Heliophysics and Space Weather Science at ~1.5 AU: Knowledge Gaps and Need for Solar and Solar Wind Monitors at Mars

A White Paper submitted to the Decadal Survey for Solar and Space Physics 2024-2033

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Synopsis

This White Paper discusses knowledge gaps and open questions about the solar and interplanetary drivers of the space weather conditions experienced at Mars during active and quiescent solar periods, and the need for continuous, routine observations to address them. For both advancing science and as part of the strategic planning for human exploration at Mars by the late-2030s, now is the time to consider a network of upstream solar and solar wind monitors at Mars.

Our recommendations to the Decadal Survey Committee for Solar & Space Physics (Heliophysics) 2024-2033 are:

1) Continue support of planetary science payloads and missions that provide measurements at Mars for advancing heliophysics and space weather science.
2) Prioritize an upstream Mars L1 monitor and/or areostationary orbiters for providing dedicated, continuous solar and solar wind observations at ~1.5 AU.
3) Establish new or support existing joint efforts between federal agencies and their divisions, in collaborations with foreign agencies, to carry out [1] and [2].

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CURRENT STATUS

Both critical infrastructure and human explorers, either in orbit or on the surface, are vulnerable to ill effects from space weather hazards. Based on decades worth of routine and detailed observations at Earth, we have an increasingly comprehensive understanding of how solar activity and the local interplanetary conditions impact the geospace environment. In contrast to Earth, Mars is weakly shielded by its "hybrid magnetosphere" with both induced and intrinsic magnetospheric features resulting from the planet's tenuous atmosphere and inhomogeneous crustal magnetic fields [DiBraccio et al. 2018]. Thus, the space weather impacts and effects on human explorers and supporting infrastructure (communications, power systems, habitat, etc.), both in orbit around and at the surface of Mars, will be different from the terrestrial experience in many aspects.

During the last two solar cycles, observations from orbit and from the ground by Mars Global Surveyor (MGS), Mars Odyssey (ODY), Mars Express (MEX), Mars Science Laboratory (MSL), Mars Atmosphere and Volatile Evolution (MAVEN), InSight, etc. have indicated that Mars can be significantly affected by solar activity [e.g., Crider et al. 2005; Zeitlin et al. 2010; Jakosky et al. 2015; Lee et al. 2018; Sánchez-Cano et al. 2019]. However, the characteristics of the space weather phenomena at Mars' location, as well as the extent of their effects and impacts on the entire Mars system warrant further investigations that require the availability of dedicated, routine space weather observations. Many important questions remain, such as "What are the effects of space weather drivers such as solar flares, coronal mass ejections (CMEs), high speed streams (HSS), stream interaction regions (SIRs), solar energetic particles (SEPs), the heliospheric current sheet (HCS), and the nominal solar wind on the Martian system (magnetosphere, ionosphere, surface)?", and "What are the planetary responses to space weather and how may this impact infrastructure that supports human explorers in orbit and at the surface?"

MOTIVATION

Near-Earth space weather monitors (e.g., ACE, SOHO, SDO, GOES) have been providing a rich data set of observations of the Sun and the influences of its activity on the interplanetary conditions around the geospace environment while also providing real-time 'beacon' information for space weather forecasting. Such observations have been tremendously valuable for the developments of 'Sun-to-mud' models and modeling frameworks for use as scientific research tools (e.g., via NASA/CCMC) and for space weather forecasting (e.g., by NOAA/SWPC).

