

The Initiation of Coronal Mass Ejections by Newly Emerging
Magnetic Flux

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Abstract

We present observational evidence that eruptions of quiescent filaments and associated coronal mass ejections (CMEs) occur as a consequence of the destabilization of large-scale coronal arcades due to interactions between these structures and new and growing active regions. Both statistical and case studies have been carried out. In a case study of a "bugle" observed by the High Altitude Observatory Solar Maximum Mission corona graph, the high resolution magnetograms from the Big Bear Solar Observatory show newly emerging and rapidly changing flux in the magnetic fields that apparently underlie the bugle. For other case studies and in the statistical work, the eruption of major quiescent filaments was taken as a proxy for CME eruption. We have found that 2/3 of the quiescent -filament-associated CMEs occurred after substantial amounts of new magnetic flux emerged in the vicinity of the filament. In addition, in a study of all major quiescent filaments and active regions appearing in a two month period we found that 17 of the 22 filaments that were associated with new active regions erupted and 26 of the 31 filaments that were not associated with new flux did not erupt. In all cases in which the new flux was oriented favorably for reconnection with the pre-existing large-scale coronal arcades; the filament was observed to erupt. The appearance of the new flux in the form of new active regions begins a few days before the eruption and typically is still occurring at the time of the eruption. A CME initiation scenario taking account of these observational results is proposed.

1. [introduction:

In 1859 an enormous solar flare was seen in white light. This flare was the first reported in the scientific literature (Barrington, 1859, Hodgson, 1859) and was followed, some 17 hours later, by a huge magnetic storm and brilliant aurora seen as far south as Honolulu, 21 degrees from the magnetic equator (see Kimball, 1960 for a recent study of the 1859 events). Carrington suggested hesitantly that the flare and the storm were related. The frequent observation of major solar flares preceding major sudden-onset geomagnetic storms and auroral displays lent credence to Barrington's suggestion and it was hypothesized that material was ejected from the sun and propagated to the Earth, causing the storm (Lindeman, 1919). These ideas have been found to be essentially correct. This was first demonstrated when helium-enhanced solar wind was observed marking the high speed material ejected from the sun in association with a major flare (Hirshberg et al., 1970). The strong southward interplanetary field accompanying the interplanetary disturbance was seen to drive a large magnetic storm (Hirshberg and Colburn, 1969). Later work on magnetic storms also showed that many sudden-onset storms seemed to be associated with the sudden disappearances of solar filaments (Joselyn and McIntosh, 1981).

Although indirect studies of the ejected material and its properties were made from observations of magnetic storms and the solar wind itself, it was not until Skylab carried a coronagraph into space that the ejection of the material from the sun could be observed directly. Now thousands of observations of CMEs have been made (Webb, 1992) and innumerable studies carried out. These studies reported that, although some CMEs are associated with solar flares, many more CMEs are associated with the eruption of filaments (Gosling et al., 1974, Munro et al. 1979, Webb and Hundhausen, 1987, see also the appendix for a discussion of flare and prominence association).

Recent work indicates that neither prominence eruptions nor major solar flares are the actual causes of the CME (Hundhausen, 1988). In the case of prominences Fisher et al., (1981) showed that the CME sometimes began before the prominence was accelerated and the prominence velocity was lower than the velocity of the CME leading edge. For the case of flares, Harrison (1986) found CMEs launched some tens of minutes before flare onset and Hundhausen (1988) reported that the material ejected from the chromosphere was

traveling slower than [the] CME front. Hundhausen also suggested that the associated flare or prominence eruption may be the result of the global change that produces the mass ejection. In their study of CMEs associated with active regions, Webb and Hundhausen (1987) concluded that most CMEs were related to the destabilization and eruption of a prominence and its overlying coronal structure, or of a magnetic structure capable of supporting a prominence. Hundhausen (1988) also has suggested that the CME event may be the cause of the prominence eruption,

CMEs associated with flares and with filaments are remarkably similar. Both typically consist of a bright looplike structure followed by a less bright inner region. The legs or sides of the loop are brighter than the top and contain more material (Steinolfson and Hundhausen, 1988, Steinolfson, 1992). A density depletion is seen within the expanding loop. This reinforces the notion that neither the flare nor the rising of a prominence is the direct cause of the initial destabilization of the CME. Instead, the cause should be sought in some process that is associated with both flares and prominence eruptions. Feynman and Hundhausen (1994) have pointed out that there is a very close evolutionary relationship between structures in which major flares take place and structures within which filament eruptions occur. Quiescent filaments represent a later stage in the evolution of magnetically active regions (Kiepenheuer, 1953) which Feynman and Hundhausen call "Evolving Magnetic Structures" or EMSs. Early in their evolution EMSs are characterized by spots and flaring, when the flaring ends and the spots fade, the filaments rotate and move poleward becoming very long east-west structures. This evolution typically takes 8 to 10 solar rotations. Feynman and Hundhausen suggest that CMEs take place in EMSs during all stages of their evolution. They also suggest that CMEs are associated with flares or rising prominences depending on the stage of evolution of the EMS.

Many questions concerning the processes involved in the initiation of CMEs remain unresolved and several different types of scenarios have been developed. These scenarios have been used as the basis of extensive computer modeling (see reviews by Harrison et al. 1990, Steinolfson, 1989 and Low, 1990). In some early models the destabilization of the large-scale magnetic arcade that becomes the CME was associated with sudden coronal heating due to reconnection of magnetic fields (Anzler and Pneuman, 1982, Forbes and Priest, 1983). In many models the cause of the destabilization lies in the

evolution to a non-equilibrium state of the large-scale magnetic structures (Low et al. 1982, Wolfson, 1982, Forbes and Isenberg, 1991). This evolution typically involves the shearing of magnetic fields through footpoint motion. In other models the addition of new flux to the region below the overlying closed coronal arcades plays an important role (Steinolfson, 1992, Guo et al., 1992).

In contrast to earlier studies which have examined activity occurring at the time of CME initiation (cf. Munro et al., 1979, Harrison, 1986, Webb and Hundhausen, 1987, Feynman and Hundhausen, 1994), here we are concerned with solar conditions several days before the CME release. This may be considered a "buildup phase" during which the conditions are established that cause the destabilization of the coronal structure and the formation of a CME.

In this study we find that CMEs are strongly associated with the emergence of new magnetic flux beneath or adjacent to pre-existing closed coronal magnetic structures. In the case of CMEs associated with solar flares, such an association is not unexpected since it has already been shown that solar flares are often associated with new emerging flux regions (Rust, 1976, Martin et al., 1983, Martin et al., 1984, Rust and Cauzzi, 1992) and flare models based on this observation have been developed (cf. Heyvaerts and Priest 1976 and references in the recent review by Priest, 1992). In much of the work described below we are particularly interested in CMEs associated with quiescent filament disappearances. Because these disappearances are not usually attributed to solar active regions, they can provide a stringent test of scenarios in which CME destabilization involves the interaction of the pre-existing coronal arcades with newly emerging flux.

The data sets are described in section 2 below and the data analysis is described in detail in section 3. For the convenience of the reader, our observational results are summarized in section 4. A suggested scenario for CME destabilization by favorably oriented newly emerging flux is described in section 5.

2. The data sets

The Solar Maximum Mission (SMM) data used in this study consists of the corona graph data from the High Altitude Observatory's (HAO) white light coronagraph/polarimeter. This instrument gave a projection of the corona against the sky that covered the distance

range from about 1.6 to 5 solar radii. See MacQueen et al, (1979), Csocke-poeckh et al. (1982), House et al. (1981) and Wagner et al. (1981) for descriptions of the instrument and its operation.

H α data from the Big Bear Solar Observatory (BBSO) were heavily utilized. Daily H α full-disk images were used to identify filaments and to monitor their development. In addition, high resolution images taken at the rate of one or more per minute, were available for detailed analysis of one of the events (section 3.1).

National Solar Observatory /Kitt Peak (NSO/KP) full-disk magnetograms were used to characterize magnetic fields in the photosphere near filaments and to identify new active regions. NSO/KP full-disk He I (10830Å) images were used to supplement H α data in the identification of filament disappearances.

