DYNAMIC LOOPS IN THE CORONA

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ABSTRACT

Various kinds of dynamic plasma loops represent the basic structural component of the solar corona. Their energy balance is determined by various heating and cooling processes and for unstable loops, like e.g. the post-flare loops, the conductive and radiative cooling leads to a formation of cool structures ($T < 10^5$ K), finally visible in the Hα line. While the physics of hot loops was extensively studied during recent years, the cool loops are less understood mainly due to a large complexity of optically-thick radiation transitions (non-LTE effects on the radiation cooling) and because some additional heating/cooling mechanisms become effective at lower temperatures (e.g. the conduction across the magnetic field lines, ambipolar diffusion or X-ray heating). In this paper we summarize several basic questions concerning the energetics and dynamics of post-flare loops, with a special emphasis on their cool state. The answer to these questions depends critically on new simultaneous high-resolution observations in EUV (SOHO) and optical (GBO) passbands. New model simulations are also required.

1. INTRODUCTION

Hot coronal loops ($T > 10^5$ K) have been extensively studied both observationally and theoretically and there exist several useful reviews on this topic (Bray et al., 1991; Klimchuk, 1992; Mariska, 1992). Moreover, the Yohkoh observations also revealed several new aspects of the coronal loop physics (see Enome and Hirayama, 1994; Fleck et al., 1994 and Rusin et al., 1994). Cooler loops, sometimes called "cool loops" in the literature, have temperatures in the range $2 \times 10^4 < T < 10^5$ K and have been studied in EUV and UV, e.g. during the Skylab and SMM missions (Cheng, 1980; Bray et al., 1991). From the theoretical viewpoint, the temperature $T \simeq 2 \times 10^4$K characterizes certain limiting value below which the loop plasma becomes optically thick in strongest transitions (hydrogen Lyman α line). This leads to several difficulties in the numerical modelling (opacity effects on the radiation cooling are important) and, therefore, most loop models are constructed in such a way that at their base the temperature is set to $2 \times 10^4$ K. In this paper we introduce a third category of loops which we call here "Hα loops".

These loops are cool at temperatures below $2 \times 10^4$ K and are usually observed in the Hα line. Their basic properties are summarized in the monograph of Bray et al. (1991), a special class called "post-flare loops" (or sometimes "cool flare loops" - see Heinzel et al., 1992) was reviewed by Švestka and Cliver (1992) and Schmieder (1992). The relationship between hot loops observed by Yohkoh soft X-ray telescope (SXT) and Hα ones recorded by MSDP was recently studied by Schmieder et al. (1994) and we shall report some new results here.

We can schematically distinguish between three classes of Hα loop structures (Fig. 1). Class I represents an Hα loop fully filled with the cool ($T < 2 \times 10^4$K) material, although it can be fragmented into individual blobs so that the loop is highly inhomogeneous. Post-flare loops are highly dynamical, showing predominantly strong downflows. In the case of post-flare loops, hotter loops typically overlay the Hα ones (Švestka et al., 1987; Schmieder et al., 1994). Second class (II) represents the loops which are presumably hot and in one or both legs we see the Hα material moving up or down (flares, surges, spicules). The class III is somewhat different,
but has certain resemblance with the class I. Namely for flares we see hot loops anchored in the chromosphere where they have temperatures below $2 \times 10^4$ K and emit Hα in the form of two ribbons. Frequently we see Hα loops below the hot ones, which is the case I. The Hα ribbons represent a natural part of the whole loop structure, but they are usually treated as the flaring chromosphere, i.e. semi-infinite plane parallel atmosphere (Avrett et al., 1986; Heinzel and Karlícký, 1992). On the contrary, the prominence-like formations I and II are modelled as isolated cool structures of finite geometrical thickness, irradiated from the solar surface (Heinzel et al., 1992). Non-LTE modelling procedures for such prominence-like structures are discussed in Gouttebroze et al. (1993), where several models for typical physical conditions are presented. These models are static, but Heinzel and Rompolt (1987) studied the influence of the plasma-flow velocities on the hydrogen lines emission.

In the following we shall concentrate mostly on the physics of post-flare loops, namely on their cool state. We summarize some results obtained during last few years and formulate several questions which, as we hope, can be answered by SOHO observations coordinated with high-resolution ground-based observations.

