Open New Horizon with L4 Mission

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Abstract: The Sun-Earth Lagrange point L4 is considered as one of the unique places where the solar activity and heliospheric environment can be observed in a continuous and comprehensive manner. The L4 mission affords a clear and wide-angle view of the Sun-Earth line for the study of the Sun-Earth and Sun-Moon connections from remote-sensing observations. In-situ measurements of the solar radiation, solar wind, and heliospheric magnetic field are critical to monitor and forecast the radiation environment for safe human exploration of the Moon and Mars. The L4 mission will significantly contribute advancing heliophysics science, improving the capability of space weather forecasting, and extending space weather studies far beyond near-Earth space. This white paper outlines the importance of L4 observations and advocates comprehensive and coordinated observations of the heliosphere at multi-points including other planned L1 and L5 missions.

1. Introduction

Solar eruptions cause a huge ejection of magnetized plasma, often including high-energy particles from solar atmosphere into the heliosphere. When they arrive at the Earth, modern technologies are exposed to severe threats such as power outages and communication disruptions. Interestingly, the Cambridge Center for Risk Studies at the University of Cambridge conducted risk studies for the world's 300 major cities and reported that South Korea as a country with a very high risk of damage from solar storms could have economic losses of about $1 billion. Based on the report, the UK's Lloyd's insurer ranked Seoul 7th in its 2014 Worldwide Urban Risk Assessment (Oughton+ 2016).

Solar energetic particles (SEPs) generated by solar activities cause malfunction of electronic components or even severe damage to the electronic circuit in space satellites. If high-energy particles stronger than 10MeV arrive near the earth, they may pose a radiation hazard to astronauts or aircraft crews on the polar route. The high-energy protons and heavy ions are also considered to be a major threat to human exploration of the Moon and Mars.

The Sun-Earth L4 is the most stable location among five Lagrange points at 1AU and the best place to carry out remote-sensing and in-situ observations that can cover the entire solar radiation hemisphere relevant for Lunar and Mars explorations. According to the technical assessment report for 2020 and 2022 from the NASA engineering and safety center, space weather monitoring assets at L4, L4/ L5, and the Sun-Mars L1 will be of great help in making sufficiently early warnings so that astronauts can have enough time to move a radiation shelter during exploration of the Moon and Mars.

South Korea successfully launched its first lunar orbiter aboard Space X's rocket in the US on August 5, 2022, which marked the first step for Korea to join the deep space exploration. Korea sets a plan to launch the space economy via the Moon landing by using its own launch vehicles in 2031, and expand participation in the Artemis program. The success of this plan will lead to the rapid development of space technology in Korea.

Korea Astronomy and Space science Institute (KASI), which is supported by Korean government, is preparing the development of a heliosphere observatory equipped with remote-sensing and in-situ instruments at L4 with international collaboration. KASI will conduct a feasibility study for the L4 mission from 2023 for three years. This study will review the comprehensive level of domestic payloads, satellites, and launch vehicle, and presents various promising options for international collaboration. Motivated by this planning study, we submit this white paper for the Decadal Survey with outlines of the L4 missions' merits, scientific goals and objectives, and some suggested instruments in the following sections.

2. Advantages of L4 Mission for Solar Physics and Space Weather Operation

Most of the regional warning centers of the International Space Environment Service (ISES) provide space weather warnings, forecasts, and effects based on the NOAA Space Weather Scales which are developed for three event types: radio blackouts (R-scale, solar flare effect), solar radiation storms (S-scale, solar proton effect), geomagnetic storms (G-scale, CME effect). For several decades, the heliophysics science community has investigating to better understand the process of emergence and evolution of solar active regions from the solar interior to the surface, triggering mechanism of solar eruptions and their propagation of magnetic fields and plasma into the heliosphere, and acceleration of solar particles. However, our understanding and forecast capability are still not much improved because of the current vantage point of our remote-sensing and in-situ observations are mostly limited to a single point at the Sun-Earth line. Therefore, persistent monitoring of the Sun and perturbations in the inner Heliosphere based on the multi-view observations from stable points is very essential. Currently, ESA is planning to launch a space weather mission, Vigil, in the middle of 2020s to the Sun-Earth L5. The main purpose of the ESA Vigil (ESA - Vigil) is to monitor the propagation of coronal mass ejections (CMEs) toward the Earth from the side. According to Petsov+ (2020), ESA Vigil data will yield a significant improvement in solar wind models and predictions at the Earth. They, however, noted that the L4 vantage point may beat the L5 at studying the cause and effect of SEP events as well as monitoring source active regions where severe SEP events mostly critical to the Earth are originated from. Note that active regions that are magnetically connected to the Earth along which the accelerated SEP flux will follow cannot be seen from L5.

