AEROSPACE REPORT NO.
TOR-2012(1550)-6

Space Weather: Synthesis

January 9, 2012

Alfred A. Fote
DMSP-Sensors
Environmental Satellite Systems
Space Program Operations

Prepared for:

Space and Missile Systems Center
Air Force Space Command
483 N. Aviation Blvd.
El Segundo, CA 90245-2808

Contract No. FA8802-09-C-0001

Authorized by: Space Systems Group

Approved for Public Release.

AEROSPACE
Assuring Space Mission Success

AEROSPACE REPORT NO.
TOR-2012(1550)-6

Space Weather: Synthesis

January 9, 2012

Alfred A. Fote
DMSP-Sensors
Environmental Satellite Systems
Space Program Operations

Prepared for:

Space and Missile Systems Center
Air Force Space Command
483 N. Aviation Blvd.
El Segundo, CA 90245-2808

Contract No. FA8802-09-C-0001

Authorized by: Space Systems Group

Approved for Public Release.

AEROSPACE REPORT NO.
TOR-2012(1550)-6

Space Weather: Synthesis

January 9, 2012

Alfred A. Fote
DMSP-Sensors
Environmental Satellite Systems
Space Program Operations

Prepared for:

Space and Missile Systems Center
Air Force Space Command
483 N. Aviation Blvd.
El Segundo, CA 90245-2808

Contract No. FA8802-09-C-0001

Authorized by: Space Systems Group

Approved for Public Release.

.

AEROSPACE
Assuring Space Mission Success

AEROSPACE REPORT NO.
TOR-2012(1550)-6

Space Weather: Synthesis

Approved by:

Patrick H. Mak, Principal Director
DMSP
Environmental Satellite Systems
Space Program Operations
Space Systems Group

Abstract

The term “space weather” refers to the fluctuating fields of electromagnetic and charged particle, plasma, and radiation that fills the otherwise empty void. Most of that radiation originates from the Sun, but the magnetic fields of both the Earth and the Sun play a major role in both the generation and the propagation of the radiation. For that reason, an understanding of space weather requires a deep understanding of magnetic phenomena.

In a previous report on the magnetic field of the Sun, the author introduced the phenomenon whereby a magnetic field inside a plasma becomes segregated into strong linear concentrations of magnetic flux tubes, separated by mostly field-free regions. Subsequent research has revealed that most solar magnetic structures have a more complex helical structure than the linear form of flux tubes. Consequently, scientists have introduced the term “magnetic flux ropes.”

Magnetic flux ropes play a much larger role than that of the processes on the Sun. They also exist, and directly affect space weather, both in interplanetary space and at the Earth. The discovery of magnetic flux tubes and ropes has resulted in a great synthesis in the science of space weather. Prior to that time, researchers had observed, and given a wide variety of names to, a similar wide variety of phoenomena envisioned as distinct. Scientists now recognize many of those phenomena as manifestations of magnetic flux ropes and of the interactions between them. This report attempts to reveal the correlations between the older terminology and that of magnetic flux ropes.

Contents

Abstract iii
1. Introduction 1
2. Magnetic Flux Ropes 3
3. Reconnection 5
4. The Solar Wind 7
5. Plasmoids 9
6. Magnetic Clouds 11
7. Sigmoids 13
8. Plasma Bubbles 15
9. References 17

1. Introduction

The term “space weather” refers to the fluctuating fields of electromagnetic and charged particle, plasma, and radiation that fills the otherwise empty void. Most of that radiation originates from the Sun, but the magnetic fields of both the Earth and the Sun play a major role in both the generation and the propagation of the radiation. For that reason, an understanding of space weather requires a deep understanding of magnetic phenomena.

In a previous report on the magnetic field of the Sun, the author introduced the phenomenon of “magnetic flux tubes.” Normally, we think of a magnetic field as mostly continuous and smooth. However, a totally different situation arises when that magnetic field exists within a dense or high-energy plasma. In that case, the magnetic field becomes segregated into strong linear concentrations of magnetic flux tubes, separated by mostly field-free regions. This occurs because the plasma does not merely respond to the magnetic field but generates and modifies it as well.

As a further consequence, as thermal or other motions drive the plasma, they also distort the magnetic field. In fact, the plasma and the magnetic field become completely interlocked, as expressed by Alfven's “Frozen Flux” Theorem. That theorem states that a perfectly conducting fluid, such as approximated by a plasma, carries along the magnetic field lines as it moves; conversely, the plasma on a given magnetic field line remains on that line and cannot move to another line.

In the previous report, the author stated how the discovery of flux tubes has introduced an entirely new method of describing and understanding the behavior of the solar magnetic field. In particular, the author showed how we can use them to easily explain the process by which the solar magnetic field reverses itself every eleven years.

Subsequent research has revealed that most solar magnetic structures have a more complex helical structure than the linear form of flux tubes. Consequently, scientists have introduced the term “magnetic flux ropes.”

