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Evolution of the Interplanetary Magnetic Field

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Abstract Remote observations of magnetic field topologies in the solar corona and *in situ* observations of the solar wind and interplanetary magnetic field (IMF) in interplanetary space are used to examine the temporal evolution of the spatial distribution of open and closed field regions emanating from the Sun. The simple "open" configuration of inward and outward pointing sectors in the IMF is periodically disrupted by magnetically distinct coronal mass ejections (CMEs) which erupt from previously closed magnetic field regions in the corona into interplanetary space. At 1 AU, CMEs contain counterstreaming halo electrons which indicate their distinct magnetic topologies. This topology is generally thought to be: (1) plasmoids that are completely disconnected from the Sun; (2) magnetic "bottles," still tied to the corona at both ends; or (3) flux ropes which are only partially disconnected. Fully disconnected plasmoids would have no long term effect on the amount of open flux; however, both *in situ* observations of details of the halo electron distributions and remote coronagraph observations of radial fields following CMEs (legs) indicate that CMEs generally do retain at least partial attachment to the Sun. Both the magnetic bottle and flux rope geometries require some mitigating process to close off previously open fields in order to avoid a "flux catastrophe". In addition, the average amount of magnetic flux observed in interplanetary space varies over the solar cycle, also indicating that there must be ways in which new flux is opened and previously open flux is closed off. The most likely scenario for closing off open magnetic fields is for reconnection to occur above helmet streamers, where oppositely directed field regions are juxtaposed in the corona. These events would serve to return closed field arches to the Sun and release open, U shaped structures into the solar wind; such disconnection events have been remotely observed with the

Solar Maximum Mission coronagraph. In interplanetary space, disconnection events may manifest themselves as heat flux dropouts (HFDs), in which the solar wind electron heat flux, driven by magnetic connection to the hot corona, is absent or greatly reduced. In this paper will we review and examine these issues and show how the synthesis of global, remote, and local, *in situ*, observations have been used to develop an understanding of the temporal evolution of the spatial distribution of open and closed magnetic field regions linking the corona out into interplanetary space.

1. Introduction

Over the past three and a half decades of space flight both *in situ* observations of the local space environs and remote imaging of distant regions have been used to examine a wide variety space physics phenomena. Regions studied span the gamut from the solar photosphere through the interplanetary medium to planetary ionospheres and magnetospheres.

Recently, considerable progress has been made on understanding the ways in which the open and closed field regions of the solar corona evolve and the effects of this evolution on the magnetic structure of the interplanetary medium. This progress has been driven by a combination of information from single point, *in situ*, observations in interplanetary space and remote coronal imaging, together they provide a good example of how a global process in space and time can be at least partially resolved by the fusion of local, detailed and remote, synoptic observations.

Coronagraph observations over the past several decades have shown that the solar corona is a highly dynamic and variable region. Short and long lasting coronal holes, where the solar magnetic field is “open” to interplanetary space, are indicated by low density (dark) regions; higher density, loop like structures are indicative of closed field regions on the Sun. Helmet streamers (closed field loops overlaid by radial high density streamer structures) map out to the heliospheric current sheet in interplanetary space [e.g., Hundhausen, 1977; Gosling et al., 1981]. These magnetically open and closed regions evolve over timescales as short as several hours and as long as the 22 year solar cycle.

In interplanetary space, the amount of magnetic field passing through 1 AU can vary substantially. The top panel of Figure 1 displays the variation in the annual averages of the magnitude of the magnetic field, $|B|$, from 1973 through 1988. This trace displays ~50% variation over solar cycle 21; while a similar result was found for solar cycle 21 by Slavin et al. [1984, 1986], the variation over solar cycle 20 was much smaller [King, 1979]. The lower panel displays the variation in the 2-dimensional “total flux integral”, Φ^* , defined by McComas et al. [1992a]. This integral, which provides a measure of the amount of 2-D magnetic flux in the ecliptic plane at 1 AU, similarly displays ~60% variation over the solar cycle.

