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Earth-Affecting Solar Causes Observatory (EASCO): A potential International Living with a Star Mission from Sun–Earth L5 ☆

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ABSTRACT

This paper describes the scientific rationale for an L5 mission and a partial list of key scientific instruments the mission should carry. 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 and a heliospheric imager 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, in situ measurements at L5 can provide information on the large-scale solar wind structures (corotating interaction regions (CIRs)) heading towards Earth that potentially result in adverse space weather.

1. Background and motivation

The solar plasma impact on Earth's magnetosphere resulting in geomagnetic storms originates from two sources on the Sun: the coronal mass ejections (CMEs) from closed magnetic field regions and high-speed solar wind streams (HSS) from coronal holes, which are open magnetic field regions. A corotating interaction region (CIR) forms when HSS overtakes the slow solar wind ahead. CIRs arrive at Earth with physical properties somewhat similar to those of the interplanetary CMEs (ICMEs). Both ICMEs and CIRs have magnetic fields enhanced above the quiet solar wind value by a factor of 3–4. Enhanced magnetic field from the Sun with a component anti-parallel to Earth's magnetic field causes magnetic reconnection, thus initiating a geomagnetic storm (see, e.g., Gonzalez et al., 2002). The sole cause of severe magnetic storms ($Dst < -150$ nT) is ICMEs, while moderate storms can be due to both CIRs and ICMEs (see e.g., Gosling et al., 1990; Zhang et al., 2007). However, there are major differences in the geospace consequences of storms caused by CIRs and ICMEs (Borovsky and Denton, 2006). CMEs can start driving shocks very close to the Sun (~0.5 solar radii above the surface) as inferred from type II radio burst observations (Gopalswamy et al., 2009a). CIR shocks, on the other hand, commonly form at a few AU from the Sun. CME-driven shocks accelerate energetic particles from near the Sun to large distances into the heliosphere. The CIR shocks also accelerate particles, but generally, beyond Earth orbit and the particle intensity is relatively small. Understanding the origin of CMEs and CIRs, their propagation in the interplanetary medium and their interaction with geospace are some of the major goals of space weather research.

The wealth of knowledge on CMEs accumulated over the last three decades has been from coronagraphs located along the Sun–Earth line (ground-based or space-borne). The occulting disk of a coronagraph located along the Sun–Earth line blocks that part of the Earth-directed CMEs that arrives at Earth. The CME plasma remote-sensed by a coronagraph located along the Sun–Earth line and the one arriving at Earth correspond to different parts of the CME. It is likely that the occulting disk also blocks the nose of the CME-driven shock, where the shock is strongest and hence likely to accelerate particles. 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

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Imager on board the Solar Terrestrial Relations Observatory (STEREO) mission and the Solar Mass Ejection Imager (SMEI)—see Harrison et al., 2009). Therefore, one needs to observe from a different vantage point that provides a full view of CMEs still close to the Sun and of CIRs well before they arrive at Earth. The fifth Sun–Earth Lagrange point (L5) is ideally suited for such an observing location. From an L5 view, one can observe the Earth-arriving parts of CMEs that eventually would to be sampled by spacecraft at L1 (this is not possible when the coronagraph is located along the un-Earth line). For shock-driving CMEs directed toward Earth, one can observe the radial structure of the entire disturbance consisting of the shock, sheath, flux rope, and prominence core. A low-frequency radio telescope can provide information on the properties of the shock in the coronagraphic field of view. An inner coronal imager at EUV wavelengths and a magnetograph can provide the necessary information on the solar sources of CMEs (active regions, filament regions) and CIRs (coronal holes). STEREO mission observes the Sun at large angles from the Sun–Earth line, but the angle is constantly changing so it is difficult to get uniform data as being provided by SOHO.

In this paper, we provide the scientific rationale for an L5 mission, which we call the Earth Affecting Solar Causes Observatory (EASCO) and describe the baseline instrumentation that can achieve the scientific objectives of such a mission. An L5 mission is ideally suited to fulfill the goals of the International Living with a Star (ILWS) program in characterizing the solar variability that affects Earth. Section 2 describes the L5 vantage point with respect to other Lagrange points. Section 3 describes the science issues related to CMEs and CIRs and the required measurements. Section 4 describes the baseline EASCO mission. Section 5 contains discussion and conclusions.

