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Spectroscopic observations of coronal waves and coronal mass ejections

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Abstract

It is common to use imaging instruments such as EUV and X-ray imagers and coronagraphs to study large-scale phenomena such as coronal mass ejections and coronal waves. Although high resolution spectroscopy is generally limited to a small field of view, its importance in understanding global phenomena should not be underestimated. I will review current spectroscopic observations of large-scale dynamic phenomena such as global coronal waves and coronal mass ejections. The aim is to determine plasma parameters such as flows, temperatures and densities to obtain a physical understanding of these phenomena.

Key words:

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1 Introduction

The importance of large-scale transient phenomena on the Sun is well accepted. Coronal mass ejections are observed clearly using coronagraph data, such as the Large Angle Spectroscopic Coronagraph (LASCO) on board SOHO. In order to understand their origin we need to observe them on the disk and as they leave the Sun. One of the methods of achieving this is using broad-band or narrow-band imaging. This method provides good time cadence, and allows us to observe the dynamics of the event. However there is always confusion as to what plasma is emitting in the range of wavelengths observed by the instrument. There can often be a mixture of hot and cold plasma, especially in the case of flaring. For example, Feldman et al. (1999) demonstrated that there is contamination from flaring emission in filters that are designed to observe predominantly the quiet Sun and active region emission.

In this review, I discuss work related to both coronal mass ejections and coronal waves when spectroscopy has been a critical element to the understanding

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of the process. Both phenomena are discussed since there is a close relationship between then. It is extremely common that when a coronal wave is observed, a coronal mass ejection will also be found.

2 Instrumentation

There are three spectrometers on board the SOHO spacecraft. Results from these instruments will be described in this paper. Details of the Coronal Diagnostic Spectrometer (CDS) instrument are described by Harrison et al. (1995). CDS consists of two spectrometers - the Normal Incidence Spectrometer (NIS) and the Grazing Incidence Spectrometer (GIS) which cover the EUV wavelength range 150-800Å. The Solar Ultraviolet Measurement of Emitted Radiation (SUMER) instrument is described in detail by Wilhelm et al. (1995). The instrument has a wavelength coverage from less than 500Å to 1610Å. The Ultraviolet Coronagraph Spectrometer (UVCS) can observe from the base of the corona up to 12 solar radii. UVCS is described in detail by Kohl et al. (1995).

3 Triggering mechanisms

The origin of coronal mass ejections is not straightforward. There are many potential sources of coronal mass ejections - as illustrated by the association with filament and prominence eruption, solar flares, trans-equatorial loops and sigmoidal structures. There are also many models to explain coronal mass ejections. Most include magnetic reconnection at some location. For example the breakout model described by Antiochos (1998), requires reconnection to occur between a multi-polar magnetic field and the field lying above a filament. In addition most models require some level of shear or twist. For example, in the tether-cutting scenario by Sturrock et al. (1984), reconnection occurs to allow the removal of a sheared bipolar arcade. In order to obtain enough energy to produce an eruption of material, it is necessary to have twist and shear in the magnetic fields, and then have some means of allowing this material to be released through the atmosphere.

The use of multi-wavelength spectroscopy by Schmieder et al. (2000) has illustrated the changes that occur in a filament before an eruption occurs. They made use of SUMER, CDS and the Multi-channel Subtractive Double Pass Spectrograph (MSDP) to study a filament for 5 hours before an eruption occurred. Part of the filament was disturbed by twisting motions and turbulence. The twisting motions were seen in Hα and He I as aligned regions of blue and red shifts along the filament. There was also strong line broadening observed.

The filament slowly rises and finally erupts. The filament seems to be ultimately destabilised by reconnection, as evidence of plasma heated to coronal temperatures is observed.