We will now discuss how magnetic flux ropes play a much larger role than that of the processes on the Sun. They also exist, and directly affect space weather, both in interplanetary space and at the Earth. They do so in three ways. First, they entrap and concentrate plasma. Second, they provide a conduit that transports the plasma from the Sun to the Earth and beyond. And third, when they interact with one another, via the processes of “reconnection,” they cause explosive events that release and accelerate the plasma and thereby produce all of the more dramatic and important phenomena of space weather. These include solar flares, coronal mass ejections, and the geomagnetic storms in Earth's ionosphere.

The discovery of magnetic flux tubes and ropes has resulted in a great synthesis, and consequent simplification, in the science of space weather. Prior to that time, researchers had observed, and given a wide variety of names to, a similar wide variety of phoenomena envisioned as distinct. This happened because our spacecraft and other methods of measurement greatly underdetermine the phenomena under study. They each can see only a small part of the whole. One instrument measures magnetic fields; another measures ultra-violet emissions, and they all make measurements highly limited in both time and space. The latter limitations present a particular problem to phenomena that cover vast regions of interplanetary space and which can fluctuate dramatically over periods of a few hours or less.

Scientists now recognize that many of those separately discovered phenomena actually represent manifestations of magnetic flux ropes and of the interactions between the ropes. This report attempts to show the relationships between the older terminology and that of the magnetic flux ropes. We have already encountered a few examples of this systhesis. We now recognize filagree, coronal holes, and sunspots as places where magnetic flux ropes of different sizes pass through the surface of the Sun. As further examples, we recognize a “prominence” as simply a flux rope that we view in profile on the limb of the Sun. A “filament” represents the same magnetic flux rope when viewed from directly above, against the disk of the Sun, and a magnetic flux rope with an S-shaped, or reverse-S-shaped, writhe, when seen from above, carries the designation of a “sigmoid”.

Although the author has made a strong attempt to organize the various terms in use by current and prior space meteorologists, the reader must be warned that not all research papers may agree upon the terminology that is presented here. Depending upon the date of publication of a research paper, the knowledge base available at that time, the specific discipline of the author, and other factors, the terms may have a different meaning from what is described.

2. Magnetic Flux Ropes

As previously described in an earlier report, a flux tube consists of a magnetic field line around which the electrons and ions of the plasma spiral. However, this has subsequently emerged as a simplistic picture for many magnetic structures. Based on observational evidence, later research literature introduced the more complex concept of “magnetic flux ropes.” They initially defined flux ropes as flux tubes with a twist. Thus, for flux ropes, they depicted the magnetic field as not merely axial but spiraling around the central axis like the strands of a rope. Still later research has led to an ever more complex structure for flux ropes. Scientists next saw them as possessing both an outer, spiraling, magnetic field sheath and an inner axial magnetic field of greater intensity.

The complexity has grown still further. The inner field, while mostly axial in direction, does vary somewhat erratically in regards to its orientation along the length of the flux rope. And we also envision magnetic flux ropes as having, not a single sheath, but multiple layers of them, with each larger layer having a greater degree of twist. The magnetic field of the outermost sheath may have a purely circumferential nature.

The term chirality refers to the direction of the twist of the outer magnetic field. They can have either a dextral, right-handed, or sinistral, left-handed chirality. The highest resolution images of magnetic flux ropes on the Sun show them as possessing “barbs” as well. These short strands resemble the loose fibers of a rope. Their orientation indicates the chirality of the rope, with the right-bearing barbs corresponding to dextral chirality and the left-bearing barbs corresponding to sinistral chirality. One researcher likened barbs to entrance and exit ramps on a freeway. That is, they reveal areas where plasma enters or leaves the flux rope.

In addition to twist, flux ropes also have “writhe.” Think of a typical stretchable telephone cord. With the cord straight, it has twist but no writhe. Loop the cord around a lamp, and it has both twist and writhe. The helicity of a flux rope describes the sum of its twist and writhe. We can convert some twist into writhe and vice versa. But, in total, we must have conservation of helicity.

Introduce too much twist into a flux rope, and it will, like a telephone cord, develope a “helical kink instability” and fold into itself in a chaotic manner. This occurs when the “winding number,” the number of times the field lines wrap around the axis, exceeds some critical value. When a kink of instability develops, different sections of that rope come into contact with one another and the explosive release of plasma will result from this interaction. Such flux rope interactions will be discussed in the next section. The outcome of any interaction of flux ropes depends upon whether or not the segments share both the same chirality and the same polarity, the latter referring to the direction of their axial magnetic field.

But before discussing reconnection, terminology must again be mentioned. The first mathematical model of magnetic flux ropes obtained a solution by a great simplification of the initially complex set of equations. The simplifications included cylindrical symmetry, and the absence of all forces, such as thermal, gravitational, and electromagnetic, on the plasma. Consequently, what we now call magnetic flux ropes originally went by the name of a “constant-alpha force-free magnetic field.” Some writers still use the term “force-free” but they may do so incorrectly. At least one paper describes “force-free” as referring to the absence of non-electromagnetic forces only, and another paper used the term “force-free” to designate non-helical flux tubes and thereby distinguishes those structures from flux ropes.

