E2.3-0019-02

SOHO OBSERVATIONS RELATING TO THE ASSOCIATION BETWEEN FLARES AND CORONAL MASS EJECTIONS

R. A. Harrison

Space Science & Technology Dept., Rutherford Appleton Laboratory, Didcot, Oxfordshire OX11 0QX, UK.

ABSTRACT

Campaigns to investigate the solar coronal mass ejection (CME) onset have been run using the Solar and Heliospheric Observatory (SOHO) since 1996. These have included coronagraph and extreme-ultraviolet (EUV) disc imaging, along with magnetic mapping of the photosphere, in concert with EUV and UV spectroscopic observations. These campaigns have included co-ordination with ground-based observatories, and with other spacecraft, especially Yohkoh and the Transition Region and Coronal Explorer (TRACE). This multi-instrument, multi-spacecraft effort has provided many rewards, with some spectacular observations of countless eruptions. It has included the discovery of unexpected phenomena such as EUV waves and ground-breaking work on coronal dimming, and the development of sigmoidal shaped structures. Much has been learnt about the CME onset yet the most basic questions still remain. We have an unprecedented view of CME eruptions, yet we are still unable to identify clearly the onset process and we do not fully understand the CME-flare relationship. With all of the campaigns producing excellent multi-wavelength observations of CMEs, how far have we progressed in the understanding of the CME onset and, in particular, the CME-flare relationship? Can we identify lines of research using the SOHO data, which will provide the answers we seek – or do we need fundamentally different observation scenarios? It is the author's opinion that we actually have the observational tools required to understand much about the onset process and the CME/flare links, and the emphasis should be on understanding the limitations of our instrumentation and on removing any preconceived ideas from our interpretations.

INTRODUCTION

The interest in coronal mass ejection (CME) activity has increased dramatically over the last 15 years, with the realisation that these eruptions are of the most fundamental importance to space weather studies, as well as to the basic evolution of the solar atmosphere. The potential geomagnetic effects of CMEs, combined with concerns for their detrimental impacts on numerous human activities, as well as their significance for the structure and evolution of the corona, and of the heliosphere, ensure that studies of CMEs are of the highest priority in solar physics.

In the most basic terms, a CME is a discrete eruption of, typically, 10^{12} – 10^{13} kg as a magnetic structure balloons out into space from the corona, with the front edge travelling, typically, at speeds of several hundred kms^{-1}. However, speeds as high as 2000 kms^{-1}, and as low as 50 kms^{-1} have been recorded. The average angular size of a CME is about 45 heliographic degrees, though events can be any size, from narrow jets through to 'halo' events. Halo CMEs are those which are either directed towards or away from Earth and therefore appear expand from the Sun over a very large range of position angles. They were first identified by Howard et al. (1982). It is not the purpose of this review to discuss the details of CME characteristsics and, thus, the reader is referred to the excellent recent reviews of CMEs by Plunkett et al. (2002), Webb (2000) and Hundhausen (1997) in particular.

Figure 1 shows a CME, originating from the solar north-east quadrant which was detected using the LASCO coronagraph (Brueckner et al., 1995) on board the SOHO spacecraft. The outer edge of the CME loop system is just beyond the edge of the image but a great deal of complexity can be seen within the CME, including the bright signatures of an erupted prominence, which is ascending within the CME structure.

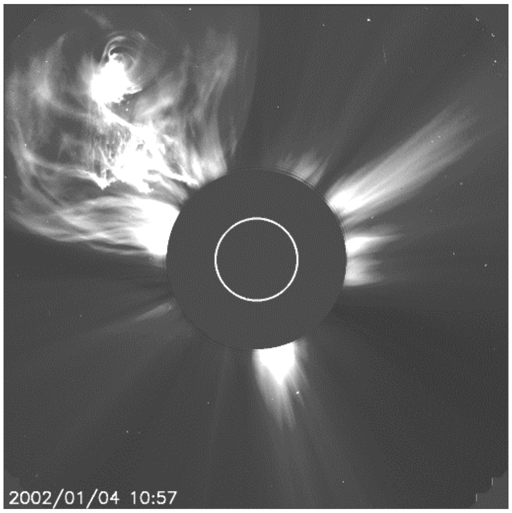

Fig. 1. An example of a coronal mass ejection, in this case, ejected from the solar north-east limb on 1 April 2002. (Courtesy: SOHO/LASCO consortium).

CMEs were discovered 30 years ago; they are detected using coronagraphs. These are instruments which occult the solar disc in order to measure the weak, diffuse intensities of the outer corona and CMEs, which typically have intensities of order 10^{-6} that of the solar disc. The occulting disc of Figure 1 is 4 solar radii across. Several solar missions have carried instruments dedicated to outer coronal and CME observation, namely, Skylab (1972-3; see MacQueen, et al., 1974), the P78-1 spacecraft (1979-1985; see Howard et al., 1985), the Solar Maximum Mission (1980 and 1984-89; see Hundhausen, 1997) and SOHO (1995 to date; see Brueckner et al., 1995).

Despite the decades of observation and the clarity of the CME observations in recent years, in particular, as demonstrated by Figure 1, we do have some fundamental observational problems and these have been the cause of much controversy and misunderstanding.

Strictly speaking, all coronagraph observations, to date, have been made in near-Earth space. Thus, our view is of the plane of the sky perpendicular to the Sun-Earth line. We detect CMEs through the detection of white light emitted through the Thomson scattering of photospheric light by free electrons confined to the CME magnetic fields. Thus, our observations are best suited to the detection of CMEs in the plane of the sky, i.e. those heading at 90^o to the Sun-Earth line. From a geomagnetic prediction point of view, these are not the events which will interact with the Earth. From a CME onset point of view, the source regions of the CMEs we readily detect are near to the limb and, thus, attempts to study the onset/source regions are thwarted by foreshortening or by occultation by the solar disc itself. In any case, we do not see the CME below the coronagraph occulting disc and must make projections in space and time to investigate associations with near-surface activity and structure observed using other instrumentation.

It should be noted that two exceptions to the near-Earth view of CMEs were the two Helios spacecraft, the first of which was launched in 1974. These were flown in solar orbits, with a perihelion of 0.3 AU. Although these spacecraft did not carry coronagraphs, they did carry three zodiacal light photometers (Leinert et al. 1975), i.e. a capability for measuring the zodiacal intensity at three points. These were mounted at 90^o, 31^o and 16^o to the ecliptic plane which, on a rotating platform, allowed the mapping of the zodiacal light, and the identification of CMEs through rather basic mapping (see e.g. Jackson and Leinert, 1985). Despite the limitations of the imaging system for such work, the photometers were used to detect some 200 CMEs in 9 years of operation and, in many cases the line of site was such that imaging could be performed at large angles with respect to near-Earth coronagraphs. This, for example, confirmed that loop-like CMEs viewed from Earth had about the same depth in longitude as latitude, and allowed mass measurements which were commonly in excess of those determined from coronagraph data of the same events (for more details, see e.g. Jackson, 1992, and refs. therein). Whilst not providing the coverage of a traditional coronagraph, this work has highlighted the tremendous potential for viewing CMEs from differing angles.