2. Analysis

The study was carried out using a variety of data analysis techniques. In section 3.1 we examine a case study of solar photospheric observations associated with a CME observed by the IIAO coronagraph. To simplify the rest of our observational study we take advantage of the fact that the majority of CMEs are associated with the disappearances of quiescent filaments and use quiescent filament eruptions as proxy for CMEs. Case studies of filament disappearances are presented in sections 3.2 and 3.4. In addition, three statistical studies are carried out. These three studies ask three somewhat different questions. In section 3.2 we ask what percentage of filaments that erupted were associated with newly appearing active regions. Although in 3.2 we find that erupting prominences are strongly associated with new flux, the 3.2 study is insufficient to conclude that there is a physical connection between the eruption of the filaments and the appearance of new flux. For this we need also to show that filaments that are not associated with new flux are unlikely to erupt. That question is studied in 3.3. In section 3.4 we study the effect of the relative orientation of the pre-existing and new magnetic fields on the probability of filament eruption.

3.1. A "Bugle"

Ideally, in order to study the relationship between CMEs and changes taking place on the solar surface, we would like to observe the coronal mass ejection itself at the same time as we observe possible

changes on the solar disk below it. The difficulty is that the CME must occur near the solar limb to be observed against the plane of the sky whereas the photosphere near the limb of the sun can not be satisfactorily observed. However, there are special events in which both the CME and the pre-event photosphere are reasonably well observed. Hundhausen (1993) has described several such events and defined a special class of CMEs which he calls "bugles". These events are characterized by the brightening of a streamer that broadens slowly and appears at higher and higher solar altitudes on successive days. After several days the structure suddenly disappears as it erupts into a CME. If successive coronagraph observations from a given height are seen on synoptic maps constructed from daily images, the structure looks something like a bugle, hence the name. These events appear to offer the best chance of observing both the CME and changes in the sun below it. We have examined the synoptic coronagraph data prepared by Hundhausen and identified 8 clear west limb erupting bugles in 1984-1985. West limb bugles were chosen so that the region of the photosphere under the coronal structure could be observed during the development of the event. The full disk H-alpha data from BBSO were examined to identify periods when both data sets were available. As could have been expected, there were only three cases in which both data sets were usable. However, by rare good fortune, instead of being observed only once per day, one of the events (June 9-12, 1985) was observed at high temporal and spatial resolution. These images showed the development of emerging flux regions below the coronal structure.

In the synoptic data, a "bugle" was seen in the southern hemisphere, at about -15 degrees. Between days 161 (June 10) and day 163 (June 12) the brightness and width of the structure increased markedly. However, the bright feature was no longer present on day 164 (June 13). This behavior is typical of "bugles". A CME about 21 degrees wide and centered at about 13 degrees south on the western limb is listed for June 12 in the catalogue of CMEs compiled by Burkepile and St. Cyr (1993). The CME is described as a slowly moving cloud superimposed on a streamer.

We study the development of the bugle in detail using the HAO coronagraph data. Since this event developed slowly, the best way to view it is by comparing coronagraph images taken at two different times. IJAC) has developed a differencing technique in which the coronagraph intensities of two images are subtracted. In difference images, the motion of a coronal streamer will appear as an

intensification in one region and a depletion in a nearby region; a simple enhancement of the corona can be recognized by the fact that there is no compensating depletion; a CME in progress will be seen as a depletion at low altitudes with an enhancement above it and at the sides. An image that differences pre- and post- CME observations will show regions of enhancement on both sides of a depletion region where the CME material was carried off from the corona.

The difference images showed that the bugle began to form slowly on June 9. Some coronal enhancement (but no depletion) was seen during that day and during the following day. More rapid changes began to take place during the 23 hours beginning at 23:34 UT June 10. The difference image shows a strong intensification and widening of the coronal structure. The next 24 hour difference image covers the eruption of the CME itself. Figure 1 shows the data of June 11 at 22:18 UT subtracted from the data of June 12 at 22:51 UT. There is a depletion bordered by an enhancement on either side; i.e., a CME has taken place. We have superimposed a magnetic map on the solar disk. This map shows the large scale solar magnetic fields calculated from the photospheric data by the Wilcox Solar Observatory (Solar and Geophysical Data, 1985). The CME structure appears to be overlying the large scale dipolar structure seen in the west below the equator. There is virtually no other important magnetic feature in the hemisphere westward of this structure. This is consistent with the notion that it is the field anchored in this large scale photospheric structure that is destabilized when the CME occurs.

Meanwhile dramatic changes were taking place on the solar disk. High resolution magnetograms of the region were recorded at intervals of about one per minute on June 7 through June 13. The BBSO observing day was from roughly 15:00 UT to 01:00 UT the next day. On these films new magnetic flux was seen to emerge and apparently interact with already existing flux. Older sunspots disappear. A substantial new active region appears and grows rapidly. It has several sites showing the consecutive appearance of many elementary bipoles (Martin, 1990). The changes are numerous and rapid and can only be fully appreciated by examining the original film. Here we can only outline the events.

In Figure 2 we show the large scale magnetic field changes seen on daily full disk magnetograms. Field into the sun (negative) is shown as black, field out of the sun (positive) is white. The top panel of the figure, taken June 8, shows two large bipolar active regions; the first

near central meridian passage and the second just west of that. The second active region has a large sunspot. "There is no indication of any active region between these two established centers of activity. In the next panel, June 9, a small new active region can be seen between the two old regions. We have enclosed it in a rectangle, to guide the eye. The rapid growth of the region is evident on the panel from June 10. The new region is complex and growing. The region continued to grow and change and in the bottom panel we can see that by June 11 the negative (black) portion of the second of the two old active regions appears to be considerably smaller than in the panels taken earlier. BBSO II-alpha data taken every 20 seconds shows rapidly changing active regions and sunspots at least as early as June 9. The data taken late on the June 11 observing day still showed rapidly changing active regions with many sunspots. The first observations on June 12 (15:02) showed that only a few small spots remained. This sequence of events is easily interpreted as newly emerging magnetic flux interacting (reconnecting) with flux that had emerged earlier. The eruption of the CME took place sometime between 06:11 UT and 19:46 UT, according to Burkepile and St. Cyr (1993).

In summation then, the development of the "bugle" in the corona was accompanied by the emergence of new magnetic flux below the large-scale arcades that anchored the developing coronal structure. Flux continued to emerge and spots formed and disappeared over a period of at least three days. The large-scale structure destabilized and the CME was observed on June 12. This is consistent with the idea that the growing active region added new flux below the large-scale structure until the time that structure became unstable and erupted. The rapid changes observed in the active region suggests that the emerging flux was reconnecting with pre-existing flux.

3.2 Filament disappearances; case studies and statistics

The second part of our study made use of observations of erupting filaments as proxies for CMEs and examined the association of the disappearances with nearby newly emerging flux. Two previous studies have presented statistical evidence that erupting filaments (and hence CMEs) are related to new and rapidly growing active regions appearing close to the filament and/or as far away as 30 heliographic degrees (Bruzek, 1952; Hermans et al, 1980).

Major filament disappearances of the quiescent type are readily identified on the disk and can be interpreted as erupting filaments (or erupting prominences if seen at the limb). Their association with CMEs and other coronal changes is well established (Sheeley et al. 1975, Munro et al., 1979; Kahler, 1987; Webb and Hundhausen, 1987; Hundhausen, 1988; St. Cyr and Webb, 1991). Prominences (and by implication, filaments) are observed to be overlain by coronal arch systems which, in association with the prominence (filament) disappearances, leave the sun as CMEs. Almost all (if not all) major quiescent prominence eruptions that have been studied have been associated with CMEs. Although the authors do not know of any studies that specifically searched for prominences that erupted without the arcades becoming a CME, it would be difficult to understand how the prominence could leave the sun without the arcades above it also leaving. With a little caution in the analyses of extremely slow CMEs and erupting filaments, it is now feasible to confidently use major filament disappearances as proxies for CMEs near disk center (St. Cyr and Webb, 1991, Hundhausen, personal communication).

