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Mission to the Sun-Earth L_5 Lagrangian Point: An Optimal Platform for Space Weather Research

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Abstract The Sun-Earth Lagrangian L_5 point is a uniquely advantageous location for space weather research and monitoring. It covers the “birth-to-impact” travel of solar transients; it enables imaging of solar activity at least 3 days prior to a terrestrial viewpoint and measures the solar wind conditions 4–5 days ahead of Earth impact. These observations, especially behind east limb magnetograms, will be a boon for background solar wind models, which are essential for coronal mass ejection (CME) and shock propagation forecasting. From an operational perspective, the L_5 orbit is the space weather equivalent to the geosynchronous orbit for weather satellites. Optimal for both research and monitoring, an L_5 mission is ideal for developing a Research-to-Operations capability in Heliophysics.

The Problem: Incomplete Knowledge of CME Propagation

Our society’s growing dependence on Global Positioning System, telecommunications, interconnected power grids, global travel, and (in the not-so-distant future) space travel brings attention to the conditions in Earth’s near space and increases the demand for accurate space weather predictions. Research from NASA heliophysics missions has established that eruptions of magnetic field and plasma from the Sun’s corona, so-called coronal mass ejections (CMEs), are the main drivers of space weather. The reaction of the terrestrial space environment to a CME impact depends mainly on the CME’s internal magnetic field configuration, time of arrival (ToA), and velocity on arrival (VoA). The objective of Space Weather (SpW) forecasting is to determine if a CME-Earth intercept is likely, and if so to obtain accurate values for all three parameters as far ahead of the CME impact as possible, mostly via remote sensing.

Of the three, the entrained magnetic field of an Earth-directed CME is beyond the reach of current remote sensing capabilities. However, ToA and VoA are readily derived from coronagraphic and heliospheric observations of propagating transients although they suffer from serious projection biases when based on observations from the Sun-Earth line. The availability of imaging off the Sun-Earth line from the Solar Terrestrial Relations Observatory (STEREO) mission has improved ToA accuracy to ±6 h from $> \pm 12$ h pre-STEREO [e.g., *Millward et al.*, 2013; *Colaninno et al.*, 2013]. The VoA accuracy is still rather low (within about ±30–40% of observed velocity). Figure 1 shows that from the L_5 vantage point, a CME can be easily followed all the way to Earth. Why are the predictions not better? How can we improve them? The answer lies in the complexity of the ambient solar wind (e.g., fast and slow streams and preceding events). The interactions may alter the CME structure or its path or both (see section 6.2 in *Webb and Howard* [2012], and references therein).

The brute force approach is to place a series of in situ probes along the Sun-Earth line—akin to the NOAA National Data Buoy Center tsunami warning network of buoys dispersed in the Pacific. Orbital mechanics make this approach impossible. Only one such stable orbit exists at the L_1 Lagrangian point, 1 h upstream from Earth. The STEREO spacecraft have long since moved past their optimum locations for such monitoring to pursue the research objectives of their mission. The best solution is to survey the whole Sun-Earth space at once by placing a satellite off the Sun-Earth line. The L_4/L_5 Lagrangian points located 60° on either side of the Sun-Earth line are perfect for this purpose (Figure 2).

Why L_5?

A satellite located at the L_5 point will be trailing Earth by 60° and, therefore, will image an additional 60° of the solar disk invisible from Earth. Since the solar rotation is about 13°/day, an L_5 satellite will be capable of a 4–5 day warning regarding the emergence, complexity, and eruptive potential of active regions and irradiance variations. Crucially, an L_5 spacecraft could provide real-time behind east limb magnetograms.