One feature of solar activity, which has intrigued us since the discovery of CMEs is their relationship to flares. The problems of projection, foreshortening, and, to be honest, scientific bias, originally led to a strong belief that flares were the cause of CMEs, that is, CMEs are the response to flare activity in the low corona. It was shown, principally through the analysis of coronagraph and X-ray observations in the mid-1980s, that this scenario was in error. The close association between flares and CMEs was not in question; it was the cause and effect that was under investigation, and it became clear that flares are not the cause of CME activity. It became clear that many CMEs are not accompanied by H-alpha or X-ray flares (Munro et al, 1979; Webb and Hundhausen, 1987). Indeed, some early analyses of CMEs with associated flares, suggested that the CME-drives-flare scenario may be the case (e.g. Harrison, 1986). An excellent review of the state of play in the early 1990's was produced by Kahler (1992). However, more complete, subsequent studies appear to reveal that rather than there being a cause and effect relationship between flares and CMEs, they should be seen as different coronal responses to a common driver, such as magnetic shear or twist (e.g. Harrison, 1991, 1995, 1996).

The debate about the relationship between CMEs and flares spilled over into the debate about the causes of geomagnetic disturbances, and the so-called 'flare-myth' was brought to the fore by Gosling (1993). The main result of this was a new emphasis on the CME as a primary solar event generating geomagnetic distrurbances.

However, it would be wrong to state that all of the views mentioned above are universally accepted and there are many papers still using phrases such as ‘large flares almost always produce a CME, but small flares rarely do’ and ‘if the flare produces a CME…’ (quotes from Forbes, 2000), which imply that there is a cause and effect relationship, and there are studies in the current literature which suggest, or appear to suggest, a flare-driver for the eruption process (e.g. Khan and Hudson, 2000; Foley et al. 2001).

The flare/CME relationship is a special one in the sense that to understand the relationship would provide a significant boost to understanding the onset mechanisms for both. This is the case for the flare-causes-CME scenario, the CME-causes-flare scenario and the flare and CME caused-by-common-driver scenario. Thus, special emphasis has been put on studying this relationship over the years, and the aim of this review is to assess where we are now in understanding the flare-CME relationship, after 6 years of SOHO operations. In the next section, we summarise the basic understanding at the time of the launch of SOHO, and in the following section we select some recent studies to illustrate the current state of our research.

BEFORE SOHO

In the years before SOHO, Yohkoh and TRACE, many papers involving multi-wavelength observations of CMEs and underlying source regions, centred on observations using the Solar Maximum Mission (SMM). Many authors were coming to similar conclusions regarding the flare-CME question, and these conclusions were listed in the review of flares associated with CMEs presented by Harrison (1995), shortly before the SOHO launch. We use this list as a benchmark, to compare to new results from the SOHO-era. The Harrison (1995) paper was a statistical study, building on experience gained from studies of individual events over previous years. The most basic conclusions were the following:

(a) There is a strong association between flares and CMEs, though it is clear that many CMEs are not flare related.
(b) Flares associated with CMEs can be of any duration, but the longer the flare duration the greater the chance that it is associated with a CME.
(c) The onsets of flares associated with CMEs can be at any time within several tens of minutes of the associated CME onset, i.e. before or after the CME onset.
(d) Flares associated with CMEs may lie anywhere under the CME-span, or even just outside the CME span; there is no preference for the flare to lie under the core of the CME.
(e) The CME source region (the original source of the CME mass, encompassed by the legs of the CME) is commonly much larger than an active region or flare-site, though it frequently encompasses an active region.
(f) Most flares are not associated with CMEs.

These are conclusions, which have been found by others, for example, Hundhausen (1996). Harrison attempted to prescribe the scenario for the CME-flare relationship, which was emerging from these conclusions and many associated studies of the late 1980s and early 1990s with the following statement (Harrison 1996, 1995): “The flare and CME are both consequences of the same magnetic ‘disease’. They do not cause one another but are closely related. Their characteristics are the results of local conditions, and thus we may witness a spectrum of flare and CME properties which are apparently unrelated, even resulting in events without the flare or CME component."

Harrison suggested that one should consider the source region as a complex magnetic hierarchy and that a single driver, such as shear or twist, may generate a situation where the response in different parts of the hierarchy results in the CME and the flare. The characteristics of each are dependent on the initial configuration, and this includes the onset timing, and the location, in addition to speeds and intensity. The complexity of the system dictates the very existence of the flare or CME component. Thus, it makes no sense to talk of cause and effect, the flare and CME are very closely associated but are different manifestations of the same driver.

It would be wrong to suggest that these conclusions were accepted by everyone, but the research which led to these conclusions was certainly compelling and this CME-flare association scenario was a popular one. Hence, we hold this up as the 'new' scenario, in the mid-1990s, to be tested by the SOHO-era observations.

WHERE ARE WE NOW?

SOHO has provided a wonderful opportunity to observe the solar atmosphere in a wide range of wavelengths simultaneously, with imaging and spectroscopic capabilities, and no orbital eclipses. The potential for CME onset studies was well understood before launch and several multi-instrument campaigns were designed, based on the experiences with SMM. Many SOHO observational campaigns were started in the initial months of operation (after April 1996). In the case of CME campaigns, especially during periods of low solar activity, this involved long periods of sit-and-stare operations on potential CME target areas, repeated on many occasions. With the increased skill in selecting targets and in using the instruments together, combined with the co-ordination with other missions such as Yohkoh and TRACE, and the increase in solar activity in the lead up to the recent maximum, we now have many multi-wavelength data-sets well suited to the study of CME onsets and the CME-flare relationship.

We summarise a few of the observations and results here. It is recognised that it is not possible to cover all published work because of the volume of the CME literature resulting from the increased interest in CMEs. The author apologises for any major omissions, but it is hoped that the work referred to here does cover the essence of the current state of CME onset research. It is stressed that the current review is concerned with the flare-CME relationship in particular. Some areas of work, such as the study of sigmoidal morphology, EUV and X-ray dimming and LDEs, are discussed separately, and then some individual studies are reviewed.

Sigmoidal Morphology

Rust (1996) examined soft X-ray, large, transient brightenings detected using Yohkoh near disc center and showed that many were sigmoidal in shape, i.e. 'S' - shaped or reverse 'S'-shaped. He showed that there was a preferred topology for each hemisphere, with reverse 'S'-shaped brightenings dominating in the northern hemisphere and forward 'S'-shaped brightenings dominating in the south at the time of the observations. He pointed out that the hemispherical segregation is consistent with the twisting patterns also detected in H-alpha filaments, and he suggested that the magnetic fields in the X-ray emitting, coronal brightenings were also twisted. This led to the suggestion that CMEs erupt because of MHD helical kink instabilities. This generated some interest in sigmoidal structures.