The daily H α full disk observations were used to generate a list of 30 erupting filaments longer than 10 degrees. (See the appendix for operational definitions of "filament types", "filament longer than 10 degrees" and "filament eruption".) Active region filaments were excluded from this list. The H α observations were supplemented by full disk daily magnetograms. In order to be included in the study list, observations had to be available for at least 2 or 3 days before the disappearance. The list was begun using the data from September 1991 and was continued until 30 events had been collected.

The 30 filaments were examined to see if there were emerging magnetic fields in the vicinity of the filament prior to eruption. Emerging fields were identified when 'new and/or growing active regions were seen on the magnetograms. The "vicinity" of a filament was defined in terms of the photospheric magnetic fields (see the appendix). An active region was said to be in the vicinity of a filament if it was within the filament channel, or within or on the edge of the two large-scale single polarity regions bordering the filament channel.

We found that in 19 cases new flux was in the vicinity of the filament when it erupted. In 9 cases, little or no new flux was evident. Two Cases were uncertain.

The results will be illustrated by two case studies in which a filament was associated with emerging flux; Feb. 22, 1992 and Sept. 14, 1991.

Feb. 22, 1992 The first event to be described is shown in Figure 3. The filament is seen as a dark feature relative to the chromospheric background. (Filaments appear dark against the solar disk and bright against the sky. Thus a dark filament seen on the disk appears as a bright prominence on the limb.) In an H-alpha photograph an active region is associated with a bright plage region and, if the magnetic fields are concentrated enough, a dark sunspot. In Figure 3 the upper three panels show the day-to-day development of a thick quiescent filament, 30 degrees in length, which crossed central solar meridian Feb. 18, 1992. It was unusual in that it spanned the equator, extending from 18 degrees North to 13 degrees South. It erupted between the times when the two rightmost panels were recorded. The lower three panels of Figure 3 show the line of sight intensity of the magnetic field. Field into the sun (negative) is shown as black regions; out of the sun (positive) as white. The generally grey regions are areas in which the fields are too weak to be observed. The relative brightness or darkness is proportional to the intensity of the field. Unfortunately, the polarity reversal in which this thick filament formed is not clearly seen in the figures (except at the southern end). However the filament itself can be used as a tracer of the polarity change. A small amount of new flux began to emerge under the filament channel on Feb. 20. This can be seen in the upper panel as a brightening in H-alpha next to or under the southernmost part of the filament. In the corresponding magnetogram a small bipolar flux region has appeared, as shown by the arrow. (The generally hazy appearance of the magnetic field observations on Feb. 20 was due to the seeing conditions.) The emergence of flux continued the next day (middle panels) and a complex active region 10 degrees wide formed. The positive and negative magnetic fields are clearly visible on the magnetograms. Since the active region developed in the filament channel itself, conditions were favorable (see the appendix) for a filament eruption. Indeed, the filament disappeared between the Feb. 21 and Feb. 22, as shown dramatically by comparing the H-alpha images.

An important question is whether the active region was still growing at the time the CME erupted or if the growth had stopped some time before. Unfortunately we have only one image per day so the evaluation of this point is sometimes uncertain. In the case described here the spot was apparently still growing at the time of the CME since it was larger on the image taken after the eruption than it had been on the image taken the day before.

Sept. 14, 1991. Not all emerging flux regions associated with filament disappearances form or grow in the filament channel itself. On Sept. 14, 1991 a quiescent filament 15 degrees in length erupted in association with an active region that had formed on the outer edge of one of the two large-scale opposite polarity regions that bordered the filament channel, as shown in Figure 4. The position of the erupting filament is encircled with a broken line. The filament erupted on Sept. 14 and was reforming by Sept. 15. The new flux, indicated by an arrow, emerged over a period of 4 days, including the day of the eruption. The filament that erupted lay in the reversal of polarity between the larger-scale single polarity regions. The active region was about 8 degrees from the filament channel and was oriented so that the positive polarity of the active region was adjacent to the negative polarity photospheric magnetic field associated with the filament. Such an orientation permits reconnection between the new flux and the existing flux, apparently destabilizing the CME. A second filament, encircled by a solid line, did not erupt although the active region was physically closer to it than to the erupting filament. However, the positive polarity of the emerging region was adjacent to the positive polarity of the pre-existing regions defining this second filament channel. Thus, reconnection could not easily take place. The influence of the orientation of the emerging fields is studied further in section 3.4.

in our set of 30 filament eruptions, 19 were associated with emerging flux regions. Sixteen of these filaments were of the quiescent type, 2 were sub-polar and one was a border filament (see the appendix for definitions of filament type). Of the 19 events, there were 17 cases in which the flux was still emerging on the last observation before the CME. The flux began to emerge from 1 to 4 days before the filaments destabilized. In 10 of the 19 eruptions, the flux emerged in the filament channel itself, as illustrated by the Feb. 22, 1992 event. In several other cases the region formed within a few degrees of the filament channel. In 6 cases the active region

formed on the outer edge of the apparent magnetic arcade as defined by the photospheric magnetic fields.

Nine filaments of our set of 30 erupted without new substantial active regions being observed in the vicinity of the filaments. There was a tendency for these filaments to have been associated with weak photospheric fields. For example, three of them were polar crown filaments, one was subpolar and another was a quiescent prominence but in unusually weak magnetic fields. In five cases (4 quiescent and 1 border filament) we were unable to identify any unusual attributes of the filaments that might explain their eruption without observed emerging flux. However, it can not be definitely concluded that these filaments erupted without emerging flux since our data consisted of only one observation per day and some flux that emerged and interacted may not have been observed. This problem must be studied further.

3.3 New flux and filament eruption: statistical studies.

To demonstrate a physical relation between the destabilization of CMEs and new magnetic flux, it is not sufficient to show that filaments that erupt are strongly associated with new flux. It is also necessary to show that filaments that are not associated with new flux rarely erupt. We study this question in this section of the paper.

We report on a statistical study using a combined list of filament observations and of observations of emerging active regions taking place during September and November of 1991. We tested the statistical significance of the association of eruptions and newly emerging flux using formal statistical measures. We analyzed a contingency table using a test of the null hypothesis. That is, we tested the statistical hypothesis that the eruption of the filaments was independent of the appearance of new flux regions.

For the filaments used in this part of our study, we generated a list of all quiescent filaments appearing on the sun during September or November of 1991. See the appendix for a detailed description of the differences in the data selection for studies 3.2, 3.3, and 3.4. We used only filaments that were longer than 10 degrees. We then categorized the filaments according to whether or not they erupted during their passage across the solar disk.

We also generated a list of new active regions from the data in Solar and Geophysical Data (SGD). For each observing day, this publication gives the position and area of each active region on the face of the Sun. Newly emerging active regions are easily identified because they do not first appear at the East limb. The growth of the active region is seen in the daily change in area. For our study we omitted all active regions that first appeared at longitudes further East than 70 degrees or further West than 60 degrees. They were omitted because we found we could not satisfactorily observe them and/or changes in any associated filaments. We included only regions that were reported by more than one observatory as larger than 10 millionths of a hemisphere.

Using the list of some 33 new active regions for September and November 1991, we identified those which emerged in the vicinity of filaments that were longer than 10 degrees and had not been previously associated with an active region. We found that 2/3 of the new active regions emerged in the vicinity of filaments longer than 10 degrees. These 22 filaments were selected for further study. Of course, the data from Sept. and Nov. 1991 were also included in the study based on the filament list, so many of the events included on the section 3.2 study also appeared in this study.

The final data set to which the statistical analysis was applied consisted of 53 filaments and 22 new active regions. We examined each new active region and each filament and constructed the contingency table shown in Table 1. Note that 17 of 22 filaments associated with new active regions erupted and 5 of the 22 did not. In addition, 5 filaments erupted without having new active regions in the vicinity. Twenty-six filaments without active regions in the vicinity did not erupt. A chi squared test shows that the chances of getting a contingency table like this is much less than 1/100 unless there is a relationship between the variables, i.e., the hypothesis of independence of the variables failed. We conclude that the variables are physically related.

