Structure and Stability of EUV Loops Originating from Sunspots

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Abstract. We study the structure and stability of loops originating from sunspot umbrae, observed in EUV lines. Their structure and energetics is still poorly understood and they are a puzzle in solar and stellar loop physics. A better understanding of these loops is particularly important for the forthcoming observations with the EUV instruments on board SOHO and the relevant data interpretation. Neither hydrostatic, nor siphon flow loop plasma models with energy balance between radiative losses, heat conduction and a volumetric heating either uniform or varying (either decreasing or increasing) along the loop, can fit the observations. In an attempt to constrain the energy balance and plasma stratification in such loops, given the rather uniform brightness distribution, we fit data, instead, assuming an isothermal plasma distribution inside the loop, either hydrostatic or - better - undergoing a siphon flow. These results may be evidence of dynamic conditions in EUV sunspot loops.

1. Introduction

Hydro models of the plasma magnetically confined in coronal loops have given insight on the loop structure and stability. The hydrostatic model by Rosner, Tucker and Vaiana (1978) provided a conceptual framework of loops in stationary conditions, and was generalized by Serio *et al.* (1981) who considered the gravity in the hydrostatic pressure balance equation, the other equations being the equation of state of plasma and that of the energy balance between thermal conduction, radiative losses according to Raymond and Smith (1977) spectral model and a phenomenological heating term. The loop model was successful in fitting the observations of coronal and upper transition region plasma but it failed to fit the EUV data on loops originating from the sunspot umbrae (Pallavicini *et al.* 1981). The physical mechanisms which make these loops so peculiar are still not understood, and this area of solar loop physics still deserves significant work. Moreover the EUV instruments on SOHO, most notably EIT, CDS and SUMER, will soon collect EUV data on loops. A better insight on EUV sunspots loops is therefore in order.

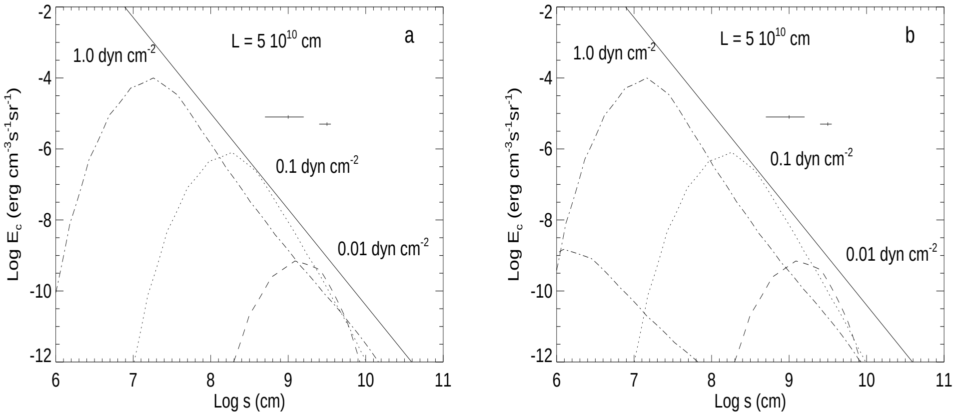

Figure 1. Left: Intensity of the Ne VII (465.2 A) line, along one leg of symmetric hydrostatic loops, all of semi-length 5×10^{10} cm and plasma pressure of 1 (dot-dashed), 0.1 (dotted), and 0.01 (dashed) $dyn\ cm^{-2}$, according to the model of Serio *et al.* (1981). The data points are from Pallavicini *et al.* (1981), for a sunspot loop; for the solid line $E_c = 10^{16.6}\ s^{-2.7}$ see the text. Right: The same as the left panel for for the siphon flow loop model of Orlando *et al.* (1995), **in critical conditions**. The ascending and the descending (mostly below the lower boundary of the graph) branches are shown with the same line-style.

