Mission to the Sun-Earth L5 Lagrangian Point: An Optimal Platform for Heliophysics & Space Weather Research

Submitted By:

A. Vourlidas, R. Howard, Y.-K. Ko, D. Biesecker, S. Krucker, M. Thomson, N. Murphy, T. Bogdan, C. St Cyr, J. Davila, G. Doschek, N. Gopalswamy, C. Korendyke, M. Laming, P. Liewer, R. Lin, S. Plunkett, D. Socker, S. Tomczyk, D. Webb

1 SUMMARY

Our field of research, heliophysics, is evolving rapidly. Sun-Earth interactions, once treated as a area of pure basic research, has now evolved into the field of Space Weather with concrete and important societal benefits as well as a strong basic research interest. The once separate research fields of solar, geospace and space physics are integrating, leading to much more productive science, under the *heliophysics* label. These accomplishments are driven by a string of highly productive NASA missions (e.g., *Wind, SOHO, ACE, STEREO*) and are based on a very successful systems approach in the mission operations and analysis of their data. We have learned that some of the observations obtained from these missions, need to be available routinely to enable the science to address the next tier of questions.

In this paper, we argue that a *research-to-operations (R2O)* approach is the best strategy to foster the vibrancy of our field in the next decade. A mission to the L5 Lagrangian point should spearhead this strategy because it maintains the highly successful and productive systems approach to NASA's missions, augments the output and societal benefit of the LWS program, and enhances research both for the benefit of future space weather applications and for the basic understanding of the Sun-Earth system. NASA has implemented such a strategy before with extreme success. The *Nimbus* series of geostationary satellites drove atmospheric physics research for decades and simultaneously established dependable 3-day weather forecasting. In the end, NASA passed the baton over to NOAA with the creation of the operational series of GOES satellites. Heliophysics is at the same level of development now as atmospheric physics was in the mid-1960s and hence a NASA-led R2O program is the next logical step.

Our society's growing technological dependence on GPS, telecommunication, an interconnected power grid, global travel, and expected growth in space travel focuses attention to the conditions in Earth's near space and increases the demand for accurate space weather predictions. Research from NASA missions has uncovered the drivers of space weather and continues to provide new insights into the physics of solar eruptions. The realization that basic research from space can benefit societal needs led to the creation of a new mission line and research program—the Living With a Star (LWS) program which aims to improve our understanding of space weather through a series of research missions in geospace. However, the LWS missions were conceived and planned early in this decade before we had a chance to absorb the results from a full solar cycle of *SOHO* and *ACE* observations and to assimilate the breakthrough science that is currently coming from the *STEREO* mission. These missions are teaching us that even the venerable solar cycle may not be as predictable as we once thought, and that simply following the evolution of the solar structures on their journey to Earth can provide critical information for space weather studies. Having the benefit of hindsight, we argue that the current heliophysics mission plan fails to address the critical science of the Sun-to-Earth evolution of the solar wind and hence it may be inadequate to fully meet the LWS program goals in the near future.

To improve our predictive capabilities, we first have to understand how the solar structures evolve during their propagation to Earth. But to understand that evolution, we need to observe the propagation of a given structure and its interaction with the ambient solar wind continuously. Continuous coverage is necessary because of the complexity of the ambient solar wind (*e.g.* fast and slow streams, preceding

events) which can alter the structure of a coronal mass ejection (CME), or alter its path or both. Orbital dynamics (and costs) make it almost impossible to monitor the Sun-Earth space with a series of in-situ probes along the way like the NOAA National Data Buoy Center tsunami warning network of buoys dispersed in the Pacific. There is only one stable orbit at the L1 Lagrangian point, located about one hour upstream of Earth. The optimum solution is the L5 Lagrangian point from here we can survey the whole Sun-Earth space at once. The L5 point is located 60º east of the Sun-Earth line and is a gravitationally stable location.