The scope of space weather research and operation is extending beyond the Earth as human activity expands to the Moon and Mars. According to NASA Engineering and Safety Center (NESC) Technical Assessment Report (Years 2020 and 2022), space weather monitoring assets at L4, L4/L5, and the Sun-Mars L1 will enable us to make sufficiently early warnings for Mars missions during astronaut's travel and stay. Among the events considered in the NOAA Space Weather Scales, solar radiation storms are the most important for the lunar and Mars missions since high-energy particles of more than 10MeV are the major threat to satellites and humans for the lunar and Mars explorations. Extreme SEPs detected from the Earth are not well understood due to a lack of detailed observations of their source regions located mostly at 45°- 60° West and their magnetic connections to the Earth.

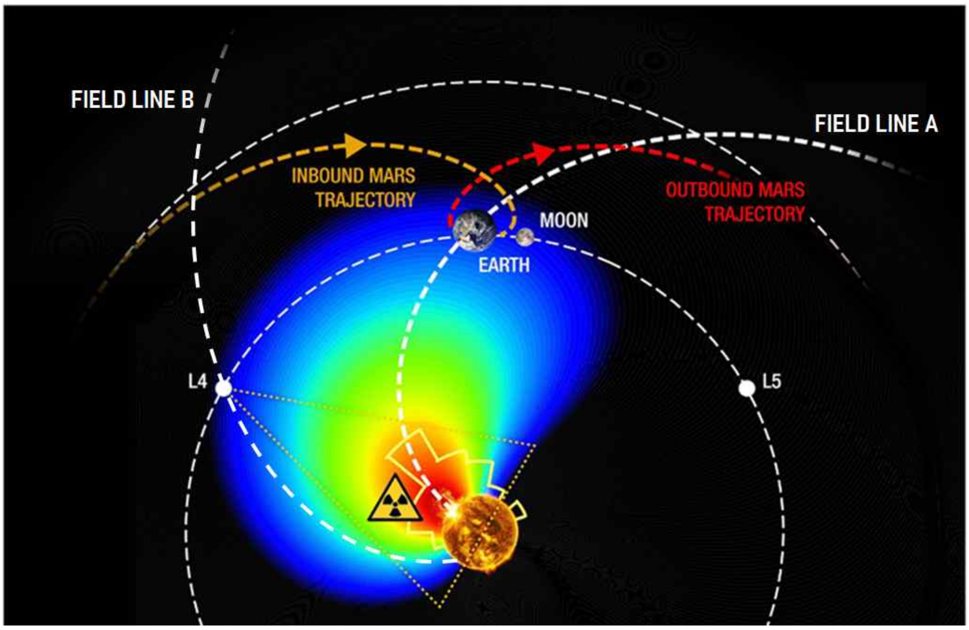

Figure 1. Two representative field lines originated from the Sun: A is connected to the Earth and B is connected to the Sun-Earth L4 point (The figure is modified from Posner+ 2021).

Figure 1 shows two representative magnetic field lines originated from the Sun: The field line A is connected to the Earth and the line B is connected to the L4 point, respectively. As Vourlidas (2015) and Petsov+ (2020) pointed out, L4 is the best place for both observations and forecast of SEP events to protect Moon and Mars explorers from radiation exposure. These SEPs can be sufficiently propagated to the Earth and Mars along with Parker spiral magnetic fields and can impact the Earth and planetary system with rapid flux enhancements. L4 is the best place for observation of SEPs to protect Moon and Mars explorers from radiation exposure.

