Multi-spacecraft Heliospheric Mission (MHM)

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Small Explorer (SMEX)-class to Moderate-scale mission

Synopsis: The Multi-spacecraft Heliospheric Mission (MHM) is a versatile mission concept addressing two science goals of 1) determining the variations and variability of solar wind streams, transients, and energetic particles (EPs) in the near-Earth inner heliosphere and 2) advancing our knowledge of how to forecast space weather using *in situ* measurements from sunward of L1. MHM provides the first systematic multi-spacecraft (SC) measurements with three or more SC of solar wind streams, structures, transients, and EPs in the inner heliosphere. MHM fills a clear gap in NASA Heliophysics System Observatory (HSO), identified in the 2003 Decadal Survey and 2021 NASA Space Weather Observation Gap Analysis. In its basic form, MHM could be as simple as a single-SC launched as a rideshare to provide a complementary point to L1 for a mission of opportunity budget. A threshold mission fits within the SMEX call as a multi-SC mission with an in-situ suite resembling that on SWFO-L1 (excluding remote-sensing instruments) and is proposed as Mission to Investigate Interplanetary Streams and Transients (MIIST) for the 2022 Heliophysics SMEX call. A baseline mission is similar to the InterMeso mission concept, highlighted in a separate white paper. Two classes of orbits, distant retrograde orbits and drifters are well adapted to address the science objectives. MHM would also pave the way for future sub-L1 sentinels by reaching space weather objectives on our understanding of forecasting geomagnetic responses using measurements upstream of L1 and east of the Sun-Earth line. As an interplanetary mission that uses an SC bus compatible with ESPA Grande volume and mass restrictions, MHM would strongly benefit from targeted launch opportunities to L1, cislunar space, or small C3 value (C~0-5 km^2/s^2).

1. Concept Description, Science Questions, Rationale and Relevance

The Multi-spacecraft Heliospheric Mission (MHM) is a versatile mission concept addressing two science goals of **1) determining the variations and variability of solar wind streams, transients, and energetic particles (EPs) in the inner heliosphere and 2) advancing our knowledge of how to forecast space weather using *in situ* measurements sunward of L1**. MHM provides the first systematic multi-spacecraft (SC) measurements of solar wind streams, structures, transients, and EPs in the inner heliosphere. MHM fills a clear gap in NASA Heliophysics System Observatory (HSO), identified in the 2003 Decadal Survey and 2021 NASA Space Weather Observation Gap Analysis.

1.1 Science Objectives (SOs) and Space Weather Objectives (SWOs): MHM is designed to reach three fundamental SOs and achieve four SWOs.

(**SO1**) Determine the global configuration of coronal mass ejections (CMEs) near 1AU.

(SO2) Characterize how solar wind streams and stream interaction regions (SIRs) vary in the inner heliosphere.

(SO3) Quantify how particle acceleration at shocks and compression regions depend on local and global conditions.

(**SWO1**) Provide real-time beacon data of the solar wind, EPs, and transients upstream of L1.

(**SWO2**) Provide real-time beacon data of the solar wind, east of the Sun-Earth line.

(**SWO3**) Determine how far away from the Sun-Earth line and how far upstream of L1 future space weather monitors should be placed for optimum forecasting.

(**SWO4**) Investigate how measurements upstream of L1 can be best used to forecast geomagnetic activity.

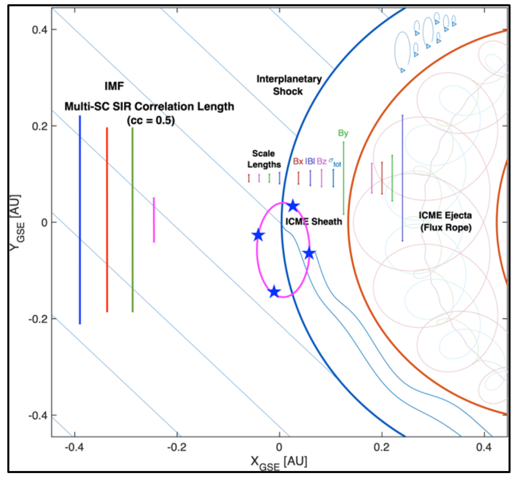


Fig 1: *MHM is the first mission to make systematic measurements near L1 and to explore how the solar wind, transients and SEPs evolve and vary on scales of 1-20° longitudinally and 0.01-0.1 AU radially. Various MHM orbits ensure that most transients impacting Earth are measured by at least three separated SCs. The plot shows the typical shape of a CME with magnetic coherence length (Ala-Lahti et al., 2020) and one MHM potential orbit (magenta oval).*