Our understanding of the interplanetary conditions at Mars heliocentric distances (1.38-1.66 AU; hereafter ~1.5 AU) have relied on Earth-based observations for periods when Mars is in opposition or Parker spiral alignment with Earth that occurs about every two years [e.g., Crider et al. 2005; Thampi et al. 2021; Palmerio et al. 2021, 2022] and on serendipitous space weather measurements by planetary science missions [e.g., Crider et al. 2005; Jakosky et al. 2015; Lee et al. 2018; Delory et al. 2012; Hassler et al. 2014]. While these measurements are able to constrain observation gaps, they provide either low temporal resolution or are indirect measurements of a space weather phenomena at Mars. Furthermore, these Earth-based observations are not reliable when Mars is in superior conjunction (i.e., on the far side of the Sun as seen from Earth). Since late-2014, MAVEN and MEX together have provided some of the most comprehensive sets of observations of the upstream interplanetary conditions at Mars, but due to their precessing, elliptical orbits, the interplanetary conditions are only sampled when their apoapsis segments are located outside the Martian bow shock. Thus, there can be periods from tens of minutes up to many months when upstream conditions are not observed [e.g., Lee et al. 2017, see Fig. 2]. In fact, the solar wind coverage for MAVEN was ~38% in 2014–2019 and ~20% in 2019–2021, and for MEX (without magnetic field measurements) about ~53% in 2014–2021.

A dedicated network of upstream solar and solar wind monitors must be a priority for heliophysics space research over the next decade in order to gain a deeper, more-detailed understanding of the space environment at ~1.5 AU and the Martian response to the varying interplanetary conditions. ***The knowledge gained will not only expand and deepen our scientific understanding of solar and interplanetary drivers that influence the space environment around Mars but will also prepare us for sending humans to Mars by the 2030s***.

KNOWLEDGE AND OBSERVATION GAPS

On interplanetary structures and energetic particles at ~1.5 AU: Detailed studies of interplanetary structures (ICMEs, SIRs, HCS, HSSs), their associated shocks, and energetic particles at Mars orbit have been very limited thus far due to the lack of continuous upstream observations at Mars. **Fundamental research on interplanetary structures and particles at ~1.5 AU is important for deepening our understanding of the solar-heliospheric origins of the interplanetary conditions experienced at Mars while helping to expand our heliophysics science knowledge that have mostly been based on research that utilize observations obtained within 1 AU.** As the solar wind structures propagate, compressions (rarefactions) form as faster streams run into (away from) slower ones emitted earlier (after) along the same radial line. Such dynamic interaction between the fast and slow parcels continue to develop beyond 1 AU and shocks in the SIR compressions become fully formed between 2 and 3 AU [Gosling 1995]. The importance of studying interplanetary structures in the inner heliosphere, which includes Mars, are highlighted in the White Papers by Lugaz et al. (Importance of Fundamental Research on the Upper Coronal and Heliospheric Evolution of Coronal Mass Ejections), Winslow et al. (On the Importance of Investigating ICME Complexity Evolution During Propagation), Palmerio et al. (New Observations Needed to Advance Our Understanding of Coronal Mass Ejections), and Filwett et al. (Importance of Stream Interaction Regions to Space Weather and Energetic Particle Predictions).

