Labrosse, N. and Li, X. and Habbal, S.R. and Gouttebroze, P. and Mountford, C.J. (2002) *Radiative transfer effects on hydrogen (and helium) in the solar atmosphere.* In: Wilson, A. (ed.) Solar Variability: From Core to Outer Frontiers, 10th European Solar Physics Meeting, 9-14 September 2002, Prague, Czech Republic. ESA Special Publication (506). ESA Publications Division, Noordwijk, The Netherlands, pp. 13-15. ISBN 9789290928164

RADIATIVE TRANSFER EFFECTS ON HYDROGEN (AND HELIUM) IN THE SOLAR ATMOSPHERE

N. Labrosse[1,2], **X. Li**[1], **S. R. Habbal**[1], **P. Gouttebroze**[2], **and C. J. Mountford**[1]
[1]Department of Physics, University of Wales, Aberystwyth, Ceredigion SY23 3BZ, UK
[2]Institut d'Astrophysique Spatiale, CNRS - Université Paris XI, 91405 Orsay cedex, France

ABSTRACT

In this work we present Non-Local Thermodynamic Equilibrium (non-LTE) computations for hydrogen for a VAL-C model of the Sun's atmosphere. The solar atmosphere is represented by a one-dimensional plane-parallel horizontal slab. The purpose of this study is to investigate the effects of the transfer of radiation in the chromosphere and the transition region. In particular, we aim at understanding how the radiative losses in the energy balance for electrons are affected by the non-LTE radiative transfer, which has to be considered in the regions where the temperature is less than 25 000 K. The numerical code used here allows us to study the properties of, and the spectrum emitted by, the hydrogen particles. The non-LTE radiative transfer equations (RT) are solved for all optically thick resonance lines. The solutions of the RT in the optically thick lines affect all population densities of atoms and ions through the statistical equilibrium equations (SE).

For the VAL-C atmosphere model there is a peak around 6 10^3 K in the net radiative cooling rates due to several lines and continua from hydrogen. To our knowledge this peak has never been considered when evaluating the radiative losses in the chromosphere in the frame of solar wind modelling. We mention some consequences for solar wind models in the description of the chromosphere and the transition region which is often made under the assumptions of full ionization and optically thin plasma.

Key words: radiative transfer; solar wind; Sun: chromosphere; Sun: transition region.

1. INTRODUCTION

A new approach in solar wind modelling has been adopted now for less than ten years and it consists in considering the chromosphere and the transition region in the models. Hansteen & Leer (1995); Hansteen et al. (1997); Lie-Svendsen et al. (2001, 2002) have demonstrated the importance of the coupling of the chromosphere and the transition region to the corona, as it was first pointed out by Hammer (1982a,b) and Withbroe (1988). This coupling obviously has a great importance for the modelling of the solar wind properties at the base of the corona as well as at 1 A.U.

As discussed by the authors, one of the limitations of the work done by Lie-Svendsen et al. (2002) lies in their physical description of the chromosphere and the transition region. For instance, they use an optically thin approximation for the computation of the radiative losses that have to be taken into account in the energy balance of the electrons in the chromosphere. As a result their radiative loss function is only dependent on the temperature. In fact this function is also dependent on the pressure, and this can be shown with a full treatment of the radiative transfer out of local thermodynamic equilibrium (see e.g. Kuin & Poland, 1991).

The purpose of the work presented in this communication is to demonstrate the necessity of considering the non-LTE radiative transfer effects in the computation of the radiative energy losses. Radiative transfer effects are important for elements such as hydrogen and helium for temperatures up to 25 000 K, namely in the lower parts of the solar atmosphere. In a first step we only illustrate these effects for hydrogen, and a study on radiative energy losses due to neutral and ionized helium transitions is in preparation.

In the following section we give a very short and partial summary of important characteristics of the chromosphere that should be taken into account in solar wind modelling, and briefly describe the method used for the non-LTE computations. Some results will then be given to illustrate the importance of considering non-LTE radiative transfer effects in the description of the chromosphere and the transition region. We finally give some comments on consequences for solar wind models and some perspectives on a future work.

