**Volume Title**

ASP Conference Series, Vol. **Volume Number**

**Author**

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The Limb Brightening and its Relationship with the Millimeter-wave Cavity

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Abstract. Through a detailed theoretical analysis of the local emission at millimeter, sub-millimeter and infrared wavelength regimes (from 10 GHz up to 10 THz), we found that, associated with the temperature minimum, there is an optically thin cavity surrounded by two regions of high local emissivity. We call this structure the Chromospheric Solar Millimeter Cavity (CSMC). In order to search for traces of this cavity in the available radio observations on the solar limb, we have developed a robust method to associate the radiation at different heights with the observed brightness temperatures. We foresee that this approach will allow us to determine the relationship between the CSMC and the solar limb brightening.

1. Introduction

The first observations of the solar radio emission showed a high brightness temperature hundreds of times greater than the observed thermal radiation from the photosphere (McCready et al. 1947). This radio emission was associated with the solar Corona region (Martyn 1946).

In Smerd (1950) the solar limb brightening and the solar radii below 24 GHz was theoretically predicted. This early work, shows that the solar radii grows in diameter while the frequency of the emission decreases. The observed apparent temperatures was associated with the chromosphere and coronal regions.

Several observations at high frequencies were performed in order to characterize the limb brightening (We can found an extended review about the observations at short millimeter range in Ahmad & Kundu 1981). These works show that the theoretical limb brightening could be affected by the spicules. However, Ahmad & Kundu (1981) shows that the height scale of the transition zone model is unimportant. Is important remark that these first models present higher temperature minimum than the actual values. The temperature minimum plays a fundamental role in the chromospheric emission because it is required to reproduce observations of CO molecule. The CO have a threshold around 4200 K to avoid their desintegration (Ayres 1978).

The relation between the limb brightening and the microstructure (spicules) was studied in detail in Selhorst et al. (2005). However, the approximation of full ionized chromosphere and the empirical model of the chromosphere is not a good approximation at millimeter region (De la Luz et al. 2011) besides that their minimum of temperature is higher than 4200 K.
In De la Luz et al 2012 (under review) we found that the temperature minimum of the chromosphere create a structure called Chromospheric Solar Millimeter-wave Cav-
ity (CSMC). This structure is the responsible of the morphology of the solar spectrum at sub-millimeter wavelengths. Inside of this structure the Bremsstrahlung emission is the most important emission mechanism.

In this work we study the relation between the CSMC and the solar radii using three opacities functions and NLTE computations using the C7 model (Avrett & Loeser 2008) that introduce the minimum of temperature at 4200 K.

We presents a theoretical limb brightening function from 2 GHz to 1 THz using our model PakalMPI (De la Luz et al. 2010) and show the behavior of the CSMC close to the limb.

2. The model

We are using PakalMPI to solve the radiative transfer equation in Non-local Ther-
modynamical Equilibrium using the C7 model for the chromosphere De la Luz et al. (2011). We compute three opacity functions to reproduce the spectrum in the contin-
uum: The Wildt’s photo-detachment mechanism (Wildt 1939), The neutral interaction (Zheleznyakov 1996), and The Bremsstrahlung for Hydrogen negative ion (Golovinskii & Zon 1980).

PakalMPI computes the brightness temperature for different position in the solar disk in NLTE using the approximation for the departure coefficient \(b_1\) defined by Menzel (1937)

\[
b_1 = \frac{n_1/n_1^*}{n_k/n_k^*},
\]

where the ratio \(n_1^*/n_k^*\) is given by the Saha equation in thermodynamical equilibrium.

We compute the electronic density using De la Luz et al. (2011)

\[
n_e = \frac{-(1 - Zd) + \sqrt{(1 - Zd)^2 + 4d(n_H Z)}}{2d},
\]

where \(n_H\) is the hydrogen density, \(Z\) is the ionization contribution function, \(T\) the tem-
perature and \(d\) the contribution in NLTE. The ionization contribution function is

\[
Z = \sum_{\xi=He} \sum_{N_\xi=1}^F N_\xi n_{\xi,N_\xi},
\]

from Vernazza et al. (1973) where \(N_\xi\) is the ionization stage and \(n_{\xi,N_\xi}\) is the ion density. The contribution in NLTE is

\[
d = b_1 \psi(T),
\]

where \(\psi(T)\) is the classical Saha equation.

3. The CSMC at Limb

We compute the CSMC structure in 13 ray paths positions, with steps of 78 km between each position, from -51 km to 2088 km over the photosphere (We plot the last 12 ray paths in the Figures 1 and 2).
For each ray path we compute the local emission efficiency for frequencies between 2 GHz and 10 THz. In this plot the “y” axe is the “z” coordinate defined in De la Luz et al. (2010), i.e. is the absolute position in the line between the center of the sun and the observer. The colors are the local emission efficiency.

We found that the CSMC change their morphology very close to the limb. In the case of 51 km below the photosphere at limb, we found that the CSMC morphology is very similar to the CSMC at the center of the solar disk. The main difference is the depth of the structure, in this case the CSMC have more than 40,000 km in depth while that in the center of the solar disk have only 2100 km.

The CSMC structure at 127 km over the limb changes dramatically (sub-figure 1 of the Figure [1]). Their morphology presents 3 regions of high emission and the depth is around 80,000 km. We observe an asymmetry in the “y” axe. This asymmetry is originated by the 2D geometry of the model.

The three region characteristic is preserved between 127 km and 662 km over the photosphere at the limb (sub-figures 1-4 of the Figure [1]), we observe that the outer regions of the CSMC gradually fall to the center, while the central peak decrease in frequency.

Between the 662 and 840 km the central peak disappear and only observe two regions of emission that gradually comes one peak around 1018 km. Finally, between 1018 and 2087 km the single structure gradually down in frequency and in height.

4. Discussion and Conclusion

The morphology of the CSMC at the limb shows three steps, the first one between -51 and 127 km over the photosphere, where the structure of the CSMC changes dramatically and the central peak of the structure is higher than the another two peaks around them. The second step is between 306 and 1375 km where the combination of the fall of the central peak in frequency and the fall of the two outer peaks to the center produces a constant total emission, i.e. while we observe away from the photosphere, the emission of at frequencies between 2 and 500 GHz remains almost constant. Finally between 1553.08 and 2087.74 km the emission fall in frequency.

These three steps in the CSMC at the limb shows that the solar radii have three region: at low frequencies the solar radii downs slowly from 2 GHz to 50 GHz, then a region between 50 GHz to 1000 GHz where the solar radii remains almost constant and finally a third region where the solar radii decreases at photosphere altitudes after the 1000 GHz.

We can conclude that the CSMC is a tool that help us in the study of the limb brightening and the solar radii. We also show that the regions of emission at the limb have several changes in opacity and could be useful to characterize the micro structure at this altitudes.

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Figure 1. Local emission efficiency of the solar limb from 127 km (upper-left) to the 1018 km over the photosphere (bottom-right). We found three optical thick regions, while the computations move to the corona, these three regions move to the center and at the same time down in frequency. The 6th sub-figure (from up to down and from left to right) shows the at 840 km over the photosphere the two regions of emission merges in a single region.
Figure 2. Local emission efficiency from 1197 km (upper-left) to 2088 km (bottom-right) over the photosphere.
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