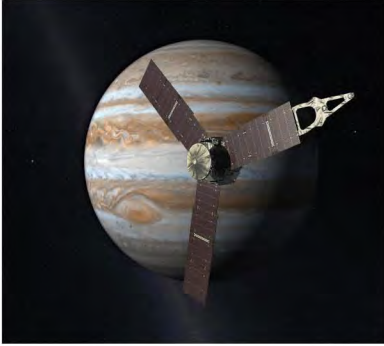




# **2025 Planetary Mission Senior Review**

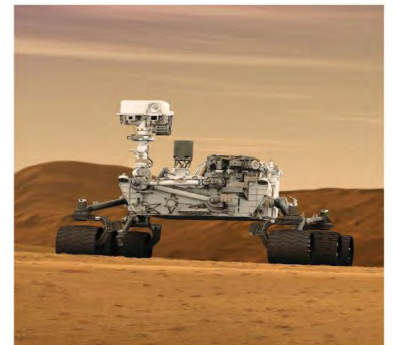
## **Final Report**

**26 March 2025**

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## **1. Introduction**

The 2025 NASA Planetary Mission Senior Review (PMSR) was conducted in a series of virtual meetings from 15 January to 28 February 2025. Six proposed mission extensions were reviewed: Juno at the Jupiter system, the Lunar Reconnaissance Orbiter (LRO), Mars Odyssey (ODY), the Mars Reconnaissance Orbiter (MRO), Mars Atmosphere and Volatile Evolution (MAVEN), and the Mars Science Laboratory (MSL). All six projects have completed their prime missions (PMs) and will have completed at least one extended mission (EM) by the end of this fiscal year.

## **2. Review Process**

The six projects submitted proposals for mission extensions by 18 December 2024, following guidelines specified by NASA Headquarters in a Call for Proposals (CfP) issued on 26 July 2024. Guideline budgets were negotiated between NASA Headquarters and each project prior to proposal submission, and the projects were given the option of submitting one or more overguide requests to perform additional activities at a budget above the guideline. The CfP stipulated that each proposal should include sections on current mission status, accomplishments during the current mission cycle, prioritized scientific objectives for the proposed mission extension, programmatic objectives for the proposed mission extension if appropriate, an EM operational plan, a summary of the health of the spacecraft and payload instruments and identified mission risks, a management plan, a Professional Development Plan, and a Project Data Management Plan (PDMP).

Panels of subject-matter experts (SMEs) having appropriate scientific and technical expertise were constituted to evaluate each proposal. Each panel was led by a distinct chair, each had a non-voting executive secretary who recorded discussion notes and drafts of panel evaluations, and the two PMSR review chairs participated as non-voting members of all six panels. Some individuals served as voting members on more than one panel. All panelists were vetted for financial and personal conflicts of interest with the mission teams and implementing organizations. Each PDMP was submitted as an appendix to the corresponding proposal, and these plans were evaluated independently by external reviewers selected for their expertise in data management. The PDMP

external reviews were summarized in written form by a panel of NASA Headquarters personnel familiar with the Planetary Data Ecosystem.

As outlined in the CfP, the EM proposals were evaluated on the basis of 10 criteria, including six primary and four secondary criteria:

*Primary criteria*

- Merit of the proposed scientific investigations
- Responsiveness to the goals of the most recent planetary science decadal strategy<sup>1</sup>, or, at a lower priority, previous decadal surveys
- Capability of the spacecraft and payload to achieve the proposed science
- Merit of any NASA programmatic objectives
- Scientific productivity of the mission team in the current mission phase
- Recent performance of the mission team in archiving data with the Planetary Data System (PDS)

*Secondary criteria*

- The extent to which the planetary science community outside the project utilize and publish new findings with data from the mission
- Value of any scientific data to be acquired but not analyzed by the mission science team
- Capabilities and experience of key project personnel
- Expected effectiveness of the project's professional development plan in training future spacecraft mission leaders

Prior to their formal proposal review sessions, each panel met for approximately two hours on 15 or 16 January 2025 to discuss the proposal assigned to them and prepare prioritized, written questions to submit to the proposing mission team. All panelists met in a 90-minute plenary session on 5 February 2025 to go over the review process and schedule. In advance of the full panel meetings, each SME submitted a written, pre-panel review of the proposal(s) assigned to them via the NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES) system.

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<sup>1</sup> *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*, The National Academies Press, 2023 (hereafter OWL).

The full panel reviews of the EM proposals were conducted during the week of 10 February 2025 for the ODY, MRO, and MSL proposals, and during the week of 24 February 2025 for the Juno, LRO, and MAVEN proposals. The lead-off session of each panel review was conducted with representatives of the proposing project team and followed a schedule outlined in the CfP. For approximately the first 90 minutes, the project made a presentation that included an overview of the proposed EM, a brief update on mission progress since proposal submission, and a detailed response to each of the written questions previously submitted by the panel. Following each presentation, the panel met in Executive Session for about 30 minutes to discuss the project presentation and develop follow-on questions. For the final 30 minutes of each lead-off session, the project representatives were invited to return to answer those follow-on questions.

The remaining meeting sessions for each panel were devoted to discussion and evaluations of their assigned proposal, conducted on the basis of the evaluation criteria specified in the CfP. In addition to the proposals and information provided by representatives of the project who met with the panels, the PDS provided each panel with a report of the data delivered by the corresponding project and whether those deliveries were made on schedule, and for the panels evaluating Mars orbiter mission extensions, NASA Headquarters provided information on the recent fraction of communications from surface missions relayed by each orbiter. Each panel had 8.5 hours of scheduled discussion time available over 2-3 successive days, in addition to the initial 2.5-hour session with the mission.

Following those discussions, voting members of each panel anonymously rated the overall merit of the proposed mission extension from Excellent (5) to Poor (1), with half-grades allowed. A separate vote was conducted on the same scale for each overguide request. Final panel votes were expressed as median adjectival scores. Each panel prepared a written evaluation of their assigned EM proposal, and copies of all panel evaluations are included with this report. Each panel's deliberations and voting were conducted independently, so no panel's assessment was influenced by that of any other panel.

The Planetary Science Division was represented at each of the panel meetings by Program Officers Henry Throop and David J. Smith. During mission presentations and portions of each of the panel's deliberations, the NASA Headquarters Program Scientist and/or Program Executive for the mission under discussion was also present to provide context if requested and answer questions from the panel.

### **3. Mission Summaries**

#### **3.1 Juno**

Juno, a Principal Investigator (PI)-led mission selected and operated under the Planetary Science Division's New Frontiers Program, was originally designed for an intensive study of the Solar System's largest planet. During its prime mission, between 2016 and 2021, the Juno spacecraft completed more than 30 orbits of Jupiter and made myriad observations that yielded major discoveries about the planet's atmospheric dynamics and chemistry, internal structure, planetary magnetic field, and magnetosphere. Juno's first extended mission (EM1), from 2021 through September 2025, has taken advantage of the natural northward progression of the spacecraft's orbital periapsis and the consequent lowering of spacecraft altitudes over Jupiter's high northern latitudes to target close flybys of Ganymede, Europa, and Io and to conduct high-resolution studies of the planet's north polar region.

During EM1, Juno's flybys of the three inner Galilean satellites yielded new constraints on the thickness of the ice shells on Ganymede and Europa and on oxygen production mechanisms and recent geological activity on Europa, led to the detection of mineral salts and organic compounds on Ganymede's surface, provided evidence from Io's gravity field against a global magma ocean, and enabled measurements of the dielectric and thermal properties of Io's surface and subsurface. Also during EM1, the Juno team sharpened limits on Jupiter's water abundance and inferred a depletion of alkali metals deep into Jupiter's atmosphere, discovered a cold region over the planet's auroral oval, and documented novel aspects of the planet's atmospheric dynamics, from circumpolar cyclones to a rapidly time-varying equatorial jet and cylindrically oriented zonal flows. The team has regularly published their analyses of mission observations (with approximately 100 team publications during EM1), and the project has met most of

its scheduled deliveries of mission data to the PDS archive, including data from systems designed for engineering information (the Stellar Reference Unit, or SRU, and the Advanced Stellar Compass, or ASC) and for education and public outreach (JunoCam). The mission is on track to complete all of its EM1 objectives by the end of this mission phase.

Juno's proposed second extended mission (EM2) would exploit the further evolution of the spacecraft's orbit to investigate Jupiter's small inner satellites, rings, intense inner radiation belts, and their interactions; conduct further investigations of atmospheric processes and aurorae in the planet's north polar region; and characterize the three-dimensional structure of Jupiter's southern magnetosphere and boundary regions and their response to changes in the planet's heliospheric environment. The Juno team has set out multiple EM2 objectives under four broad themes. Under the theme of atmospheric science, EM2 measurements would constrain polar atmospheric density and temperature variations, characterize the depth and dynamical evolution of polar cyclones, and map lightning activity. In the area of Jupiter's interior structure and dynamics, EM2 would document secular variation in Jupiter's magnetic field to probe the depth of the dynamo and advection of the field by fluid flow, constrain tidal dissipation in Jupiter and its moons by astrometric observations of the planet's inner satellites, and determine an atmospheric reference temperature through occultation measurements to sharpen constraints on Jupiter's dilute core. Passage of the spacecraft through Jupiter's ring system and close approaches to the planet's larger inner moons Thebe, Amalthea, Adrastea, and Metis would permit characterization of ring particle densities and searches for imbedded satellites, determination of the mass of Metis and the physical characteristics of Thebe and Amalthea, and characterization of interactions among the moons, rings, and inner radiation belts. Juno's evolving orbit during EM2 will also enable new observations near orbital apoapsis of the shape of Jupiter's large magnetosphere and its links to solar wind and auroral forcing.

Juno's proposed EM2 objectives align well with the major questions of the OWL decadal strategy devoted to giant planets, as well as aspects of the latest decadal strategies for solar and space physics and for astronomy and astrophysics.

The Juno instruments and spacecraft subsystems are generally healthy, and power margins and consumables are all adequate for continued orbital operations through a second extended mission. Although Juno experiences high levels of potentially damaging radiation during short portions of its 33-day orbit, annealing at elevated temperature has proven effective at mitigating much of the radiation damage. The mission is producing pioneering information on spacecraft operation in a high-radiation environment that can be leveraged for spacecraft now in flight (Europa Clipper and the European Space Agency's Jupiter Icy Moons Explorer, or JUICE) as well as future missions involving extended operations in environments with high radiation dosages.

