Solar Wind: Manifestations of Solar Activity

The Sun's outer atmosphere, the corona, is continually heated and expands to create the solar wind. Solar activity waxes and wanes with the 11 yr cycle of the Sun's magnetic field, and these activity changes also affect the solar wind. The brightest structures in the corona are a bright belt of streamers, the source of the slowest solar wind. These streamers are occasionally disrupted as coronal mass ejections (CMEs) which spew large amounts of gas and magnetic fields into the solar wind. CMEs appear to be a fundamental way in which the Sun loses mass and releases the magnetic flux and field twist built up during the cycle.

The solar magnetic field and the solar wind

The Sun's magnetic field controls much of its surface activity which evolves with an 11 yr period. The field tends to simplify with height in the corona, but the corona, and its outward expansion as the solar wind, also evolves on time scales related to the evolution of the surface field. The simplest magnetic configuration of the Sun occurs during activity minimum. At this time the Sun's magnetic field can be approximated as a dipole whose axis is tilted slightly with respect to the axis of rotation. Large CORONAL HOLES cover the Sun's polar regions and extend toward the equator. These open-field regions are of opposite magnetic polarity. The polar holes are separated by a wide band centered over the heliomagnetic equator within which lie the magnetically closed structures near the surface, i.e. active regions and sunspots. CORONAL STREAMERS extend over these regions forming a bright band around the Sun. The high-speed wind flowing from the polar holes constricts the oppositely directed fields over the streamers to a narrow current sheet which has the appearance of a ballerina's skirt (figure 1). This rotating, warped heliospheric current sheet (HCS) appears as a sector boundary crossing at Earth, such that during one solar rotation the Earth will be immersed in a minimum of two large sectors of opposite polarity each with the relatively high-speed wind of its parent hole. During the solar cycle new magnetic flux emerges at higher solar latitudes leading to a more complex and disturbed corona. The streamer belt and heliomagnetic equator become more complicated and more inclined to the rotation axis, and the magnetic sector structure observed in the solar wind is more chaotic. Near maximum activity a simple, single current sheet surrounding the Sun may not even exist.

On a global scale the slow solar wind is confined to the streamer belt and the HCS (see SOLAR WIND: GLOBAL PROPERTIES). It now appears that this band is the source of most transient activity which affects the heliosphere, except possibly near sunspot maximum. Near the solar surface most activity occurs on smaller scales within regions of strong magnetic fields (see ACTIVE REGIONS) in the form of flares and active region loop expansions. However, in the corona the most rapid, dramatic and energetic form of evolution occurs in large events called CMEs. Most CMEs tend to cluster within ~30° of the coronal base of the HCS over the cycle. Thus, there is a close relationship among coronal streamers, the HCS and CMEs and their evolution. Since CMEs dominate the transient activity in the solar wind, they are the focus of this article.

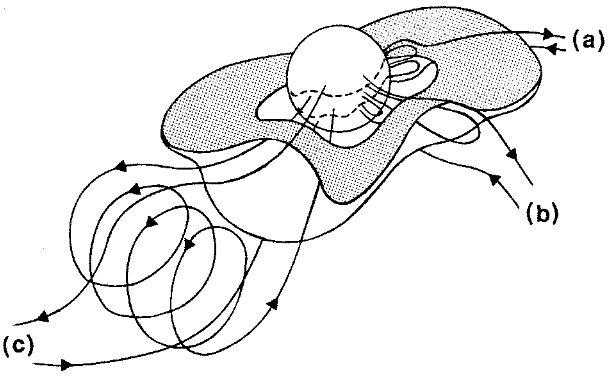

Figure 1. Schematic model of the coronal streamer belt as a disk of variable thickness forming a conduit for transient outflow from (*a*) steady-state helmet streamers, (*b*) small-scale ejections and (*c*) large-scale CMEs, some with flux rope structure. After Crooker *et al* (1993).