Again, using soft X-ray observations from Yohkoh, Canfield et al. (1999) announced that active regions with a sigmoidal shape indeed possessed higher probabilities for eruption. This resulted in a great deal of excitement regarding the potential for CME onset prediction and the modelling of CME onsets, and generated a period of intense study into the nature of sigmoidal shaped active regions.

Canfield et al. selected active regions from 2 years of data, which could be well viewed over long periods, 117 in all, and classified each as either sigmoidal or non-sigmoidal. Some 52% of the active regions were classified as sigmoidal. All of the active regions were also classified as eruptive or non-eruptive, as defined by the appearance of

X-ray arcades or cusps. From this, it could be seen that 65% of the eruptive active regions were sigmoidal. Stating the figures in another way, 84% of the sigmoidal regions were classed as eruptive and 50% of the non-sigmoidal regions were classed as eruptive. Thus, there is an association between sigmoidal structure and eruptive activity.

Two points must be made at this point. First, the Canfield et al. study did not use coronagraph data. The eruptive nature was defined by the morphology and evolution of soft X-ray structures, and it is not known how many of the eruptive events were related to CMEs. Second, the study was concerned with active region morphology and the study of eruptive activity within an active region. The average CME size is far in excess of that of an active region suggesting a source which is much larger than an active region (alone) (see e.g. Harrison, 1986) and the relevance of that to the sigmoidal analysis needs to be considered.

Hudson et al. (1998) included coronagraph data in a sigmoidal structure study. They selected LASCO halo events in the period December 1996 to May 1997 in order to identify a set of clear on-disc source regions. Of the 11 halo events, 7 had identifiable X-ray features at consistent locations on the disc; the remaining events were assumed to be directed away from Earth. Hudson et al. claimed that studies of the 7 events showed evidence for a characteristic sigmoidal pattern, evolving into an arcade, presumably in response to the CME eruption. In all cases, the activity was associated with a flare. However, the flare X-ray maximum intensity ranged from A1 to M1. Hudson et al. also identified patches of dimming in the X-ray images (see below). The paper did not show any LASCO images of the halo events and did not provide clear image sequences to demonstrate the sigmoid-to-arcade development of the source regions. This was unfortunate, because it is essential to link clearly the sigmoid analyses to coronagraph data to confirm the sigmoid-CME relationship; this is the key element of the work.

The demonstration of the imaged structure of four of Hudson et al.'s events was left to Sterling et al. (2000). The events were shown using X-ray and EUV data from Yohkoh and SOHO. Note again that in each case there was a flare confined to the sigmoidal configuration. It has to be said that the classification of an active region as sigmoidal or non-sigmoidal is rather subjective and may depend on the line-of-sight and any forshortening. However, for one event of the Sterling et al. and Hudson et al. studies, that of 19 December 1996, the sigmoidal shape of the X-ray features is beyond doubt, and its evolution to an arcade between approximately 15:45 UT and 16:20 UT is quite apparent. For that event, the halo CME was first detected by LASCO's C2 instrument at 16:30 UT and a straight projection to the flare site suggests a CME onset at about 15:35 UT. The GOES flare onset appears to be about 15:10 UT, with a flare duration of about 3 hours. These events appear to be well related and the sigmoid-to-arcade evolution seems to be closely associated with the eruption of a CME in an active region, which is flaring.

However, there are two concerns. First, the size of the sigmoidal active region is shown to be about 200 arc seconds. We have no measure of the angular spread of a halo CME, but for an average CME of 45 heliographic degrees, the source region may be expected to be of size about 750 arc seconds. Thus, surely for most CMEs, we must be looking for source regions which are much larger than active regions. This does not preclude the association of this particular active region with the CME, even if the CME's source was much larger than the active region. However, the fact that most sigmoidal structures, which are being associated with CMEs in the research literature, must be only part of the source region is almost ignored by the authors. We note that this is the case for the other three events of the Sterling et al. study as well. Second, the 19 December event is the best example of a sigmoid-to-arcade development and this author for one finds it rather difficult to accept a sigmoidal classification for the other three events shown by Sterling et al. The classification is rather subjective. Having said that, the events shown do demonstrate some X-ray restructuring in association with a CME onset and a flare. It should also be pointed out that the study was deliberately restricted to events showing the sigmoid-to-arcade evolution in order to investigate the physics of such events. This is a fair procedure as long as the community is aware that it is pre-selecting the sigmoidal events in this way. The Sterling et al., study concluded with a cartoon model showing the basic idea for a sigmoidal configuration evolving to an arcade during an eruption.

Sterling (2000) reviewed the sigmoid studies and stressed the following three conclusions:

(a) Pre-eruption sigmoids are more prominent in soft X-rays than in EUV (suggesting that the hotter plasmas are confined to the basic sigmoidal structures);

(b) Sigmoidal precursors are present in over 50% of CMEs;
(c) Some CMEs have no associated sigmoidal structure and no prominent soft X-ray signature.

Remembering the pre-SOHO CME studies (above) the last point should be no surprise.

One issue which has been hotly debated is the question of line of sight. Given that the most basic coronal structure is the loop and given the complexity of the solar atmosphere, is it not true that a sigmoidal classification could be made in error, quite frequently, simply because of the particular orientation at the time of observation? This has been a common criticism, which was taken up by Glover et al. (2000). Using LASCO, EIT and H-alpha data, Glover et al. attempted to reclassify active regions as 'sigmoidal', 'non-sigmoidal' and 'appearing to look sigmoidal due to projection'. They still came to the conclusion that the sigmoidal regions were well associated with CMEs but stressed a requirement for a quantitative observational definition of the term sigmoidal, and stressed the need for better spatial resolution in determining sigmoidal topology.

Despite the concerns of projection, subjectivity etc… the basic association between the sigmoidal active regions and an increased chance of CME occurrence seems to be sound. However, one major question remains. Is it the sigmoidal structure itself of the active region that is related to the CME and flare onset, or is the sigmoidal shape simply an indicator of a magnetically complex active region which due to its complexity has a greater chance of an association with an eruption and a flare? If the latter is true, then modelling the sigmoidal configuration will not necessarily provide answers to the CME and flare onsets or their relationship, i.e. it is not the sigmoidal shape that is important, just the complexity of the magnetic structure. This complexity could be due to shear, to the interaction of magnetic structures or to the excessive twist in a filamentary structure.

Coronal Dimming

It is natural to examine X-ray or EUV coronal images to look for the low coronal effects of CMEs. Rust and Hildner (1976) observed an X-ray transient and depletion event on the limb, associated with a CME. Rust (1983) followed this up and coined the phrase 'transient coronal holes', identifying many transient dimming events in the Skylab X-ray images. Noting the 21 brightest X-ray enhancements or Long Duration Events from a list by Webb, he found that in 11 cases there was a transient coronal hole nearby (within 0.2 solar radii); in 7 cases there was ambiguous evidence for a transient coronal hole, and in only 3 cases was no transient coronal hole identified. Assuming a close link between the X-ray Long Duration Events and CMEs, this suggests an association between CMEs and these low coronal depletions. Further evidence for such depletions has come from Yohkoh, also in X-ray images (e.g. Watanabe et al., 1992).

