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Flares and Coronal Activity

Fabio Reale[1]

Dipartimento di Scienze Fisiche & Astronomiche, Universitá di Palermo, e-mail: reale@astropa.unipa.it

Abstract. Recent works of Italian groups on flares and coronal activity are reviewed in the framework of the current status and with emphasis on the analysis of X-ray and UV observations and their interpretation with models. The role of coronal missions as Yohkoh and TRACE for investigation of flares, and of Yohkoh, SoHO and TRACE for coronal active loops is discussed.

Key words. Sun: X-rays – Sun: UV – Hydrodynamics

1. Introduction

The increasing quality of X-ray and UV data obtained with recent solar missions, such as Yohkoh (Ogawara et al. 1991), SoHO (Domingo et al. 1995) and TRACE (Handy et al. 1999) have brought a quantum leap in the investigation of the structure, dynamics and heating of the solar corona. Here, recent developments in the study of coronal flares and of bright coronal loops as the main contributors to coronal activity are discussed in the perspective of the observation results and of their interpretation with detailed models of coronal plasma.

Coronal flares and coronal loops will be discussed as separate topics. Each topic will be introduced with a general overview and then related Italian studies will be mentioned and briefly described.

Send offprint requests to: F. Reale
Correspondence to: F. Reale, c/o INAF/Osservatorio Astronomico di Palermo, Piazza Parlamento 1, 90134 Palermo

2. Flares

2.1. Overview

We start this overview of coronal flares from the conventional classification in two main categories: compact and two-ribbon flares (Pallavicini et al. 1977). Compact flares mainly occur inside single loops whose shape and volume do not change significantly during the flare. Two-ribbon flares, instead, occur in loop arcades, and higher and higher loops are involved as the flare progresses. The arcade footpoints, best seen in Hα band, appear as two ribbons which get more and more distant with time.

Progresses in the analysis and theory of two-ribbon flares are amply discussed in a recent review by Priest & Forbes (2002), which shows how many features have been understood, but that the scenario is so complex that it still requires much investigation. As for single flaring loops, there are some basic questions directly linked to the interpretation of the observational data and that have been addressed by flare studies:

- What is the connection between the evolution of the plasma confined in the loops and the observed X-ray evolution?
- What it the location, timing and duration of the heating that triggers and drives the flares?
- Can we discriminate between different heating mechanisms, e.g. by currents vs high-energy electron beams?

In order to answer such questions, time-dependent hydrodynamic loop models have been developed and largely applied to describe in detail the evolution of flaring plasma. The models rely on the assumption that plasma confined inside coronal loops behaves like a fluid which moves and transports energy exclusively along the magnetic field line, i.e. along the loop. This holds true in compact flares. Pioneeristic works based on this approach were performed in the 80's on the Solar Maximum Mission (SMM) flare data (Peres et al. 1987).

The Yohkoh mission has brought a quantum leap of flare data, and in particular the Solar X-ray Telescope (SXT, Tsuneta et al. 1991) allowed to obtain simultaneously high space (2.5") and time (few seconds) resolution and to monitor the evolution of the flare even in the fast initial rise phase. Yohkoh data represented a new challenge for hydrodynamic modeling of flaring loops. 1-D hydrodynamic loop models have been shown to be able to well reproduce flare SXT light curves (Reale et al. 1996), but also to detect deviations from a purely hydrodynamic evolution. In particular, a brightness excess often detected in the later phases at the apex of flaring loops must be explained with a different regime: a region where plasma is governed by a turbulent regime, which is detached from the rest of the loop (Jakimiek et al. 1998). This turbulence may be strictly connected to the presence of non-thermal effects well detected in hard X-rays (Fletcher & Martens 1998).

More recently, the TRACE mission has also been able to provide new data on coronal flares, with unprecedented spatial resolution (0.5"), although in a different spectral band. TRACE is a normal incidence XUV telescope, and its filter bands are much narrower than the Yohkoh SXT broad filter bands and more sensitive to non-flaring plasma around 10^6 K. This makes the interpretation of flare data collected with TRACE very complex and unimmediate, inhibiting a systematic application of single loop models. Some attempts of analysis of TRACE flare data have been performed but without entering in a much detailed interpretation and matching with models (Antiochos et al. 2000, Warren et al. 2001, Aschwanden et al. 2001).