1.2 Rationale: Solar wind streams, transients, and EPs are the main drivers of our space weather. They are by nature three dimensional (3D) and time-dependent. Our understanding of the properties of CMEs, shocks, EPs, and solar wind streams and their variability within an event have been built primarily on single-point *in situ* measurements obtained from 0.1 AU (PSP) to several 10s of AU (Voyager and New Horizons) with most measurements having occurred between 0.3 AU (Helios, MESSENGER, Solar Orbiter) and 5.4 AU (Ulysses). A few multi-spacecraft measurements have highlighted the limitations of our approach to explore the nature of CMEs, and variability of solar wind streams and EPs. Such ***multi-SC measurements*** are required to investigate and determine the effects of shock and turbulence properties on the local particle acceleration and the 3D configuration and time-dependent nature of solar wind streams and transients. MHM makes measurements for the first time in the region of the near-Earth heliosphere to reach the three science objectives. In addition, one of the main space weather threats is associated with the arrival of interplanetary (IP) shocks at Earth, with potential catastrophic consequences due to the associated geomagnetically induced currents (GICs). Shock properties and accurate arrival time can only be reliably forecasted from *in situ* measurements, and current 15-to-60-minute lead times provided by L1 measurements are often not sufficient for mitigation. Shocks, CMEs, and solar wind streams have never been reliably and consistently measured ***upstream of L1*** to forecast with several hours of lead time their consequence on space assets and the power grid. Sub-L1 or Solar Sentinels have been proposed for more than two decades to improve upon this timing. However, before launching such operational space weather missions, in-depth scientific investigations are required to understand how the solar wind and associated transients evolve during their propagation from the SC to Earth (SWO4) and to determine the optimal mission configuration (SWO3). The MHM constellation has one SC at all times making measurements upstream of L1 and east of the Sun-Earth line to reach the four space weather objectives.

1.3 Relevance to NASA: MHM has the same name and is a very similar concept to the mission ranked as Moderate-4 in the 2003 Decadal Survey. We note that Medium-1 was a concept that became MMS and Medium-5 GDC. In the recent NASA Space Weather Gap Analysis (2021), solar and solar wind observations, including off the Sun-Earth line was ranked as the top priority to fill the critical observational gaps. Within the solar-heliospheric ranking, a "multipoint (grid) in situ particles & fields, upstream of L1 (within 0.9 AU)" was the third-highest priority to improve and was a component of the top priority to advance space weather forecasting or now-casting. The key differences with the mission from the 2003 Decadal Survey are 1) that new knowledge on CMEs, shocks, SIRs, and EPs have revealed that SC separations on intermediate scales (0.02 – 0.2 AU, 1-20°) are required to have meaningful multi-SC measurements, 2) that advances in smallsat technology can make a simplified version of this mission fit within the explorer cost cap.

Table 1: *MHM Threshold Science Traceability Matrix (MIIST)*

SOs/ SWOs	Observation Requirements
SO1: Magnetic Configuration of CMEs	**I-R1** Magnetic field vector ±150 nT @ 2 min
	I-R2 H^+ moments for N ~0.5-80 cm^{-3} @ 2 min **I-R3** H^+ moments for 280< V<1,200 km/s @ 2 min – 10% accuracy for N and T and 5% for **V**
	I-R4 He^{2+} moments for V<860 km/s @ 2 min
	I-R5 e^- moments for V<1,200 km/s @ 2 min
	I-R6 Suprathermal e^- PADs @ 2min
SO2: Stream Interaction Regions	**I-R7** Magnetic field measurements @ 1 s
	I-R8 N-S and E-W H^+ flows within 5°
	I-R1-R2-R3-R4-R5-R6
SO3: Particle acceleration at shocks and SIRs	**I-R9** Ions 50 keV - 5 MeV @ 5 min
	I-R10 Protons 4 keV - 20 keV @ 5 min
	I-R11 Electrons 50 keV - 1 MeV @ 5 min
	I-R12 Electrons 100 eV - 2 keV @ 5 min
	I-R13 Magnetic field from 0.01 to 4 Hz
	I-R1-R2-R3-R4-R5-R6-R7
SWO1-4	All previous requirements (I-R1 to I-R13)