CMEs are immense structures of plasma and magnetic fields that are expelled from the Sun into the heliosphere. As such they are the nearest example on a large scale of the common process of magnetohydrodynamic (MHD) expulsion of material from objects throughout the universe. Although the range of CME speeds is large, even the slowest CMEs (slower than the in-ecliptic solar wind) never fall back to the Sun. This suggests that their internal magnetic fields control the dynamical evolution of CMEs near the Sun. CMEs can cause large geomagnetic storms at Earth and their attendant effects, such as auroral displays. Faster CMEs drive transient interplanetary shocks, which in turn can accelerate solar energetic particle (SEP) events. At the Sun the onset of CMEs can be associated with both flares and filament eruptions, but most flares occur without CMEs and some CMEs cannot be associated with any surface activity. Other articles discussing the origins and early evolution of CMEs are SOLAR CORONAL MASS EJECTION: OBSERVATIONS, SOLAR CORONAL MASS EJECTION: THEORY, SOLAR PROMINENCE ERUPTION and SOLAR FLARES: RELATION TO CORONAL MASS EJECTIONS.

CMEs near the Sun

CMEs are best viewed in white light from space-borne coronagraphs; these reveal that, even near the Sun, a CME can dwarf the solar disk. CMEs often appear to have a bright leading looplike structure followed by a dark cavity and a bright core of denser material, suggesting the eruption of a pre-existing prominence, its overlying coronal cavity and the ambient corona (figure 2). Prominences are elongated regions of dense, cooler

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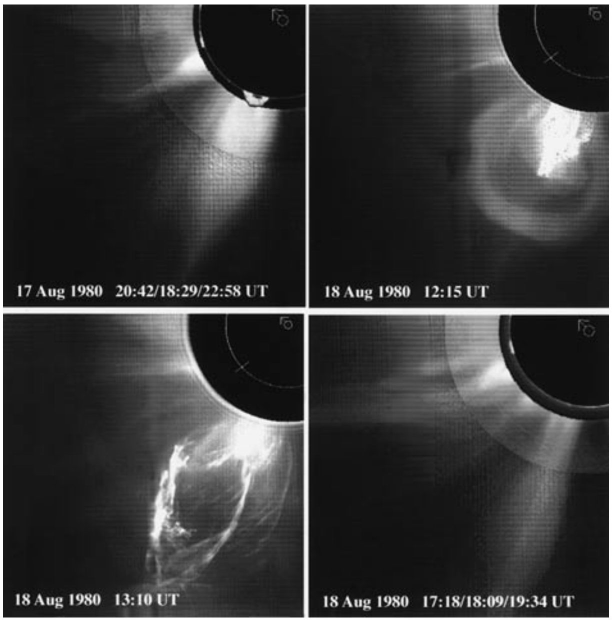

Figure 2. A CME and prominence eruption on 17–18 August 1980. The first and fourth panels are composites of an Hα (inner) image from Mauna Loa Observatory showing the prominence, an MLO K-coronameter image of the mid white light corona from 1.2 to 1.8 solar radii, and a solar maximum mission (SMM) coronagraph image of the white light corona from 2 to 5 solar radii. The second and third panels show only SMM data. The inner circle on each panel marks the solar limb and the arrow points to solar north. From Hundhausen (1997).

material suspended in the low corona in helical magnetic fields (see SOLAR PROMINENCE MODELS). Large prominences are surrounded by dark voids called cavities which have less coronal material but may be shaped by strong, helical magnetic fields (discussed later). There is a large range in the basic properties of CMEs. Their speeds, masses and energies range over 2–3 orders of magnitude, and their widths exceed by factors of 3–10 the sizes of flares and active regions. Occurrence rates of CMEs vary in phase and amplitude with the sunspot cycle.

CMEs arise in large-scale, closed structures, such as coronal streamers, where the magnetic field is strong enough to prevent the plasma from expanding outward. The temporal and latitudinal distributions of streamers and prominences are similar to those of CMEs, being confined to low latitudes about the current sheet near sunspot minimum and becoming broadly distributed near maximum. This evolution is very different from that of active regions, flares or sunspots, which migrate from mid to low latitudes during the solar cycle. Many energetic CMEs result from the disruption of a pre-existing streamer, which increases in brightness and size for days before erupting as a CME (figure 2). Possible causes of such disruptions include the emergence through the surface of new magnetic flux, the dynamical evolution of arcades and the shearing of field lines.

Signatures of CMEs in the solar wind

The CME's plasma is entrained on magnetic field lines and transported into the solar wind, where it can be detected by remotely measuring the plasma along the line of sight or by measuring directly its properties as the material passes over a spacecraft. CME plasma in the solar wind has been remotely detected by white light photometers on the Helios spacecraft and by measurements of interplanetary scintillation (IPS) of galactic radio sources from the ground.

