Chromospheric Heating and Low-Chromosphere Modeling

J. M. Fontenla\textsuperscript{1}, K. S. Balasubramaniam\textsuperscript{2} and J. Harder\textsuperscript{1}

\textsuperscript{1}LASP - University of Colorado, Boulder, USA
\textsuperscript{2}National Solar Observatory, Sunspot, USA

Abstract. Updated modeling of the “quiet” Sun low chromosphere based on existing observations show that at least all the data we examined in detail is consistent with a single model that has a very low temperature minimum and a sharp temperature increase above it. Such a model explains simultaneously the deep CO lines observed on the disk and off the limb, as well as the UV and radio continua and thus solves the controversy regarding the minimum temperature without resorting to “bifurcation”. This results simply from considering both: the spatial extent of the intensity contribution functions, and non-LTE. The model also shows that the structure of the low-chromosphere cannot be unambiguously inferred from any simple diagnostic but rather needs to be examined by forward modeling with consideration of full-NLTE radiative transfer and observations at many wavelengths. In addition, the characteristics of this model are consistent with the magnetic heating of the chromosphere. The mechanism proposed consists of small scale magnetic fields and sudden triggering of their free-energy dissipation by a plasma instability starting at the base of the chromospheric plateau. As a result of such a mechanism a complex spatial structure would result in the upper chromosphere that can hardly be explained in terms of shocks but instead shows magnetic patterns.

1. Introduction

Observations of the CO lines have been discussed in the literature often and are usually explained in terms of “bifurcated” models, e.g. Ayres et al. (1986), in which at the same altitude two atmospheres exist. One of these models has a very low temperature minimum set to explain the CO line intensities, e.g. Ayres et al. (2006) and another that has a higher temperature minimum to explain the UV and radio continuum, e.g. Fontenla et al. (1993). The high temperature models have also been invoked for explaining the Ca II line wings, e.g. Avrett and Loeser (1981). However, there is no observational evidence that confirms such “bifurcated” models because even at the highest resolution the material in the low chromosphere seems to be almost homogeneous with small fluctuations in space and time, e.g. Ayres and Rabin (1996).

Here, as part of our ongoing revision of the set of one-dimensional steady state models for the solar atmosphere at medium resolution (1–2") we discuss a new model of the low chromosphere in network cell centers. Our study finds that such a “bifurcated” model is not required by any of the existing observations and that instead a single model can explain them all. We briefly explain why the new model can explain such disparate observations and discuss a physical mechanism that could be responsible for the model structure.
Of course we do not argue that a one-dimensional model is able to explain all the observations because it is clear that the upper chromosphere has a remarkable spatial structure and dynamics (e.g., elsewhere in these proceedings).

Moreover, the chromospheric heating mechanism we propose (see Fontenla 2005) leads naturally to strongly inhomogeneous and fluctuating upper chromospheric structure very different from the much smaller fluctuations at the low chromosphere that relate to the photospheric granulation. The one-dimensional model we show here may not be a bad approximation for the low chromosphere but is just a first or initial approximation for the upper chromosphere where “realistic” 3-dimensional models with magnetic fields and consistent heating need to still be developed.

2. The Model

Figure 1 shows the new model compared with the previous FAL model C. The new model essentially coincides with the previous model up to about 500 km (where the previous model reached a minimum temperature) but the new model temperature continues to decrease above this height and reaches a much lower temperature minimum of about 3800 K (set to explain the off-limb CO observations). Unlike the old model, the new model has a very steep temperature increase above the temperature minimum height (at about 800 km above the $\tau_{5000} = 1$ layer) and reaches a very shallow temperature plateau at we designate as the chromospheric plateau. The upper chromospheric portion of the model is still somewhat undefined but we believe that it can be better defined by using UV observations (e.g., Avrett in these proceedings). Although a one-dimensional model may be somewhat crude for the chromospheric plateau it would be able to produce useful data for more sophisticated calculations.

3. Discussion

Characteristics and findings in the new model are:

1. Recent low abundances of C, N, and O are able to explain not only photospheric but also low chromospheric lines when NLTE is considered. We slightly adjusted these abundance values basing on observed lines that also include molecular species. Thus, no significant elemental separation occurs between the photosphere and the low chromosphere, and any FIP effect (if present) occurs elsewhere. Since similar values were used by Avrett (in these proceedings) for the upper chromosphere and transition region in order to match UV lines, it may very well be that there is no significant FIP effect and only that the older high abundances were not realistic.