2. DESCRIPTION OF THE CHROMOSPHERE AND TRANSITION REGION

An important quantity for the energy balance in the lower parts of the atmosphere is the net radiative cooling rate Φ, defined by

$$\Phi = \sum_{\text{lines,continua}} h\nu \left[n_u (A_{ul} + B_{ul}\bar{J}) - n_l B_{lu} \bar{J} \right] ,$$

where the summation is made over all bound-bound and bound-free transitions between the lower level l and the upper level u (all symbols have their usual meanings). In the general case, Φ is dependent both on temperature and pressure. Since it is difficult to calculate this quantity in the frame of a full treatment of the radiative transfer, most authors use numerical approximations which are obtained with the optically thin assumption (e.g. Cox & Tucker, 1969; Rosner et al., 1978). It allows one to evaluate the radiative losses as a function of the temperature. But for temperatures lower than 25 000 K, several hydrogen transitions (Lyman lines and continua), as well as transitions of other elements (He, Ca II, ...), are optically thick. This of course will lower the radiative losses compared to the optically thin approximation. Even if one mimics the existence of optically thick transitions by adding an ad hoc *opacity heating term* for low temperatures (Hansteen et al., 1997), one cannot reproduce the correct behaviour of the radiative loss function, and on top of that, the dependence on the pressure disappears with the optically thin approximation.

Another approximation which is often found in the literature is the fully ionized approximation for hydrogen and helium. This assumption is not reasonable around the temperature minimum region, and also gives rough estimates of the electron density at the base of the transition region. In that case the electron densities are overestimated. A correct treatment needs to solve the ionization equilibrium equations in the frame of non-LTE radiative transfer.

In a recent paper, Fontenla et al. (2002) studied the energy balance in the solar transition region with particle and mass flows for hydrogen and helium. Their calculations showed how mass flows in the transition region affect the ionization and radiative losses of H and He.

In view of these considerations we are implementing non-LTE radiative transfer (RT) calculations in a six-fluid hydrodynamic solar wind code starting from the chromosphere, with the upper boundary at 1 A.U. This code includes ionization and Alfven wave heating. Our aim is to get a better understanding of the global system chromosphere – transition region – corona – solar wind.

In our RT code, the solar atmosphere is in hydrostatic equilibrium and is represented by a one-dimensional plane-parallel semi-infinite horizontal slab. The plasma is a mixture of hydrogen, helium and some other elements. Only hydrogen is treated out of LTE. We solve the ionization equilibrium equations, the statistical equilibrium (SE) and radiative transfer equations for our 20 bound levels hydrogen atom. From this we obtain the electron densities, hydrogen level populations and the radiation due to hydrogen. For further details on the numerical approach one can refer to Gouttebroze et al. (1999) and references therein (see also Lemaire et al., 1981). It is possible in a second step to solve SE and RT equations for other elements such as helium or calcium, taking into account the electron densities derived from the hydrogen ionization equilibrium, and the internal radiation in the slab due to hydrogen.

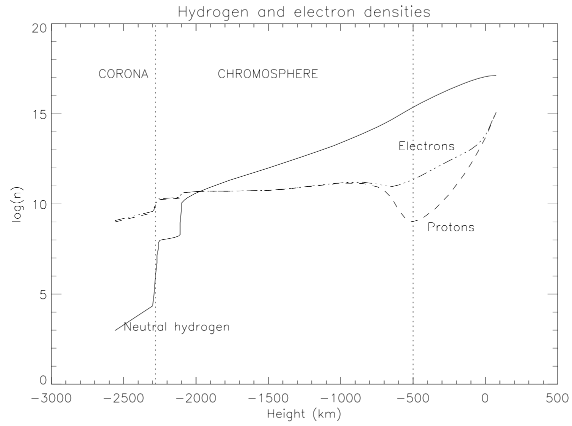

Figure 1. Atomic hydrogen, proton and electron densities (in cm^{-3}) as a function of height in the solar atmosphere. Height zero corresponds to the photospheric level where the continuum optical depth at 500 nm $\tau_{500} = 1$.

Figure 1 shows the resulting hydrogen and electron densities from our calculations for a VAL-C atmosphere model (Vernazza et al., 1981). Hydrogen is far from full ionization in the low chromosphere. The calculations are done assuming statistical equilibrium and thus neglecting the chromospheric dynamics. Time-dependent computations are beyond the scope of the present work, but one can refer to Carlsson & Stein (2002) who studied hydrogen ionization in a dynamic solar atmosphere. They found that the hydrogen ionization in a dynamic atmosphere is driven by the same mechanisms that in the static case.

