Effect of Superthermal Particles in the Quiet Sun Radio Emission

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Abstract. The bremsstrahlung emissivity and absorption coefficient, in the radiofrequencies range, are derived in the assumption that the electron population is not purely thermal, but presents a tail of high energy particles. This population is approximated by a bi-Maxwellian distribution. It is shown that, if the temperature ratio of the two Maxwellians is larger than 10, the absorption coefficient and the effective temperature depend only on the fraction $R$ of particles in the highest temperature Maxwellian. The microwave radio spectrum is computed for some values of $R$, finding brightness temperatures lower than those computed with a pure thermal distribution. This fact could explain some inconsistencies found between radio and EUV observations.

Key words. Emission and absorption coefficients, Non thermal particles

1. Introduction

The upper layer of the solar atmosphere, transition region (TR) and Corona, can be investigated by means of the radiation emitted in the X-UV and radio domain. In the microwave range, where the refraction index can be safely assumed $n \approx 1$, the radio optical depth depends on temperature and on the differential emission measure: $DEM(T) = N_e^2 dh/dT$, where the temperature gradient is different from zero, and on the emission measure $EM(T) = \int N_e^2 dh$ in the corona where $T \sim constant$. These two quantities are also proportional to the EUV line intensities. However, very often radio and UV emissions do not agree with the same model of the solar atmosphere. (see, for instance, Zirin et al 1981; Noci, 2003). It has been recently shown by Chiuderi Drago and Landi (2003) (hereafter referred to as Paper I) that the observed average quiet sun brightness temperature, $T_b$, can be fitted by the following model:

- The DEM in the TR derived by matching the cell center model B of Vernazza, Avrett and Loeser (1981) (VAL) at $logT \leq 4.3$ with the DEM derived from EUV lines observed in the cells by SUMER and CDS instruments at $4.6 \leq logT \leq 6.1$
- The EM derived in the assumption of an homogeneous corona in hydrostatic equilibrium at $T = 1.2 \times 10^6$, with a maximum electron density $N_e(0) = 2 \times 10^8$. 

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2. Emission and absorption from a non-thermal distribution of electrons

The free-free radio emission per unit time from a single electron of velocity \( v \) in a plasma with an ion density \( N_i \) is given by:

\[
\epsilon_\nu(v) = \frac{c N_i}{v} \ln(alpha T^3/2/\nu) 
\]

where the logarithmic term comes from the ratio between the maximum and minimum collision parameters. In the radio frequencies range \( a = m/4\pi ze^2 = 3.15 \times 10^{-10} \) The total emission \( j_\nu \) and the absorption coefficient \( k_\nu \) of a population of electrons \( N_e(v) \) is therefore given by:

\[
j_\nu = \int_0^\infty \epsilon_\nu(v) N_e(v) 4\pi v^2 dv \\
k_\nu = - \int_0^\infty \frac{dN_e(v)}{dv} \epsilon_\nu(v) 4\pi v^2 dv 
\]

(see for instance Wild et al., 1963) In case of a Maxwellian distribution at temperature \( T \), the above integrals give the well known relations:

\[
j_0(\nu) = C N_i N_e T^{3/2} / T^2 /ln(\alpha T^{3/2}/\nu) \\
k_0(\nu) = C' N_i N_e T^{3/2} / T^{3/2} /ln(\alpha T^{3/2}/\nu) 
\]

with \( \alpha \approx 5 \times 10^7 \) (Rohlfs and Wilson, 2000). In the assumption of a bi-Maxwellian distribution at \( T_0 \) and \( T_1 \) with \( T_1 > T_0 \), and assuming that a fraction \( R \) of the total number of particles belongs the hottest one, \( R = N_1/N_\text{tot} \), we get the following expressions for the emissivity \( j_{2g} \) and the absorption coefficient, \( k_{2g} \):

\[
j_{2g} = j_0 \times (1-R) \left(1 + \frac{c_1}{c_0} \frac{R}{1-R} \left(\frac{T_0}{T_1}\right)^{0.5}\right) \\
k_{2g} = - \int_0^\infty \frac{dN_e(v)}{dv} \epsilon_\nu(v) 4\pi v^2 dv 
\]

