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Solar flares: the observations

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Abstract. The understanding of solar flares has progressed enormously in the past decades. There is now strong observational evidence that magnetic reconnection is occurring. I will discuss the observational indicators of reconnection - and also the areas where the observations contradict the theory. The actual trigger for flares is not well understood and I will discuss how observations from the recently launched Hinode space mission will be able to address this problem.

Key words. Sun: flares

1. Introduction

Our understanding of solar flares has developed substantially over the past few decades, with new observations providing ever changing boundary conditions for the theory. Our basic understanding of flares is founded on magnetic reconnection. Models such as that proposed by Kopp and Pneuman (1976) require a 'transient' that opens up the magnetic field lines. As they close down and reconnect energy is released that goes into accelerating electrons which travel down the magnetic field lines. These highly energetic particles will heat the dense chromosphere at the footpoints and this plasma is heated and conducted into the loops. This is seen in X-ray and EUV emission. Figure 1 shows a cartoon of this process. Various observations have been made that are consistent with this picture. In this review I will discuss these, and the observations that are inconsistent.

One of the issues that this simple model does not attempt to address is how exactly the flare is triggered. We will address this and show what models and observations can currently tell us. Indeed what the basic flare models also do not address is how the flare interacts with its environment - a critical issue in understanding the Sun-Earth connection.

I will finish with discussing preliminary results from the Japanese mission Hinode and how this new data will impact our understanding of flares in the next couple of years.

2. Evidence supporting the 'standard' flare model

From the basic model described in the introduction there are various characteristics that should be observed in a flare. These include:
(a) *increasing height of loops with time.*This is due to the reconnection point gradually moving to higher altitudes. There have been many examples of this observed. Tsuneta et al. (1992) analysed a flare at the limb that shows a clear increasing in height of loops with time. Also the loops seen show a cusp shape which is indicative of the reconnection site lying high in the corona. Schmeider et al. (1995) have shown that cooler Hα loops lie under the hotter coro-

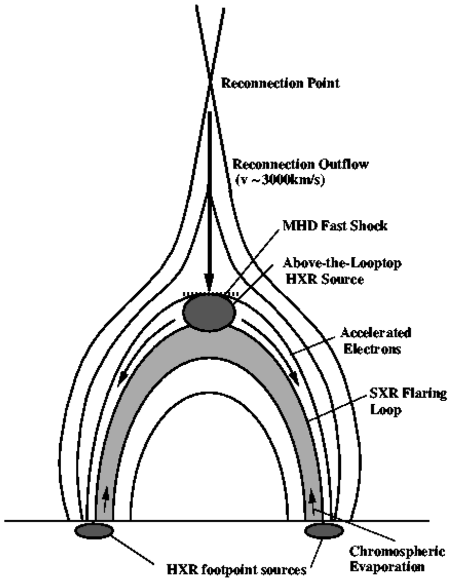

Fig. 1. A basic cartoon of a solar flare, that demonstrates some observational components that have been observed.

nal loops. These are the earlier hot, recently reconnected loops that have cooled down to Hα temperatures.
(b) *footpoint separation increasing with time*. Same as above except see in the lower atmosphere at the bottom of the loops.
(c) *evidence of accelerated particles*. This is needed in order to be able to heat the plasma. Hard X-ray emission is often observed at the footpoints of flare loops (e.g. Masuda et al. 1994). These hard X-rays are produced by electron-ion Bremsstrahlung from the highly energetic particles during the early phases of the flare, and hence are assumed to be accelerated from the reconnection site. There is also evidence of accelerated particles from the existence of hard X-ray loop top sources. These are sometimes seen to lie above the soft X-ray loops, and one possibility is that they are created from outflow from the reconnection site colliding with the higher energy loops. RHESSI observations show evidence for hard X-ray loop top sources moving downwards before moving upwards again. This downward motion can last between 2-4 minutes (Sui, Holman and Dennis, 2004). One explanation for this is that relaxation of the magnetic field lines occur following reconnection when the shape of the field lines changes from a sharp cusp to a potential semicircular shape.
(d) *evaporation of plasma*. This is expected once the plasma is heated - it will conduct up into the higher atmosphere. There is often mass flow observed in spectral lines during flares. Mariska (1994) used a statistical study of spectral data and found that there is a trend in velocity decreasing from the centre of the Sun to the limb suggesting radial flow. More recently Czaykowska et al. (1999) and Harra et al. (2005) show spatially resolved evidence of upflows. These tend to lie just outside the bright X-ray loops, which is consistent with