3.4 The effect of orientation of magnetic fields.

In this section we study the effect of the orientation of the newly emerging magnetic fields on the probability of eruption. We begin with a case study and then report on a statistical study.

Sept. 23, 1991 Figure 5 illustrates a case in which flux emerged in the vicinity of a filament but the filament did not erupt. The left-hand panel of the figure shows a clear and well-developed filament. The right-hand panel shows the reversal of magnetic fields in which the filament formed. The active region, indicated by an arrow, is a new and developing one. However the orientation of the active region is such that the negative polarity newly emerging fields are adjacent to the negative polarity fields that make up the arcade spanning the filament. Thus little or no reconnection could take place and the filament was not destabilized. For a second example of this type of event see the description of the events of Sept. 14, 1991 in section 3.2 above.

We used the 22 new active regions associated with filament eruptions described in section 3.3. We characterized the events according to the orientation of the new active regions relative to the magnetic field polarities in the unipolar photospheric regions adjacent to the filaments. The orientation of the active region was said to be favorable or unfavorable as discussed in the appendix. The results are shown in table II. We found that there were 17 favorably oriented newly emerging flux regions that were associated with erupting filaments. (This includes cases in which more than one newly emerging region is associated with a single eruption. In these cases each region was counted separately for this part of the study.) In all 17 cases in which there was newly emerging flux with a favorable orientation, the filament...erupted. In contrast, when the new flux was unfavorably oriented or the orientation was neither favorable nor unfavorable, there were eruptions in some cases and not in others, with no statistical preference evident in our small sample of such events. We conclude that when a major new flux region appears in the vicinity of a filament and the flux has a favorable orientation for reconnection with the pre-existing flux, the filament has a very high probability of erupting.

4. observational conclusions.

The relation between the initiation of CMEs and newly emerging magnetic flux has been studied here using several different techniques.

We presented data (section 3.1) in which the evolution of a coronal structure and a CME was observed at the same time as high resolution observations were being taken of the relevant region of

the solar disk. In (his case, active regions were seen to emerge and to interact with nearby already existing regions. The evolution of the active regions and the coronal structure had continued for over four days before the CME occurred.

We have also used disappearing filaments of the quiescent, polar and subpolar types as proxies for CMEs in several statistical studies of the relationship between emerging flux regions and CMEs. We found that, in the cases of 19 of 30 erupting filaments, new active regions were observed to develop during the few days before the eruption (section 3.2). We also showed that the observed association between a sample of 53 filaments and 22 filament-associated newly emerging flux regions was statistically significant on the 1/100 level. That is, there is much less than one chance in one hundred that the observed contingency table would appear if the parameters were unrelated (section 3.3 above). We also found that, in all 17 cases in which there was newly emerging flux with a favorable orientation, the filament erupted (section 3.4 above). In all of our data sets the active regions typically began to emerge several days before the CME eruption.

About 1/3 of our sample of erupting prominences (section 3.2) were not associated with substantial regions of emerging flux. However, we were unable to conclude that these eruptions occurred without any new flux emergence because of observational difficulties. The data used had a one day time resolution so that flux present for less than a day may have gone undetected. In addition, we did not consider the flux contributed by small emerging bipoles. To do SO would have required a much more difficult and sophisticated statistical technique than was used in this first study. Note that there appeared to be a tendency for the eruptions without observed new flux to occur in prominences associated with weak unipolar regions so that less flux may have been required to destabilize them. Further study is required to determine whether or not these prominences erupted in the absence of new flux.

5. A Discussion and a scenario

These observations show a very strong relation between newly emerging flux regions and CMEs. In this section we discuss ways in which the emergence of new flux can strongly influence the gradual

evolution of the large-scale magnetic field arcades. We outline a scenario in which this new flux reconnects with the pre-existing magnetic flux that, as a consequence, erupts as a CME. These CMEs are accompanied by either solar flares, erupting filaments or both.

We first argue that flare associated and quiescent filament associated CMEs can be expected to involve the same physical processes. We note that CMEs associated with active regions and with quiescent filaments are alike in important aspects such as velocity, angular extent and three-part structure (Hundhausen, 1988). In addition CMEs associated with both flares and prominences are accelerated as they pass through the corona (Hundhausen, 1994). (There is some evidence that flare-associated CMEs are accelerated at lower coronal heights than prominence associated CMEs (Mac Queen and Fisher, 1983). However, statistical studies have not shown any latitude dependent differences between the outer coronal velocity distributions or forms of CMEs (Hundhausen et al. 1994). Since quiescent filaments tend to be at higher latitudes than flares, this finding suggests that there is no difference between the final velocities reached by flare and filament associated CMEs (Hundhausen, personal communication). Thus the differences in acceleration altitudes do not require a fundamental difference in acceleration mechanism.)

We further note that the emergence of new flux and apparent reconnection with pre-existing flux is a very commonly observed in the case of both flares (Martin et al. 1983, Martin et al., 1984, Rust and Cauzzi, 1992) and filament eruptions (Bruzek, 1952, Hermans et al., 1980, this paper). In this study we have found that the appearance of new flux influences the eruption of filaments in the sense that the filament is very likely to erupt if there is new flux and very unlikely to erupt if there is not. Although we have not yet carried out a quantitative study, it is our impression that the magnetic flux in the newly forming active regions appears to be less than, but comparable to, the flux in the overlying arches.

To understand why flare associated and filament associated CMEs can be so much alike, an important point to keep in mind is that the regions of the sun in which flares occur and in which quiescent filaments occur have a strong evolutionary relationship. In early studies of the relationship of flares and filaments (Kiepenheuer, 1953) it was found that filaments in spotless regions represent a

later stage in the evolution of active regions. During the early stages of evolution there is a rapid formation of spots and occurrence of flares. Filaments are present but tend to be narrow and not conspicuous. This description holds for one or perhaps two solar rotations. During the next several rotations the flaring ends and the spots fade away as the filaments elongate and become more obvious. The filaments continue to lengthen as they move poleward, and become more east-west in their orientation. During perhaps the sixth to tenth rotation the filament, now a predominantly east-west structure, approaches the sub-polar crown of filaments and is apparently incorporated into it. Feynman and Hundhausen (1994) call these regions "Evolving Magnetic Structures" (EMSs) and have pointed out that CMEs take place in EMSs during all stages of their evolution. They have suggested that all CMEs arise in EMSs.

In summary, there appears to be a convergence of evidence that most CME eruptions (whether associated with flares, flares and filaments, or quiescent filaments alone) are directly initiated by the emergence of favorably oriented new magnetic flux under the large-scale closed magnetic field regions of EMSs. Steinolfson (1992) has numerically modeled the response of magnetic arcades to new flux and his results show many of the attributes of the CME observations. Note however that the modeled scenario was one in which no reconnection took place between the pre-existing arcades and the new magnetic flux. Our observations indicate that reconnection is a strongly contributing factor to destabilization.

The observations reported here suggest the scenario shown in Figure 6. These sketches concentrate on the processes occurring at the interface between the overlying arcade and the newly emerging flux. Panel 1 shows the newly emerging flux appearing below the pre-existing arcade. (Although not shown in the sketch, the arcade may also be undergoing shearing by footpoint motion.) The orientation of the new flux is such as to facilitate reconnection. For simplicity the orientation of the emerging flux is shown as strictly opposite to that of the existing flux. The current sheet corresponding to the flux direction reversal is shown as a shaded area. Although the sketch is drawn as if the fields were centered over the emerging flux, nothing in the scenario would be changed for the asymmetric case.