**Although the panel gave high marks to the Juno team's scientific objectives for EM2, they judged the project's reliance on ballistic trajectories through the full extended mission, as described in the guideline budget proposal, to be a major weakness.** Without a capability for propulsive trajectory-correction maneuvers, observations of the inner moons of Jupiter would be severely degraded relative to what could be accomplished with targeted maneuvers (e.g., marked improvements to our knowledge of inner satellite shapes, sizes, and mean densities; multi-spectral feature mapping of inner satellite surfaces that have yet to be spatially resolved; and new details about inner satellite surface structure and composition, the potential role of these satellites as ring particle sources, and evidence of radiation weathering of surface materials). Equally importantly, the spacecraft would be vulnerable to passage through the most intense portions of the inner radiation belts and potentially mission-ending collisions with ring particles in the most hazardous portions of the rings. One of five overguide requests included by the Juno team in their EM proposal would support trajectory maneuvers that would mitigate this major weakness (see Overguide 3, Table 1).

The five overguide requests submitted by the Juno team address the following tasks: (1) conversion of Juno PM and EM1 data to PDS4 format; (2) archiving PM data from Juno's SRU and ASC with the PDS; (3) engineering staff support to enable propulsive trajectory-correction maneuvers to avoid ring hazards and optimize flybys of Jupiter's inner moons, ring systems, and inner radiation belts; (4) additional resources to implement the project's Professional Development Plan; and (5) additional resources to

make up for the cost of inflation. **Table 1 shows the panel evaluations of the overguide requests along with that of the guideline mission.**

**Table 1. Evaluation of Juno EM2 Proposal**

| <b>Proposal Section</b>                       | <b>Panel Evaluation</b> |
|-----------------------------------------------|-------------------------|
| <b>EM2 Guideline Mission</b>                  | <b>E/VG</b>             |
| <b>Overguide 1: PM/EM1 PDS4 Conversion</b>    | <b>E/VG</b>             |
| <b>Overguide 2: Archiving SRU/ASC PM Data</b> | <b>E</b>                |
| <b>Overguide 3: Trajectory Maneuvers</b>      | <b>E</b>                |
| <b>Overguide 4: Professional Development</b>  | <b>VG</b>               |
| <b>Overguide 5: Inflation</b>                 | <b>VG/G</b>             |

The panel devoted considerable attention to Overguide 3. It was the strong consensus of the panel that the trajectory-correction maneuvers described in the request for Overguide 3 would reduce mission risk and significantly improve the scientific return from the observations of Jupiter’s inner moons, rings, and inner radiation belts. Moreover, the panel agreed – although no formal vote on this score was taken – that the overall merit of the main extended mission proposal would have been higher (perhaps to the point of an Excellent rating) had these maneuvers been included in the guideline budget.

The panel offered two additional recommendations to NASA. The first is to consider offering a Participating Scientist Program (PSP) for Juno’s EM2, as was done for Juno’s PM and EM1, to expand the expertise of the Juno science team and provide opportunities for mission experience to a new cadre of planetary scientists. The second recommendation is for the dedicated archiving of telemetry, environmental, and engineering data from the orbital phase of the Juno mission to enable root-cause analysis of spacecraft system anomalies and risk reduction for current and future space missions targeting high-radiation settings.

### **3.2 Lunar Reconnaissance Orbiter**

The Lunar Reconnaissance Orbiter was launched to the Moon in June 2009 and outfitted with a suite of seven instruments, including the Lunar Reconnaissance Orbiter

Camera (LROC), the Lunar Orbiter Laser Altimeter (LOLA), the Cosmic Ray Telescope for the Effects of Radiation (CRaTER), the Diviner Lunar Radiometer, the Lyman Alpha Mapping Project (LAMP), the Lunar Exploration Neutron Detector (LEND), and the Mini-Radio Frequency (Mini-RF) technology demonstration.

Now in its current fifth extended mission (EM5), LRO is in an eccentric polar orbit. Broadly, the science objectives defined for EM5 were related to volatiles, dust, mantle and crustal compositions, volcanic history, mechanical properties of the crust, cratering rates and surface degradation, and space weathering. Although not described in detail, the data collected used “a coordinated, multi-instrument, nadir, off-nadir, multi-wavelength observing campaign of key targets.” The team adapted the communications system to perform radio occultation experiments to probe the lunar ionosphere. The funded EM5 overguide supported Commercial Lunar Payload Services (CLPS) missions with lunar data and relevant analyses for landing site selection, operations, traverse planning (e.g., data for temperature and hazard mapping), and, upon landing, constraining the location and orientation of the lander on the Moon to improve communication with Earth.

Many of the stated science objectives for a proposed sixth extended mission (EM6) would be a continuation of those from EM5, and the proposed collection of the data would largely be done using the same strategy as in EM5 to augment the existing LRO data set. The eccentric polar orbit is migrating to a higher inclination that will allow repeated and enhanced observations near the north pole for better study of the volatiles and geologic features in that region. The LRO team would study how volatiles affect the surface and near-surface properties of polar craters, and determine how volatile reservoirs differ at the two poles and how they are influenced seasonally, with particular interest in understanding volatile behavior in permanently shadowed regions. During EM6 the mission would study the exosphere by using higher LAMP detector voltages (invoking higher signal-to-noise) to improve the study of helium, molecular hydrogen, and neon in response to the radiation environment and the dynamics of the ionosphere. By the end of EM6, the LRO spacecraft will have been collecting lunar data for almost two full solar cycles (i.e., one Hale cycle of 22 years), thus providing a long-baseline data set for how solar activity interacts with and affects the lunar environment. Other

studies will focus on volcanism and tectonic activity to assess the origin, location, and timeline for basaltic, pyroclastic, and silicic magmatism, and determine if young contractional faults have been recently active. More emission phase function (EPF) data will be collected using the Diviner instrument to further study millimeter-to-meter-scale surface roughness, as also was done during EM5. Because the south polar region is very important for future Artemis missions, Diviner slews will allow data acquisition from -55° to +55° off-nadir to establish the range and variability of temperatures around the south pole and to generate thermal maps.

The proposed EM6 studies generally are responsive to major questions in the OWL decadal strategy, and are relevant to NASA's Moon to Mars Objectives and the *Scientific Context for Exploration of the Moon*.

LRO's battery has experienced some degradation and is monitored closely, along with the propellant and solar arrays. Nonetheless, the spacecraft is relatively healthy overall and appears able to conduct the proposed investigations for EM6.

LRO is the only orbiter currently at the Moon and thus is unique in its capability to monitor modern changes on the Moon's surface. It is also the only orbital asset that can collect new targeted data for landing-site studies for future missions, to monitor and support these future landings (e.g., Artemis, CLPS) by collecting data needed for their traverse planning, and to acquire data from orbit that can be correlated with surface measurements. In addition to CLPS deliveries, more than 35 international-agency payloads are scheduled for the lunar surface during EM6, so LRO could be used to promote international collaboration and good will.

The LRO data have been consistently delivered to the PDS on time according to the LRO PDS Mission Report Card, with the minor exception of the most recent LAMP reduced data records (RDRs) and Diviner data releases that have been delayed but are "in progress."

The LRO EM6 proposal requested three overguides: Overguide 1 would enable LRO to provide support for CLPS landing-site selection. The LRO team would utilize their expertise in hazard mapping, terrain analysis, and illumination simulations. Overguide 2 would fund the development of a centralized "Return-to-the-Moon" website. This website would host mission-specific data for CLPS teams or other researchers and

would include integrated visualization tools such as QuickMap. Overguide 3 would enable reprocessing of Mini-RF data from the south pole region. Early X-band data (2009-2011) suffered from poor quality due to limitations in the commercial processing software used. After transitioning to bistatic operations in 2012, a new processing pipeline significantly enhanced X-band data quality, and recent reprocessing of early monostatic observations as a test case has shown substantial improvements that would continue under this overguide. **The panel evaluations of the guideline mission and the overguide requests are shown in Table 2 below.**

**Table 2. Evaluation of LRO EM6 Proposal**

| <b>Proposal Section</b>                          | <b>Panel Evaluation</b> |
|--------------------------------------------------|-------------------------|
| <b>EM6 Guideline Mission</b>                     | <b>E/VG</b>             |
| <b>Overguide 1: CLPS Landing Site Analyses</b>   | <b>E/VG</b>             |
| <b>Overguide 2: Return-to-the-Moon Website</b>   | <b>G</b>                |
| <b>Overguide 3: Reprocessing of Mini-RF Data</b> | <b>E/VG</b>             |

### **3.3 Mars Odyssey**

The Mars Odyssey spacecraft has been in orbit around Mars since October 2001 and has offered many scientific returns from the instruments on board that include (1) the Thermal Emission Imaging System (THEMIS), (2) the Gamma Ray Spectrometer (GRS) package with the High Energy Neutron Detector (HEND) and Neutron Spectrometer (NS), and (3) the Mars Radiation Environment Experiment (MARIE).

Following the failure of MARIE in 2003 and GRS in 2009, ODY's current ninth extended mission (EM9) and the proposed tenth extended mission (EM10) have exploited the capabilities of the remaining THEMIS and HEND/NS instruments. During EM9, the THEMIS instrument has been used for a systematic investigation of fan-shaped deposits to build a global catalogue of alluvial fans, which yielded 175 newly identified ones and showed a wider distribution of fan environments than previously recognized. The thermal inertia of more than 400 fan-like features indicated cementing, likely by hydrated minerals; related geomorphologic evidence suggests a periglacial formational environment. THEMIS continued to monitor sublimating CO<sub>2</sub> ice, supporting an EM8 finding that H<sub>2</sub>O ice is concentrated into piles when CO<sub>2</sub> ice sublimates away.

During EM9, THEMIS data (infrared and visible off-nadir imaging) were calibrated and assigned geometric backplanes to aid the further study of the thermal inertia behavior and chemistry of Phobos and potentially constrain its origin as coalesced basaltic material ejected from Mars. During EM9 HEND and NS data were acquired to continue the 23-year baseline radiation measurements that also can be coordinated with measurements from surface assets, especially as solar activity has been increasing.