It has been pointed out in Paper I that any contribution of the network emission added to the so obtained radio brightness temperature, will produce an excess of this latter with respect to the observations. In this paper we will show that an electron distribution consisting of a small tail of superthermal electrons added to a Maxwellian distribution produces a decrease of the computed \( T_b \), thus permitting a more realistic scenario of the 'average' quiet sun radio emission, including cell and network contributions. In this first approach the assumed electron distribution will be approximated by two Maxwellians at temperature \( T_0 \) and \( T_1 \) with \( T_1 > T_0 \). An example of such distribution is shown in Fig. 1. The calculation of the emission and absorption coefficients for such a bi-Maxwellian distributions of electrons will be presented in the next Session. In Session 3 we will compute the microwave spectra, obtained with different amounts of high energy particles and we will compare them with the Zirin et al. (1991) and Borovik et al. (1992) observations.

Fig. 1. Example of a bi-Maxwellian particles distribution with \( T_0 = 5 \times 10^4, T_1 = 5 \times 10^5 \) and \( R = N_1/N_\text{tot} = 0.2 \).
Fig. 2. Ratio of the absorption coefficients $k_2g/k_0$ plotted as a function of $R$ for the following values of $T_0/T_1$: 0.5 (dotted-dashed), 0.1 (dashed), 0.05 (dotted), 0.01 (full). Each curve is plotted for $T_0 = 5 \times 10^4$ and $T_0 = 5 \times 10^5$, but they are not distinguishable.

In the above equations $c_{0,1} = 1.5 \ln T_{0,1} - 4.6$ are the logarithmic terms present in Eq. 1, computed for $\nu = 5$ GHz and $T = T_0$ and $T_1$ respectively. From the ratio $j_2g/k_2g$, we derive the source function and the effective temperature:

$$T_{\text{eff}} = T_0 \times \frac{1 + c_1 \frac{R}{1 - R} \left( \frac{T_0}{T_1} \right)^{0.5}}{1 + c_0 \frac{R}{1 - R} \left( \frac{T_0}{T_1} \right)^{1.5}}$$

Plots of $k_2g/k_0$ as a function of $R$ for $T_0 = 5 \times 10^4$ and $5 \times 10^5$ and different values of the ratio $T_0/T_1$ are shown in Fig. 2. It is interesting to notice that, the $k$-ratio is practically independent of the temperature $T_0$ and, for $T_0/T_1 < 0.1$, also of the temperature ratio. The effective temperature is plotted in Fig. 3 as a function of $T_0$ for $R=0.1$ and 0.5 and three values of the ratio $T_1/T_0$. The plot shows that $T_{\text{eff}}$ is strictly proportional to $T_0$.

3. Comparison with observations

The two quantities shown in the figures enter the radio transfer equation:

$$T_b = \int T_{\text{eff}} e^{-\tau} d\tau$$

where, in case of thermodynamic equilibrium $T_{\text{eff}} = T_0$ and $d\tau = k_0 ds$.

Since both the ratios $k_2g/k_0$ and $T_{\text{eff}}/T_0$ are independent of the local temperature $T_0$ and depend only on $R$, if we assume that the fraction of particles in the hottest maxwellian is constant along the TR, we may easily integrate Eq. 1, by multiplying $k_0$ and $T_0$ by the above ratios.

We have used the model mentioned in the Introduction to compute the microwave spectrum in the assumption of thermodynamic equilibrium. We have then changed $k_0$ and $T_0$ into $k_2g$ and $T_{\text{eff}}$ obtained assuming $T_1/T_0 = 10$ with $R=0.2$ and $R=0.25$. The resulting radio $T_b$ are plotted in Figure 4. Notice that the dotted line
number of electrons in the TR plasma, decreases the computed $T_b$ from $\sim 10$ to $\sim 2$
% going from the lowest to the highest frequencies. We plan to repeat the above calculations with the following distributions of electrons:

a) a Maxwellian distribution to which a small tail of particles following a power law distribution is added.

b) a Kappa function.

References

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Fig. 4. Brightness temperature spectrum obtained by a Maxwellian distribution (dotted line), by a bi-Maxwellian distribution with $T_0/T_1 = 0.1$ and R=0.2 (full line) and R=0.25 (dashed line). Points with error bars are from Zirin et al. (1991), diamonds from Borovik et al. (1992)

is the same as that plotted in Figure 3 of Paper I. It appears from the figure that the presence of a number of superthermal particles equal to about 20 % of the total