Both $|B|$ and Φ^* show basically the same variation over solar cycle 21; the maximum amount of flux observed in the ecliptic plane at 1 AU occurs in 1982, shortly after solar maximum while the minima occur in 1976 and 1986-1987, shortly after solar minima. Figure 1 clearly demonstrates that the amount of magnetic field open from the Sun into interplanetary space can and does vary substantially. In order for this to be true, there must be methods for both 1) opening new, previously closed field regions in the corona and 2) closing off previously open field regions and returning closed loops to the Sun. Since the solar wind will carry out any field structures formed past the Alfvénic point (~10 solar radii), closing off of previously open fields must occur down in the solar corona.

In this paper we examine how magnetic fields may be opened and closed from the Sun into interplanetary space and review and synthesize the

observations and interpretations of four phenomena which may be manifestations of this process. In Section 2 we examine coronal mass ejections (CMEs) as observed remotely with coronagraphs. Section 3 examines counterstreaming electron events observed with *in situ* plasma data in the solar wind at 1 AU. We argue that CMEs and counterstreaming electron events are actually different manifestations of the same phenomena, and use both data sets to examine the topologies of these CMEs. In Section 4 we discuss heat flux dropouts (HFDs) in the solar wind at 1 AU and examine whether these phenomena could be the interplanetary manifestation of the disconnection of previously open magnetic fields in the solar wind. Section 5 examines coronal disconnection events observed, again, remotely with coronagraphs. We argue that at least some fraction of the HFDs observed at 1 AU are the interplanetary manifestations of coronal disconnections, and examine the implications of these topologically detached structures. Finally, in Section 6 we examine these phenomena in terms of their topological implications for opening and closing magnetic fields from the sun and summarize our results.

2. Coronal Mass Ejections and the Opening of New Magnetic Fields

Coronal mass ejections were first discovered in sequences of Skylab observations [Gosling et al., 1974]. While CMEs have been observed with a wide range of shapes, sizes, and speeds in the corona, the classical picture of a CME is that of a region of previously closed magnetic field loops erupting from the corona and expanding out into interplanetary space.

Figure 2, adapted from Gosling et al. [1974], shows two images from the

CME eruption of August 10, 1973. The bright loops on the west limb of the Sun are indicative of higher plasma density on closed magnetic field arches. Due to the very high conductivity of the coronal plasma, these loops are almost universally interpreted as mass loaded field lines. In the left panel, closed arches rise high up into the corona. The right panel is taken 24 minutes later. Over this short interval the CME has expanded outward with an apparent radial speed of $\sim 400 \text{ km s}^{-1}$.

At later times in this event the CME continues to expand outward until it leaves the Skylab field-of-view (see Gosling et al. [1974]). After the passage of the CME, long lasting, bright radial structures are observed to persist for at least another half day. These structures, called the “legs” of the CME, are typically found along the edges of the region of CME eruption. In some examples legs are observed to persist for several days; such structures have generally been interpreted as direct evidence for continued magnetic connection of the CME to the Sun. It is worth noting that even though the existence of long lasting legs has generally been interpreted as evidence of continued solar magnetic connection, Kahler and Hundhausen [1992] recently suggested the alternate interpretation that such structures may simply be coronal streamers containing magnetic neutral sheets.

The only four fundamental topologies possible for magnetic field lines in the heliosphere are displayed schematically in panels A, B, D, and E in a “flat heliosphere” representation in Figure 3. Panel A shows normal “open” field lines which link the Sun to the outer heliosphere. Panel B displays a magnetic tongue or bottle geometry in which the magnetic field closes to the Sun at both ends [Gold, 1959; Hundhausen, 1972]; conversely, panel E

shows a disconnected region which closes in the outer heliosphere at both ends [McComas et al., 1989]. Panel D displays a fully disconnected plasmoid which closes on itself rather than to either the Sun or outer heliosphere. The solar wind flows everywhere outward from the Sun (bottom to top in Figure 3) so that over time the field lines in panel B naturally evolves into open fields (panel A) while field lines in panels D and E simply propagate out (upward) through the system.