4 Where does the ejected material come from?

This appears to be a trivial question, but CMEs are observed in coronagraphs when you are actually blocking out the disk of the Sun. It is impossible to determine what direction the CME is traveling in, and even if it originated from the front-side or back-side of the Sun. Coronal 'dimmings' - that is a region of the corona that undergoes an intensity decrease - are one way to determine the origin of coronal mass ejections. These are frequently determined with imaging instruments such as the soft X-ray telescope on board Yohkoh. For example, Sterling and Hudson (1997) measured areas of coronal dimming that were related to the eruption of a highly sheared and twisted coronal loop system. There was a coronal mass ejection related to this event. It is natural to assume that these regions are due to the depletion of coronal material and hence demonstrate the origin of the CME. However coronal emission detected by soft X-ray and EUV telescopes will be confused because they pick up emission from a broad temperature range and hence it will be difficult to determine if the apparent dimming is due to a temperature change in the plasma or an actual mass loss. The advantage with imagers, of course, is the large field of view, and good temporal resolution.

Spectrometers have recently observed coronal dimming. Harrison and Lyons (2000) analysed CDS data for one event on the limb, in a wide range of emission lines from He I at $\approx$ 20,000K up to Fe XVI at 2MK. There was no flaring in the active region, but gradual dimming (over a period of many hours) was apparent from the million K plasma only. There was activation of a large prominence, but it did not erupt. The CME was seen in LASCO, but the dynamics observed above the occulting disk, were not seen in the lower corona. The density decrease was measured, and it was determined that 70% of the mass of the CME was from million degree plasma. Howard and Harrison (2004) carried out a more comprehensive study and highlight difficulties with assuming that dimming is due to mass loss. When using spectroscopic data it was found in some cases that it was due to a temperature change. Harra and Sterling (2001) analysed two separate CME events with the CDS spectrometer. The first event originated from an active region on the limb. Dimming regions were seen in Mg IX (1MK) and Fe XVI (2MK) and also in the lower temperature OV (250,000 K) and He I (20,000K). A determination of velocities was made of these four emission lines, and it was found that blue-shifted material emitted from the dimming regions in the corona only. Figure 1 illustrates the location of the dimming region, and the contours highlight the region of blue-shifted plasma. This confirms that coronal dimming, in this case, is due to plasma leaving the Sun. Such dimming has also been observed further away from the Sun using UVCS. Antonucci et al. (1997) found dimming in Lα during a CME. Spectroscopy is proving to be an extremely useful CME trigger diagnostic.

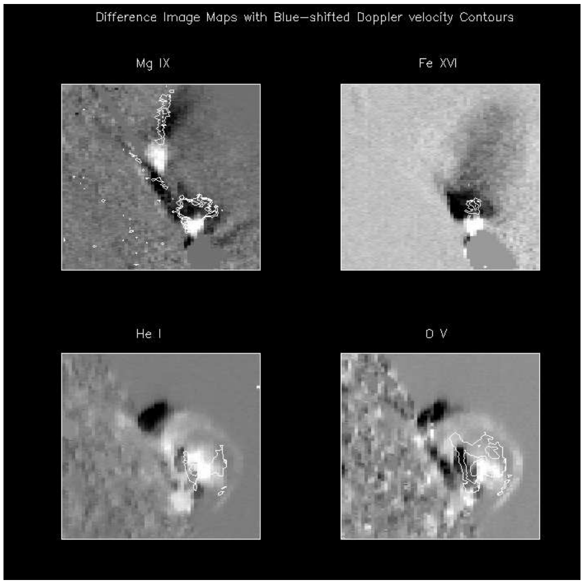

Fig. 1. Difference images of an active region on the limb observed by SOHO CDS. The top figures show coronal emission in Mg IX (left) and Fe XVI (right). The lower figures show cooler, transition region emission in He I (left) and O V (right). The contours show the blue-shifted emission, with levels of -40, -30 and -20 km/s (from Harra and Sterling, 2001).

5 Leaving the Sun

It is clear that regions that have some twist and shear in the magnetic loops are more likely to erupt than those regions without that additional energy source. This has been investigated by Canfield, Hudson and McKenzie (1999) who studied a large number of twisted (S-shaped) active regions and found that they were more likely to erupt than non S-shaped active regions. It is naturally difficult to define what is a twisted shape from images alone as pointed out by Glover et al. (2000).