The two Helios spacecraft were placed into highly elliptical solar orbits ranging from 0.3 to 1 AU from the Sun and operated from 1974 to 1983. The on-board photometers were able to produce crude images of $\approx$200 CMEs out to the orbit of Earth. The occurrence rates, widths and speeds of these CMEs were consistent with those of the coronagraph observations within 30° of the Sun. In these views of CMEs in the inner heliosphere, the CMEs are obviously expanding but otherwise their shapes are unchanged, with two brighter 'legs' behind and flanking a tenuous leading front. The interplanetary (IP) masses and energies of the Helios CMEs were factors of 2–10 higher than those determined by the earlier coronagraphs. However, the more sensitive measurements from the SOHO LASCO coronagraphs now indicate that mass flows out of the corona behind the leading edges of CMEs for a prolonged period of time, yielding higher masses consistent with the Helios observations. CMEs can contribute a sizable fraction of the total mass and energy flux of the solar wind, especially at solar maximum and in or near the ecliptic. The mass contribution ranges from a few percent at minimum to possibly as much as 40% at maximum.

The IPS technique detects transient disturbances in the solar wind as enhanced scintillation of distant astronomical sources in the sky along the line of sight. The scintillation is caused by small-scale turbulence in the wind due to the enhanced density of a transient such as a CME. By observing daily changes in the scintillation of a large number of sources distributed over the sky, crude maps of IP transients can be produced. A related technique involves the tracking and analysis of signals from deep-space spacecraft such as Pioneer Venus, Ulysses and Galileo as the extended solar corona transits between the spacecraft and the Earth. This technique is particularly sensitive to the enhanced density and density fluctuations in the compressed plasma between a CME and a shock if there is one and in the CME itself. However, these techniques have poor spatial and/or temporal coverage and are most useful when combined with other data sets on a particular event.

Most of our understanding of CMEs in the solar wind has come from direct measurements of the plasma and magnetic fields as the CME material passes over a spacecraft which is situated outside of the Earth's magnetosphere. A variety of signatures have been proposed as identifiers of CME ejecta in the solar wind. Table 1 summarizes those signatures which

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Table 1. Signatures of CMEs in the solar wind.

Transient interplanetary shock waves
He abundance enhancements
Unusual ionization states (e.g. He^+)
Brief density enhancements and longer-duration density decreases
Proton and electron temperature depressions
Bidirectional field-aligned flows of halo electrons and/or low-energy protons
Magnetic field variations usually associated with magnetic 'clouds' or flux ropes:
Strong magnetic field
Smooth field rotation
Low plasma β
Low field strength variance

are different from the normal solar wind and usually observed for at least several hours. These include shock waves, density changes, depressed temperatures, flows with enhanced helium abundances and magnetic field structures consistent with looplike topologies. Although the front and sides of a CME are visible near the Sun because they are denser than the ambient solar wind, expansion of the CME can yield lower than average densities further from the Sun. Many of these signatures were first identified in the plasma which followed an IP shock by several hours and was considered to be the piston (CME) driving the shock (see figure 3). Some signatures can also be observed elsewhere in the solar wind where they may identify relatively slower CMEs not driving shocks.

More sensitive instruments show that the abundances and charge state compositions of elements and ions are systematically different in CME flows as compared with other kinds of solar wind (see SOLAR WIND COMPOSITION). As the solar wind–corona expands outward from the Sun, the electron density decreases so rapidly that the plasma becomes collisionless and the relative ionization states become constant, thus reflecting the conditions in the corona where this occurs. The charge states of so-called 'minor ions' ($Z > 2$) in CME flows usually suggest slightly hotter than normal coronal conditions at their origin (i.e. >2 MK). However, mixtures of charge states and, therefore, ionization temperatures are also found. In addition, transient flows often exhibit element and ion abundances (especially He and Fe) that are enhanced relative to the nominal solar wind. The coronal composition of transient flows are also seen in the systematic enhancement of elements with low first ionization potentials (FIPs) (see TRANSITION REGION: FIP EFFECT). Abundances of elements with FIPs <10 eV are enhanced by a factor of ~4 relative to those high-FIP elements, an effect which is typical of coronal, not photospheric material. Finally, the Ulysses spacecraft (see SOLAR WIND: ULYSSES) showed not only that is there a latitude dependence on the speed of IP CMEs but also that their compositional dependence is different. The He and minor ion abundances and charge states become more and more similar to coronal hole flows the higher the ecliptic latitude.