Panel C displays a magnetic flux rope which is an intermediate field configuration between the bottle (B) and the plasmoid (D) geometries [Gosling, 1990]. In the flux rope geometry the field loops around or possibly even through itself instead of being simply connected. Fundamentally, however, this topology is equivalent to panel B in that it connects back to the Sun at both ends. In theory, open (A), plasmoid (D), and disconnected (E) field lines can all be similarly more complicated than drawn in Figure 3 by wrapping around and/or through themselves. However, just as the flux rope is simply an extension of the bottle topology, such complicated forms would be simply complications of these other structures. The structures shown in panels A, B, D, and E are only four fundamentally distinct ways that IMF field lines can connect within the boundary conditions of the Sun and outer heliosphere.

Three of the five geometries shown in Figure 3 have been proposed for CMEs: magnetic tongues or bottles (B) and their cousins, flux ropes (C), and plasmoids (D). Bottle and flux rope geometries maintain magnetic connection to the Sun and, consequently, open previously closed magnetic fields into interplanetary space. Plasmoids are magnetic structures which

become fully detached from the Sun, and, as a consequence, do not permanently open any new fields from the Sun into interplanetary space.

The fundamental problem with opening previously closed magnetic field regions on the Sun to interplanetary space is that in the absence of other mitigating processes, the amount of open magnetic field in interplanetary space, and hence IMF magnitude, would grow without bound. This so called “flux catastrophe” was first pointed out by Gosling [1975]. MacQueen et al. [1980] used Skylab CME sizes and rates to estimate that the IMF magnitude should approximately double over ~100 days (at solar maximum CME rates) if all of the magnetic flux in the observed CMEs remained rooted in the Sun (B from Figure 3).

3. Counterstreaming Electron Events: the Interplanetary Signature of CMEs

Ever since the discovery of CMEs in the mid-1970s, researchers have looked for the signature of these structures in the interplanetary medium. Over the years a number of interplanetary signatures have been associated with CMEs. These various signatures, which have recently been summarized by Gosling [1990], include 1) helium abundance enhancements, 2) ion and electron temperature depressions, 3) unusual ionization states, 4) strong magnetic fields, 5) low magnetic field variances, 6) anomalous field rotations, 7) counterstreaming energetic protons, and 8) counterstreaming suprathermal electrons. Of all of these signatures, counterstreaming suprathermal (halo) electrons [e.g., Gosling et al., 1987] is presently the most robust signature of CMEs in the interplanetary medium [Gosling, 1990]. For example, this author showed that the various other possible CME

signatures listed above represent only small subsets of all counterstreaming halo electron events.

If CMEs remain at least partially attached to the Sun, as indicated in the previous section, then counterstreaming suprathermal electrons would be expected. This is because, in the normal solar wind, the electron heat flux is carried by an excess of halo electrons streaming outward along the local magnetic field. This beam of energetic electrons, or "strahl", is observed nearly continuously in solar wind. Since the normal IMF is connected to the Sun at one end and the outer heliosphere at the other (A in Figure 3), the strahl has been almost unilaterally interpreted as hot electrons streaming outward along the field from the $\sim 10^6$ K corona. Observations of strahls both directions along the local magnetic field would then be naturally explained as a hot coronal source both directions back along the local magnetic field.

A similar explanation is also proposed for the disconnected, plasmoid topology; in this case hot electrons initially streaming outward along both ends of the loops continue to circulate both directions around the plasmoid even after the field has been disconnected. One important question with this explanation is whether such electrons are sufficiently non-interacting that they can maintain their field aligned distributions over the 2-3 day transit to 1 AU while they are convected outward from the Sun at normal solar wind speeds.

In addition to the topological explanation of counterstreaming events as CMEs, the overall solar cycle variation of CMEs very closely matches that of

counterstreaming events [Gosling et al., 1992]. Figure 4 displays this correlation. This figure compares the solar cycle variations of the percentage of the time that counterstreaming electrons are observed at 1 AU (top panel) and an estimate of the annual whole-Sun occurrence rates of CMEs (middle panel). The smoothed sunspot number (bottom panel) indicates the phases of the solar cycle. Clearly the CME and counterstreaming electron rates closely track each other.