The spacecraft is currently in an approximately 6:00 a.m./p.m. Local Mean Solar Time (LMST) orbit. This near-terminator orbit provides the opportunity for unique, late-day, bent-pipe relays for surface landed assets (*Perseverance* and MSL *Curiosity*) that are used for data downlink and rover operation commanding.

During EM10 the THEMIS instrument, the only currently orbiting mid-infrared camera at Mars, would use the near-terminator, Sun-synchronous orbit to continue to observe high-altitude water-ice clouds through limb observations that also reveal lower-level dust clouds. These ice and dust cloud measurements would extend the temporal/seasonal baseline observations of such atmospheric phenomena and their structures that began in EM9. Other science objectives of the THEMIS instrument are to investigate surface properties and temperature-dependent processes to enable continued study of rock abundances and fill gaps in rock-abundance maps, and continued mapping of ground ice and high-latitude seasonal cap retreat, especially in response to any global dust event that may occur during EM10. In addition, thermal inertia measurements will be used to continue to investigate the particle-size properties of various fan-shaped deposits in an attempt to determine their mode of formation and to study explosive volcanic deposits. Proposed large-emission-angle measurements may also reveal discoveries about the composition of the surface, particularly Mars' chloride deposits. THEMIS will also target new craters and their ejecta to characterize the shallow regolith.

The HEND/NS will collect measurements useful for monitoring seasonal CO<sub>2</sub> frost thickness, mapping subsurface hydrogen abundance and inferring water depth, and extending the space weather baseline measurements at Mars by detecting solar particle events and gamma-ray bursts. These measurements can be coordinated with radiation measurements taken on the Martian surface by the MSL rover to characterize the

radiation environment of Mars, information helpful for planning future human excursions to that planet.

The science objectives of ODY's EM10 support the goals of NASA's Planetary Science Division as described in the most recent OWL decadal strategy.

A proposed overguide task is to support reprocessing and conversion of previously acquired THEMIS data into PDS4 format and submit them to the PDS archive. The ODY team has transitioned their THEMIS and GRS data processing pipelines to PDS4 standards, and newly acquired data will be delivered in PDS4 format as of this calendar year. To date, the Mars Odyssey team has made all of their scheduled data deliveries to the PDS on time. **The panel evaluations of the guideline mission and overguide request are shown in Table 3 below.**

**Table 3. Evaluation of ODY EM10 Proposal**

| <b>Proposal Section</b>                       | <b>Panel Evaluation</b> |
|-----------------------------------------------|-------------------------|
| <b>EM10 Guideline Mission</b>                 | <b>E/VG</b>             |
| <b>Overguide 1: Reprocessing Data to PDS4</b> | <b>E</b>                |

### **3.4 Mars Reconnaissance Orbiter**

The Mars Reconnaissance Orbiter spacecraft, which has been observing Mars from orbit since August 2006, has yielded many discoveries about the planet's atmosphere, surface, and subsurface. MRO has also served as an important source of landing site information and as a communications relay for multiple missions to the Martian surface. The spacecraft is in the third year of its sixth extended mission (EM6), and the science payload instruments – with the exception of the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), which ended data acquisition in May 2022 after the failure of the last of its three cryocoolers – remain generally healthy. All spacecraft subsystems are operational as well, with known risks judged by a recent Mars Projects Operational Risk Review to pose only low-probability threats to completion of a new EM. There are propellant reserves that will sustain spacecraft operations well beyond another three years.

During EM6, MRO has conducted a variety of observational campaigns that address the broad EM6 scientific goals of understanding the surface and climate of Mars through time; the evolution of Martian ices; active geological processes on modern Mars; and dynamical, chemical, and meteorological processes in the modern Martian atmosphere. With the exception of a portion of a campaign to characterize mid-latitude ices in the southern hemisphere, which will not be finished until the next EM, all EM6 science investigations either have been completed or are expected to be complete by the end of this fiscal year.

For its seventh extended mission (EM7), the MRO team has proposed investigations that will build on discoveries from EM6 and extend the temporal baseline over which the spacecraft has documented changes to the Martian surface and atmosphere. Four broad scientific goals for EM7 span three major time domains in Martian history: (1) explore climate change on Early Mars, a time of possibly habitable water-related environments; (2) explore ice, volcanism, and climate changes on Late Mars, when Milankovitch-like cycles determined the long-term spatial distribution of ice; (3) explore surface, volatile, and aeolian changes on Modern Mars; and (4) explore diurnal to decadal changes to atmospheric processes on Modern Mars. A novel observational configuration for the spacecraft – involving very large rolls (up to 120° off nadir) to give the Shallow Radar (SHARAD) instrument a less obstructed view of the planet, higher gain, and deeper radar penetration – was demonstrated in three trials during EM6 and will figure more prominently in EM7 (up to 10 times per Earth year) for subsurface mapping of ices and shallow sedimentary and volcanic material.

The panel rated highly the scientific investigations proposed by the MRO team for EM7. Moreover, those investigations were judged to be responsive to the OWL decadal strategy. The productivity of the MRO science team has remained substantial through EM6 (68 peer-reviewed publications in the last three years), and the MRO team has met, for the most part, their schedule of delivery of mission data sets to the PDS archive. Through attention to professional development and succession planning, the mission team has well-qualified individuals in place to step into the positions of Project Scientist and Principal Investigator for three payload instruments. During EM7, MRO would continue to provide crucial support to the *Curiosity* and *Perseverance* rovers

operating on Mars, including serving as a communications relay, scheduling high-resolution imaging to assist with rover traverse planning, and characterizing regional weather in the vicinity of the rovers.

The MRO team proposed a single overguide task: an upgrade to their Electra telecommunications relay system. The upgrade involves the implementation, in fiscal years 2026 and 2027, of the low-density parity-check (LDPC) software upgrade now operating in Mars orbit on MAVEN and the ExoMars Trace Gas Orbiter (TGO) managed by the European Space Agency and Roscosmos. From experience on these other orbiters, the MRO team estimates that throughput via the UHF relay link could be increased by ~40% with this upgrade, a change that would accommodate correspondingly greater data downlinks from *Curiosity*, *Perseverance*, and future landed assets. Such an upgrade would not affect the scientific return from MRO, however, and would add only a small (~1%) increase to the total volume of data transmitted by MRO to Earth. **The panel evaluations of the guideline mission and the overguide request are shown in Table 4 below.**

**Table 4. Evaluation of MRO EM7 Proposal**

| <b>Proposal Section</b>                      | <b>Panel Evaluation</b> |
|----------------------------------------------|-------------------------|
| <b>EM7 Guideline Mission</b>                 | <b>E/VG</b>             |
| <b>Overguide 1: Electra Software Upgrade</b> | <b>VG</b>               |

### **3.5 MAVEN**

The Mars Atmosphere and Volatile Evolution (MAVEN) mission, a PI-led mission originally selected under the Planetary Science Division's Mars Scout Program, has been in orbit about Mars since 2014. Now in its fifth extended mission (EM5), MAVEN has provided key information on atmospheric loss processes through measurements of the interaction of the Martian upper atmosphere, ionosphere, and magnetosphere with variations in solar activity and the planet's heliospheric environment. A long-term goal of the mission has been to improve our understanding of current processes at Mars so that the long-term evolution of the Martian atmosphere and climate and the contributing

roles of dust storms, extreme solar events, and global and crustal magnetic fields can be modeled.

MAVEN's scientific accomplishments during the current EM5 group naturally under the three thematic questions posed by the team for the current EM: (1) How does solar maximum affect the Martian atmosphere and climate? (2) How does the upper atmosphere respond to Mars's seasons and dust? (3) How does the hybrid magnetosphere control the basic physical properties that govern Mars–solar wind interactions? All of the team's objectives under these three themes will have been completed by the end of the current mission cycle. The team has continued to publish their mission findings regularly in peer-reviewed journals (at a rate of greater than 40 papers per year), and the MAVEN project has consistently made all their deliveries of mission data to the PDS on schedule. MAVEN has archived all project data in PDS4 format since the beginning of the mission and was the first planetary mission to do so.

The MAVEN spacecraft plays a critical role as a relay for communication between Earth and Mars surface assets, currently including the *Curiosity* and *Perseverance* rovers. To preserve propellant reserves and ensure continued availability as a relay into the early 2030s, the project has been directed by the Mars Exploration Program (MEP) Office to raise the spacecraft's periapsis altitude from its current value of approximately 180 km to above 200 km; periapsis will be raised by 5 km in 2026, and a larger increase is scheduled for early 2028. In coordination with the Community Coordinated Modeling Center and Moon to Mars Space Weather Analysis Office at the NASA Goddard Space Flight Center, the MAVEN team sends alerts to those operating other spacecraft at Mars regarding any enhanced solar activity that could adversely affect spacecraft operations or hardware. The MAVEN project is also collaborating with teams operating other NASA and international spacecraft missions at Mars as well as at Earth and Venus to coordinate multi-point measurements of planetary responses to variations in solar activity.

As of the time of this review, the MAVEN spacecraft was generally healthy, and all nine payload instruments were operational. The project has maintained an effective risk management plan in the face of degradation of subsystem capabilities and has identified contingency plans for ongoing risks. For instance, attitude control has been

accomplished since 2022 primarily with the spacecraft's star trackers, in an All-Stellar Mode, to preserve the lifetime of the probe's remaining operational Inertial Measurement Unit. Battery health and charging time are being carefully monitored and factored into trajectory correction maneuvers and planned changes to the spacecraft orbit. Also carefully monitored is performance of the Articulated Payload Platform, a deployable boom that permits precise pointing of three payload instruments, and plans are in place to accommodate evidence of gimbal degradation.

The MAVEN project proposed a sixth extended mission (EM6), to span government fiscal years 2026–2028, with four scientific goals that build on results from earlier in the mission and exploit both the current periapsis altitude and the extreme solar conditions expected early in the declining phase of the current solar cycle. The first goal is to conduct coordinated instrument observations to characterize the reservoir for atmospheric escape, by determining profiles of water vapor, the nightside magnetospheric structure that drives aurorae, and the effect of dust storms on interannual and interhemispheric variability. The second goal is to characterize the physics of acceleration from just above the exobase (approximately 180–200 km altitude) to space, including the initial ion energization processes and the effects of dust activity as well as the influence of low-altitude electric currents. The third goal is to determine the response of the neutral atmosphere and ionosphere to heating from solar storms, including the effects of increased solar radiation and high-energy particle fluxes, as well as to compare with the corresponding response at Earth. The fourth goal is to extend measurements of the various atmospheric escape processes to span a full solar cycle, to be in a better position to extrapolate backwards to early Mars, when the Sun was younger and more active. These goals address directly several major questions in the OWL decadal survey.

