Earth-Affecting Solar Causes Observatory (EASCO): A New View from Sun-Earth L5

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Abstract: This white paper outlines the concept of a mission that will make remote-sensing and in-situ measurements from the Sun – Earth Lagrange point L5 to understand the origin and evolution of large-scale solar disturbances such as coronal mass ejections (CMEs) and corotating interaction regions (CIRs). The L5 mission is named the Earth-Affecting Solar Causes Observatory (EASCO), which will make measurements of solar variability from the solar interior, atmosphere, and the interplanetary (IP) medium. The L5 vantage point provides an unprecedented view of the solar disturbances and their solar sources that can greatly advance the science behind space weather. A coronagraph/heliospheric imager combination at L5 will be able to view CMEs broadsided, so space speed of the Earth-directed CMEs can be measured accurately and their radial structure discerned. In addition, an inner coronal imager and a magnetograph from L5 can give advance information on active regions and coronal holes that will soon rotate on to the solar disk. Radio remote sensing at low frequencies can provide information on shock-driving CMEs, the most dangerous of all CMEs. Coordinated helioseismic measurements from the Sun-Earth line and L5 provide information on the physical conditions at the base of the convection zone, where solar magnetism originates. Finally, the in situ measurements at L5 can provide information on CIRs heading towards Earth that potentially result in adverse space weather. Observing energetic particles from L5 and combining them with observations along the Sun-Earth line will help disentangle contributions from flares and CMEs.

EASCO will build upon the advances made during the last decade from heliospheric missions such as the Solar and Heliospheric Observatory (SOHO), Wind, and the Advanced Composition Explorer (ACE) that observe the Sun from the L1point.

1. Introduction

This white paper outlines the concept of a mission that will make remote-sensing and in-situ measurements from the Sun – Earth Lagrange point L5 to understand the origin and evolution of large-scale solar disturbances that affect Earth's space environment. Coronal mass ejections (CMEs) and corotating interaction regions (CIRs) are the large-scale disturbances that concern us, which can be best observed from the L5 vantage. We call the proposed mission as the Earth-Affecting Solar Causes Observatory (EASCO). The mission will contain instruments that will probe the solar interior where the magnetic field originates, to the solar atmosphere where the magnetic energy is released to the interplanetary medium into which the disturbances propagate.

More details on the L5 vantage point can be found in Akioka et al. (2005), Webb et al. (2010) and Gopalswamy et al. (2010).

A wealth of knowledge on CMEs and CIRs has been accumulated over the past three decades. However, many fundamental questions remain unanswered: How are CMEs initiated in closed magnetic regions? How do CMEs accelerate particles, alone and in combination with flare reconnection? Where and when do shocks form in the corona and how do they evolve? What is the radial profile of shock-driving CMEs? What is the internal magnetic structure of CMEs that cause magnetic storms? How do CMEs and CIRs evolve in the inner heliosphere? What are the changes that occur in the convection zone before active regions erupt? Answering these questions requires making accurate measurements of physical parameters from the solar interior to the atmosphere and into the heliosphere using a variety of techniques. The measurements include the magnetic and plasma properties of the source regions (active regions and filament regions for CMEs; coronal holes for CIRs) as well as the disturbances themselves. The observations involve multi-wavelength imagery and time series.