Steps forward in investigating and modeling solar coronal flares will be probably represented by the development and application of specific flare models with a more complete and consistent magnetohydrodynamic description including the interaction with the ambient magnetic field. Initial attempts have already been performed (e.g. Yokoyama et al. 2001), but further refinements are necessary. On the other hand, further insight in the mechanisms originating flares is being obtained thanks to the space and time resolved flare data collected by the RHESSI (Lin et al. 2003) mission in the hard X-ray band.

2.2. *Italian works*

Recent Italian studies on coronal flares have mainly concerned the hydrodynamic modeling of specific events with high resolution in the transition region (Betta et al. 2001) and the analysis of the Sun as a flaring X-ray star (Reale et al. 2001). The former work revisits the analysis of a flare well-observed by SMM on 12 november 1980, already modeled in detail in a previous work (Peres et al. 1987). A hydrodynamic loop model had been shown to be able to fit well the light curves in several X-ray lines, providing constraints on the loca-

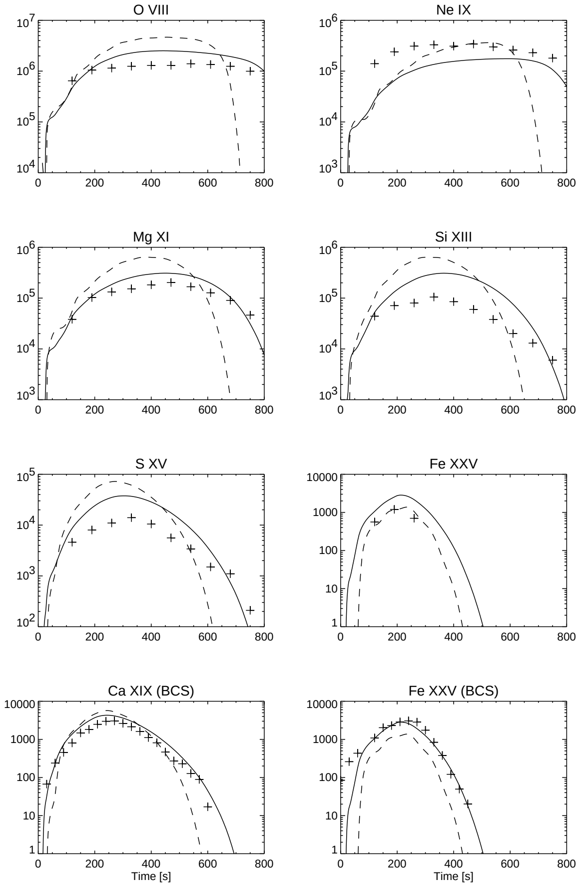

Fig. 1. Light curves in several X-ray lines of a flare well-observed with Solar Maximum Mission (*data points*), and their fitting with loop models including a heating at the loop apex (*solid lines*) and a heating at the loop footpoints (*dashed lines*).

tion, timing and duration of the heating release in the flaring loop. In the revisitation, the adaptive grid allows to study the UV lines emitted from the flaring loop transition region. The work shows that the single loop model well-describing the X-ray lines (Fig. 1) is insufficient to explain the UV flare emission detected by the Ultra-Violet Spectrometer and Polarimeter (UVSP) on board SMM. A candidate to explain this discrepancy is the presence of significant deviations from equilibrium of ionization in the transition region, especially in the initial phases of the flare (Orlando et al. 2003).

The aim of the second work is to describe the Sun during an X-ray flare as a spatially unresolved star and to compare it to the other stars. In order to do that homogeneously, a method is used to translate the solar X-ray data – and in particular the Yohkoh data – into the same format as that of data coming from stellar X-ray observations (Peres et al. 2000). The first step has been to derive the distribution of the emission measure vs temperature ($EM(T)$) throughout the flare. This already provides an intermediate important result: the emission measure distribution of the flaring region has invariably a peak distinct from – and much hotter than – the peak of the EM(T) distribution of the whole non-flaring Sun, in any moment of the solar cycle (Fig 2). This may indicate that flaring loops represent a distinct class of loops from standard non-flaring loops, and that the heating mechanisms may be of different nature. On the other hand, there is evidence of a second hot peak of EM(T) in several active stars (Griffiths & Jordan 1998) even in the absence of any distinct flare, indicating that a continuous flaring activity, made of a time-unresolved sequence of events, may be present.

