NRL Has a Flare for Studying CMEs: Staring into the Sun to See the "Rosetta Stone" of Flux Rope Formation

While there might be "nothing new under the Sun," observations by NRL scientists in 2012 offered a new understanding of what bursts forth from the Sun.

Coronal mass ejections (CMEs), the massive and explosive releases of plasma and magnetic material from the solar corona, can have tremendous, sometimes devastating effect on satellites, radio communications, and the Earth's power grids. Their effects on Earth and its near-space environment is called space weather, and accurately predicting that weather could aid in protecting both ground and space-based civilian and military systems. Therefore, learning how CMEs form and what they are made of is critical. Since not all CMEs are created equal, knowledge of their three-dimensional magnetic structure is necessary to determine whether or not a given CME could damage these assets.

An estimated 40 percent, at least, of CMEs contain large-scale, slinky-shaped magnetic fields called flux ropes (FR). For many years, solar physicists hotly debated the question of whether CMEs originate in the lower solar corona from preformed FRs or whether FRs form from the eruption of CMEs. While the existence and formation of FRs had been postulated for many years, the formation of a flux rope was not actually observed until July 19, 2012. This was when the LASCO imager in combination with the AIA instrument aboard the Solar Dynamic Observatory (SDO), viewing the phenomenon at the correct temperature (131 Å), were able to capture the formation of a flux rope and the ensuing CME eruption and thus elucidate the role of preformed flux ropes in large CMEs.

We may never be able to answer the chicken-and-egg problem, but it appears that NRL scientists have made great progress in answering a hotter and maybe more useful question.

The Stuff Coronal Mass Ejections Are Made Of

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Knowledge of the magnetic structure of coronal mass ejections (CMEs) is essential for assessing their damaging effects on satellites and radio communications. In the past year, we made great strides towards uncovering the three-dimensional structure of CMEs thanks to observations from space-borne imagers designed, assembled, and operated in the Space Science Division (SSD). We devised methods to determine whether large, potentially damaging CMEs contain large-scale coiled magnetic fields reminiscent of a slinky toy, called a magnetic flux rope. We found that at least 40% of them do. We have also discovered that the flux rope forms in the low corona (within 50,000 km of the solar surface) just before the eruption of the CME. Our results validate a long-standing theoretical prediction that CMEs are driven by the formation and ejection of flux ropes. This is an important step towards achieving a CME predictive capability for improved Space Situational Awareness.

INTRODUCTION

CMEs are explosive releases of plasma and magnetic field from the solar corona. A typical CME carries away four billion tons of magnetized coronal material at speeds in excess of two million km/hour. The associated kinetic energy of 5×10^{23} joules corresponds to the release of 120,000 gigatons of TNT equivalent, 12 times higher than the energy released during the 2004 Indian Ocean earthquake. However, we have measured events with at least 100× larger energies. CMEs are the manifestations of the largest explosions in our astrophysical neighborhood, and their effects can be sensed at the outer boundaries of the solar system months or even years after they left the Sun.

CMEs have another, more direct effect on our society. The Earth's magnetic field creates the magnetosphere, a cocoon that encircles the planet and protects it, and the nearby space, from high-energy radiation. But CMEs can compress the magnetosphere to such an extent that satellites become exposed to open space and may suffer damage to their electronic systems. On the other hand, the (as yet unknown) magnetic fields within CMEs can interact and even blow a hole in the magnetosphere, allowing the high energy particles entrained in the CME to enter. The glowing lights of the auroras are a beautiful and relatively benign manifestation of this interaction. But the CME collision throws the whole upper atmosphere of the Earth (ionosphere, magnetosphere, and thermosphere) out of balance, causing geomagnetic storms that can result in further damage to satellites and even drive currents on the ground that may damage power grids and disrupt GPS and communications. Given our society's growing dependence on global communications and networks, both civilian and military authorities place great importance on a reliable assessment of the damaging potential of an Earth-directed CME. But the first step is to understand what CMEs are made of.

FROM LOOPS TO ICE CREAM CONES AND NOW TO CROISSANTS

CMEs are traditionally detected and analyzed in visible light images obtained by coronagraphs, telescopes that feature a disk at the telescope entrance to create an artificial eclipse by blocking the Sun, thus making the extended corona visible. Their emission is caused by the Thomson scattering of photospheric light by the free electrons within the CME and hence it is optically thin and quite weak. Typical CME brightnesses are about 8 to 10 orders of magnitude fainter than the solar disk. Despite centuries of eclipse observations from the ground, CMEs were discovered only in 1971 by SSD researchers[1] using their pioneering coronagraph aboard the OSO-7 satellite. Space-based coronagraphy, a field that is still led by NRL, is today the primary means for the study of CMEs and an indispensable tool for space weather, as the terrestrial effects of CMEs are collectively known.