Along with the currently planned L5 and L1 missions such as ESA Vigil and the NOAA Space Weather Follow On-Lagrange mission (SWFO Instruments | NESDIS (noaa.gov)), we address that the L4 mission has the following advantages and produces synergy for heliophysics science and operational space weather forecasts. First, L4 is favorably located (i.e. at a point 60° ahead of Earth's orbit) to carry out remote-sensing, spectro-polarimetric observations of solar active regions that often produce the geo-effective SEPs. Through the spectro-polarimetric observation of magnetically sensitive lines with multiple points, we can precisely determine magnetic field vectors by removing 180 ° ambiguity in the magnetic field azimuth, which would help accurately infer and study the magnetic field property of SEP-producing solar regions (Figure 2 a). In addition, imaging spectrography of the SEP-producing active region at solar chromospheric or coronal lines will provide important dynamical properties such as plasma speed in terms of Doppler shifts, temperature change or non-thermal turbulent motions in terms of Doppler widths, that could be utilized as some physical precursors to predict any possible eruptions (Seki+ 2017, Seki+ 2021). Spectroscopy of any SEP-producing active regions from the Sun-Earth line is inherently obstructed by the projection effect. If we need to do any continuous monitoring of plasma's thermal and dynamical changes in active regions with the aim of SEP forecasting, L4 will be the most suitable vantage point. Second, it allows continuous observations of both solar poles (with a viewing angle of >~ ±3.6° from the heliographic equator) by launching L4 and L5 into an inclined orbit (~14.5° out of the ecliptic plane) as shown in Figure 2 b. Both poles could be observed continuously, which helps understand the solar dynamo and predict the solar cycle. Third, the determination of the 3-D structure of CME by multiple coronagraphs would be essential for space weather forecasts (Lee+ 2015). The construction of 3D structure from three 2D observations (L1, L4, and L5) would be an interesting topic for further study. Lastly, the L4 mission will provide a unique dataset for validation of inner-heliosphere modeling for space weather prediction as shown in Figure 2 c. Solar wind models in general use synoptic maps of the photospheric magnetic fields as their inner boundary so that the model outputs depend on the accurate implementation of the input boundary magnetic field. Magnetic field detection from a single point such as L1 cannot allow precise measurements of the magnetic field near the solar poles/limbs as well as the far side of the Sun. The coordinated observations from L1, L4, and L5 will provide the most reliable and useful data for the improvement of the solar wind models, thus significantly boosting space weather forecasting capabilities.

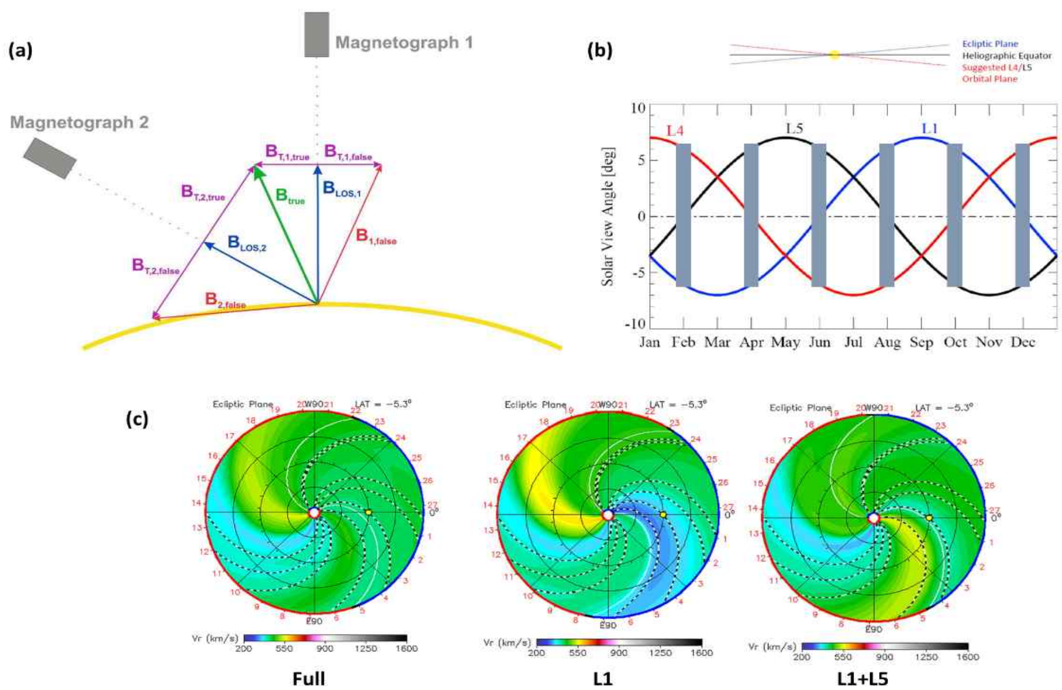

Figure 2. Merits of L4 observation: (a) solve Zeeman ambiguity using magnetograph multi-view observations (Posner+ 2021), (b) continuous observations of both solar poles (Posner+ 2021), (c) validation of inner-heliosphere modeling (Pevtsov+ 2020)