upflow occurring which is transporting plasma into the loops. The areas showing the upflow have not yet 'filled' the loops with hot plasma. Downflows are observed when the loops have cooling material in them. Upflow velocities are often lower than that predicted from models (e.g. Brosius and Phillips (2004)). This has been explained by Warren and Doschek (2005) who modelled a succession of independently heated threads. The emission of the strongly blue-shifted threads are masked by the emission from other threads.

(e) *inflow of plasma*. As reconnection of the magnetic field lines occurs, the pressure causes plasma to be forced outwards and downwards (the outflowing plasma) and because of pressure balance inflowing plasma is also induced. Inflow has been observed only once to date by Yokoyama et al. 2001.

(f) *outflow of plasma*. Outflow has been seen numerous times (e.g. Shibata et al., 1995). The plasmoids ejected tend to have weak emission with velocities around hundreds km/s moving outwards. There also needs to be reconnections flow moving downwards. In a number of long duration flares a downward flow of plasma has been observed (McKenzie & Hudson 1999, McKenzie 2000). The velocities are between 90-500 km/s. Further investigation by Asai et al. (2004) has shown that these downflows are associated with non-thermal emission and radio bursts.

(g) *the transient that opens the magnetic field lines*. This is not always observed clearly. At times filament eruptions are seen clearly in imaging data. In other examples it is through the careful analysis of spectroscopic data that such a transient can be observed. For example Goff et al. (2005) found evidence for a flux rope leaving the Sun followed by a flare. The flux rope was evidenced in spectroscopic data through red and blue shifts side by side indicated a high level of untwisting. It has also been found that there is a strong correlation between the reconnection rate of flares and the acceleration of erupting filaments (Jing et al. 2005).

3. Evidence not consistent with the 'standard' flare model

There are many examples that are consistent with one or several aspects of the 'standard' flare model. However as expected solar flares are more complicated and there are many aspects that we do not yet understand. A few examples of issues that are not understood are:

- We have seen evidence of inflow clearly once - that is in dispute.
- We occasionally see outflow - but not always
- The chromospheric evaporation velocities predicted from models are higher than that observed. There is one explanation for this so far and that needs confirmed with higher resolution datasets.
- There are often bright loop top seen in soft X-rays that stay in position for significantly longer than the conduction time.
- Flare loops often show strong evidence of twist.

We do not know what exactly triggers a flare, although there are various suggested mechanisms that we will discuss.

4. The elusive trigger

There has been a lot of effort trying to understand what actually triggers a flare or eruption. In the standard flare model it is expected that there is some mechanism that opens up the magnetic field. This is commonly assumed to be a filament eruption, and this is sometimes observed. However it is not necessary to have a filament eruption in order to have a flare. I will discuss a few other possibilities in this section and the observational evidence for them.

4.1. Kink Instability

The kink instability is the process where twist is abruptly converted into writhe. We see many examples of loops that look highly twisted. Recently observations have shown consistency with numerical simulations of the kink instability. Williams et al. (2005) demonstrated this by showing data from a flare observed with TRACE that showed a clear untwisting as it erupted (see Figure 2). This was compared with numerical simulations and found to be consistent. Leka et all (2005) determined from vector magnetograph data that there is enough twist available in the magnetic field for the kink instability to be a trigger mechanism by comparison with theory. In addition for the kink instability the twist and writhe must have the same sign - this was found to be the case by Rust and LaBonte (2005). They also observed that the S-shaped structures, named sigmoids, seen in the corona have exactly the right features of a kink that is in stable equilibrium. These features have been known to erupt (e.g. Canfield et al. (1999), Glover et al.(2000), Sterling and Hudson (1997)).