The continued emergence of flux in the growing active region brings more and more new flux to the vicinity of the current sheet. This

new flux takes part in driven reconnection. The rate and position of the reconnections within the current sheet will be a function of the Alfvén velocity across the sheet and of some distance corresponding to the width of the region in which the field reversal takes place. As in the magnetotail current sheet, magnetic islands and reconnected loops will be formed. They are shown schematically in panel 2 and have been found in computer simulations for emerging flux in the solar case (Shibata et al., 1992). These reconnection events may be related to the surges and discrete events typically seen at the boundaries of newly forming active regions (Brueckner, et al, 1988). "[t]he gradient in magnetic intensity with solar altitude will cause the magnetic islands to tend to rise. As the islands come into contact with one another, further reconnections will take place and the islands will coalesce (Shibata, et al., 1992) into larger magnetic island structures as shown in panel 3. The important role of regions of detached flux in destabilizing CMEs has been emphasized by Low and Smith (1993). In our scenario the magnetic islands are prevented from escaping by the pre-existing arcade structure above them. They do, however, represent an increase in the magnetic pressure confined within the arcade. We suggest that the effect of the emerging flux is to increase the magnetic pressure within the arcade until the arcade becomes unstable. Energy released in the reconnection may also serve to heat the coronal plasma, further increasing the pressure within the arcade.

After several days the increase in magnetic pressure (and perhaps the increase in the fluid pressure due to heating the coronal plasma) causes the overlying arcade to become unstable and erupt. Of course our scenario does not preclude additional reconnections also taking place elsewhere in the erupting structure and/or later in the process, as suggested in many other scenarios.

As noted earlier, the process we have studied is a generalization of a process modeled by Steinolfson (1992). He considered the case when the orientation of the emerging flux was the same as that in the overlying arcade. Thus reconnection did not play a central role and the only effect of the emerging flux was to add new flux to the arcades in the already existing overlying structure. In our case, flux is added in such a way as to form magnetic islands. In either case the overlying structure must adjust to the increased field strength. In the Steinolfson case the new flux is anchored in the solar surface and the tension in the new field helps to stabilize the structure against CME eruption. In our case, the magnetic islands are not

anchored in the sun. The destabilization effect of the increase in flux is not opposed by magnetic tension. Thus, if the newly emerging flux is favorably oriented for reconnection with the pre-existing flux, the large scale coronal structure should be more unstable to eruption than when the new flux cannot reconnect with the arcade. This is exactly what we have observed as shown in Table 1.

Our scenario, emphasizing the importance of newly emerging favorably oriented flux in the destabilization of CMEs, does not conflict with scenarios that are based on the effects of shearing. The shearing of magnetic fields can be due to a variety of causes including the emergence of new flux. Indeed, in their study of flare initiation Rust and Cauzzi (1992) emphasize the shear resulting from the emergence of new flux. Many numerical models based on shear, however, are more concerned with shear due to footpoint motions and differential rotation. Our observations indicate that the emergence of new favorably oriented magnetic flux also plays an important role in the destabilization of most CMEs. It is interesting to note that both new flux emergences and large scale shearing occur in EMSs during their evolution. The relative importance of large scale shear and of emerging flux in CME initiation may be a function of the age of the EMS, with the flux emergence being more important during the early (flaring) and mid-life (mid latitude quiescent filament) stages of the EMS and less important for the latest stages characterized by the highest latitude filaments.

The idea that the large-scale magnetic field structures overlying active regions and filaments are destabilized by newly emerging flux reconnecting with the existing lines of force is an attractive one and the studies reported here strongly support the notion that this process is involved in the initiation of most CMEs. This finding can be of great importance for the prediction of geomagnetic storms and major solar proton events, both of which are caused by CMEs (cf. Gosling, 1993). Observation of magnetic flux newly emerging in active regions or in the vicinity of filaments, may well provide several days warning of impending CMEs, proton events and geomagnetic storms.

Acknowledgments: We thank Victoria Good for her help in making the H-alpha prints and generating the list of prominences including those that erupted. We also thank G. J. Hundhausen for supplying us with information anti data on bugles anti acting as host when one

of us (JF) visited the High Altitude Observatory, NCAR. Joan Burkepile of HAO was of great help in working with the bugle data. We are grateful to the National Solar Observatory at Kitt Peak for the magnetic field data and for the He I 0830 data. This work was carried out at California Institute of Technology and at the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA.

Figures

1. The eruption of the "bugle" of June 1985. The coronal image taken June 11 (before the eruption) is subtracted from the image taken about a day later (after the eruption). The dashed line shows the outer rim of the coronagraph occulting disk. Density enhancement and depletion regions typical of a CME are seen (see text). The coronal density is enhanced (seen as white speckles) to either side of a dark region. A depletion (shown as grey speckles) is seen below and between the enhancements. The Stanford magnetogram data from June 12 has been superposed on the solar disk and shows the large-scale structure of the photospheric magnetic field.
2. Active regions observed for four days during the development of the bugle, before the eruption of the CME.
3. A filament eruption of Feb. 22, 1992 and the associated emerging flux. The new active region forms in the filament channel.
4. The filament eruption of Sept. 14, 1991 is seen in the region encircled with a broken line. The new active region forms adjacent to a large-scale single polarity magnetic field region. This large-scale region is one of the two that make up the magnetic field reversal in which the erupting filament forms. The polarity of the new active region favors reconnection. A filament that did not erupt is encircled with a solid line. The polarity of the erupting flux did not favor reconnection for the encircled filament. See text.
5. A non-erupting filament seen on Sept. 23, 1991. The magnetic fields are configured much like those shown for the erupting filament in figure 4 except that the polarity of the emerging field is reversed. The polarity of the emerging flux is not favorable for reconnection and the filament did not erupt.

6. Schematic of the processes taking place at the interface between the newly emerging flux and the pre-existing coronal arcade in our scenario.

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Appendix : Definitions

Flare and filament associations with CMEs.

Many early studies of CME associations with flares and/or filament eruptions used the Solar and Geophysical Data reports to identify the solar events. For these reports, the optical flare data and filament eruptions are derived from examination full disk H-alpha data. The x-ray flares are from the GOES soft x-ray observations. Using those lists, some CMEs were seen to be associated with flares, some with filaments and some with both. It is in the same spirit that the terms "flare associated" and "quiescent filament associated" are used in this paper. However, most of our data was obtained directly from the observations, as described in the body of the paper. Recently it has been shown that many flares appearing in the 10830 Å line are not visible in H-alpha (K. Harvey, personal communication). Other flares may be so weak as to be unobserved. The question of whether all CMEs are accompanied by flares but some of the accompanying flares are small or not seen in either H-alpha or soft x-rays is beyond the scope of this paper.

In studies of coronagraph images of CMEs about half the CMEs do not appear to have associations with events visible on the solar disk. Coronagraphs observe CMEs projected against the plane of the sky. Let us assume, for the moment, that all CMEs are associated with some solar surface activity. Assume further that the surface feature is at some distance from the limb of the sun. It is clear that the probability that the CME will rise above the limb of the sun is the same whether the associated feature appears on the visible side of the sun or on the far side. Thus, in only half of the cases would the surface feature be observable. This is in agreement with the results of studies which find that about half of CMEs can be associated with an observed surface feature; implying that the vast majority (if not all) CMEs are associated with solar surface activity.

Filament types.

We distinguish five types of solar filaments:

- 1) Filaments occurring in active regions. These filaments form in the polarity reversal regions in active region complexes. Filaments of this type have been eliminated from our data set.

2) Quiescent filaments. These filaments form in the polarity reversal regions between large-scale photospheric areas of single dominant polarities. Their formation is associated with the decayed remnants of active regions.

3) Border filaments. These form on the outside borders of active regions.

4) Polar crown filaments. These form in the most poleward polarity reversal region. The large-scale fields defining these filament channels are very weak.

5) Subpolar crown filaments. These filaments are in the second to the most poleward polarity reversal regions.

Filament longer than 10 degrees.

The length of each filament was estimated using a Stoneyhurst diagram (a grid of latitude and longitude drawn on a circle the size of the solar image used). The measurement was made along the filament itself rather than just considering the distance between the two ends of the filament. In some cases the candidate filament was fragmentary in that the filament channel was filled in some places and not in other places. We required that at least one fragment be at least 10 degrees in length.

