PHYSICS OF CORONAL LOOPS

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ABSTRACT. Coronal loops are the basic elements of the solar corona and are responsible for the totality of the coronal X-ray emission. Loop physics is therefore important to understand the structure, heating, dynamics and evolution of the corona. A well-established and useful approach to study loop physics has been the detailed hydrodynamic modeling of the confined plasma, coupled to the synthesis of observable quantities to be compared to X-ray and EUV data, such as those from Yohkoh, NIXT and SOHO. In the light of this approach, some recent aspects, concerning microflares, cool loops, redshifts in UV lines, loop filamentation, and the flare decay phase, are discussed.

1. Introduction: Loop Physics

The solar corona is entirely structured by the solar magnetic field, mostly into loop-like closed flux tubes. Coronal loops are therefore the building blocks of the solar corona, and their emission dominates the X-ray coronal luminosity. Our knowledge of coronal loops is now well-established after more than 30 years of more and more detailed X-ray observations (e.g. Vaiana et al. 1973), and it is continuously enriched by new data coming from the most recent missions such as Yohkoh and SOHO.

In the context of the general coronal problems which concern the coronal structuring, heating, dynamics and evolution, we can distinguish several specific problems linked to specific observational evidence. This review will focus on some of these problems, currently investigated, in the perspective of a detailed physical interpretation of observational data, in particular taken in the X-ray and UV bands.

Before entering into some details, in order to put the problems into the right context, the main observational and physical loop characteristics will be briefly outlined (see Peres & Vaiana 1990 for an extensive review and references therein). Coronal loops are typically observed on a wide range of spatial sizes, from $10^7 - 10^8$ cm of the bright points, to $\sim 10^9$ cm in the core of active regions, to $\geq 10^{10}$ cm of Large Scale Structures (LSS). The temperature of the plasma inside loops typically ranges from $\sim 10^5$ K (or maybe less) in relatively cold UV loops to $\geq 10^6$ K in steady X-ray loops. The temperature reaches $\sim 10^7$ K and more in flaring loops as observed in soft and hard X-rays. In coronal loops significant plasma motions are extensively detected, at typical speeds of a few km/s (and more) in Doppler-shifted UV lines (e.g. Brekke 1993 and references therein) up to several hundreds km/s in He-like X-ray lines during flares (e.g. Antonucci et al. 1987). The life-time of loops ranges from few hours for bright points to days for core active region loops and weeks for LSS. On such time scales most of the structures are recognized to be very stable and their morphology changes very little. Transient phenomena occur on much smaller time scales: brightenings and flares typically last from few minutes in small loops to hours, up to ~ 1 day, in long enduring events (LEE). However, even very energetic flares, reaching a luminosity equivalent to the whole remaining "quiet" corona, are observed to occur in loop structures which maintain unaltered their shape and dimensions during most of the event (compact flares).

Given their morphological stability, most coronal loops can be considered as self-standing atmospheres, independent of, and isolated from, the others, and the plasma confined therein can be described as a fluid which moves and transports energy exclusively along the magnetic field lines. In these conditions one can assume a one-dimensional purely hydrodynamic description of the confined plasma, moving along the field line coordinate (e.g. Rosner et al. 1978, hereafter RTV).

In the typical coronal regime, plasma thermal conduction plays a dominant role in structuring coronal plasma. The modeling of loop plasma structure and evolution should also take into account the effects of solar gravity and of the radiative losses from an optically thin plasma. Since the loop life-time is typically longer than the plasma conductive and radiative cooling times, a prolonged heating deposition is necessary in corona. In steady state conditions, the loop plasma is generally well described by scaling laws which link the maximum loop temperature T_{max} and heating intensity H to the pressure p at the loop base and to the loop length L (RTV, Serio et al. 1981):

$$T_{max} \approx 1.4 \times 10^3 (pL)^{1/3} \;\; K, \qquad H \approx 10^5 p^{7/6} L^{-5/6} \;\; \mathrm{erg\ cm^{-3}\ s^{-1}} \tag{1}$$

An approach which has provided us with important results in the interpretation of coronal observations and in constraining the plasma physical conditions and mechanisms, is the detailed hydrodynamic modeling of the confined loop plasma, coupled to the synthesis of observable quantities, such as the plasma luminosity in specific spectral bands, to be compared directly to observational data. The latter step is fundamental: the interpretation of coronal observations is non-trivial because what an X-ray telescope detects derives from the combination of the plasma emission and the telescope spectral response, and it is anyhow the result of an integration on finite spatial pixels and temporal exposures.

In the following some coronal loop problems are overviewed especially in the light of the approach outlined above. They represent specific aspects of more general problems of the coronal physics: the structure, stability, dynamics and energetics of the loops and of the plasma confined therein. Indeed, all of them have many interconnections and common aspects.