The *Nimbus* program offers a proper analogy. The L5 orbit is the space weather equivalent of the geosynchronous orbit for weather satellites. Reliable 3-5 days predictions of terrestrial weather became viable only after the successful launch of the *Nimbus* satellite series in geosynchronous orbit in 1964-74. We argue that a heliospheric mission to L5 can accomplish a similar leap in space weather prediction and in our understanding of the inner heliosphere. The L5 point is a uniquely advantageous viewpoint because it provides global coverage of the inner heliosphere, allows imaging of solar activity and the in-situ sampling of solar wind structure, such as CIRs, four to five days before it arrives at L1 or geospace.

Table 1 Summary of L5 Mission Concept

Mission Profile	L5 orbit: 60º nominal relative to Sun-Earth line, orbit may vary from 40º – 90º relative to Sun-Earth line.		
Strawman Payload	EUV disk imager to 2 Rs. Line-of-sight Magnetograph HXR imager/spectrometer	White light coronagraph Heliospheric Imager Off-limb UV Spectrometer	On-disk spectrometer/imager Fields & Particles Solar wind composition.
Operational Capability	- 4-5 day warning for recurrent disturbances (e.g., CIRs, Irradiance variations). - 4-5 day warning of coronal activity (e.g., flux emergence, flaring history of active region. - 5hr – 4-day CME prediction capability using streamer swelling (**L5 unique capability**). - Few-hr eruption prediction by measuring height of Earth-aligned rising prominences (**L5 unique capability**). - Evaluation of CIR geoeffective potential by in-situ measurements of CIR shock and energetic particle production 4-5 days before they hit Earth. (**L5 unique capability**).		
Scientific Capability	- Solar wind measured at L1 originates at limb as seen from L5. - Sources/footpoints of Earth-connected field lines are occulted allowing HXR/SXR imaging of looptop sources, and measuring altitudes of erupting loops. - Sources/footpoints of field lines connecting to L5 s/c are close to central meridian (from Earth) allowing direct measurement of the photospheric magnetic field and coronal conditions. - Long-term studies of the heliosphere with correlation in properties between the solar structure and the solar wind at two vantage points. - Stereoscopic analysis of EUV sources, CMEs and CIRs using Earth-orbiting assets. - Two-point measurements of SEPs place stringent tests on models of SEP production. - Measurement of the longitudinal structure of the tachocline.		
Cost	$500M to $1B.		

The mission concept builds on our growing experience with observations off the Sun-Earth line from the *STEREO* mission[1]. The Behind *STEREO* spacecraft (STEREO-B) actually crossed the L5 point during 2008-09. It obtained many observations of Earth-directed events which provide the proof-of-concept for our proposed mission. For example, STEREO-B data are regularly used by NOAA for space weather assessment while active research from many groups is providing new insights in the evolution of CMEs. Hence, a future L5 mission will have a unique blend of operational and science objectives. It will also greatly enhance our understanding in solar and heliospheric physics by providing a second vantage point with Earth/L1.

[1] Webb, D. F. et al. 2010, Space Research Today, 178, 10

The mission science objectives, instruments and anticipated measurements are summarized in Table 1. In the following, we describe a set of key science questions that could be answered with this mission concept.

2 KEY SCIENCE QUESTIONS

2.1 L5 *is an Ideal Location for Heliophysics Research*

Observations from L5 can help answer key science questions over the full spectrum of solar and heliophysics studies starting from helioseismology and extending to CME initiation and the propagation of SEPs in the heliosphere. These questions are outlined below and the research benefits of an L5 mission are summarized in **Error! Reference source not found.**. The L5 location permits the direct viewing of structures propagating towards Earth, in contrast to the L1 location.

2.1.1 What Is The 3-D Structure Of The Corona Before An Eruption?

EUV and SXR observations of the low corona have shown that the most energetic CMEs originate in active region neutral lines. These regions are often characterized by complex loop topologies that include loops highly inclined from the local normal, serpentine filaments, semi-circular loops and loops with distant connections outside the active region. However, only a small subset of these structures participates in the formation of the CME and is subsequently ejected while the rest of the loop system remains relatively stable. Why is that? Why only part of the neutral line is activated during a CME? What determines the length of the post-eruptive flaring arcade? What is special about the erupting loops?

