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Physical structure of solar cool loops

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Abstract. Recently, studies and observations focused on the solar transition region and the low corona have shown the importance of small and cool magnetic loops in producing most of the solar EUV output at temperatures below 1 MK. This kind of structures has remained only poorly characterized in terms of physical properties. We study the possibility of obtaining cool loops using unidimensional hydrodynamic simulations, performed with a state-of-the-art numerical code with a fully adaptive grid. The dependence of their physical structures on the form of the radiative losses function has been explored. We find, as a first result, that the shape of the radiative losses function for T< 10^5 K imposes restrictive conditions on the existence and the stability of such cool loops.

Key words. Hydrodynamics – Sun: corona – Sun: transition region

1. Introduction

In the last 30 years, different theories have been proposed and debated to explain the origin of the solar EUV output at temperatures below 1 MK. The idea that the transition region emission originates from the bases of the hot large-scale coronal loops was not confirmed by the measured DEMs (Differential Emisson Measure) that resulted to be orders of magnitude larger than the predicted ones (Gabriel 1976; Athay 1981). Dowdy et al. (1986), in order to explain the increase of the DEM towards the chromosphere, suggested the existence of a second structural component of the lower transition region: very small and cool magnetic loops (height∼ 5 Mm, T∼ 10^5 K), isolated from the hot ones (T∼MK). Antiochos & Noci (1986) studied the general properties of static cool loops and demonstrated quantitatevely that a mixture of static cool loops with different temperatures, can account for the missing lower transition region DEM.

Some recent observations with the VAULT (Very high Angular Ultra-Violet Telescope, Korendyke et al. 2001) instrument in the Ly-α line at subarcsecond–scale, showed looplike structures with estimated temperatures and densities that could be appropriate for predicted cool loops (Patsourakos et al. 2007; Vourlidas et al. 2010). But it is not clear if these observed threads are really cool loops (Judge & Centeno 2008).

Since the theoretical works of Antiochos & Noci (1986) and Klimchuk et al. (1987), there was no new effort to study quantitatively the structure and stability of static cool loops and this

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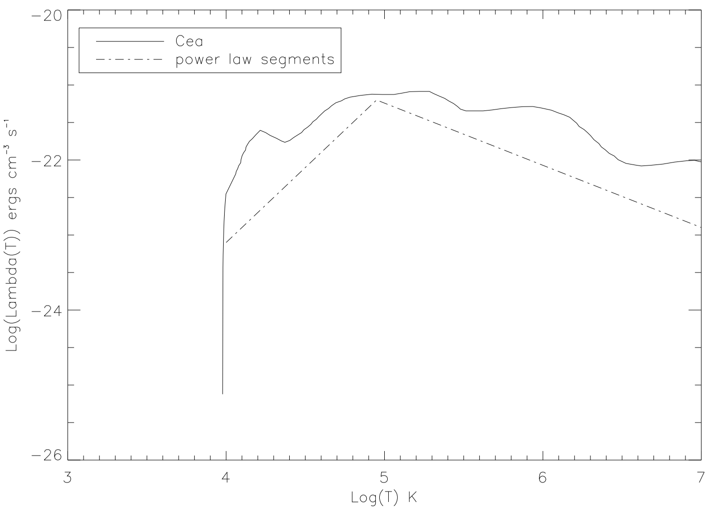

Fig. 1. Dependence of the radiative losses function from the temperature for two different cases. Dot-dashed line: function of radiative losses represented by power law segments. Solid line: function of radiative losses presented in the work of Colgan et al. (2008).

kind of structures has remained only poorly characterized in terms of their physical properties. On the other hand, there has been a number of recent works (e.g.: Spadaro et al. 2006) studying the structure and evolution of hot coronal loops, using sophisticated hydrodynamic simulations. There is the need of a quantitatively analysis of static loops with $T_{max} \sim 10^4 - 10^5$ K.

We want to perform this analysis using unidimensional hydrodynamic simulations. In this way, it is possible to obtain information also on the stability of the loops.

2. Loop Modelling

The hydrodynamic equations of mass conservation, momentum and plasma energy have been solved for a unidimensional loop magnetically confined, using ARGOS, a 1-D hydrodynamic code with a fully adaptive grid (Antiochos et al. 1999; MacNeice et al. 2000). A fully adaptive grid is necessary to solve the thin sections of the transition region chromosphere-corona of the loop.

We make some basic assumption. One is that the background heating (E_0) is considered to be constant and as another assumpation, we consider optically thin radiative losses that can be expressed as $n^2\Lambda(T)$, with n the electron number density and $\Lambda(T)$ the radiative losses function. We set our boundary conditions (the top of the chromosphere) at $T=10^4$ K.

All previous studies have adopted a highly idealized (power laws) treatment of radiative losses. We want to explore the behaviour of the loops introducing more realistic radiative losses functions, based on recent works. For this purpose, the code was modified in order to use tabulated radiative losses functions.

The simulations are performed using two different functions of the radiative losses. In one case, we use power law segments, $\Lambda(T)=T^a$ (as in Antiochos & Noci 1986; Klimchuk et al. 1987) with a=2 for $T< 10^5$ K (dot-dashed line in Fig. 1) and in the other case, we take the function presented in the work of Colgan et al. (2008) (Cea, solid line in Fig. 1).