In order to assess whether counterstreaming halo electron events represent magnetic structures which are still connected to or disconnected from the Sun, Phillips et al [1992] examined several details of the electron distributions in counterstreaming events at 1 AU. In short, these authors find that CMEs appear to maintain some magnetic connection to the corona. This result was based on several independent aspects of the observations relating to asymmetries in the dominant direction of the beam and the typical variation of the field orientation during transit through CMEs.

In addition to statistical evidence for a tongue or flux rope geometry over a closed plasmoid, Phillips et al. [1992] also showed the first examples of a new type of distribution that they refer to as "strahl on strahl" (SOS). Figure 5 displays an SOS distribution in which halo energy electrons are observed in two broadly counterstreaming beams with an additional narrow strahl superposed in the direction running outward along the local magnetic field. These authors interpret this sort of distribution as direct evidence for continued connection (the narrow, pristine strahl) while simultaneously within a largely closed magnetic structure (the broader peaks, caused by

mirroring and trapping of halo electrons both directions along the field).

The increasing trace in Figure 6 shows the rate at which 2-D magnetic flux is opened from the Sun and added to the IMF under the assumption that all counterstreaming electron events represent simply connected magnetic bottles (B in Figure 3). The dashed line indicates the 2-D magnetic flux (described above and defined by McComas et al [1992a]) open, on average, in the ecliptic plane at one AU. This figure shows that for simple bottle geometry CMEs (assuming solar maximum CME rates) the amount of open flux would double over ~9 months in the absence of any mitigating processes.

A twist on the flux catastrophe is that if CMEs remain magnetically attached, but are flux ropes (C in Figure 2) [Gosling et al., 1990], that rate of build-up would be reduced. If, for example, a field line in a typical CME came out from the Sun, looped around once, and then returned to the Sun, the rate of flux build-up shown in Figure 6 would be only one half as fast as that for simple bottles. The above estimate for magnetic flux doubling would then be increased from ~9 months to one and one half years. However, it must be stressed that if CMEs retain any attachment to the Sun whatsoever, the flux catastrophe will ultimately occur in the absence of some other process to close off previously open fields.

A schematic representation of how CMEs may form as flux ropes is displayed in Figure 7. The process begins with closed field loops in the corona (top panel). Given the appropriate conditions, the closed loops begin to expand upward. In addition, motions of the magnetic field footprints down in the

photosphere can create a shear in the coronal fields (second panel). The same sort of footprint motions can also bring the feet closed together (third panel). Reconnection occurs between oppositely directed magnetic field regions which are pushed up against each other with sufficient force. Because of the imposed shear, the field line in a single loop does not match up with itself: rather, field lines interconnect with adjacent lines. This process leads to both flux rope topology CME and the creation of underlying magnetic loops (bottom panel). Since the ends of the newly formed flux rope which still connect back to the Sun are not located physically near to each other, its hard to imagine how these fields could reconnect to form a fully detached plasmoid.

The schematic representation shown in the bottom panel of Figure 7 could account for all of the observed aspects of CMEs. Continued connection of the field at the ends of the structure seems a likely explanation for the long-lived “legs” while formation of loops underlying the rising CME are also commonly observed (A. Hundhausen, private communication). In addition, such structures would best account for the statistical evidence for continued CME connection provided by Phillips et al. [1992] and would provide a very ready explanation for SOS distributions.

In my opinion, the flux rope geometry, as represented in Figure 7 is the most likely configuration for CMEs in general, and does the best job of explaining both the remotely observable gross features and *in situ* observations of detailed particle distributions within these structures.

4. Heat Flux Dropouts: A Signature of Closing IMF?

The interpretation of 1) the normal mono-directional heat flux as evidence for magnetic connection back to the Sun along open field line (Figure 3, panel A) and 2) counterstreaming halo electron events as evidence for magnetic connection back to the Sun both directions along the local magnetic field (Figure 3, panels B and C) led McComas et al. [1989] to examine whether there were also intervals devoid of electron heat flux in the solar wind. If so, these intervals might provide evidence that portions of the IMF are magnetically disconnected from the Sun and open to the outer heliosphere at both ends. Panel E of Figure 3 schematically displays this sort of magnetic topology.