2. STRUCTURE OF Hα FLARE LOOPS

High-resolution Hα images of cool post-flare loops, obtained by MSDP at Pic-du-Midi (resolution $\sim 0.5$ arcsec), reveal highly inhomogeneous structure. These loops consist of many fine-structure blobs, falling down along the both legs (Schmieder et al., 1994; Wiik et al., 1994). This is demonstrated in Fig. 2 for the case of 26 June 1992 flare loops. The downflows are clearly visible in Fig. 2b (MSDP velocity map). The first question arises when looking at these images: What kind of plasma is in between the cool Hα blobs? If this plasma is also cool at temperatures below $2 \times 10^4$ K, then it must have very low density. If it is hotter, then it should be visible in UV or EUV. Although it is rather complicated to make an exact co-alignment between images taken in Hα and UV or X-rays, a few observations do indicate that the hotter post-flare loops are resolved above the cooler ones, at least for temperatures higher than about $2 \times 10^6$ K (Švestka et al., 1987; Schmieder et al., 1994). In Fig. 3 we show such an example of co-alignment of Hα and SXT images of 26 June 1992 loops.

It is difficult to say whether the Hα blobs move inside the hotter rare plasma. Even if we would have exactly ospaceal images with the same spatial resolution in both UV and Hα, there exists a possibility that we see a transition-region sheath in UV around the cool magnetic loop (see Heinzel and Vial,

Figure 2: MSDP observations of 26 June 1992 post-flare loops. (a) - intensity fluctuations (bright is white), (b) - Doppler shifts (white/black represents blueshift/redshift). From Schmieder et al. (1994).
1992). In fact, the hotter loops seem to be thicker or more diffuse (Hirayama, 1994; Takeda et al., 1994), but some observers ascribe this to seeing and spatial-resolution effects. Nevertheless, we hope that simultaneous SUMER/CDS and optical observations with a spatial resolution around 1 arcsec could reveal a relationship between these plasma components.

3. LOOP DYNAMICS

The second question is: What is the Hα-loop dynamics? In Fig. 2b we see the Doppler velocities, which can be detected even better in the case of disk observations (e.g. Heinzl et al., 1992). Using the geometrical reconstruction procedure of Loughhead et al. (1983), Heinzl et al. (1992) and Wiik et al. (1994) arrived at flow velocities of the order of tens km/sec, which is consistent with other authors. However, the basic problem is whether these downward motions correspond to a free fall (Engvold et al., 1979) or if some acceleration/deceleration mechanisms play a role. Xu (1987), Heinzl et al. (1992) and Wiik et al. (1994) arrived at the conclusion that the falling blobs move with velocities smaller compared to a free-fall motion, sometimes almost constant along a part of the blob path. This could indicate the presence of a plasma which we don’t see in Hα - see the question one. The dynamics of cool blobs moving inside the hotter plasma which fills the loop was studied by Karlický and Simnett (1992) who have shown that significant deceleration can take place due to gas-pressure gradients. Other deceleration mechanisms are proposed in Heinzl et al. (1992), including a twisted magnetic fluxtubes.

Another aspect of the Hα-loop dynamics is that the motion of blobs strongly affects the hydrogen lines emission provided that the velocities are of the order of tens km/sec. As demonstrated quantitatively by Heinzl and Rompolt (1987) (see Fig. 4), Hα is enhanced due to so-called Doppler brightening effect, while Doppler dimming affects the hydrogen Lo line. Multilevel non-LTE effects cause that the Lβ is first enhanced like Hα and for velocities higher than about 80 km/sec it is decreased. Observed with SUMER, Lo dimming and Lβ brightening, i.e. the ratio of integrated intensities of these two lines, can serve us as a diagnostics tool for determining the velocity component complementary to that derived from Doppler shifts. This ratio will substantially eliminate other possible intensity-variation effects (e.g. density fluctuations), not related to velocities.

4. EMISSION MEASURE AND ELECTRON DENSITIES

In the case of hot loops, electron densities can be derived in a rather straightforward way from the emission measure analysis. For cool Hα loops one can use a new method recently suggested by Heinzl et al. (1994a). Using extensive set of non-LTE models of prominence-like cool structures (Goulettebroze et al., 1993), these authors have found almost unique correlation between the integrated Hα intensity $E_H(\alpha)$ and the emission measure $EM = n_e^2D$ ($n_e$ is the mean electron density and $D$ is the geometrical thickness of the emitting plasma). For Lo or Lβ lines, such a correlation is more sensitive to temperatures. Hα high-resolution MSDP observations have been used to derive the electron densities in 26
June 1992 post-flare loops, where \( n_e = 2.2 \times 10^{10} \) cm\(^{-3}\) was found (Schmieder et al., 1994). However, this density is lower than the corresponding one derived under the assumption of a static loop. The reason is that the Doppler brightening enhances the integrated H\(\alpha\) emissivity as demonstrated in Fig. 5.

It is generally assumed that for most cases of post-flare loops the electron density is lower than \(10^{12} \) cm\(^{-3}\) because these loops are usually seen in absorption against the solar disk (Heinzel and Karlický, 1987; Svestka et al., 1987; Heinzel et al., 1992). The electron density must be known with relatively high accuracy (much better than one order of magnitude), in order to correctly specify the radiative cooling of the loop plasma (see next section). The problem is that we don’t know the true geometrical thickness \(D\) and therefore an independent derivation of \(n_e\), based on other lines or line ratios, is highly desirable.