4.2. The 'breakout' model

The 'breakout' model has been developed over a number of years since it was first suggested by Antiochos et al.(1999) In this model the overlying magnetic field is removed to allow the eruption of material. So any signature of the flare trigger will occur away from the subsequent main flare site. Gary and Moore (2004) analysed TRACE data and found small-scale brightenings before the flare that are consistent with breakout occurring. Harra et al. (2005) also found outflows at these brightenings that are related to small scale reconnection. The upflow is evidence of reconnection occurring in the overlying loops, and chromospheric evaporation occurring, Figure 3 shows a sketch of the breakout model.

5. Flare interaction with its surroundings

The flare models that exist tend to concentrate on the flare 'site', so the core active region magnetic fields. It is frequently seen that flares have a more global response. The simplest example is the well analysed 12th May 1997 event - this started its life as being consistent with the standard model. A filament erupted resulting in a small GOES class flare which led to a halo coronal mass ejection. There was no other active regions on the disk at the time. A coronal wave took place - that is a structure which propagates in wave-like fashion across the disk. It has a bright wave front and is followed by a weak dimming region. The coronal 'wave' interacted with the coronal hole at the north pole when it reached it and reconnected with it. This caused a brightening that moved along the coronal hole boundary, and indeed changed the boundary and hence the size of the coronal hole (Attrill et al., 2006).

It has also been found that larger scale loops are important in the activity on the Sun. Khan and Hudson (2000) found that trans-equatorial loops can erupt leading to coronal mass ejections. Harra et al. (2003) found that many of the characteristics of trans-equatorial loops show similarities to the observational signatures of the standard flare model. This fact is certainly interesting to compare with stellar flares which are often predicted to be larger in size relative to the stellar radius than the Sun's flaring loops (e.g. Mitra-Kraev et al. 2005).

Trans-equatorial filaments are also of great importance - indeed these could have been mentioned in the section on flare trigger since an example has been found by Wang et al. (2006) when a non- active region trans-equatorial filament has been activated and this triggers a large solar flare confined within an active region (the well-known Bastille day flare).

6. The future with Hinode

The japanese space mission Solar-B was launched on September 22nd 2006. Following its first successful orbit it was renamed Hinode meaning 'sunrise'. It has 3 instruments on board:

– The Solar Optical Telescope (SOT): this instrument has a 50 cm aperture and an angular resolution of 0.25′′ covering a wavelength range of 480-650 nm. SOT also include the Focal Plane package (FPP) vector magnetograph and spectrograph.