2. The L5 vantage point

A restricted three-body problem (one of the masses is much smaller than the other two) yields five equilibrium points, known as Lagrangian points L1–L5 named after the French-Italian mathematician Joseph Lagrange (see Cornish, 1999 for a detailed analysis of the Lagrange points). For the Sun–Earth gravitational system (see Fig. 1), the L1 point is most familiar because it is a stable location used by spacecraft such as SOHO, Wind, and the Advanced Composition Explorer (ACE) that continuously observe the Sun by remote sensing and in-situ techniques. The L2 point is located on Earth's night side, which is well suited for deploying astrophysical observatories. L1 and L2 are at 1.5×10^6 km away from Earth. The L3 point is behind the Sun at Earth's orbit, roughly 2 AU from Earth. The L4 and L5 points lead and trail Earth and are located at 60° away from the Sun–Earth line. The Sun, Earth and L4 or L5 make an equilateral triangle, so L4 and L5 are ~1 AU away from Earth. In this paper, we are concerned with the L5 point. L4 is equally suitable for observing Earth-directed CMEs, but not for observing CIRs before they hit Earth (CIRs first arrive at Earth and then at L4).

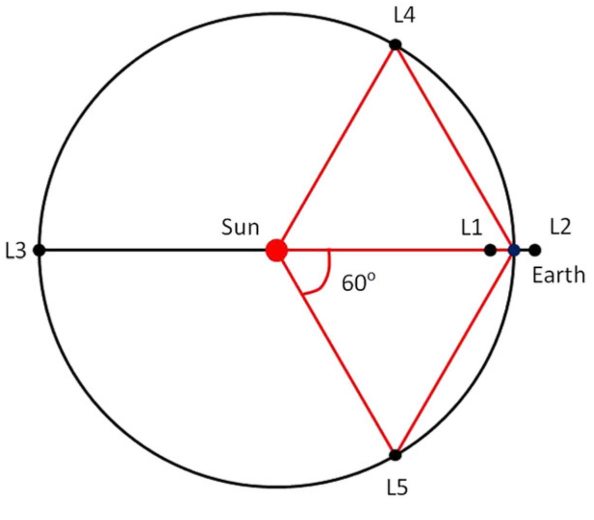

Fig. 1. A sketch of the Sun–Earth system showing the five Lagrange points, L1–L5 with respect to Earth's orbit around the Sun. All the Lagrange points view the Sun continuously save L2, which is located on the night side of Earth. L5 is located at 60° away from the Sun–Earth line, trailing Earth.

The Ahead and Behind spacecraft of the STEREO mission have recently crossed the L4 and L5 points, respectively, providing valuable information for a future L5 mission (Webb et al., 2010), including on the dust accumulation around L4 and L5 thought to be hazardous to spacecraft. STEREO observations indicate that there is no unusual level of dust or other objects at these Lagrange points, reducing one of the major risk factors of an L5 mission (St. Cyr et al., 2009; St. Cyr, 2010, private communication). The STEREO-B (SB) spacecraft also provides a benchmark orbit to get to L5, except that the spacecraft needs to be stopped and stationed at L5.

3. Scientific measurements from L5

The key science drivers for making measurements from L5 can be recognized from the following science questions: 1. What is the origin of solar magnetism and how does it relate to the solar sources of CMEs and CIRs? 2. What is the source of energy for CMEs? 3. How do CMEs accelerate particles, alone and in combination with flare reconnection? 4. Where and when do shocks form in the corona and how do they evolve? 5. What is the internal magnetic structure of CMEs and CIRs that cause magnetic storms? Answering these questions require making accurate measurements from the solar interior to the atmosphere and into the heliosphere. The measurements include the magnetic and plasma properties of active regions, filament regions, and coronal holes as the solar sources of Earth-affecting disturbances. These measurements are also made at the photospheric and coronal levels and inference is made about the solar interior. Measurements of the solar disturbances are made as they propagate into the heliosphere. Finally, in situ measurements of the solar wind plasma and magnetic field are made when the disturbances reach L5.