3. Reconnection

In general we can think of magnetic flux ropes as mutually repulsive rubber bands. They have a magnetic pressure perpendicular to their long axis and a tension along that axis. When forced together by the motion of the plasma in which they find themselves embedded, magnetic flux ropes can interact with one another in a number of ways. Such interactions include bouncing, merging, tunneling, pinching, and slingshotting. These events carry the general name of "reconnection" since they involve the physical breaking open of flux ropes and their reconnection in a different spatial configuration. When first observed in 1978 as short-lived deflections in Earth's dayside magnetopause, reconnection events acquired the name of "Flux Transfer Events." Other names for such local-Earth reconnection include "sheath events" and "magnetospheric events."

When magnetic flux ropes do break open, they release and accelerate their entrapped plasma and thereby produce all of the more dramatic and important phenomena of space weather. One can find an analogy in what happens when two high current electrical cables short circuit to one another. For magnetic flux ropes, the consequences include such events as solar flares, coronal mass ejections, and the geomagnetic storms in Earth's ionosphere.

If their magnetic pressure dominates, magnetic flux ropes might merely bounce off of one another. However, if they share the same polarity and chirality, and if they are pushed together strongly enough, they might merge into a single, larger magnetic flux rope.

In a tunnel event, two magnetic flux ropes meet at an angle and temporarily form a cross. They then pass through one another and otherwise continue on as before. In such a tunnel event, each of the flux ropes loses a full turn of twist and the system experiences an overall lowering of energy as a result.

The pinching and slingshotting events cause the most explosive release of plasma and energy. A slingshot event begins like a tunnel event, with the two flux ropes forming an "X" by coming together at an angle. However; instead of passing through one another, each one breaks in two and then connects with one of the severed ends of the other flux rope. The two newly-reconfigured flux ropes fly apart rapidly and violently like a released slingshot, hurling away previously entrapped electrons and ions at high energy. Each of the flux ropes loses a half-turn of twist and thereby loses less energy than does a tunneling event. However, the reconfiguring shortens the flux ropes as well and this makes for a much larger contribution to the release of energy.

Pinching begins when two parallel flux ropes bow in towards one another and touch to form an "X" in that manner. Once again, both flux ropes break apart and each half then connects to the nearest half of the other flux rope. Therefore, if they had started out as two vertically-running parallel flux ropes, they would end up as two horizontally-running ones. Again the reconfiguration, or reconnection, would result in a great release of energy due to a shortening of the flux ropes.

A great amount of theoretical work has attempted to model the process of reconnection. Initial models, such as the "Sweet-Parker" model, predicted reconnection rates a factor of ten thousand too slow to account for observations. The subsequent introduction of "shocks," by Petschek, can adequately speed up the rate but the origin of such shocks remains theoretically unjustified. Other approaches involve two-fluid effects in which the ions and electrons move separately, vortex effects and turbulence effects. We can get an idea of the current state of knowledge from the acronyms for the zoo of competing models. These include the following.

- BSXR (Bursty Single X Line Reconnection)
- MXR (Multiple X Line Reconnection)
- PIR (Patchy Intermittent Reconnection)

- SXIR (Single Line Intermittent Reconnection)
- SXQR (Single X Line Quasi-Steady Reconnection)
- VITM (Vortex Induced Tearing Mode).

The models differ as to the range of the reconnection (from a huge region down to a flux rope diameter of one Earth radius), the reconnection generation method (instability, turbulence, or percolation), the number of flux lines involved (single or multiple X lines), and, for multiple X lines, whether the events occur simultaneously or successively.

4. The Solar Wind

In the prior report on the solar magnetic field, TOR-2012(1550)-3, the author discussed how the Sun, unlike the Earth, has a wide variety of magnetic regions, on an equally wide variety of scales. The smallest magnetic regions have an extremely local character. Their two poles exist only a short distance apart on the solar surface and their fields, between the poles, loop only a short distance above the surface. Most of the field lines do not even extend outside of the corona. These magnetic field lines have magnetic flux ropes associated with them. These local magnetic flux ropes serve to keep their entrapped plasma close to the surface of the Sun where they do not contribute to space weather.

In contrast, other magnetic field lines, and their associated flux ropes, extend far into interplanetary space before looping back to the surface of the Sun. Because the Sun rotates, those ropes actually spiral out from the Sun along “Parker spirals.” Astrophysics often refers to the local magnetic fields as “closed” and the interplanetary fields as “open.” This unfortunate terminology implies an incorrect distinction. All magnetic fields must ultimately return to their source and hence deserve the term “closed.”

Since the plasma entrapped in the flux ropes will drift along the flux as akin to long electrical cables that transport the plasma all the way to the Earth and beyond. In particular, they act as the conduits for the solar wind, the stream of charged particles that constantly leaks out from the Sun.

As the Sun rotates, the interplanetary magnetic flux ropes periodically sweep past the Earth. Thus, at the Earth, we can often detect a solar wind that has an oscillating intensity and exhibits a periodicity close to that of the Sun's rotation. However, we may not always detect such a periodicity. Some of the originating magnetic regions, and their associated magnetic flux ropes, may not persist long enough to appear at the next solar rotation.