Inst	Instrument Parameters	Instrument Requirements
PESA	Species	Proton and alpha
	Energy Range	0.4 - 20 keV/q at $\Delta E/E = 0.1$
	FOV & Resolution	60° (E-W) x 40° (N-S) w/ 5° x 5° res.
	Dyn. Range	0.5 - 80 cm^{-3} (protons)
	Time Res.	2 min 3D
MAG	Range	±150 nT
	Accuracy	± 0.25 nT
	Time Res.	4 vect/sec (2 Hz Nyquist)
EPD	Energy Range and Resolution	Ions: 50 keV - 5 MeV at $\Delta E/E = 0.5$
		Electrons: 50 keV - 1 MeV at $\Delta E/E = 0.5$
	Flux Range	$10^2 – 3x10^6$ $cm^{-2}/s/sr/eV$
	FOV & Resolution	360° (E-W) w/ 30° res. x ±45° (N-S) w/ 45° res.
	Time Res.	5 min.
EESA	Energy Range	10 eV - 10 keV at $\Delta E/E = 0.4$
	Flux Range	10^4-10^8 ($eV/cm^2/s/sr/eV$)
	FOV & Resolution	360° (E-W) w/ 30°res. x ±90° (N-S) w/ 20° res.
	Dyn. Range	0.5 – 80 cm^{-3}
	Time Res.	2 min 3D

1.4 Measurement Requirements: To reach the SOs and SWOs, MHM must measure the plasma and magnetic field of CMEs, IP shocks, and SIRs for the vast majority of expected conditions near 1 AU. These observation requirements are summarized in Table 1 and can be compared to SWFO-L1 or IMAP *in situ* instrument requirements. With several decades of measurements at L1 and near 1 AU (e.g. see Jian et al., 2018; 2019), the range of parameters for solar wind plasma and magnetic field is well-known, with CMEs and SIRs being the leading cause of extreme values of magnetic field, density (both low and high for CMEs), velocity, non-radial flows, temperature, and dynamic pressure, with the values in I-R1 to I-R8 corresponding to more than 99.9% of the time period measured near L1. Suprathermal electrons with energies in the 100s of eV (I-R6) provide unique information about the magnetic topology of CMEs and heliospheric current sheets (HCSs) and must also be included. MHM must also measure EPs that are associated with local shock acceleration (typically 100s of keV to a few MeV for protons, I-R9) and the upstream conditions necessary to understand their acceleration (I-R10 to I-R13). These measurements are similar to those from SWFO-L1, *Wind*, or from IMAP *in situ* instruments. For large-scale transients, 2-min resolution is enough as it represents ~0.2% of the typical duration of a CME (20 hours) and ~ 0.1% of the typical duration of an SIR (36 hours). To determine shock properties, high-resolution magnetic field data are required (at a cadence of at least 1 measurement per second). ACE and *Wind* have shown how shock properties can be determined accurately by combining high-resolution magnetic field data with lower-resolution plasma data. Table 1 lists the measurement requirements for such a mission and how they map to the instrument requirements.