3.1. *Geoeffective and SEP-producing CMEs*

The solar source locations of CMEs that caused major space weather events (large gradual solar energetic particle (SEP) events and/or major geomagnetic storms) during solar cycle 23 are shown in Fig. 2. The CME sources were identified as either the H-alpha flare location listed in the Solar Geophysical Data (SGD) or the location of the EUV eruption identified in the Extreme-ultraviolet Imaging Telescope (EIT) images. The source locations of storm-producing CMEs tend to cluster near the central meridian because only these CMEs head directly to Earth and interact with the magnetosphere (Gopalswamy et al., 2007). There is a slight western bias to these source locations (average around W15) because of the eastward deflection of CMEs due to the solar rotation (Gosling et al., 1987). W15 in Earth view corresponds to W75 from L5. From Earth view, energetic 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 (Gopalswamy et al., 2010). On the other hand, these CMEs are limb CMEs for L5 view and hence the sky-plane speed from L5 view is close to the space 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

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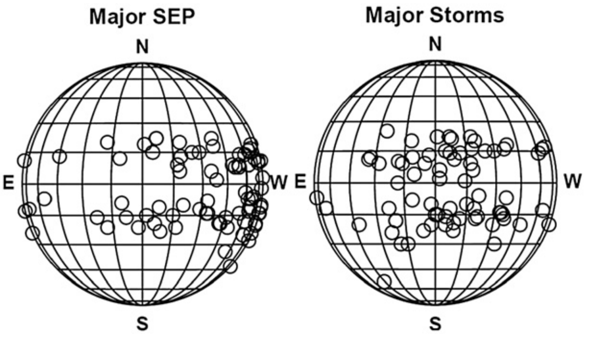

Fig. 2. The solar sources (active regions or filament regions) of CMEs that resulted in major (> 10 MeV proton intensity ≥ 10 pfu) SEP events (left) and large geomagnetic storms (Dst ≤ −100 nT).

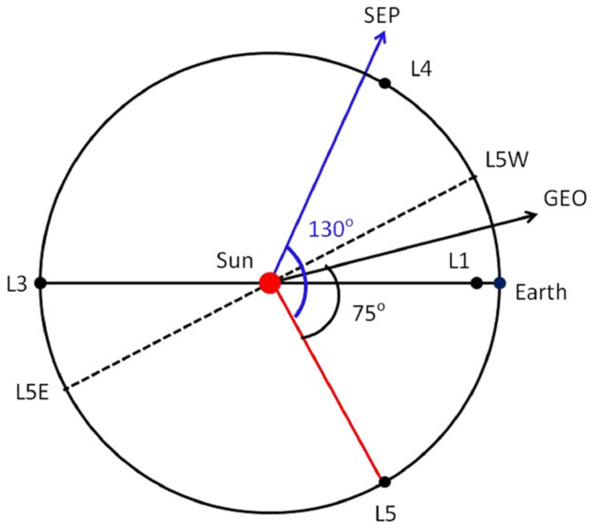

Fig. 3. Average directions of Earth-affecting CMEs with respect to the Sun–L5 line marked GEO (geoeffective CMEs) and SEP (CMEs producing SEPs). Also marked is the solar hemisphere visible to L5 (L5E and L5W are the east and west limbs in the L5 view). GEO CMEs are limb CMEs in the L5 view, so they can be measured with minimal projection effects. SEP CMEs are behind-the-limb CMEs most of which can also be measured with minimal projection effects.

deciding whether a CME is front sided or backsided. A frontsided 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 it is headed towards Earth or away from it. Resolution of such ambiguity is very important for space weather applications.

It is well known that CMEs associated with large SEP events typically originate from E45 to W90 (some even beyond W90) (see e.g., Gopalswamy et al., 2010). For fast (speed > 900 km/s) and wide (width > 60°) CMEs, the SEP association rate peaks for CMEs originating from W40 to W50 in 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 DH type II bursts are excellent indicators of SEP events because the same shock accelerates electrons (observed as type II bursts) and ions (detected as SEP events). A combination of the coronagraph and radio remote sensing is important in detecting SEP-producing CMEs as they leave the Sun (Gopalswamy, 2006). DH type II bursts occur in the heliocentric distance range of ∼2–10 Rs, so there is a good overlap of the spatial domains probed by the coronagraph and the radio telescope. Such early tracking will be useful in identifying shock-driving CMEs and predicting 1 AU shock arrival times. The direction "SEP" in Fig. 3 corresponds to about 40° behind the west limb for L5 view and is at the limit of CME measurement without projection effects.