2. Our calculations show that the controversy about the value of the temperature minimum is not justified, and that “bifurcated” models are not needed for explaining the observations. We find that a single model can explain all the observations ranging from the CO lines to the UV and radio continua. Further calculations are in progress and based on these we believe this model (perhaps with some modifications in the upper chromospheric layers) can also explain the Ca II and Mg II line wings, the Mg I lines, and probably all others.
3. The above occurs essentially because of the combination of two factors:

(a) The most important factor is the finite extent of the intensity contribution function that includes layers above that of $\tau=1$ at any given wavelength. Therefore, when the optical depth unity occurs at the $T_{\text{min}}$ and a sharp temperature rise occurs above it, the higher temperature layers mask the emission from those at $T_{\text{min}}$ and even in LTE the emitted radiation brightness temperature can be well above the value of $T_{\text{min}}$. The situation is different in molecular lines because they are not dependent on the slowly varying electron density, but also because these species depend on the square of the hydrogen density and inversely on the temperature. Thus, molecular species quickly disappear above the $T_{\text{min}}$ layer and are not affected by the chromospheric plateau.
(b) Not only is the emitted intensity at many wavelengths affected by the chromospheric plateau, but also the mean intensity at the $T_{\text{min}}$ layers is larger than in LTE due to the photons originating at the base of the plateau. As a consequence of this illumination important over-ionization and NLTE effects cause the source function in many transitions to be above that of LTE at the layers around that of $T_{\text{min}}$. This effect, and the previous, were minimized in the previous models because the value of $T_{\text{min}}$ was higher and located at higher pressure, and because the chromospheric temperature was assumed to smoothly rise in the layers above $T_{\text{min}}$. Most conclusions about the approximate validity of LTE in certain transitions at certain locations are far from general and only rested on the particulars of the models chosen. In our new model most atomic transitions are importantly affected by NLTE effects at the $T_{\text{min}}$ layers.

4. A secondary issue is that in our model we change the previous scheme for parametric departures from hydrostatic equilibrium. We now discard the use of the “turbulent pressure velocity” and instead use a “non-gravitational acceleration”. The parameter in our new scheme can be chosen to describe not only velocity effects that were described in the previous formulation, but also can describe the effects of Lorentz forces. Thus this new more general formulation is used to extend the pressure height-scale at and around the layers of $T_{\text{min}}$ in such way as to match the observed emission in CO lines above the continuum limb. However, this issue is not essential for the simultaneous matching off the CO lines and the UV and radio continua but is only critical to models for matching the off-limb data which indicates a larger extension than that resulting from hydrostatic equilibrium. Because of the combined changes in the temperature structure and pressure stratification our new model has a pressure stratification in the chromospheric plateau that departs considerably from our previous models. Eclipse, off-limb, or space observations should be carried at several wavelengths and comparing such with models should be carried to establish better the chromospheric height scale. Stereo observations at critical wavelengths can also help in this.

4. Conclusions

Modeling must resort to all wavelengths including molecular lines in order to resolve the inherent ambiguity of interpretation of observations due to line and continua formation in the chromosphere.

One-dimensional modeling may be a reasonable approach for the lower chromospheric structure where fluctuations in space and time are not too large. However, for the upper chromosphere more sophisticated 3-dimensional models are needed and probably time-dependent as well. Such models must consider magnetic effects and magnetic heating in order to be able to explain the observed spatial structure of the upper chromosphere. While more sophisticated models are produced, one-dimensional semi-empirical ones would provide first estimates about the chromospheric structure that can help the more sophisticated ones.

The one-dimensional model presented here is just a representative one of a range of variations existing in the solar atmosphere. Such variations occur at the
medium resolution scale we consider, e.g. supergranular structure or even structure observed within a supergranule cell interior (e.g., Fontenla et al. 2007). The existence of these variations does not invalidate the one-dimensional approach as long as the radiative interaction between them is small compared with the interaction within the resolution element addressed. This approach can be called “in-pixel” modeling, and may not be completely valid in the upper chromosphere but it still is a good first approximation for estimating radiation effective parameters and the spectrum observed at medium (1–2") angular resolution. Also, temporal variations on time-scales that are long compared with those characteristic of ionization do not significantly affect the modeling.

However, if large spatial variations occur within a resolution element then one-dimensional modeling of separate components would not be adequate because it would not consider the radiative interaction between these components. Furthermore, if very rapid strong temporal variations occurred, the chromosphere elemental ionization would not be able to reach equilibrium and would not be properly computed by an instantaneous statistical equilibrium. Because of these reasons, and the lack of observational evidence for medium-scale strong temporal or spatial variations in the CO lines, we believe the “bifurcated” models that have been proposed are not physical meaningful. However, small scale structure obviously exist, as can be seen in several papers in these proceedings, and should be modeled using more sophisticated 3D time-dependent codes that consider MHD and plasma processes.

Acknowledgments. JMF thanks the CSPM organizers for inviting him to this very good meeting. Fontenla and J. Harder work that was presented here was supported by NASA contract NAS5-97045 at the University of Colorado. K. Balasubramaniam was supported by NSO.

References