In recent years, the dimming of the corona in X-rays and EUV under CMEs has been reported in many studies using SOHO and Yohkoh (Harrison, 1997; Sterling and Hudson, 1997; Gopalswamy and Hanaoka, 1998; Zarro et al., 1999; Harrison and Lyons, 2000). The dimming events have been identified using imagers (X-ray and EUV), but the particular advance due to SOHO is the observation using spectroscopy, which has been particularly useful for confirming that the dimming is due to mass loss rather than temperature changes. Harrison and Lyons (2000) examined the spectroscopic details of a dimming region, using the SOHO CDS instrument under a modest CME event detected by LASCO. The analysis of a number of emission lines confirmed that the mass-loss due to dimming was approximately equal to the mass of the overlying CME, that the position angle and width of the CME were consistent with that of the dimming region, and that the dimming onset and CME onset were near in time. This analysis was for one event, which was not flare-related. This work has now been extended, by Harrison et al. (2003), who have identified five dimming events under CMEs, using EUV spectroscopy and found mass losses consistent with the overlying CME masses.

Why is the dimming so important, and, what relevance has it to the flare-CME relationship? The importance of the dimming question was reviewed by section 1 of Harrison et al. (2003). It effectively allows an identification of the source region of a CME and thus a thorough analysis of these source regions prior to, during and after the dimming/eruption, could provide major insights to the CME onset question.

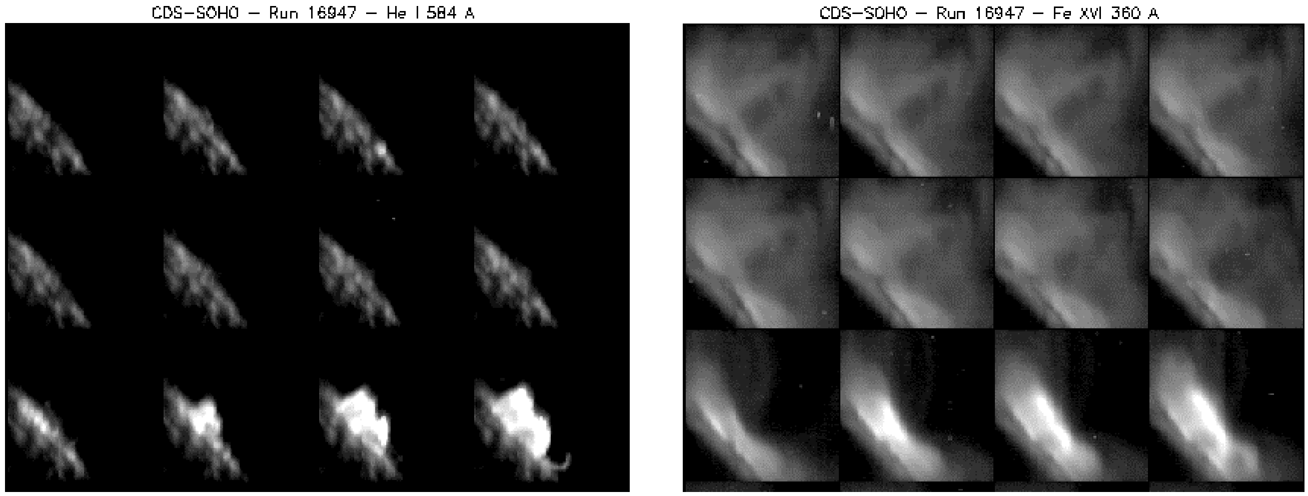

Fig. 2. Two 12 image 4 arcmin x 4 arcmin sequences of the north-west limb on 25 July 1999. The left-hand panel shows images with 16 minute cadence (top left to bottom right) starting at 11:03 UT utilising the 20,000 K He I 584 Å emisson line. The right-hand panel is identical, but for the 1 million K Mg IX 386 Å line (Harrison et al., 2002).

That being the case, what about the flare? In the Harrison et al. (2003) study, only one of the dimming events was associated with a flare, that of 25 July 1999. This stresses the fact that many CME events are not flare related. The 25 July event occurred on the solar north-western limb where a bright flare arcade was observed. The image sequence from CDS is shown in Figure 2 for the 20,000 K He I 584 Å and 1 million K Mg IX 368 Å emission lines. The flare can be seen clearly late in the He I sequence, as a bright arcade. Prior to the flare, weak, large EUV arches could be seen, in the Mg IX data, gradually ascending above the flare-site at approximately 20 kms^{-1}. The coronal dimming can be seen clearly in the 9th frame of the Mg IX data; it is characterised by the weak loops suddenly disappearing. The dimming is at the projected onset time of the CME and appears to lead the flare onset. So, this event was seen as a sudden dimming of the corona, off-limb, above an active region, using spectroscopic EUV observations, but with a limited field of view. The CME itself is shown in Figure 3. It is clearly associated with the flare-site but is almost certainly involving a much larger source region. The dimming is shown by Harrison et al. (2003) to represent the loss of up to 3.4×10^{12} kg. The Sterling and Hudson (1997) and Zarro et al. (1999) dimming observations also include a flare, that of 7 April 1997, which was one of the halo events discussed above. X-ray dimming was identified in pockets on either extreme of a sigmoidal region, which had flared. A mass was calculated from the missing intensity, which was much smaller than the anticipated mass for the overlying CME. This raises the questions: (a) how accurate is the mass calculation when estimated using wide-band observations rather than spectroscopic means, and (b) observations of dimming against the disc may be underestimated due to the loss of emission in the corona which may not be viewed efficiently due to line of site considerations; observations off the limb may provide the best estimates of coronal mass-loss, but are not suited to studies of the morphology of the associated regions. The Sterling and Hudson, and Zarro et al. dimming 'patches' are not only smaller than the associated active regions but are tiny compared to the associated CME scales. It is difficult to see how they relate. How relevant are sub-active region dimming patches when compared to the CME process?

To understand the CME source region better, the improved observation of the coronal dimming under CMEs would seem to be a very high priority. This must be done with both imaging and spectroscopic means. As a natural consequence of such observations, any associated flare activity will be viewed. In determining the flare's association with the dimming phenomenon, we may understand better the flare-CME relationship.