Further steps of this work involved the synthesis from the EM(T) of the parent and focal-plane spectra. Such spectra can be used as templates for comparison with stellar X-ray data.

3. Active coronal loops

3.1. Overview

Concerning non-flaring coronal loops, several questions are still open even after the most recent X-ray and UV missions. In particular, there is ample debate on the detailed thermal structure of loops, both along and across them (Lenz et al. 1999, Reale & Peres 2000, Aschwanden et al. 2000), on their fine spatial structure, regarding their thinnest elementary component (Gomez et al. 1993, Testa et al. 2002), and on the distribution and evolution of the heating release which makes them bright (Priest et al. 2000, Aschwanden 2001, Reale 2002, Warren et al. 2002).

Three missions have contributed most to the investigation of the loop structure and evolution. The Yohkoh mission (1991-2001, Ogawara et al. 1991) was tailored to analyze the high temperature and flaring corona during the maximum of the solar cycle. As mentioned in Section 2, its imaging instrument, the SXT, had a good spatial resolution (2.5") in a broad X-ray band, which could be segmented by means of several filters. The ratio of image counts collected in the same pixel in two different filters yields a weighted average of the plasma temperature lying along the line of sight in that pixel. The SXT was mostly sensitive to plasma hotter than 2 MK.

The SOlar Heliospheric Observatory (SoHO) mission (Domingo et al. 1995), launched in 1995 and still operating, is instead more tailored to investigate the quiet Sun, far from the highest levels of coronal activity. In addition to remarkable imaging instruments – the Extreme ultraviolet Imaging Telescope (EIT), the Large Angle and Spectrometric Coronagraph (LASCO) – many SoHO instruments – the Coronal Diagnostic Spectrometer (CDS), the Solar Ultraviolet Measurements of Emitted Radiation (SUMER), the Ultraviolet Coronagraph Spectrometer (UVCS) – are well-suited to probe the multi-thermal structure ($10^5 - 10^7$ K) of the corona and the transition region along the line of sight, by means of high resolution spectroscopy. Unfortunately the excellent spectroscopic capabilities could not always be conjugated with a spatial and temporal resolution high enough to detect loop changes and variability on small time scales.

The Transition Region And Coronal Explorer (TRACE, Handy et al. 1999), active since April 1998, achieves a very high spatial resolution (0.5" pixel side) with a reasonable time-resolution (typically between 10 and 100 s). The multi-layer optics are sensitive to radiation in a very thin spectral band ($\sim$ 10 Åwide) in the EUV band. Three EUV filters are available with passbands centered around 171 Å, 195 Å and 284 Å, which contain Fe lines with a peak sensitivity around logT=6.0, 6.1 and 6.2, respectively. The relatively low temperatures and the thin spectral passbands make the data detected by TRACE deeply different from those obtained with Yohkoh/SXT, and not easily comparable, and their interpretation non-trivial also for non-flaring loops. TRACE has been anyhow the first telescope to be able to resolve

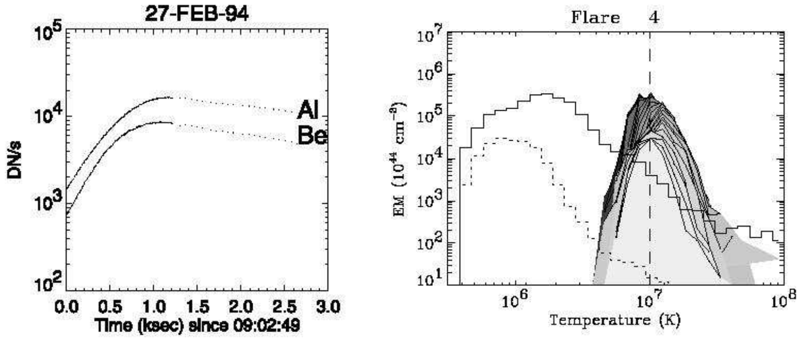

Fig. 2. Light curves in two filters passbands (*left*) and emission measure distributions sampled at various times (*right*) of a flare observed with Yohkoh/SXT (Flare 4 in Reale et al. 2001).

at some level the filamentary structure of the coronal loops.