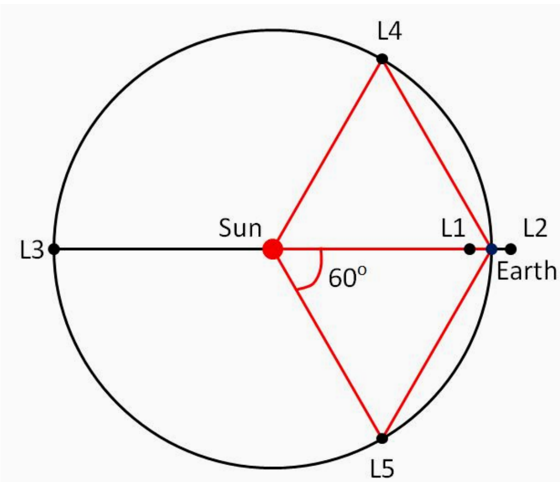

Figure 1. A sketch showing the five Sun – Earth Lagrange points, L1 – L5 with respect to Earth's orbit around the Sun. All the Lagrange points view the Sun continuously save L2, which is located on the night side of Earth. L5 is located at 60° away from the Sun-Earth line, trailing Earth. There have been many spacecraft located at L1. The Behind spacecraft of the STEREO mission went past the L5 point recently (end of 2009).

Coronagraphs have an occulting disk to block the direct photospheric light so the faint coronal structures can be imaged. This is a problem for observing CMEs originating on the solar disk along the Sun-Earth line: the occulting disk obscures the nose of the CME and CME-driven shock, where the shock is strongest and likely to accelerate particles. CME measurements are subject to severe projection effects, which prevent us from obtaining accurate Sun-Earth travel times. The case of CIRs is worse because we can observe them only when they are about to hit Earth (except for the white light observations using Heliospheric Imagers and SMEI). These difficulties can be readily overcome by EASCO because the L5 vantage point provides the full view of the CMEs when they are still close to the Sun and the CIRs well before they arrive at Earth (see Fig. 1).

2. Earth-affecting Solar Disturbances

CMEs from closed magnetic regions and CIRs from coronal holes are the two large-scale disturbances that seriously impact Earth's space environment. These large-scale disturbances are characterized by enhanced density and magnetic field with respect to the ambient solar wind. The enhanced magnetic field, if it has a southward component, interacts with Earth's magnetosphere producing geomagnetic storms. Both CIRs and CMEs drive shocks, but at different heliocentric distances: CME-driven shocks are known to form very close to the Sun

(~300,000 km above the solar surface), while the CIR shocks form only occasionally within 1 AU, but not within 0.3 AU. The CME-driven shocks accelerate particles from the corona and IP medium to very high energies. These solar energetic particles (SEPs) present a huge radiation hazard to humans and their technology in space in addition to affecting the conductivity of the ionosphere and ozone level in the atmosphere.

2.1 CMEs

CMEs responsible for SEPs at Earth and geomagnetic storms have different paths in the heliosphere (see Fig. 2). To drive a shock the CME speed V_{CME} above the solar wind speed V_{SW} must exceed the magnetosonic speed V_{MS} of the ambient medium. SEP production typically starts when the CME-driven shock is within a few solar radii from the Sun. The shock continues to produce SEPs in the IP medium so long as it remains strong enough. When the shock arrives at the observing spacecraft, a sudden increase in SEP intensity is observed (the so-called energetic storm particle event). The shock-driving ability of a CME is crucial for the production of SEPs and the shocks need to be strong enough to efficiently accelerate SEPs. Apart from the CME speed, the shock strength depends on the magnetosonic speed (or Alfven speed) in the ambient medium. Geomagnetic storms, on the other hand, occur only upon the arrival of the CME and/or its sheath at Earth's magnetosphere, provided these structures contain southward magnetic field components. The shock is also important for geoeffective CMEs in compressing the magnetosphere, but the intensity and duration of the southward component of the magnetic field in the shock sheath and CME determine the strength of the resulting magnetic storm. Thus the magnetic structure of the CME is important for geomagnetic storms, but not for SEPs.