The Long Duration Event

Many researchers talk about the 'LDE' or long duration event, as though it is a distinct class of flare, and believe that the association between LDEs and CMEs is one to one. For example, the study by Rust (1983) mentioned above found an association between transient coronal holes and LDEs, and translated that to a CME-transient coronal hole association. However, the LDE is an event-type which has never been well defined. Harrison (1995, section 6) showed that many different LDE definitions are in use, and, furthermore, that statistical studies of flares have never identified a distinct class of long-duration flare. Thus, the association of CMEs with flare duration was explicitly studied (Harrison, 1995) and the conclusion, as reported above, was that the *longer* duration flares had a greater chance of being CME-associated. This is an important result because it suggests a physical link between the flare and CME processes, but it does not suggest that there are fundamentally different flare types. Certainly, this author feels that the term LDE is misleading and ought to be dropped. However, it is in common use. For example, all of the 7 flares associated with the halo CMEs of the Hudson et al. (1998) study (which includes the four events of Sterling et al. (2000)) were classified by the authors as LDEs.

If we are to use the term LDE, we must (a) accept that it refers to one part of the flare-duration spectrum, and not suggest that it is a different event-type without clear evidence to that effect, (b) we must identify a definition for the LDE which can be commonly agreed, and (c) we must not forget that CMEs can be associated with flares of any duration or even no flares. For more detailed arguments, the reader is referred to section 6 of Harrison (1995).

Individual Studies

We now describe a number of papers which must be mentioned separately, either because they bring out specific points which are not related to the issues already discussed, or because they encompass many of the major issues in a single study.

The first paper we report on is the paper by Zhang et al. (2001) which attempts to bring together a unique set of multi-wavelength observations for a set of four CMEs. They use data from LASCO and EIT on SOHO, as well as the X-ray data from the GOES spacecraft. The observations are made of CMEs originating near the solar limb, but the key feature of the study is the use of the C1 coronagraph of the LASCO instrument. C1 is the innermost coronagraph of LASCO, which was lost in mid-1998. C1 allowed observations down to 1.1 solar radii of Sun-centre. By far the majority of LASCO data-sets used for onset studies are restricted to an inner limit of 2 solar radii (the C2 inner edge) because the loss of C1 occurred prior to the build up of CME activity for the current maximum. There are few events where we have clear CME observations down to 1.1 solar radii combined with ‘surface’ observations in X-rays or/and the EUV, so the study of Zhang et al. is particularly important both to investigate the lowest altitude activity and to test past thinking.

The time-altitude curves of the LASCO data, including data from all three coronagraph components of the instrument, show clear profiles for the events reported by Zhang et al. Three of the events show a three-phase ascent. First, the ‘initiation phase’, displays a gradual expansion in the CME loops at speeds of under 80 kms^{-1}. The events under study show initiation phases lasting from half an hour to 2 hours. This phase is followed by an ‘impulsive acceleration’ phase during which there is a sudden increase in the CME speed of ascent, at altitudes in the range 1.3 to 4.6 solar radii above Sun-centre. For the events in question, this coincides in time with the onset and rapid rise in intensity of an associated flare. This is followed by the ‘propagation phase’, where the events ascend at constant or near-constant velocities. It should be noted that the fourth event discussed by Zhang et al. appears to display the impulsive acceleration phase and propagation phase only.

Zhang et al.’s time-altitude profiles assume that the bright C1 loops are identical to those seen in the outer coronagraphs. C1 is an emission line coronagraph, utilising the 2 million K Fe XIV 5303 Å emission line, whereas the outer coronagraphs are white-light coronagraphs sensitive to Thomson scattered photospheric light. Thus, C1 is sensitive to the square of the density of 2 million K plasma, whereas the other coronagraphs are sensitive to electron density alone. This does mean that care must be taken in the projection of structures from C1 to the outer coronagraphs, but the association appears to be strong in this case because of the well-defined loop structures. In addition, Zhang et al. show the flare-sites relative to the C1 CME images, which demonstrate a flare-CME asymmetry, which appears to confirm the pre-SOHO scenario. It should be noted also that the CMEs even at the lowest altitudes are much larger than flares.

Zhang et al. conclude the following:

(a) The results reject the scenario where CMEs are driven by flare-induced coronal responses, because the initiation phase of the CME is clearly pre-flare;
(b) The initiation phase may be caused by the destabilization and quasi-static evolution of a large-scale coronal magnetic structure;
(c) If a critical point is reached, violent magnetic activity may be triggered that induces the magnetic force to drive the CME, whilst simultaneously triggering the flare;
(d) CMEs and flares are two different manifestations of the same magnetic process; they have a strongly coupled relationship but not a cause and effect one.

They point out that the projections required to cater for the larger occulted regions of pre-SOHO observations gave cause for some controversy. However, it is interesting to note how similar their conclusions are to the pre-SOHO scenarios given above. In other words, the SOHO data in this case have served to apparently confirm the scenarios listed by Harrison (1995, 1996) and others in the pre-SOHO era.

There are studies where ascending structures in X-ray or EUV coronal imaged data have been linked to overlying white-light CME structures but this is always fraught with difficulty. Thus, the coronagraph-coronagraph comparison of the Zhang et al. work, to such low altitudes is extremely valuable. Using Solar Maximum Mission data, Harrison et al. (1985) identified ascending X-ray emitting plasma at the time of projected CME onsets. They concluded that the ascending hot plasma may well have been part of the ascending CME structure and that it suggested that there was early acceleration in the event. The events they studied showed a large X-ray arch with a subsequent flare in one footpoint. We are now seeing further evidence for such activity, within remarkably similar topologies. Alexander et al. (2002) studied activity associated with an X1.2 flare and a CME on the south-eastern solar limb, using Yohkoh X-ray data, in comparison to SOHO coronagraph data. Their event also consisted of an X-ray coronal arch extending from the brightest region of the flare. The arch showed signs of an ascent consistent with the CME, but showing significant acceleration. However, the CME extended between two active regions, AR8214, north of the equator and AR8210, south of the equator, and the ascending X-ray loop, and the X1.3 flare were confined to AR8210. Alexander et al. (2002) note this and state that it is not clear how the accelerating, ascending X-ray structure relates to the white light structure of the CME. These low altitude studies are invaluable in that they are able to provide information of the region from which the CME mass originates, but the comparison of X-ray or EUV activity and structure, with higher altitude white-light activity and structure is not easy.

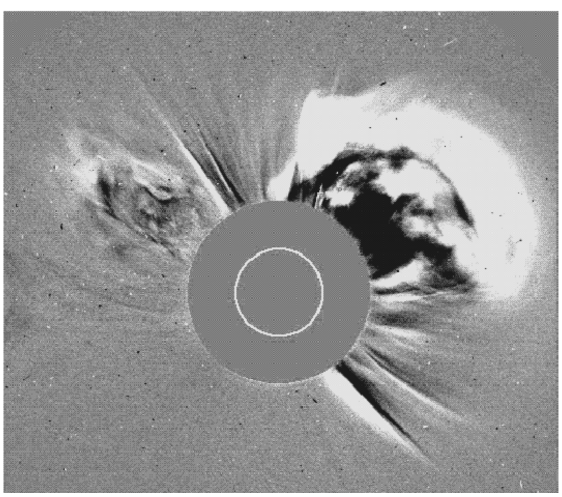

Fig.3. The 25 July 1999 CME detected by LASCO. The principal event was in the north-west, but effects from the event, as well as associated eruptions, were detected across a broad range of position angles.