These are the minimum requirements for a threshold mission. A baseline mission may add additional important observation and instrument requirements, including a) solar wind composition and charge state (adding a Time-Of-Flight –TOF– on the proton electrostatic analyzer –PESA), building for example on the Heavy Ion Sensor –HIS– of Solar Orbiter, a NASA-funded instrument, b) a dedicated suprathermal instrument building on such instruments on ACE, STEREO, IMAP, among others (like CODICE on IMAP), c) a high-energy particle instrument with abundance, to measure protons, Helium and heavier nuclei up to Fe for energies of several 10s of MeV/nucleon, as well as electrons for energies above 1 MeV, and d) a radio and plasma wave instrument, similar to RPW on Solar Orbiter, to measure radio waves as well as local magnetic and electric field. Remote-sensing instruments, such as an X-Ray telescope or a coronagraph may also be added but this would require a 3-axis stabilized platform rather than allowing for a spin-stabilized platform. A spinning platform significantly simplifies the design, cost, and complexity of the plasma instruments removing deflectors and the associated high-voltage power supplies. In addition, remote-sensing instruments typically come with significantly higher telemetry requirements. The trade study of adding remote-sensing instruments is left to a more in-depth study.

Table 2: *MHM Orbit and Mission Requirements*

Orbit Requirement	Mission Requirements
O-R1 1°< Max separation < 20°	**M-R1** adequate power in all planned orientations
O-R2 Within 1° of ecliptic	**M-R2** spin stabilized or rolling
O-R3 Reaches 0.01 – 0.2 AU upstream of L1	**M-R3** roll/spin axis knowledge within 0.5°
	M-R4/5 PESA and EESA unobstructed
O-R4 Reaches > 0.02 AU along Parker spiral	**M-R6** EPD unobstructed FOV - non-Sun pointing
	M-R7 MAG isolated from SC magnetic fields
O-R5 1 SC spends > 20% of time sunward of L1	**M-R8** store and downlink 3kbps of data
	M-R9 take data > 90% of time
O-R6 1 SC spends > 20% of time > 1° east of the Sun-Earth line	**M-R10 Constellation of 2-4 SCs with mission duration of at least 2 years**
DRO* or *drifter, or combination	**M-R11** Provide beacon measurements at >70bps

1.5 Number of SC: The HSO currently provides systematically one SC measurements at L1 (since *Wind*, ACE, or other spacecraft within the Earth-L1 space can be considered as co-located for studies of large-scale transients). Systematic measurements by two SC (L1 + one MHM SC) would enable the testing and validation used for many studies (invariance, static nature, etc.), make progress towards all SOs, and also enable progress on the SWOs if one of the SC reaches upstream of L1 and east of the Sun-Earth line. Measurements by three SC (L1 + two MHM SC) would enable the investigation of the radius of curvature of shocks and the angular width of EP events, but unless the SC are exactly at the same heliocentric distance, the results would combine temporal (evolution) effects with spatial (variation) effects. As such, four SC (L1 + a 3-SC constellation) are required to achieve closure on all SOs and SWOs. Having a constellation of four SC would allow for a longer mission duration with one SC providing redundancy, provide 5-SC measurements (L1 + four MHM SC) and dedicated 4-SC measurements based on MHM instruments only.

1.6 Orbit Requirements Recent work (e.g, see Winslow et al, 2021; Lugaz et al., 2022) have revealed that CMEs are best measured by multi-SC at angular separations of < 20° (~0.35 AU); this also corresponds to the estimate of the magnetic field strength coherence length within CMEs (Owens et al., 2017; Lugaz et al., 2018). Work with STEREO on SIRs (e.g., see Bailey et al., 2020; Allen et al., 2021) have also shown that SIR properties, especially the component of the magnetic field outside the ecliptic plane (B_z), vary significantly for two SC separated by more than 20°. The overall orbit requirements are listed in Table 2. Numerous orbits for a variety of launch configurations and launchers allow us to reach the SOs and SWOs. Two such classes of orbits are 1) Sun-Earth distant retrograde orbits (S-E DROs, see St Cyr et al., 2000), and 2) heliospheric drifters. DROs have the advantage of providing a stable orbit from which a single SC goes upstream of the L1 point and also to the side of the Sun-Earth line but they require ΔV ~300 m/s for final orbit insertion, whereas drifters require less propellant and have been already employed for STEREO. These orbits can be reached with small positive C3 (C3 ~5 km^2/s^2), which can be achieved with lunar or Earth flybys starting from a cislunar or L1 orbit. As described below, the SC can easily be built to fit within ESPA Grande class and could be launched one or two at a time as rideshare, or all at once within a 5-m fairing. **MHM paves the way for any future sub-L1 space weather operational mission** by providing the measurements necessary to investigate how transients evolve in the few hours before impacting Earth and demonstrating how measurements upstream of L1 and east of the Sun-Earth line advance our knowledge of space weather. A beacon mode on the mission provides real-time data for the part of the orbit upstream of L1 that can be fed into existing models to forecast geomagnetically induced currents (GICs), energetic storm particles (ESPs), and effects of IP shocks and CMEs on Earth's magnetosphere and radiation belts.