Spectroscopy is also used to determine twist in regions as discussed in section 3. So what happens to a flux tube when it erupts? Pike and Mason (2002) measured the velocity of a flux rope leaving the Sun using CDS. Their interpretation is that the flux rope had a rotational twist as it was leaving the Sun of ± 350km/s. Foley et al. (2001) analysed the same flux rope with CDS and interpreted the data in a different way. They measured the flux rope accelerating close to the disk of the Sun. There were several phases to the acceleration with a slow acceleration and a fast acceleration phase. In this case a flux rope was violently disconnected from the Sun, potentially providing the energy to drive the CME. It is suggested in Foley et al. (2003) that the rising flux rope produces a piston driven shock, which opens the magnetic field, and subsequently produces density enhancements which propagate across the disk of the Sun. The latter are known as coronal waves, and this scenario is consistent with the numerical simulations of Chen et al. et al. (2002).

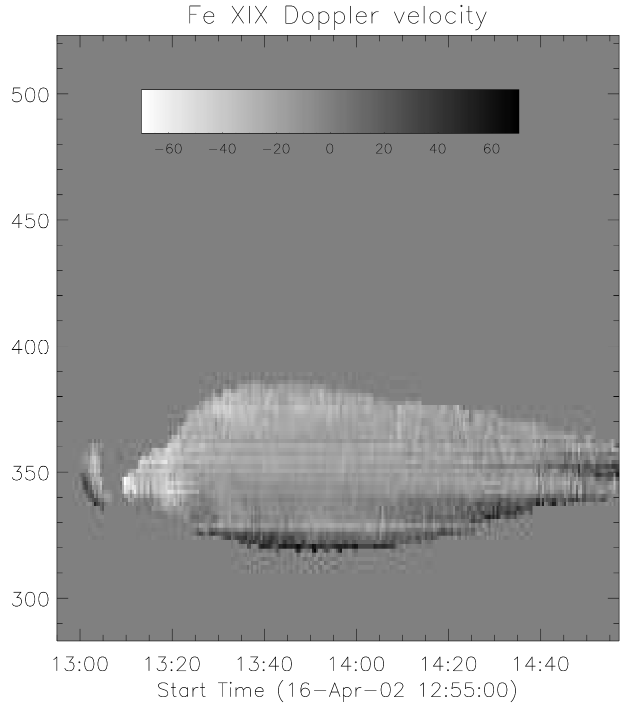

Fig. 2. A velocity map of a CDS 'slit' that was positioned above a flaring region (from Goff et al., 2004). The is the FeXIX emission line. The y axis shows the direction in arcseconds along the slit. The x-direction shows the time. This figure is essentially showing the velocity changes in the Fe XIX emission line as the plasma travels past the CDS slit.

Spectroscopy provides a different perspective on material that is leaving the Sun. A flare that was observed by TRACE, CDS, SUMER and RHESSI was described by Sui, Holman and Dennis (2004). They concentrated on the hard X-ray sources in the flare, and did not find any related CMEs. On the other hand, Goff et al. (2004) found that there was a small CME related to the flare in the LASCO data. The source was an erupting flux rope which was weak and hard to detect in the imaging data, but the spectroscopic data showed it clearly. Figure 2 shows the CDS data from this flare. The CDS slit was located above the flaring active region, off limb and operated in sit and stare mode. A region of red-shifted and then blue-shifted material went through the slit just as the weak flux rope seen by TRACE was seen to pass through that location. This behaviour (red and blue-shifted) is similar to the other flux ropes described. It suggests that the plasma leaving the Sun was twisted. After the flux rope leaves, there is a gap and then the flare proper begin, with plasma being further accelerated by the removal of the flux rope.

Of course, such behaviour is also seen further away from the Sun. The Ultraviolet Coronagraph Spectrometer (UVCS) on board SOHO observes from 1.5 to 12 R_{solar}. Antonucci et al. (1997) analyse a CME with UVCS and find evidence for mass motions that are consistent with untwisting magnetic fields around an erupting flux rope. Once field lines are twisted, they will always want to reach a state when they can relax to a force-free configuration. Untwisting after eruption is a way to achieve this state. These helical flux ropes have often been observed in interplanetary space, and it is now possible to observe them closer to the Sun.