The typical CME appears in the images as an outward propagating cloud of emission with a well-defined curved front, followed by an area of depressed emission (cavity), and a bright core (Fig. 1). The interpretation of this appearance led to the first controversy on CME structure. Some researchers suggested that CMEs are essentially two-dimensional objects, coronal loops ejected from the lower corona, while others proposed that CMEs were the projections of three-dimensional bubbles of coronal plasma. The scale tilted towards the "bubble" camp in the mid-1980s when a group of SSD researchers[2] using another SSD-made coronagraph (Solwind) realized that Earth-directed CMEs appeared as halos encircling the Sun and, hence, had to be projections of 3D objects. The resulting model of CMEs as "ice cream cones" is still in use today.

theories and simulations of CME eruption mechanisms kept coming up with the same result — *the ejected structure is always a flux rope irrespective of the actual eruption mechanism*. While this idea was able to explain the observations of a subset of events, the great majority of CMEs lacked many of the expected characteristics such as filamentary structure or a cavity. Why? Was there a class of non-flux rope ejections that defied our theoretical understanding? The answer could have profound implications for the physics of energy release and came from the observations of the latest SSD-led set of coronagraphs: the Sun-Earth Connection Coronal and

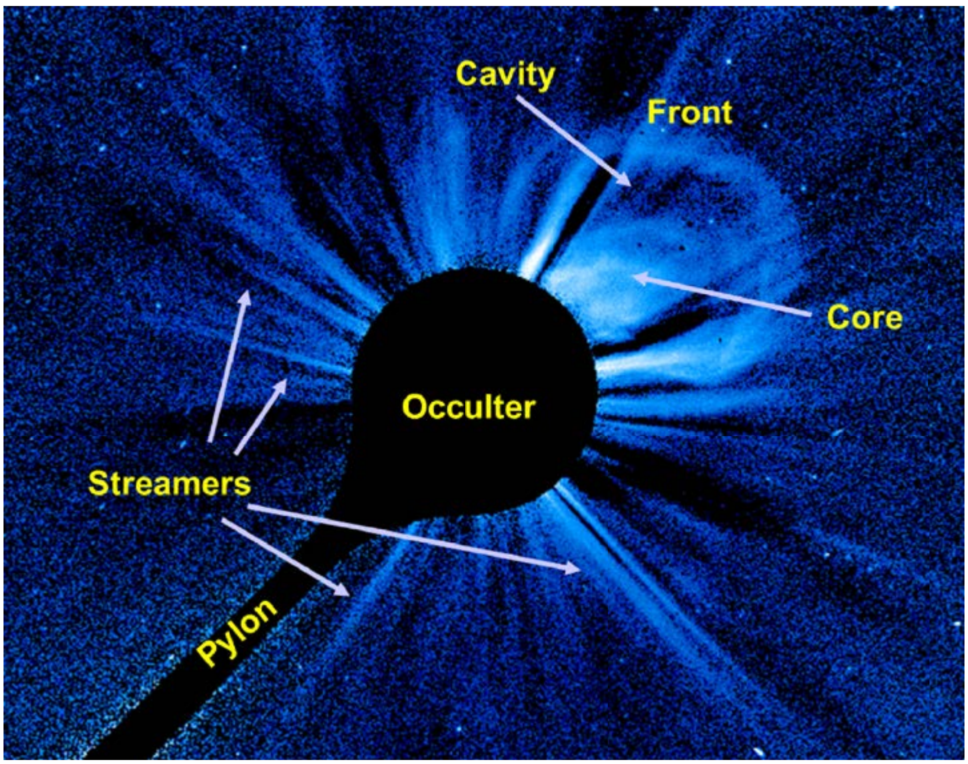

FIGURE 1
A typical CME captured in a LASCO coronagraph image. The occulter is a disk at the entrance of the telescope supported by a pylon. It creates an artificial eclipse by blocking the bright light from the solar disk thus making visible the much fainter corona. The CME consists of a front, cavity, and a core. The streamers are structures of the quiescent background corona.