An inner coronal imager similar to the EUV instruments on board SOHO and STEREO can readily observe the solar source location of CMEs, which is generally located radially beneath the CME front (see Yashiro et al., 2008 for details). 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 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. Fig. 4 illustrates this using observations from STEREO's Extreme Ultraviolet Imager (EUVI). SOHO/EIT data were not available for several days around this period due to CCD bake out and SOHO Keyhole (a failure in the mechanism for the SOHO high gain antenna resulted in the lack of contact with ground stations four times a year), so we have used Hinode's X-ray Telescope (XRT) images for Earth view. STEREO B (SB) EUVI observed two active regions at the east limb (in SB view) on May 5, 2009. These regions were about 137° and 185° behind the limb in the Earth and STEREO A (SA) views, respectively. Three days later, the active regions rotated on to the disk in Earth view (see the XRT image at 08:16 UT on May 8, 2009). An L5 EUV instrument will be able to provide information on regions that are up to 60° behind the east limb. Magnetograms obtained from L5 view can also provide information on the complexity and evolution of the active regions well before they come to the Earth view. EUV images also provide similar information on coronal holes that are likely to rotate to the frontside and hence provide advance warning of HSS and CIRs. Fig. 4 shows a small coronal hole near the disk center (in SB view), which is observed close to the east limb in Earth (Hinode) view, demonstrating that SB provides detailed information on the coronal hole before it appears in Earth view.

Since coronagraphs can readily image CMEs from ∼30° behind the limb and measurements can be made with minimal projection effects, an L5 coronagraph can also observe CMEs headed directly in the anti-earthward direction. In addition, similar observations in EUV can corroborate backside imaging of active regions using helioseismic observation from SOHO.

3.2. *Observing CIRs before they arrive at earth*

Since CIR structures approximately corotate with the Sun, one observes a CIR structure at L5 several days before its arrival at Earth. This is because CIRs align themselves along the Parker spiral and rotate in the direction of planetary motion. Fig. 5 shows the Parker spiral structure when STEREO B was at L5 on October 25, 2009. The spiral field lines at STEREO B connect to the coronal hole at roughly the central meridian in Earth view. It takes a little more than 4 days for the CIRs to reach Earth. CIRs cause geomagnetic storms because of the amplified Alfvenic fluctuations contained in the stream interface, with a magnetic field strength similar to that in magnetic clouds (Gopalswamy, 2008). CIRs are 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

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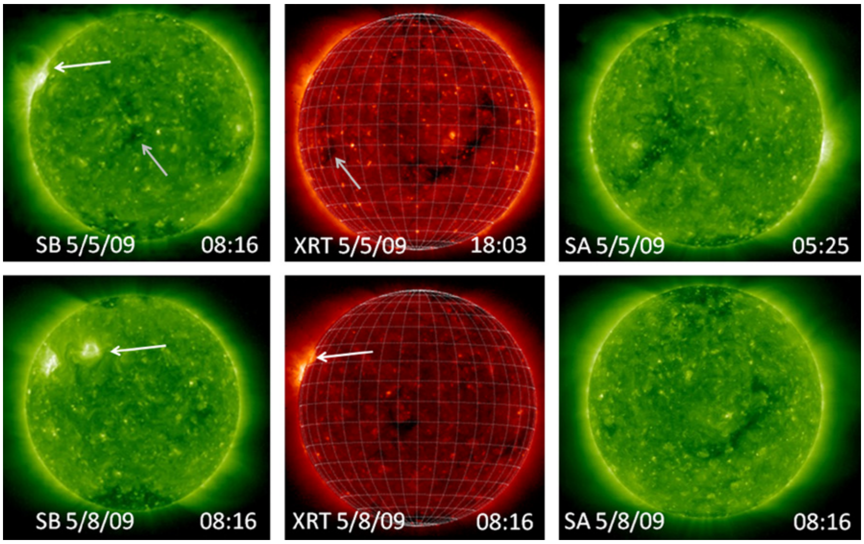

Fig. 4. A set of active regions was observed by only STEREO B (SB) EUVI at the east limb on May 5, 2009. There was actually an eruption from one of these regions (pointed by arrow). The regions were not seen in Earth view (as shown by the Hinode XRT view) or STEREO A (SA) because the regions were behind the limb from these views. SB and SA were separated by 47° and 48°, respectively from Earth. The regions just appear at the east limb in Earth view on May 8, 3 days later as seen in the XRT image taken at 08:16 UT. The regions are still 48° behind the east limb in SA view because SA was located 48° west of Sun–Earth line. A small coronal hole (pointed by gray arrows) close to the disk center in SB view is near the east limb in Earth view, again demonstrating the importance of an L5 view for obtaining information on the coronal holes ahead of time.