Filament eruption,

A filament was said to erupt if at least half the filament or a section 10 degrees long (whichever is longer) is present on the image of the sun one day and is absent some time in the next few days. Most of these filaments erupted in a single day but a few erupted over several days. Occasionally less than half the filament erupted. These cases were omitted from the statistical parts of the studies since they could not be unambiguously assigned to either the category of "erupting" or "not erupting".

It has been shown by numerous early studies that almost all filaments eventually erupt (Kiepenheuer, 1953). Rarely do they gradually fade away. After many eruptions the channel in which the filament had formed can still be seen outlined in the H α images.

A new filament may form in the old filament channel. This second filament eventually erupts again.

Vicinity of a filament.

Quiescent filaments are anchored in channels that form between two large-scale regions of opposite magnetic polarity, whereas the associated CMEs involve the coronal arcades that span the two magnetic regions. The "vicinity of a filament" was defined relative to the magnetic fields seen on the full disk magnetograms. The active region was said to be in the vicinity of a filament if it appeared in the polarity inversion associated with the filament or within or near the edge of the regions of single dominant polarity fields which bordered the polarity inversion. Thus the "vicinity" was defined from the photospheric magnetic field observations rather than the heliographic distance.

Active region orientations favorable for reconnection.

If the newly emerging flux appeared within the filament channel, the orientation was considered favorable for reconnection (see figure 3). If the flux appeared on the outer edge of the presumed magnetic field arcade anchored in the large-scale single polarity regions bordering the filament channel, then the orientation was considered favorable when the polarity was arranged so that reconnection was facilitated (figure 4). If the orientation inhibited reconnection (figures 4 and 5) the orientation was said to be unfavorable. A few active regions were oriented so that they were neither favorable nor unfavorable. In addition, if an active region appeared inside one of the single polarity regions, it was said to be neither favorably nor unfavorably oriented.

Eruption of a filament associated with a new active region.

As usual in studies of this kind, the sun did not make it easy for us to count events. It did not pay adequate attention to the categories we would have liked to use. It would have been easier if each new active region was in the vicinity of only one filament or if each filament was near only one new active region. However, in a few cases, there were two filaments in the vicinity of a single spot. If either filament erupted we counted the event as a filament eruption. There were also, occasionally, more than one new active region in the vicinity of a single filament. If the filament erupted we counted that

as a single event. In one case there were three spots associated with two filament eruptions. It was Counted as two events.

Note also that we used two different lists, one based on filaments and one based on new active regions. They were collected over two overlapping but not identical time periods so that many, but not all events studied were on both lists. The differences in the lists are the reason that the numbers of events in the different studies do not appear to be compatible at first glance. The reason for using a longer time period for the erupting filament list was that we wanted to get a large enough sample (30) to have a statistically convincing result during the filament study. Since the results of the emerging flux study was so strongly significant with the smaller sample, we feel that it is not necessary to extend that study to a larger sample,

TABLE I

CONTINGENCY TABLE COMPARING FILAMENT ERUPTION (CME) AND
NEWLY EMERGING FLUX

		DOES THE FILAMENT* ERUPT?	
		YES	NO
EMERGING FLUX IN VICINITY OF FILAMENT#?	YES	17	5
	NO	5	26

* note: All the filaments in this table were longer than 10 degrees.
#note: The orientation of the emerging flux relative to the arcade fields is not considered in this table.