Table 2 Mission Summary

We cannot answer these questions because we do not yet have a good handle on the 3D magnetic topology of the corona, the sites of energy storage, or the distribution of currents within the coronal part of an active region. It is difficult to discern the evolution of erupting structures low in the corona from a single viewpoint. The spatial scales are small and the magnetic topology in the core of active regions is quite complex. The problem is more acute for observations from an Earth-based location because the structures that are ejected towards Earth are at large angles from the sky plane and hence almost invisible. Recent STEREO EUV work has shown that single viewpoint observations, even with high cadence, can lead to misidentification of the erupting structure[2]. Other STEREO observations have associated jets (and 3He rich events in the heliosphere) with small impulsive flares[3]. Are these flares the sources of the seed particles for SEP events?

STEREO results demonstrate the power of two viewpoint observations even at large angles from Earth. Unlike STEREO, our strawman payload includes both a magnetograph and an X-ray imager and will remain in orbit around L5. Thus, the mission will provide stereoscopic and quadrature observations of flares and erupting active regions on a routine basis with the combination of an Earth-based platform (e.g., from SDO).

2.1.2 What Are The Sources Of Seps And How Does Scattering Affect Their 1 AU Properties?

The uncertainty of the source of SEPs is a major hindrance in understanding their production and propagation. Both the flare reconnection region and the CME-driven shock are viable candidates for SEP production. A combination of the two, as flare-accelerated particles may be further processed by the CME shock, is another likely scenario. Composition is a way to trace the origin of SEPs but measurements at 1 AU are inconclusive because we have limited compositional information in the inner corona and lack sufficient *concurrent* off-limb coronal observations above the erupting site to understand the environment

[2] Patsourakos, S., Vourlidas, A., Kliem, B., 2010, A&A, in print
[3] Mason, G., 2007, Sp. Sci. Rev., 130, 231

through which SEPs accelerate and propagate, such as the seed particle population characteristics and shock geometry. How can we resolve the origin of SEPs? The answer to this question will have profound implications both for basic physics and for space weather predictions.
Any SEP events detected by an L5 spacecraft will tend to propagate along magnetic field lines from a flaring region located on the Earth-viewed disk thus allowing detailed measurements of the photospheric magnetic field and EUV structure. The L5 hard X-ray imager will frequently observe the looptop emission from these sources since many of the flaring regions will be occulted or close to the western limb as seen from L5. The associated CMEs and their shocks will be imaged clearly as limb events. The off-limb UV spectrograph will provide composition, density and temperature measurements of the corona above the flaring site *before and after* the event, the associated CME and its shock, as well as the post-CME current sheet. In-situ measurements at L1 and L5, such as the arrival time of SEPs at different energies and their composition will provide another piece of the puzzle. The relative timing between HXR, and EUV reconnection events, the CME shock parameters, the coronal conditions derived from the spectrograph data and the in-situ measurements, and the application of transport models will bring a new understanding not only on the origin of SEPs but also on their propagation in the heliosphere.

2.1.3 What Is The Connection Of Hard X-Ray Looptop Sources To The CME And Accelerated Particles?

RHESSI observations of looptop HXR sources have shown that these sources are visible whenever the bright emission from the flaring footpoints is occulted[4]. Some hard X-ray sources are located up to 100 arcsec or more above the surface and may contain a surprising number of non-thermal particles[5,6]. How are these particles accelerated and where do they come from? When combined with EUV observations, the HXR sources tend to lie close to the post-CME current sheet. So the HXR source and the post-CME current sheet may be closely related. But how are the HXR sources related to the CME formation? Are they a source of SEPs that may be later reaccelerated by the CME shock? Do the HXR footpoints mark the locations where the particles are accelerated instead?

To answer these questions we need frequent multiple view-angle observations of HXR looptop sources in association with their footpoints and with eruptive events. These are difficult to obtain from Earth as the scarcity of such events reveals. As discussed above, the footpoints of occulted flares, that are best for the detection of looptop sources from an HXR imager at L5, will be visible from Earth. While Earth-based SXR or EUV observations are frequently available, an HXR image at L5 will provide observations from a different view angle to study partially occulted events in combination of on-disk events.