McComas et al. [1989] examined color spectrograms from the ISEE-3 solar wind electron experiment and found intervals which they identified as “heat flux dropouts” (HFDs). Figure 8 displays cuts through the electron distribution function, $f(v)$, for an interval of normal solar wind (circles) and during an HFD (squares). The vast majority of the electrons lie within the core population which is seen in Figure 8 as the tall central peak with electron speeds between ~ -5 and 5 km s^{-1} . The superposed halo peak is broader and hotter ($|\text{electron speeds}| > \sim 5 \text{ km s}^{-1}$), and has a substantially enhanced component one direction along the field in the normal solar wind (negative electron speeds in this case); during the HFD, this enhancement is absent and the distribution looks very similar both to the distribution moving in the opposite direction along the field and to distributions moving at all angles with respect to the field (not shown).

Heat flux dropouts were identified by McComas et al. [1989, 1992b] purely on the basis of the electron distributions. However, when these intervals are compared to the interplanetary magnetic field, a surprisingly good correlation is observed. Figure 9 shows the correlation of HFDs (black squares) with the in-ecliptic spiral angle (135° and -45° are along the normal spiral at 1 AU). Over the ~18 months covered by this plot, the sector structure is easily observable by the quasi-regular transitions back and forth between the two spiral angles. While not all sector boundary crossings have associated HFDs, when HFDs do occur, they are clearly associated with large rotations of the IMF in, general, and sector boundary crossings, in particular.

The obvious explanation for HFDs, which led McComas et al. [1989] to search for such dropouts in the first place, is that they represent regions magnetically disconnected from the hot coronal source of electrons. Figure 10 displays a time sequence of schematic diagrams which show how reconnection between oppositely directed open magnetic fields can lead to their disconnection. Such structures would be carried outward with the normal solar wind, passing 1 AU in typically 2-3 days. However, the hot halo electrons run out past 1 AU in only a few hours so that there is a very large probability that once such a structure is formed, it would be observed as an HFD in interplanetary space McComas et al. [1989, 1992a,b]. The association of HFDs with the heliospheric current sheet would also be naturally explained by this process since oppositely directed fields are juxtaposed above helmet streamers, at the base of the heliospheric current sheet.

In an independent study of the HFD list published by McComas et al. [1989], Lin and Kahler [1992] examined the electron distribution at much higher energies. In particular, they examined 2-8.5 keV solar electrons; due to their higher energies, when present, such electrons are superior tracers of magnetic topologies compared to 0.1-1 keV halo electrons. Of the 25 events originally published by McComas et al. [1989], Lin and Kahler found that in nine of these events the >2 keV electrons still exhibited strong monodirection streaming indicating that they probably still connected to the Sun. For the majority of the identified HFDs (13 of 25), only a weak monodirectional streaming was observed, leaving in doubt the ultimate connectivity of these events. In addition, two of the cases exhibited real dropouts even at these higher energies indicating that at least these events probably represented real disconnections.

In addition to the obvious explanation for HFDs given above, other explanations for these intervals may be possible. In particular, McComas et al. [1989] and Lin and Kahler [1992] both discussed the possibility that HFDs may simply be caused by enhanced coulomb collisions due to the higher densities often associated with the heliospheric current sheet in interplanetary space [Borini et al., 1981]. In fact, McComas et al. [1989] showed that HFD associated current sheet crossings are, on average, higher density than those not associated HFDs. While this explanation may be correct for some HFDs, Lin and Kahler [1992] showed that it cannot account for all of the HFD observations. Perhaps both disconnected field structures and enhanced collisions and lead to HFDs.

5. Coronal Disconnections: Direct Evidence for Closing of Open IMF

As can be seen from Figure 10, the topological effect of reconnecting oppositely directed previously open fields near to the Sun is to 1) return closed field loops to the Sun and 2) release disconnected U-shaped field structures onto interplanetary space. It was, in fact, the interpretation of HFDs as disconnected magnetic structures, and schematic diagrams such as Figure 10 which lead McComas et al. [1991] to examine coronagraph observations for direct evidence of such disconnections in the solar corona.

