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Structure and dynamics of magnetic loops in the solar corona

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Abstract. This paper is a short review of the principal results obtained by the investigations concerning the physical structure and the dynamics of coronal magnetic loops, and put into particular evidence the interesting contribution given to these studies by the most recent space missions. It also indicates the principal constraints on the theoretical/numerical models of magnetic loops that arise from these new findings.

Key words. Solar corona – Transition region – Coronal heating

1. Introduction

Determining the physical conditions in the outer solar atmosphere is crucial for understanding the physical mechanisms that produce coronal heating, accelerate the solar wind and trigger transient energetic phenomena such as solar flares, which can significantly affect the heliosphere and the terrestrial magnetosphere. In recent decades our knowledge of these conditions has improved dramatically as a result of X–ray, EUV and UV instruments flown on rockets and many orbiting spacecraft (e.g., Skylab, SMM, Yohkoh, SOHO, TRACE).

These observations have shown, in particular, that magnetic loops are the dominant structures in the outer solar atmosphere (e.g., Bray et al. 1991) and have been extensively used to study the general properties of such coronal structures. They typically appear as arch–shaped structures connecting regions with more intense magnetic fields and opposite polarities, that are hot on the top ($\sim 10^6$ K) and have a thin transition to the chromosphere ($\sim 10^4$ K) near their foopoints (e.g., Mariska 1992).

High resolution EUV spectrometers and imagers, moreover, have extended our knowledge of the plasma dynamics and temporal behaviour of magnetic loops, allowing to study the distribution along the loop, the Doppler shifts and the time variability of the plasma emission in several lines forming in the temperature range characterizing the solar transition region and low corona.

Given the role of magnetic loops in the overall structure of the solar transition region and corona, it is important to review the principal results obtained by the investigations concerning these coronal features, particularly those carried out by the most recent space missions, and put into evidence the constraints on the theoreti-

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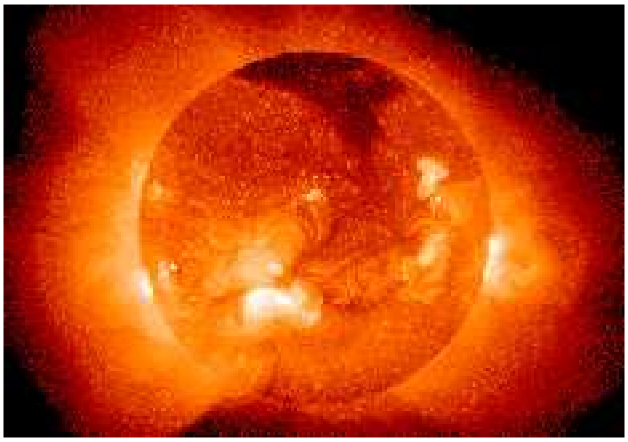

Fig. 1. Soft X-ray image of the whole Sun acquired by the Soft X-ray Telescope (SXT) on board the Yohkoh satellite. The SXT instrument was designed to study the hottest part of the Sun's atmosphere.

cal/numerical models of loops that arise from these new findings.

2. The 'classical' picture

Soft X-ray images obtained by the S-054 instrument onboard the Skylab spacecraft (cf. Vaiana & Tucker 1974), and later on by the SXT instrument onboard Yohkoh (Tsuneta et al. 1991), have shown the presence of bright, elongated and arch-shaped structures confining the coronal plasma at a temperature of $\sim 2 \times 10^6$ K (see Fig. 1). They often appear stable for more than a day (e.g., Webb & Zirin 1981), that is considerably longer than any characteristic dynamic or thermal time. Therefore, these observations have led to consider coronal loops as stationary structures that are hot on the top ($\sim 10^6$ K) and have a thin transition to the chromosphere ($\sim 10^4$ K) near their footpoints.

According to this picture, hydrostatic models of magnetic loops have been developed in the past (e.g., Landini & Monsignori Fossi 1975; Rosner et al. 1978; Vesecky et al. 1979; Serio et al. 1981), solving the standard set of equations for mass, momentum and energy in a one-dimensional plasma, i.e., along the magnetic field lines defining the loop. This class of models resulted in the well-known scaling laws, which connect the length of the loop with the maximum temperature, the base plasma pressure and the average (steady) volumetric non-radiative energy deposition, assuming optically thin radiative losses for the loop plasma (see, e.g., Rosner et al. 1978; Vesecky et al. 1979). The subsequent work of Pallavicini et al. (1981) confirmed the satisfactory agreement of scaling laws with EUV and X-ray observational data obtained by the Skylab instruments.

The experience gained with the solar corona has convinced the stellar community that magnetic structuring into loops and the related scaling laws are fundamental characteristics also of stellar coronae. Along this line of thought, considerable effort has been devoted to modelling the X-ray emission of stellar coronae as the effect of a large number of loops (e.g., Landini et al. 1985; Schmitt et al. 1985).