The event of 25 July 1999, discussed above, and shown in Figures 2 and 3, shows very similar characteristics to those of Zhang et al. However, in the absence of available C1 data, the lowest altitude loops, in the initiation phase – as labelled by Zhang et al. – are detected to be ascending slowly using observations in the 1 million K Mg IX 368 Å emission line detected by the SOHO CDS instrument. These loops were detected prior to the flare, ascending at a speed of approximately 20 kms^{-1}. The CME, shown in Figure 3, was later measured to be achieving speeds of up to 1118 kms^{-1}. As discussed above (Figure 2), at the time of flare onset the corona above the flare site showed significant EUV dimming, which was effectively due to the sudden disappearance from the CDS field of the ascending loops. This was at the projected onset time of the CME, which is consistent with Zhang et al.'s impulsive acceleration and propagation phases.

The work of Khan and Hudson (2000) is also discussed here because it is one of the few studies that considers the true large-scale nature of CME source regions. They used Yohkoh X-ray images in conjunction with LASCO data and showed three events where active region interconnecting loops disappeared in association with a flare event in one active region and with an overlying CME. Their interpretation of the morphology and timing was that flare-generated shocks may destabilize an associated active region interconnecting loop, which becomes the source of the CME. The asymmetry is clearly akin to that suggested by the pre-SOHO studies, and often seen in more recent studies. The timing, however, certainly puts the flare onset first; it is seen as the driver of the event sequence - at least for the events in question. Given the fact that many CMEs are not flare related and that some flares certainly start well after the onset of the initial CME ascent, this cannot be a general picture.

However, the fact that Khan and Hudson demonstrate a link between a coronal feature much larger than an active region, and a CME is important. Again, it is interesting to note that SMM studies had suggested that active region interconnecting loops were a most likely the source of CMEs (Harrison, 1986) and that there was evidence for ascending X-ray fronts (Harrison et al., 1985) – these are both conclusions now made by Khan and Hudson. The one major difference between the work of Khan and Hudson and many other reports is that they believe that the flare initiates the CME onset.

Another flare-related CME was reported by Foley et al. (2001). They studied the X2.3 flare of 10 April 2001, which was south of Sun-centre and was thought to be the source region of a halo CME. Their study included observations which showed an EUV spike-like jet of material heading southwards from the flare-site. Their spectroscopic observations allow a velocity analysis of the event, which they interpreted as an ascending flux rope travelling at up to 480 kms^{-1}. Apart from the fact that the activity during this event involved a flare, a halo CME and a velocity event seen using the CDS instrument, there is no evidence to link the CDS velocity event to the halo CME. The CDS data showed a very narrow spike-like jet, which is a feature reported on numerous occasions (e.g. Pike and Mason, 1998; Harrison et al. 2001) and such a small jet is very unlikely to represent the EUV counterpart of the eruption that becomes the halo CME. If it was, the projected onset times of the CME and the flare coincide. However, a further study of the event by Pike and Mason (2002) concluded that the EUV jet was a flare spray; this cannot be related directly to the CME material or the CME onset without further evidence.

Plunkett et al. (2002) discuss the EUV signatures of CMEs, specifically referring to the EIT instrument on SOHO (Delaboudiniere et al., 1995). They identify the common signatures as (i) dimming, (ii) the formation of bright post-eruption arcades or loops, (iii) erupting filaments, (iv) the expansion of pre-existing loops or arcades, and (v) large-scale wave disturbances. The nature of dimming associated with CME source regions is discussed above. The EIT observations of filament eruptions, using the He II 304 Å filtered images with typical temperatures in the 80,000 K range, can be identified clearly. However, the overlying CME structure is not so easy to identify and many CMEs do not include filament or prominence eruptions. With regard to loop expansions, post-eruption loops etc… identified in the EUV, as Plunkett et al. note, the precise relationship between the various EUV signatures to the structures observed in white light by the coronagraphs is very unclear at present. Great care must be taken in comparing the two wavelength regions. The EUV observations are restricted to the detection of plasma at specific temperatures whereas the white-light observations are sensitive to density alone. A careful comparison of LASCO CME and EIT eruptive activity has been made by Delannée et al. (2000). They did not conduct a study of the CME-flare relationship specifically, though 9 of their events were flare-related. Their principal aim was to identify a set of EUV eruptive events and look for LASCO counterparts. In this, they were somewhat successful, but the precise CME-flare relationship study required that the projected onsets and relative locations be investigated further. However, it is important to note that of 17 EUV eruptions, 13 were found to be closely associated with CMEs.

As Plunkett et al. conclude, ‘some CMEs have no EUV signature, even when there is good reason to believe the source region is on the visible side of the solar disc, and other EUV eruptions do not correspond well with white-light CMEs’. This stresses that a CME must never be identified by anything other than a white-light coronagraph, at least until we are clear about the relationship between CMEs and other activity. This is stressed because it is becoming more common to see any outward expanding feature labelled as a CME even without supporting coronagraph data. However, studies such as that by Delannée et al. do suggest that we are making good progress.

The identification of large-scale EUV wave disturbances, or EIT waves, is an important one. These events are probably identical to those detected in coronagraph data, where the impact on surrounding coronal structures can be seen (e.g. St Cyr and Hundhausen, 1987). Plunkett et al. (2002) suggest that they are probably fast-mode MHD waves that propagate outward from the CME initiation site. The waves are detected in differenced EUV images as disturbances propagating outward from a CME/flare site, often crossing the entire solar disc (see Thompson et al., 1998; Delannée et al., 2000). The possible role that such waves may play in the CME-flare relationship is unclear. If the wave is a response to the CME initiation (probably to the impulsive acceleration phase – as suggested by Zhang et al.), then there may be no such role. However, the Khan and Hudson (2000) study did call upon a front propagating from the flare site, which destabilised an active region interconnecting loop system. Could this be the EIT wave? Certainly, there is a strong association between the EUV waves and type II radio bursts, suggesting that both are signatures of a coronal shock wave associated with a flare (e.g. Klassen et al., 2000). This suggests that the EUV wave association with the CME is linked through the flare-CME association, rather then the EUV wave being a direct result of the CME.

DISCUSSION

The first conclusion to make is that the pre-SOHO scenario has indeed been supported by many recent studies involving far more sophisticated instrumentation. The idea that the flare and CME do not cause one another but are different responses to the same driver has become a common conclusion, with some exceptions (e.g. Khan and Hudson, 2000). The close association between flares and CMEs was never in question but there are always 'flareless' CME events. Certainly the view that longer duration flares have a greater chance of CME association appears to be upheld, as do the pre-SOHO conclusions about relative flare-CME locations and asymmetry.

So, what is new from the recent observations? The identification of sigmoids as potential CME sources has generated some excitement, but is this simply another way of saying that the more complex active regions have a greater chance of CME generation? There needs to be a more quantitative way of defining a sigmoidal region and thorough statistical analyses must be performed on their association with CME and flare activity to establish whether it is the sigmoidal shape or just the complexity that is important.