Artificial intelligence (AI) is a key driver of the 4th Industrial Revolution through deep learning and big data. Solar farside magnetograms have been generated by deep learning using the farside EUV observations of Solar Terrestrial Relations Observatory (STEREO) (Kim+ 2019). There has been demonstrated that the AI-generated magnetograms could improve global photospheric field maps and coronal magnetic field extrapolations (Jeong+ 2020). As shown in Figure 3, we can generate real-time basis global magnetic field data to cover the full Sun using the AI-generated magnetograms from the STEREO and magnetograms from the L4, L5, and near Earth observatories in 2030, which is approximate starting time of the L4 mission. The improved global data will be useful as better input conditions for the solar wind and interplanetary magnetic field forecasting, which are one of the major components for space weather. Deep learning approaches can be applied in solar astronomy and space weather: translation between EUV observations (Park+ 2019), denoising magnetograms (Park+ 2020), and super-resolution (Rahman+ 2020). The L4 observations can be translated into other types of observations or improved as high quality data by the deep learning.

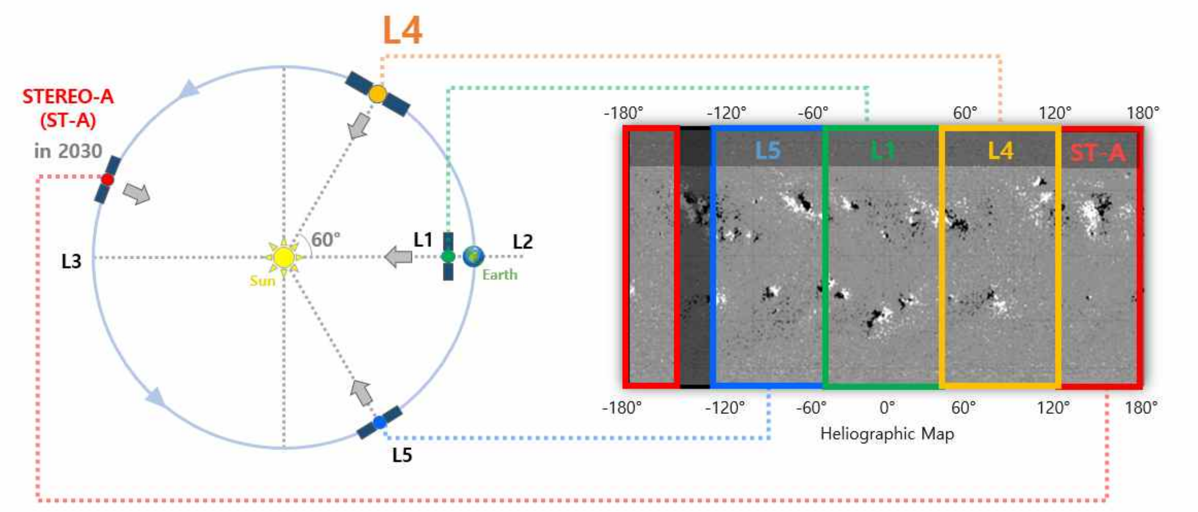

Figure 3. Locations of spacecrafts at Sun-Earth Lagrange points and STEREO-A in 2030 (left). The s coverage on the solar surface from the multi-viewpoint observations (right).