3.2. A Recent Work on Yohkoh data

Coronal loops observed with Yohkoh/SXT have been the object of recent studies aiming at the determination of their heating function. A first work by Priest et al. (2000) developed a method to determine the spatial distribution of the heating function in loops from the shape of the temperature distribution along them, as measured with the filter-ratio method from Yohkoh/SXT data. As a result of the application of this method, a large and long-lived coronal system, well-observed on the solar limb (Fig. 3) with a maximum temperature of 2 MK, appeared to be well described with a heating uniformly distributed along it.

A later work (Aschwanden 2001) showed that the assumption of such a heating distribution led to inconsistent results. The X-ray emission in the SXT band predicted by the model loop above is by far too low (at least four orders of magnitude) to be consistent with the detected count rate. Aschwanden (2001) conducted an independent analysis which led to the conclusion that the loop system is better described as made by two loop components, with the dominant one heated at the footpoints and with a maximum temperature of 2.6 MK. This model led to a reasonable SXT count rate, but has other implications which require specific explanations. First of all, the heating function is very peaked at the footpoints and leads to a temperature maximum much below the loop apex. This configuration is well-known to be unstable

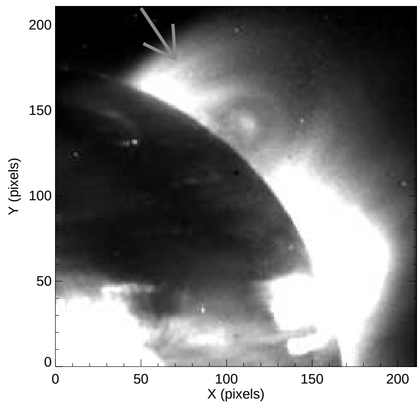

Fig. 3. Coronal loop system observed in the X-ray band with Yohkoh/SXT. The loop indicated by the arrow has been analyzed to determine its heating function in three subsequent works, leading to different results and conclusions. The problem of the heating distribution in coronal loops is still open.

(e.g. Serio et al. 1981). The loop system is instead observed to be steady and stable for almost a whole day, a very long time scale compared to the charactestic cooling times of the loop plasma. Furthermore, the coronal density implied by this loop model is above 10^{10} cm^{-3}, much higher than that of typical large scale structures. Finally, the analysis does not take into account the high diffuse emission in which the loop system is embedded and which certainly affects the modeling especially close to the loop apex, where the emission is particularly low.

Such puzzling findings stimulated a third independent analysis and modeling of the same loop system (Reale 2002). The analysis includes the subtraction of the background emission along the line of sight to the loop region, and explores loop models with three alternative distributions of heating: uniform, at the footpoints, at the apex. From the detailed fitting of the data, either with or without background subtraction, the result is that the background subtracted data are the only ones to yield a best-fit at an acceptable significance level. The best-fit model loop has a maximum temperature of 3.7 MK, and is heated *at the apex.* This model also leads to an X-ray emission reasonably compatible with the observation. The conclusion of this work is that the question of the heating distribution inside coronal loops is still open, and that better constraints from data, and, in particular, a more accurate selection of the loops to be analyzed, are required.

3.3. Studies on SoHO data

As mentioned above, the SoHO mission includes several instruments with high spectral capabilities. Italian studies on coronal loops observed with SoHO are mostly focussed on spectral analysis. In a work by Spadaro et al. (2000) the study of a loop observation made with the SUMER instrument is especially aimed at analyzing the Doppler-shifts in several UV lines. Localized flows are detected at speed larger that 15 km/s and a temptative explanation may be that of loop siphon flows, but this interpretation requires further confirming evidence. Non-thermal line broadenings are also detected.

A more recent study based on SoHO loop data is a loop modeling of a multi-line observation with a detailed preliminary methodological approach (Landini & Landi 2002) and the application to proper data collected with SoHO/CDS (Brkovic et al. 2002). The temperature of maximum formation of the selected lines spans a range between $\log T = 4$ and $\log T = 6.4$. The data analysis shows quite uniform density and temperature distributions along a selected bright loop. The authors find that the temperature distribution can be described with a hydrostatic loop model with detailed energy balance adding an isothermal region at the top of the loop and with a large conductive flux at the loop footpoints.