The observations of Doppler shifts in EUV transition region lines, indicative of plasma velocity of the order of several km s^{-1} (e.g., Kopp et al. 1985), have consequently stimulated the development of a class of models characterized by steady

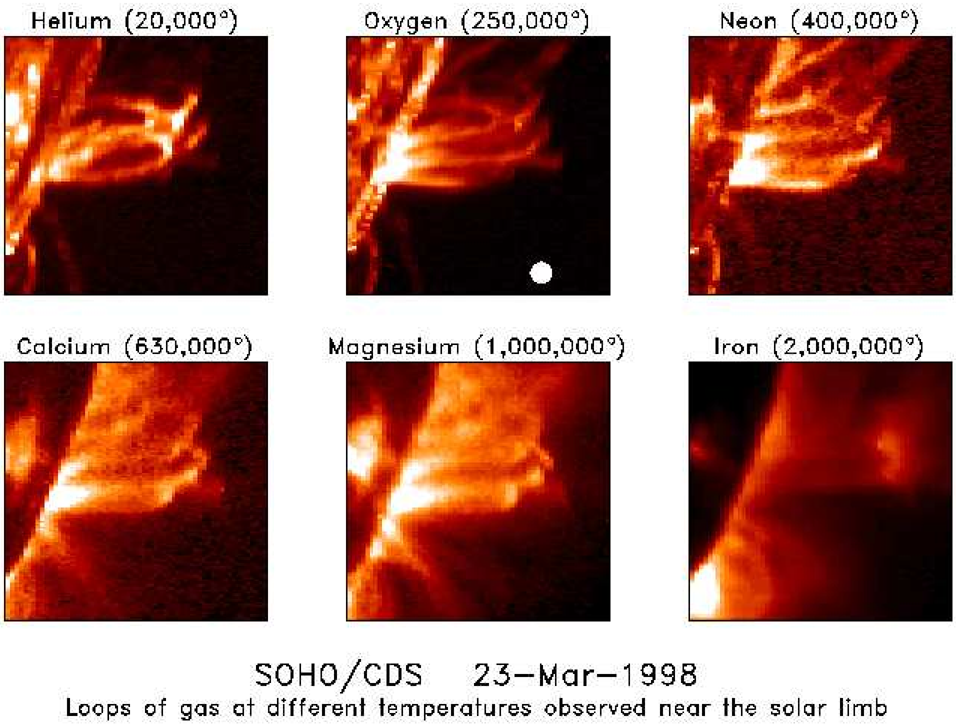

Fig. 2. CDS images of magnetic loops which extend high into the Sun's atmosphere. The elements and their characteristic temperatures are indicated on the individual images. The white disc plotted on the oxygen image shows the Earth to the same scale.

mass flows along the field lines, such as siphon flow loop models, in which a pressure difference between the two footpoints drives a steady flow along the field lines (Cargill & Priest 1980; Noci 1981; Mariska & Boris 1983; Antiochos 1984; Mariska 1988; Orlando et al. 1995). These models can describe the outer solar atmosphere in steady conditions with wider generality than static models, and in some cases they better reproduce the EUV emission observed in transition region lines (Peres et al. 1992).

3. The last decade: more details on magnetic loops

Recent observations of the solar transition region and corona with the high spatial and temporal resolution EUV spectrometers and imagers on board the space missions SOHO (Domingo et al. 1995) and TRACE (Handy et al. 1999) have confirmed the role of magnetic loops as the dominant structures in the outer solar atmosphere. Moreover, the improved spectral resolution and wavelength coverage of the SOHO spectrometer have provided significantly more complete information on the physical conditions of the plasma inside coronal loops than before (see Fig. 2).

These observations have also shown that magnetic loops are often intrinsically dynamic, even in apparently nonflaring conditions. Specifically, their physical structure is characterized by temporal variability and significant plasma flows along the magnetic field lines. Kjeldseth-Moe & Brekke (1998), for instance, reported clear evidence of varibility on timescales of order 1 hr in the CDS (Harrison et al. 1995) observations of loops above active regions, particularly in emission lines forming at temperatures in the 0.1–0.5 MK range (e.g., the OV λ629 line). At temperatures between 0.5 and 1.5 MK the variability appears less striking but is still pronounced, whereas at temperatures above 1.5 MK conditions are seemingly much more stable. These intensity variations are accompanied by high Doppler shifts with corresponding speeds typically around 50 - 100 km s^{-1}, although values as high as 300 km s^{-1} have been recorded.

While monitoring the evolution of a solar active region at high time cadence (30 s) with TRACE's λ171 channel, Reale et al. (2000a) detected the transient, highly dynamic brightening of a coronal loop lasting about 2 hr. Approximately 10 min after the initial, significant brightening of the loop footpoints, a moving brightness front rose from one footpoint, followed after $\sim$7 min by a similar front rising from the other footpoint. The brightness distribution along the loop appeared considerably asymmetric with respect to the loop apex at all times, whereas the loop geometry and shape remained practically unchanged during the event. More recently, in a study of evolving structures in the center of an active region observed by TRACE, Schrijver (2001) found evidence for frequent catastrophic cooling and evacuation of nonflaring coronal loops with time scales of an hour or less, characterized by high speed downflows (up to 100 km s^{-1}) at temperatures traditionally associated with the transition region or even the chromosphere.