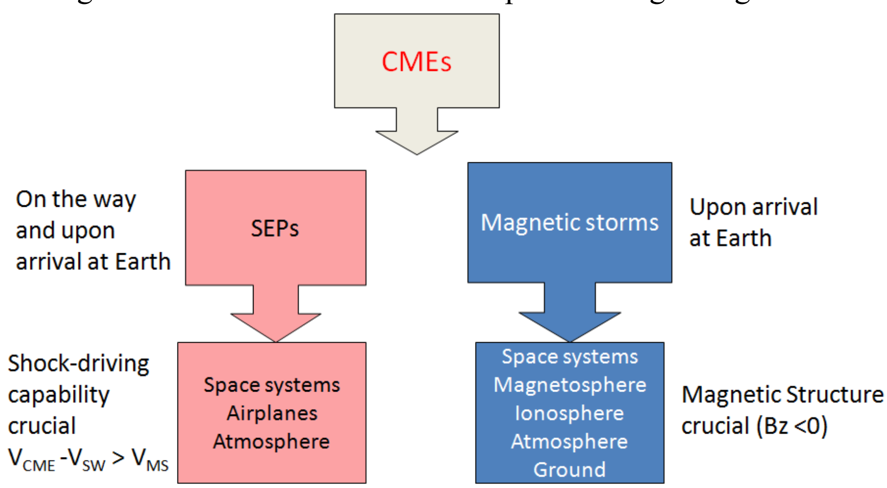

Figure 2. CME-driven shocks produce large SEP events and intense geomagnetic storms. CIRs also drive shocks, accelerate particles and produce geomagnetic storms. Only the magnetic storms are significant for CIRs because the CIR shocks accelerate particles typically at several AU.

The importance of an L5 view can be appreciated from the solar source locations of geoeffective and SEP-producing CMEs during solar cycle 23 (see Fig. 3). The source locations of geoeffective CMEs tend to cluster near the central meridian because only these CMEs head directly to Earth. There is a slight western bias to these source locations (average around W15) because of the eastward deflection due to the solar rotation. W15 in Earth view corresponds to W75 from L5. From Earth view, CMEs from W15 generally appear as halo CMEs, so it is difficult to measure their speeds accurately from a coronagraph viewing along the Sun-Earth line. On the other hand, these CMEs are limb events for an L5 view and hence the sky-plane speed from an L5 view is close to the true speed. The average direction of geoeffective CMEs is marked as “GEO” in Fig. 3. One other difficulty with the halo CMEs from an Earth view has been deciding whether a CME is front sided or back-sided. A front-sided CME with weak or no obvious near-surface signatures may be mistakenly classified as a backside event. An L5 view can resolve this ambiguity, so one can readily say whether it is headed towards Earth or away from it. Resolution of such ambiguity is very important for space weather applications.