2. The EUV Loops Rooted in Sunspot Umbrae

Foukal (1976) studied systematically loops rooted in the sunspot umbrae and observed with S-055/Skylab in the EUV line emission of various ions (e.g. O IV 554 A, O VI 1032 A, Ne VII 465 A, Mg X 625 A). He found that such structures are rather thin and that the emission scale height is significantly longer than the one derived from the *temperature of maximum ion formation*, assuming hydrostatic conditions. Only the lower part of the loops originating from the sunspots was typically detected and these loops were not observed in X-rays.
These loops appeared fundamentally different from all the other loops observed and, in particular, from the hot, X-ray emitting, coronal loops. The hydrostatic loop model by Serio *et al.*, either with uniform volumetric heating or with a heating exponentially decreasing from the loop base to its apex, indeed failed to fit the observations of these loops. The emission synthesized from the model closer to observations, reported by Pallavicini et al., was off by two orders of magnitude; the same work instead found a good agreement of the model with the X-ray emitting loops. Whereas, since then, the model of hot coronal loops have been successfully applied to a large variety of X-ray emitting loops and extended also to the stellar coronae (cf. Ciaravella *et al.* 1995; Maggio and Peres 1995, for recent developments), these EUV loops above sunspot still remain a puzzle.

3. Modelling the EUV Loops

Here we try to model the intensity along one of these loops on the basis of some loop models: from the density and temperature distribution computed we synthesize, taking advantage of the ASAP environment (Maggio *et al.* 1994), the emission along the field lines using the plasma emissivity from the spectral codes by Raymond and Smith (1977) or by Landini and Monsignori Fossi (1990). In order to put stringent constraints on the models we make a careful comparison of the synthesized emission with detailed observations: the data points on the EUV line of Ne VII (465.2 A) reported in Pallavicini *et al.* (1981). Analogous data points are hard to extract from other papers on this problem. We assume stationary conditions.

After revisiting the analysis by Pallavicini *et al.* with the hydrostatic loop model and the ASAP emission synthesis tool, we confirm that the hydrostatic model by Serio *et al.* with uniform heating fails to fit the emission by at least two orders of magnitude. We have explored over a wide range of loop lengths, base pressure and maximum temperature and *invariably the spatial distribution of emission falls too rapidly along the loop to fit the observations: typically the plasma in the higher part of the loop is too hot and does not yield enough line emission.* Fig. 1a shows that the surface brightness of representative models lay well below the data points independently of the loop characteristics; in particular the models are invariably below a region in the graph whose approximate boundary is marked by the line $E_c = 10^{16.6}\ s^{-2.7}$ where E_c is the intensity and s is the field line coordinate reckoned from the loop base.

The siphon flow loop model by Orlando *et al.* (1995) does not improve matters significantly: also with this model we have explored a wide range of model parameters and here we report siphon flows in critical conditions, i.e. in which the flow is subsonic in the ascending branch, reaches sound speed close to the loop apex and is supersonic in the descending branch, in order to show the models most different from hydrostatic loop models. Also these cases, even considering non-equilibrium ionization, poorly fit the observations and the modelled intensity is below the aforementioned line, as shown in Fig. 1b.

All the above models do not fit neither the value nor the slope of the data. We have considered also a heating exponentially decreasing along the loop legs in both class of models; even for the heating most concentrated at the base of the loop, and still yielding equilibrium solutions in energy balance, we obtain a slight increase of the emission (at most by a factor of three in some parts of the loops) but still off the observations by orders of magnitude. The slope of the data point is much flatter than that of the results from these loop models and it appears as if the plasma were practically **isothermal**, much more than what occurs in stationary loop models, governed by normal plasma thermal conduction.

