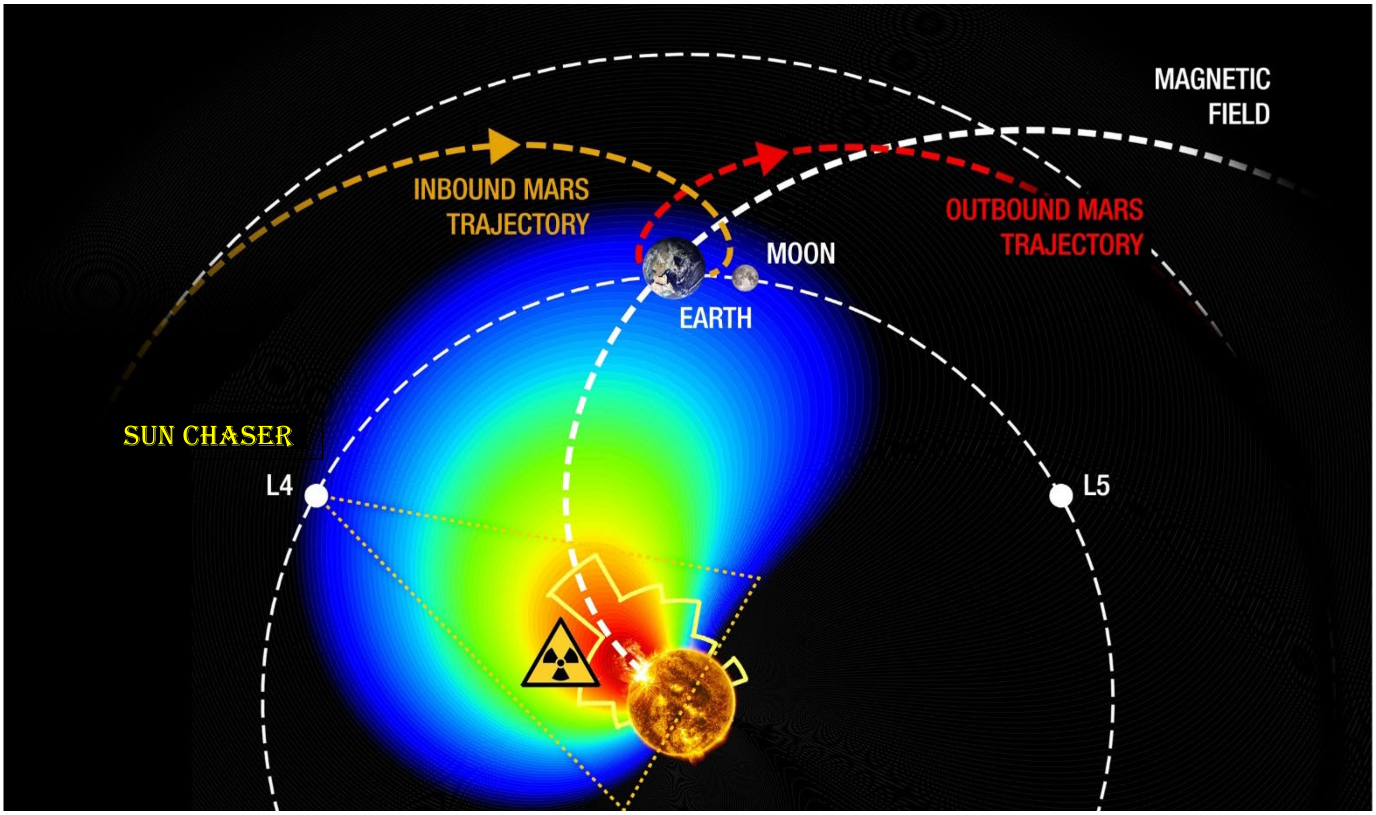

SUN CHASER* - A Mission to the Earth-Sun Lagrangian Point 4

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Placed at L4, *Sun Chaser* is a mission concept that will follow (or chase) high-energy processes around the west limb, combining solar remote sensing & in situ observations, and overseeing the entire solar radiation hemisphere. *Sun Chaser's* remote sensing is essential for ~90% of current physics-based and empirical solar energetic particle (SEP) event forecasting techniques. Without *Sun Chaser*, there cannot be a basis for SEP event all-clear forecasting. It establishes and maintains a space weather (SWx) radiation safe zone that supports all near-term human missions to the Moon and Mars. *Sun Chaser* latitude in-situ coverage also provides a unique opportunity for solar wind-, interplanetary- and interstellar-dust science. In combination with existing and planned observatories at L1 and L5, the three locations provide 240° longitude coverage of resolving photospheric magnetic field structure and safe Earth-directed CME viewing. A ~14°-inclination of both L4 and L5 out of the ecliptic guarantees continuous viewing of both solar poles and continuous in-situ presence on both sides of the heliographic equator, with >3.6° elevation. Extended observations in both longitude and latitude will revolutionize global solar wind modeling and immediate validation, and enables the development of local helioseismology, with potential for long-term solar activity forecasting.

* "The *Sun Chaser* vanished into the west, still searching for the lands beyond the Sunset Sea, and was never seen again. Except…" in "Fire & Blood", The Long Reign, by George R. R. Martin ©2018

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Sun Chaser and Sun Chaser⁺

