The Multiview Observatory for Solar Terrestrial Science (MOST)

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Abstract: Understanding the emergence of magnetic flux from the solar interior through the photosphere and its global impact on the inner heliosphere is a key scientific goal of the heliophysics community. This white paper outlines the concept of the Multiview Observatory for Solar Terrestrial Science (MOST) mission, which will make measurements of solar variability from the solar interior, atmosphere, and the interplanetary (IP) medium. MOST will be a 4-spacecraft mission with one each at L4 (MOST1) and L5 (MOST2) and the other two (MOST3 and MOST4) at variable locations along Earth orbit. MOST1 and MOST2 will each carry seven remote-sensing and 3 in-situ instruments. All four spacecraft will carry elements of a novel radio package known as the Faraday Effect Tracker of Coronal and Heliospheric structures (FETCH). FETCH will systematically probe the magnetic content of transient IP structures including coronal mass ejections (CMEs) and stream interaction regions (SIRs). The Faraday rotation measurements will provide magnetic information of these structures at various heliocentric distances from the outer corona to Earth's vicinity. Photospheric and chromospheric magnetograms will cover >70% of the solar surface providing synchronic maps needed for accurately modeling the corona and solar wind. EUV, coronagraph, radio spectrograph, and heliospheric imager (HI) observations from multiple viewpoints provide 3-d information on CMEs/CME-driven shocks, SIRs, and other solar wind structures. The Hard X-ray imagers will provide the flare aspects of solar eruptions to complement the CME aspects. MOST, a 10-year mission, is well aligned with NASA's Heliophysics objectives and will provide an unprecedented opportunity to achieve these objectives with broad participation from the heliophysics community.

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1. Introduction

The Sun is an ordinary star, but it is unique and vital to life on Earth. The magnetic variability of the Sun affects human technology in space and on ground. The Sun is the only star that can be observed in great detail through both remote-sensing and in-situ techniques. Unprecedented advances in heliophysics made possible by great observatories such as the Solar and Heliospheric Observatory (SOHO) and Solar Terrestrial Relations Observatory (STEREO) have demonstrated the need for comprehensive observations that can enable the science of a large swath of the community. These observatories helped us accumulate a wealth of knowledge on the solar and heliospheric structures. However, many fundamental questions remain unanswered: What are the changes that occur in the convection zone before active regions emerge? Why does flux emergence occur predominantly in active regions? How are eruptions initiated in closed magnetic regions? How do solar eruptions result in particle acceleration, alone and in combination with flare reconnection? Where and when do shocks form in the solar atmosphere and how do they evolve in the inner heliosphere? What is the radial profile of shock-driving coronal mass ejections (CMEs)? What is the internal magnetic structure of CMEs that cause magnetic storms? How do CMEs and corotating interaction regions (CIRs) evolve in the inner heliosphere? What are the implications of the interchange reconnection taking place between open and closed field lines? Clearly, many of these questions involve solar magnetic fields at various layers of the solar atmosphere and we do not have sufficient knowledge about them.

Simulations show that with a dramatic improvement in the magnetic observational coverage of the solar surface (including the poles) the solar wind structures can be more accurately modeled (Petrie et al. 2018; Pevtsov et al. 2020). Clear improvements are already achieved when the Sun can be observed from Sun-Earth L1, L4, and L5 providing coverage of over >65% of the solar surface. Wider and longer duration Doppler coverage of the solar surface from Sun-Earth L1, L4 and L5 will provide the necessary signal-to-noise for helioseismic localization of non-axisymmetric changes in the convection zone. In the photosphere, plasma controls the magnetic field, while the control switches to the magnetic field in the chromosphere. Thus, extending the magnetic field measurements to the chromosphere provides information on the magnetic roots of large-scale coronal structures and adds fidelity to coronal/heliospheric models. Currently, we obtain the magnetic flux over only a 60° to 90° wedge observable from the Sun-Earth line, while what is ideally needed is over the entire solar surface. While coronal magnetic field measurement techniques are maturing but largely lacking, substantial progress can still be made with routine photospheric and chromospheric magnetic field measurements. Far away from the Sun, magnetic fields are measured in situ by spacecraft at Sun-Earth L1. Parker Solar Probe and Solar Orbiter provide information on several locations in the inner heliosphere, but not systematically. Faraday rotation (FR) provides a different and unique way to measure magnetic field in large-scale coronal and heliospheric structures by transmitting and receiving spacecraft radio signals through such structures. By suitable frequency and antenna choices, one can probe structures over the Sun-Earth distance. This white paper outlines the concept of a mission called the *Multiview Observatory for Solar Terrestrial Science (MOST)* that will provide comprehensive imagery and time series data needed to understand the magnetic connection between the solar interior and the atmosphere. MOST will build upon the successes of SOHO and STEREO with new views from Sun-Earth L4 and L5 and from the vicinities of those points.