Space meteorologists have introduced the term “geoeffectiveness” to indicate the degree to which a specific solar phenomenon contributes to space weather on the Earth. In the case of the solar wind, this term describes whether the plasma simply streams harmlessly past the Earth or injects charged particles into our magnetosphere and ionosphere. This outcome depends upon the orientation of the interplanetary magnetic field, IMF, relative to the magnetic field of the Earth. Recall that the magnetic field of the Earth begins at the magnetic South Pole, loops northward past the equator, and rejoins the Earth at the magnetic North Pole. In consequence, the geomagnetic field has a southward direction at both the North and the South magnetic poles of the Earth. If the IMF also has a southward direction at the Earth, the two fields, those of the Earth and of the IMF, can merge at the Earth's poles. This results in a direct path for the plasma to flow along magnetic flux ropes from the surface of the Sun to the surface of the Earth. Therefore, such a southward-directed IMF has the greatest geoefffectiveness. In contrast, while a northward-directed IMF can also fill Earth's magnetosphere with plasma, it does so less efficiently at the noon-position “cusp” or at the flanks of the magnetosphere. Also, a southward IMF has greater geoeffectiveness because it generates far more energy-releasing reconnection events than does a northward IMF.

Predicting the geoeffectiveness of the solar wind therefore depends upon our ability to predict the direction of the incoming IMF. Two factors complicate such attempted predictions. First, as the Sun's rotation causes the flux ropes to sweep past the Earth, the IMF would vary even without the second factor, due to the helical configuration of the rope's magnetic field. Altogether, these two factors can result in a rapidly changing reconfiguration of magnetic field lines above the Earth. The coincident series of energy-releasing reconnection events on Earth's dayside results in one of the important causes of space weather.

Reconnection plays another important role in regards to solar wind. Scientists have observed two kinds of solar winds, the fast and the slow solar winds. The fast solar winds stream along flux ropes that originate at the large coronal holes that exist in the polar regions of the Sun during solar minimum. The slow solar winds stream along flux ropes that originate from the more numerous, smaller, coronal holes of solar maximum and from intergranular lanes, both of which exist in the so-called lower-latitude “streamer belt” of the Sun. In interplanetary space, a fast solar wind may overtake, and collide with a slow one. Space meteorologists have given the collision zone the uninspired name of “stream interaction region,” or SIR. If an SIR persists long enough to recur on more than one solar rotation, they use the alternate term of “corotating interacting region,” or CIR.

The respective strengths, speeds, chiralities, and polarities of the colliding magnetic flux ropes will determine the amount of energy release of the resultant reconnection event. All of these factors will contribute to the geoeffectiveness of SIRs and CIRs when they eventually impact the Earth.

The solar wind also contains small-scale magnetic flux ropes, of an average diameter of approximately 300 Earth radii, and which typically persist for less than an hour. They occur more often at solar minimum. They most likely originate in interplanetary space by reconnection events but the exact mechanism remains under debate.

5. Plasmoids

The solar wind has the responsibility for pumping the majority of the plasma into Earth's magnetosphere. As will be discussed, explosive events on the Sun, driven by the reconnection of magnetic flux ropes, provides another, smaller contribution in the form of “magnetic clouds” that impact the Earth. But, although contributing less plasma, magnetic clouds introduce far more variability into space weather and therefore have the far more important effect. Before discussing the rather complex subject of the generation and structure of magnetic clouds, however, we will first turn to the simpler topic of the expulsion of plasma from Earth's magnetosphere in which reconnection and magnetic flux ropes also play a central and similar role.

Although it incorporates the term “sphere,” the magnetosphere, the region of space around the Earth dominated by Earth's magnetic field, actually has the shape of a comet or water droplet, with its blunt end facing the Sun. It takes this shape because the solar wind presses upon the Sunward side and stretches out the opposite side into a long “magnetotail.” The envelope of the entire magnetosphere has the name of the “magnetopause”.

Most of the plasma from the Sun passes by the Earth outside of the magnetopause. That which does enter Earth's magnetosphere, meanwhile, only stays there for a limited period of time. Eventually, the concentration of plasma becomes too great for the magnetosphere to retain and a reconnection process expels a large amount of it. In this process a portion of the magnetotail narrows down and the sides of the magnetopause come into contact. When those sides actually touch, in the form of an “X” in cross section, they produce a pinching style of reconnection. After the radial magnetic lines have broken apart and reconnected into transverse ones, a large portion of the magnetotail farthest from the Earth has become detached. The detached section, named a “plasmoid,” speeds away from the Earth into deeper interplanetary space. The remaining magnetotail retracts in the opposite direction toward the Earth. Once shortened, the magnetotail gradually regrows into its former length until the next expulsion.

The pinching reconnection does not merely detach the plasmoid but also, as described previously, accelerates charged particles and emits electromagentic radiation as well. Between November 1998 and April 1999, the GEOTAIL spacecraft took approximately 1400 hours of measurements in the magnetotail at a distance of between 14 and 30 Earth radii from our planet. It determined that plasmoid expulsions took place at the rate of once every five hours. This rate compared well to that previously observed for electromagnetic storms in the near-Earth magnetotail. All of this provided a consistent picture of pinching reconnections as the initiator.