**The panel evaluation of the overall merit of the MRO EM6 proposal is shown in Table 5 below.**

**Table 5. Evaluation of MAVEN EM6 Proposal**

| <b>Proposal Section</b>                | <b>Panel Evaluation</b> |
|----------------------------------------|-------------------------|
| <b>EM6 Guideline Mission</b>           | <b>E</b>                |
| <b>No Overguide Requests Submitted</b> | <b>–</b>                |

The panel made two further recommendations. To the MAVEN project, the panel suggested that it would be timely for the science team to update their synthesis of what the mission has revealed about atmospheric loss processes on Mars and their relative importance since early in the history of the planet, similar to the analysis 7 years ago by Jakosky et al. (2018). To NASA, the panel suggested that a new PSP, not utilized for MAVEN since prior to mission launch in 2013, be funded to expand the opportunities for mission participation by scientists not currently on the spacecraft team.

### **3.6 Mars Science Laboratory**

The Mars Science Laboratory mission delivered the *Curiosity* rover to Gale crater on the surface of Mars in August 2012. From its landing site *Curiosity* has roved to and up Aeolis Mons, a large, central deposit within Gale crater informally known as Mount Sharp.

During its current fourth extended mission (EM4), MSL has roved from just above a lower clay-bearing strata into a section dominated by Mg-sulfate and other salts. Within the lower Mg-sulfate section there is a Marker Band that could not be drilled despite four attempts. This hard lithology displayed fossilized, symmetric wave ripple marks, suggesting movement of shallow water over once-wet sediment. The ripple geomorphology suggested that the lake into which the sediment was deposited was not ice-covered, indicating that during the era of sediment deposition Mars was warmer and wetter than today's arid and cold climate. Slightly higher up the Mg-sulfate section, the unit offered mineralogic evidence of 5-10 wt % pure Fe-carbonate (i.e., siderite) at a few locations. This siderite unit was particularly interesting because it offered evidence of precipitated carbonate, a mineral class that once was expected to be abundant on Mars as a result of chemical sequestration of Mars' hypothesized thicker CO<sub>2</sub> atmosphere,

but is not widely exposed on the surface. Another “first” on Mars was the discovery of native sulfur when a rover wheel crushed some clasts of material and exposed yellow crystalline material in the lower Gediz Valles. The formational setting of the sulfur remains uncertain. Also, measurements of the radiation environment during EM4 extended earlier observations to a complete 11-year solar cycle.

To begin the proposed investigations of a fifth extended mission (EM5), the rover is making its way to the Boxwork structure to investigate cemented fractures that appear from orbital images to be more resistant to erosion than the surrounding host material, leaving a grid of decameter-scale inverted fracture features. Rover measurements are planned to test the hypothesis that the original fractures were filled with sediment (and possibly entrained organic molecules) and that subsurface cementation of the fracture fill (perhaps due to rising groundwater) may have preserved evidence of a former habitable environment.

The planned traverse for the proposed EM5 would take the rover through the remainder of the thick Mg-sulfate-bearing unit to the overlying Yardang unit that is observable from orbit. Between the Mg-sulfate section and the Yardang unit is a geologic contact postulated to be an unconformity marking the boundary between the shallow-water-lain sulfate/evaporite unit and the younger wind-deposited Yardang unit. This contact would thus offer the possibility of documenting a major transition in Martian climate from wet to dry conditions.

The traverse of *Curiosity* since the beginning of the mission through the proposed EM5 would allow the MSL team to construct a large geological “reference section” that documents the overall evolution of surface/near-surface environments on Early Mars from wetter to drier. The geology indicates sustained wet–dry cycling and intermittent surface water, but the general trend indicates an earlier wet environment with clay-dominated geochemistry, to a wet and mildly alkaline environment that allowed the deposition of siderite, to an intermittently wet environment dominated by deposition of shallow-water Mg-sulfates and evaporitic salts. Finally, it is anticipated that the contact between the Mg-sulfate-bearing unit and the Yardang unit represents a major environmental shift from episodic surface waters to a dry environment capable of forming the Yardang unit as air-deposited sediments with wind-eroded ridges.

The instrument package on *Curiosity* is still moderately healthy, and measurements will be made with ChemCam (including its Laser-Induced Breakdown Spectrometer and the Remote Micro Imager), CheMin, Sample Analysis at Mars (SAM), Alpha-Particle X-ray Spectrometer, the Mastcams (without the use of the filter wheels), Mars Hand-Lens Imager, the Mars Descent Imager that is now used to image beneath the rover, the modified drill, and the scoop to study the geology. During EM4, the Dynamic Albedo of Neutrons instrument's neutron generator failed, but it can still do passive neutron spectroscopy. Furthermore, the instruments will be acquiring data about the current atmospheric composition, cycles of water vapor and dust, and the ultraviolet and high-energy radiation environment, thus extending these “baseline” data sets beyond those acquired by any other former or current surface asset.

The EM5 proposal briefly described the investigation of methane as a “recent effort” by the MSL mission. However, a key finding and recommendation from the previous 2022 Planetary Mission Senior Review (for EM4) was that the MSL team should address the discrepancy between methane measurements by MSL and TGO to determine the origin of this potentially biologically generated gas. The MSL EM5 proposal suggests that origin models (e.g., continuous micro-seepage, abrupt seepage due to a rover disturbance, or barometric pumping) can be discriminated, but it did not provide sufficient detail as to what distinct measurements by the SAM Tunable Laser Spectrometer will accomplish this important goal. The panel recommends that the MSL team increase their focus on the study of methane during EM5.

The proposed EM5 science investigations are responsive to major questions in the OWL decadal strategy, particularly those regarding solid body interiors and surfaces, dynamic habitability and the search for life, and solid body atmospheres and climate evolution.

The MSL team proposed an overguide to enable more operational planning sessions and utilize the full output of the rover's power system, effectively hastening the pace of the rover to arrive at the contact between the Mg-sulfate-bearing unit and the Yardang unit sooner than would be possible with the guideline budget. Then, following investigations of the contact and the Yardang unit, the rover would move to a

neighboring area in the upper Gediz Vallis to be in position to begin study of that valley early in an extended mission following EM5.

After lengthy discussions, the panel suggested an alternative overguide investigation that also uses funds for additional operational planning sessions, but with a greater focus on the postulated unconformity and the Yardang unit. Such a shifted focus would align the overguide more fully with the highest-priority goals of the MSL mission. In particular, the contact-bounding lithologies represent very different environmental conditions and likely will require more time than described in the EM5 proposal for a thorough investigation of this key transition on Early Mars from wet to dry conditions. In this alternative overguide scenario, the rover would spend more time studying the Yardang unit and would not prioritize reaching the upper Gediz Valles before the end of EM5. **The panel evaluations of the guideline mission and the requested and panel-alternative overguide investigations are shown in Table 6 below.**

**Table 6. Evaluation of MSL EM5 Proposal**

| <b>Proposal Section</b>                                          | <b>Panel Evaluation</b> |
|------------------------------------------------------------------|-------------------------|
| <b>EM5 Guideline Mission</b>                                     | <b>E/VG</b>             |
| <b>Overguide 1: Additional Planning Cycles</b>                   | <b>G</b>                |
| <b>Overguide 2: Panel-alternative Additional Planning Cycles</b> | <b>E/VG</b>             |

#### **4. General Comments on the Review**

This PMSR ran smoothly, for several reasons. The Program Officers who oversaw the reviews were effective at explaining procedures, the evaluation criteria, and how review recommendations might be used by NASA. The group chiefs were well chosen and experienced, and each panel had the collective expertise to evaluate the mission proposal they were assigned. The panels were efficient and thorough. Because several of the panel members had participated in the 2022 PMSR and previous final reports were publicly available, there was corporate memory of the review procedures and an ability to reference past findings. The live interactions between the panels and representatives of each project were productive and clarifying, and made efficient use of

everyone's time. Several panelists served on more than one mission review panel, and the two Review Chairs participated with each panel; this crossover helped to level the discussions and reduce the potential for disparities among the panel reviews. The availability of NASA Headquarters-based Program Scientists and Program Executives for portions of each panel's discussion was helpful so that many panelist questions could be quickly answered, and some programmatic context for project actions could be provided. Finally, the reviewer community has benefitted from five years of intensive experience with virtual meetings, and such a format permits the easy inclusion of expert panelists from a wide range of time zones.

The external and NASA Headquarters reviews of the mission PDMP documents were thorough and helpful. None of the issues raised by those reviewers rose to levels that warranted specific discussion in this overview report. It was also very useful for some panel discussions to have received from NASA a summary of recent Mars Relay Network downlink statistics.

For improving the next PMSR, it was generally agreed that all extended mission proposals should include a current mission risk matrix as well as an end-of mission plan, in the eventuality of an earlier end to operations than planned. Also benefitting the review would be abbreviated curriculum vitae of key personnel. A couple of panels commented that they would have preferred seeing budgets in a different format or more detailed information on proposed funding support of team members, but neither of these issues was a major factor in the panel evaluations.

The timeline of the review was appropriate. Sufficient time was allotted for reading the proposals, generation of questions for the project teams, panel discussions, preparing the panel evaluations, and writing the final report.

## **5. Conclusion**

The six spacecraft missions evaluated in this 2025 Planetary Mission Senior Review have all successfully completed their prime missions and multi-year mission extensions and have yielded novel observations that have altered our view of our Solar System's largest gas-giant planet, our Moon, and one of our nearest planetary neighbors. All spacecraft are generally healthy, their mission teams have identified new and highly

rated science objectives that appear to be achievable during an additional three-year extended mission, and all missions are playing important programmatic roles that would be valuable to continue. The cost for funding the proposed mission extensions would be modest in comparison with comparable new missions to these bodies.

