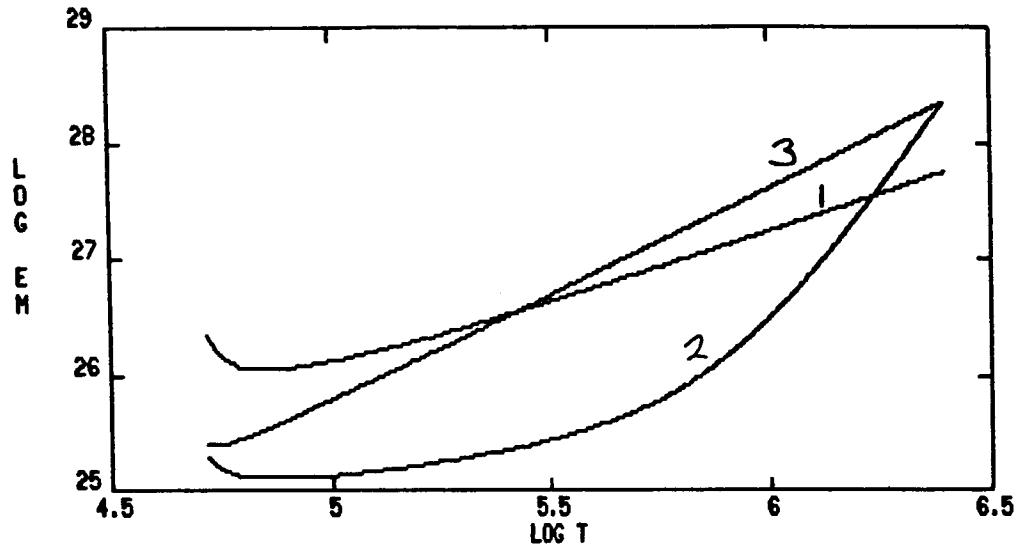enable the validity of the present model to be further evaluated (Brosius and
Holman, 1986).

Fig. 4. Log_5 EM versus Log T. Emission measure is in
units of cm^{-5}. Curve 1: L_N=360 km, L_T=250 km;
curve 2: L_N=360 km, L_T=1000 km; curve 3: L_N=L_T=1000 km.

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