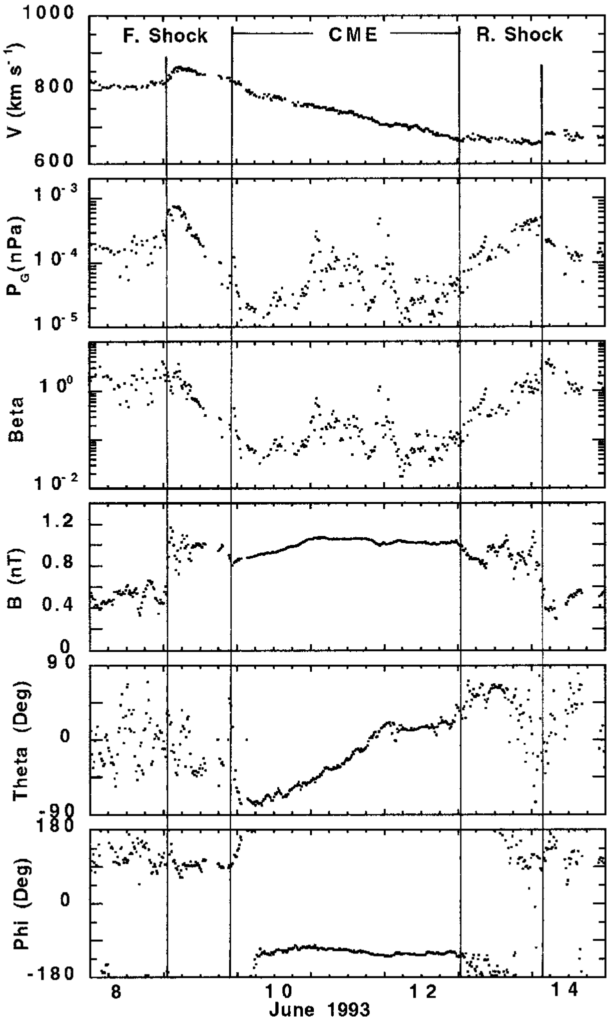

Figure 3. Ulysses plasma and magnetic field observations of an expanding CME–magnetic flux rope in the solar wind. From top to bottom the parameters plotted are bulk flow speed, plasma pressure (ions plus electrons), plasma β, magnetic field strength, field polar angle and field azimuthal angle. The bar marked 'CME' defines the region of bidirectional electron streaming. Ulysses was at 4.6 AU from the Sun and at a heliographic latitude of S33°. From Gosling (1996).

Infrequently, unusually low ionization states of He and minor ions such as O, Fe and C are detected in CME flows. Although rarely observed before this decade, enhanced He^+ flows have been detected in at least four Earth-directed CMEs with the SOHO and WIND spacecraft during 1997–1998. In each of these events an erupting filament–CME could be associated with an unusually dense and narrow 'plug' of cool plasma at WIND in the trailing edge of a magnetic cloud. It is likely that such material is the solar wind signature of the filament itself and, therefore, is chromospheric in origin.

Although the speeds of the leading edges of CMEs near the Sun exhibit a wide range from ~50 to >2000 km s^{-1}, the average speed is slightly less than the typical solar wind speed in the ecliptic. The speeds of most CMEs beyond several solar radii appear constant, indicating that they are rapidly accelerated low in the atmosphere. In the ecliptic within 1 AU of the Sun it appears that the fastest CMEs decelerate as they interact with the slower ambient plasma, while the slowest CMEs are accelerated, possibly by the same forces acting on the normal solar wind. At high heliographic latitudes the speed profiles of CMEs are different. Using bidirectionally streaming events observed at Ulysses as CME proxies, the speeds of high-latitude CMEs (730 km s^{-1} on average) were much higher than in the ecliptic plane and comparable to the surrounding solar wind flow characteristic of polar coronal holes (figure 3). This again suggests that CMEs are accelerated along with the surrounding solar wind.