As a baseline, we describe a two-spacecraft (s/c), single-launch mission, Sun Chaser⁺, 60° ahead (at L4) and behind (at L5) Earth that provide synergistic benefits when injected in an orbital plane that is tilted by ~14° out of the ecliptic. *A descope option is Sun Chaser, a single s/c mission to L4.* Sun Chaser⁺-type concepts have been discussed in detail in *Posner et al.* [2021] and *Bemporad* [2021]. This White Paper synthesizes the science opportunities that Sun Chaser⁺ provides, in terms of fundamental science and SWx research, their rapid transition to potential operational use, and their expected advance of SWx metrics.

Cover Page Figure (Figure 1): The Solar Radiation Hemisphere is the relative solar hemisphere from a 1 AU observer (such as the Earth-Moon system in this case) that has the potential to severely affect its local radiation environment. It spans solar longitudes from 30°E to 150°W relative to the observer and is centered around and fully observable from a location 60° ahead in the observers' orbit (here the Sun-Earth L4 location). The histogram shows the relative source longitudes of maximum solar energetic particle (SEP) 14–24 MeV proton intensity of all three-spacecraft SEP events in the STEREO era as described in *Richardson et al.* [2014]. The relative trajectories of the Earth/Moon system with respect to sample Hohmann transfer orbits to and from Mars, and the Earth/Sun Lagrangian Point 4, the baseline location of Sun Chaser.

Understanding Solar Eruptions – Science of SWx

Much of the underlying physics of SWx is not yet understood. This includes the initiation of flares and coronal mass ejections (CMEs), the acceleration of the solar wind and particles to high energies, and the identification of where particles are accelerated and how they are transported. The difficulty in forecasting solar eruptions is expressed well in the quote from *Schrijver* [2009]: "Flux rope-emergence may lead to major flares within about a quarter of a day". The severity of the impact of SWx is understood to be a function of the relative locations of the SWx source on the Sun, often an active region or filamentary magnetic neutral line, and that of the observer. Sun Chaser⁺ focuses on two aspects of severe SWx: SEPs directed at current human exploration targets and Earth-directed CMEs, the main source of geomagnetic storms.