Figure 11 displays a sequence of four SMM coronagraph images from 1 June 1989. In this sequence a large, closed loop structure (6:32 UT) appears to disconnect. Reconnection is evidenced by the formation of a dark band across the structure in the 11:10 UT image (see arrow). In the 14:16 UT image reconnection appears to continue with the enhancement of bright loops below the dark band and a large U-shaped structure above it. Finally, in the 17:05 UT image the U-shaped structure appears to have lifted-off from the corona into interplanetary space, leaving only an arcade of bright, low-lying loops.

In order to assess the importance of these coronal disconnection events, McComas et al. [1992c] carried out a statistical study of three months of SMM coronagraph observations. The interval chosen extended from 1/1/88 through 3/26/88. The initial SMM survey [St. Cyr and Burkepile, 1990] found no obvious disconnections during this interval. It is worth noting, however, that the initial SMM survey was not particularly sensitive to disconnected structures and that only ~3% of structures observed were identified as potentially detached.

Over the ~3 months of observations, St. Cyr and Burkepile identified 53 events in which some outward motion of material/structures were observed. On careful reanalysis [McComas et al., 1992c], looking specifically for evidence of disconnection, 6 of the 53 (11%) showed evidence of disconnection in more than one frame. In addition, 13 (23%) showed 1 Frame with an outward "U" or "V" structure. These latter structures may not be significant in light of the fact that there are ambiguities in interpreting images from optically thin media. In any case, of the six more likely detachments, most appeared as detachments of coronal streamers. These observations led McComas et al. [1992c] to conclude that magnetic disconnection events on previously open field lines (above helmet streamers) are far more common than previously appreciated.

There is an interesting example of a possible coronal disconnection as far back as the 16 April 1893 solar eclipse. Figure 12, taken from Cliver et al. [1989], shows both the locations of three observing sights (Chile, Brazil, and Senegal) and sketches made at each of these sights indicating the outward motion of a large U-shaped structure. This structure was originally interpreted as a comet, but much more recently reanalyzed by Cliver et al. [1989] as evidence for formation of a fully detached, plasmoid topology CME. While this latter interpretation may indeed be correct, the sketches of the event do not display any leading edge of a CME. Rather, the size and shape of this event are highly reminiscent of the coronal disconnection on 27 June 1988 shown previously by McComas et al. [1991].

Another independent line of evidence for magnetic reconnection above

helmet streamers is provided by "high coronal fares" [Cliver and Kahler, 1991]. These impulsive low energy (<10 keV) solar electron events have been inferred to arise from acceleration in the corona, at heliocentric distanced greater than 1.5 solar radii [Potter et al. 1980]. Reconnection across the based of the heliospheric current sheet, above helmet streamers, is the most likely location for such high altitude reconnection [Cliver and Kahler, 1991]. Lin [1985] found 135 such events over a 15 month period, corresponding to one event roughly every three days; such a high rate indicates that these events, and the consequent formation of detached coronal magnetic structures, are a common feature of the solar corona.

6. Discussion

Coronal mass ejections have been inferred to be 1) bottles, 2) flux ropes, or 3) plasmoids. If they are either of the first two, then they serve to open previously closed coronal magnetic fields to interplanetary space. In the absence of some method for closing off previously open flux then the open field could build up without bound leading to the so called "flux catastrophe.

There are several other conceivable methods for mitigating this build up of magnetic flux. First, it is possible that the newly opened magnetic flux could fall back to the Sun. If this were to happen frequently, I would expect regular evidence in sequences of coronagraph pictures of bright structures moving sunward. However, there is no evidence that I am aware of for sunward moving structures in the corona with the exception of one unpublished counterexample. It is also conceivable that the magnetic loops return to the Sun after being depleted of high density plasma (and are

consequently unobservable in coronagraph images). This suggestion seems extremely unlikely in light of the fact that CMEs generally accelerate over the region observable in coronagraphs and once the solar wind transitions to super-Alfvénic (near the outer edge of coronagraph fields-of-view), the outward flow energy vastly dominates the magnetic pressure so that beyond this point the structures cannot snap back in.