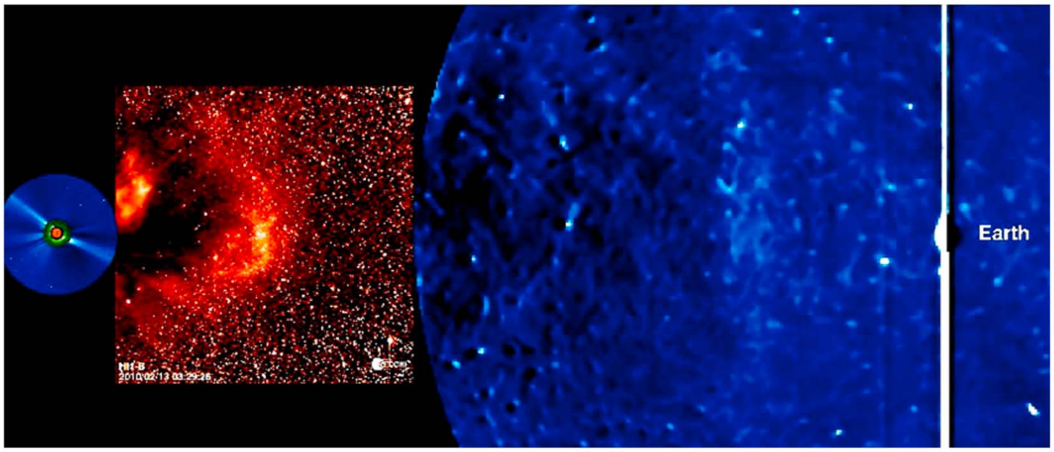

Figure 1. STEREO-B observation of an Earth-directed CME from the L_5 Lagrangian point. The CME is expanding into the HI-1 telescope's (red colors) field of view (around 40 R_S from the Sun). The vertical streak through the Earth is from CCD saturation due to the high brightness of Earth.

Currently, the boundary conditions for all heliophysics and SpW modeling are full disk photospheric magnetograms built over the 27 day solar rotation. The data just beyond the east limb are the oldest and thus least reliable inputs leading to large discrepancies in the modeling outputs (e.g., missing fast streams, pseudostreamers, etc.) during periods of solar activity. The addition of the L_5 magnetogram information to the Earth-based maps will provide instantaneous coverage of two thirds of the photosphere leading to huge quality improvements of the background solar wind models, which are essential for operational CME propagation models. As an added bonus, the modeling results could be validated against the solar wind measurements at L_5.

After its ejection, a CME can be followed throughout its inner heliospheric path as was done with STEREO [e.g., *DeForest et al.*, 2013]. The L_5 location is optimal for such studies because the CME lies within the Thomson surface of maximum scattered brightness throughout its travel to Earth [*Vourlidas and Howard*, 2006; *Webb et al.*, 2010]. Even if there is no other coronagraph in operation (either at Earth or at another vantage point) to provide stereoscopic information, the CME path can be estimated from a single viewpoint and the events tracked to large distance with the j-map technique [e.g., *Möstl et al.*, 2014]. The estimates can be adjusted continuously as observations further from the Sun become available and the Earth-arrival predictions can be updated.

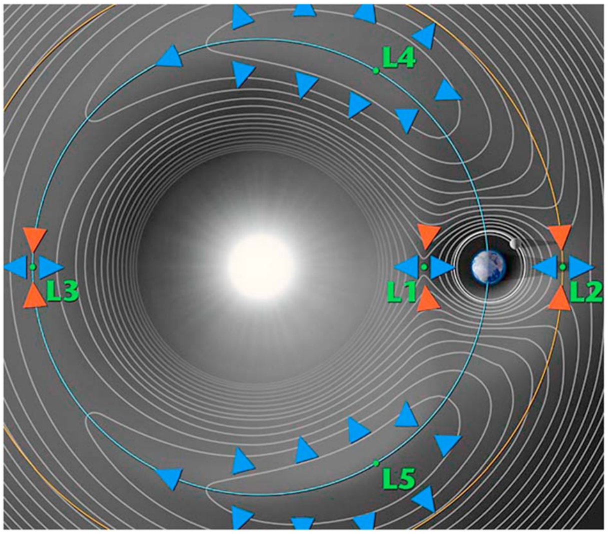

Figure 2. Not-to-scale diagram of the gravitational potential (white lines) associated with the Sun-Earth system. Lagrange points, designated by L1 to L3 (dynamically unstable) and L4 and L5 (stabilized by Coriolis effect), are positions in space where the gravitational forces produce enhanced regions of attraction (red arrows) and repulsion (blue arrows). Source: "NASA/WMAP Science Team."

In the heliosphere, an L_5 spacecraft could use its in situ instrumentation to detect recurrent disturbances such as Corotating Interaction Regions/High Speed Streams [*Gosling and Pizzo*, 1999] and measure their geoeffective properties such as whether they are driving a shock, or accelerating energetic particles, or presenting interplanetary magnetic field structures that excite the radiation belts [*McPherron et al.*, 2009] or cause neutral density enhancements [*McGranaghan et al.*, 2014]. These