Melissa D. Lane, Fibernetics, PMSR Co-chair

Sean C. Solomon, Columbia University, PMSR Co-chair

26 March 2025

## 6. Panel Evaluations of Individual Missions

### 6.1 Juno

#### 2025 NASA Planetary Mission Senior Review Panel Evaluation

**Proposal** 25-PMSR25-0002  
**Title** Juno Second Extended Mission  
**Principal Investigator** Scott Bolton / SwRI

### Summary of Proposal

The proposal is for a second extended mission (EM2) of the highly successful Juno mission to Jupiter. A remarkable feature of the Juno mission is orbital precession that has taken the periapse of Juno's highly elliptical polar orbit from above Jupiter's equator in the prime mission (PM) to high northern latitudes at present. During EM2 the periapse will continue to precess across Jupiter's north pole. This orbital precession enables detailed investigations of Jupiter's northern regions including studies of atmospheric processes and aurora. Because the orbit is elliptical, precession leads to inward migration of equatorial plane crossings as the spacecraft approaches Jupiter and outward migration of crossings as the spacecraft recedes. During EM2, migration of these crossings enables Juno for the first time to make detailed measurements of the small inner satellites (Thebe, Amalthea, Adrastea, and Metis), the rings, the intense inner radiation belts, and their complex interactions. Further, at apoapse Juno explores the southern boundaries of the magnetosphere, providing unique measurements of the shape of the magnetosphere and its response to the solar wind. EM2 is thus effectively a new mission scientifically, pursuing science goals different from and complementary to those of the PM and the first extended mission (EM1). The spacecraft health, power margins, and propellant reserves are more than adequate to carry out the planned science investigations.

### **Overall Rating:** Excellent / Very Good

*This reflects all criteria for the guideline proposed mission. The Primary criteria carry a greater weight in the overall rating than the Secondary criteria.*

## Primary Evaluation Criteria (1 – 6)

### 1. Intrinsic merit of the proposed science investigations to be undertaken during the EM

#### Major Strengths

**The natural evolution of Juno's orbit during EM2 will provide opportunities to investigate previously unexplored regions of the Jovian system, particularly the coupled inner moons and rings, the intense inner radiation belts, and the distant southern magnetosphere and boundary regions.** As the perijove of the highly elliptical polar orbit migrates northward, crossings of the equatorial plane migrate as well. Crossings move inward for portions of the orbit where the spacecraft is approaching Jupiter and outward where the spacecraft is receding. This equatorial crossing migration (both inbound and outbound) enables for the first time flybys of the small inner satellites Thebe, Amalthea, Adrastea, and Metis, as well as crossings of much of the ring system and the inner radiation belts (the source of Jupiter's most intense synchrotron emission). At the same time, the apojoove migrates toward the outer magnetospheric boundaries in the direction of Jupiter's southern magnetic pole, enabling new investigations of the shape of the magnetosphere and its interactions with the solar wind. EM2 is thus effectively a new mission scientifically, pursuing science goals different from and complementary to those of the prime mission and the first extended mission.

**Juno's northward perijove migration will enable focused investigations of Jupiter's turbulent north polar regions, providing data critical to understanding polar cyclones, convective processes, and other poorly understood atmospheric processes.** The proposed Microwave Radiometer (MWR) observations and gravity flyovers of the polar cyclones would provide powerful and unique diagnostics of their depths and three-dimensional structures that largely are not well understood but could address the nature of the transition between tropospheric and interior circulations on Jupiter and gas giant planets in general. These observations would be complemented by JunoCam, Jovian InfraRed Auroral Mapper (JIRAM), and Stellar Reference Unit (SRU) observations of polar cyclone morphology. The continued lightning observations in the north polar region provide valuable constraints on the poorly understood process of moist convection on gas giants. A compelling case is made in the discussion associated with Fig. 4-2 that EM2 has a factor of 4 greater contamination-free limb darkening opportunities than did EM1, which would significantly improve the temperature resolution.

**The proposed campaign to synergistically explore the inner satellites, the rings, and their interactions with Jupiter's intense inner radiation belts and magnetic field will enable a substantial advance in our knowledge of this complex aspect of the Jovian system.** Unprecedented observations of the small inner satellites' orbital dynamics would yield tidally induced orbital recession rates, providing new information about the tidal Love numbers and tidal dissipation of Jupiter and its satellites — results

that are critical to understanding the role of tidal heating in maintaining subsurface oceans on the icy Galilean satellites. The new ring data would reveal details of their structure, composition, and dynamics, including clumping, waves, smaller satellites within the rings, temporal variations in ring structure, and size distributions and densities of particles within the rings. The campaign would also explore the strong equatorial magnetospheric interactions between the rings, moons, and dust, including dust-perturbation from charging. With Overguide #3 (OG3) support (see Sections 1 & 3 “Major Weaknesses” and OG3 comments below), great improvement of our knowledge of the inner satellite shapes, sizes, and mean densities is also possible. These observations could provide rotational multi-spectral feature mapping of inner satellite surfaces that have yet to be spatially resolved. Spectrophotometric observations enabled by optimized trajectory maneuvers using OG3 resources would provide new details about inner satellite surface structure and composition, the satellites’ potential role as ring particle sources, and evidence of radiation weathering on the satellite surfaces. Maneuvers could also reduce radiation noise in equatorial-plane-crossing measurements.

**Spacecraft orbital evolution during EM2 would enable major new measurements of the size, shape, and dynamics of Jupiter’s magnetosphere as well as auroral precipitation and its accompanying energy deposition.** Near apojove, Juno would observe the magnetopause, bow shock, and cusp region of Jupiter’s magnetosphere. These measurements would provide valuable insights into the magnetosphere’s overall shape and structure. By distinguishing among the dusk-side cusp particle populations (e.g., particles originating from Jupiter, Io, and the solar wind) we can better understand how solar conditions influence a massive, rotation-dominated magnetosphere. Juno would also directly measure the solar wind while remotely observing the aurora, helping to determine the extent to which solar activity, such as shocks, affects the aurora compared with internal processes such as mass loading and loss down the magnetotail. A fundamental question will be addressed: how “open” (i.e., influenced by the solar wind) or “closed” (dominated by rotation) is Jupiter’s magnetosphere? Juno’s orbit in the nightside northern polar region would enable vertical limb imaging across multiple wavelengths (ultraviolet, visible, infrared, and microwave) as well as vertical profiles of ionization via radio occultations. These observations would enhance our understanding of auroral energization processes and where energy is deposited in Jupiter’s atmosphere.

**The proposed planetary limb occultations at high latitudes would significantly improve our knowledge of the shape of Jupiter, a key boundary condition for accurately modeling the planet’s interior and vertical structure.** The broad latitude coverage of Juno’s radio occultations provides key information on the shape or dynamical flattening of Jupiter. Determining a reference temperature at a given pressure through radio occultations serves as fundamental input for interior model inversion, particularly in characterizing the abundance of heavy elements. Furthermore, measurements of vertical pressure and temperature profiles resolve fine-scale structure in the stratosphere and upper troposphere, offering significant improvements

over remote sensing observations. The EM2 radio occultations would help resolve discrepancies with MWR temperature measurements across different latitudes.

## Minor Strengths

None

## Major Weaknesses

**Important and uniquely valuable scientific observations (as well as critical operational capability related to spacecraft safety—see Section 3 below) are relegated to an Overguide request (OG3), lessening the scientific return (and spacecraft safety) during EM2 if OG3 is not approved.** Critical observations of the inner satellites discussed above as a Major Strength *if the corresponding Overguide request is approved* will not be conducted in the absence of that approval. Further, the Overguide request (Section 12.4—“Trajectory Maneuvers”) that would enable these observations would also permit avoidance of the principal known hazards associated with main ring crossings and possible avoidance of currently undetected hazards identified during EM2. See further discussion of this Overguide request below (Section 3 “Major Weaknesses” and OG3 comments).

## Minor Weaknesses

**The proposal did not adequately explain how the combination of radio science occultations and MWR-derived temperature measurements would ensure internally consistent pressure-temperature profiles of Jupiter at 0.5 bar atmospheric pressure, as stated.** The methodology for reconciling potential discrepancies between these two techniques was insufficiently detailed, and did not demonstrate that there would not be continued systematic biases in atmospheric retrievals. Furthermore, the ability of radio occultation to achieve the <5 K uncertainty objective for atmospheric temperature constraints was not well supported by a thorough discussion of retrieval techniques, error sources, and validation methods.

**The methodology for using EM2 astrometric observations, combined with previous PM data, to evaluate the migration rates of Thebe and Amalthea was insufficiently detailed.** The required number of measurements, ephemeris sampling interval, and approach to isolating tidal dissipation effects from other perturbations were not well-defined, casting uncertainty on the robustness of the proposed constraints and their contribution to refining Jupiter’s internal structure models.

## **2. Responsiveness of the proposal to goals described in the 2023 Decadal Survey “Origins, Worlds, and Life”**

*Missions may optionally also refer to goals in Vision and Voyages for Planetary Science in the Decade 2013-2022 (2011), and/or New Frontiers in the Solar System: An Integrated Exploration Strategy (2003), depending on when the mission was originally proposed. The proposal should make clear from which Decadal Survey each goal is taken. Goals from later Decadal Surveys should be prioritized over earlier ones. Proposals may mention goals from other Decadal Surveys (e.g., from other science divisions at NASA), but these will not contribute to the mission’s evaluation.*

### **Major Strengths**

**The proposal directly addressed key science questions outlined in the Decadal Strategy for Planetary Science and Astrobiology 2023-2032, particularly those related to the structure, evolution, and interactions of giant planets.** The Science Traceability Matrix (Sec 4.5, pp. 4-21/22) provided a clear and convincing connection between 62 detailed questions from the past three decadal surveys (2003, 2013, and 2024) and the measurement objectives for EM2, categorized by Atmosphere; Interior; Inner Moons, Rings, and Radiation Belts; and Magnetosphere. There is a high probability that EM2 will provide significant advances in each of these Decadal Survey areas.