A far more conventional explanation is that all CMEs may be fully detached plasmoids and, consequently, open no new magnetic flux from the Sun. If this were the case, some other process would need to account for the increase in $|B|$ and the 2-D flux in the ecliptic plane, Φ^* , observed over the rising portion of solar cycle 21 (Figure 1). In addition, the persistence of long lasting “legs” along the flanks of the regions that CMEs rise out of have generally been interpreted as continued magnetic connection to the Sun. *In situ* observations of the interplanetary manifestations of CMEs, counterstreaming halo electron events, provide additional support for the idea that CMEs remain magnetically attached to the Sun. One final note is that it is hard for this author to imagine how all of the magnetic field lines in every CME could somehow find oppositely directed partners to reconnect with to form truly disconnected plasmoids.

If CMEs do retain at least some magnetic attachment to the Sun as they expand out into interplanetary space, then they must open up new magnetic field regions. Both in order to stop this process from leading to a flux catastrophe, in which the IMF magnitude builds up without bound, and to explain the reduction in $|B|$ and 2-D flux over the declining phase of solar cycle 21, some other process must be functioning to close off previously

open field regions from the Sun. The most likely method for removing open field regions and returning closed field arches to the Sun is by reconnecting oppositely directed fields at the base of the heliospheric current sheet above helmet streamers. This process, combined with CMEs opening new flux from the Sun provides a ready method for moderating the amount of coronal magnetic flux open to interplanetary space at any given time.

There is also independent evidence for this sort of reconnection above helmet streamers in the corona. Coronal disconnection events remotely observed in sequences of coronagraph (and eclipse) images appear to provide direct evidence for such reconnection. In addition, at least some heat flux dropouts appear to represent the interplanetary manifestation of magnetic field structures which are disconnected from the Sun and connected to the outer heliosphere at both ends. Finally, common impulsive electron events with energies <15 keV appear to be best explained in terms of acceleration in reconnection regions above helmet streamer at heights $>0.5 R_S$.

In order to maintain the open IMF in interplanetary space, it seems likely that there must be some feedback process between the opening and closing of magnetic field regions from the Sun. McComas et al. [1989, 1991] proposed just such a process in which the pressure in the corona could maintain a quasi equilibrium between opening and closing of coronal magnetic fields. In this model, the magnetic field pressure from newly opened field regions would enhance the transverse pressure around the Sun until this pressure was just large enough that oppositely directed magnetic fields were marginally stable against reconnection. Thereafter, the opening

of more regions would increase the pressure to the point that the oppositely directed fields would be unstable, and reconnection would commence until such a time that sufficient flux was removed to again reduce the pressure to a marginally stable configuration. As an example of this process, the coronal disconnection event on 27 June 1988 was preceded by a substantial disruption of the streamers in the corona in which these structures were observed to fold around the Sun toward the region of the disconnection [McComas et al., 1991]. These observations provide direct evidence that the coronal pressure was enhanced in the region of the disconnection just prior to the detachment.

In addition to the evidence provided by direct coronal observations, the suggestion that the balance between opening and closing of fields was examined numerically by Linker et al. [1992]. These authors used a 2-D MHD simulation of the corona to examine the effect of increasing the overall magnetic pressure around an equilibrium helmet streamer. Figure 13 displays a sequence of magnetic field traces at times, t , following the increase in pressure. Once the pressure is enhanced, the streamer configuration reconnects initially on closed fields lines. Ultimately, however, reconnection eats through to the adjacent, previously open field lines and continues there until sufficient flux has been removed to decrease the pressure to point where an equilibrium can again be maintained. This process, on open fields, returns closed arches to the Sun and reduces the overall magnetic pressure.

In addition to accounting for 1) the variation in the amount of open magnetic field observed in interplanetary space over the solar cycle and 2)

all of the observed features of CMEs and coronal disconnection events, the opening and closing processes described here could also account for how coronal holes and closed, loop structures can quickly move around between various widely spaced locations on the Sun. Large modifications in the overall magnetic configuration of the corona can occur on relatively short timescales; it seems more reasonable that such large changes be accomplished by the opening and closing processes described here than the large scale motion of magnetic footprints across the Sun.

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Figure Captions

Figure 1. Annual averages of $|B|$ (top) and the 2-dimensional magnetic flux, Φ^* , (bottom) in the ecliptic plane over solar cycle 21.