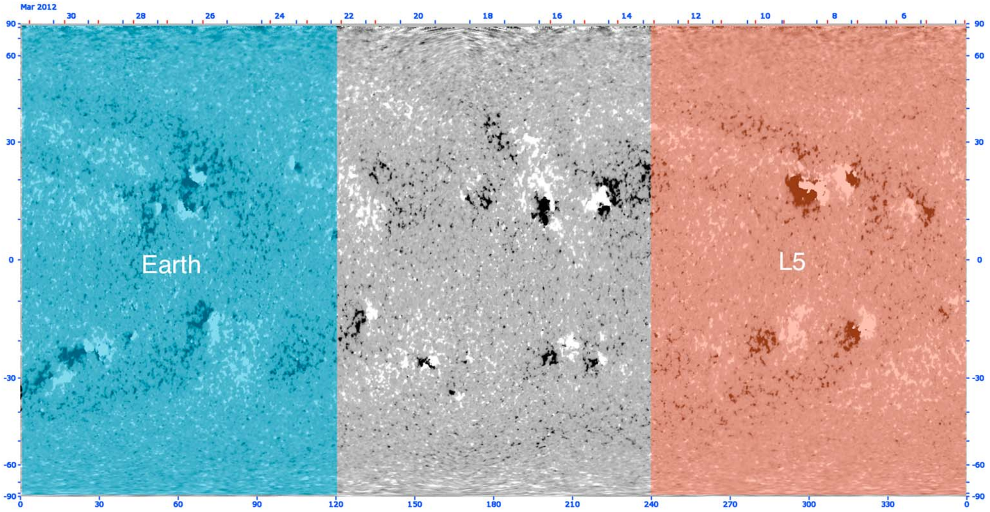

Figure 3. An NSO/SOLIS synoptic magnetogram used for the initiation of solar wind models. The map merges real-time data (289°–50°, blue box) with synoptic data recorded at the date shown along the top axis. Earth is at 349°. Similar L_5 data would extend the real-time coverage (169°–289°, red) to two thirds of the map.

measurements will characterize the CIR geoeffective potential, 4 days before crossing Earth, thereby providing a high-quality prediction, which is unattainable from an L_1 observatory.

Why Not L_4?

Obviously, L_4 can provide the same type of measurements as an L_5 viewpoint but there is a snag. The L_4 viewpoint lies over the west limb. Therefore, there is little SpW concern from much of the L_4-only observed activity, be it coronal hole evolution, photospheric flux emergence, or EUV irradiance variation. The gap in the magnetogram (grey area in Figure 3) observations can be addressed, to some extent, by flux-transport modeling of the Earth-based magnetic field data [*Arge et al*., 2013]. In that sense, L_4 observations have a lower SpW priority than observations from L_5. The exception is studies of solar energetic particles whose sources are close to the L_4 central meridian for Earth-connected field lines (nominally at 54° west). Hence, an L_4 mission is a natural follow-on to one at L_5.

Implementation

The gravitational configuration of the L_4/L_5 points offers great flexibility in the mission design [*Llanos et al*., 2013]. The spacecraft can get there with direct injection, via a parking orbit or even via a lunar flyby. The trip can last anywhere from 300 days to 4 years, depending on available energy. More interestingly, the spacecraft can either be parked exactly at L_5 or orbit L_5 with amplitudes as large as 0.52 AU [*Lo et al*., 2010]. In such a wide orbit, the angular separation of the L_5 spacecraft from Earth would vary between 40° and 80°, thus expanding the coverage of the solar photospheric field and of the geoeffective active regions.

There is strong community interest for an L_5 mission with several concepts put forth. *Kamide* [2001] and *Akioka et al*. [2002] were the first to discuss an L_5 concept for SpW purposes. Their detailed study included several instruments now considered standard complement for this mission, such as a heliographic imager and a coronagraph. The passage of STEREO-B through L_5 during the last quarter of 2009 demonstrated the SpW potential of CME observations away from the Sun-Earth axis and led to renewed interest [*Webb et al*., 2010]. The latest concepts are quite similar to each other. They consider a standard spacecraft bus with a STEREO-like payload (heliospheric imager, coronagraph, EUV imager, particles, and fields) and the addition of a magnetograph. They vary mainly on their focus on research (L5 Mission Concept: *Decadal Strategy for Solar and Space Physics* [2012], Earth-affecting solar causes observatory: *Gopalswamy et al*. [2011], and INvestigation of Solar-Terrestrial Associated Natural Threats: *Lavraud et al*. [2014]) versus operations [*Trichas*, 2014].