The detection of EUV dimming using spectroscopic techniques is extremely important because it suggests that we can identify the CME source region and investigate its plasma characteristics. If this is the case, we can study the pre-event activities of the region and obtain information on the nature of the flare and CME activity from that region. Many of the detailed dimming studies so far have not included flare-associated CMEs but it is essential that we investigate this topic with the flare-CME relationship in mind. This has not been done effectively to date but we do have many relevant observations and the potential to make more, so this should be an area to watch out for key development on the CME/flare question.

One association, which is commonly accepted is the association between flares of longer duration and CMEs. As mentioned, the evidence suggests that the chance of a CME association increases with flare duration, but any flare can be CME-associated. Thus, whilst recognising the association, we must take care to not use the term LDE to denote an event which is a different flare class. This was a point made prior to the launch of SOHO and it is as important to establish it now.

Another new aspect is the three phase CME ascent shown by Zhang et al. (2001), which made use of the low-altitude C1 observations. Their suggestion of a CME initiation phase, followed by an impulsive acceleration phase and a propagation phase fits well with many aspects of the pre-SOHO picture. They concluded that the flare and CME events were driven by the same magnetic driver. They also demonstrated that the CME activity, for three of their events, was certainly initiated before the associated flare.

Khan and Hudson (2000) suggested a scenario which had been discussed previously using SMM data, that of the active region interconnecting loop as a source for CMEs. This fits well with the pre-SOHO picture of the flare-CME asymmetry and the relative sizes of the flare and CME. However, their picture demands that the flare be the initiator of the event sequence. This is at odds with many other studies but, before we assume that there must be an error in interpretation, we have to keep in mind that there may be more than one way to generate a CME!

Finally, as demonstrated by the review by Plunkett et al. (2002) and by Thompson et al. (1998) and Delannée et al., (2000) we are making some headway in associating EUV coronal activity with CMEs, but there is a long way to go.

CONCLUSIONS

Much could be said about the current state of CME onset research, but the following points are perhaps the most important to stress:

(i) Many authors claim to detect signatures of CME onsets without detailed correlations with CME data or without evidence to provide convincing links between the surface activity and the CME events. This is especially worrying. Good examples of attempts to perform detailed correlations between CMEs and underlying activity are Delannée et al. (2000) and Zhang et al. (2001). Claims of associations must be supported by clear demonstrations of links in time or space; for example, it is not sufficient to say that there was a CME and we see an EUV outflow so it must be the CME onset.

(ii) Perhaps the most significant result of recent CME-onset research is that the pre-SOHO scenario (see above), has, in general, been upheld by the results of studies from the SOHO era.

(iii) New results include the detection of features such as EUV and X-ray dimming (especially using spectroscopy), EUV waves and sigmoidal morphology, and the relevance of these to the CME-flare relationship is discussed above. Another new result is the three-phase CME ascent suggested by Zhang et al., which explicitly couples the flare and CME in a scenario where there is a common driver. It is this author's belief that the dimming work, in particular, holds a key to linking the CME onset and the flare and it is certainly desirable to obtain more results in support of the Zhang et al. time-altitude analysis, which was done with only 3 events.

(iv) One aspect of CME-onset research which is often ignored is the scale of the CME versus the scale of the flare or active region. In particular, the sigmoidal morphology studies almost invariably talk of one active region as the CME source even though the projected source area may be 5-10 times the size of a single active region. However, some studies do take this into account or show the scale of the CME clearly against the scale of surface features (e.g. Khan and Hudson, 2000; Delannée et al., 2000).

As is often the case, we find ourselves supporting past results and raising more questions. Given the tools we have available, with SOHO in particular, there is no reason why we cannot expand the onset studies, in particular to investigate the dimming process, to confirm the three-phase scenario of Zhang et al., to extend the EUV and white-light associations started by Delannée et al. and others, to investigate the nature of active region interconnecting loops, etc…. We have the ability to do this now.

New aspects of CME-onset research will emerge with the advent of the STEREO and Solar-B missions, especially if we still have SOHO in operation. Most of the studies I have mentioned involve near-limb observations with the problems of foreshortening. In most CME onset studies, for example, there is no chance of using magnetograph data. However, with spacecraft at different viewing angles, on and off the Sun-Earth line, we may be able to detect CMEs near the limb whilst observing the source regions on the disc from other platforms. The Helios observations were a forerunner of this. This 'new view' will open up totally new aspects of CME onset research, but will also introduce complex problems of event recognition from different angles. However, this will open up the next chapter in CME onset research, to which we can look forward.

REFERENCES

Alexander, D., T.R. Metcalf, and N.V. Nitta, Fast acceleration of a CME-related X-ray structure in the low solar corona, *Geophys. Res. Lett.* **29**, 10, 41 1-4, 2002.

Brueckner, G., R.A. Howard, M.J. Koomen et al., The Large Angle Spectroscopic Coronagraph (LASCO), *Solar Phys.* **162,** 357-402, 1995.

Canfield, R.C., H.S. Hudson, and D.E. McKenzie, Sigmoidal morphology and eruptive solar activity, *Geophys. Res. Lett.* **26,** 627-630, 1999.

Delaboudiniere, J.-P., G.E. Artzner, J. Brunaud et al., EIT: Extreme Ultraviolet Imaging Telescope for the SOHO mission, *Solar Phys.* **162,** 291-312, 1995.

Delannée, C., J.-P. Delaboudiniere, and P. Lamy, Observation of the origin of CMEs in the low corona, *Astron. Astrophys.* **355,** 725-742, 2000.

Forbes, T.G., Solar and stellar flares, *Phil. Trans. R. Soc. Lond. A* **358,** 711-727, 2000.

Foley, C.R., L.K. Harra, J.L. Culhane et al., Eruption of a flux rope on the disk of the Sun: Evidence for the CME trigger, *Astrophysical J.* **560,** *L91-94, 2001.*

Glover, A., N.D.R. Ranns, L.K. Harra et al., The onset and association of CMEs with sigmoidal active regions, *Geophys. Res. Lett.,* **27,** 2161-2164, 2000.

Gopalswamy, N. and Y. Hanaoka, Coronal dimming associated with a giant prominence eruption, *Astrophys. J.* **498,** L179-L182, 1998.

Gosling, J.T., The solar flare myth, *J. Geophys. Res.* **98**, 18,937-18,950, 1993.

Harrison, R.A., Solar coronal mass ejections and flares, *Astron. Astrophys.* **162,** 283-291, 1986.

Harrison, R.A., Coronal mass ejection, *Phil. Trans. R. Soc. Lond.* A. **336,** 401-412, 1991.

Harrison, R.A., The nature of solar flares associated with CMEs, *Astron. Astrophys.* **304,** 585-594, 1995.

Harrison, R.A., Coronal magnetic storms: A new perspective on flares and the 'solar flare myth' debate, *Solar Phys.* **166,** 441-444, 1996.