2.1.4 What Are The Origins Of The Solar Wind Detected At L1?

The most obvious contribution of L5 observations is on solar wind studies. Currently, we cannot make a direct connection between the solar wind arriving at Earth and its origins. Upcoming missions such as Solar Orbiter and Solar Probe will focus on the problem of the solar wind origin but both are encounter missions providing measurements only for a few days/orbit through perihelia. An L5-orbiting spacecraft will allow long-term synoptic studies of the heliosphere. Tracking variations in the solar wind with corresponding variations in the solar magnetic and EUV structures at two vantage points will provide insights into the origin of the solar wind.

The solar wind intercepted by Earth including CMEs, CIRs and streamer blobs, is emanating from the western limb as seen from L5. It is therefore easily detectable, with minimal projection effects, by the

[4] Krucker, S., Lin, R. P., 2008, ApJ, 673, 1181
[5] Krucker, S., et al., 2007, ApJ Lett., 671, 193
[6] Krucker, S., et al., 2010, ApJ Lett., 714, 1108

white light coronagraphs, EUV imager and off-limb spectrometer. The evolution of the wind is also easily traced from L5 because the wind remains within the Thomson surface[7] during its propagation to 1 AU.

2.1.5 Where Do Active Regions Come From?

The large-scale solar dynamo is still not understood. Helioseismology with global modes has revealed the existence of the tachocline rotational shear layer at the base of the convection zone and has enabled its radial and latitudinal extent to be quantified[8]. The tachocline is now widely believed to be the seat of the solar dynamo and there is evidence of changes in wave-speed in the tachocline over the solar cycle[9], suggestive of a varying magnetic field there. Various theoretical works suggest that MHD instabilities in the tachocline should give rise to *longitudinal* variations in the region[10]: such longitudinal structures may be the origin of "active longitudes" where active regions preferentially emerge over multiple solar rotations and even over successive solar cycles. Time-distance helioseismology provides a way of mapping the solar interior in three dimensions. To date, however, their application has been restricted essentially to the upper convection zone, mapping bulk flows, magnetic structures, and thermal inhomogeneities there. The reason for the limitation is that to probe down to a given depth in the Sun with these techniques requires that both ends of acoustic rays that penetrate at least to that depth be observable simultaneously: observing the Sun from a single vantage point -- particularly given foreshortening as one observes further away from disk center -- severely limits which rays can be observed to those and means that only the upper convection zone is accessible. With identical magneto-optical filter (MOF) Doppler/magnetographs at both the Earth and the L5 point, time-distance helioseismic analyses using rays that penetrate to the tachocline and even deeper can be observed simultaneously, allowing longitudinal resolution of the region. As the Sun rotates, a full longitudinally-resolved synoptic view of the tachocline will be obtained. The technique can be used to reveal both bulk flows (using travel-time differences for waves traveling in opposite directions along the ray) and wave-speed anomalies (using mean travel times along rays). At typical 5-minute periods, waves corresponding to spherical harmonic degree 40 and smaller penetrate to the tachocline and below. This will provide a resolution in longitude at the tachocline of 10-15º using a 100x100 grid as a baseline for observations.

2.2 *L5 is an Ideal Location for Space Weather Studies*

A satellite located at L5 point will be trailing Earth by 60º and therefore will be able to image an additional 30º of the solar disk invisible from Earth. Since the solar rotation (from 1 AU) is about 13º/day, an L5 satellite will be capable of a 4-5 day warning regarding the emergence, complexity, and eruptive potential of active regions and irradiance variations. An L5 satellite will also provide up-to-date behind-east-limb magnetograms better suited for building background solar wind models that are essential for CME propagation models, and provide additional validation opportunity through the solar wind measurement at L5.

The progressive widening and brightening of a streamer, known as '*streamer swelling*', is a reliable short-term predictor of an eruption as it always precedes a many CMEs by a few hours to a few days (Figure 1). Synoptic coronagraph observations from L5 will provide our first reliable predictions for Earth-directed eruptions because Earth-aligned streamers will be located on the sky-plane as viewed from L5. The swelling rate is roughly inversely proportional to the final CME speed but we need more analysis to make these observations an operational tool. Additional information can come from low corona EUV observations of the rising prominence/cavity. Since these prominences become unstable after a certain height which is dependent on the separation of their footpoints, a simple height-time measurement during the early rise phase of the prominence can be used as a near-term forecasting tool.