Sun Chaser: A Critical Investigation for Human Exploration

Extreme SEP events were first observed in ionization effects they create at ground level [*Lange & Forbush,* 1942]. Through 60+ years observed from space, the phenomenon has not been sufficiently understood to reliably predict their occurrence time or intensity, in part due to lack of observations from locations off the Sun-Earth line. The study of longitudinal distribution of three-s/c SEPs in the ecliptic plane by *Richardson et al.* [2014], has been transformational, while confirming that the most severe and rapid rise in intensity occurs when the source of the eruption is at or near W60 from the view of the 1 AU observer, they also pointed out that SEP events originating behind the W limb can be hazardous and need to be taken into consideration. Statistics presented by *Li et al.* [2016] show that nominal magnetic field connection to the Sun are frequently near or beyond 80° W. About ~30% of three-s/c SEPs originate behind the W limb, with their source region and underlying magnetic field obstructed from view. This poses enormous challenges to current efforts of forecasting the occurrence of and absence of (all-clear forecasting) hazardous SEP event conditions for the Earth/Moon system. Table 1, based on *Whitman et al*. [2022], identifies all current SEP forecasting/all-clear techniques by their dependency on remote sensing inputs. The inclusion of the ~30% of SEPs originating from behind the W limb could be readily provided, in near-real-time, by Sun Chaser at L4.

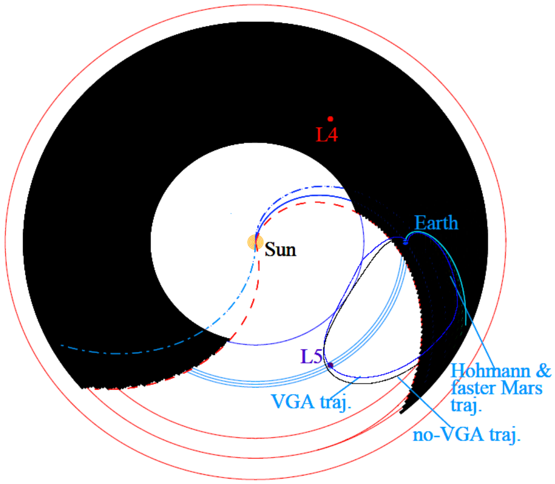
SEP Forecasting or All Clear Forecasting Method	Sun Chaser (L4) Input Needed
FORSPEF[1], MEMPSEP, Sadykov Mod.[2], SAWS-ASPECS[1]	Magnetograms + X-Ray Brightness/Imaging
AMPS[3], EPREM[4], iPath[5], SEPMOD[6], SPREAdFAST[7]	Magnetograms + EUV Imaging
GSU Mod.[8], MAG4[9], MAGPy, M-FLAMPA[10], PARADISE[11], SEPCaster[12], SMARP[13], STAT[14]	Magnetograms
ESPERTA[15], PROTONS[16]	X Ray Brightness/Imaging + Solar Radio
A-G Mod.[17], Boubrahimi Mod.[18], COMESEP[19], Lavasa Mod.[20], PCA[21], PHSVM, South African Mod.[22], SPARX[23], SPRINTS[24], UMASEP[25]	X Ray Brightness/Imaging
AFRP-PPS[26]	X-Ray Brightness/Imaging + Solar Radio + H-Alpha
SEPSTER[27], SEPSTER2D[28]	EUV Imaging
ADEPT[29], REleASE[30], *SOLPENCO[31], SOLPENCO2[31]*	*None*

Table 1: Current SEP forecasting and all-clear models from lists of *Whitman et al.* [2022] and *Posner et al.* [2021]. Of 37 models (left column), 33 would require specific additional observations from L4 (right column) to capture behind-the-limb SEP events. (Note that *SOLPENCO* and *SOLPENCO2* explicitly exclude behind-the-limb events from forecasting.) For Table 1 reference linkages see Reference section.

The addition of Sun Chaser expands for the existing SWx safe zone (Fig. 2, left) to include the Moon (Fig. 2, right), but also the entirety of short-term round-trip trajectories to Mars. Observations of the region behind the solar W limb will become available to drive models and potentially render many of the listed SEP forecasts robust. Thus, over the course of the Decadal Survey period, this new zone would become increasingly safe for human exploration.

Longer-term forecasts depend on understanding and predicting solar activity. Recently, progress has been made in flare forecasting [e.g., *Kusano et al.,* 2020, *Wang et al.,* 2020, *Chen et al.,* 2020; *Kasapis et al.,* 2022], and it is expected that with artificial intelligence and machine learning, patterns leading up to eruptions and flares can be recognized even more reliably. These would be enhanced by Sun Chaser$^+$ remote sensing capabilities (see below). All such methods have in common, when applied to SEP forecasting, that the Solar Radiation Hemisphere is observed continuously, requiring Sun Chaser anchored at Earth/Sun L4.