In a hydrodynamic plasma regime, a dense region moving through a uniform, background flow at a sufficiently faster speed will produce a shock wave which stands out ahead of the driver (see SOLAR WIND SHOCK WAVES AND DISCONTINUITIES). Such shocks are frequently observed throughout the universe, but our detailed understanding of them comes from direct measurements of their properties made in the interplanetary medium and in Earth's bow shock. Within 1 AU of the Sun the strongest shocks are driven by CMEs whose leading edges are often a few hundred km s^{-1} faster than the normal wind speed. A spacecraft sees a forward-moving shock as a discontinuous increase, or jump, in most plasma and magnetic field parameters. In figure 3 a shock at Ulysses is encountered first (left) and stands off from the leading edge of the CME driver by about 20 h. Between the shock and the CME lies a turbulent region where the ambient solar wind plasma and interplanetary magnetic field (IMF) are compressed ahead of the CME. Depending on the signatures used, approximately 1/3–1/2 of all ejecta in the solar wind within 1 AU follow IP shock waves. When these shocks first develop is unclear, but there is evidence that most CMEs moving outward in the low corona with speeds greater than the local Alfvén speed (~400 km s^{-1}) are associated with coronal shock waves. Coronal shocks are remotely detected as Moreton waves at the surface and metric radio type II bursts in the corona. At heights and densities typical of the solar wind, shocks can be tracked outward at kilometric wavelengths (see SOLAR WIND: INTERPLANETARY RADIO BURSTS).

Simple hydrodynamic model simulations have been successful in reproducing the basic speed and pressure profiles of shocks and CMEs even out to large distances from the Sun. Usually a simple pressure pulse of appropriate duration and amplitude is initiated into a uniform ambient flow with characteristic solar wind parameters. As the front of the faster CME overtakes the slower wind, a strong gradient develops and pressure waves eventually steepen into a forward shock propagating into the ambient wind ahead and, occasionally, a reverse shock that propagates back through the CME towards the source (the Sun). Because of its interaction with the ambient plasma, the CME slows until it eventually 'rides along' at the solar wind speed. This may not occur until several AU from the Sun. A different class of forward–reverse shock pairs was observed by Ulysses at high latitudes. In the event shown in figure 3, the speed declined from the front to the rear of the CME and the pressure was maximum immediately downstream from the shocks. Since the CME was not traveling faster than the solar wind ahead of it, the shocks were not caused by the relative motions between the CME and ambient wind but by expansion of the CME due to its high internal pressure. Simulations show that such features can be reproduced by the ejection of a dense CME into a uniform, high-speed solar wind. Initial propagation pressure waves steepen into shocks at a distance of about 3 AU.

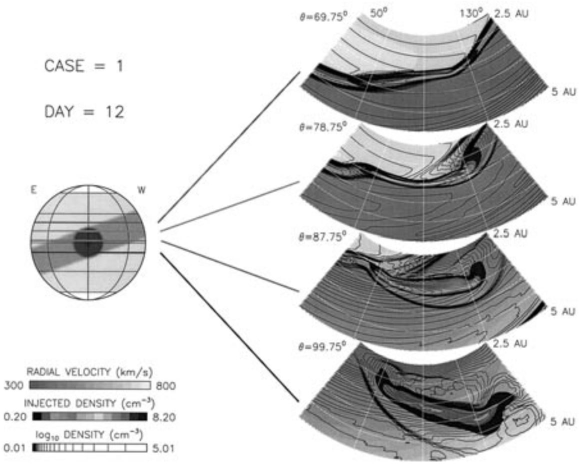

Figure 4. Results of a 3D simulation of a CME moving through a typical ambient solar wind. Here the CME is injected in the center of the HCS–streamer belt (left), specified as a high-density, low-temperature, slow-speed structure tilted to the solar rotation axis. The CME is represented as a 30° wide, 12 h duration pressure pulse. The resulting CME interaction with the solar wind flow is shown as the slices in heliolongitude and at distances 2.5–5 AU from the Sun 12 days after launch. The slices are through four different heliolatitudes and show that the CME's shape, pressure and speed will vary significantly depending on the characteristics of the ambient medium it encounters. Courtesy V Pizzo, NOAA Space Environment Center.

In recent two-dimensional (2D) and 3D hydrodynamic simulations attempts are being made to include more realistic solar wind conditions in which to inject the transient. For example, if an initially large but homogeneous CME is injected into a more realistic, latitudinally inhomogeneous solar wind, it will evolve very differently in the fast and slow wind regimes. Figure 4 demonstrates one such 3D simulation wherein a pressure-pulse CME is injected into a bimodal solar wind which is slow and dense at low latitudes and fast and tenuous at higher latitudes. The CME extends across the boundary between the two regimes and is distorted into two sections. The parts separate radially owing to the strong velocity shear between the slow and fast ambient wind and latitudinally as a result of pressure gradients associated with rarefaction regions as the CME moves outward. This simulation also incorporates features of the wavy 'ballerina skirt' HCS which adds to the complexity of the interaction in the longitudinal direction. Full 3D MHD simulations using the observed photospheric magnetic field as an inner boundary condition have been successful in replicating gross coronal structure near the Sun, as well as the initiation of transients by shearing of the magnetic footpoints. However, none of these efforts is as yet sufficiently developed to reproduce the complex magnetic and plasma structure of the actual solar wind or the transients that flow through it.