Harrison, R.A., Overview of results from IACG campaign 3: CME onsets, in *Proc. 31st ESLAB Symp. ESA SP* **415**, 121-129, 1997.

Harrison, R.A. and M. Lyons, A spectroscopic study of coronal dimming associated with a coronal mass ejection, *Astron. Astrophys.* **358,** 1097-1108, 2000.

Harrison, R.A., P.W. Waggett, R.D. Bentley et al., The X-ray signature of solar coronal mass ejections, *Solar phys.* **97,** 387-400, 1985.

Harrison, R.A., P. Bryans, and R. Bingham, EUV sprays: Jet-like eruptive activity on the solar limb, *Astron. Astrophys.* **379,** 324-335, 2001.

Harrison, R.A., P. Bryans, G.M. Simnett et al., Coronal dimming and the coronal mass ejection onset, *Astron. Astrophys.* **400**, 1071-1083, 2002.

Howard, R.A., D.J. Michels, N.R. Sheeley et al., The observation of a coronal transient directed at Earth, *Astrophys. J.* **263,** L101-104, 1982.

Howard, R.A., N.R. Sheeley, M.J. Koomen et al., Coronal mass ejections: 1979-1981, *J. Geophys. Res.* **90,** 8173-8191, 1985.

Hudson, H.S., J.R. Lemen, O.C. St Cyr et al., X-ray coronal changes during halo CMEs, *Geophys. Res. Lett.* **25,** 2481-2484, 1998.

Hundhasuen, A.J., Coronal mass ejections: A summary of SMM observations from 1980 and 1984-1989, in *The many faces of the Sun: Scientific highlights of the Solar Maximum Mission,* edited by K.T. Strong, et al., Springer-Verlag, Berlin, 1996.

Hundhausen, A.J., Coronal mass ejections, in *Cosmic Winds and the Heliosphere*, edited by J.R. Jokipii, C.P., Sonett and M.S. Giampapa, pp. 259-296, The University of Arizona Press, Tucson, USA, 1997.

Jackson, B.V., Solar generated disturbances in the heliosphere, in *Solar wind seven: COSPAR Colloq. Ser. Vol. 3*, edited by E. Marsch and R. Schwenn, 623-634, 1992.

Jackson, B.V. and C. Leinert, Helios images of solar mass ejections, *J. Geophys. Res.* **90**, 10759-10764, 1985.

Kahler, S.W., Solar flares and coronal mass ejections, *Ann. Rev. Astron. Astrophys.* **30**, 113-141, 1992.

Khan, J.I. and H.S. Hudson, Homologous sudden disappearances of transequatorial interconnecting loops in the solar corona, *Geophys. Res. Lett.* **27,** 1083-1086, 2000.

Klassen, A., H. Aurass, G. Mann et al., Catalogue of the 1997 SOHO-EIT coronal transient waves and associated type II radio burst spectra, *Astron. Astrophys. Suppl. Ser.* **141**, 357-369, 2000.

Leinert, C., H. Link, E. Pitz et al., Helios zodiacal light experiment, *Raumfahrtforschung,* **19**, 264-267, 1975.

MacQueen, R.M., J.A. Eddy, J.T. Gosling et al., The outer corona as observed from Skylab: Preliminary results, *Astrophys. J. Lett.,* **187,** 85-88, 1974.

Munro, R.H., J.T. Gosling, E. Hildner et al., The association of coronal mass ejection transients with other forms of solar activity, *Solar Phys.* **61**, 201-215, 1979.

Pike, C.D. and H.E. Mason, Rotating transition region features observed with the SOHO Coronal Diagnostic Spectrometer, *Solar Phys.* **182,** 333-348, 1998.

Pike, C.D. and H.E. Mason, EUV spectroscopic observations of spray ejecta from an X2 flare, *Solar Phys.* **206**, 359-381, 2002.

Plunkett, S.P., D.J. Michels, R.A. Howard et al., New insights on the onsets of CMEs from SOHO, *Adv. Space Res.* **29,** 1473-1488, 2002.

Rust, D.M., Coronal disturbances and their terrestrial effects, *Space Sci. Rev.* **34**, 21-36, 1983.

Rust, D.M., Magnetic helicity, MHD kink instabilities and reconnection in the corona, in *Magnetic reconnection in the solar atmosphere,* eds. R.D. Bentley, and J.T. Mariska, ASP Conf. Ser. **111**, 353-358, 1996.

Rust, D.M. and E. Hildner, Expansion of an X-ray coronal arch into the outer corona, *Solar Phys.* **48,** 381-387, 1976.

Rust, D.M., E. Hildner, M. Dryer et al., Mass ejections, in *Solar Flares: A Monograph from Skylab Solar Workshop II*, Ed. P.A. Sturrock, P.A., Colorado Assoc. Univ. Press. 273-339, 1980.

St Cyr, O.C. and A.J. Hundhausen, On the interpretation of halo coronal mass ejections, in *Proc. 6th Int'l Solar Wind Conf. NCAR Tech. Note* 306, eds. Pizzo, V.J., Holzer, T.E. and Sime, D.G., 235-241, 1987.

Sterling, A.C., Sigmoid CME source regions at the Sun: Some recent results, *J. Atmosph. and Solar Terrestr. Phys.* **62,** 1427-1435, 2000.

Sterling, A.C. and H.S. Hudson, Yohkoh SXT Observations of X-ray dimming associated with a halo coronal mass ejection, *Astrophys. J.* **491,** L55-L58, 1997.

Sterling, A.C., H.S. Hudson, B.J. Thompson et al., Yohkoh SXT and SOHO EIT observations of sigmoid-to-arcade evolution of structures associated with halo CMEs, *Astrophys. J.* **532,** 628-647, 2000.

Thompson, B.J., S.P. Plunkett, J.B. Gurman et al., SOHO/EIT observations of an Earth-directed CME on May 12 1997, *Geophys. Res. Lett.* **25,** 2465-2468, 1998.

Watanabe, T., Y. Kozuka, M. Ohyama et al., Coronal/interplanetary disturbances associated with disappearing solar filaments, *Publ. Astron. Soc. Japan* **44**, L199-L204, 1992.

Webb, D.F., Understanding CMEs and their source regions, *J. Atmosph. and Solar-Terrestr. Phys*. **61**, 1415-1426, 2000.

Webb, D.F. and A.J. Hundhausen, Activity associated with the solar origin of coronal mass ejections, *Solar Phys.* **108**, 383-401, 1987.

Zarro, D.M., A.C. Sterling, B.J. Thompson et al., SOHO EIT observations of extreme-ultraviolet dimming associated with a halo coronal mass ejection, *Astrophys. J.* **520,** L139-L142, 1999.

Zhang, J., K.P. Dere, R.A. Howard et al., On the relationship between coronal mass ejections and flares, *Astrophys. J.* **559,** 452-462, 2001.

E-mail address of R.A. Harrison r.harrison@rl.ac.uk