Meanwhile, beginning in the 1980s, space meteorologists, based upon observational evidence, and both two- and three-dimensional simulations, began to equate plamoids and the magnetotail with magnetic flux ropes. Measurements detected strong axial magnetic fields and weaker circumferential ones. Immediately after reconnection, roughly half of the flux ropes remain in the truncated magnetotail and retract Earthward while the other half move away from the Earth in the plasmoid. In the far magnetotail, they have grown to a size of 10 to 20 Earth radii. It remains unclear whether these represent the growth or the merging of initially smaller magnetic flux ropes.

In a key measurement completed in 2007, four Cluster spacecraft, at an average distance of approximately 19 Earth radii from Earth, simultaneously traversed the magnetotail and therefore mapped its structure to a higher degree than ever before. They found the characteristic signature of a magnetic flux rope of approximately 2 Earth radii in size. It had its long axis perpendicular to the Earth-Sun line, an outer spiral-shaped magnetic field, and an inner, irregular, but mostly axial magnetic field. It had a dawnward electric field at its leading edge and a duskward electric field at its trailing edge. An electric current flowed duskward along both edges. In general, however, other measurements have indicated a broad distribution of orientations of the flux ropes with the Sun-Earth line.

The mechanism of the formation of magnetic flux ropes in the magnetotail, such as by reconnection or by some type of instability, remains unclear.

This section concludes with another note about terminology. Some papers actually give a different name to the flux ropes that, after the pinching reconnection, head towards or away from the Earth. They use the term “plasmoid-type” flux ropes for the latter and “BBF-type” flux ropes for the former, although we know of no real difference between them. BBF, stands for “Bursty Bulk Flow.”

6. Magnetic Clouds

The study of space weather first became important with the development of the wireless by Marconi when radio operators encountered erratic bursts of static interfering with their communications. They soon related the static to “geomagnetic storms,” or large disturbances of the distribution and energy of charged particles in Earth's ionosphere. Because the storms correlated with the solar cycle, the early space meteorologists attributed them, in turn, to bright flashes that they saw on the surface of the Sun, which they called solar flares. However, the correlation remained a loose one and, in 1993, J. T. Gosling, in a paper entitled “The Solar Flare Myth,” attacked this long-standing theory and introduced a new one. He found that the geomagnetic storms correlated more closely to another recently discovered phenomenon, that of large explosions on the Sun called “Coronal Mass Ejections.” Whereas solar flares emit electromagnetic radiation, CMEs hurl huge clouds of plasma into space. Solar flares accompany some CMEs but not all of them. Conversely, a solar flare may occur without a CME. This created some debate as to the relationship between CMEs and solar flares.

We now know that geomagnetic storms have a variety of causes besides CMEs. Other causes include the fluctuations in the solar wind and the ejection of plasmoids from the Earth's magnetotail. In fact, the solar wind injects ten times more plasma into space than do CMEs. However, CMEs, because of their greater short-term intensity and variability, cause the most important class of geomagnetic storms when their ejecta impact the Earth.

Depending on the 11-year solar cycle, CMEs occur at the rate of one to five per day. Once they have left the immediate vicinity of the Sun, the ejecta have a slightly different structure from CMEs and go by the name of “Interplanetary Coronal Mass Ejections” or ICMEs. In the same way, space meteorologists use the term IMF to distinguish the interplanetary magnetic field from that of the Sun. The IMF depends on local conditions as well as on the solar field. For example, the magnetic flux ropes embedded in the solar wind stream interaction regions, SIRs, and CIRs, cause substantial short-term variations in the IMF as they pass by.

Spacecraft have observed that at least half of all ICMEs cause a similar variation of the IMF. Those that do have acquired the name of magnetic clouds. In particular, an ICME must meet three conditions to deserve the designation of a magnetic cloud. They must possess a higher than average magnetic field, typically twice that of the background field. They must exhibit a smooth rotation of the direction of their magnetic field as measured by a traversing spacecraft. And they must have a lower than ambient proton temperature or energy. All of this indicates that magnetic clouds represent yet another manifestation of magnetic flux ropes. But since spacecraft enormously undersample the global structure of ICMEs, we do not know whether all ICMEs contain magnetic flux ropes.

Magnetic clouds, unlike the other magnetic flux ropes that have been described in this report, have a truly gigantic size. In the vicinity of the Earth, they have a radial dimension of some 6000 Earth radii, equivalent to a quarter of the distance from the Earth to the Sun. This makes them many hundreds of times the size of those associated with the plasmoids ejected from Earth's magnetotail.

As with the solar wind, faster magnetic clouds can overtake and collide with slower ones, resulting in reconnection events, the creation of shock waves, and the acceleration of the charged particles that comprise the plasma. Such collisions can result in rather complex structures when they reach the Earth.

Magnetic clouds, both because of their association with shock waves, and because they possess, at some point, a southward directed magnetic field, have the greatest geoeffectiveness of all ICMEs. But because of the great size of magnetic clouds, and of the helical nature of their magnetic fields, we have great difficulty in predicting the orientation of their magnetic fields, and hence of their geoeffectiveness, when they impact the Earth.