This "ice cream" model, however, seemed inadequate when the SSD-led Large Angle and Spectrographic Coronagraph (LASCO) experiment aboard the SOHO mission began high resolution observations in the late 1990s. CMEs exhibited lots of fine structure (Fig. 2), incompatible with the simple bubble concept. Again, the breakthrough came from NRL researchers[3] who proposed that CMEs can be understood as projections of a 3D structure of helical magnetic fields, a so-called flux rope (FR). The striations inside CMEs were simply the emission from plasma trapped inside the flux rope helical fields. At the same time, however,

Heliospheric Investigation (SECCHI) suite aboard the STEREO mission.

STEREO comprises two spacecraft with identical instrumentation drifting ahead and behind the Earth's orbit at an annual rate of 22.5°. The simultaneous SECCHI observations of the Sun and its extended corona from two vantage points provides unique 3D information on the CME properties, including their structure. Observations like the ones shown in Fig. 3 and simulations quickly revealed to us[4] that the lack of flux rope structure was the result of projection effects and not an intrinsic difference among CME events. It allowed

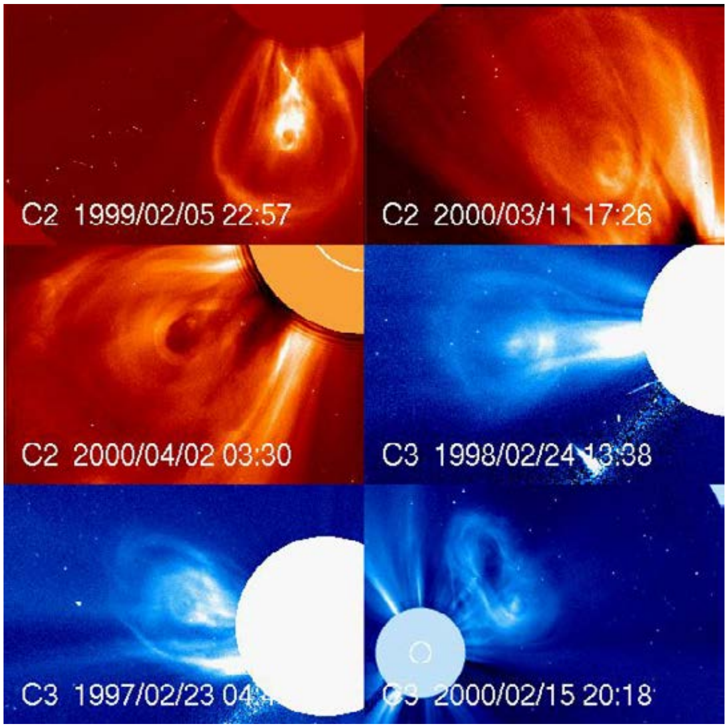

FIGURE 2
LASCO observations of CMEs with fine-scale internal structure consistent with a magnetic flux rope. The solar disk size is represented by the white circle in some of the images.