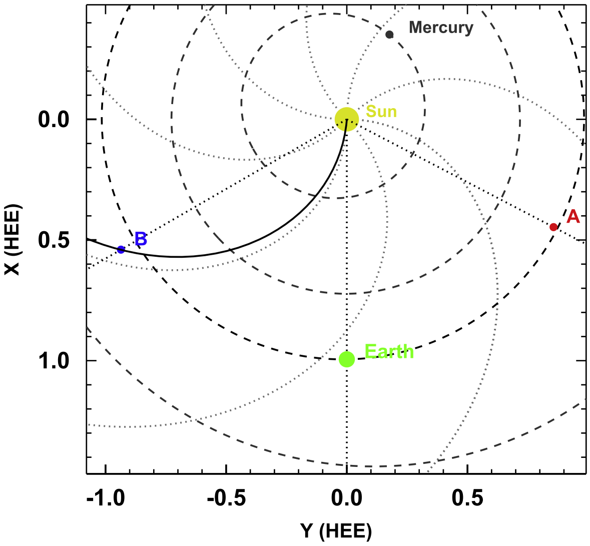

Fig. 5. Solar magnetic field in the interplanetary medium represented by the Parker spiral for October 25, 2009 (in heliocentric Earth Ecliptic (HEE) coordinate system). On this day, STEREO B (marked by the blue dot B), was located near the Sun–Earth L5 point (trailing Earth by 60°). STEREO A (marked by the red dot A) was located near the L4 point. One of the spiral field lines with its foot point near the Sun center in Earth view is connected to STEREO B. If there were a coronal hole near the disk center, then this spiral would roughly correspond to a CIR and would rotate to Earth in about 4 days (neglecting the orbital motion of Earth, which is very small compared to the solar rotation). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

measurements additionally characterize the CIR magnetic content and structure, which decide the strength of the geomagnetic storm.

The EUV imager also detects coronal holes responsible for HSS and CIRs as they evolve and rotate to face Earth. The coronal hole evolution is important because it leads to the change in CIR properties, so one can adjust the predictions. Recently Simunac et al. (2009) used in-situ observations from STEREO B and A separated by ~60° to show that it is possible to predict the properties of CIRs 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.

3.3. *Helioseismic Investigation of solar magnetism*

The origin of the heliospheric magnetic field, 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—at the bottom of the solar convection zone. 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 have attained maturity in probing various layers of the solar interior using acoustic modes trapped inside the Sun. 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, making 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 bottom of the convection zone. The STEREO mission did not carry a magnetograph. Obtaining line of sight magnetograms from L5 is essential to observe the source regions of CMEs before they rotate to Earth view. Surface field measurements from L5 will be helpful to modeling efforts that depend on the extrapolation of photospheric fields.

4. A baseline L5 mission

Table 1 shows the elements of a straw man EASCO mission. The EASCO mission will carry instruments to make both remote-sensing and in-situ measurements. The Magnetic and Doppler Imager (MADI) will measure the photospheric magnetic and velocity fields. When combined with similar observations available from the Global Oscillations Network Group (GONG) or other space-borne observatories along the Sun–Earth line, it is possible to infer the conditions at the bottom of the convection zone where the Sun acquires its magnetism. MADI will also observe

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Table 1
Elements of a straw man L5 mission.

Instrument	Measurements	FOV
Magnetic and Doppler Imager (MADI)	Photospheric B, V	Full disk
White-light Coronagraph (WCOR)	Coronal images	2–20 Rs[a]
Inner Coronal Imager at EUV (ICIE)	Coronal Images	0–1.2 Rs
Low-frequency Radio Telescope (LRT)	Dynamic spectrum	1–100 Rs
Solar Wind Plasma Instrument	Plasma parameters	In situ
Solar Wind Magnetometer (MAG)	Solar wind magnetic field	In situ
Energetic Particle Detector (EPD)	SEP intensity	In situ

[a] Inclusion of a heliospheric imager will increase the FOV significantly.