2. The problems

2.1. Microflares

As mentioned above, coronal loops are often stable and stationary on time scales longer than the characteristic plasma cooling times. Heating must then be deposited continuously to maintain them steady. It has been long debated whether this heating is constant or slowly-varying in time, or it is released by rapid and relatively intense episodes, the

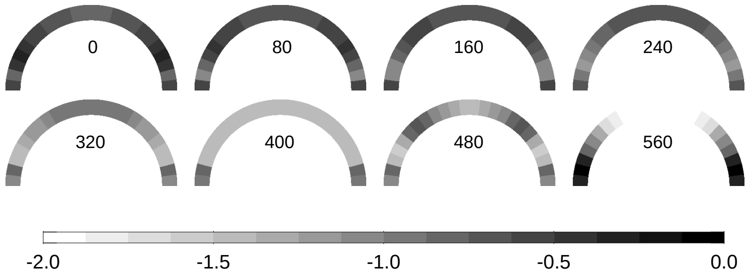

Fig. 1. Brightness along the loop in the SOHO EIT 284Å filter at the labelled times (sec) reckoned since the beginning of the simulation (steady-state loop), synthesized from a hydrodynamic model of a loop with half-length 2×10^9 cm, heated by a sequence of random microflares with an average repetition time of 480 sec. The luminosity grey scale is logarithmic (black is bright) and normalized to the maximum. A pixel size 2.5" has been assumed.

so-called *microflares* (or nanoflares). There are theoretical models which predict their presence (e.g. Parker 1988), but there is also extensive observational evidence, especially in X-rays (e.g. Lin et al. 1984, Shimizu & Tsuneta 1997).

The largest problem concerning microflares has been so far their difficult identification and diagnostics. They are in fact expected to be so rapid, weak and localized, that current instruments are not able to resolve them and to make possible their detailed analysis. Therefore a series of questions are still open, i.e. the origin of microflares, where they are deposited, their intensity spectrum, duration and frequency. SOHO observations are expected to give an important contribution to answer them.

Detailed model studies of microflares have been presented by Kopp and Poletto (1993) and by Peres et al. (1993). The former study is based on a simplified hydrodynamic model which describes average loop quantities, tailored to the observational limitations, and provides a global diagnostics of microflares, predicting that, if any, they are more detectable in small loops. Peres et al. (1993) consider a detailed hydrodynamic model of loops maintained steady either by periodic or by randomic heating pulses. The synthesis of the loop plasma emission from the model results allows the authors to develop diagnostics appropriate to constrain the time scales of the heating episodes.

Such studies are currently going on: Fig.1 shows an example of the predictions of microflare detectability with SOHO EIT, obtained from hydrodynamic loop modeling. From the model, significant variability is expected on time scales of the order of typical EIT observation times in core active region loops only if the time interval between subsequent heating episodes is at least of several minutes (480 sec in the specific case).

2.2. Cool Loops

Cool loops at temperatures $T \sim 10^5$ K have been observed for a long time in the EUV band (e.g. Foukal 1976). The Foukal's loops are long ($L \geq 10^{10}$ cm) and rooted in sunspots. Their quite uniform temperature and luminosity distributions could not be fitted either with hydrostatic loop models (Pallavicini et al. 1981), or with more general

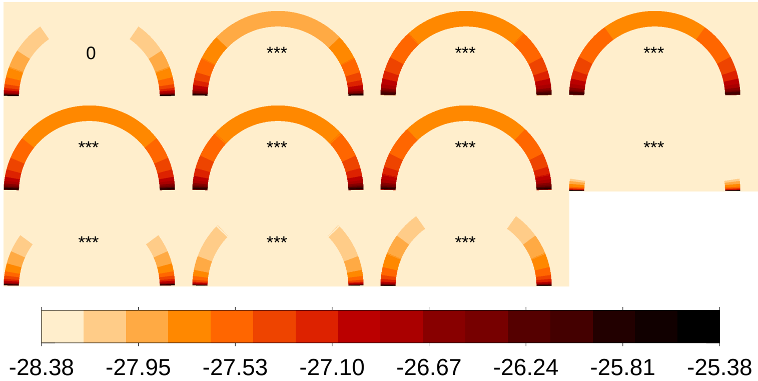

Fig. 2. Brightness along the loop in a relative logarithmic scale in the O V (629.7 Å) line, for a hydrodynamic model of a long loop (length 2 $\times 10^{10} cm$) heated by a sequence of random microflares with an average repetition time 3600 (see Fig.1). The times of each loop picture (from left to right and from top to bottom), since the beginning of the simulation, are 0 s, 2520 s, 11520 s, 11880 s 32040 s, 32400 s, 32760 s, 33480 s, 33840 s, and 34200 s (from Peres 1997).

siphon flow models (Peres & Orlando 1996). In the latter study it was concluded that such loops cannot be steady, but must be dynamic and unstable, in spite of the evidence of stability of the observed structures on relatively long time scales. Recently, detailed observations have been performed by SOHO, and some loops have been indeed found to be very dynamic with regular flows at several tens of km/s (Brekke et al. 1997).