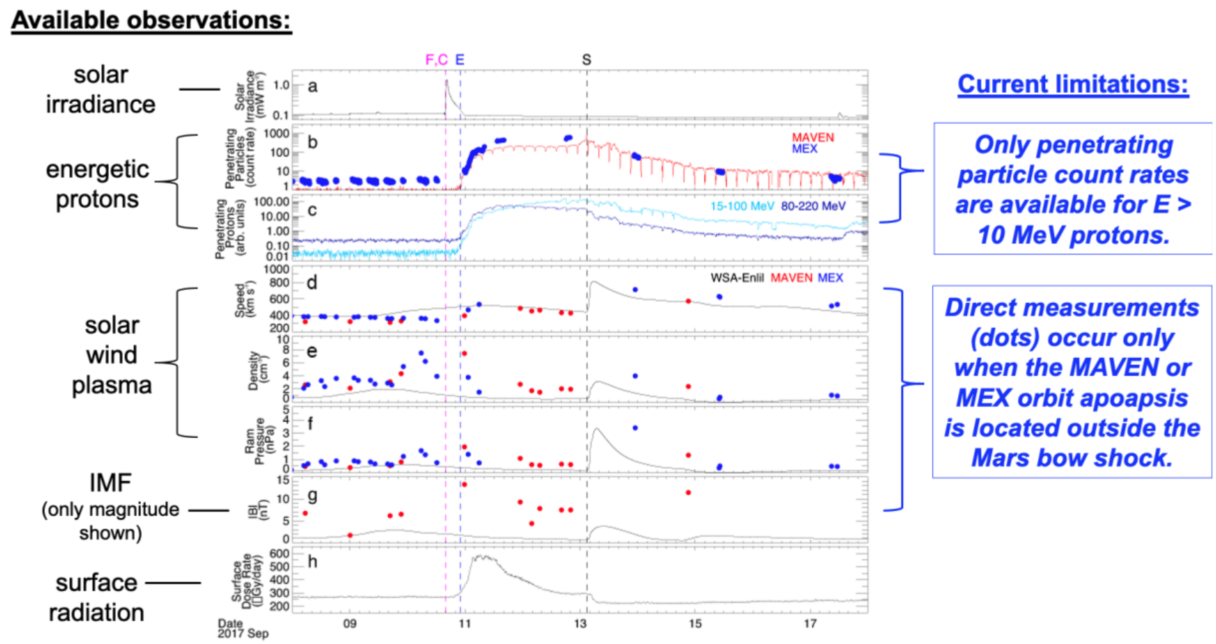

Figure 1. A missed opportunity to study in detail an ICME at Mars due to observation gaps during the September 2017 period. The MAVEN apoapsis location entered the Mars bow shock while the observation coverage was limited for Mars Express (MEX) due to power restrictions.

Researchers have been utilizing planetary science mission data sets to infer information about space weather activity at Mars, such as evidence of an ICME impact via radar sounder measurements that reveals a compressed magnetosphere [Fig. 12a in Palmerio et al. 2021] or ICME shock arrival via detection of energetic storm particles (ESPs) by a SEP detector [Fig. 3b in Lee et al. 2018], or the occurrence of a SEP proton event based on increased background counts of a non-SEP instrument [Delory et al. 2012]. When direct measurements are available—e.g., solar wind moments from MEX and MAVEN; solar irradiance, interplanetary magnetic field (IMF) and SEP measurements from MAVEN; surface radiation by MSL/RAD [Barabash et al. 2007; Hassler et al. 2012; Connerney et al. 2015; Eparvier et al. 2015; Halekas et al. 2015; Larson et al. 2015]—observation gaps in the data and/or lower temporal data resolution have prohibited in-depth studies, such as those who seek to understand the physical differences of a given interplanetary structure observed at 1 AU and at Mars [e.g., Geyer et al. 2021; Palmerio et al. 2022].

Fig. 1 shows an example of a missed opportunity to directly study in detail an ICME structure (shock, sheath, and/or ejecta) at Mars that is associated with the 10 September 2017 solar activity. **Fig. 1d-1g** reveals the sparse solar wind and IMF observations by MAVEN and MEX during the ICME impact. Evidence for the ICME shock (dashed line labeled 'S') was inferred from a signature of ESPs (**Fig. 1b**, spike marked by 'S' dashed line), while evidence for the ICME was inferred from the Forbush-like decrease in the MSL/RAD surface radiation dose rates (**Fig. 1h**). Because of significant gaps in the IMF data (**Fig. 1g**; components not shown), it was not possible to determine which part of the ICME structure impacted Mars. Furthermore, **Fig. 1c** illustrates the limitations of the MAVEN/SEP data for studying acceleration and transport of E > 10 MeV protons out to Mars. No spectral information is available for the 15-100 MeV and 80-220 MeV protons, hence only count rates are shown. Meanwhile, E < 6 MeV proton spectra are available (not shown) but not the pitch angle information due to gaps in the IMF data (**Fig. 1g**).

