Chapter 5: Flares and plasma eruptions

Solar and Stellar Flares and their Effects on Planets
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Mass ejections from the Sun

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Abstract. Coronal mass ejections are the most spectacular form of solar activity and they play a key role in driving space weather at the Earth. These eruptions are associated with active regions and occur throughout an active region's entire lifetime. All coronal mass ejection models invoke the presence of a twisted magnetic field configuration known as a magnetic flux rope either before or after eruption onset. The observational identification of magnetic flux ropes in the solar atmosphere using remote sensing data represents a challenging task, but theoretical models have led to the understanding that there are signatures that reveal their presence. The range of coronal mass ejection models are helping build a more complete picture of both the trigger and drivers of these eruptions.

Keywords. Keyword1, keyword2, keyword3, etc.

1. Introduction

Coronal mass ejections are the most spectacular form of solar activity, ejecting around 10^{12} kg of magnetised plasma into the interplanetary medium. These ejections originate in the low plasma beta environment of the lower solar corona, in regions where magnetic flux has emerged into the atmosphere from the solar interior. The magnetic flux configurations that give birth to a coronal mass ejection vary in flux content, ranging from spotless ephemeral regions with 10^{20} Mx, (e.g. Mandrini *et al.*, 2005) to large active regions that contain sunspots and 10^{22} Mx. These magnetic field concentrations can produce coronal mass ejections throughout their lives; sometimes starting during the flux emergence phase and going through to the break-up and redistribution of the magnetic field into the quiet Sun, which can take many months and is driven by convective motions, differential rotation and meridional flows. In this way, active regions can be the source of many coronal mass ejections during their lifetime (Démoulin *et al.* 2002) and long-lived active regions have been seen to be the source of over 60 (Green *et al.*, 2002). Coronal mass ejections can be produced by the eruption of filaments that have formed in or around an active region and which can stretch over significant distances across the solar surface. In light of the link between coronal mass ejections and the emergence and evolution of magnetic flux it is easy to understand that the occurrence frequency of coronal mass ejections tracks with the solar cycle. Around solar minimum there are around one to two coronal mass ejections per day, whereas at the maximum phase of the solar cycle the Sun can produce up to eight per day (Robbrecht, Berghmans & Van der Linden 2009a).

The outward moving plasma can be monitored using remote sensing instruments across a range of wavelengths from radio to X-ray (Gopalswamy *et al.* 1999). Once a coronal mass ejection has left the Sun, it can then be detected directly using in situ instrumentation. For coronal mass ejections which are Earth directed in situ measurements are made at the first Lagrange point by instrumentation that can provide a measurement of the vector magnetic field and bulk plasma properties such as density and velocity.

The escape of a coronal mass ejection involves an enormous amount of energy (10^{25} Joules), which comes from the conversion of free magnetic energy stored in field aligned electric currents in the corona. For a review see Forbes (2000). In addition to energy an important, and related, aspect of these current carrying magnetic fields is the quantity known as magnetic helicity. This is a parameter that describes the topological structure of the magnetic field. That is, how twisted the magnetic field is and how magnetic flux tubes are distorted, linked or braided together. Magnetic helicity is an approximately conserved quantity, even during resistive processes, and it is thought that coronal mass ejections act as a 'valve' which removes magnetic helicity from the corona (Rust 1994) and Low (1996). So even though coronal mass ejections eject only a small amount of mass as compared to that lost by the solar wind every day (around 10^{14} kg per day), they may play an important role in the ongoing solar cycle removing energy and helicity that accumulates in the corona with the emergence of new magnetic flux and the evolution of those fields.

Coronal mass ejections may also be a phenomenon that is common to other stars on the main sequence which have magnetically drive coronae. Although eruptions may not be observed directly, the observation of an associated form of activity, namely a flare, could be used to investigate their occurrence. This is illustrated through the 'standard model' for eruptions that has been developed using observations of the Sun. This model is also known as the CSHKP model after the seminal work by Carmichael, Sturrock, Hirayama and Kopp and Pneuman that led to its development. For a review on these works see McKenzie (2002). In the standard model for a solar eruptive event, a magnetic field structure rises rapidly. Associated with this motion is the onset of magnetic reconnection in a current sheet that forms under the rising structure. Magnetic reconnection in this current sheet acts to "cut" the tethers of the overlying magnetic field and transforms free magnetic energy into plasma heating and particle acceleration. If downward directed particles have sufficient energy to reach the lower atmosphere the energy is deposited there. If the rate of energy deposition is greater than the rate at which energy can be radiated away, the heating results in an explosion expansion of the chromospheric plasma and a strong thermal X-ray and EUV emission. This emission is the flare and if this sequence of events takes place on other stars, whilst the coronal mass ejection may be hidden from our view, the stellar flare could be detected.