### **Minor Strengths**

**EM2 would also support the Decadal Survey for Solar and Space Physics (2024) goal of learning from comparative studies of magnetospheres and magnetospheric processes throughout the solar system, as well as the Decadal Survey on Astronomy and Astrophysics (2023) goal of learning from studies of the Jovian system as an analogue to extra-solar giant planet systems.**

### **Major Weaknesses**

None

### **Minor Weaknesses**

None

### 3. Capability of the spacecraft to achieve the proposed science

#### Major Strengths

**The overall health of the spacecraft appears very good despite it having been in space for nearly 14 years and having spent almost 9 years in the harsh Jovian radiation environment.** Power margins are positive and propellant reserves (>40 kg at the end of EM1) are more than adequate to carry out the planned investigations. Most of the science instruments and engineering systems on the spacecraft are in good health. Although minor degradation and component failures have occurred for some instruments and systems, the proposal is convincing that the operational health of Juno would be adequate to achieve EM2 science objectives as planned. (Only ~4 kg of propellant is needed to carry out the guideline EM2 ballistic trajectory. The trajectory maneuvers of OG3 would require 10-20 kg of propellant.)

**Temperature annealing has proven effective in mitigating some radiation degradation.** Juno experiences high radiation levels during short (<1 day) periods of its 33-day orbit that can cause defects in semiconductors and degrade materials. Passive annealing, where materials naturally recover to a less damaged state, occurs naturally, but missions can speed up the process through active annealing by maintaining components at elevated temperatures. Juno has shown that some degradation of JunoCam, the Advanced Stellar Compass (ASC), and the Inertial Measurement Units (IMUs) can be reversed through passive and planned active thermal annealing. For example, the team showed that keeping IMU-1 powered for half the orbit prevented further degradation of the Laser Intensity Monitor and reversed some previous damage.

#### Minor Strengths

**The SRU and Advanced Stellar Compass (ASC) spacecraft systems are being used for imaging and radiation monitoring science. JunoCam, a public outreach instrument, is also being used for science investigations.** The use of these non-science instruments for scientific investigations demonstrates the Juno team's ability and commitment to using all available spacecraft resources to advance science.

**The spacecraft has sufficient fuel reserves for trajectory maneuvers that would potentially avoid damaging or mission-ending ring particle and radiation hazards as well as substantially increase EM2 science return.** During EM2, Juno instruments could be used to observe and identify possible hazards, such as regions of main ring particles that pose a collision hazard, and regions of extremely dangerous radiation. The spacecraft has sufficient fuel reserves to adjust its orbit with the aim of avoiding these hazards, some of which could be mission-ending. *(Note that the mission's ability to realize this desirable outcome is dependent upon Overguide funding. See first Major Weakness in this section and comments on OG3 further below.)*

**The absence of the need to dispose of the Juno spacecraft to satisfy planetary protection requirements allows continued collection of science data for the full operational life of the spacecraft.** The evolution of the Juno orbit away from the Galilean satellites reduces the risk of accidental contamination of Europa, Ganymede, or Callisto sufficiently that a deorbit burn at end of mission is no longer required under planetary protection protocols. Juno's science investigations can therefore continue as long as the relevant instruments and spacecraft systems are adequately operational.

## **Major Weaknesses**

**The ballistic trajectory proposed for the guideline mission would compromise achievable science investigations, particularly of the small inner satellites, and introduces potentially avoidable risks of mission-ending particle collisions in the main ring, as well as severe radiation degradation.** The absence of trajectory maneuvers in the baseline proposal severely degrades the spatial resolution achievable at small inner satellite flybys and eliminates the ability to optimize those measurements with respect to radiation noise. In addition, it also eliminates the ability to avoid regions of the main ring where mission-ending collisions with ring particles are most likely to occur (or to avoid other hazardous ring regions identified during EM2) and to avoid the regions of most intense radiation. *This weakness is mitigated if OG3 is selected, which would allow for trajectory planning.*

## **Minor Weaknesses**

**The proposal did not sufficiently address the ground segment/DSN capabilities for supporting radio science data collection and orbit reconstruction during EM2.** The noise in radio tracking data, which is critical for both gravity science and navigation, is primarily influenced by interplanetary solar plasma. The loss of the onboard Ka-band Translator (KaT) precludes the use of the Ka/Ka/ radio link, which is only available at the Goldstone ground station, for direct calibration of this noise. This hardware limitation reduces constraints on DSN ground station support, resulting in no formal requirement for synchronization with Goldstone. However, during EM2, Juno's tracking passes will span a range of Sun-Earth-spacecraft configurations including periods when solar plasma effects are minimal and tropospheric noise becomes the dominant source of error. Goldstone's auxiliary facilities, including advanced water vapor radiometers (AWVRs), have the capability to reduce tropospheric noise by approximately 50% when applied for calibration. The proposal does not sufficiently address the potential improvements in gravity science and overall scientific return enabled by these enhancements, nor does it evaluate their impact on risk avoidance strategies.

**It is unclear how the spacecraft and instruments will be affected by the high-radiation environment that will be encountered during EM2.** While instrument damage may not be critical, past Juno data suggest that some observations could be impacted in ways that compromise the science investigations. Total ionizing radiation

dose would be more than double at the end of EM2 compared to EM1, which already exceeds the flight testing level in most cases.

**The Ultraviolet Spectrograph (UVS) instrument occasionally reboots with an outdated software version, causing data loss that might impact EM2 science goals.** This issue may particularly impact the ability to monitor the aurora when Juno crosses magnetospheric boundaries near apojove. A possible remedy was identified by the team, i.e., to better control the UVS thermal state and to power it on earlier before apojove, but reliance on this remedy introduces risk.

#### **4. Merit of any programmatic objectives**

*This may include activities such as data relay for other NASA or international missions; science which advances the goals of NASA directorates beyond SMD; international cooperation; or other significant non-science activities.*

##### **Major Strengths**

**Juno is contributing to Jovian science and long-term monitoring broadly, helping lay a foundation for NASA's Europa Clipper and ESA's Jupiter Icy Moons Explorer (JUICE) missions currently in transit to Jupiter.** Critical objectives of both of those missions hinge to some degree on understanding the plasma and field environment of the targeted Galilean satellites. Juno's EM2 would improve our understanding of that environment. For example, it would provide additional data on the magnetic periodicities experienced by the Galilean satellites as Jupiter's inclined magnetic field rotates with the planet. These data will be important support for Clipper and JUICE's induction-based studies of the Galilean satellite interiors.

**The lessons learned from monitoring both the instruments and subsystems of the long-lived Juno spacecraft (9 years in the Jovian system as of this review) will contribute significantly to understanding environmental effects on spacecraft in high-radiation environments, benefiting any such future missions and Europa Clipper and JUICE in particular.** The behavior of the spacecraft in the record-breaking high-dosage radiation environment that will be experienced during EM2 will add unique and valuable engineering data to that already collected during the prime mission and EM1. In particular, the experience with thermal annealing to mitigate radiation damage may prove of particular importance for Europa Clipper, which is flying electronic components (MOSFETs) that are less radiation-tolerant than originally expected.

##### **Minor Strengths**

**Citizen science involvement with JunoCam and the Juno science team's collaboration and involvement with Earth-based astronomers (professional and amateur) is a model for NASA public outreach programs.** JunoCam was flown explicitly for education and public outreach (EPO) purposes, funded from the mission's EPO budget. It has been a great success. Amateur astronomers contribute

Earth-based telescopic observations that are then used by the JunoCam ops team for planning. Amateur image processors download JunoCam images to create science and art products. Almost 12,000 processed images have been produced. JunoCam also has been used extensively for scientific investigations of Jupiter, its satellites, and its rings.

**The Juno mission has attracted a high level of European scientific participation, in part likely in connection with preparation for the JUICE mission.** Juno has numerous European Co-Investigators as well as the European Principal Investigator for JIRAM, an instrument provided by the Italian Space Agency. Since international participation is conducted on a no-exchange-of-funds basis, these collaborations are effectively a no-to-low-cost contribution to the mission as well as a sustaining strong connection between the American and European scientific communities.

### **Major Weaknesses**

None

### **Minor Weaknesses**

None

## **5. Scientific productivity of the mission team in the current phase**

### **Major Strengths**

**The Juno team's scientific output has been prolific and impactful throughout the baseline and extended mission.** According to a corrected tally from the mission, team members have led 275 peer-reviewed publications and non-team members have led over 450 since the beginning of the mission. For EM1 alone, the corresponding numbers are approximately 100 and 225. The scientific results from EM1 have been particularly impactful, with publications on the Ganymede, Io, and Europa flybys featured in dedicated special journal issues. These studies reflect the extensive analysis of Juno's data and its support for refining models of planetary processes across the Jovian system.

**Juno's flybys have provided significant advancements in understanding the geophysical and atmospheric properties of the Galilean satellites.** At Ganymede, MWR provided the first spatially resolved measurement of the subsurface ice shell, while JIRAM detected evidence of mineral salts and organics indicative of endogenous processes. High-resolution imaging refined geologic and topographic maps, enhancing surface characterization. Europa flyby observations placed new constraints on oxygen production mechanisms, identified tectonic features consistent with true polar wander, and revealed regions of recent geologic activity, providing critical context for Europa Clipper. MWR provided the first constraints on ice shell thickness, while radiation

environment characterization improved models of surface weathering. Io flybys reshaped models of its interior structure, with gravity field analysis refuting the existence of a global magma ocean. MWR-derived constraints on the dielectric constant and subsurface temperature of lava flows have refined understanding of Io's thermal and volcanic properties, while Juno Waves measurements detected fresh plasma injections linked to interchange instability in the Io torus, advancing knowledge of its dynamic environment.

### **Minor Strengths**

**Juno's innovative use of multiple instruments across a diverse range of scientific objectives demonstrates the mission team's adaptability and ability to maximize scientific return.** For example, the team used Juno's SRU, originally a navigational star camera, to obtain the highest-definition images ever acquired of Europa's surface. Its use on the ring satellites would provide better spatial resolution than possible with any of the other onboard imaging instruments. Additionally, the combined use of multiple instruments for characterizing Circumpolar Cyclone (CPC) structures over time will offer valuable insights into their drift motion and circulation, improving knowledge of vortex stability and evolution on Jupiter. Long-term monitoring of these features, leveraging JunoCam, JIRAM, and SRU, will provide a comprehensive dataset spanning an entire Jovian year.