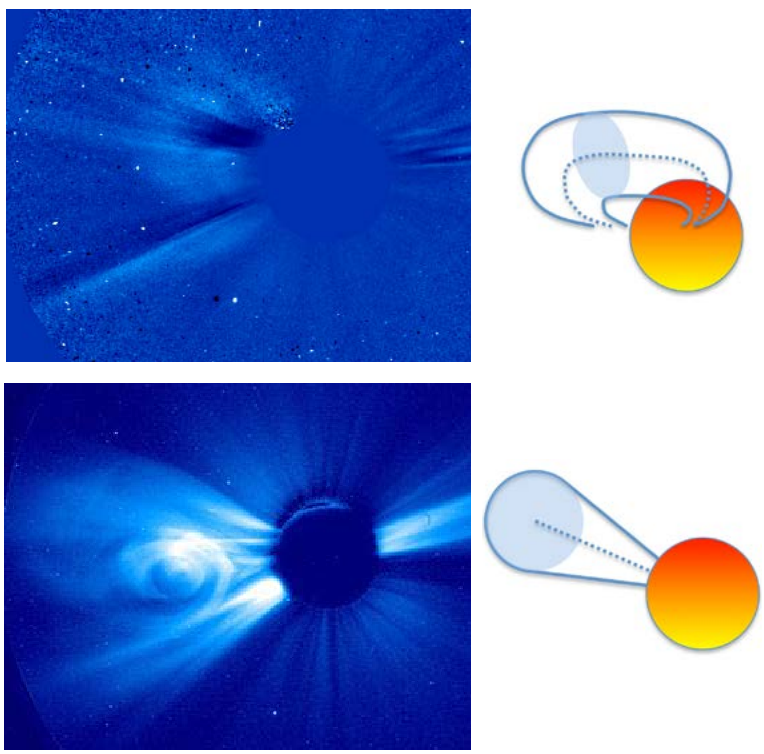

FIGURE 3
Simultaneous observations of a CME from the SSD-led SECCHI COR2 coronagraphs on the STEREO mission. Top: The CME appears as a faint cloud of emission in COR2-B. Bottom: The same CME at the same time appears as a highly structured flux rope in COR2-A. The angular distance between the two viewpoints is 39°. The figures on the right are cartoon representations of the approximate projection of the event on the sky plane of each instrument.

us to revisit the single-view, but 16-year long, LASCO database and count the appearance of flux rope CMEs during a full solar cycle. Fully 40% of the CME sample (962 out of 2403 events) had unambiguous flux rope structure while another 40% had some hints but the emission was either too faint or the background was too disturbed to make a definitive identification. We were not able to identify any other characteristic CME morphology apart from jets, which also have helical fields but are too small to be geoeffective. The absence of solar cycle dependence in the FR-CME occurrence rate was another indication that we are dealing with an intrinsic property of the eruption rather than the phase of the cycle. The preponderance of FR-CMEs, the lack of another common morphology and absence of solar cycle influence, all point out that the ejection of flux ropes is very likely the only way to produce large scale CMEs.

FLUX ROPE FORMATION AND ERUPTION MECHANISMS

So the eruption theories are correct on what comes out from the solar corona but when does the flux rope form? This question is the heart of another major controversy in solar physics because the answer will determine the dominant physical mechanism behind solar eruptions and consequently how the magnetic energy is released into light, mass motion, and accelerated particles. In a nutshell, if the flux rope is formed before the CME ("preformed"), then most theories propose that the eruption is primarily driven by ideal processes, i.e., plasma instabilities such as kink, and torus instabilities, that act on the large-scale flux rope structure. The spectacular eruptions from polar crown filaments are examples of this mechanism (Fig. 4, left). On the other hand, if the flux rope forms during the eruption ("on-the-fly"), then the eruption is driven by non-ideal processes such as magnetic reconnection, a topological change in the magnetic connectivity of neighboring field lines, which liberates magnetic energy. Highly impulsive eruptions accompanied by flares are usually put forth as examples of this mechanism (Fig. 4, right). Both types of theories predict that the actual eruption occurs over very short time scales of minutes.

The ideal vs non-ideal debate has been raging on for several years due mostly to the inability of instrumentation to capture the formation of flux ropes and the birth of CMEs in the low corona with sufficient temporal and spatial resolution. Again, SSD researchers and collaborators[5] have made considerable progress over the last year, thanks to the full 360° coverage of the solar corona achieved by a combination of SSD-led and other space instrumentation.

On July 19, 2012, the corona expelled a large CME in excess of 1000 km/s. A flux rope was clearly detected at its center by the LASCO coronagraph (Fig. 5, top right). Usually, the low corona source is identified in images of highly ionized Fe captured in the extreme ultraviolet (EUV) wavelength of 193 Å (Fe XII) corresponding to plasmas at the average coronal temperature (1.4 million K). In this case, the best viewing was offered by the Atmospheric Imaging Assembly (AIA) EUV imagers on the SDO mission. The 193 Å images showed nothing more than expanding loops, seen many times before in such eruptions. But AIA is equipped with filters at 131 Å (Fe XXI or 10 million K) and 335 Å (Fe XVI or 2.8 million K), among others. When we investigated, we found a flux rope structure hiding in the 131 Å images, completely invisible in the other, cooler wavelengths (Fig. 5, top middle). What is more, that structure was there for at least eight hours