For a review of activity on M-type stars see Scalo *et al.* (2007) and references therein. These stars produce strong flares which could be understood as being created by physical processes taking place in their atmospheric magnetic fields, which are similar to the processes that drive flares on the Sun. Since many solar flares have an associated coronal mass ejection, it is therefore not unreasonable to think that some flares on other stars might also occur in concert with a coronal mass ejection. But it is only on the Sun that we can currently directly observe this eruptive phenomenon.

2. Kinematic evolution of coronal mass ejections

Coronal mass ejections were first discovered in data gathered by the the OSO satellite in the 1970s (Tousey 1973). Since then, it has been shown that these eruptions exhibit certain kinematic phases. These phases have been discussed in Zhang *et al.* (2001) and Zhang & Dere (2006) as follows:

Phase 1 A slow rise phase that lasts for 10s of minutes and where the structure ascends with a speed from a few kms^{-1} to tens of kms^{-1}

Phase 2 An impulsive acceleration phase over which time the speed can increase by two to three orders of magnitude

Phase 3 A propagation phase

If the coronal mass ejection is accompanied by a flare, the flare soft X-ray emission from the thermal plasma also tracks these kinematic evolutionary phases (see Figure 1 in Zhang & Dere 2006).

Since coronal mass ejections are a magnetically driven phenomenon, the details of the magnetic field involved must be understood in order to explain the physical processes behind these events. However, our understanding of the magnetic field configuration involved decreases in confidence from phase 3 to phase 1. This is a consequence of the measurements that can be made. During phase 3 a coronal mass ejection can be measured directly as it passes across in situ instrumentation. These (mostly single point) measurements have shown that the magnetic field can be described by a current carrying twisted magnetic field configuration known as a flux rope (Jian *et al.* 2006). This aligns well with coronal mass ejection models which all involve a flux rope in this evolutionary stage. What is debated is in which phase the flux rope forms (phase 1, 2 or even before) and without direct measurements of the coronal magnetic field, in the regions where coronal mass ejections originate, this has been a lively area of research for many years. Is the rope already there by stage 1 or does it form during the magnetic reconnection that sets in as phase 1 transitions to phase 2?

3. When do magnetic flux ropes form?

The energy required to power coronal mass ejections cannot be supplied to the corona on the timescale of a dynamic event. Instead, the energy is thought to be built up in the coronal magnetic field and stored there in the hours and days before the eruption. Does the magnetic flux rope also form over these timescales? To answer this question the physical processes that are involved in generating the flux rope must be understood. Tied up with the question of when magnetic flux ropes form is how they can be identified. Since we cannot measure the magnetic field in the solar corona, observational signatures must be used to act as a proxy for the presence of a flux rope. The following observational features should be considered when looking for flux ropes in the solar atmosphere:

Inverse crossing of photospheric vector field For flux ropes that have their underside in the photosphere/chromosphere, concave up sections will be produced by field lines at the bottom of the flux rope, which can be detected in vector magnetic field measurements (Athay *et al.* 1983, Lites 2005). These concave-up sections will cross the polarity inversion line in the 'inverse' direction.

Sigmoids An inverse crossing of the polarity inversion line made by the middle section of S shaped field lines in some sigmoidal regions (Fan & Gibson 2006 and Green & Kliem 2009). If the S-shaped field lines survive the eruption a sheared arcade configuration can be excluded (Antiochos *et al.* 1994).

Plasmoids/hot flux ropes Plasma structures which are formed and heated as a result of magnetic reconnection to temperatures of around 10 MK (Shibata *et al.* 1995, Reeves & Golub 2011, Cheng *et al.* 2011, Patsourakos *et al.* 2013).

Coronal cavities Dark cavities seen in white light coronagraph data, sometimes containing a filament in their lower section, and representing the cross section of a flux rope seen crossing the limb of the Sun (Gibson *et al.* 2006, Reeves *et al.* 2012).