The entire three-dimensional shape of magnetic clouds remains a subject of research. Some models see them as huge looping structures which extend all the way back to the Sun where one or both of their extremities remain attached. However, the process of magnetic cloud generation described in the next section seems to support the theory of a structure fully detached from the Sun. In consequence, some envision the ropes as closing back upon themselves to form a torus. Others see them as banana shaped, with pinched ends. And yet others model them as elipsoidal, either prolate or oblate.

7. Sigmoids

The magnetic clouds that we discussed in the last section originate at the Sun and, in particular, from structures given the name of “helmet streamers.” They derive this name from their similarity to a type of pointed German military helmet, the point at the top of the helmet serving to deflect an enemy's downward sword stroke. You can see examples of this type of helmet among some of the knights of Gondor in the movie adaptation of “The Lord of the Rings” trilogy.

We see helmet streamers in profile as very large glowing structures projecting out from the limb of the Sun. Helmet streamers function much like the Earth's magnetotail. One to five times a day they detach a cloud of plasma and send it into deeper space. For the magnetotail, we have called these detached clouds plasmoids. For the helmet streamers, we call the detached clouds coronal mass ejections or magnetic clouds. In the case of the Sun, the process often results in the additional release of an intense burst of electromagnetic radiation, from radio waves to gamma rays, which we see as a solar flare.

With the ejection of a magnetic cloud, the Sun has managed to rid itself of some of the excess of magnetic field helicity, which had built up over time, from the rotational and coriolis forces acting on its plasma.

Space meteorologists have very many unresolved questions about solar flares, helmet streamers, and the Sun's corona. Regarding the corona, they do not understand what process heats it to more than a million degrees, some two orders of magnitude hotter than the photosphere. They suspect reconnection events as the best candidate but the specific mathematics has proven elusive. Solar flares pose the same difficulty. Theory predicts that they would require up to a million years to evolve, but in fact, they do so in minutes. The author previously discussed the difficulties of modeling the fast rate of reconnection events and of the extreme acceleration of the charged particles.

Regarding coronal mass ejections, theorists would very much like to understand what causes a helmet streamer to suddenly become unstable and to eject a magnetic cloud. A helmet streamer, in its stable configuration, consists of an “arcade” of magnetic flux ropes looping over a cooler cavity. Below the cavity, at the base of the streamer, close to the surface of the Sun, we find a “prominence,” a brightly glowing flux rope. Over time the height of the prominence gradually increases. Approximately two days after it reaches 50 Mm in height, the prominence may erupt. The prominence will suddenly burst loose and upwards, pushing the aracade before it. The flux ropes above the arcade break open, allowing the bulk of the plasma to escape into deeper space. Behind the ejecta, the ropes close in a pinching reconnection process. A solar flare may result from this reconnection.

The above description of an eruption explained it as seen in profile above the limb of the Sun. Earlier, the author described a filament as the same thing as a prominence, namely a magnetic flux rope in both cases, except that in the former case we view it against the disk of the Sun. The disk view of pre-eruption events gives us additional clues as to their cause. In a disk view, we find a sub-class of filaments called sigmoids. This refers to s-shaped, or reverse s-shaped, filaments. Sigmoids have a higher probability of leading to flare-associated coronal mass ejections than do linear filaments.

We can actually see linear filaments evolve into sigmoids. We conclude from this that, as the filament rises in height, the Coriolis force adds further twist to the flux rope and some of that twist becomes converted into writhe. A kink instablity then develops, and, when the two supporting legs of the flux rope come into contact, an explosive pinching type of reconnection takes place. That, in turn, leads to the coronal mass ejection.

The above picture seems to best fit the various observational data that we have available. Still, as with any complex phenomenon, a specific event may depart in detail from the average behavior. In some situations, the flux rope does not show a two-stage ascension, consisting of a slow phase followed by a fast phase. It may, in contrast, have only a fast phase and the resulting ejecta goes by the name of a "spray." Probably, an alternate model applies in this case in which the kink instability had developed before the magnetic flux rope had emerged from the photosphere into the corona.

Furthermore, the merging of flux ropes, or the development of a kink instability, may cause a solar flare without a coronal mass ejection. The reconnection may have eliminated enough helicity to remove the impetus for a full scale ejection of plasma from the helmet streamer.

8. Plasma Bubbles

This report is concluded by passing from the high-energy processes on the Sun to lower energy, but nevertheless quite important, events in Earth's ionosphere. During the post-sunset time period, plasma density “irregularities” often develop in the “E” and “F” layers of the ionosphere near the equator. These irregularities consist of sinisoidal waves of depleted plasma that grow in magnitude. They may create and send plumes of depleted plasma, called plasma bubbles, to much higher levels. Plasma bubbles can rise to heights of 1000 km or more and they cause scintillation that degrades radio communication and navigation. Debate persists as the exact cause of the originating instability. The overall phenomenon has acquired the names of “Convective Ionospheric Storm” or “Equatorial Spread F,” or ESF, a subject of considerable research, such as by the C/NOFS satellite. Of relevance to this report, researchers often designate the plasma bubbles as “depleted flux tubes.” This represents an unfortunate terminology. It may cause the reader to confuse plasma bubbles with magnetic flux tubes. In fact, plasma bubbles do not exhibit a region of anomalous magnetic field as do magnetic flux tubes.