3. First results and conclusions

In Figs. 2 and 3 we show the behaviour of the thermodynamic parameters and the terms of the energy equation for one example of loop

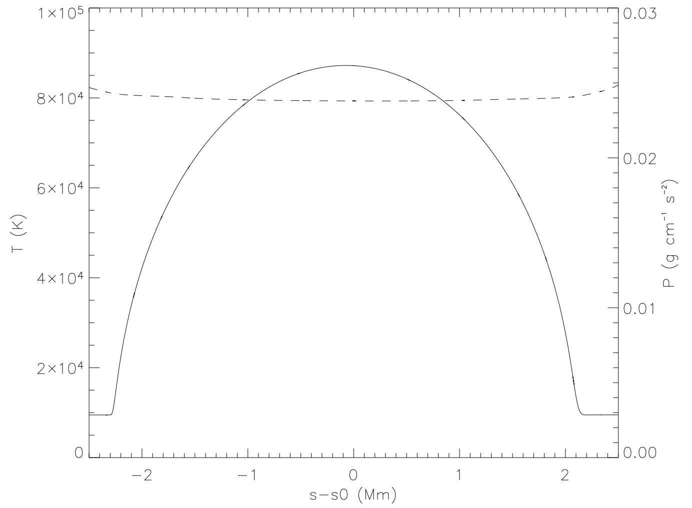

Fig. 2. Temperature (solid line) and pressure (dashed line) as a function of the curvilinear coordinate along the field lines, s. s_0 is the loop top.

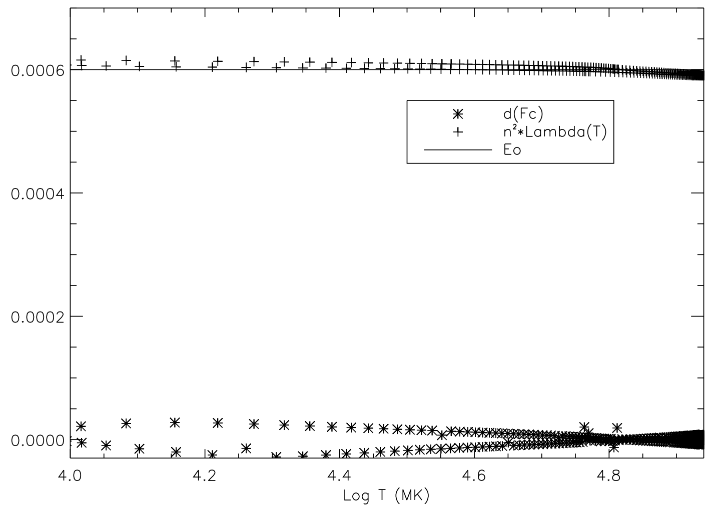

Fig. 3. The divergence of the conductive flux (asteriscs), the radiative losses function multiplied by the electron number density (n) squared (crosses) and the background heating, E_0 (solid line) as a funcion of the temperature.

obtained. In Fig. 2 we plot the temperature (solid line) and the pressure (dashed line) as a function of the curvilinear coordinate along the field lines, s. The maximum temperature of the loop is $\sim 8.7 \cdot 10^4$ K and it is nearly isobaric. In Fig. 3 instead the three terms of the energy equation are shown: the divergence of the conductive flux, the radiative losses function multiplied by the electron number density squared and the background heating, E_0.

Antiochos & Noci (1986) solved the hydronamic equations in a static and stationary case and found that for cool loops, even for the maximum possible temperature (T= 10^5 K), the conductive flux is negligible. So, the energy balance is primarily between the terms of the radiative losses and background heating. From Fig. 3, we see that for the loop found, there is an approximate balance between these two terms (the divergence of the conductive flux is a small term). The loop does not follow the scaling laws for coronal loops derived in the work of Rosner et al. (1978). The physical properties of this loop are in agreement with the ones derived by Antiochos & Noci (1986) for cool loops.

Using the function of radiative losses of the work of Colgan et al. (2008), we obtain static loops only for values of E_0 higher than $\sim 6.5 \cdot 10^{-4}$ ergs cm^{-3} s^{-1}. But we do not obtain any static cool loop, they are all loops with temperatures higher than 10^5 K.

The simulations we have done show that the shape of the radiative losses function for T< 10^5 K impose restrictive conditions on the existence of static cool loops. We are able to obtain static cool loops only in the case of radiative losses represented by power law segments and imposing a value for the costant background heating E_0 around $6 \cdot 10^{-4}$ ergs cm^{-3} s^{-1}. For values of E_0 lower than $5.5 \cdot 10^{-4}$ ergs cm^{-3} s^{-1} there are no static solutions and for values higher then $6 \cdot 10^{-4}$ ergs cm^{-3} s^{-1} we obtain static coronal loops.

If we change the shape of the radiative losses function for T< 10^5 K from simple power law segments to a more complex but realistic one, it is not possible to obtain static cool loops. It is still possible, however, that by improving the models, with the introduction of a full treatment of optically thick radiative losses and/or partial ionization some solutions with characteristics of the cool loops could be found.

The results found, if confirmed, could mean different things. It is possibile that the idea proposed by Dowdy et al. (1986) of the existence of small and cool loops to explain the behaviour of the DEM in the transition region is not valid and these structure do not exist. It may also be that cool loops exist but not as a static structure. In this case, the threads observed by VAULT could be dynamic cool loops, changing on faster time-scales than big coronal loops.

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