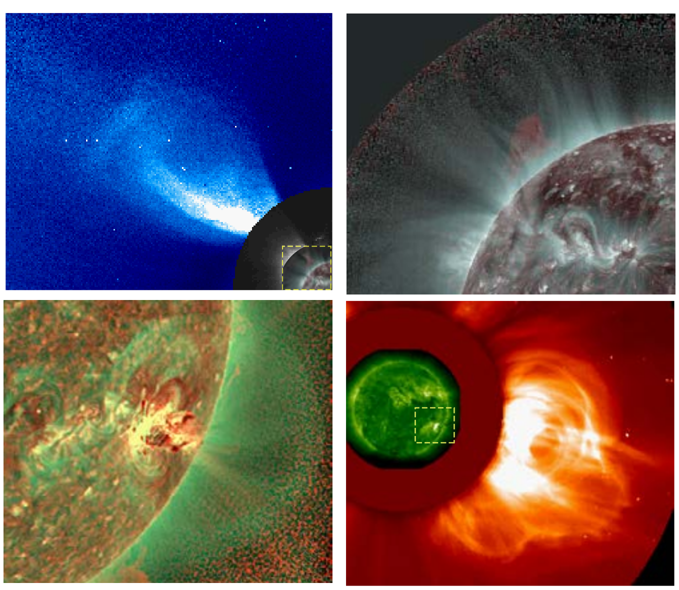

FIGURE 4
Top left: A flux rope CME morphology caused by the eruption of a polar crown filament. The yellow dashed box marks the source region. Top right: Detail of the source region about 8 hours prior to the eruption. A faint cavity with helical structures is already visible in the EUV images. Red (sliver) show plasma at 80,000 (1.4 million) K. Bottom right: An impulsive CME associated with a large flare and energetic particles above 100 MeV. A flux rope can be discerned at the center of the CME. The yellow dashed box marks the source region. Bottom left: Detail of the source region just half an hour earlier when the eruption became evident. A shock front is visible but there is no clear flux rope in the image. Red (green) show plasma at 80,000 (1.4 million) K.