---

[7] Vourlidas, A. & Howard, R. A., 2006, ApJ, 642, 1216
[8] Christensen-Dalsgaard, J. & Thompson M. J. 2007 in The Solar Tachocline, D. W. Hughes, R. Rosner & N. O. Weiss (eds), Cambridge Univ. Pr. Cambridge, UK, 2007, p.53
[9] Chou, D. -Y.& Serebryanskiy, A. 2002, ApJ, 578, L157
[10] Cally, P. S., Dikpati, M. & Gilman, P. A. 2003, ApJ, 582, 1190

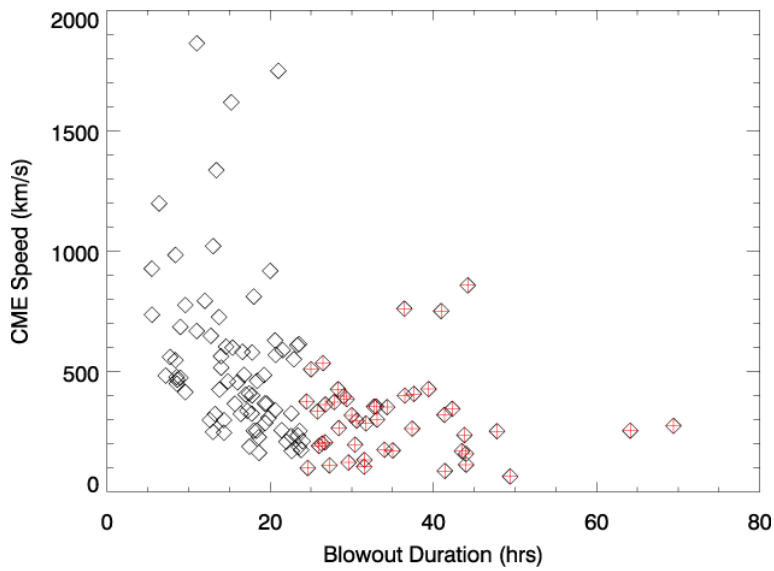

Figure 1 Relation between the duration of streamer swelling and the final speed of the associated CME[11].

After its ejection, the CME can be followed throughout its inner heliospheric path and its trajectory determined as it is currently done with STEREO[12,13,14,15,16]. Again, the L5 location is optimal for such studies because the CME will lie within the Thomson Surface of maximum scattering[7] throughout its travel to Earth. Even if there is no other coronagraph in operation (either at Earth or other 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[17]. The estimates can be adjusted continuously as observations further from the Sun become available and the Earth-arrival predictions can be updated.

In the heliosphere, the L5 satellite will use its in-situ instrumentation to detect recurrent disturbances such as CIRs and measure their geoeffective properties such as whether they are driving a shock, or whether they are accelerating energetic particles. These measurements will characterize the CIR geoeffective potential 3 days before crossing Earth thereby providing a high quality prediction which is unattainable from an L1 observatory. The benefits of an L5 mission to operational space weather are summarized in **Error! Reference source not found.**.

2.3 *Strawman Payload*

To meet the scientific and operational objectives outlined above, and the restrictions on spacecraft resources for a mission to L5, we have compiled a strawman payload in Table 2. We used the STEREO spacecraft as our starting point. It carries about 70 kg of science payload and operates within the X-band constraints (480 kbits/s) from L5. Technological progress will surely result in a more capable instrument payload with lower mass and power resources than STEREO. Already, CMOS imaging detectors developed for the Solar Orbiter and Solar Probe mission require 4x less power than the STEREO CCDs. Newer instrument designs enable us to cover the sun-earth space with 3 telescopes instead of the five telescopes on STEREO.