On solar irradiance variability at ~1.5 AU: The White Paper by Chamberlin et al. (The Next Decade of Solar Ultraviolet Spectral Irradiance – Continuity, Modeling, and Physics) highlights the importance of having direct solar ultraviolet (UV) irradiance observations. At Mars, solar irradiance is modulated by both the solar variations themselves (time scales from seconds to decades) and the variable Sun–Mars distance and is the primary energy source driving the Martian atmosphere. In addition to heating and regulating the thermosphere, solar irradiance also ionizes the constituents to create the ionosphere. Episodic increases of irradiance caused by flares are one of the main space weather drivers. When Mars is far in longitude from Earth, these flares and new active regions cannot be observed from Earth and consequently cannot produce warnings for Mars. During an X-class flare event, for example, the electron densities in the ionosphere can increase up to an order of magnitude at low altitudes [Mendillo et al. 2006] and affect the ability of an orbiting radar to penetrate through the ionosphere to see the surface, while increased thermospheric temperatures [Jain et al. 2018; Thiemann et al. 2018] can impact orbital maneuvers and control.

MAVEN/EUVM has been continuously measuring irradiance at Mars (e.g., **Fig. 1a**) and demonstrating the benefit of direct observations of the solar irradiance input to the Martian system. However, when MAVEN is located behind Mars or when the spacecraft is reoriented for data downlinks to Earth, EUVM is unable to observe any flare activity that occurs on the Mars-facing side of the solar disk. Near continuous monitoring of solar UV irradiance at Mars is critical for understanding the Mars atmospheric dynamics on all timescales, especially when Mars and Earth are on opposite sides of the Sun, rendering Earth-based observations useless.

The following are open questions that are compelling from a fundamental science perspective but are also highly relevant for human exploration and infrastructure at Mars:

- What are the average interplanetary conditions (solar irradiance, solar wind plasma and fields, GCR background radiation) for stronger and weaker solar cycles at ~1.5 AU?
- How efficiently do SIR-related compression regions transition to shocks from 1 AU to ~1.5 AU? Under what conditions can SIRs be more impactful than ICMEs in driving magnetospheric [e.g., Gruesbeck et al. 2017] and ionospheric disturbances?
- What is the nature of the evolution of ICMEs, ICME-driven shocks, and the associated SEPs as they propagate from the Sun out to ~1.5 AU?
- How often are the interplanetary structures at ~1.5 AU a confluence of structure types, e.g., a CME merged behind an SIR (near/not near an HCS), interacting CMEs, etc.? For example, **Fig. 2 (left)** illustrates a modeled CME partially merged behind an SIR at 1 AU which has fully merged by ~1.5 AU in **Fig. 2 (right)**. How do the merged structures affect SEP acceleration, transport, and space weather impacts to Mars?
- What ICME and/or SIR characteristics are responsible for the observed (or unobserved) variability in the surface radiation? Can these also be the cause of observed surface magnetic field fluctuations [e.g., Mittelholz et al. 2021]?
- How much does the background GCR radiation at ~1.5 AU get modulated over time scales of a solar modulation? How much do the different interplanetary structure types (ICMEs, SIRs, or merged CME-SIR structures) play a role in these changes [e.g., Schwadron et al. 2018; Guo et al. 2021]?
- What SEP energy range(s) and with what intensity are most hazardous for instruments and crews in Mars' orbit or at the surface? What precursor observations may serve as warning [e.g., Posner & Strauss 2020]?