Adding to the complexity of the real solar wind are interactions which occur between the transient flows, including their shock waves, and pre-existing faster or slower flows and the interaction regions bounding them. For example, a fast CME can overtake a slower CME or a fast flow can overtake a slow CME. In the inner heliosphere these interactions produce compound streams. These systems can continue to evolve and merge with other CMEs and shocks as they move outward. Eventually, well beyond the 5 AU orbit of Jupiter, such structures can form what are called merged interaction regions. These regions can become very extensive, sometimes essentially encircling the Sun like a distant belt. Such regions can diminish the flux of high-energy particles which continually stream into the heliosphere, called galactic COSMIC RAYS, causing solar-cycle-dependent decreases in their flux.

Energetic particle events associated with solar activity (SEPs) are also commonly associated with IP shocks (see SOLAR WIND: ENERGETIC PARTICLES). Solar activity produces two classes of SEPs, gradual and impulsive, depending on their energy versus time profiles. About 10 gradual events occur per year near maximum and each can last for several days. Although flares were once considered the source of SEP events, we now know that most of these particles are accelerated directly from the coronal and solar wind population by CME-driven IP shocks. Impulsive events are much more frequent, ~100 per year near maximum, but last for only a few hours. They are generally much weaker than the gradual events and are only observed in space when a spacecraft or Earth intersects the pre-existing field lines which connect back to the flare–active region site. These are also called ^{3}He-rich events because the ^{3}He/^{4}He ratio in them is much higher than in the normal solar wind. During impulsive events is about the only time we can sample flare material and its associated accelerated particles in the solar wind.

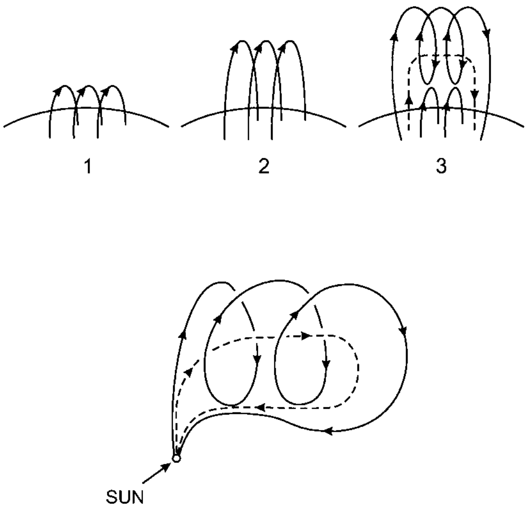

Figure 5. Schematic diagram of a reconnection model of magnetic flux rope formation at the Sun. In the top row from left to right rising, sheared field lines reconnect to form a rising flux rope and a closed arcade at the surface. Bottom: the flux rope structure as it would appear later and further out in the solar wind. Adaptation courtesy of J Gosling.

The magnetic field topology of CMEs

Recent research has focused on those solar wind signatures indicative of the topology of the ejected magnetic fields. Most such studies involve observations and modeling of magnetic clouds and bidirectionally streaming particle flows (see below). Magnetic clouds are long-lived solar wind flows having enhanced field strengths which exhibit smooth, coherent rotations. Figure 3 shows an example of such a cloud embedded in an expanding CME; note the strong and smooth magnetic field strength, B, the smooth rotation of the polar field angle, θ and the low plasma β (ratio of plasma to magnetic pressure). Such a structure can be modeled as a force-free flux rope, which is a series of helical field lines, like the coils of a spring (figures 1(c), 5) with pitch angles increasing towards the outer edge.