Using the simultaneous Yohkoh-SXT and MSDP observations, Schmieder et al. (1994) have derived for the first time both hot and H\(\alpha\) loop electron densities (\(7 \times 10^9\) and \(2.2 \times 10^{10}\), respectively), which have been subsequently used to determine the cooling times in the post-flare loop system (Fig. 6).

5. ENERGY BALANCE

Finally, we want to address some questions related to the heating and cooling of post-flare loops. Our third question is: What is the behaviour of time-dependent radiative cooling at temperatures below \(2 \times 10^4\) K? As mentioned at the beginning, non-LTE opacity effects become very important in derivation of radiative losses (see e.g. Kuin and Poland, 1991). Nevertheless, an approximate estimate of the cooling times can be made using a simple formula (Svestka, 1987)

\[
\frac{dT}{dt} = -\epsilon(T)n_e^2 + 1.1 \times 10^{-6}T^{7/2}/L^2/3k, \tag{1}
\]

where \(T\) is the temperature, \(\epsilon\) the radiative cooling function, \(n_e\) the electron density and \(L\) the semilength of the loop (see also Schmieder et al., 1994). This equation is based on the assumption that the loop was initially heated and then it cools without any additional heating. Solution of this differential equation was performed in Schmieder et al. (1994), for starting hot-loop temperature \(5.5 \times 10^6\) K and electron densities indicated in Fig. 6. Even if we stopped this solution at \(T = 2 \times 10^4\) K (for reasons discussed elsewhere in this paper), it seems to be evident that the cooling below this limit will be also fast. Now it is important to know the answer to our following fourth question: What is a typical life-time of a cool H\(\alpha\) plasma blob? Preliminary answer to this question is tens of minutes. This follows from high-resolution observations of individual H\(\alpha\) blobs which suggest that their life-time is comparable to a fall-time (Tarbell, 1994; Wiik et al., 1994). For a free-fall motion, a characteristic fall-time can be of the order of tens of minutes (Heinzel et al., 1992), and with certain deceleration it is even longer. This might also indicate that the H\(\alpha\) blobs are formed (by cooling) at the top of the loops, rather than along the legs. In the latter case, a hot plasma component should be observable in between H\(\alpha\) blobs (question one). Therefore, we meet the situation that a characteristic radiative cooling time is much shorter than the life-time of the blob falling downwards. Without any heating, the blob would eventually cool down to temperatures around \(T_{RE} \approx 4600\) K, which corresponds...
to the radiative equilibrium state of the prominence-like structure (Heasley and Mihalas, 1976). Since the observed temperatures of these Hα blobs are higher as reported by many authors (although a better temperature diagnostics is still required, using multoline observations), we expect certain heating processes to be present. So that our fifth question is: Which heating mechanisms are present in cool flare loops, namely at $T < 2 \times 10^4$ K? According to Heinkel and Vial (1992) and Svestka (1994), we can summarize possible mechanisms as follows: thermal conduction (both along and across the magnetic field lines with the respective conductivities $\kappa_l$ and $\kappa_t$ (see Chiuderi and Chiuderi-Drago, 1991), ambipolar diffusion ($AD$) according to Fontenla et al. (1990), dissipative terms ($E_H$) and an enthalpy flux divergence term ($E_E$). The energy-balance equation can be written as

$$\frac{d}{dh} \left[ (\kappa_l T^{5/2} + \kappa_t (B) T^{-5/2}) \frac{dT}{dh} \right] = L_r + E_{AD} + E_H + E_E,$$

where $L_r$ are the radiative losses, $B$ is the magnetic induction, and $h$ measures the path along the loop. Note that a possibility of cool-loops heating by strong soft X-ray emission from overlying hot loops was recently suggested by Heinkel et al. (1994b).

6. CONCLUSIONS

The questions formulated in this paper, and perhaps some others, can be answered only if new theoretical and observational studies are conducted in parallel, as sketched in our Fig. 7. On the left we draw the attention to the necessity of radiation-hydrodynamical simulations of the temporal behaviour of cool plasma blobs moving inside the magnetic loop. The cool Hα blob is surrounded either by the plasma with similar temperatures but very rarified, or by hotter plasma which should be visible in EUV or even in X-rays. Prototype computations of this kind have been presented during the first SOHO workshop by Karlický and Simnett (1992) and are currently continued at Ondřejov observatory. From the observational side (right-hand part of Fig. 7), we need new space and ground-based observations with good spatial and temporal resolution, both in EUV (SOHO SUMER/CDS) and optical (e.g. THEMIS, see Schmieder and Mein in this volume).

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