3. Instruments

To maximize the synergy and budget efficiency of the L4 mission, an identical or at least similar set of instruments from L5 (e.g., ESA Vigil) and L1/Earth (e.g. NOAA SWFO) may be recommended. Bemporad+ (2014) suggested a similar suite of instruments on board a twin mission to the L4 and L5 vantage points. This idea has many advantages. For example, the inclusion of a vector magnetic field observed at L4 would be great for magnetic field modeling for space weather forecasting (specifically, the modeling of the heliospheric magnetic field, i.e., the parker spiral, connecting from the western limb or behind the solar front disk to the Earth). This requires spectro-polarimetric observations. One possible option is to adopt optical instruments similar to SDO/HMI which will allow us to reliably carry out the L4 mission because HMI is successfully conducting its mission over the past decade, and the calibration and coordinated/stereoscopic observations would be much easier between the L4 mission and HMI. Other instruments planned by the EAS Vigil mission such as a solar magnetograph, EUV imager, coronagraph, heliospheric imager (HI), solar wind plasma instruments, high-energy particle analyzer, and solar wind magnetic field detector are also considered to be essential for the L4 mission. Including solar imaging spectrograph may maximize the effectiveness and uniqueness of the L4 mission. These unique spectroscopic data and results can be jointly compared with velocity information given by current Solar Orbiter/SPICE and IRIS or future Solar-C_EUVST mission. In addition, high-energy solar particle (electron, proton, and heavy ions) detectors and solar radio instruments would be recommended for SPE monitoring and forecast. Last but not least, we may also include a state-of-art instruments to observe magnetic fields in the chromosphere, corona, and heliosphere by using the Hanle and Faraday effects.

Table 1. Instruments for remote sensing and in-situ observations at L4.

	Instruments	**Approximate weight**	**Remarks**
Remote sensing Observation	Photospheric magnetograph	28 kg	Planned ESA L5 Vigil instruments
	EUV imager	10 kg	
	WL Coronagraph	22 kg	
	Heliospheric Imager (HI)	10 kg	
In-site measurements	Magnetometer	3 kg	
	Solar wind plasma analyzer	10 kg	
Optional	Solar spectro-polarimeter	30 kg 5 kg	Chromospheric or Coronal magnetic field measurements
	High energy particle detector		SEPs (e-, p+, Heavy ions)
Total		118 kg	

4. Mission Design

A rough estimation of the total weight of the instruments is ~ 118 kg as summarized in Table 1. Based on the study of Mission Design Laboratory of NASA Goddard Space Flight Center for Earth-Affecting Solar Causes Observatory (EASCO)-L5 mission, Gopalswamy+ (2011) suggested that a hybrid propulsion system combining the Solar Electric Propulsion (SEP) and monopropellant hydrazine (MH) is the best option for L5 mission. Their estimated transfer time using SEP-MH is ~2 years for a lunch of C3 (Earth-escape energy) ~2.2 km^2/s^2 and a delta-V of ~1.5 km/s. For 10 instruments (7 remote sensing and 3 in-situ detectors) with a total weight of 138 kg, they proposed a spacecraft with a dry mass of ~ 900kg. We can consider the similar weight of spacecraft for the L4 mission. The EASCO mission can be adapted for details of spacecraft design, mechanical assembly, proposition, fight dynamics, power, and launch vehicle. The Deep Space Network (DSN) in US and Yeoju deep space antenna equipped with 34 m and 35 m dishes will be used for a science dump, commend and telemetry, and ranging. For space weather beacon data, a Korean 13-meter Radio Research Agency (RRA) ground station will be used.

5. Summary and International Collaboration

A mission to L4 will advance heliophysics science and significantly improve space weather forecasting capability by providing continuous and unique observations of the heliosphere at the metastable vantage point. Combined with planned L1 and L5 missions, the L4 mission will produce unprecedented synergy for future human exploration of the Moon, Mars, and beyond.

South Korea successfully launched the Korea Pathfinder Lunar Orbiter (KPLO) on August 5, 2022. The 678 kg satellite successfully will reach the target orbit and fuel-saving flight to L1 to put into an orbit around the Moon. KPLO will orbit the Moon for at least a year with its five scientific instruments. According to the mid- and long-term Space Development Plan (SDP), Korea is developing a lunar lander and a rover, joining the NASA ARTEMIS project, and Mars Orbiter. For the lunar lander and Mars orbiter mission, Korean SDP contains the development of a medium-shift launch vehicle with a lift capability of more than 3 tons for the geosynchronous orbit.

NASA contributes to KPLO not only by providing technical assistance on mission design, deep space communications, and navigation technology, but also by selecting nine scientists to join KPLO's science team to help enhance the mission's science output. It is also expected that the cooperation between the two counties will be tighter by the recently signed Artemis Accords on May 24, 2021.

KASI recently started a planning study for the L4 mission. The main goal of this study is to submit the L4 mission as a part of the Korea SDP. Through this study, KASI will review the comprehensive technical level of instruments, spacecraft, and launch vehicles in Korea and suggest a participation level of an international collaboration for the L4 mission.

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