Table 1. Potential Instruments for an L5 Mission[a]

Telescope	FOV	Wavelength (Å)	Highlights	Mass (kg)	Power (W)	Telemetry(Kbps)
EUV imager	2 R_S (0°–0.5°)	131, 171, 131, 304	STEREO Heritage	6	8	50
COR2 coronagraph	2–15 R_S (0.5°–4°)	600–700	STEREO Heritage	6	8	40
Heliospheric imager	15–225 R_S (4°–64°)	600–700	10 times sensitivity over STEREO-HI	5	3	30
Magnetograph	Full disk	Na 5890 K 7700	Magneto-Optical Filter	17	20	50
Off-limb spectrograph	Two 3 R_S long slits at 2 R_S and 3.5 R_S	500–1040	OVI dbl, CIII, Lyβ-γ, ArXII, SiXII, FeX, XIII, XVIII	4.4	4.4	50
HXR imager/spectrometer	Full disk	64–150 KeV 0.7 ~ 1 KeV resolution	Same as STIX on solar orbiter	14	24	0.5
Solar wind ions	2π	5 °	0.05–20 keV/q	2	3.5	
Solar wind electrons	4π	22.5°	0.005–6 keV/q	4	6	
Energetic particles	240°		0.02–100 MeV/nuc	4	3.1	5
Magnetometer				1.25	2	

[a] FOV, field of view.

Fiscal constraints and recent technology advancements have inspired a novel class of mission designs based on small satellites. Instead of sending a classical monolithic (and expensive) spacecraft to L_5, *Liewer et al.* [2014] propose a "fractionated" satellite concept where the payload and spacecraft functions are spread among several small satellites. In this case, the high gain antenna and associated communications hardware, and individual instruments (coronagraph, in situ monitors, etc.) reside on dedicated 6U CubeSats propelled to L_5 using solar sails. These CubeSats should be built for deep space operations. The maintenance of such cluster is straightforward with replacements/upgrades of individual instruments flown in on regular intervals or on an as-needed basis. A variation of this concept is the "flock" formation where the imaging and communications payload is mounted on a standard, but smaller spacecraft bus while the in situ monitors fly in close formation as spinning CubeSats. This configuration simplifies the observatory-level integration and testing, reduces electromagnetic interference requirements on the payload, and optimizes the measurement range of the in situ instrumentation. The flock concept could result in significant cost savings, compared to a standard single spacecraft mission, while maintaining high Technology Readiness Levels on the scientific payload.

Strawman Payload

To derive a SpW benefit from an L_5 perspective, an SpW mission requires a coronagraph and a magnetograph as the bare minimum payload. A comprehensive operational mission would benefit from increased heliospheric coverage (heliospheric imager), imaging of the CME sources (EUV imaging), and solar wind measurements. A scientific mission could add an off-limb spectrometer to measure the properties of the solar wind near the Sun, or a hard X-ray (HXR) imager and an energetic particle in situ suite to investigate particle acceleration. Available spacecraft resources and the particular scientific and/or operational objectives of the mission will determine the actual payload. A "shopping list" of possible instruments is shown in Table 1 using 2010 estimates. As a rough guide, each STEREO spacecraft carries about 70 kg of science payload and downlinked 480 Kbits/s from L_5. Technological progress will surely lower mass and power resources compared to Table 1.

Toward a Space Weather R2O Program

An L_5 mission is the first stepping-stone toward understanding the solar drivers of space weather and improving its prediction. But observations from a single viewpoint or two—if we consider Earth/L_1 assets—are not going to solve the problem any more than a single GOES satellite can improve terrestrial weather forecasting around the globe. A comprehensive research-to-operations (R2O) program is needed to make SpW forecasting robust enough to act upon and to serve the needs of civilian and military customers. Such a program should stand on two pillars: efficient data gathering and focused modeling. The data gathering starts with the deployment of imaging payloads at the libration points, in priority order ($L_1 \rightarrow L_5 \rightarrow L_4 \rightarrow L_3$), combined with in situ monitors at orbits sunward of L_1 to capture both the large- and small-scale physics of the transients. It will drive technological innovation (e.g., solar sails, miniature imagers, etc.). The modeling pillar should be designed around the expected observations, with assimilative and ensemble-modeling techniques embedded from the beginning, and with strong focus on operationally relevant problems. This *Space Weather Systems Observatory*, possibly managed by a dedicated R2O entity to ensure cross agency efficiency, will undoubtedly lead to fundamental improvements in the scientific understanding of our environment while maintaining a vibrant heliophysics community. International participation, always welcome, will most likely be required given the range of the undertaking and the global importance of Space Weather.

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References

Akioka, M., K. Ohtaka, T. Nagatsuma, K. Maruhashi, and W. Miyake (2002), L_5 mission and observation of interplanetary CME, *J. Commun. Res. Lab.*, *49*(4), 13–26.