2. MOST Goals and Objectives

The **primary science goal** of MOST is to understand the magnetic coupling of the solar interior to the heliosphere. The **science objectives** of MOST address three major science questions related to solar and heliospheric magnetic fields, solar eruptions, and the solar wind (Table 1).

Table 1. MOST Science Traceability Matrix.

Science Question	**Objectives**	**Measurement Requirements**	**Instrument Requirements**	**Mission Requirements**
1. How do active regions evolve before and after emerging to the solar surface?	1.1 Derive the physical properties of the convection zone helioseismically	Dopplergrams (velocities better than 20 m/s in each 0.5 Mm^2 pixel) from viewing angles separated by 30°-90°	Sun-pointed telescope to obtain full disk images with 1” pixels; 1-min cadence	Identical telescopes on MOST1&2. Telescope at Earth/L1 assumed
	1.2 Determine the complete life cycle of active regions	Photospheric and chromospheric LOS magnetograms from viewing angles separated by 30°-90°	Sun-pointed telescope to obtain full disk images with 1” pixels; 1-min cadence	Identical telescopes on MOST1&2. Telescope at Earth/L1 assumed
	1.3 Determine the global magnetic field distribution on the Sun	LOS magnetograms from viewing angles separated by 30°-90° angles to cover at least 65% of the solar surface	Sun-pointed telescope to obtain full disk images with 1” pixels; 90-min cadence	Identical telescopes on MOST1&2. Telescope at Earth/L1 assumed
2. How do CME flux ropes form, accelerate, drive shocks, and evolve from near the Sun into the heliosphere?	2.1 Track and characterize 3-D CME acceleration and the evolution of the CME-shock complex through the outer corona and young solar wind; determine forces acting on CMEs.	EUV images at multiple wavelengths (17.1-20.5 nm); white light (WL) coronagraph and heliospheric images from spatially separated viewing angles; in-situ plasma and B measurements; remote and local radio waves; FR angle of spacecraft signals from multiple views (uncertainty better than ±8°)	Sun-pointed EUV imager (1” pixels; FOV 0-3 Rs), hard X-ray imager (HXI) (3.5”-90” pixels, FOV $2^o \times 2^o$) and WL coronagraph (15” pixels; FOV 2-15 Rs); Heliospheric imager (2’ pixels; 3^o-65^o; 10 min cadence); radio telescope (0.02 to 20 MHz); radio transceiver (f in 100-200 MHz range); magnetometer; plasma analyzer	Identical set of instruments on MOST1&2. FR package with elements on MOST1&2; additional elements on MOST3&4.
	2.2 Reconstruct and track flux ropes and flare	Multiview LOS magnetogram, EUV, HXI, WL coronagraph, HI,	Same as above	Same as above

	structure from eruption data	and FR properties of spacecraft signals		
3. How do CIR magnetic fields evolve in the inner heliosphere and accelerate particles?	3.1 Track longitudinal evolution of CIRs from L5 to Earth to L4	In-situ plasma and magnetic field (B) measurements at L4 and L5; multiview heliospheric images and FR angle of spacecraft signals along multiple ray paths	Heliospheric imager (2' pixels; 3° - 65°; 10 min cadence); radio transceiver (f in 100-200 MHz range); magnetometer; plasma analyzer	Heliospheric imagers on MOST1&2. FR package with elements on MOST1&2; additional elements on MOST3&4
	3.2 Determine role of interchange reconnection between active region and coronal hole in providing seed particles to CIR accelerator	LOS magnetogram for active region B, EUV coronal hole properties, HI, Faraday rotation angle of spacecraft signals, remote and local radio waves; energetic particle detector	Sun-pointed magnetograph (1" pixels; 1-min cadence) and EUV imager (1" pixels; FOV 0-3 Rs); Heliospheric imager; radio telescope; radio transceiver	Magnetograph, EUV, Heliospheric imager, and EPD on MOST1&2. FR package on MOST1, 2, 3 & 4