These observational signatures allow the investigation of when a flux rope forms. In some cases there is observational support for the presence of a flux rope prior to the onset of phase 1 (slow rise phase). For flux ropes that form in active regions where there are well defined photospheric polarity inversion lines along which flux is converging, flux ropes have been seen to form over a few days and reveal themselves in hot plasma emission that traces out an S-shape known as a sigmoid. The S-shape is thought to be caused by the emission of plasma that is heated by electric current enhancements at the periphery of the flux rope. The S-shape indicates that the twist in the rope is around 1.5 turns from end to end. Flux ropes in sigmoidal active regions have been seen to form through a process known as flux cancellation following the model of van Ballegooijen & Martens (1989). Observationally, this process manifests itself as the convergence of opposite polarity photospheric magnetic fragments along a photospheric polarity inversion line. Upon colliding, the fragments undergo magnetic reconnection in the lower atmosphere. The resulting magnetic field configuration is comprised of a small loop that has a high tension force due to its small radius of curvature. The magnetic tension form of this small loop can no longer overcome buoyancy and it submerges below the photosphere. Higher up in the atmosphere a longer magnetic loop is produced and this builds into the flux rope. The schematic for this is laid out in Figure 1 in van Ballegooijen & Martens (1989) and a corresponding observational occurrence is seen in Green, Kliem & Wallace (2011). Once formed, a study of a small number of flux ropes that formed in sigmoidal regions suggests that they remain stable on the Sun for up to around 14 hours (Green & Kliem 2014). Magnetic reconnection at higher heights in the atmosphere is also able to build a rope prior to phase 1. For example, Patsourakos *et al.* (2013) discuss a flux rope that formed via magnetic reconnection in the corona on a timescale of 20 minutes and around 7 hours prior to its eruption.

There is also the possibility that the flux rope may only partially form before phase 1. For example, flux cancellation may not proceed uniformly along the length of the flux rope so that concave-up sections of the magnetic field are not distributed along the full length of the rope. Likewise, field lines spiralling over the top of the rope (concave-down sections) may also not be uniformly distributed. Cheng *et al.* (2011) show observations where the flux rope is built during phase 2 (impulsive acceleration phase). In this case the flux rope is seen through emission from plasma at around 7 to 11 MK, and forms at a height of around 70 Mm. The formation/build of the flux rope is by magnetic reconnection in the corona triggered by the eruption itself.

Not all erupting magnetic field configurations are possible to investigate prior to their eruption though. Some coronal mass ejections have earned the name stealth coronal mass ejections because they do not exhibit any observational signatures in the lower atmosphere such as erupting material or flare emission (Robbrecht, Berghmans & Van der Linden 2009a). There are many open questions related to this category of coronal mass ejections, their magnetic configuration and its formation.

4. Flux rope stability

The mechanisms involved in the eruption of a flux rope are being investigated for ropes that form before the onset of phase 2 (fast rise phase). Models that invoke the presence of a formed magnetic flux rope prior to the onset of the steep change in ascension speed between phase 1 and 2 involve the flux rope undergoing an ideal MHD instability (Torok & Kliem 2009, Kliem & Torok 2006)or a loss of equilibrium (Forbes & Isenberg 199)) or force imbalance (van Ballegooijen & Mackay 2007).

Models that form a flux rope during the onset of the coronal mass ejection involve the resistive process of magnetic reconnection which both forms the flux rope and cuts its tethers so that it is rapidly ejected from the Sun (Moore *et al.* 2001). In this model, runaway magnetic reconnection must set in for the eruption to occur.

The remaining class of models forms the flux rope when an inflating sheared arcade starts to erupt (Antiochos *et al.* 1999). This class of model requires a strong photospheric shearing to occur at the footpoints of an arcade embedded in a multipolar field configuration. As the sheared arcade rises, there is magnetic reconnection with the