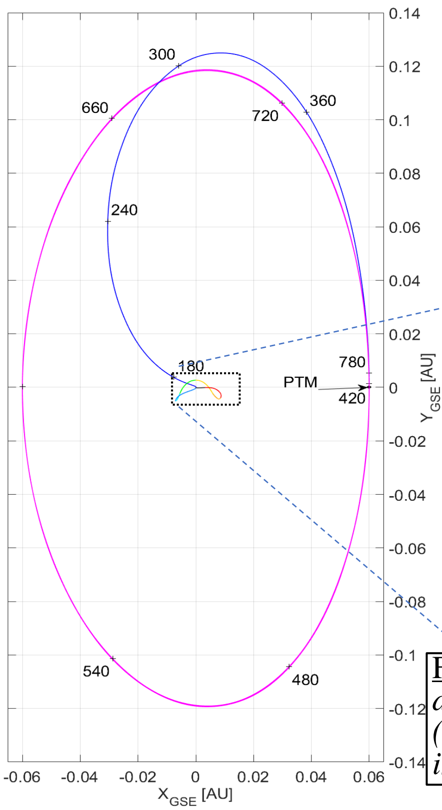
2 Mission Implementation: SMEX-Class Mission (MIIST)

MIIST is being proposed as a 2022 Heliophysics SMEX as one implementation of MHM. It builds upon the heritage of numerous missions for its instrumental suite, mission design, and project management, in particular THEMIS, a 5-SC MIDEX, for mission design, PSP, SWFO-L1, and STEREO for the instrumental suite, and STEREO for the concept of operations. Without remote-sensing instrumentation, each of the MHM SC can be spin-stabilized or slowly rolling (taking advantage of 3-axis stabilized SC buses). For maximum flexibility, each MHM SC should be compatible with ESPA-Grande specifications. This would enable the constellation to be launched as a rideshare with SLS, a primary SC to L1, or possibly to GTO. A dedicated launch to IP space would also be possible and preferred but for maximum launch option, ESPA-compatible SC are preferred. The SC is mostly a standard smallsat with a propulsion system and X- or Ka-band High Gain Antenna (HGA) for primary communication. Expected radiation exposure is fairly benign (15krads behind 100mils, RDM=2). The maximum distance from Earth would be < 0.35 AU (based on O-R1) allowing for relatively simple communication and relatively high data rate.

Table 3: *MHM Orbit Milestones and Characteristics*

Event	L + Days
|Y| > 0.01 AU Reached	**182**
|Y| > 0.1 AU Reached	271
X < 0.99 AU Reached	~330
X < 0.95 AU Reached	**380.7**
Insertion to Final Orbit	421
Orbit Period	358 days
Max. Distance from Ecliptic	<0.001AU
Eclipses	None
% of orbit r < 0.95 AU	
2-SC	58%
4-SC	100%
% of orbit |ΔY| > 11°	
2-SC	53%
4-SC	100%