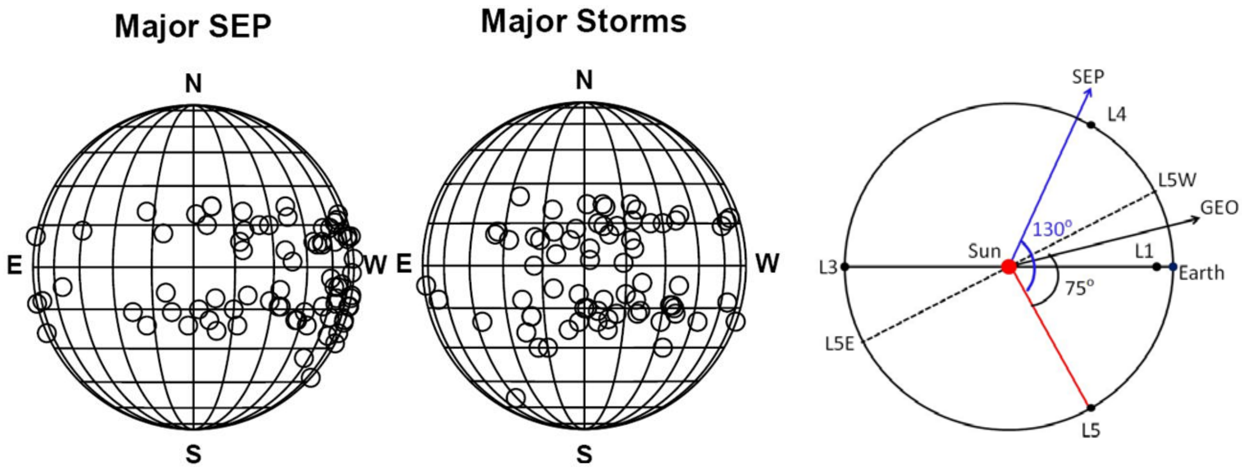

Figure 3. Heliographic coordinates of the solar sources of CMEs that produces major SEPs (left) and geomagnetic storms (middle). GEO and SEP denote the average directions of geoeffective and SEP-producing CMEs (right). The east (L5E) and west (L5W) limbs from L5 view are also shown.

CMEs associated with large SEP events typically originate from E45° to W90° (some even beyond W90). For fast (speed > 900 km/s) and wide (width > 60^o) CMEs, the SEP association rate peaks for CMEs originating from W40° – W50° in an Earth view (Gopalswamy et al., 2008). If we consider CMEs accompanied by type II radio bursts in the decameter-hectometric (DH) wavelengths, then the SEP rate peaks for CMEs originating from ~W70. This direction is marked as “SEP” in Fig. 3. The direction “SEP” in Fig. 3 corresponds to about 40^o behind the west limb for an L5 view and is at the limit of CME measurement without projection effects. The CMEs can also be observed with minimal “snow-storm” effects [coronagraph detector saturated by SEP events] because SEP events well connected to Earth are poorly connected to L5.

Simultaneous white-light and low-frequency radio observations will help reveal the shock signature ahead of the flux rope for geoeffective and SEP-producing CMEs. The radial structure of CMEs with shocks recognized in coronagraphic images (Gopalswamy, 2009; Gopalswamy et al., 2009a; Ontiveros and Vourlidas, 2009) and confirmed by radio dynamic spectra at DH wavelengths can directly provide accurate estimates of the coronal Alfven speed (Va) and hence the magnetic field if the electron density is inferred. Since the projection effects are minimal for Earth-directed CMEs, one can measure the shock standoff distance ΔR from the images. Since the CME speed (V) and distance (R) are known, one can get the Alfvénic Mach number (M = V/Va) from the following well-known relation that connects ΔR to R, M, and γ, the ratio of specific heats (Bennett et al., 1997):

$$\Delta R = 1.1\, R\, [(\gamma-1)M^2 + 2]/(\gamma+1)M^2].$$

This is especially important because there is no easy way of measuring magnetic field strength in the outer corona and near-Sun IP medium. Finally, a heliospheric imager at L5 can provide the density estimates in IP CMEs, which can be combined with Faraday rotation measurements to get the CME magnetic field strength and orientation.

2.2 CIRs

When a high speed stream from a coronal hole overtakes a slow wind ahead of it, a CIR is formed. This is because CIRs align themselves along the Parker spiral and rotate in the direction of planetary motion, so one observes a CIR structure at L5 ~4 days before its arrival at Earth. Figure 4 shows the Parker spiral structure when STEREO B was at L5 on 2009 October 25. The spiral field lines at STEREO B connect to the central meridian in an Earth view. Recently, Simunac et al. (2009) used in-situ observations from STEREO B and A separated by ~60^{o} to show that it is possible to predict the properties of a CIR at STEREO A based on the observations at STEREO B. This separation is similar to the L5 – Earth separation and, hence, demonstrates the usefulness of the method. CIRs cause geomagnetic storms because of the amplified Alfvénic fluctuations and compression contained in the stream interface, with a magnetic field strength similar to that in magnetic clouds (Gopalswamy, 2008). CIRs are primarily identified using plasma signatures such as proton density (peaks at the stream interface), proton thermal pressure (peaks at the interface), solar wind speed (peaks about half a day after the interface), and the flow direction, which changes from west to east at the interface (see Gosling 1996 for a review). Simultaneous magnetic field measurements additionally characterize the CIR magnetic content and structure, which decide the strength of the geomagnetic storm. Although the STEREO mission's Heliospheric Imagers can identify CIRs, the in situ measurements provide information on the magnetic field, density, and speed of CIRs, which are crucial in predicting the strength of the geomagnetic storm that would occur when the CIR arrives at Earth.