3. Mission Overview

MOST will include all essential instrumentation on four spacecraft named MOST1, MOST2, MOST3, and MOST4 located in Earth orbit. MOST1 and MOST2 will be located at the relatively stable Lagrange points L4 and L5, respectively (Figure 1). MOST1&2 will each carry seven remote-sensing and three in-situ instruments. MOST3&4 will carry just the Faraday rotation radio package. MOST will generate the following science data products: magnetograms, Dopplergrams, EUV images, hard X-ray images, coronagraph images, heliospheric images, radio dynamic spectra and time series, Faraday rotation time series, time series of solar wind plasma parameters, solar wind magnetic field vectors, and solar energetic particle intensity and spectra.

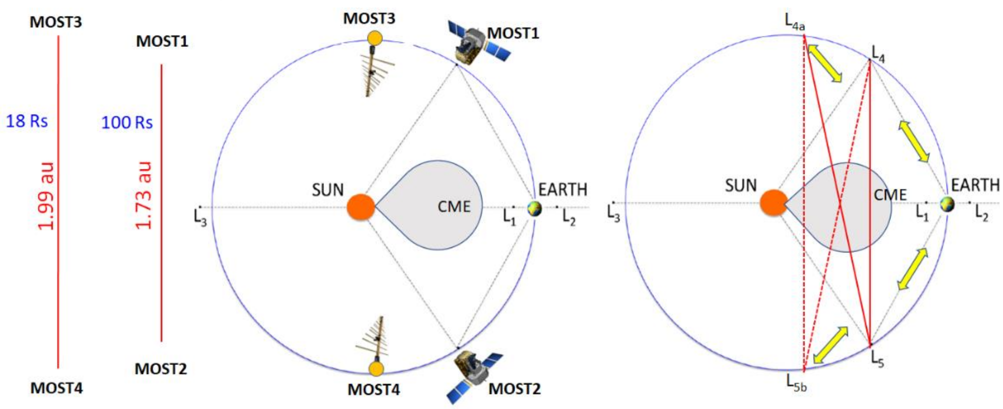

Figure 1. Overview of the MOST mission with the four constituent spacecraft at L4 (MOST1), L5 (MOST2), ahead of L4 (L4a, MOST3) and behind L5 (L5b, MOST4). MOST1&2 will have identical remote-sensing and in-situ instrument suites. MOST3&4 will carry only radio equipment for Faraday rotation measurements. The approximate MOST1-MOST2 an MOST3-MOST4 distances are shown at the left indicating the long signal paths for spacecraft radio signals. The red lines in the right indicate FETCH signal paths. The yellow double arrows indicate communication links.

The seven remote-sensing and three in-situ instruments to be carried by each of MOST1&2 are listed in Table 2. Additional details on the instruments are given in Table 3. The instruments are optimized to obtain maximum information on the Sun-heliospheric system in accordance with the science traceability matrix given in Table 1.

Table 2. Science instruments and their purpose

Instrument, Heritage, and Improvements	**Purpose**
Magnetic and Doppler Imagers (MaDI), ***SOHO, Solar Orbiter, SDO*** New: Routine chromospheric magnetograms	To study surface (photosphere, chromosphere) and subsurface magnetism by combining magnetic and Doppler measurements. Also routinely obtain chromospheric magnetograms
Inner Coronal Imager in EUV (ICIE) ***SWAP, SUVI*** New: Extended FOV to have significant overlap with coronagraph FOV	To study active regions, coronal holes, post-eruption arcades, coronal waves, and coronal dimming by capturing the magnetic connection between the photosphere and the corona
Hard X-ray Imager (HXI), ***Solar Orbiter***	To image thermal and non-thermal component of flares and study the relationship with radio bursts and CME flux ropes
White-light Coronagraph (WCOR) ***STEREO, BITSE*** New: Polarization detector, two-stage optics	To track quiescent and transient coronal structures seamlessly from ICIE FOV and connect to the heliospheric imager FOV
Heliospheric Imager with Polarization (HIP), ***STEREO*** New: Polarization capability	To track solar features into the heliosphere, their impact on Earth, provide line-of-sight electron column densities for FETCH analysis
Faraday Effect Tracker of Coronal and Heliospheric structures (FETCH) New instrument	To determine the magnetic field structure and evolution of solar wind structures in the Sun-Earth connected space
Radio and Plasma Wave instrument for MOST (M/WAVES), ***STEREO*** New: Improved antennas to minimize dust impact	To track shocks and electron beams from Sun to 1 au, determine the source region configuration of type III storms and the implications of seeds particles accelerated at the storm source
Solar Wind Plasma Instrument (SWPI) ***Rosetta, SWFO-L1*** New: CME speeds up to 2500 km/s	To infer solar magnetic structures at 1 au and CIR evolution
Solar Wind Magnetometer (MAG) ***Parker Solar Probe***	To infer solar magnetic structures at 1 au, CIR evolution
Solar High-energy Ion Velocity Analyzer (SHIVA) ***CeREs, CUSP CubeSats, Van Allen Probes*** New: Proton energy channels up to 500 MeV	To determine spectra of electrons, and ions from H to Fe at multiple spatial locations and use energetic particles as tracers of magnetic connectivity