DRO Maneuvers and ΔV Budget Hereafter, we describe the mission concept for a constellation in a DRO orbit, where each SC reaches 0.05 AU sunward of L1 and 7° east of the Sun-Earth line on a DRO (Table 3 shows the main milestones and characteristics of this orbit). Total SC separation reaches 0.12 AU and 14° for a 2 or 4-SC constellation. This example is meant to highlight how MHM can be launched as a rideshare to L1 (a very similar concept also applies to cislunar launch). Each SC executes a series of ΔV maneuvers to transfer from the initial orbit to the final science orbit (see Fig 2). We have run mission simulations over the range of initial conditions with C3 = -0.68 to -0.48 km^2/s^2 (corresponding to a launch as a rideshare to L1) and for various launch dates (21 days consecutive days); the maximum required ΔV for all maneuvers is 620 m/s. Including finite burn and cosine losses as well as ACS, the maximum required **ΔV < 800 m/s,** or about 37% fuel over dry mass for a green propellant system (41% for hydrazine). A SC with a ***dry mass of ~100 kg and wet mass of 140 kg*** can therefore be considered with chemical propulsion. This enables the launch of 4 SCs on 2 ESPA Grande ports (assuming a 465 kg limit and 25 kg for the separation system, it gives a 50% mass margin) or 2 SC on 2 ESPA ports, if the SC complies with the more stringent ESPA requirements in term of volume. The ΔV requirement would be less for a launch as a rideshare on SLS if specific lunar flybys can be targeted. A launch to GTO would require an electric propulsion system or additional final rocket booster to raise the orbit first to cislunar. For a launch as a rideshare to L1, a series of 6 phasing maneuvers (ETM) burns correct for the initial launch variation and target the DRO transfer burn (DOI) by altering the line of apsides and orbital period, setting up the maneuver of a Hohmann Transfer to DRO. The final maneuver (PTM) completes the transfer into the desired DRO. During the transfer orbit, the SC is put into science mode to maximize science data collection.



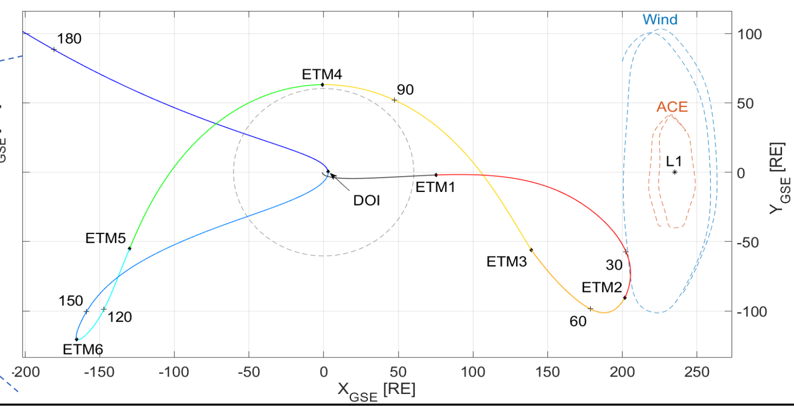


Fig 2: *MHM potential DRO (left) with the transfer orbit (blue) and final orbit (purple) in GSE coordinates centered at Earth (Sun is at x = 1 AU, y = 0). (right) A zoom-in on the maneuvers is shown in right. Days are marked as well as L1 halo orbits.*

Telecom Strategy Each MHM SC generates ~250 Mbit/day (CBE, science and housekeeping), which can be downlinked in an 8-hour DSN passes from the HGA to a 34m station, once every 2-4 weeks, for 1-2 weekly passes depending on the size of the constellation and the exact orbit. For the DRO highlighted above, the downlink rate varies with range to maintain a 3dB link margin. At maximum range, the link can maintain 295kbps. DSN can command at 2kbps to the HGA throughout the mission. During Safe mode when communicating via the low-gain antennas (LGAs), telemetry rates drop to 200bps downlink (1400bps command), at maximum range to (from) a 34m DSN station, adequate to recover sufficiently to get the HGA pointed at Earth.

Beacon Mode A beacon mode is possible via the 10-m class Near-Earth Network (NEN) antennas for rates of 200bps – 5kbps using 5-7W of transmit power for distances up to 0.12 AU (exact beacon rate available depends on the antenna – worst case using 5W transmit from 0.12 AU to a 220K 45 dBi NEN antenna with 3dB of margin). This allows the SC to transmit a beacon mode containing real-time solar wind data and housekeeping when each SC is upstream of L1. A proposed beacon mode and science data allocation is listed in the instrument section.

Power Budget Table 4 lists the power budget including contingencies under the assumption of a 7W radio that requires 35 W in transmit mode and a green propellant system that requires 40 W during 30 min for thruster warming. These are well within the capabilities of most smallsats.