One possible explanation of the apparent contradiction and challenge represented by these loops has been suggested by Peres (1997), in terms of loops dynamically heated by microflares and alternating between coronal and chromospheric conditions. A large loop ($L \sim 10^{10}$ cm), such as that observed by Brekke et al. (1997), may be subject to a sequence of heating episodes, exactly as those described in section 2.1, with a very long average repetition time, of the order of hours. Such loop is a regular coronal loop during the heating, visible in X-ray at a temperature of the order of 1 MK. After each heating episode the plasma begins to cool down. Since, according to Serio et al. (1991), the cooling time is of the order of one hour, the plasma has enough time to cool down to temperatures detectable in the UV band. Hydrodynamic simulations (Peres 1997) show that such a loop would be well-visible, and with a relatively uniform brightness, in the O V 629 Å for a relatively long time, since the cooling is very slow, as shown in Fig.2. Further extensive observations by SOHO will provide further constraints for such kind of hypotheses.

2.3. UV Redshifts

Another challenging problem for the current coronal models is the extensive evidence of redshifts in UV line observations (e.g. Brekke 1993). Observations of the solar disk in many UV lines show redshifts significantly dominant over blueshifts, of the order of several km/s, a largely subsonic speed in the transition region. Such evidence has been recently confirmed and enriched with a wealth of details by SOHO/SUMER observations (Betta et al. 1997).

Several hypotheses have been explored to explain the presence of these dominant redshifts (see Brekke 1993 for a review of possible mechanisms), e.g. backflows from spicules, loop siphon flows (e.g. Peres et al. 1992), loop asymmetric heating, local heating with opacity effects (Spadaro et al. 1996), MHD waves generated by nanoflares, downdrafts due to local thermally unstable condensations (Reale et al. 1996, 1997b). Only the latter two models are able to reproduce dominant redshifts in UV lines. Although they appear different from each other, one is based on the heat deposition in a loop, the other is a more local and mechanic effect, they may not be alternative because both of them are ultimately linked to local deformations of the loop magnetic field.

I will briefly discuss the latter mechanism: a condensation formed in a loop is more luminous than the surrounding region (because the emission is proportional to the square of the density) and is subject to fall down toward the chromosphere by gravity. Its emission will therefore be redshifted and more intense than that of the surrounding plasma. This scenario is complicated by the interaction of two competing effects: radiative cooling would lead to a thermal instability of the condensation, thermal conduction tends to smooth out any perturbation very effectively (Reale et al. 1994). A realistic description of the condensation evolution requires detailed 2-D numerical hydrodynamic modeling (Reale et al. 1996): the exploration of the parameter space shows that only relatively intense and large perturbations formed high in the transition region can produce significant redshifts in the UV lines (Reale et al. 1997b).

The results obtained are in agreement with the observed correlation of the redshift to the line intensity and decrease of the redshift with increasing temperature of line formation (the redshifts disappear at ~ 1 MK). However further constraints and checks on this model are in order from the analysis of data such as those from SOHO/SUMER.

2.4. High resolution and loop filamentation

The problem of the loop fine structure and filamentation is connected to the general problem of coronal structure and heating. Several models predict the coronal heating to be released on very small spatial scales (e.g. Parker 1988). This has produced a vigorous effort toward the development of solar X-ray telescopes with high angular resolution. A prototype of such telescopes has been the Normal Incidence X-ray Telescope (NIXT, Golub et al. 1990), characterized by an angular resolution of ~ 1 arcsec in a spectral band 1.4 Å wide at ~ 64 Å. NIXT has acquired high quality X-ray images of the solar disk in several rocket flights.

The single thin spectral band of NIXT makes it difficult to apply spectral methods for the determination of physical parameters such as the temperature of the emitting plasma. Other multi-band telescopes, such as the Yohkoh/SXT, take advantage of the ratio of the brightness as detected in two different filters to determine the temperature, but this is not possible with NIXT.

A method has been developed to determine the plasma pressure in loops observed with NIXT (Peres et al. 1994). The method is based on the prediction from loop models

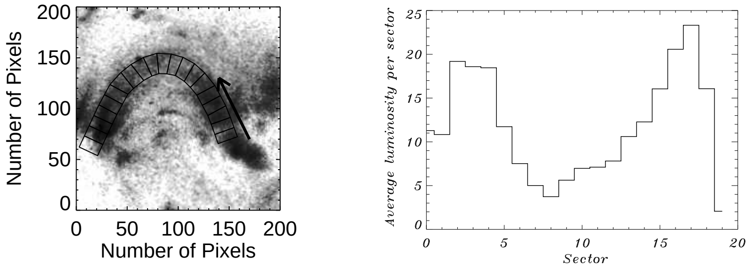

Fig. 3. Large loop structure observed by NIXT on April 12, 1993: it is marked with a strip divided into 20 rectangular sectors. The brightness profile on the right panel is taken along the strip and is integrated in each sector. The arrow indicates the direction of the X axis in the plot. This brightness profile yields a pressure 0.08 dyne cm^{-2} and a filling factor $\sim 20\%$ when matched to hydrostatic loop models (Di Matteo et al. 1998).