The instrument suites provide imagery and time series data to reveal magnetic connectivity across solar and heliospheric domains. Actively probed Faraday rotation studies form a hybrid between in-situ methods, which provide detailed field information at each sampled point, and imaging methods, which provide mostly distributions of material density across space. Data from a combination of MOST instruments are needed for investigations that lead to achieving the science objectives.

Table 3. High-level specifications of the science instruments

Instrument	FOV	Spatial resolution	Temporal Resolution	Mass (kg)	Average Power (W)	Data Rate (kbps)
MaDI	Full disk	2"	90 min	25	35	70
ICIE	0 - 3 Rs	2"	1 min	30	35	48
HXI	Full Disk	7-100"	0.1 -1 s	6.5	8	1
WCOR	2.5 – 15 Rs	30"	1-15 min	20	20	15
HIP	10-220 Rs	2'-4'	20 min	16	20	15
FETCH	18-107 Rs	--	100 s	20	20	2
M/WAVES	2 –215 Rs	--	1 min	13	15	2
SWPI	In situ	--	1 min	5	7.7	16.8
MAG	In situ	--	1 min	1.2	1	2
SHIVA	In situ	--	1 min	4	5.5	30

4. Spacecraft Bus and Payload Accommodation

The spacecraft bus for MOST1&2 with the ten scientific instruments, the high-gain antenna (HGA), the solar panels, and the solar electric propulsion (SEP) assembly are shown in Fig. 2. The S/C bus will be a rectangular composite honeycomb structure, with a 62-inch separation system. The cluster of remote sensing telescopes (MaDI, ICIE, HXI, and WCOR) is placed together on the Sun-facing side of the spacecraft. The HI instrument is mounted on a platform to clear the HGA. The FETCH antenna is mounted on deployed boom. The spacecraft design used for the Earth Affecting Solar Causes Observatory (EASCO) mission (Gopalswamy et al. 2011a,b) has been adapted for MOST.