9. References

1. Burlaga, L. F., “Magnetic Clouds and Force-Free Fields with Constant Alpha”, J. Geophys. Res. 93(A7), 7217 (1988)

2. Canfield, R. C., H. S. Hudson, and D. E. McKenzie, “Sigmoid Morphology and Eruptive Solar Activity”, Geophys. Res. Lett. 26, 627 (1999)

3. Cartwright, M. L. and M. B. Moldwin, “Heliospheric Evolution of Solar Wind Small-Scale Magnetic Flux Ropes”, J. Geophys. Res. 115, A08102 (2010)

4. Dasso, S., C. H. Mandrini, P. Demoulin, and C. J. Farrugia, “Magnetic Helicity Analysis of an Inerplanetary Twisted Flux Tube”, J. Geophys. Res. 108(A10),1362 (2003)

5. de La Beaujardiere, et. al., “C/NOFS: A Mission to Forecast Scintillations”, J. Atmos. Sol.-Terr. Phys., 66, 1573, (2004)

6. Falconer, D. A., “A Prospective Method for Predicting Coronal Mass Ejections from Vector Magnetograms”, J. Geophys. Res. 106(A11), 25185 (2001)

7. Farrugia, C. J., L. F. Burlaga, V. A. Osherovich, I. G. Richardson, M. P. Freeman, R. P. Lepping, and A. J. Lazarus, “A Study of an Expanding Interplanetary Magnetic CLoud and its Interaction with the Earth's Magnetosphere: The Interplanetary Aspect” J. Geophys. Res. 98 7621 (1993)

8. Feng, H. Q., D. J. Wu, and J. K. Chao, “Size and Energy Distribution of Interplanetary Magnetic Flux Ropes”, J. Geophys. Res. 112, A02102, (2007)

9. Filippov, B. P. and O. G. Den, “A Critical Height of Quiescent Prominences Before Eruption”, J. Geophys. Res. 106(A11), 25177 (2001)

10. Fote, A. A., “Space Weather: The Geomagnetic Field”, The Aerospace Corporation Report No. TOR-2012(1550)-1, (Oct. 25, 2011)

11. Fote, A. A., “Space Weather: Solar Magnetism”, The Aerospace Corporation Report No. TOR-2012(1550)-3, (Oct. 25, 2011)

12. Frey, C. D., W. Sun, C. S. Deehr, M. Dryer, Z. Smith, S. -I. Akasofu, M. Tokumaru, and M. Kojima, “Improvements to the HAF Solar Wind Model for Space Weather Predictions”, J. Geophys. Res. 106(A10), 20985, (2001)

13. Glover, A., L. K. Harra, S. A. Matthews, K. Hori, and J. L. Culhane, “Long Term Evolution of a Non-Active Region Sigmoid and its CME Activity”, Astron. & Astrophys 378, 239 (2001)

14. Golub, L. and J. M. Pasachoff, “Nearest Star: The Surprising Science of Our Sun”, Harvard University Press, Cambridge, Massachusetts, 2001

15. Gosling, J. T., “The Solar Flare Myth”, J. Geophys. Res. 98(A11), 18937, (1993)

16. Horbury, T. S., D. Burgess, and M. Franz, “Magnetic 'Field Turnings”, J. Geophys. Res. 106(A12), 30001 (Dec. 1, 2001)

17. Huba, J. D., and G. Joyce, "Global Modeling of Equatorial Plasma Bubbles", Geophys. Res. Lett. 37, L17104 (2010)

18. Hysell, D. L. "An Overview and Synthesis of Plasma Irregularities in Equatorial Spread F", J. Atmos. Terr. Phys. 62, 1037 (2000)

19. Jacobs, C., and S. Poedts, "Models for Coronal Mass Ejections", J. Atmos. & Sol. Terrestrial Phys. 73, 1148 (2011)

20. Kelley, M. C., and J. P. McClure, "Equatorial Spread-F: A Review of Recent Experimental Results", J. Atmos Terr. Phys. 43, 427 (1981)

21. Lepping, R. P., D. H. Fairfield, J. Jones, L. A. Frank, W. R. Paterson, S. Kokubun, and T. Yamamoto, "Cross-Tail Magnetic Flux Ropes as Observed by the GEOTAIL Spacecraft", Geophys. Res. Lett. 22, 1193 (1995)

22. Lepping, R. P., J. A. Jones, and L. F. Burlaga, "Magnetic Field Structure of Interplanetary Magnetic Clouds at 1 AU", J. Geophys. Res. 95, 11957 (1990)

23. Linton, M. G. and S. K. Antiochos, "Theoretical Energy Analysis of Reconnecting Twisted Magnetic Flux Tubes", Astrophys. J. 581, 703 (2002)

24. Linton, M. G., and M. B. Moldwin, "A COmparison of the Formation and Evolution of Magnetic Flux Ropes in Solar Corona Ejections and Magnetotail Plasmoids", J. Geophys. Res. 114, A00B09 (2009)