Figure 2. Coronagraph images showing the release of a coronal mass ejection on 10 August, 1973; the two images are separated by only 24 minutes. These images clearly indicate the rise of closed magnetic field loops which appear to maintain magnetic attachment to the Sun. Adapted from Gosling et al. [1974].

Figure 3. Schematic diagram showing normal open magnetic fields (A), a magnetic bottle closed to the Sun at both ends (B), a plasmoid magnetically closed on itself (C), and a coronal disconnection in which the field is open to the outer heliosphere at both ends (D). B displays a magnetic flux rope which is topologically similar to the magnetic bottle, however, the field loops around on itself before ultimately closing back to the sun at both ends.

Figure 4. Greyscale coded electron counts in the energy ranges from 137-362 eV and 500-958 eV from March 22 and 23, 1979. Prior to ~14:00 UT a beam or strahl carrying the bulk of the solar wind electron heat flux is observed. After this time the spectrogram displays an interval of counterstreaming halo electrons. From Gosling et al. [1986].

Figure 5. "Strahl on strahl" distribution showing counts in the 161-223 eV range of halo electrons versus in ecliptic angle. Dotted lines indicate range of magnetic field orientations during the measurement interval. Taken from Phillips et al. [1992].

Figure 6. Monthly and integrated 2-D magnetic flux (Φ^*) observed in CMEs

(bidirectional electron events) for the interval from August 1978 through February 1980. The dashed line indicates the average amount of 2-D flux present in the ecliptic plane on average. From McComas et al. [1992b].

Figure 7. Schematic diagram of the formation of a magnetic flux rope. Closed field arches (top panel) expand upward; motions of the footprints down in the photosphere can cause a shear in the field (second panel) and increase the likelihood of reconnection (third panel). Because of the shear, field lines do not reconnect with themselves, but rather with their neighbors, leading to a flux rope and underlying closed field arches (bottom panel).

Figure 8. Cuts through the electron distribution function, $f(v)$, along the local magnetic field direction prior to (16:01:59 UT) and during (21:00:50 UT) a heat flux dropout. The difference between the two curves at large negative speeds (left third of figure) represents the missing strahl electrons which carry the majority of the heat flux. Taken from McComas et al. [1989].

Figure 9. Hourly averaged IMF spiral angle plotted as a function time for the 18 month interval from 8/78-2/80. The squares indicate times of 83 HFD events. Note the excellent correlation between HFDs and large rotations of the field, especially sector boundary crossings. From McComas et al. [1992d].

Figure 10. Schematic diagrams of a coronal disconnection. The top panel displays a helmet streamer geometry. Reconnection begins, in this case on a closed field loop, but quickly eats through to the adjacent open field lines (middle). As reconnection continues (bottom), closed field arches are returned to the Sun and a disconnected, U shaped structure is released. From McComas et al. [1992c].

Figure 11. Sequence of four coronagraph images from SMM displaying a coronal disconnection event on 1 June 1989. The arrow in the 11:10 UT image indicates where the reconnection line is presumably forming. By 17:05 UT the entire structure has lifted off leaving only small underlying arches. From McComas et al. [1992c].

Figure 12. Possible coronal disconnection observed from Chile, Brazil, and Senegal during the 16 April 1893 solar eclipse. The sketches indicate the time sequence of coronal structure observed from the three independent locations. Taken from Cliver et al. [1989].

Figure 13. 2-D MHD simulation of the effect of increasing the magnetic pressure around an equilibrium helmet streamer. The panels display magnetic field traces at times, t , following the increase. Reconnection begins shortly after the increase and proceeds until sufficient magnetic pressure has been removed to again achieve an equilibrium. Taken from Linker et al. [1992].

Figure 1

Fig. 2

F. 4

Fig. 6

Fig. 9

1 JUN 1969 06:32

1 JUN 1969 11:10

1 JUN 1969 14:16

1 JUN 1969 17:05

a) $t = 0$

b) $t = 4$ hours

c) $t = 8.8$ hours

d) $t = 12.8$ hours

e) $t = 17.6$ hours

f) $t = 24$ hours