A significant Sun Chaser benefit would be the expected demonstration of SWx SEP metrics that will improve over time based on the addition of the proposed observations. Improving metrics is a transparent way to justify the investment in Heliophysics new mission capabilities.



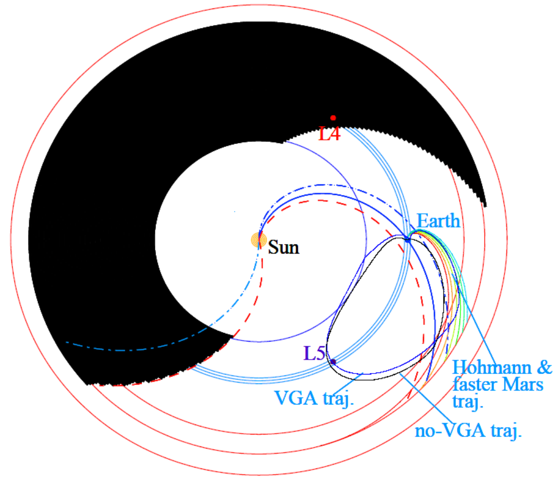


Figure 2: On the left: Current SWx Safe Zone (unshaded area) supported by Sun-remote-sensing from the Earth only. Boundaries are at 15° distance (red dashed lines) from Earth's magnetic horizon (blue dash-dotted lines), the set of field lines expanding into heliosphere originating from the Solar limb, by considering the longitudinal intensity distribution of SEP events [*Richardson et al.*, 2014]. On the right: The addition of Sun Chaser L4 expands the current SWx safe zone to include for the first time human exploration of the Moon and the complete short-term round trip trajectory to Mars [*Hatten et al.,* 2022]. The Sun-Earth line is held fixed. VGA: Venus Gravity Assist.

Sun Chaser$^+$ and Inner Heliospheric Solar Wind Modeling

Earth-directed coronal mass ejections are the source of all major geomagnetic storms. A historically significant space weather event was witnessed by R. Carrington on 1 September 1859. Magnetometer records suggest a very fast, <17h [*Carrington,* 1859; *Cliver & Svalgaard,* 2004] disturbance propagation time from Sun to Earth as compared to the more typical solar wind propagation time. Early ground-based magnetometer readings have been interpreted as equivalent to the disturbance storm time (Dst) index value of ~-850 to -1,760 [*Siscoe et al.,* 2006; *Tsurutani et al*., 2003], which, although contamination by auroral currents may be possible, would so far be unsurpassed in the space age. As a context, geomagnetic storm conditions are considered severe when Dst dips below ~-150. *Riley* [2012] statistically analyzed occurrence rates of space weather parameters including Dst and predicted that the likelihood of occurrence during the next decade of a similar or larger storm would be ~12%.

Space weather forecasting critically depends upon availability of timely and reliable observational data. Extreme space weather creates challenging conditions under which instrumentation and spacecraft may be impeded or in which parameters reach values that are outside the nominal observational range. An assessment of reliability of current and near-future space weather assets found that at least two widely spaced coronagraphs covering the Sun-Earth line, including Sun Chaser at L4, would provide reliability for Earth-bound CMEs [*Posner, Hesse & StCyr*, 2014].