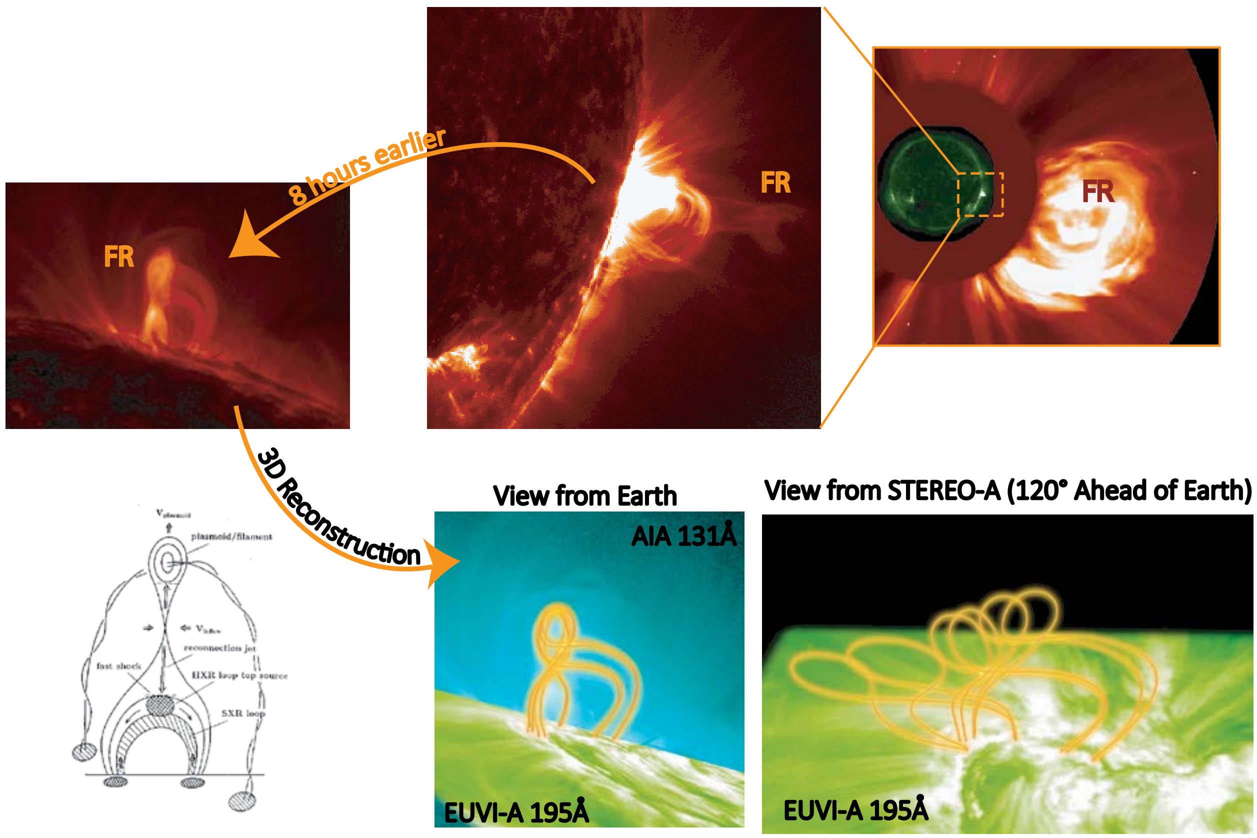

FIGURE 5
The CME-flare event of July 19, 2012. A "Rosetta stone" event that elucidates the role of preformed flux ropes in CME eruptions. The flux rope structure is marked by "FR" in the top three panels. Top right: The LASCO image shows an impulsive CME with flux rope morphology. Top middle: The same flux rope is seen in the low corona at a temperature of ~10 million K. Top left: The same flux rope forms 8 hours prior to the eruption but is observed only at a single EUV wavelength (131 Å or 10 million K), which has been available only since 2010. This observation explains immediately why flux ropes have not been detected directly in the past 16 years of EUV observations…at lower temperatures. Bottom left: Cartoon of the "standard" model of CME-flare eruptions from Shibata et al. (1995). The similarity with the 131 Å above is uncanny. Bottom right panels: Thanks to the SECCHI EUV observations, we can derive the 3D structure of the flux rope. It is a collection of kinked field lines that explains the high temperature and instability of the structure.

before the eruption and looked exactly as theories have predicted since the 1970s (Fig. 5, top and bottom left). It appeared during a flaring episode on July 18. The structure was extremely hot, (around 10 million K) since it was initially visible only in 131 Å. As it cooled down, it progressively appeared in cooler wavelengths (335 Å→94 Å→211 Å→193 Å) while it kept rising slowly at a speed of a few km/s. When we incorporated the SECCHI EUV observations to derive the 3D structure of the flux rope, we found that only a kinked loop morphology was consistent with the observations (Fig. 5, bottom). This event can be thought of as a kind of "Rosetta stone" for solar eruptions. It exhibits three of the expectations of ideally driven eruption theories with exceptionally clear observations: the preformed FR, the kink instability, and the slow rise (drive towards torus instability). Other observers have identified several more events where the FR makes its appearance in a hot channel at various times before the CME.

PUTTING IT ALL TOGETHER

A coherent picture of solar eruptions is emerging. FRs form a few minutes to several hours before the CME, rise through the low corona until they reach a critical height where a plasma instability (most likely the "torus instability") sets in and, then, they explode outwards carrying with them overlying plasma and magnetic field. This picture does not exclude non-ideal processes. Magnetic reconnection is required to sever the magnetic links between the outgoing structure and the Sun and provides additional energy during the initial acceleration phase. The scenario is applicable to large-scale, structured CMEs as compared to the small "puffs" and cloudlike ejections that occur frequently but never make it beyond 10 solar radii or so. Our findings last year imply that all such CMEs carry flux ropes, whereas the absence of the flux rope from the images is a matter of projection effects.

Besides clearing the debate on the internal structure of CMEs, this scenario is quite attractive for space weather operations. If the flux rope always forms before the CME, we should be in position to track its evolution and eventually predict when the eruption will take place. But first we must detect it. The reason we failed for some many years is because we have been looking at the wrong place…or, more precisely, at the wrong temperature. Our EUV results show that we should be looking both at hotter temperatures (3 to 10 million K) and at many temperatures simultaneously to trace the rise and temperature evolution of this structure.

WHERE DO WE GO FROM HERE?

Now that we are confident about the internal structure of CMEs and can estimate their 3D properties from SECCHI, we are left with one major outstanding piece of their geo-effectiveness puzzle: the strength and orientation of their internal magnetic field. This is, at present, impossible to measure remotely. An interplanetary fleet of in-situ probes distributed along the Sun-Earth line seems highly unlikely given the current fiscal climate. Empirical approaches to estimating the magnetic field with existing data and instrumentation are being developed by NRL researchers and scientists throughout the world. Their work and the advancement of space weather prediction will benefit greatly from instrumentation optimized by the lessons learned last year: use many EUV wavelengths, look over the limb in the EUV, and cover the low corona to Earth seamlessly. A payload of EUV imagers and visible light coronagraphs at the L5 Lagrangian point will be the perfect fit.

[Sponsored by NASA]

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