It is currently in progress (Di Giorgio et al. 2002) the study of a multi-line time-resolved observation of an active region loop made with SoHO, and in particular with CDS, aimed at detecting signatures of the loop heating time structure. Two loops are studied in detail: i) a hot (> 2 MK) loop, which is $\sim 50,000$ km long and relatively steady on the time scale of the observation duration (~ 1 hour), although showing a few significant brightness variations in all detected lines; ii) a cool (~ 0.1 MK) loop, $\sim 20,000$ km long, observed to brighten up and fade away within the observation in cool O lines only, and showing significant Doppler shifts. The hot loop appears to be a typical coronal loop and the observed brightness variations are not enough to indicate a continuous microflaring activity. The cool loop is highly transient, confirming indications of previous observations of similar cool structures (e.g. Brekke 1997).

3.4. Studies on TRACE data

TRACE loop observations have been the subject of a very dynamic dibate in the recent past, because of the non-trivial interpretation of data with such high spatial resolution but in so thin – though not spectrally resolved – spectral bands.

A very high quality observation of the ignition of a coronal loop allowed to conduct its detailed hydrodynamic modeling and to constrain the typically elusive location and time-structure of the driving heat release. This study was composed by two parts: i) a detailed data analysis which also produced constraints for modeling (Reale et al. 2000a); ii) hydrodynamic simulations of the loop ignition, with different assumptions on the heating location and evolution (Reale et al. 2000b). The model which best reproduces the observed brightness evolution involves that the heating is released in the coronal segment of the loop, i.e. far from the footpoints, and that it must be initially impulsive and then slowly decaying (with a time-scale of hundreds of seconds).

Another work on modeling TRACE data was stimulated by the puzzling extensive evidence of a flat filter ratio profile along many observed loops. The most immediate interpretation of this evidence is that loops are isothermal along the magnetic field lines (Lenz et al. 1999). This is in contrast with conventional loops models based on detailed energy balance and needs "ad hoc" explanations. It has been shown that long loops heated mostly at the footpoints may be nearly isothermal (Aschwanden et al. 2001). On the other hand it has also been shown that a bundle of thin hydrostatic and non-isothermal loop filaments with the same length and different temperatures, even very hot (> 3 MK), if analyzed as a single loop, will yield a flat filter ratio profile (Reale & Peres 2000). The detailed analysis of single loop strands (Fig. 4) has indeed shown that, together with cool (~ 0.1 MK) non-equilibrium structures, TRACE may indeed detect hot structures (~ 5 MK) provided that they have enough emission measure (Testa et al. 2002).

These works show how the usage of the filter ratio method on TRACE data as temperature indicator is very delicate and needs further investigation, as addressed by Schmelz et al. (2001), and recently debated in a specific workshop on coronal loops at Orsay in November 2002.

4. Conclusions

The investigation of solar coronal flares have made remarkable progresses, thanks to the valuable and extensive data provided by the Yohkoh mission. However, further work is needed to reach conclusive results on flare mechanisms and the hard X-ray data made available by the RHESSI mission will certainly be of great help.

Recent extensive studies on active coronal loops have been based on the data collected by the Yohkoh, SoHO and TRACE missions. The coherent interpretation of all such data and the construction of a general consistent scenario is still under debate and needs further investigations.

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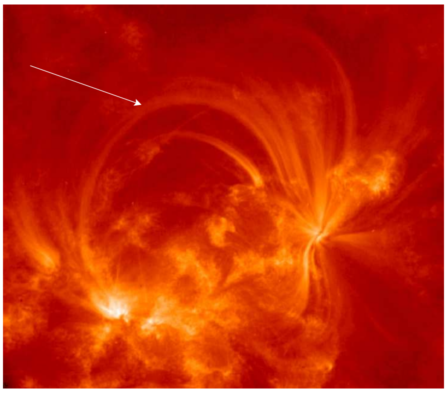

Fig. 4. Coronal loop system observed with TRACE. The strand indicated by the arrow has been modeled in detail by Testa et al. (2002).

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