Moreover, it is essential to fully understand the inner heliospheric solar wind. There are several models capable of predicting the background or ambient solar wind. They vary from relatively simple, quick running models such as the Wang-Sheeley-Arge (WSA) model [*Arge et al*., 2004; *Wallace et al.,* 2019] to highly advanced MHD models such as Enlil [*Odstrçil et al.,* 2004, 2005], CORHEL [*Riley et al.,* 2012], MS-FLUKSS [*T. K. Kim et al.,* 2014], Gamera [*Zhang et al.,* 2019], SWMF [*Tóth et al.,* 2012], and EUHFORIA [*Pomoell & Poedts*, 2018]. WSA + Enlil [*Odstrçil et al.,* 2020] is a hybrid model that runs relatively quickly and has been used to make operational forecasts at NOAA since 2011 [*Pizzo et al.*, 2011]. Reliable forecasts of the ambient solar wind are critical for accurately predicting the arrival time of CMEs [*Kilpua et al.,* 2019; *Pizzo et al.,* 2015] or the magnetic connectivity of a spacecraft back to the Sun. There have been numerous validation studies evaluating their reliability and forecast capability [e.g., *MacNeice,* 2009a, 2009b; *MacNeice et al.,* 2011; *Norquist,* 2013; *Norquist & Meeks*, 2010].

Virtually all models use global maps of the Sun's photospheric magnetic field as their primary driver. Historically, these maps have been constructed from magnetograms of the LOS magnetic field that have been converted to radial orientation, where it is assumed the field is radial [*Svalgaard et al.,* 1978; *Y.-M. Wang & Sheeley*, 1992]. More recently, global maps of the radial field are being constructed from vector magnetograms from SOLIS, SDO/HMI [*Schou et al.,* 2012], and soon the PHI instrument [*Solanki et al.*, 2020] on Solar Orbiter [*Müller et al.,* 2020]. However, there are several complexities intrinsic to these maps that often introduce errors into the coronal and solar wind solutions.

So far, constructing global maps of the photospheric magnetic field required acquiring about 27 days of magnetograms and then assembling them into maps, typically by using a weighting function that is sharply peaked at central meridian. Other approaches include constructing maps by taking narrow strips along the central meridians (as seen by the observer) from a series of magnetograms. The resulting maps represent the time history of central meridian-, that is, diachronic maps. But they do not represent what the Sun's field looks like at any given moment in time, that is, synchronic maps, which are the real need. Attempts to produce maps that are more nearly synchronic have been generated using flux transport models [e.g., *Arge et al.,* 2011; *Hickmann et al.,* 2015; *Schrijver & DeRosa*, 2003; *Upton & Hathaway*, 2014]. While these models can generate maps that are more nearly synchronic in nature, they are still rife with problems. They have two critical limitations that have been discussed previously resulting from the lack of global, simultaneous observations: a) flux emergence on the solar far-side and b) large measurement uncertainties near the solar limb. With simultaneous magnetograms from Sun Chaser^{+} (L4 + L5) and Earth, only about a quarter of the Sun's surface magnetic field will lack new observations at any given moment in time, which will greatly reduce the likelihood of missing significant flux emergence and its subsequent adverse impact on SWx model forecasts. Flux transport models will also be able to manage these narrower gap regions much more effectively. Helioseismic holography [*Gizon et al.,* 2018; *Liewer et al.,* 2014; *Lindsey & Braun*, 2000; *Yang*, 2018] and time-distance helioseismology [*Duvall et al*., 1993; *Zhao et al.,* 2019] could be a further interesting application of magnetograph data from Sun Chaser^{+} locations. Both techniques enable the detection and specification of active regions on the far side of the Sun. They can thus be monitored and even inserted into photospheric maps before they enter the field-of-view as seen from L5, which would further improve SWx predictions.

Sun Chaser+ Focused Solar Magnetic Field Investigations

The Sun Chaser+ Observatories in addition to an Earth-based one would enhance the quality, not only the quantity of observations of the photosphere seen over most of the solar disk as viewed from Earth. By combining the LOS components recorded from different vantage points, the magnetic field vector can be determined with higher precision, as the LOS component is usually measured with much greater reliability. Since all three spacecraft will be roughly in the ecliptic, mainly two components of the field can be determined in this manner. Similarly, such "stereoscopic observations" will also allow determining two components of the velocity vector instead of just the LOS component.