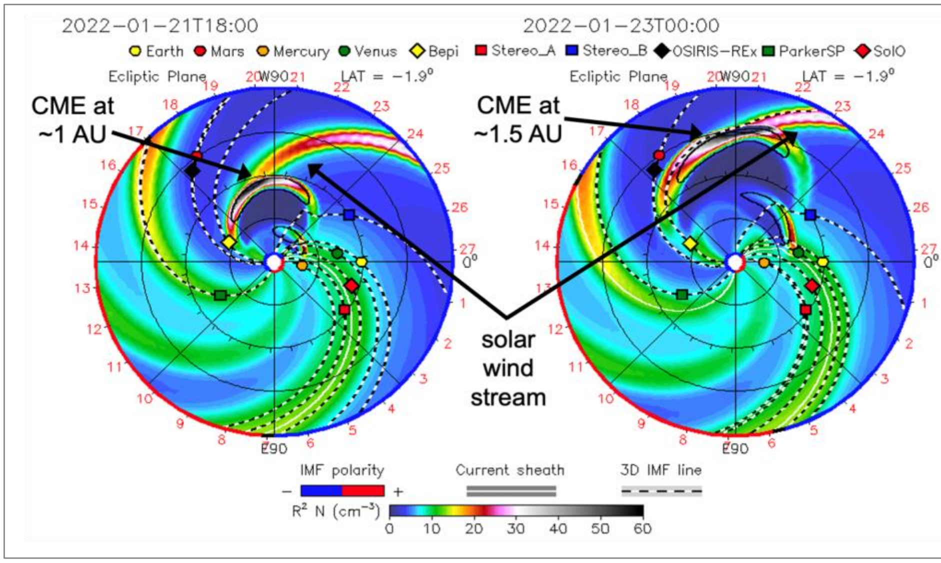

Figure 2. Illustration of a modeled 'cone' CME structure (left) partly merged into a preceding dense solar wind stream at 1 AU and (right) fully merged into the solar wind stream at 1.5 AU. The WSA-ENLIL simulation snapshots of the scaled solar wind densities in the ecliptic plane are courtesy of NASA/CCMC/M2M.

- Which types of SEPs can penetrate deepest into Mars' ionosphere to cause the most extended radar blackouts [e.g., Sánchez-Cano et al. 2019]? For example, during a SEP event, diffuse auroral emissions originating from ~60 km on the nightside have been attributed both to SEP electrons [Schneider et al. 2018] as well as SEP protons [Nakamura et al. 2022], but there are insufficient observations to constrain this. Do the enhanced crustal magnetic field regions at Mars provide some shielding of SEPs at the surface?
- What are the physical changes induced by solar flares in the Martian atmosphere? How will these changes impact technology and assets that are planned for human exploration to Mars?
- What are the space weather implications of near-radial IMF on the hybrid magnetosphere? How often do radial IMF conditions occur? During such conditions, the IMF no longer drapes around Mars to form a magnetic barrier and the solar wind flow can penetrate much deeper into the ionosphere [e.g., Chang et al. 2020].

NEED FOR DEDICATED SPACE WEATHER OBSERVATIONS AT MARS

The planetary and heliophysics divisions of several world-wide space agencies are recognizing the importance and need for having upstream monitoring and observations of the Sun and its influence on the interplanetary conditions at Mars. For example, the NASA Heliophysics Division expanded the Heliophysics System Observatory (HSO) fleet of missions by funding the ESCAPADE mission, which have two spacecraft in elliptical orbits (apoapsis ~8,000 km) to investigate solar wind energy flow into the Mars plasma system to provide simultaneous upstream and downstream measurements, and transitioned MSL/RAD to provide routine, near-real time information (SEPs, dose rate progression) at Mars' surface. Meanwhile, there is an ongoing collaboration between the NASA Moon to Mars (M2M) Space Weather Analysis Office with the MAVEN mission team to develop data products (event catalogs, data sets) that are of relevance to the analysis and validation of predictions of space weather at Mars. Submitted as an invite-only Phase 2 proposal to the ESA Medium-size mission of opportunity, the "Mars Magnetosphere Atmosphere Ionosphere and Space-weather Science" concept has two spacecraft orbiting Mars (apoapsis ~10,000 km) to investigate the dynamic response of the magnetosphere, ionosphere, and thermosphere system to space weather activity [Sánchez-Cano et al. 2022]. For the recent Planetary Science Decadal Survey, NASA HQ explored the Planetary Mission Concept Study

"Mars Orbiters for Surface, Atmosphere, and Ionosphere Connections" [Lillis et al. 2021], which have observing platforms that will measure upstream conditions from altitudes of ~17,000 km.