In addition to these specific observations, other widely-observed features of coronal loops strongly imply dynamic characteristics, with significant mass flows, for these magnetic structures. Transition region redshifts apparently peaking at temperatures $\sim$0.1 MK have been observed by all UV/EUV telescopes since Skylab (e.g., Athay & Dere 1989; Achour et al. 1995; Brekke et al. 1997; Chae et al. 1998; Peter 1999), and have even been seen on nearby late-type stars (e.g., Wood et al. 1996). Besides, Spadaro et al. (2000) have detected significant plasma flows at the footpoints of both large and compact loops in an active region observed on the solar disc by the SUMER/SOHO spectrometer (Wilhelm et al. 1995). They have the typical characteristics of siphon flows along the magnetic field lines, i.e. from one footpoint to the other of the loop. The observations also showed that the *downflowing* legs are usually brighter than the *upflowing* ones, particularly in transition region lines. This implies that siphon flows could be the concurrent cause of the systematic redshifts observed in the transition region of both the Sun and late-type stars.

Furthermore, recent observations with TRACE have revealed a class of persistent, "overdense" active region loops at temperatures of order 1 MK (Aschwanden et al. 2000a, 2001; Lenz et al. 1999; Winebarger et al. 2002), in which the density substantially exceeds the values predicted by the quasi-static scaling laws (Rosner et al. 1978; Vesecky et al. 1979). They are also apparently isothermal along much of their lengths, as suggested by the TRACE 195/171 filter ratios.

The above physical properties derived from recent SOHO and TRACE observations cannot be satisfactorily reproduced by both hydrostatic and steady-state flow numerical models of loops (e.g., Rosner et al. 1978; Serio et al. 1981; Noci 1981; Antiochos 1984; Orlando et al. 1995), as already pointed out by several authors (e.g., Peres 1997; Aschwanden et al. 2000b, 2001; Reale et al. 2000b). Hence these loops cannot be considered in equilibrium and time-dependent hydrodynamic modelling is required to match the observations.

4. Hydrodynamic loop modelling and constraints on coronal heating

The SOHO and TRACE results are so giving a new stimulus to the detailed physical modelling of coronal magnetic structures. In particular, the wealth of observational evidence for flows and intensity variations in nonflaring coronal loops reported in the previous section leads to the conclusion that coronal heating is intrinsically unsteady. Moreover, its deposition along the examined structures appears nonuniform.

Hence several authors are using hydrodynamic modelling to simulate in detail the temporal evolution of the plasma distributed along specific loops observed by the space experiments, focusing on the amount, spatial distribution and time profile of the heating deposited in the loop to make the modelled evolution close to that observed (e.g., Reale et al. 2000b; Warren et al. 2002; Spadaro et al. 2003). It is worth noting that this investigation on the heating processes which ignite the loops is very important to put constraints on the physical mechanisms that produce coronal heating, a fundamental problem for solar and stellar physics.

Some authors (Warren et al. 2002; Spadaro et al. 2003), for instance, have concluded that transient heating spatially localized near the chromospheric footpoints of the loop and with timescales comparable to the coronal radiative cooling time ($\sim$ 1000 s) is capable to produce higher densities and flatter temperature profiles in the corona than those expected from the scaling laws, in agreement with the TRACE observations quoted above. Spadaro et al. (2003), moreover, have shown that transient heating also causes persistent downflows at transition region temperatures, producing a net redshift at temperatures around 0.1 MK, thus solving one of the major outstanding puzzles in solar physics. Furthermore, strong transient heating yields catastrophic cooling to temperatures below the equilibrium value, producing cool, dynamic, Lyα-emitting material in the corona as observed (e.g., Schrijver 2001).

So these results strongly support the hypotheses that coronal heating is transient in nature and localized near the chromosphere. However, although these models provide a compelling explanation of certain facets of loop behaviour, other aspects of the observations remain a challenge to understand. For example, many Yohkoh and TRACE loops are observed to persist for times that are much longer than the expected cooling times (Winebarger et al. 2002). On the other hand, in order to match the observed evolution and distribution of the brightness along the loop observed by Reale et al. (2000a) with TRACE, Reale et al. (2000b) have found that the heating is nonsymmetrical in the loop and deposited between the apex and one footpoint, but closer to the apex.

Therefore, the picture emerging from the observations is rather complex and a coordinated diagnostic approach involving different instruments is required in order to get exhaustive and reliable data for modelling and theoretical interpretation. It has been pointed out, for instance, the need for simultaneous spectroscopic and imaging observations. The former can give detailed information on physical parameters such as temperature, density, velocity and chemical composition, but only in a limited instantaneous field of view, whereas the latter are suitable for determining the overall morphology of the magnetic structures and following their temporal evolution at high cadence. Moreover, it is important to observe 'isolated' loops, to avoid contamination by the background emission and by other coronal structures along the selected line of sight. It may also be possible that these loops are collections of hundreds or even thousands of unresolved strands, as suggested by several authors.

New detailed observations carried on with the SOHO and TRACE instruments, as well as the contribution of the future solar space missions (Solar-B, Solar Dynamics Observatory, Solar Orbiter), should help to address these issues concerning coronal loop physics.

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