Another significant improvement would be the removal of the 180° ambiguity in the direction of the transverse component of the magnetic field vector innate to the Zeeman effect. This ambiguity is a bane for the accurate extrapolation of the magnetic field from the photosphere to the corona. Whereas potential fields only require measurements of the longitudinal component of the magnetic field, the more realistic non-linear force-free fields require the full magnetic vector [e.g., *Wiegelmann et al*., 2014]. The methods currently available for removing the ambiguity all suffer from having to make assumptions about the magnetic field [*Leka et al.,* 2009; *Metcalf et al*., 2006]. By combining observations from L4 and Earth, overcoming this ambiguity will be possible without additional assumptions for a swathe of the solar surface covering roughly 60° in longitude (between the Sun-L4 and the Sun-Earth lines). If an identical magnetograph is also present at L5, then the ambiguity can be overcome over most of the visible disk of the Sun, allowing for greatly improved magnetic field extrapolations into the corona. The method is illustrated in Figure 3.

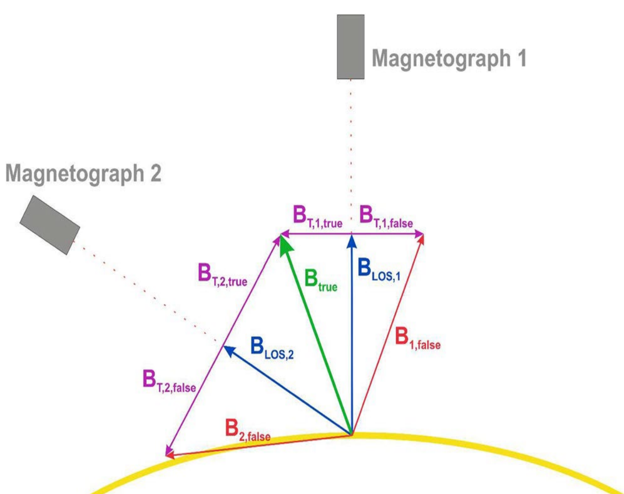


Fig. 3: Illustration of how the 180° ambiguity in magnetic field azimuth can be removed with measurements carried out from two directions. Shown is the solar limb (yellow curve), observed from two locations (magnetographs 1&2). The long. component of the fields as seen from both ($B_{LOS,1}$ and $B_{LOS,2}$) is uniquely determined, but there is an ambiguity in the according azimuthal components ($B_{T,1,true}$, $B_{T,1,false}$ and $B_{T,2,true}$, $B_{T,2,false}$). That is, the Zeeman effect can't distinguish between $B_{T,1/2,true}$ and $B_{T,1/2,false}$ (purple). If the observations from the two vantage points are carried out simultaneously, then only the green arrow (B_{true}) satisfies both constraints.

The lack of knowledge of the coronal magnetic field is a main obstacles towards forecasting solar eruptions. While photospheric magnetograms provide fundamental information about the emergence of new magnetic flux, there is no information about how the overlying corona responds to these changes. Sun Chaser+ will observe coronal magnetic field strength in active regions. Placing a magnetograph at L4 near quadrature with an EUV spectrograph at L5 will facilitate dual diagnostics of the photospheric and coronal fields of an active region simultaneously [*Landi et al.,* 2020]. Sun Chaser^{+}'s diagnostics is optimized for 30W of Earth's central meridian, a critical source location for geomagnetic storms and severe SEPs.

Sun Chaser and Interplanetary Dust:

Zodiacal dust forms the main component of interplanetary dust, and it is ordered by ecliptic latitude, Ulysses [*Wenzel et al.,* 1992] was the only spacecraft that carried a dust detector into high ecliptic latitudes and thus for the first time measured a latitudinal profile of interplanetary dust [*Grün et al*., 1997]. Yet, the three orbits of Ulysses and limited number of particles detected in the inner heliosphere, during its "fast latitude scans" were insufficient to fully characterize the orientation of the disk. Science questions related to the zodiacal dust cloud to be addressed by Sun Chaser are: What is the vertical extent of the zodiacal dust cloud? What is its symmetry plane and what dynamics cause it to be inclined? What amount of β-meteoroids are escaping the system? Is there nanodust to be detected that is related to solar phenomena? Can interplanetary dust particles reside in the L4 point and for how long?