3 ESTIMATED COST

A mission to L5 is a deep space mission and will involve a large booster, moon and/or Earth flybys and DSN resources. Recent studies have shown that a stable orbit with minimum stationkeeping and fast downlinks (2-3 Mb/s) is achievable[18]. A proper mission study is required to derive a reliable cost. We

[11] Vourlidas, A. et al., 2002 in Solar-Terrestrial Magnetic Activity & Space Environment, Proc. of the COSPAR Coll., H. Wang & R. Xu. (eds), Boston: Pergamon, 2002, p.201
[12] Davis, C. J., et al 2009, GRL, 36, L08102
[13] Byrne, J. P., et al 2010, Nature Comm,, 1, 6, 74
[14] Liu, Y. et al 2010, ApJ, 722, 1762
[15] Lugaz, N. et al 2010, ApJ, 715, 493
[16] Lynch, B. J. et al 2010, JGR, 115, A07106
[17] Sheeley, N.R. et al, 2008, ApJ Lett., 674, L109
[18] Lo, M. Lianos, P., Hintz, G., AAS-AIAA Astrodynamist Specialist Conf, San Diego, 2/2010.

can, however, provide a rough estimate by using the STEREO mission as a basis. We adopt the same spacecraft, telemetry and mission profile. So our constraints are: (1) 620 kg total mass (2) 70 kg instrument mass, (3) 480 kbits/s telemetry over X-band, and (4) a relatively slow journey to L5 using lunar flybys. A slower drifting rate than STEREO's 22.5º/yr would be preferable because it allows more time for 2-point measurements with in-situ instruments hence increasing the science return of the mission. We estimate conservatively ~$240M for the instruments by assuming an average of $30M (FY10 dollars) per instrument (in-situ instruments may cost less but the spectrograph and magnetograph may cost more). Significant savings may be achieved if some imaging instruments (e.g., EUV imager, coronagraph, HI) are part of a suite as they were in STEREO. Since the total cost of the STEREO mission was ~$480M in FY06 dollars, we expect that a single spacecraft mission should cost less than $1B.

4 RELEVANCE TO THE DECADAL SURVEY

As we argued in the Summary, an L5 mission in the next decade is a logical next step for Heliophysics. The mission objectives extend across several of the National Capabilities Working Groups; namely, 'Research to Operations', 'Theory & Modeling', 'Explorers', and 'Innovations'. The mission combines both operational and research objectives and therefore has both societal benefits and advances the state of knowledge for the Sun-Earth system. It is not overlapping with the objectives of any other mission in operation around that time, yet it provides strong synergies with all of them. In this sense, an L5 mission is a cornerstone of the Great Observatory concept. The mission design and payload is of low risk. The STEREO mission has already demonstrated the feasibility and benefits of putting a payload of 620 kg at L5. Technological progress in hardware components (e.g., CMOS detectors, telemetry links) will result in the launch of a much more powerful platform than STEREO with reduced power and mass requirements. Most of the payload systems and components are at TRL 7 and above.

Table 2 Notional Payload for an L5 Mission

Telescope	FOV	Wavelength (Å)	Highlights	Mass (kg)	Power (W)	Telemetry (kbps)
EUV Imager	2 Rs (0° - 0.5°)	171, 195, 304, 284	STEREO Heritage	6	8	50
COR2 Coronagraph	2–15 Rs (0.5° – 4°)	600-700	STEREO Heritage	6	8	40
Heliospheric Imager	15–225 Rs (4° – 64°)	600-700	10x sensitivity over STEREO-HI	5	3	30
Off-limb Spectrograph	Two 3Rs-long slits at 2Rs and 3.5 Rs	500 – 1040	OVI dbl, CIII, Lyβ-γ, ArXII, SiXII, FeX, XIII, XVIII	4.4	4.4	50
Slit/Slot Imager	Full disk	170-210	Imaging spectroscopy 'on the cheap'	15	10	50
Magnetograph	Full disk	Na 5890 K 7700	Magneto-optical Filter	17	20	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 Solar Wind Electrons Energetic Particles Magnetometer	2π 4π 240º	5 º 22.5º	0.05 – 20 keV/q 0.005 – 6 keV/q 0.02 – 100 MeV/nuc	2 4 4 1.25	3.5 6 3.1 2	5