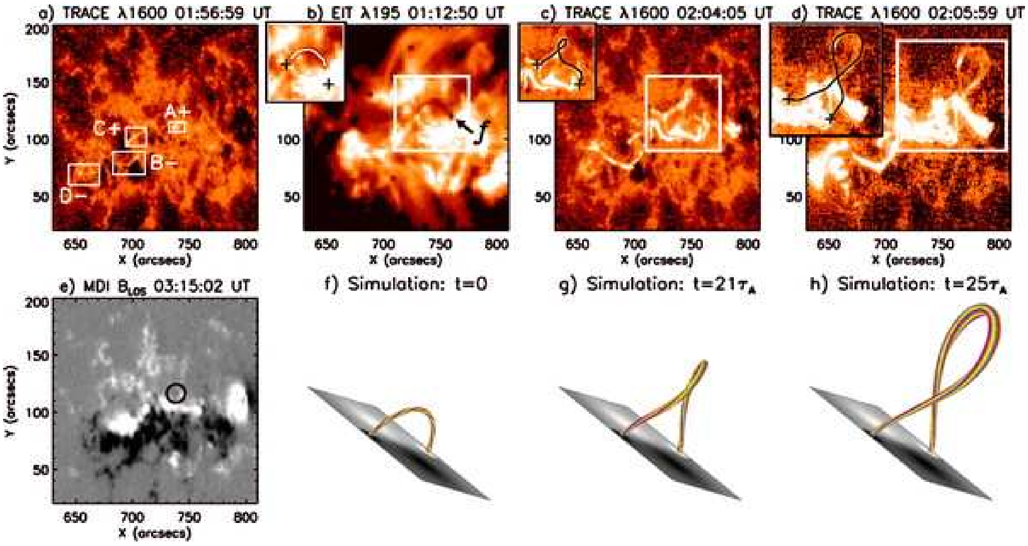

Fig. 2. An example of a case (Williams et al. 2005) where the kink instability was shown to have taken place. The figure shows the observations taken by TRACE (top row) along with the numerical simulations (bottom row)

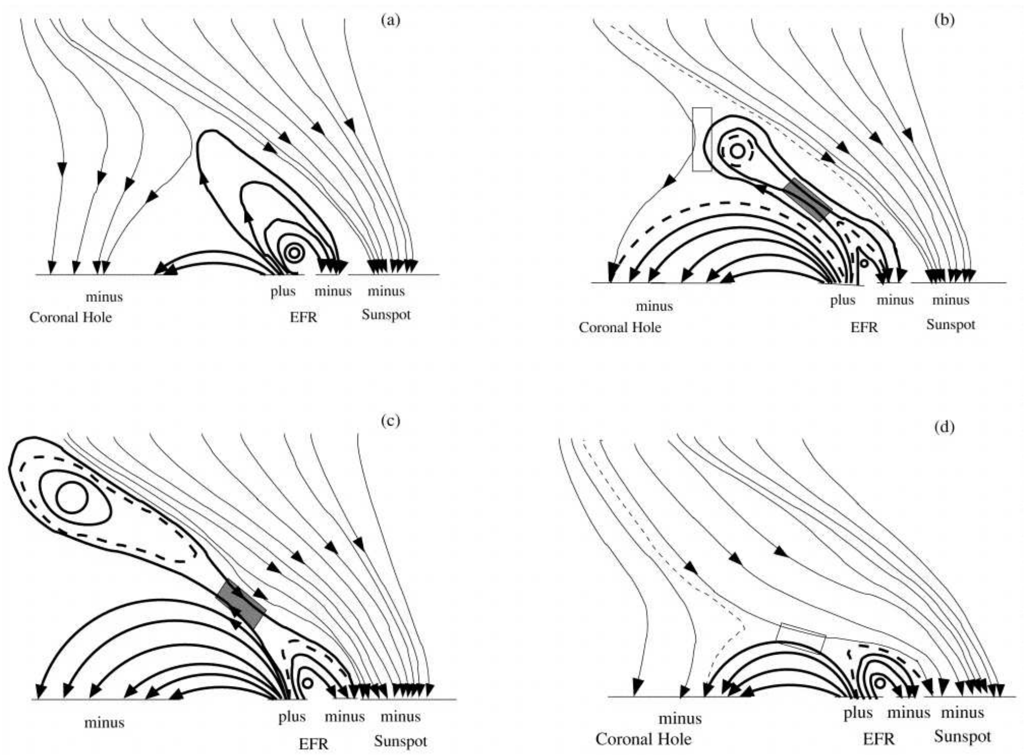

Fig. 3. A cartoon illustrating the breakout model (Sterling and Moore 2001)

– The X-ray Telescope (XRT): The XRT provides coronal images at different temperatures, both full disk and partial fields of view. The temperature range is $6.1 < \log T < 7.5$ with an angular resolution of $2''$.
– The EUV Imaging Telescope (EIS): EIS is an imaging spectrograph covering the wavelength ranges 170-290 Å and 250-290 Å. The angular resolution is $2''$ and there are 4 slit/slots available allowing detailed spectral analysis to spectrally pure images.

Since Hinode has been taking science data, it has shown a wealth of new dynamical features on the Sun. Dynamics are seen from the photosphere right into the corona in a way we have not been able to observe before. The next years will dramatically change our understanding of flares.

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