In order to obtain neverthless some constraint on the physics of this loop we have tried to fit the data points assuming that the loop plasma is **isothermal**. Fig. 2a shows that a loop with a hydrostatic and **isothermal** plasma at a temperature of 7.5×10^5 K (slightly higher than that of maximum ion formation) can fit the data point; we also show two loop models of the same kind having different plasma pressure at the loop base: a higher pressure yields a higher density and therefore a higher emission. In Fig. 2b we show the same **isothermal** loop model with two other **isothermal** models of different plasma temperatures: the

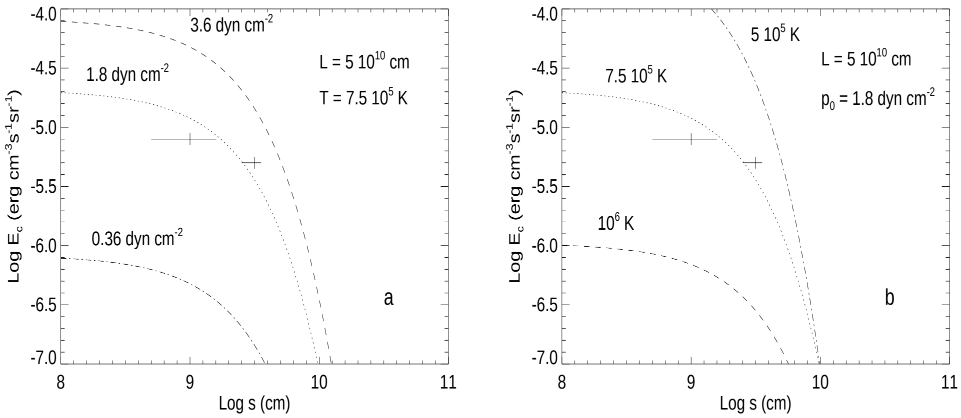

Figure 2. Left: Intensity profile of the Ne VII (465.2 A) line along one leg of three loops filled with isothermal plasma in hydrostatic conditions, all with the same semilength 5×10^{10} cm and temperature 7.5×10^5 K. The plasma pressure is 3.6 (dashed), 1.8 (dotted), and 0.36 (dot-dashed) $dyn\ cm^{-2}$; same data points as in Figure 1. Right: The same as in the left panel for loops with the same semilength 5×10^{10} cm and pressure: 1.8 $dyn\ cm^{-2}$. The plasma temperature is 5×10^5 K (dot-dashed), 7.5×10^5 K (dotted), and 10^6 K (dashed).

Ne line brightness distribution is lower at the higher temperature because the plasma emissivity in the line is lower; the profile is also flatter. Experimenting with different values of the pressure and of the temperature we can try to fit the data points with other models. Fig. 3a shows three **isothermal** hydrostatic loop models with different temperatures and pressures which fit the data points.

We have also experimented with **isothermal** siphon flows and in order to ascertain how much the flow can influence our results, we show a flow in critical conditions, as defined above. Fig. 3b shows three critical isothermal siphon flows of different temperature and base pressure which fit observations. The **isothermal** siphon flow model yields results, in the ascending branch, similar to those of the **isothermal** hydrostatic loop model. However, at variance from hydrostatic model, which is symmetrical, the descending branch is much less visible in the line emission, because the flow speed is higher and, in order to conserve mass flow, density is lower; therefore emission is lower, in particular by a factor 10^6 for the coldest loop and 10^{10} for the hottest loop reported in Fig. 3b. Observations show that the part of the loop emerging from the sunspot umbra is much more visible than the rest, therefore the isothermal siphon flows yeld a better agreement with observations.

An additional constraint to apply to these models is the lack of loop detection in X-ray. The S054/Skylab and the SXT/Yohkoh telescopes have provided the almost totality of X-ray images of the Sun. Both are characterized by a band pass which falls very rapidly at lower temperatures, making it hard the detection of plasma around a million degrees. Therefore the loops reported above would not be detected by these telescopes, with the possible exception of the loop with