(Serio et al. 1981) that the brightness distribution detected by NIXT along the loop depends on the loop plasma pressure: high pressure loops appear very bright at the footpoints and faint at apex, whereas at lower pressure the brightness is more uniform.

This method has been recently applied for the first time to a NIXT observation, simultaneous to a Yohkoh/SXT observation on April 12, 1993 (Di Matteo et al. 1998). The pressure of several loops has been evaluated as the pressure of the model loops whose synthesized brightness distributions best approaches the observed ones. In addition, the ratio of the observed total loop luminosity to that predicted by the model is a quantitative measure of the fraction of the available loop volume effectively occupied by the plasma emitting in the NIXT band. As a result, for the smallest loops ($L \sim 10^9$ cm) this filling factor has been found to be very small, $10^{-3} - 10^{-2}$, whereas it is of the order of unity in the large structure ($\sim 10^{10}$ cm) shown in Fig.3. The very low filling factors of the compact loops strongly suggest a very fine loop filamentation, and represent an interesting preview for the future high resolution missions, such as HIRES.

2.5. Flare decay studies

The study of the decay phase of X-ray flares is well-established and has provided interesting diagnostics, for instance, on the presence of heating during the decay (Sylwester et al. 1993). Along this line a method has been recently developed to evaluate reliably the length of compact flaring loops from the analysis of the flare decay phase (Reale et al. 1997a). This method, tested on spatially resolved solar flares, is useful to be applied to stellar X-ray flares, for which any angular resolution is missing. In this sense the Sun has been used as a laboratory to study the other stars.

The plasma confined in a compact flaring loop (i.e. whose magnetic structure maintains substantially unaltered during the flare) has been shown to cool down spontaneously with a characteristic time proportional to the length of the loop (Serio et al. 1991). However this flare decay time cannot be directly used to estimate the loop length, because significant heating can be released during the decay, thus making the decay

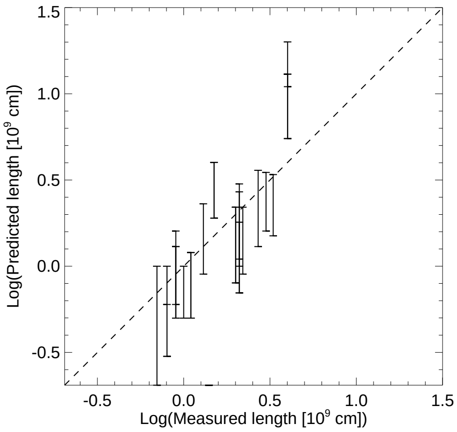

Fig. 4. Ranges of the dimensions (projected on the disk) obtained from the analysis of the decay of the SXT flare light curves and n-T diagrams vs measured linear dimensions of 19 flares observed with Yohkoh/SXT (adapted from Reale et al. 1997a).

longer and bringing to overestimate the loop length. However, such a heating can be traced by analyzing the temperature evolution during the decay, such as in density-temperature (n-T) diagrams (Sylwester et al. 1993). With the aid of extensive numerical hydrodynamic flare modeling, Reale et al. (1997) have derived an empirical formula of the loop length as a function of the light curve decay time and the slope of the decay curve in the n-T diagram. The formula has been tested on a set of flares observed with Yohkoh/SXT, which provides us with both the light curve and a temperature diagnostics, as well as with the necessary angular resolution to measure the loop length directly on the images. Fig.4 shows the good agreement of results of the method with the loop dimensions measured on the SXT images.

The results show the validity and self-consistency of this approach. In addition to the obvious application to infer the size of stellar flaring loops (Reale & Micela 1998), this method can find interesting applications to solar flares observed by instruments with no angular resolution, such as the large database of the GOES series.

3. Conclusions

After two decades since the development of the first loop models (RTV), the physics of coronal loops is well-established both as for the approach and as for the results obtained, and it offers a precious and important tool to interpret solar, and also stellar, observations. As for its immediate future, much attention, both in theory and observations, is being devoted to study small scales in corona, both temporal (e.g. microflares) and spatial (e.g. loop filamentation). Furthermore loop physics will be very useful to interpret the high quality data from the new generation non-solar X-ray missions, such as AXAF and XMM.

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