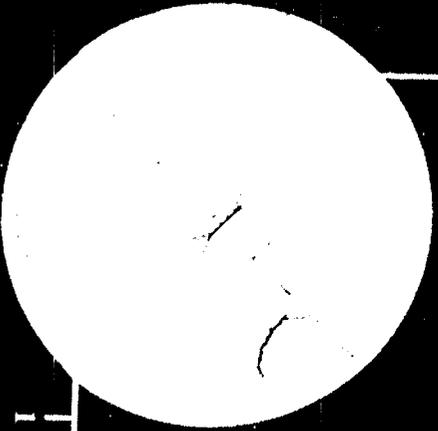
TABLE 11

ORIENTATION OF EMERGING FLUX RELATIVE TO EXISTING ARCADE

	FAVORABLE FOR RECONNECTION	UNFAVORABLE FOR RECONNECTION	NEITHER
FILAMENT ERUPTED	17	2	2

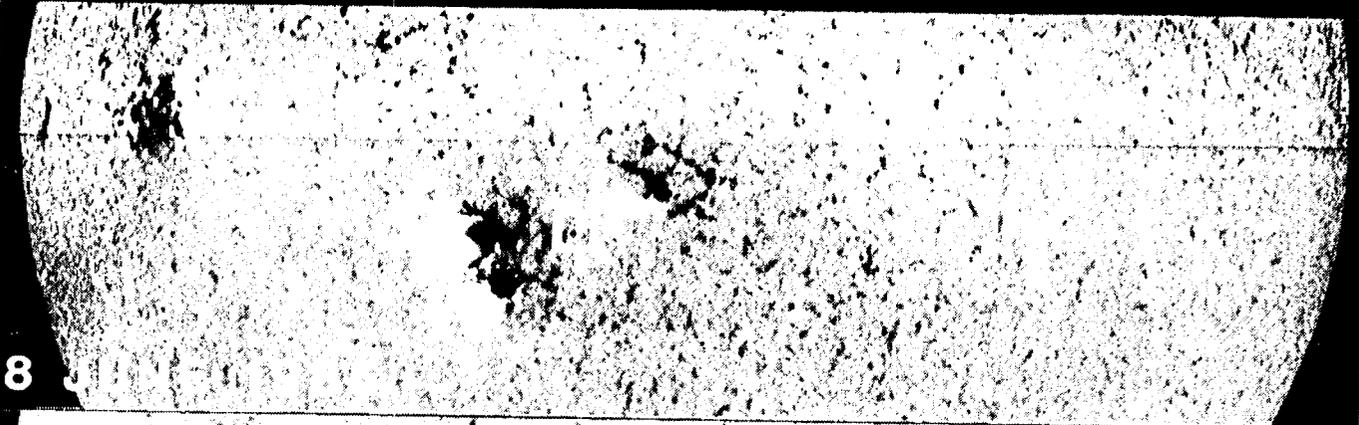
FILAMENT DID NOT ERUPT	0	3	3

Jun 12 1985 22:51
MINUS Jun 11 22:18

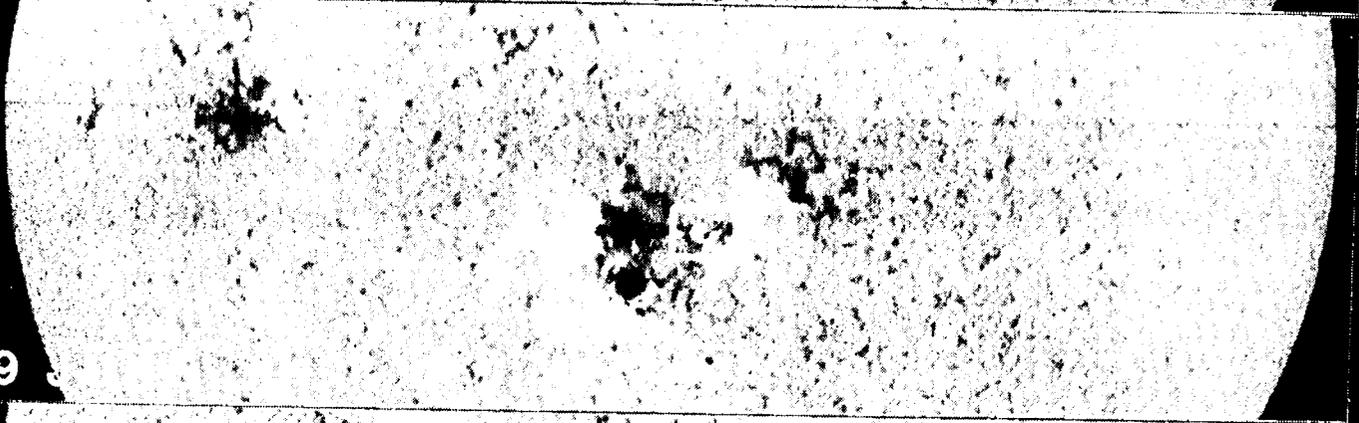


R ⊙

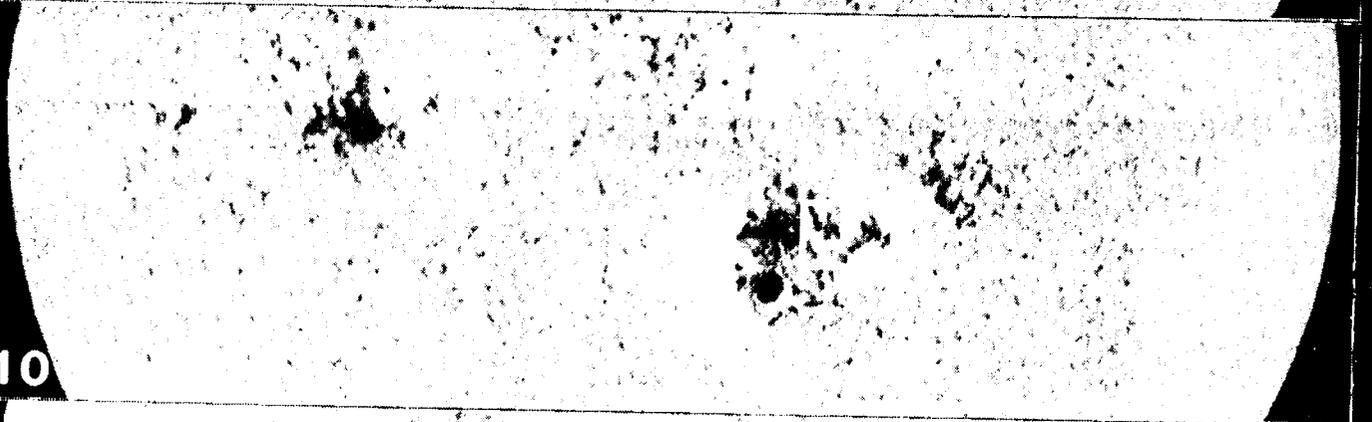
H&D/SMM CORONAGRAPH



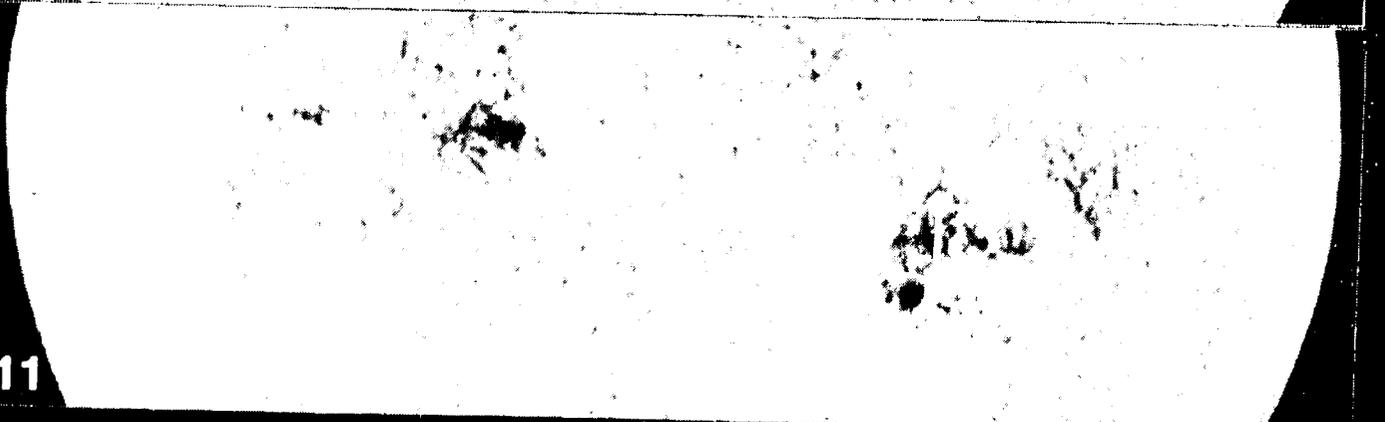