### **Major Weaknesses**

None

### **Minor Weaknesses**

None

## **6. Performance of the mission in archiving data to the PDS in the current phase**

### **Major Strengths**

**The Juno team has successfully archived data from most spacecraft instruments in accordance with the schedule agreed upon by the PDS and the mission team according to the PDS Mission Report Card.** All data deliveries have been performed on time, demonstrating strong adherence to data management and accessibility requirements. During the PM and EM1, significant efforts were undertaken to support the migration of datasets to PDS4 while maintaining availability of PDS3 data sets for selected instruments. These efforts, coordinated with the PDS, ensured that MWR, UVS, JIRAM, and Gravity Science investigations were properly archived in formats compatible with both PDS3 and PDS4, enhancing long-term data accessibility.

**The team has undertaken the archiving of SRU and ASC data, originally considered engineering subsystems.** These datasets have contributed to major scientific discoveries. Their inclusion in the archiving plan for EM1 and EM2 ensures that valuable engineering-derived science data remain accessible for further analysis. (A proposed EM2 overguide, OG2, would deliver PM data for these two systems to the PDS.)

### **Minor Strengths**

None

### **Major Weaknesses**

None

### **Minor Weaknesses**

None

## **Secondary Evaluation Criteria (7 – 10)**

### **7. Extent to which the science community beyond the mission science team utilizes data and conducts published research**

#### **Major Strengths**

**The proposal demonstrates Juno's engagement with the professional community.** The professional community was highly engaged in EM1, with non-team publications (per an updated report from the mission) doubling from approximately 225 to 450 in just over three years.

**During EM1, the Juno team held several open workshops to involve the wider planetary community in Juno scientific analysis and to foster collaborations.**

Separate workshops were held on Jupiter's atmosphere and interior, the magnetosphere, and the Galilean satellites. These workshops not only facilitated interdisciplinary exchange but also contributed to training early-career researchers. By providing direct access to mission data and methodologies, these efforts have helped cultivate the next generation of planetary scientists and future mission leaders.

### **Minor Strengths**

#### **The proposal demonstrates Juno's engagement with the amateur community.**

Juno's citizen science model using JunoCam data has set a benchmark for interconnectivity and public engagement. EM2 would continue this success, supporting over 60 astronomical groups and a global network of amateur astronomers contributing near-continuous imaging of Jupiter.

### **Major Weaknesses**

None

### **Minor Weaknesses**

None

## **8. Intrinsic merit of science data to be acquired and archived, but not analyzed**

### **Major Strengths**

**The science data to be acquired and archived (but not analyzed) during EM2 will provide unique and valuable contributions to the characterization of Jupiter's environment, including its magnetosphere, main ring, small moons, and overall system properties.** These datasets will serve as critical resources for future investigations, enabling studies that extend beyond the immediate objectives of the Juno mission. The availability of these data will be particularly beneficial for upcoming missions such as JUICE and Europa Clipper, offering essential context and complementary observations that will enhance their scientific return. Such Juno data include MAG, JEDI, JADE, and Waves, as well as range (distance) measurements to the spacecraft.

### **Minor Strengths**

**The archiving of data from the engineering instruments ASC and SRU that are also being used for science will also be valuable, as will the archiving of the JunoCam images.**

### **Major Weaknesses**

None

### **Minor Weaknesses**

None

## **9. Demonstrated capabilities and expertise of key personnel**

### **Major Strengths**

**The Juno team is led by highly experienced key personnel (both science and project management leadership) who have successfully navigated the mission through numerous challenges and capitalized on unique scientific opportunities, including flybys of the Galilean satellites.** Their leadership has ensured that all necessary data have been collected to address the primary science objectives, while also demonstrating adaptability by utilizing data from ancillary systems (e.g., the SRU and ASC) to enhance scientific returns. The team has been expanded as needed to address new scientific investigations enabled by the evolving orbit (e.g., satellite and ring studies).

### **Minor Strengths**

None

### **Major Weaknesses**

None

### **Minor Weaknesses**

None

## **10. Expected effectiveness of the proposed Professional Development Plan (PDP) in training future mission leaders, and demonstrated progress toward the goals of the PDP in the current mission phase**

### **Major Strengths**

**The proposal demonstrated that EM2 supports NASA's goals to train the next generation of planetary science mission leaders.** During EM2, the team would mentor early-career scientists, providing hands-on experience in mission management, while instrument leads and working group chairs would cultivate future science leaders. The team has identified upcoming leadership and assigned each a mentor corresponding to each instrument on the spacecraft. These early-career scientists have an ownership stake in EM2, having led the development of the proposal and now being tasked with carrying out the science it would accomplish. During EM1, the Juno team led or participated in two early-career workshops to develop the next generation of mission and space scientists. The EM1's PDP identified leadership candidates through open announcements and team recommendations, engaging both internal and external scientists.

### **Minor Strengths**

None

### **Major Weaknesses**

None

### **Minor Weaknesses**

**The proposal did not sufficiently describe whether or how it will develop deputy leaders for instruments other than UVS, MAG, and MWR or for mission leadership positions (PI/PS/PM).** The EM2 PDP plan describes appointing 7 new working group deputy leads and 3 new deputy instrument leads (UVS, MAG, MWR) that will be mentored by more experienced personnel. However, the proposal did not sufficiently describe whether or how it would develop deputy leaders for the remaining instruments or for mission leadership positions (PI/PS/PM). The proposal also did not adequately describe whether deputy leaders might transition into leadership positions within the Juno team. A comparison of Table 9-1 and 9-2 indicates that only Becker has moved from a deputy role to a leadership role in a working group. Deputy leads for the inner satellites (SWG) and ring (RWG) working groups had not yet been identified.

## 11. Comments on Budget

*The panel will not perform a detailed cost analysis of the proposal. However, please give any comments about the details and appropriateness of the baseline budget presented. Budget comments do not contribute to the mission's overall score.*

The proposal clearly states that the budget guidelines were, at least in part, a driver for the unconstrained perijove altitude and ballistic trajectory (Page 11-1 "To fit within budget, EM2 uses a ballistic trajectory"). By making this decision, \$2.2M per year in EM2 has been saved. But putting this funding into an overguide (OG3) has also caused a significant loss of science return for the guideline mission, particularly with respect to investigations of the small inner satellites, and introduced spacecraft hazard risks at main ring crossings and possibly within the most intense radiation regions.

## 12. Budget Overguides (OGs)

*Missions may propose optional OGs to their budgets. Please provide comments about OGs here, including assessment of their potential merit, risk, and/or value.*

### **Overguide #1: PDS4 Conversion for Prime + EM1**

**Overguide #1 Score:** Excellent / Very Good

### **Overguide #1 Comments**

This contribution to conversion of PM and EM1 data from PDS3 to PDS4 formats seems highly cost effective. It will improve the value of the converted data in future investigations requiring data cross referencing.

### **Overguide #2: PDS Archiving for SRU + ASC**

**Overguide #2 Score:** Excellent

### **Overguide #2 Comments**

The Juno team has demonstrated the value of the SRU and ARC engineering instruments for producing new science, e.g., aurora investigations. Archiving of the PM SRU and ASC data should be given high priority.

**Overguide #3: Trajectory Maneuvers****Overguide #3 Score:** Excellent**Overguide #3 Comments**

As detailed elsewhere in this review (Sections 1 and 3), the relegation of this funding to support trajectory maneuvers to an Overguide request is a Major Weakness of the baseline EM2 proposal. Funding this Overguide would lead to greatly improved inner satellite science return as well as allow the spacecraft team to lessen the likelihood of hazardous events, including the possibility of a mission-ending collision with main ring particles.

**Overguide #4: Professional Development****Overguide #4 Score:** Very Good**Overguide #4 Comments**

This funding would provide opportunities to train and contribute for scientists who wish to assume leadership roles, for example in mission management.

**Overguide #5: Inflation****Overguide #5 Score:** Very Good / Good**Overguide #5 Comments**

Inflation adjustment, while important, was seen by the panel as of lower priority than other Overguide requests.

**Overguide #6: PIP [Not Assessed]**

## **Additional Comments for the Mission**

*Comments here may include suggestions, or feedback about portions of the proposal which were not covered by the evaluation criteria. None of these comments affect the score.*

The panel supports the project's plan to archive radio occultation data (e.g., vertical temperature and ionospheric electron density profiles), as per the oral presentation.

Conclusions derived from critical dusk-side cusp measurements of particle entry and energizing processes, including relations to the aurora, will have to be tempered by the known local time dependence of the jovian magnetosphere.

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## 6.2 Lunar Reconnaissance Orbiter

### 2025 NASA Planetary Mission Senior Review Panel Evaluation

|                               |                                                                     |
|-------------------------------|---------------------------------------------------------------------|
| <b>Proposal</b>               | <b>25-PMSR25-0005</b>                                               |
| <b>Title</b>                  | <b>Lunar Reconnaissance Orbiter:<br/>Extended Science Mission 6</b> |
| <b>Principal Investigator</b> | <b>Noah Petro / GSFC</b>                                            |

### Summary of Proposal

The proposed Lunar Reconnaissance Orbiter (LRO) Extended Science Mission 6 (EM6) would continue observations from October 2025 through September 2028. LRO would address questions relating to volatiles, regolith processes, interior dynamics, and the Moon's space interactions. LRO would support ongoing and upcoming lunar missions, including Commercial Lunar Payload Services (CLPS) deliveries and Artemis. Its elliptical orbit, with low passes over the north pole and gradual inclination drift, would provide a unique view of the Moon's polar environment. By the end of EM6, LRO would have observed almost two full 11-year solar cycles, allowing scientists to analyze how solar activity affects the lunar environment.

Importantly, LRO would conduct new observations on several important lunar processes, including the following:

- LRO would expand studies on the distribution of polar volatiles and make new observations to better understand the seasonal stability of these materials with special attention to permanently shadowed regions. Changes in the orbital inclination of the spacecraft would also allow new observations to be made of the volatile deposits at the north pole so that differences between the north and south poles could be assessed.
- LRO data would refine our understanding of the amount and distribution of impact melt deposits associated with large impact craters. Previous observations made by LRO have shown that melt deposits are more widespread than previously thought. By combining measurements made by the Lunar Reconnaissance Orbiter Camera (LROC), the Diviner Lunar Radiometer Experiment (Diviner), the Lunar Orbiter Laser Altimeter (LOLA), and the Miniature Radio-Frequency instrument (Mini-RF), LRO will enable mapping and separation of impact melt from impact ejecta. This result would improve our understanding of lunar melt production and deposition processes, including the effects of target properties on melt volume, the material's spatial distribution, and the effects of mixing melt with pre-existing regolith.