Table 4: *MHM* SC *Power Requirements*	
Science mode	41 W
Telecom mode	68 W
Thrusting	45-71 W
Safe Mode	30 W

Schedule A similar design and development schedule to current SIMPLEX or SMEX projects can be pursued for this mission: 12 months to PDR, KDP-C to launch duration of ≲3 years (9 months to CDR, 10-12 months from CDR to SIR, and 13-16 months from SIR to launch) with the uncertainties depending on rideshare options being considered, launch schedule constraints, and number of SCs. This includes typical schedule reserves of 3.5 months (before SIR, shipping, and integration).

3. Instruments

The MHM payload is composed of simple, well-understood, and high-heritage instruments that provide all required measurements (as detailed in Table 1) of the near-Earth heliosphere for real-time space weather data and to make breakthrough discoveries on the structure and evolution of solar wind streams and transients. Table 5 summarizes the instrument size, mass, telemetry rate, and power requirements. Each of MHM's four instruments per SC meets or exceeds the driving instrument requirements listed in Table 1 to perform the science investigation. To obtain 3-D measurements without deflectors, the particle instruments (PESA, EESA and EPD) require a rotating or spin-stabilized platform (**M-R2,** see Table 2). As the SC slowly rolls, adequate power is provided in all planned orientations (**M-R1**). The instruments' command, telemetry and power all conform to the SC standard interface. EESA and PESA are thermally coupled to the SC.

Table 5: *MHM/MIIST Nominal Payload, with the payload size given in U = (10 cm)^3*

Name	Mass (kg)	Size	Power (W)	Science Data Rate (bps)	Beacon Rate (bps)	TRL	Example Heritage	Requirements
Proton Electrostatic Analyzer (PESA)	~5	~15-20U	~4	~1,200	~20	6-9	SPAN-i, PLASTIC	I-R2-4, 8, 10
Magnetometer w/ boom (MAG)	~3	1-2U + boom	~1.5	~400	~15	6-9	SWFO-L1, Hermes	I-R1, 7, 13
Energetic particle detector (EPD)	~3	4-6 U	~2	~600	~20	6-9	SWFO-L1, Hermes	I-R9, 11
Electron ESA (EESA)	~3	~3U	3	~800	~15	6-9	SPAN-e	I-R5, 6, 12
Total	**~14**		**~11**	**~3,000**	**~70**			**all**

Data Sufficiency During science mode, MHM plasma and particle instruments (PESA, EESA, and EPD) provide 60s and RFGM provides 8 vec/s resolution measurements. The volume of returned data is sufficient to meet the requirements. This drives our requirements to store and downlink 3 kbps of data (**M-R8**). In addition, MHM has a beacon mode which is transmitted when each SC is upstream of L1 and within 0.12 AU from Earth (**M-R11**). A proposed beacon allocation consists of the following, based on STEREO beacon data (Biesecker et al., 2008) but with higher rates throughout:

MAG: magnetic field vector every 5 sec for each sensor (~15 bps).

EPD: ions and electrons at 4 energies over 4 viewing angles from each of the 4 EPD telescopes as well as summed fluxes at 4 energies over all angles every minute (~20 bps).

EESA: electron moments and pitch-angle distributions at 4 energies in 24 look directions every minute (~15 bps).

PESA: Peak counts and position, moments for protons and alpha, suprathermal rate every minute and count rate over 16 energies and 32 (4x8) viewing sectors every 5 minutes (~20 bps). Higher rates are possible and could include higher-cadence data from MAG and higher-resolution data from the other instruments.