Sun Chaser^{+} Mission Architecture, Mission Design, and Resource Assessment

Since many of the aspects of operating from Sun Chaser's L4 vantage point are equivalent to L5, it is useful to review some of the published studies. *Gopalswamy et al*. [2011a] described an L5 mission design carrying both remote-sensing and in-situ instrumentation. A hybrid propulsion architecture containing both solar electric and chemical propulsion was the most effective solution for the cruise and station-keeping phases of their proposed 900 kg spacecraft. *Strugarek et al*. [2015] proposed a pair of >500 kg spacecraft carrying both types of instrumentation. A single launch would put both in heliocentric drift orbits, but they did not specify what propulsion system would provide the necessary delta-V such that one leads Earth by 34 degrees and the other lags Earth by the same amount. The STEREO mission [*Kaiser et al*., 2008] provides a useful comms baseline for the desired payload composition including continuous low latency beacon data as well as daily downloads of full-resolution telemetry from comparable distances [*Driesman et al.,* 2008]. The actual communications rates for the full-resolution telemetry stream as the STEREO spacecraft drifted through L4/L5 were 240-360 kbps using the DSN 34m antennas. Comparable data downlink capability is also found on Parker Solar Probe with conservatively estimated 138 kbps at a spacecraft-Earth distance of 1AU, using a 0.6 m high-gain antenna with a 40 W RF system in Ka-band [*Kinnison et al.,* 2013].

We have examined conceptual mission design criteria for transfer to L4 with the goals of minimizing cruise time to L4; increasing ecliptic inclination in conjunction with and a stable orbit in the L4 region for multiple years. In *Posner et al*. [2021] we examined propulsion requirements to increase the orbital inclination to 14.5° and drift-then-dwell at L4, which required some solar-electric propulsion. We have since updated the analysis for use of recent, more capable LVs and found that they have sufficient C3 to change the orbital inclination initially. Our updated study found that C3 of 52 km^2/s^2 is needed for achieving an orbital inclination of ~14.5° directly (for a single s/c of up to 5,000kg), requiring onboard propulsion to only provide 0.3 km/s delta-V to cancel the heliocentric drift rate. An initial study indicates that, without altering the delta-V requirement for the L4 vehicle, only a small amount of additional mass would be needed as propulsion for the combined vehicles (<2,000kg each) destined for L5.

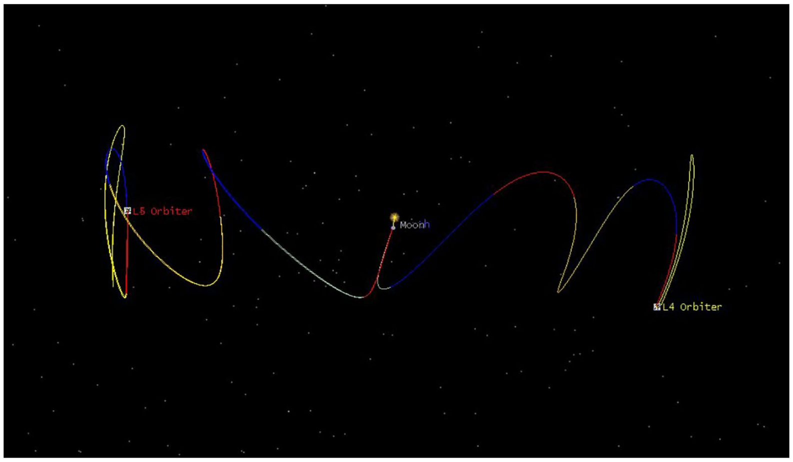


Figure 4: Transfer trajectory shown in solar rotating coordinate frame viewed toward the Sun [Posner et al., 2021]. Initial departure toward south ecliptic pole achieves 10° ecliptic inclination. Updated LVs can inject to 14.5° inclination directly.