Another observation which could explain the source of acceleration close to the surface of the Sun is from SUMER by Innes et al. (2001). This was also discovered by making use of a sit and stare slit observation which was above an active region, off limb. The active region flared, and very strong Doppler shifts reaching 650km/s were observed. The strong shifts were observed minutes after an optical shock wave was observed to travel through the corona. The shifts were observed at every position, and hence unlikely to be due to reconnection jets. It is hypothesized that the shock wave interacts with the active region loops, and caused heating and accelerating to occur.

6 Coronal waves

In the 1960s shock waves were discovered in Hα observations. They traveled across the disk of the Sun with velocities ranging between 440-1125 km/s and were named Moreton waves. The wave front causes a depression and successive relaxation of the fine structure of the chromosphere (also known as a 'down-up swing'). Theory has shown that the waves cannot be traveling in the chromosphere due to the small sound speed as the waves would dissipate very quickly. Wave propagation must occur in the corona. The favoured interpretation by Uchida (1968) is a fast mode wave that propagates quickly in the corona and the Skirt of the wavefront sweeps over the chromosphere with a velocity exceeding the fast mode velocity in the chromosphere itself. So it was expected that such large-scale waves would be observed in the corona.

A large-scale corona phenomena was found in EIT on board SOHO by Thompson et al. (1998) and seen as a bright wave front propagating across the disk. The wave front is followed by a region of dimming. These coronal waves have typical speeds of 250-300 km/s and are sometimes associated with flares. Chen et al. (2001) found that they are virtually always associated with CMEs. This is why both of these phenomena are described in this review. There are several explanations for the coronal waves. One suggestion is that they are the shock waves predicted by Uchida. Another suggestion is that the bright wave front is showing when the field lines are opening up. To date there are only two EUV spectroscopic observation of coronal waves. Harra and Sterling (2003) found that there is a high velocity feature which occurs related to a coronal wave. This high velocity event appears to be cool, filament material lifting away from the Sun's surface with speeds of more than 300 km/s. Interestingly, this high velocity feature was seen in many different temperatures, right into the corona, showing the coronal response to a filament eruption. This observation also has similarities with the numerical simulation by Chen et al. et al. (2002). They suggest that a coronal wave consists of two parts with a faster propagating piston driven portion and a more slowly propagating portion due to the opening of field lines associated with a filament eruption. We certainly observe the filament eruption that was very difficult to see in the imaging data alone (see figure 3). A different coronal wave was analysed by Harra and Sterling (2001). In this event, the wave front was missed due to the rastering of the spectrometer, but observations were made of the dimming region behind the bright front. In this case outflow velocities were observed confirming again that the dimming region was caused by outflowing plasma.

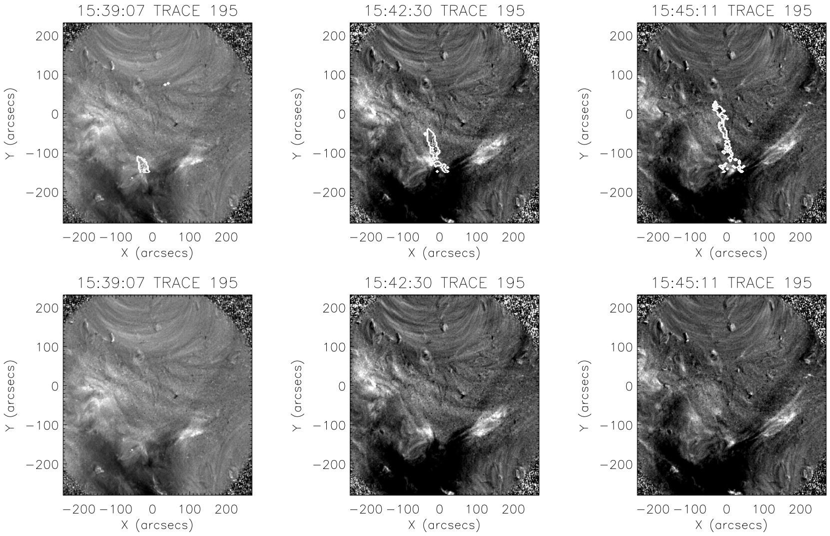

Fig. 3. A time sequence of TRACE difference images illustrating the coronal wave front. There is an active region to the north, and the active region to the south was the source of the large flare. The contours on the images show the source of the high velocity emission seen by CDS (from Harra and Sterling, 2003).