active regions and their magnetic complexity well before they rotate on to the disk facing Earth. A white light coronagraph (WCOR) will detect CMEs (within ~20 solar radii (Rs)), whose solar sources can be identified by an Inner Coronal Imager in EUV (ICIE). The coronagraph observations will also serve as input to inner heliospheric physics-based models such as ENLIL (inner boundary 21 Rs) (Odstrcil, 2008). CMEs can be tracked into the heliosphere by a Heliospheric Imager. ICIE can also provide advance warning of active regions and coronal holes soon to be rotating on to Earth view. A combination of MADI and ICIE images can characterize the solar surface and corona containing magnetic regions with eruptive potential. A low-frequency radio telescope (LRT) will isolate CMEs driving shocks near the Sun using the type II radio bursts, providing valuable information on shocks that eventually impact geospace. The spectral range of LRT corresponds to the heliocentric distance range of 2–100 Rs and hence has good overlap with the WCOR images. This greatly helps in identifying the shocks in WCOR data based on the frequency of type II bursts. A Solar Wind Plasma Instrument (SWPI) and a magnetometer (MAG) will make in-situ measurements of the solar wind providing information on CIRs that would arrive at Earth ~4 days after being detected at L5. The energetic particle detector (EPD) will be particularly useful in addressing the unsolved issue of flare and CME-shock contributions to large SEP events. Two-point observations from L1 and L5 will be able to help separating these components for a given SEP event.

Note that we have not discussed in any detail the flight dynamics and the launch issues of the EASCO mission, which will be studied based on the mass estimate of the payload and the fuel needed to station the spacecraft at L5. Since L5 is a stable point, the amount of station-keeping fuel is minimized. The fuel mass (and hence the spacecraft mass for a given launch vehicle) depends on the time taken to reach L5 from Earth. The shorter the transfer time the larger is the launch vehicle energy because the final speed of the spacecraft must match the speed of Earth for capture. The STEREO mission has demonstrated that we can get to L5 and make useful measurements, but details on stopping a spacecraft at L5 and keeping it there need further study.

5. Discussion and conclusions

The L5 is the next logical location for observing Earth-affecting solar disturbances such as coronal mass ejections (CMEs) and corotating interaction regions (CIRs) following the extensive remote sensing (SOHO) and in situ (Wind, SOHO, ACE) observations made from L1 for more than a decade. The wealth of knowledge gained from the SOHO and STEREO missions, which are not best suited for making measurements on Earth-directed CMEs and CIRs, will form the basis for the Earth-Affecting Solar Causes Observatory (EASCO) mission. We provided illustrative examples based on STEREO observations because STEREO was recently at or near L5 (Webb et al., 2010). The STEREO information serves as a proof of concept for getting there and making coronagraphic, radio, and EUV observations as well as in situ observations (except for magnetographic and Doppler measurements). A coronagraph similar to SOHO's C2+C3 or STEREO's COR2 can be used to make CME measurements near the Sun. Coronagraphic measurements of Earth-directed CMEs near the Sun are important to maximize the advance warning time for predictive purposes. However, including a heliospheric imager (HI) similar to HI-1 on STEREO will be highly beneficial in studying the evolution of CMEs and tracking substructures such as shock sheath, flux rope, and prominence. Previously, Akioka et al. (2005) performed a study on an L5 mission focusing on the tracking CMEs for long distances into the heliosphere using a wide field imager that covers the entire Sun–Earth distance. From an L5 view, the reduced emission due to Thomson scattering is minimized for HI viewing of an Earthward CME (see Vourlidas and Howard, 2006 for a discussion on the Thomson sphere issues). Note that the L5 mission concept studied by Akioka et al. (2005) does not include instruments similar to ICIE and MADI in EASCO. The magnetic and Doppler measurements will be important additions that address the basic issue of solar variability originating from solar magnetism. Finally, EASCO has a radio instrument to readily identify SEP-producing CMEs so that minutes to hours of advanced warning of such CMEs would be possible.

We presented the scientific basis for a Sun–Earth L5 mission EASCO that can sit-and-stare at the Sun as a CME watcher and sample the local solar wind, thus providing valuable scientific data on the two primary sources of space weather. EASCO can measure the space speed of all geoeffective CMEs and most of the SEP-producing CMEs. When the CMEs from the western hemisphere are accompanied by type II radio bursts, they are sure to produce an SEP event at Earth. Thus a combination of EUV, white-light, and radio observations can readily identify SEP-producing CMEs. While the SEP prediction is of limited value, the prediction of shock arrival based on CME and type II burst observations near the Sun will be valuable (Gopalswamy et al., 2005). In conclusion, the EASCO mission is capable of advancing the scientific understanding of Earth affecting CMEs needed for a quantitative assessment of their space weather consequences.

Acknowledgements

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