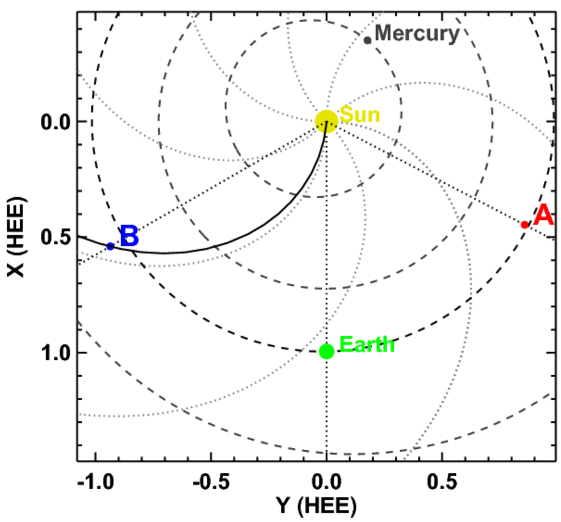

Figure 4. Solar magnetic field in the IP medium represented by the Parker spiral for 2009 October 25 (in heliocentric Earth Ecliptic (HEE) coordinate system). STEREO B and A were located near the Sun-Earth L5 and L4, respectively. The CIR observed at L5 (marked by the solid spiral field line) would rotate to Earth in about 4 days (neglecting the orbital motion of Earth, which is very small compared to the solar rotation).

3 Solar Sources

An inner coronal imager similar to the EUV instruments on board SOHO and STEREO can readily observe active regions and coronal holes, which are the solar sources of CMEs and CIRs, respectively. EUV images show several signatures of an eruption: the flare arcades, EUV waves, coronal dimming surrounding the flare location, and the eruptive filament (see Gopalswamy et al., 2009b for details). In addition, the EUV images from L5 can provide advanced warning of active regions and flaring activity that would be rotating on to the disk to face Earth. Active regions at the east limb in L5 view are almost at the backside of the Sun in Earth view (E150). Backside CMEs and their solar sources observed from L5 thus provide advance warning of activity centers moving on to Earth view in a few days. An L5 EUV instrument will be able to provide information on regions that are up to 60° behind the east limb in Earth view. EUV images also provide similar information on coronal holes that are likely to rotate to the front side. Magnetograms obtained from L5 view can also track the complexity and evolution of the active regions and coronal hole regions well before they come to the Earth view. Surface magnetic field measurements from L5 will be helpful to modeling efforts that depend on extrapolation of the photospheric field. Note that the east limb contains the least known (oldest) fields and weakest input to the heliospheric models and hence the L5 input will greatly improve this situation.