Arge, N., C. J. Henney, I. Gonzalez Hernandez, W. A. Toussaint, J. Koller, and H. C. Godinez (2013), Modeling the corona and solar wind using ADAPT maps that include far-side observations, *AIP Conf. Proc.*, *1539*, 11, doi:10.1063/1.4810977.

Colaninno, R., A. Vourlidas, and C. C. Wu (2013), Quantitative comparison of methods for predicting the arrival of coronal mass ejections at Earth based on multiview imaging, *J. Geophys. Res. Space Physics*, *118*, 6866–6879, doi:10.1002/2013JA019205.

Decadal Strategy for Solar and Space Physics (2012), *Solar and Space Physics: A Science for a Technological Society*, 319 pp., NRC, Washington, D. C.

DeForest, C. E., T. A. Howard, and D. J. McComas (2013), Tracking coronal features from the low corona to Earth: A quantitative analysis of the 2008 December 12 coronal mass ejection, *Astrophys. J.*, *769*, 43–56.

Gopalswamy, N., et al. (2011), Earth-affecting solar causes observatory (EASCO): A potential international living with a star mission from Sun-Earth L5, *J. Atmos. Sol. Terr. Phys.*, *73*, 658–663.

Gosling, J. T., and V. J. Pizzo (1999), Formation and evolution of corotating interaction regions and their three dimensional structure, *Space Sci. Rev.*, *89*(1/2), 21–52.

Kamide, Y. (2001), Space weather: Japanese perspectives, in *Space Weather*, *Geophys. Monogr. Ser.*, vol. 125, edited by P. Song, H. J. Singer, and G. L. Siscoe, pp. 59–64, AGU, Washington, D. C.

Lavraud, B., et al. (2014), INSTANT: INvestigation of Solar-Terrestrial Associated Natural Threats, paper presented at L5 Consortium Meeting, Boulder, Colo., Dec. [Available at http://cdaw.gsfc.nasa.gov/meetings/2014_L5C/Presentations/00_Agenda_v3.htm.]

Liewer, P. C., et al. (2014), A fractionated space weather base at L_5 using CubeSats and solar sails, in *Advances in Solar Sailing*, Springer Praxis Books, pp. 269–288, Springer, Berlin.

Llanos, P. J., J. K. Miller, and G. R. Hintz (2013), L5 mission design targeting strategy, paper AAS 13-223 presented at AAS/AIAA Astrodynamics Specialist Conference, Kauai, Hawaii, 12–14 Feb.

Lo, W. M., P. J. Llanos, and G. R. Hintz (2010), An L_5 mission to observe the Sun and space weather, paper presented at AAS/AIAA 20th Flight Dynamics Conference, San Diego, Calif.

McGranaghan, R., D. J. Knipp, R. L. McPherron, and L. A. Hunt (2014), Impact of equinoctial high-speed stream structures on thermospheric responses, *Space Weather*, *12*, 277–297, doi:10.1002/2014SW001045.

McPherron, R., D. Baker, and N. Crooker (2009), Role of the Russell-Mcpherron effect in the acceleration of relativistic electrons, *J. Atmos. Sol. Terr. Phys.*, *71*, 1032–1044, doi:10.1016/j.jastp.2008.11.002.

Millward, G., D. Biesecker, V. Pizzo, and C. A. de Koning (2013), An operational software tool for the analysis of coronagraph images: Determining CME parameters for input into the WSA-Enlil heliospheric model, *Space Weather*, *11*, 57–68, doi:10.1002/swe.20024.

Möstl, C., et al. (2014), Connecting speeds, directions and arrival times of 22 coronal mass ejections from the Sun to 1 AU, *Astrophys. J.*, *787*, 119.

Trichas, M. (2014), Carrington: The UK Space Weather Mission, paper presented at L5 Consortium Meeting, Boulder, Colo., Dec. [Available at http://cdaw.gsfc.nasa.gov/meetings/2014_L5C/Presentations/00_Agenda_v3.htm.]

Vourlidas, A., and R. A. Howard (2006), The proper treatment of coronal mass ejection brightness: A new methodology and implications for observations, *Astrophys. J.*, *642*, 1216.

Webb, D. F., and T. A. Howard (2012), Coronal mass ejections: Observations, *Living Rev. Sol. Phys.*, *9*, 3.

Webb, D. F., D. A. Biesecker, N. Gopalswamy, O. C. St. Cyr, J. M. Davila, B. J. Thompson, K. D. C. Simunac, and J. C. Johnston (2010), Using STEREO-B as an L5 space weather pathfinder mission, *Space Res. Today*, *178*, 10–16.

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