8



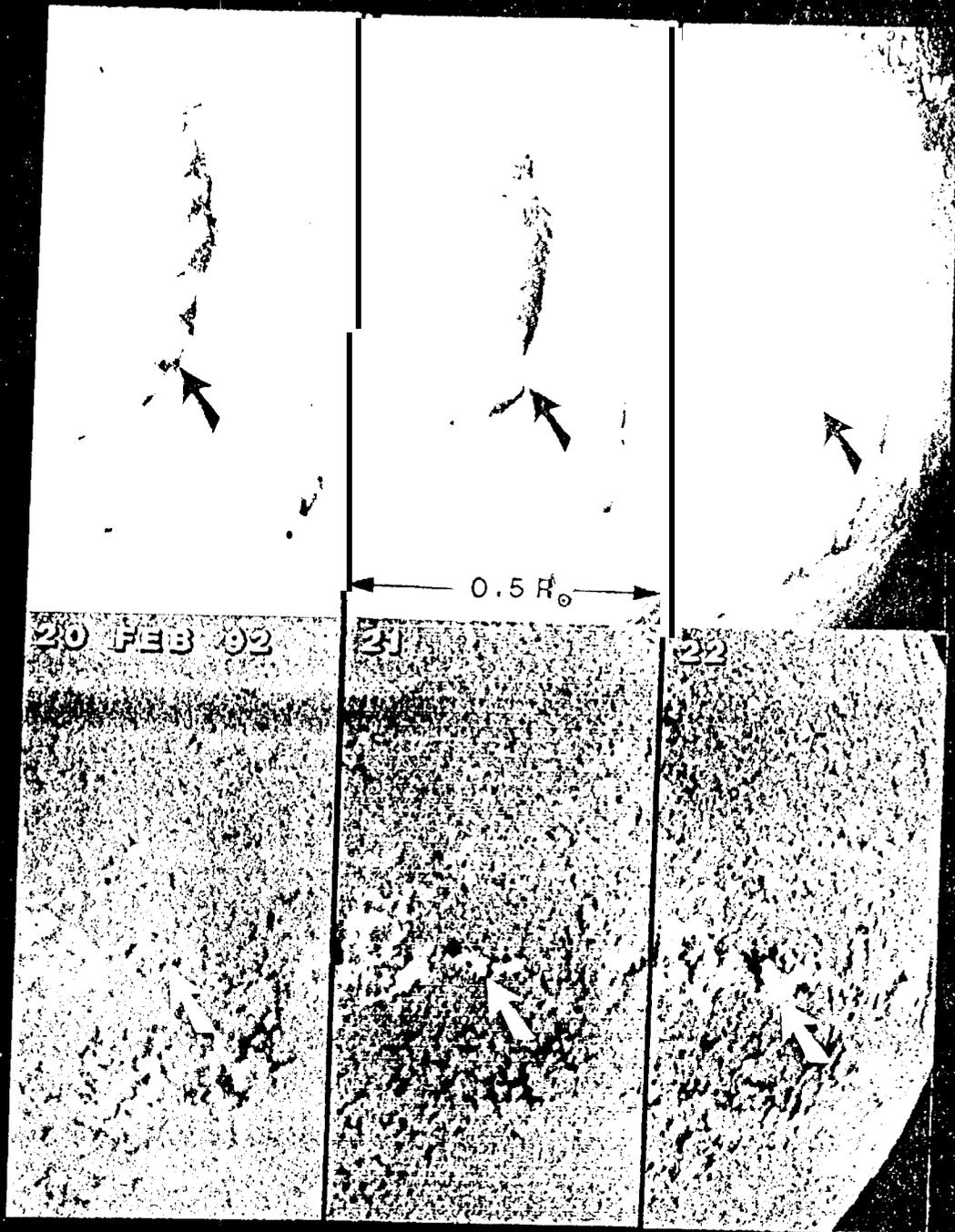
9



10

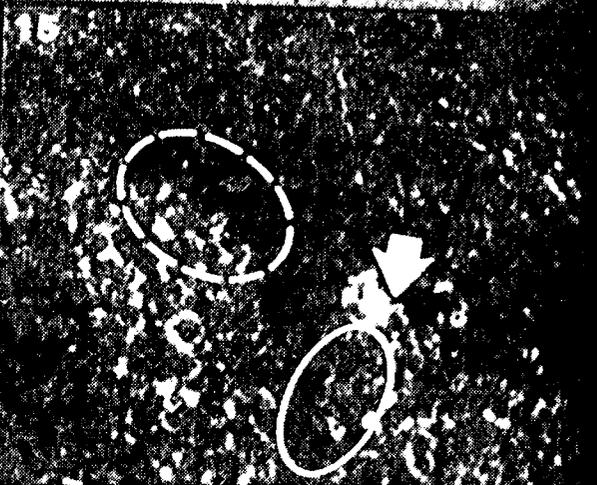
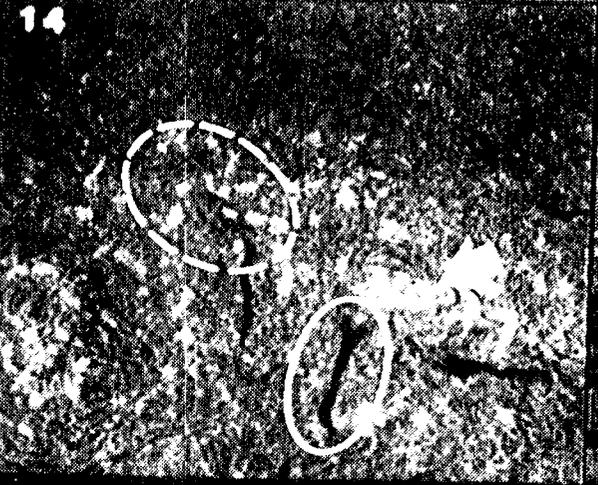
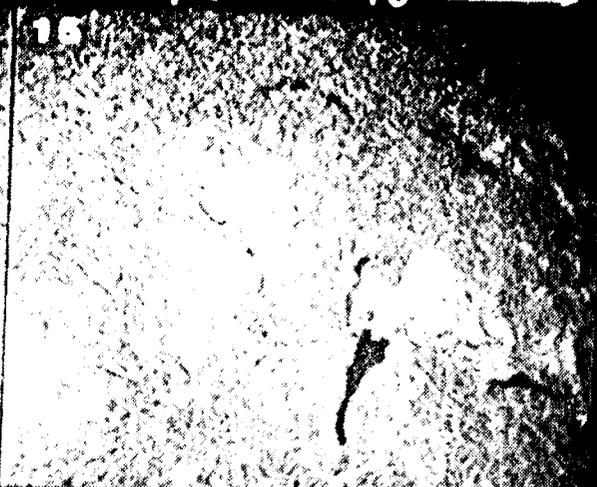
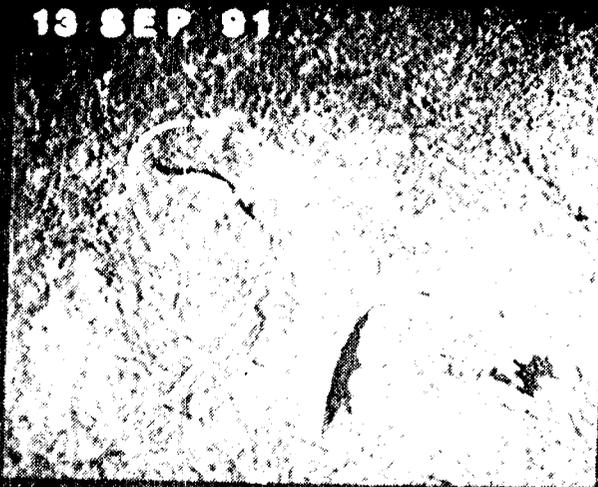


11



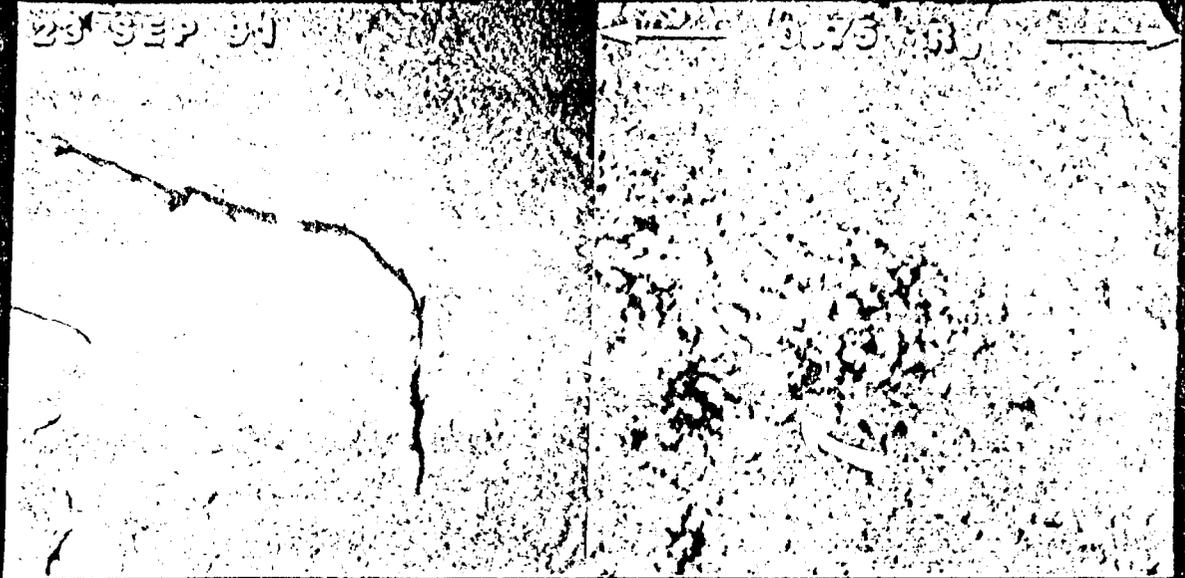
13 SEP 91

← 10' →



23 SEP 84

0175 WRS



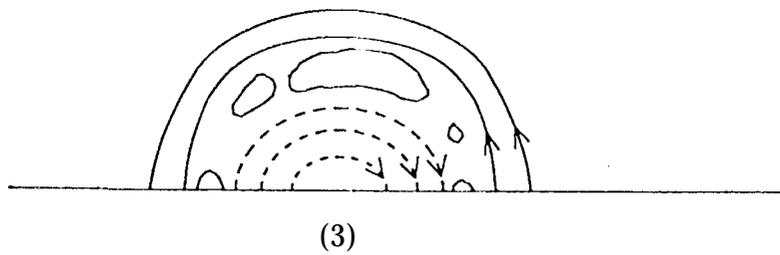
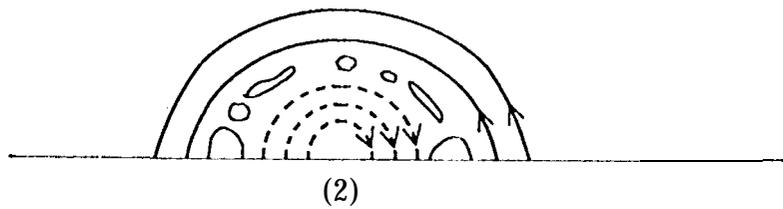
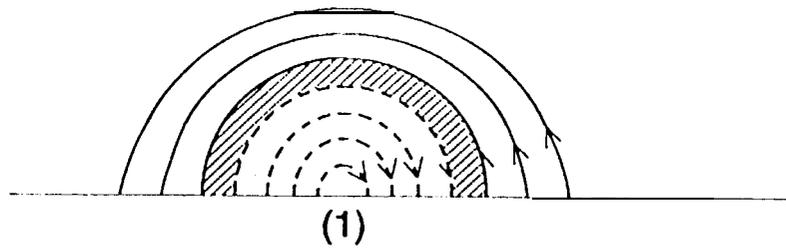


Fig 6