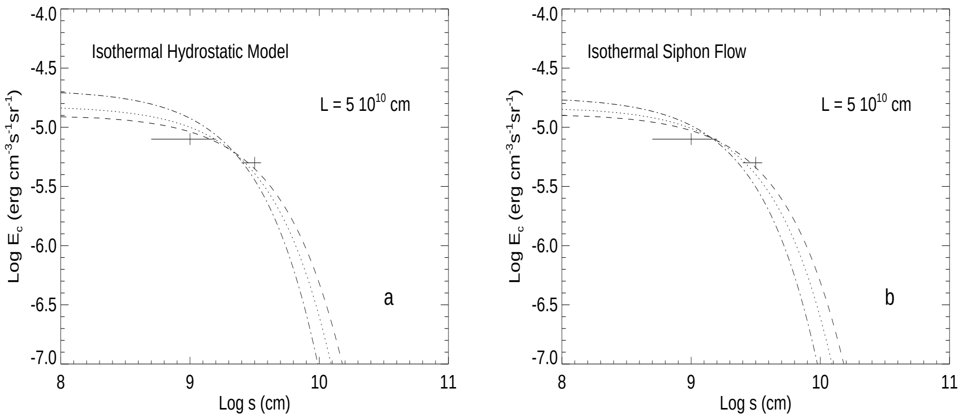

Figure 3. Left: Intensity profile in the line emission of Ne VII (465.2 A) along one leg of three loops filled with isothermal plasma in hydrostatic conditions, all with the same semilength: 5×10^{10} cm. The temperature and base pressure values are, respectively, 7.5×10^5 K and 1.8 $dyn\ cm^{-2}$ (dot-dashed), 1×10^6 K and 6.8 $dyn\ cm^{-2}$ (dotted), 1.25×10^6 K and 18 $dyn\ cm^{-2}$ (dashed). Right: The same as in the left panel for isothermal and critical siphon flow loops with the same length: 5×10^{10} cm. The temperature and base pressure values are, respectively, 7.5×10^5 K and 1.66 $dyn\ cm^{-2}$ (dot-dashed), 1×10^6 K and 6.7 $dyn\ cm^{-2}$ (dotted), 1.25×10^6 K and 18.1 $dyn\ cm^{-2}$ (dashed).

temperature of 1.25×10^6 and pressure 18 $dyn\ cm^{-2}$.
In spite of the acceptable fitting to data, however, an isothermal loop plasma does not appear physically sound.

4. Discussion and Conclusion

Both the hydrostatic and the stationary siphon flow loop models with energy balance among heat conduction, radiative losses and a phenomenological uniform heating term invariably fail to fit the surface brightness distribution of the EUV loops originating from sunspot umbrae. A heating exponentially decreasing from the loop base to its apex improves model results only slightly but not significantly. In an attempt to put some constraint on the energy balance of the plasma in these loops, apparently with a rather uniform thermal distribution, we have tried an **isothermal** plasma distribution inside the loop, either in hydrostatic conditions or undergoing a siphon flow. The observations are fitted better, especially by the siphon flows. At variance from Foukal's analysis, in such a scenario the plasma can be hotter than the maximum temperature of ion formation, and still emit significantly and fit observations. Foukal was also concerned that the pressure scale height was longer than expected, a possible evidence of departure from hydrostatic conditions. The isothermal distribution, instead, with a temperature higher than that of maximum line formation can fit the observations. Rather, the departure from hydrostatic conditions might be

better motivated with the significant loop asymmetry: typically only the loops' legs departing from the umbrae are detected.
Far from being a satisfying physical model, the **isothermal** loop (either hydrostatic or siphon flow) plasma distribution is, for us, just a way to fit observations and to put constraints on the physics of such loops and to show that usual stationary models, even with a highly non uniform heating distribution, **but in equilibrium**, appear inadequate to these loops. In order to explain these results, rather than to look for a mechanism which leads to a very flat temperature distribution in stationary conditions, we prefer to assume that these loops are out of equilibrium (the observations do not last long enough to address this aspect). Much study has still to be done on these loops, including a thorough study with dynamic loop plasma models and a reanalysis of the S055/Skylab observations, to examine more cases quantitatively as well as to get more data points. New observations with the EUV instruments on board SOHO, on the other hand, promise to provide crucial information on the characteristics and the evolution of these loops.

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