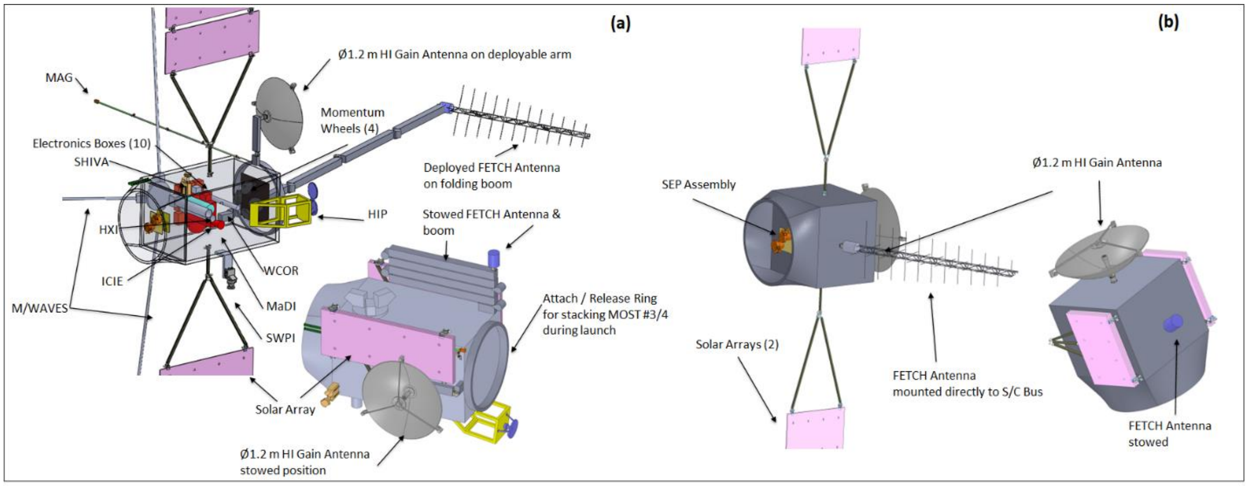

Figure 2. (a) MOST1&2 with the full instrument suite. (b) MOST3&4 with FETCH elements. The solar electric propulsion (SEP) assembly is pointed to in (b).

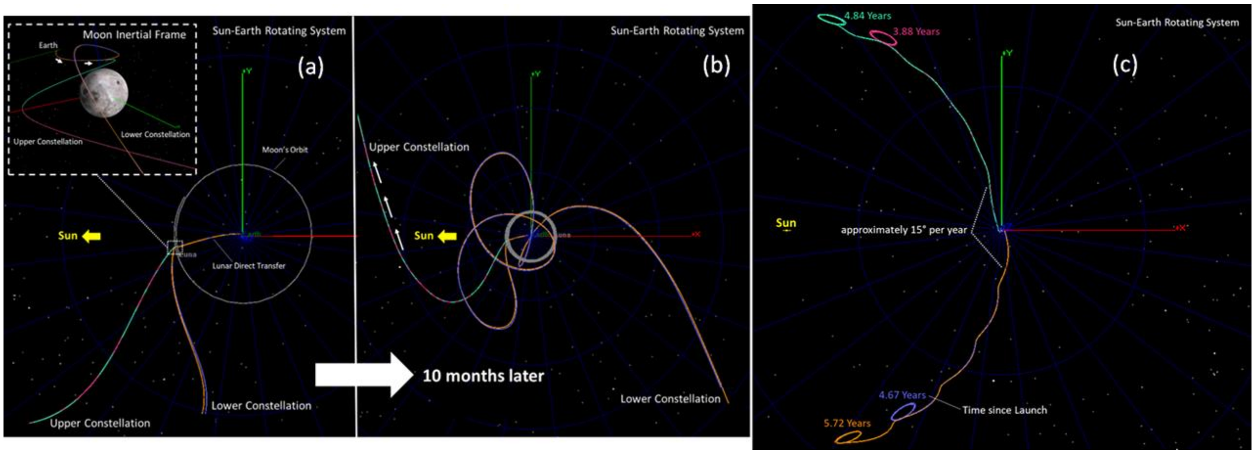

Figure 3. Results of a flight dynamics analysis for a separation angle of 15° per year between the upper and lower constellations. (a) early after launch, (b) 10 months into the mission, and (c) when the initial configuration of all the spacecraft is established. MOST1-4 arrive in their respective locations at 3.88, 4.67, 4.84, and 5.72 years, respectively.

5. Flight Dynamics

From the flight dynamics (FD) point of view, there are four phases to the MOST mission: 1. launch and lunar flyby, 2. transfer phase toward the desired locations (L4, L4a) and (L5, L5b), 3. dwell phase when all spacecraft are in place for a steady one year of observations, and 4. drift phase when MOST3&4 drift toward Earth and, at mission's end, each of the two spacecraft occupies the original position of the other. In phase 1, two initial conditions were considered, the difference being the arrival times at the final points. The 4 stowed MOST spacecraft are mounted in a Vulcan dual manifest fairing in two groups, each composed of one MOST3,4 mounted on top of one MOST1,2. For this study, chemical propulsion was used for the lunar flyby phase. Low thrust should be feasible for this phase as well. In the drift phase, the drift back towards Earth was modeled with an impulsive burn but could be modeled with a low-thrust architecture as well. All four spacecraft are launched together into a direct lunar transfer orbit (5-day transfer period) as illustrated in Fig. 4. MOST1&3 form the upper constellation heading to Sun-Earth L4. MOST2&4 form the lower constellation heading to Sun-Earth L5. Each spacecraft will perform a Trajectory Correction Maneuver (TCM) in order to plan a particular lunar flyby. The flybys place the upper and lower constellations into heliocentric drift-away orbits: towards the L4 point (upper constellation) and toward L5 point (lower constellation). This procedure is similar to how the STEREO spacecraft were placed into their desired heliocentric drift-away orbits. For a drift of 15° per year, the initial configuration is established in 5.72 years. For MOST1-4, the ΔV requirements for the full mission are 464, 494, 522, and 521 m/s, respectively. When the initial configuration is desired to be established a year early, the ΔV requirements nearly double for each spacecraft.