25. Low, B. C., "Coronal Mass Ejections, Magnetic Flux Ropes, and Solar Magnetism", J. Geophys. Res. 106(A11), 25141, (2001)

26. Lui, A. T. Y., M. W. Dunlop, H. Reme, L. M. Kistler, G. Gustafsson, and Q. -G. Zong, "Internal Structure of a Magnetic Flux Rope from Cluster Observations", Geophys. Res. Lett. 34, L07102 (2007)

27. Lynnyk, A., J. Safrankova, Z. Nemecek, and J. D. Richardson, "Deformation of ICMEs/MCs along their Path", Planetary & SPace Sci. 59, 840 (2011)

28. Martin, S., "Conditions for the Formation and Maintenance of Filaments", Sol. Phys., 182, 107 (1998)

29. Moldwin, M. B., S. Ford, R. Lepping, J. Slavin, and A. Szabo, "Small-Scale Magnetic Flux Ropes in the Solar Wind", Geophys. Res. Lett. 27, 57, (2000)

30. Moldwin, M. B., and W. J. Hughes, "Plasmoids as Magnetic Flux Ropes", J. Geophys. Res. 96, 14051 (1991)

31. Moreno-Insertis, F., "Rise Times of Horzontal Magnetic Flux Tubes in the Convection Zone of the Sun", Astron. Astrophys. 122, 241 (1983)

32. Mostl, C. M., Temmer, T. Rollett, C. J. Farrugia, Y. Liu, A. M. Veronig, M. Leitner, A. B. Galvin, and H. K. Biernat, "STEREO and Wind Observations of a Fast ICME Flank Triggering a Prolonged Geomagnetic Storm on 5-7 April 2010", Geophys. Res. Lett. 37 L24103 (2010)

33. Mustajab, F., and Badruddin, “Geoeffectiveness of the Interplanetary Manifestations of Coronal Mass Ejections and Solar-Wind Stream-Stream Interactions”, Astrophys. Space Sci. 331, 91 (Jan. 2011)

34. Roberts, P. H., and G. A. Glatzmaier, “Geodynamo Theory and Simulations”, Rev. Mod. Phys. 72, 1081, (2000)

35. Rust, D. M., and A. Kumar, “Helical Magnetic Fields in Filaments”, Sol. Phys. 155, 69 (1994) Scholer, M., “Models of Flux Transfer Events”, Physics of the Magnetopause, Geophysical Monograph 90, The American Geophysical Union (1995)

36. Schrijver, C. J., and M. L. De Rosa, “Photospheric and Heliospheric Magnetic Fields”, Solar Physics 212, 165 (2003).

37. Sibeck, D. G., G. L. Siscoe, J. A. Slavin, E. J. Smith, S. J. Bame, and F. L. Scarf, “Magnetotail Flux Ropes”, Geophys. Res. Lett. 11, 1090 (1984)

38. Slavin, J. A., R. P. Lepping, J. Gjerloev, D. H. Fairfield, M. Hesse, C. J. Owen, M. B. Moldwin, T. Nagai, A. Ieda, and T. Mukai, “Geotail Observations of Magnetic Flux Ropes in the Plasma Sheet”, J. Geophys. Res. 108, 1015 (2003)

39. Tian, H., S. Yao, and Q. Zong, “Signatures of Magnetic Reconnection at Boundaries of Interplanetary Small-Scale Magnetic Flux Ropes”, Astrophys. J. 720, 454 (2010)

40. Vandas, M., S. Fischer, P. Pelant, and A. Geranios, “Spherical Models of Magnetic Clouds and Their Comparison with Spacecraft Measurements”, J. Geophys. Res. 98(A7), 11467 (1993)

41. Verma, V. K., “Relationship of Great Soft X-Ray Flares with Other Solar Activity Phenomena”, Astrophys. Space Sci. 334#1, 83, (2011)

42. Vrsnak, B, “Dynamics of Solar Coronal Eruptions”, J. Geophys. Res. 106(A11), 25249, (2001)

43. Walker, R. J., R. L. Richard, and M. Ashour-Abdalla, “The Entry of Solar Wind Ions into the Magnetosphere”, Physics of the Magnetopause, Geophysical Monograph 90, The American Geophysical Union (1995)

44. Wang, Y. -M., S. H. Hawley, and N. R. Sheeley, “The Magnetic Nature of Coronal Holes”, Science 271, 417, (1996)

45. Wang, Y. M., S. Wang, and P.Z. Ye, “Multiple Magnetic Clouds in Interplanetary Space”, Solar Physics 211, 333 (2002)

46. Wang, Y. M., P. Z. Ye, and S. Wang, “Multiple Magnetic Clouds: Several Examples during March-April 2001”, J. Geophys. Res. 108(A10), 1370 (2003)

47. Yamada, M., R. Kulsrud, and H, Ji, “Magnetic Reconnection”, Rev. Mod. Phys. 82, 603 (2010)

48. Zheng, R., Y. C. Jiang, L. H. Yang, and Y. Bi, “The COronal Mass Ejection Associated with the Loop Eruption and Coronal Dimmings on 2009 December 13”, Astrophys. Space Sci. 332, 81 (2011)