Influence of Mass Flows on the Energy Balance and Structure of the Solar Transition Region

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Abstract. We have extended our previous modeling of energy balance in the chromosphere-corona transition region to include the effects of particle and mass flows. We consider quasi-steady cases satisfying the momentum and energy balance equations throughout the transition region and low corona. We include particle diffusion as well as flows in the optically thick non-LTE radiative transfer equations for the lines and continua of H, HeI, and HeII. Mass flows substantially affect the degree of ionization and the radiative losses of H and He, thereby affecting the structure and extent of the transition region. We find that the H and He line profiles are greatly affected by flows, and that line shifts are much less important than the changes in line intensity and central reversal due to the effects of flows on atmospheric structure. The Lyman alpha profiles we compute can generally explain the observed range of profiles obtained with high spectral and spatial resolution. The present paper is a brief summary of the detailed account given by Fontenla, Avrett, and Loeser (2002, FAL4).

1. Introduction

The Sun is among the class of cooler stars that have outer atmospheres which significantly depart from radiative equilibrium. Non-radiative (i.e., mechanical) heating produced as a result of convective motions deep in the atmosphere together with magnetic fields produce much higher temperatures in the outer regions than the temperature values close to the visible surface. Observations indicate that the temperature decreases outwardly in the solar photosphere reaching a minimum near 4000 K. The temperature then generally increases, reaching 9000 K at a height roughly 1500 km above the temperature minimum region. This higher temperature region is the solar chromosphere. Hydrogen is neutral in the low chromosphere and is partially ionized at 9000 K where the temperature starts to increase rapidly with height, reaching 100,000 K within a few kilometers (where hydrogen is almost fully ionized). This sharp rise in temperature is a result of radiative cooling by the hydrogen Lyman-alpha line (and the other Lyman lines and the helium resonance lines): this efficient radiative cooling prevents higher temperatures in the upper chromosphere, but becomes ineffective once hydrogen and helium become fully ionized.
Anderson & Athay (1989) have estimated that mechanical heating of the order of \(10^{14}\) ergs atom\(^{-1}\) s\(^{-1}\), roughly constant with height throughout the chromosphere, and presumably extending into the corona, would roughly account for the known temperature structure. There are many candidates for this mechanical heating and we do not attempt to list them here. Our present purpose is to discuss the transition region between the chromosphere and corona, which to a first approximation can be treated without specifying a local source of mechanical heating.

Thus we consider the transition region above an upper-chromospheric boundary where the temperature and other atmospheric parameters are considered to be given from separate chromospheric modeling. There has to be mechanical energy dissipation to heat the chromosphere and produce these boundary conditions, and further mechanical dissipation is needed in the low-density corona to produce the high temperatures there, but in order to study the transition region we need only specify the boundary conditions at the top of the chromosphere. At the outermost point in our calculation we let the inward heat flow from the corona into the transition region be the amount needed to balance all the radiative losses from the transition region. In the lower transition region where the hydrogen and helium resonance lines are formed, the radiative losses are calculated in detail from solutions of the radiative transfer equations.

The heat flow from the corona consists of three components: conduction, diffusion, and advection. Thermal conduction is significant for large values of the temperature gradient. Ambipolar diffusion of ions (moving inward) and atoms (moving outward) in a partially ionized gas also depends on the temperature gradient and is more important than thermal diffusion in the lower transition region. The main contribution to the heat flow made by diffusion is the ionization energy carried by ions that recombine and release energy at lower temperatures. Most of the energy emitted in the Lyman-alpha line is carried into the lower transition region from higher temperatures by diffusion. Advection refers to the effects of mass and particle flow velocities. An inward flow through the partially ionized region also carries ions to lower temperatures where these ions release their ionization energy and heat the gas, but this component of the heat flow does not depend on the temperature gradient. If roughly the same total inward heat flow is needed to balance the radiative losses, the temperature gradient will be reduced in the case of an inward flow, in order to reduce the conduction and diffusion contributions. Conversely, an outward flow counteracts the inward flow of heat carried by diffusion and conduction, so that the temperature gradient must be larger in order to enhance this inward heat flow, given roughly the same radiative losses to be balanced.