6. MOST Project Life Cycle and Cost Estimate

Figure 4 shows the project life cycle of the MOST mission. During the 10-year phase E and F, the first year will be in the dwell phase and the remaining 9 years will be in the drift phase. Table 4 summarizes the cost, which totals to $906 M. MOST will be a Great Observatory with a cost less than half the cost of the BepiColombo mission. Given the large swath of the heliophysics community that will use the data, the benefit far outweighs the cost.

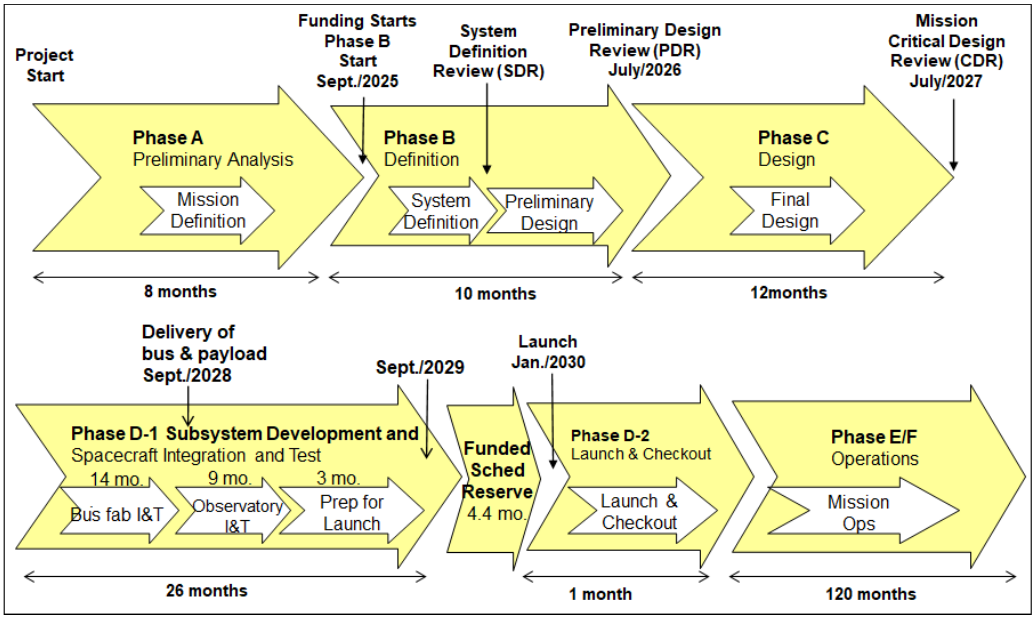

Figure 4. Project life cycle of the MOST mission, showing the extents of various phases and the tasks to be completed.

Table 4. Estimated Mission Cost

Item	**Description**	**Cost (M$)**	**Remark**
Instrument cost	9 instruments × 2, FETCH × 4	128	All but FETCH: EASCO heritage
MOST1&2	2 buses	168	150×1.12, EASCO
MOST3&4	2 buses	84	75×1.12, EASCO
WRAPS	Instruments + S/C	351	380 × 0.925
Total cost	Instruments+S/C+WRAPS	731	If launch provided
Launch vehicle	Vulcan with dual manifest fairing	175	Rough estimate
Total cost	Mission+WRAPS+LV	906	<$1B

7. Summary

MOST is focused on two things: Observing subsurface magnetic flux concentrations ahead of emergence through the photosphere and understanding the global impact of the emerging flux from the inner corona out to 1 au. Such a comprehensive study needs a great observatory with a complete set of instruments. MOST also includes one of the viable instruments for measuring magnetic fields in the inner heliosphere – FETCH, which is a novel concept requiring the analysis of spacecraft-to-spacecraft radio signals (see FETCH white paper, Jensen et al. 2022). MOST will be a large mission benefiting a large swath of the heliophysics community as a significant part of the next generation Heliophysics System Observatory.

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