The orbits would be phased by choosing launch windows centered around the periods when Earth crosses the heliographic equator to maximize viewing the Sun's poles from Earth, L4, and L5. There are now numerous cost-effective options for launch vehicles that meet the C3 requirements for this conceptual mission. A model payload is shown in Table 2:

Instrument type	**L4/L5**	**Approx. Power**	**Approx. Mass**	**Approx. Telemetry**	**Instr. Heritage**
Coronagraph/Heliosph. Imager	L4	45 W	35 kg	20 kbps	STEREO/ SECCHI[1]
Solar X Rays	L4	8 W	7 kg	0.7 lbps	Solar Orbiter/STIX[2]
Interplanetary Dust (L4)	L4	19 W	8 kg	1.0 kbps	DESTINY/DDA8
Solar EUV Imager (L4)	L4	8 W	10 kg	30 kbps	STEREO/SECCHI[1]
Solar Radio	L4&5	16 W	14 kg	2.2 kbps	STEREO/SWAVES3
SEPs (e-, p+, Heavy Ions)	L4&5	5 W	2 kg	1.0 kbps	MSL/RAD[5]
Sol. Magnetograph	L4&5	40 W	28 kg	54(+) kbps	Solar Orbiter/PHI[6a,b]
Sol. Wind Plasma	L4&5	5 W	10 kg	3.0 kbps	(multiple)[7]
Sol. Wind Magn. Field	L4&5	3 W	3 kg	3.0 kbps	(multiple)[7]
EUV Spectrograph	L5	~60 W	60 kg	~50(+) kbs	Hinode/EIS4
Total L4		**149 W**	**117 kg**	**114.9 kbps**	
Total L5		**129 W**	**117 kg**	**113.2 kbps**	

Table 2: Resource requirements for a sample payload of instruments of the necessary capabilities for Sun Chaser+ (L4+L5) and Sun Chaser (L4 only). Table 2 reference 1-7 linkages see Reference section.

In Summary: Sun Chaser+ is a cost-effective, single-launch, two-s/c mission to Earth-Sun L4 & L5 that will provide simultaneous magetographic and coronal magnetic field observations to advance understanding of solar activity through application of new observational techniques, and to improve understanding of the global solar wind structure in latitude and longitude with immediate *in-situ* validation observations. The descoped L4 Sun Chaser will boost solar energetic particle event forecasting metrics and establish SWx safe zones that enable safe human exploration missions to the Moon and short-term round trips to Mars.

References Table 1:

[1]*Anastasiadis et al*. [2017]; [2]*Sadykov et al*. [2021]; [3]*Tenishev et al*. [2021]; [4]*Schwadron et al*. [2010]; [5]*Hu et al.,* [2017]; [6]*Luhmann et al*. [2007]; [7]*Kozarev et al*. [2017]; [8]*Ji et al*. [2020]; [9]*Falconer et al*. [2011]; [10]*Sokolov et al*. [2004]; [11]*Wijsen* [2020]; [12]*Li et al*. [2021]; [13]*Kasapis* [2022]; [14]*Linker et al*. [2019]; [15]*Laurenza et al*. [2009]; [16]*Balch* [1999]; [17]*Aminalragia-Giamini et al*. [2021]; [18]*Boubrahini et al*. [2017]; [19]*Dierckxsens et al*. [2015]; [20]*Lavasa et al.* [2021]; [21]*Papaioannou et al*. [2018]; [22]*Strauss & Fichtner* [2015]; [23]*Marsh et al*. [2015]; [24]*Engell et al.* [2017]; [25]*Núñez* [2011]; [26]*Smart & Shea* [1979]; [27]*Richardson et al.* [2018]; [28]*Bruno & Richardson* [2021]; [29]*Kahler & Ling* [2017]; [30]*Posner* [2007]; [31]*Aran et al.* [2006]

References Table 2:

[1]*Gopalswamy et al.* [2011], *Howard et al.* [2008]. [2]*Krucker et al.* [2020]. [3]*Bougeret et al*. [2008]. [4]*Culhane et al.* [2007]. [5]*Posner et al*. [2005].[6a]*Staub et al.* [2020], [6b]*Solanki et al*. [2020]. [7]*Gopalswamy et al.* [2011]. [8]*Pers. comm. R. Srama/Univ. Stuttgart*.

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