Some magnetic clouds have been associated with solar filament disappearances. Since filament plasma is embedded in helical, horizontal magnetic fields, the close association of CMEs with filament eruptions and shearing fields near the surface has led to the modeling of CMEs as flux ropes. One idea is that the interior fields of a rising, sheared CME reconnect, resulting in an ejected flux rope and new, closed coronal loops at the Sun (figure 5). (Magnetic reconnection is a dynamic plasma process whereby field line systems interact, resulting in a change in their topology.) At least 1/3 of all CMEs in the solar wind appear to be flux ropes but this fraction may be higher considering the limited sampling available from a single spacecraft. In several studies magnetic clouds have been found to have the same orientation and polarity as associated erupting filaments at the Sun. Furthermore, larger filaments always have twist in the same sense in a given hemisphere, even though the hemispherical polarity reverses every solar cycle. These suggest that the sign of the magnetic helicity (or sense of twist) of the erupted structure in the solar wind can be predicted from a given solar filament eruption. Filament eruptions and CMEs may be important ways that the Sun sheds magnetic helicity as well as flux built up over the solar magnetic cycle.

Although CMEs clearly involve the ejection of magnetic fields from the Sun, our understanding of the strength and topology of these structures is poor. Partly this is because instruments such as coronagraphs view the optically thin coronal material in projection against the sky. The circular CME structures we see (figure 2) are likely to be 2D projections of 3D structures such as arcades, flux ropes or shells. A prominence and its associated helmet streamer can be modeled as a dual flux system, one part of which is a flux rope and its surrounding coronal cavity which may help to drive the eruption once the streamer is disrupted. It appears that the prominence itself may be only a small part of this system, lagging the bulk of the CME–flux rope in the solar wind. This seems to be supported by the recent WIND observations.

In the normal solar wind field lines are 'open', i.e. connected to the hot corona at only one end. This results in an outward flux of hot electrons from the Sun streaming along the IMF. Bidirectional flows of these electrons are occasionally observed in which the electrons flow in both directions along the field lines. These are interpreted as evidence that the associated transient field lines are closed with both footpoints connected either to the Sun (a bottle) or to each other (a plasmoid) and, thus, a good proxy for CMEs in the solar wind. Bidirectional proton flows have also been detected, often but not always in association with shocks and ejecta flows. Although both magnetic clouds–flux ropes and bidirectional flows are usually considered good evidence for closed structures and CMEs, it is still difficult to ascertain the field topology of a given structure, i.e. entirely closed (bottle or plasmoid), entirely open or a hybrid (flux rope).

Reconnection of magnetic field lines is thought to be an important energy release and heating process near the surface of the Sun, especially in flares. The disconnection from the Sun of the field lines stretched outward during CMEs and their associated reconnection in the low corona may also be fundamental to the ejection process. In a popular eruptive flare model, field lines stretched open during the eruption of a prominence and CME reconnect near the surface to form a magnetic arcade, accounting for the long-duration optical and x-ray events commonly associated with CMEs (e.g. figure 5). Other observations, such as the ejection of plasmoid-like structures and evidence for newly forming streamers beneath CMEs, support this concept. Some degree of disconnection–reconnection of transient field lines seems necessary to prevent a continual increase of the net IP magnetic flux, which is not observed. For instance, it has been estimated that, in the absence of any reconnection, CMEs should double the field magnitude in the ecliptic every 9 months. There are several ways of alleviating this problem. First, recent LASCO observations suggest that the occurrence of structures within CMEs having a concave outward appearance is much greater than recorded with older, less sensitive coronagraphs. Nearly half of LASCO CMEs show evidence for such features, which are prime candidates for loops disconnecting from the Sun. (However, in some CMEs these structures could be the projection of a rising pre-existing cavity–flux rope in the skyplane which would, therefore, not require reconnection–disconnection.) Second, there are a few observations and a model of outward-moving 'U-shaped' structures suggesting the disconnection of *previously open* field regions at the top of streamers, resulting in the expulsion of a detached structure open to the heliosphere. These might be associated with so-called 'heat flux dropout' events, intervals in the solar wind devoid of the normal halo electron flux. Third, it is evident that the bidirectional streaming signature is not always present throughout all parts of an IP CME, or can be missing entirely from CMEs identified by other signatures such as a magnetic cloud. This suggests that some field lines within the CME may be 'open' in the sense that they do not have both ends connected back to the Sun. Although the CME may begin at the Sun as a pre-existing flux rope connected to the surface at two ends, continual small-scale reconnection associated with the CME may produce a mixture of closed, open and disconnected field lines as it moves through the solar wind.