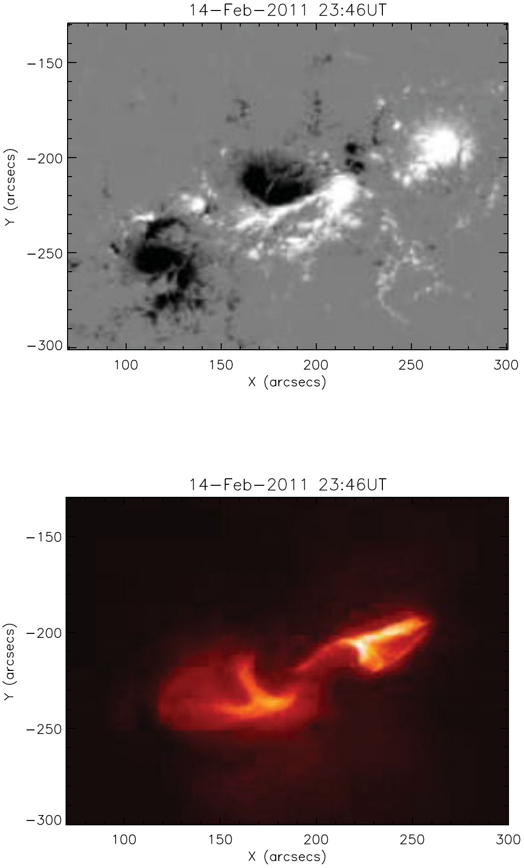

Figure 1. Top: image of NOAA active region 11158 showing the line-of-sight photospheric magnetic field as observed by the HMI/SDO magnetograph. White (black) represents regions where the magnetic field is directed toward (away from) the observer. Bottom: image of the soft X-ray emission from the coronal magnetic field configuration which exhibits an S-shaped structure as captured using the Hinode X-ray Telescope.

oppositely directed overlying field. This allows the bipolar field to 'break-out' forming a flux rope via magnetic reconnection in a current sheet formed within the arcade.

Determining the time when a flux rope forms can help discriminate between these different classes of models. And studying aspects such as the photospheric motions in the run up to the coronal mass ejection, the height of any pre-existing flux rope, how sheared or twisted the field is and the ratio of flux within the rope to that of the overlying and restraining field are important factors to quantify in order to link the models to the processes taking place on the Sun. In reality though, discriminating between these different groups of models in an attempt to narrow down the physical processes involved might not be necessary. For example, consider the following evolutionary sequence. A flux rope is forming in the lower solar atmosphere and as its magnetic flux content increases, it grows in cross section and height. Meanwhile photospheric motions or breakout reconnection could inflate the overlying field so that the rope further rises (or the growth of the rope itself could cause this) so that the critical height needed for it to become unstable or lose equilibrium is reached. Once the rope starts its rapid ascension phase, and a current sheet develops in its wake, magnetic reconnection sets in which cuts the tethers of the overlying field, builds more poloidal flux into the rope and aids its acceleration and escape from the Sun. The conversation then becomes one that needs to include both triggers and drivers of the eruption.

Another approach used to investigate the presence and stability of magnetic flux ropes involves reconstructions of the coronal magnetic field. The flux rope insertion method involves inserting a flux rope into a potential field model of the active region being studied (van Ballegooijen 2004). The potential field model is computed from the line-of-sight component of the observed photospheric magnetic field. The flux rope is inserted, with its length and location guided by observations of the active region filament, and the magnetic system is allowed to relax to a non-linear force-free state. The axial and poloidal field of the inserted rope are varied until a stable solution is found that best fits the observed plasma emission features in the corona. This method therefore provides a way to investigate the axial and poloidal flux of the rope and its height in the atmosphere.

Early studies using this technique in active regions found that flux ropes forming in active regions may only be able to contain around 10% of the flux of the active region before they become unstable. This was found in Bobra *et al.* (2008) who studied two regions, NOAA active regions 9997/10000 and 10005, when they were close to the central meridian but away from the times that the regions produced eruptions. Su *et al.* (2009) studied NOAA active region 10953 which was more active, but still found an upper limit on the axial flux that the modelled rope could contain whilst still being stable as around 10% of that of the active region flux. A later study by Savcheva *et al.* (2012) using the same technique found that flux ropes might contain up to 60% of the active region flux whilst still remaining stable in the atmosphere. All models suggest that the flux ropes are weakly twisted and have an axial height of around 10 to 40 Mm above the photosphere.

Flux ropes that become eruptive can be seen over a wide range of heights in the solar atmosphere. The very lowest lying ones are seen in active regions at heights of a few Mm (Lites 2005). These ropes are overlaid by strong magnetic fields and can also contain filament material that may or may not participate in the eruption. At the other end of the height spectrum are the so-called stealth coronal mass ejections which could involve the eruption of flux rope at heights of hundreds of Mm which equates to larger than 0.1 Solar radius (Robbrecht *et al.* 2009b).

Even though no erupting structure has been directly observed on other stars, stellar spectra have revealed features that might be relatable to certain pre-eruptive structures on the Sun. For example, transient H-alpha absorption features suggest the presence of clouds of relatively cool dense gas that could be a stellar analogue to solar filaments/prominences (Collier Cameron & Robinson 1989). On the Sun these gas clouds are thought to be suspended in magnetic flux ropes or dipped field configurations and they frequently erupt as a coronal mass ejection. However, solar filaments are located much lower in the solar atmosphere than the height of a few stellar radii above the surface of the star that are seen for the stellar gas clouds. In the stellar case, where observations are much more limited, studies have indicated that ropes might lie much higher in the atmosphere than they do on the Sun.

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