4. Cost Estimate

We have performed a bottom-up costing of a single MHM SC and estimated the cost of a multi-SC constellation based on a past multi-SC missions using this single SC costing.
This cost is for the threshold mission described above (excluding more complex instruments). The total budget is shown in Table 6, excluding any reserves. For more than one SC, we made the following assumptions based on UC Berkeley experience with the 5-SC MIDEX program THEMIS: (i) WBS6 is increased by the cost of 1 SC excluding NRE, SC PM and PSE ($8M/SC), (ii) WBS5 is increased by the cost of new FMs for each instrument + 50% due to more work being performed in parallel ($7.5M/SC), (iii) WBS10 is kept as a constant percentage of hardware cost (additional $1.4M/SC), (iv) WBS5 is increased by 25% per additional SC ($1.5M/SC), (v) Other WBS are increased by 10% per additional SC ($2M/SC). This highlights that many of these costs do not change much when identical hardware is added. The WBS1/2/3 total goes from 36% of WBS5/6/10 for 1 SC to ~20% for 4 SC. **The cost with 25% reserves is within the typical SMEX range for a 4-SC mission (148.25 M$), excluding launch cost.**

Table 6: *MHM Nominal Cost (1 SC and multi-SC constellations)- Costs in FY21$*

<table>
<tr><th>WBS/ All costs in FY21 M$</th><th>Phases B-D</th><th>ICE 50% Phases B-D</th><th>Commercial Analog</th><th>Phases E-F</th><th>Total 1 SC</th><th>Cost Per Additional SC</th><th>Total 2 SCs</th><th>Total 4 SCs</th></tr>
<tr><td>WBS1</td><td>5.4</td><td rowspan="4">6.0</td><td rowspan="4">8.3</td><td>0.5</td><td>5.9</td><td rowspan="3">1.1</td><td rowspan="3">12.15</td><td rowspan="3">14.35</td></tr>
<tr><td>WBS2</td><td>3.3</td><td>0.2</td><td>3.5</td></tr>
<tr><td>WBS3</td><td>1.6</td><td>0.05</td><td>1.65</td></tr>
<tr><td>WBS4</td><td>1.4</td><td>4.7</td><td>6.1</td><td>1.5</td><td>7.6</td><td>10.6</td></tr>
<tr><td>WBS5</td><td>18.2</td><td rowspan="2">39.4</td><td rowspan="2">36.9</td><td>0.15</td><td>18.35</td><td>7.5</td><td>25.85</td><td>40.85</td></tr>
<tr><td>WBS6</td><td>9.9</td><td>0.1</td><td>10.0</td><td>8</td><td>18</td><td>34</td></tr>
<tr><td>WBS7</td><td>3.5</td><td rowspan="3">3.4</td><td rowspan="3">6.2</td><td>2.5</td><td>6.0</td><td rowspan="2">0.9</td><td rowspan="2">10.5</td><td rowspan="2">12.3</td></tr>
<tr><td>WBS9</td><td>3.0</td><td>0.6</td><td>3.6</td></tr>
<tr><td>WBS10</td><td>2.3</td><td>0</td><td>2.3</td><td>1.4</td><td>3.7</td><td>6.5</td></tr>
<tr><td>Total</td><td>48.6</td><td>48.8</td><td>51.4</td><td>8.4</td><td>57.4</td><td>16.9</td><td>77.8</td><td>118.6</td></tr>
</table>

Comparison with Independent Cost Estimate (ICE) An ICE was produced by an outside consultancy, Economic Strategies LLC for the 2018 IMAP Science Mission of Opportunity version of this mission concept (named MIMIS at the time), to which there have been some minor modifications. Table 6 compares the Phases B-D of our bottom-up budget to the 50th percentile ICE value. Overall, the 2018 budget excluding reserves was within 0.15% of the median ICE, validating our approach. The cost estimate has been inflated by 1.055 (to FY21$ from FY19$) using NASA inflation table. A commercial/private analog was within 35% of the mass MEL and represents the best available sanity check, also listed in Table 6.
Regarding the additional SC, we note that the 4-SC constellation cost represents 206% of the cost of first SC. It was found that the cost to design and deliver the first of the five THEMIS probes was half of the mission total cost, see Harvey et al. (2008), further validating our approach.

Baseline Mission: The more complete approach, with instruments measuring solar wind and energetic particle composition as well as solar X-rays and electric field (similar to the baseline mission highlighted above), can be found in the mission concept, InterMeso (Allen et al., 2022 and Allen et al.'s WP), for which the cost of a 4-SC mission is within the budget cap of a flagship Moderate-scale mission.

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