In the 2023-2032 Planetary Decadal Survey Final Report, there was no clear mention about advancing fundamental research on Mars space weather science for future human exploration at Mars despite the need for these observations. **To address the open science questions of relevance for heliophysics and as part of the strategic planning for human exploration at Mars by the late-2030s, now is the time for upstream monitors at Mars to be prioritized by NASA and other space agencies.** To draw parallels with Earth, from the mid-1980s through the mid-1990s there was no dedicated solar wind and IMF monitor near our planet [see Fig. 1 in Elliot et al. 2012] that could provide short-term forecasts or provide the solar wind and IMF conditions necessary to understand the source and cause of geoeffective events. Having a dedicated monitor at Mars, given the weak shielding by its hybrid magnetosphere and tenuous atmosphere, is therefore even more critical for forecasting the radiation levels at the surface.

Prioritize a Mars L1 monitor: An upstream L1 monitor at Mars **(Fig. 3)** would provide continuous, unobstructed coverage of solar UV irradiance, solar activity, and interplanetary conditions. Measurements obtained from Mars L1 would enable new detailed studies for addressing our open science questions. The beacon data would provide advance warning of extreme Mars-impacting solar events to explorers in orbit and at the surface, especially when considering the lag-times for Earth-based warnings to reach Mars or when direct communication with Earth cannot occur for several weeks due to superior conjunction. For example, a fast CME (v ~1500 km/s) would be detected within ~12 minutes at L1 before impacting the planet, thereby providing the necessary time for safety shutdown of electronic systems and for astronauts to reach the radiation storm shelters. The Mars L1 instrument suite would have high heritage and include an EUV monitor, magnetometer, energetic particle detectors, and solar wind analyzers. A NASA