2. Results

Here we show some of the results from the FAL4 paper. Figure 1 shows the calculated temperature distributions in the stationary case and for two outflow and three inflow cases. The inflow and outflow cases have constant particle fluxes of 2, 1, \(-1\), \(-5\), and \(-10 \times 10^{15}\) particles cm\(^{-2}\) s\(^{-1}\) (with the product of velocity and mass density constant with height). Figure 1a shows the calculated temperature distributions in the low transition region while Figure 1b shows
these distribution in the upper transition region and low corona. Clearly, the flow velocities considered here strongly affect the energy-balance temperature structure throughout the transition region and low corona. The calculations shown here extend from the given lower boundary to temperatures above $10^6$ K or to the height where the flow velocity approaches the sonic value.

As noted above, inflows lead to much smaller temperature gradients as a result of the much smaller need (or no need) of thermally driven heat transport to support the radiative losses. Large inflow velocities lead to an extremely extended transition region in which the variation in energy transported downward by the mass flow through each large height interval is dissipated by the radiative losses in that interval.

The opposite is true for outflows. The temperature gradient must increase as the outward mass flow increases so that the inward thermally driven heat transport variation can compensate for the large variation of the velocity-driven outward energy flow and the radiative losses.

For simplicity we have not included mechanical dissipation in the transition region. This assumption is justified in the stationary case and for outflows because of the small vertical extent of the transition region, where the radiative losses (per unit volume or unit mass) are very large compared with those in the underlying chromosphere or overlying corona. However, mechanical dissipation should be included in the inflow cases that have smaller temperature gradients and extend over greater heights. Here we do not extend our models higher into the corona since without mechanical dissipation the radiative and conductive losses cause the temperature to rise unchecked. Mechanical energy dissipation balances the radiative and conductive losses at coronal temperatures, allowing the calculation of models that reach a maximum temperature. The calculations shown here are applicable to conditions only at moderate heights, and they neglect complicated three-dimensional and radiative transfer effects that may arise when the transition region becomes very extended as a result of inflows. Our results here apply to the footpoints of loops, as described in the FAL4 paper.
3. Line Profiles

Figures 2, 3, and 4 show our calculated disk-center intensity profiles for lines of H, HeI, and HeII, respectively. As discussed by FAL4, the calculated behavior of the Lyman-alpha line is consistent with the detailed observations of Fontenla, Reichmann, & Tandberg-Hansen (1988). It should be noted that all six cases assume the same lower boundary condition, corresponding to an average chromospheric model. More realistic comparisons with observations should be possible when we have included results based on the boundary conditions for fainter and brighter components of the chromosphere. Our Lyman-beta profiles show no central reversals, whereas some central absorption is seen in almost all of the Lyman lines. Such central absorption could be caused by small amounts of relatively cool spicular or prominence material, not included in our modeling, located high in the atmosphere along the line of sight.

SUMER observations do not show HeI 58.4 nm profiles having central reversals (C. Wilhelm, private communication), although the central reversals we calculate would be smoothed to some extent by the spectral, spatial, and temporal resolution of the SUMER observations. Hence the centrally reversed HeI profiles shown in Figure 3a may not be consistent with solar observations, and require further study.
Figure 3. Calculated disk center HeI line profiles
Figure 4. Calculated disk center HeII line profiles
Our calculated HeI and HeII profiles generally indicate that flows, either inflows or outflows, strengthen the emission in emission lines and strengthen the absorption in absorption lines. The changes in the profiles due to the influence of flows on the structure of the transition region are substantially greater than the direct line shifts produced by the flow velocities.

4. Future Work

Here we have summarized the main results that are presented in much more detail in the FAL4 paper. In subsequent papers we plan to 1) add the effects of mechanical dissipation in the transition region, 2) extend the calculations to include a range of lower boundary conditions based on the properties at the top of the chromosphere for active as well as quiet regions, 3) include the detailed effects of particle diffusion and radiative energy losses due to atoms and ions other than H, HeI, and HeII, 4) extend the calculations with flow velocities higher into the corona, past the sonic point, to investigate the onset of the solar wind, 5) adapt the present one-dimensional formalism to apply to the conditions along the axis of a magnetic loop extending into the corona, 6) calculate the effects of magnetic fields not parallel to the flow, and 7) investigate the relative abundance gradients caused by ambipolar diffusion and gravitational mass separation.

References