As mentioned earlier, CMEs tend to arise in coronal streamers which form a belt that encircles the Sun and is the base of the HCS. The HCS is essentially the heliomagnetic equator of the Sun, separating the opposite-polarity fields in the northern and southern hemispheres. A recent model suggests that the base of the HCS may often be broad, encompassing multiple helmet streamers and their current sheets. Most CMEs might then be spatially associated with the HCS (figure 1). In this view the HCS and its associated plasma are more dynamic than previously thought, acting as a conduit for a range of activity from slowly evolving streamers to large CMEs.

Indeed, it appears that in many, if not most, cases, CME–flux ropes in the solar wind expand through the current sheet in such a way that they carry the sector boundary, or polarity change, in the form of a large-scale rotation rather than a radially expanding current sheet (figure 1(*c*)). Reconnection near the Sun then re-establishes the current sheet behind the CME. In the solar wind following transients at sector boundaries there is evidence of small intertwined flux ropes which might result from disconnection and distension of the fields. In addition, quiet, radially aligned fields are often found in the trailing portions of CMEs and may be the legs of magnetic structures carried out by the CME. The Helios photometer images and the bidirectional electron data also indicate that the closed-field regions of CMEs can extend well beyond the magnetic cloud portion.

Finally, such transient activity can also compress, amplify and align pre-existing magnetic discontinuities in the HCS and at the leading edge of high-speed streams. In addition, since the closed fields of a CME effectively isolate its interior from the surrounding solar wind, the ambient IP field and its associated plasma will be deflected around the oncoming CME. This interaction causes the ambient field to be compressed and to drape about the CME, much as a moving body in a fluid pushes the ambient medium aside. Compression will increase the ambient field strength and draping can reorient its direction, especially ahead of a fast CME.

The effects of CMEs on the solar wind also help explain why CMEs cause the largest geomagnetic storms. Geomagnetic storm indices are well correlated with the speed of the solar wind and the strength and direction (southward) of the IMF (see MAGNETOSPHERE OF EARTH: GEOMAGNETIC STORMS AND SOLAR WIND ORIGINS) parameters, which are also enhanced during the passage of CMEs. For example, compression and draping of magnetic fields at the leading edge of CMEs and of the ambient IP field are prime causes of strong southward fields. Good associations are also found between storms and other IP proxies of CMEs, in particular strong southward fields in magnetic clouds and compound streams (formed by faster streams overtaking slower ones), rapid decreases in the galactic cosmic ray flux, enhanced He abundance events and filament disappearances which can be isolated from flares. Storms are often preceded by sudden commencements which are well correlated with the IP shocks driven by faster CMEs. In general, CMEs which are associated with storms are among the largest and fastest structures in the solar wind. Since the occurrence rate of CMEs follows the solar activity cycle so that they are much more frequent around activity maximum, it is not surprising that geomagnetic storms are also more frequent and stronger during maximum.

Other sources of transient activity in the solar wind

Finally, we briefly mention several other kinds of solar activity that may have an influence on the solar wind. There is some evidence, although controversial, from global IPS measurements that solar active regions provide a source of small-scale density variations in the quiet solar wind. If they directly add denser-than-ambient plasma to the flow, then active regions can contribute to the mass flux of the solar wind. Previously, active regions had been thought to be small-scale, entirely closed magnetic structures with no direct access to the solar wind. The revisionist view is supported by x-ray images from the YOHKOH satellite showing that loops overlying active regions are continually expanding outward in the corona. There is also some evidence that open field lines overlie some active regions and could act as conduits for mass flow into the wind. Although it is well known that most of the material in the slow component of the quiescent solar wind originates from the vicinity of the coronal streamer belt, the details of where this material comes from and how it is transported outward are unknown. Recent results from LASCO, IPS and total solar eclipse data suggest that the streamer belt is very filamentary and highly structured. Blobs of material can now be observed being ejected from the cusps of streamers, probably through a quasi-steady reconnection process. Although the fast component of the solar wind, known to originate from the open fields of coronal holes, has low density, it does contain small-scale plasma structures whose source is not known. It has long been conjectured that the source of this material might be POLAR PLUMES, bright, radially elongated structures that emanate over polar coronal holes. Plumes often, but not always, have bipolar magnetic fields at their base, suggesting that reconnections with the prevailing open fields drive plasmoid-like structures into the wind. Recent observations from SOHO show upward motions of plasma in plumes, supporting this view.

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