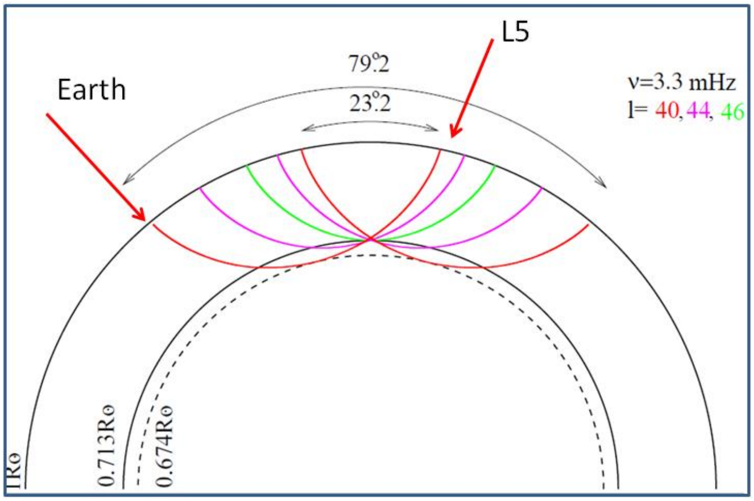

Figure 5. Simulation results show that acoustic modes with a frequency of ~3.3 mHz with l values between 40 and 46 reach the tachocline (to heliocentric distances of 0.67 and 0.71 Rs). Two views from Earth and L5 can study the l = 40 mode using correlation techniques. The computations were performed using the standard solar model and ray theory calculations.

4 Helioseismic Investigation of Solar Magnetism

The origin of all the magnetic field in the heliosphere, starting from the active region fields that result in violent eruptions to the field clumps in the heliosphere that modulate galactic cosmic rays, is thought to be at the tachocline. The generation and maintenance of the solar magnetic field and its evolution are central to the solar variability that affects Earth's space environment and the entire heliosphere. Helioseismic techniques aid in probing various layers of the solar interior using acoustic modes trapped inside the Sun (see e.g., Christensen-Dalsgaard et al. 1996). Of particular interest are the modes trapped between the base of the convection zone and the solar surface. It is expected that the modes that reach the bottom of the convection zone bounce off at the surface at 60° intervals (see Fig. 5), rendering it attractive to make Doppler measurements from L5 and Sun-Earth line. Existing helioseismic measurements from the Sun-Earth line (ground and space) can be combined with those from L5 for studying the base of the convection zone. Subsurface flow pattern changes (indicative of twisted magnetic fields) preceding large flares have been reported recently (Reinard et al. 2010), showing that local helioseismology may become useful in predicting large solar eruptions.

5 The Baseline Mission

Table 1 shows the elements of the straw man EASCO mission to make both remote-sensing and in-situ measurements along with nominal spatial (SR) and temporal (TR) resolutions. The mission will not need much instrument development and will use instruments similar to those on existing L1 missions. The mission could be launched around 2020 to begin observations in cycle 25. The Magnetic and Doppler Imager (MADI) will measure the photospheric magnetic and velocity fields. A white light coronagraph (WCOR) and a heliospheric imager (HI) will image the corona in the range 2.5 – 45 Rs. Combination of polarized brightness images from WCOR and those at L1 will be useful in predicting Earth-arriving CMEs. The Inner Coronal Imager in EUV (ICIE) will provide coronal images at EUV wavelengths. A combination of MADI and ICIE images can characterize the solar surface and corona containing magnetic regions with eruptive potential. The low-frequency radio telescope (LRT) will isolate CMEs driving shocks near the Sun using the type II radio bursts, providing valuable information on the shocks that eventually impact geospace. The Solar Wind Plasma Instrument (SWPI) and a magnetometer (MAG) will make in-situ measurements of the solar wind providing information on CIRs that will arrive at Earth ~4 days after being detected at L5. The energetic particle detector (EPD) will detect protons in several energy channels that will be useful in addressing flare and CME-shock contributions to large SEP events.

Table 1 Baseline Payload of the EASCO mission

Instrument	**Measurements**	**FOV**	**SR**	**TR**
Magnetic and Doppler Imager (MADI)	Photosph. B, V	Full disk	2”	90 min
White-light Coronagraph (WCOR), HI	Coronal images	2.5 – 45 Rs	1-2’	10, 60 min
Inner Coronal Imager at EUV (ICIE)	Coronal images	0 – 1.2 Rs	2”	5 min
Low-frequency Radio Telescope (LRT)	Dyn. spectrum	1 – 100 Rs	--	1 min
Solar Wind Plasma Instrument (SWPI)	Plasma param.	In situ	--	1 min
Solar Wind Magnetometer (MAG)	Magnetic field	In situ	--	1 min
Energetic Particle Detector (EPD)	SEP intensity	In situ	--	1 min

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