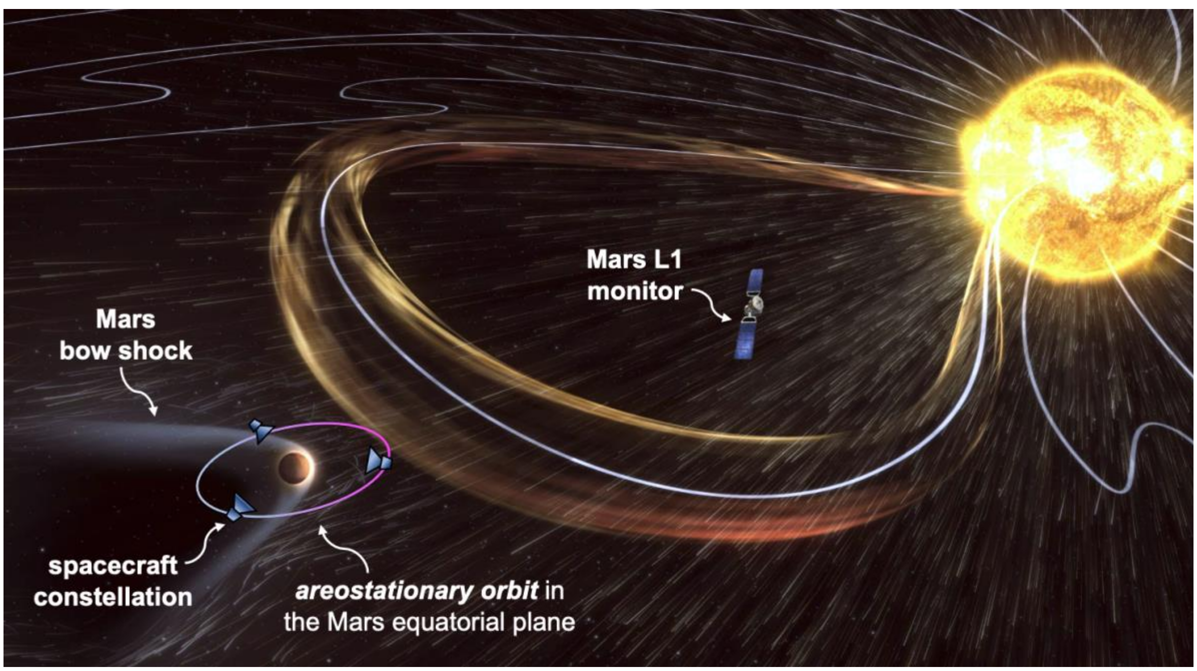

Figure 3. Concept of upstream monitors at Mars L1 and in areostationary orbit (the Mars-equivalent of geostationary orbit) situated in the Mars equatorial plane. Image adapted from NASA/GSFC.

Goddard Space Flight Center Mission Design Lab (MDL) study to design a Mars L1 monitor will take place in early 2023. The findings can be made available to the committee upon completion if requested.

Prioritize areostationary orbiters: The Mars-equivalent of the geostationary orbit is the areostationary (hereafter, areo) orbit. Located at ~17,000 km above the surface, an areo orbiter would spend ~75% of the time outside the Mars bow shock and ~25% in the magnetosheath and magnetotail. A constellation of three areo orbiters separated in longitude by 120◦ and situated in the Mars equatorial plane (**Fig. 3**) would guarantee at least one (but usually two) probe is sampling the upstream conditions while the other two (or one) are observing the conditions inside the Mars plasma system. The orbiters would be equipped with particles, plasma, and fields instruments and could be equipped with visible/infrared weather monitoring sensors and relay antennas to ensure uninterrupted communication with surface assets/outposts and relay data to Earth. (See Montabone et al. [2021] for orbital dynamics, benefits, and applications of an areostationary orbit.)

Mars L1 monitor plus areostationary orbiters: This constellation would provide a coordinated set of observations that are needed to address the observation and knowledge gaps discussed in this White Paper. As part of the HSO spacecraft fleet, the constellation would enable investigations of large-scale variabilities in the interplanetary conditions observed near Mars (see the White Paper by Allen et al., The Future of Heliophysics Research through Targeted use of Constellations, that highlights the importance of constellations together with HSO to address open heliophysics science questions) and would set in place a solar storm warning system that will be critical for protecting human explorers, their technology, and infrastructures at Mars.

CONCLUDING REMARKS

Real-time space weather forecasting at Mars is currently very challenging because, among other factors, it needs a continuous solar and solar wind-monitoring platform to provide timely and accurate space weather information. At the moment, the most available measurements of the Mars-facing Sun and upstream solar wind at Mars occur when Mars and Earth are in apparent opposition or perfectly aligned along the Parker spiral such that Earth-based assets can be used. The challenge arises when both planets are not closely aligned, which happens for ~1.5 Earth years. In those situations, Mars does not have a sufficiently accurate monitor of the Sun and local space environment, therefore the analysis of space weather drivers and effects on the Martian environment can be extremely difficult. Currently, these depend on solar and solar wind observations taken, in the best of the cases, during the reduced periods in which the spacecraft is located in the solar wind [e.g., Lee et al. 2018].

The future of the heliophysics science at Mars requires new upstream solar and solar wind observations at Mars L1 and in areostationary orbit in combination with assets at lower altitudes and those at the surface to understand the effects and impacts of space weather activity. The constellation of coordinated multi-point measurements would not only enable us to better understand the nature of the interplanetary conditions at the variable Mars heliocentric distances—and their impacts on the dynamic Martian system—but these observations would also help us build upon the current space weather modeling and forecasting capabilities in for deep-space conditions. In addition, the mission architecture and development activities for the upstream monitors would foster cross-divisional and cross-agency capabilities, as well as establish new joint international efforts for planetary and human exploration to Mars. With the current efforts to send human explorers to the Moon and within a decade out to Mars, the need is now for upstream solar and solar wind monitors at ~1.5 AU.

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