Shocks from flares have now been observed to cause other effects such as oscillations in loops. These were seen for the first time spatially by TRACE (Nakariakov et al. (1999)), where coronal loops away from the main flare site, were observed to oscillate in a transverse direction. Wang et al. (2003) have observed Doppler shift oscillations that are also associated with flares. Using SUMER, they detect oscillations in Doppler shifts in the hot coronal Fe XIX and Fe XXI emission lines. The oscillations have periods in the range of 7-31 mins and decay within 37 mins. They have a similar decay rate to the TRACE transverse waves, but have longer periods. Wang et al. (2003) suggests that they are compressive magneto-acoustic waves that are excited at one footpoint.

7 Coronal Mass Ejections and Coronal Waves on other stars

It is expected that phenomena that occur on the Sun due to the magnetic fields, will also occur on other magnetic stars. There are many stars with magnetic activity far exceeding that on the Sun, and hence a CME could be much more energetic, losing much more mass than the average solar CME. **?**) study the late-type flare star in the V471 Tauri system. This is an eclipsing binary with a period of 0.52 days and consists of a cool main-sequence star (dK2) and a hot white dwarf. It is a good system to search for mass loss since there is a strongly UV-emitting, nearly point-like source that shines through the stellar coronae. Observations were made using the Goddard High Resolution Spectrograph (GHRS) on board the Hubble Space Telescope and a transient absorption in the Si III 1206 Å resonance line appeared suddenly. The transient features are assumed to be due to material ejected from the chromosphere or corona of the K2 star and through the line of sight to the white dwarf. From these observations it is predicted that the K2 star produces CMEs at a rate more than 100 times that of the Sun.

Observations of oscillations related to flares that were described in the previous section are also actively sought in other stars. Mathioudakis et al. (2003) found evidence for oscillations in optical stellar flares. The first observations in X-ray were recently obtained of AT Microscopii by Mitra-Kraev and Harra (2004) using XMM-Newton. They found sustained oscillations in the X-ray regime during a flare. In the solar case, it is difficult to observe these variations in an X-ray light curve as the emission measure is low relative to the flare itself. Hence in the case of AT Mic, the loops that are oscillating must be very bright, suggesting that they are involved in the flaring process. As in the case of the Sun, making use of spectroscopy to get information on the density and temperature of the plasma, along with measurements of the period of the oscillation, allows a determination of the magnetic field.This is an extremely useful tool, and will no doubt be used extensively in the future in non-solar objects.

8 Future Space Instrumentation

During the next couple of years, there will be two solar missions that will provide extremely useful information regarding CMEs and coronal waves. Solar-B will be launched in 2006 and has three instruments on board: a high resolution EUV imaging spectrometer (EIS), a Solar Optical Telescope (SOT) and an X-ray telescope (XRT). This will provide information on velocity fields right from the photosphere to the corona, and high resolution imaging. The combination of imaging and spectroscopy is vital to understand these global phenomena. At a similar time, the STEREO mission will be launched. This will provide 3-D imaging of the Sun in EUV and imaging for CMEs, helping us pin down the source of CMEs. Session E2.2 in the 35th COSPAR meeting covered details of instrumentation and science background for both the Solar-B and STEREO mission.

9 Conclusion

Spectroscopy is an important tool in understanding global phenomena, and allows us to see dynamics that cannot be seen by a broad-band imager. Although, to date, high resolution spectroscopy has only observed a small field of view, a lot has been learnt from using it that cannot be gained from imaging. The ideal instrument will have it all - imaging and spectroscopic capability without the need to 'build up an image', and over a large field of view with high time cadence. This is an extremely difficult thing to achieve, but progress is being made in that direction. Harra et al. (2005) describes a design for an instrument that will produce both spectral and imaging information simultaneously for a limited number of spectral lines.

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