3. NON-LTE RADIATIVE LOSSES FROM HYDROGEN

Figure 2 shows the computed net radiative cooling rate from hydrogen as a function of the temperature, up to 10^5 K. For higher temperatures the hydrogen net radiative cooling rates become negligible compared to those due to other elements. We observe the presence of a main peak around 1.9 10^4 K, which is due to the Lyα line as it becomes optically thin. The most interesting feature is the presence of another peak around 6 10^3 K, which results from several hydrogen lines and continua (except the Balmer continuum which is heating). To our knowledge, this has never been taken into account so far in radiative

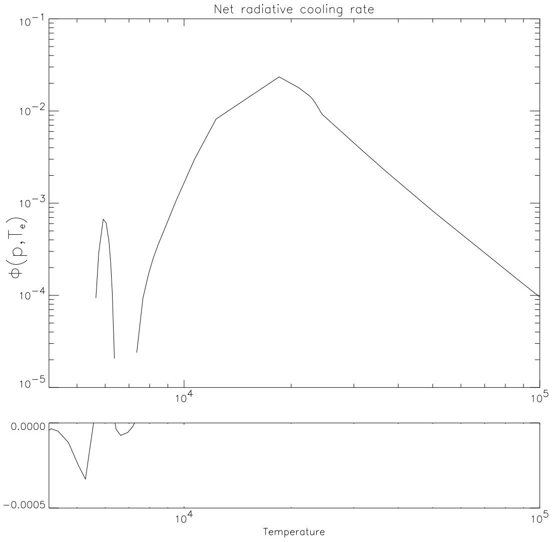

Figure 2. Net radiative cooling rate $\Phi(p, T_e)$ in erg s^{-1} cm^{-3} as a function of the temperature. The upper panel shows positive values with a logarithmic scale, the bottom panel shows negative values in a linear scale.

cooling estimates for the computation of the electron energy balance in the chromosphere for solar wind modelling. This can be compared with fig. 3 from Cox & Tucker (1969) where the radiative energy loss per unit volume is shown as a function of temperature for several elements separately. Their plot for hydrogen is similar to our figure 2, but no peak is found around 6 10^3 K. The Cox & Tucker (1969) work is done in the optically thin approximation for a low-density plasma but is nevertheless widely used for the evaluation of the radiative losses in optically thick plasmas.

This result shows the importance of a full treatment of the non-LTE radiative transfer in the lower parts of the atmosphere. Of course, other elements are contributing to the radiative losses in the solar atmosphere. We plan to include calculations for helium in our RT code in the next step to take into account the radiative transfer effects on helium in the computation of the radiative losses, and possibly consider other lines and continua of Ca II and Mg II. We also plan to modify the RT code in the future to investigate the radiative transfer effects in a moving atmosphere.

4. CONCLUSIONS

This communication was aimed to illustrate the importance of considering the non Local Thermodynamic Equilibrium radiative transfer in the evaluation of the radiative losses in the chromosphere and the transition region. Two facts will act to lower the radiative losses in comparison with an optically thin and fully ionized plasma approximation. First, hydrogen (and helium) are not fully ionized, which means that there are less free electrons. Second, some resonance transitions can be optically thick (Lyman lines and continua for H, He I, He II, Ca II and Mg II resonance lines and continua), which means that the radiation does not freely escape the plasma. Instead the photons are absorbed and reemitted several times before leaving the medium.

Lowering the radiative losses in the energy balance means that we will need less chromospheric heating in our solar wind models to balance these losses. Thus, taking into account the non-LTE radiative transfer in the chromosphere and the transition region will improve the physical description of these regions and of the lower boundaries of solar wind models. This should lead to a more consistent coupling between the chromosphere, the transition region and the corona. It could have some interesting consequences on our understanding of the heating of the solar corona and the acceleration of the solar wind.

ACKNOWLEDGMENTS

Computations were made using the MEDOC (Multi-Experiment Data Operation Centre)/IAS facilities.

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