The proposed observations of different lunar materials collected at a variety of incidence, emission, and phase angles through a variety of instruments and wavelengths would provide valuable insights into how regolith development varies with lithology. This research will improve our understanding of regolith properties, enhancing the context for future in situ measurements during upcoming missions.

LRO would collect new observations to search for and document sites of anomalously young volcanic features to determine their locations, characteristics, and distribution, particularly on the lunar farside.

LRO would enhance its study of the lunar exosphere, ionosphere, and radiation environment by increasing the Lyman Alpha Mapping Project (LAMP) detector voltages for more sensitive investigations of volatile species and utilizing adaptive communications for radio occultation experiments. Additionally, it would collect extended Cosmic Ray Telescope for the Effects of Radiation (CRaTER) data through the Sun's 22-year Hale cycle to improve understanding of radiation variations under different solar conditions.

The proposal confirmed that the spacecraft can successfully carry out EM6, with ample power from its solar array and a battery that retains a full margin despite some degradation. As of November 2024, LRO had 10.093 kg of usable propellant, sufficient for station-keeping, orbital adjustments, and minimizing eclipse time during future mission phases.

Overguide 1 would augment LRO support for CLPS landing site selection. The LRO team would provide expertise in hazard mapping, terrain analysis, and illumination simulations. LRO data would be analyzed to identify optimal landing sites based on scientific, technological, and safety criteria.

Overguide 2 would fund the development of a centralized "Return-to-the-Moon" website that would compile mission-specific data, integrate visualization tools such as QuickMap, and provide datasets for researchers.

Overguide 3 requests funding to reprocess Mini-RF data from the South Pole. The Mini-RF instrument collects data at S-band (12.6 cm) and X-band (4.2 cm) wavelengths. Early X-band data (2009-2011) suffered from poor quality due to the limitations of the commercial processing software used. After transitioning to bistatic operations in 2012, a new processing pipeline significantly enhanced X-band data quality, and recent reprocessing of early monostatic observations has shown substantial improvements.

## **Overall Rating: Excellent/Very Good**

*This reflects all criteria for the guideline proposed mission. The Primary criteria carry a greater weight in the overall rating than the Secondary criteria.*

### **Primary Evaluation Criteria (1 – 6)**

#### **1. Intrinsic merit of the proposed science investigations to be undertaken during the EM6.**

##### **Major Strengths**

**LRO would continue to collect important observations of the lunar surface and environment, extending our understanding of the temporal changes related to volatiles, space weathering, and impact cratering.** The proposal established LRO as a critical and unique orbital asset that has provided temporal baseline measurements at the Moon for over a decade. Continued observations collected by the suite of instruments on board LRO would extend our understanding of the lunar atmosphere and radiation environment through a complete 22-year solar cycle, provide additional stereo photogrammetric coverage for a variety of geologic features, and add to the legacy data collected by LRO that would support additional scientific investigations by researchers outside the LRO team.

**The proposed multi-angular observations using LROC off-nadir images, LOLA passive radiometry, LAMP, and Diviner data focused on the photometric properties of regolith would provide valuable new insights into how regolith development depends on the target type.** LRO's multi-instrument approach would observe and analyze lunar swirls, volcanic deposits, crater rays, impact melts, and radar-dark halos at various incidence, emission, and phase angles to better constrain regolith properties. This would advance our understanding of the variety and origin of regolith materials, offering crucial context for in situ measurements during future missions.

**New and innovative LAMP, HGA, and CRaTER measurements of the lunar exosphere, the ionosphere, and the radiation environment would improve understanding of how volatiles are transported and eventually lost to space.** The proposed LAMP measurements would be acquired using increased detector voltages over those used previously that would enable more sensitivity (better signal-to-noise) during off-nadir slew campaigns of volatile exospheric species (e.g., helium, molecular hydrogen, and neon) to track how they are transported and eventually lost to space. LRO's high-gain antenna (HGA) would be used to characterize the properties of the putative dense lunar ionosphere and its variability. Collection of additional CRaTER data through the Sun's 22-year Hale cycle would enhance our understanding of the radiation environment under varying solar conditions.

**The proposed search for anomalously young volcanic features using LOLA passive radiometry, LROC photometry, Mini-RF X-band, and Diviner nighttime coverage would provide valuable data to better understand how volcanic activity persisted into more geologically recent times.** Identification of additional young volcanic features and characterization of these deposits would provide a better spatial and temporal context for this process while advancing our fundamental understanding of the Moon.

## **Minor Strengths**

The proposed multi-instrument observations of impact melt deposits would advance our understanding of cratering processes. The suite of instruments that would be used, including LROC, Diviner, LOLA, and Mini-RF, are uniquely suited to undertaking the proposed comprehensive study of the physical and chemical properties of melt deposits associated with fresh craters. These observations would improve our understanding of impact melt production and deposition processes and improve our ability to recognize impact melts on the lunar surface.

Enhanced nadir coverage of the Amundsen crater would provide a better understanding of the seasonal behavior of volatiles in permanently shadowed regions (PSRs), which is important for understanding the volatile budget of the Moon. The proposed investigations would include observations of the Amundsen PSR, illuminated regions, and transition regions, providing an understanding of the surface roughness and reflectance properties of all thermal regions within the Amundsen crater. These observations would be placed into context with the properties of other polar craters. Understanding the surface characteristics and environments that influence the presence of volatiles is of high scientific importance.

The proposed investigations of the small mare ridges using LROC NAC high-incidence-angle images and stereo coverage would provide important advances toward our understanding of recent tectonic activity on the lunar surface. The proposed additional observations, particularly stereo coverage, would help to quantify the scale of seismic activity as well as the timing of these events.

The expected observation of at least eight new craters in long-baseline image pairs during EM6 would provide valuable new data on the small crater production rate that will be used to age-date lunar surfaces. Documenting the formation of new impact craters on the Moon is a unique capability of the LRO mission, being the only orbiter currently at the Moon, and is important for understanding the impact flux rate on the Moon and throughout the solar system.

## **Major Weaknesses**

**The proposal did not effectively explain the coordination and overlap of many of the proposed investigations.** Five broad science themes were presented along with five strategies for approaching data collection, as well as seventeen individual scientific

objectives. However, the proposal did not adequately explain how these pieces fit together. For example, “Regolith and Impact Processes” are described as the second broad science theme, but this study is listed as the first scientific objective. None of the other science themes or objectives are called out in the proposal’s “Integrated Measurement Strategy” (Foldout 2), which could have provided additional context for how many of the proposed investigations overlap, enhance, or complement one another.

**The proposal did not provide adequate details or justification for the number and locations of new observations to be collected for many of the proposed scientific investigations.** For example, the importance of new observations focused on recent tectonic activity, impact melt deposits, or even volatiles in the South Pole was not effectively described, particularly since LRO has already made extensive observations over the entire lunar surface. The proposal did not contain sufficient details regarding why new images were needed to obtain stereo coverage of particular features, for example, or why data from a specific instrument had not been collected yet for certain areas.

### **Minor Weaknesses**

None noted.

## **2. Responsiveness of the proposal to goals described in the 2023 Decadal Survey “Origins, Worlds, and Life”**

*Missions may optionally also refer to goals in Vision and Voyages for Planetary Science in the Decade 2013-2022 (2011), and/or New Frontiers in the Solar System: An Integrated Exploration Strategy (2003), depending on when the mission was originally proposed. The proposal should make clear from which Decadal Survey each goal is taken. Goals from later Decadal Surveys should be prioritized over earlier ones. Proposals may mention goals from other Decadal Surveys (e.g., from other science divisions at NASA), but these will not contribute to the mission’s evaluation.*

### **Major Strengths**

The LRO Extended Mission proposal was responsive to the Planetary Science Decadal Survey, Origins, Worlds, and Life (OWL), as outlined by the objectives enumerated in Foldout 1. The major decadal-related goals involve the composition and origin of volatiles, differentiation of planetary interiors, characterizing surface geology, the role of small impacts in surface modification, and solar wind and magnetic field interactions. The specific decadal questions associated with each of the seventeen proposed science investigations are also listed in Foldout 1.

### **Minor Strengths**

The LRO Extended Mission proposal was also responsive to NASA's Moon to Mars Strategy and Objectives as well as the Scientific Context for Exploration of the Moon (SCEM),

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **3. Capability of the spacecraft to achieve the proposed science**

### **Major Strengths**

**The proposal demonstrated that power and propellant margins of the spacecraft are sufficient to conduct the proposed extended mission plan.** LRO's solar array will generate more power than required for EM6 and, despite some degradation, the battery still maintains a 100% margin even at the lowest voltage limit that triggers entry to safe mode. As of November 2024, LRO had 10.093 kg of usable propellant. The available fuel is sufficient for station-keeping maneuvers and orbital re-phasing for special science operations or to phase the orbit to minimize time in shadow for long eclipses during EM6 and beyond. The proposal reports that the use of momentum-reduction attitude slews will significantly reduce the current use of ~2 kg of propellant per year, extending the fuel lifetime to at least 2032 and perhaps even to 2037.

### **Minor Strengths**

The spacecraft has aged as expected, and the team has developed effective strategies to deal with any issues that arise (e.g., pointing the high-gain antenna away from the Sun to maintain its temperature).

The mission has been proactive in dealing with challenges due to the White Sands 1 antenna (of the Deep Space Network) going down for upgrades on July 1, 2025. This antenna will be upgraded for the Roman Space Telescope mission and will be available again for LRO on July 1, 2026. While this facility is not available, LRO would use the Solar Dynamics Observatory (SDO) antenna 2 (SDO2), which is also located in White Sands, NM. An agreement has already been reached for eight hours of access per day to this antenna.

## **Major Weaknesses**

None noted.

## **Minor Weaknesses**

None noted.

## **4. Merit of any programmatic objectives**

*This may include activities such as data relay for other NASA or international missions; science that advances the goals of NASA directorates beyond SMD; international cooperation; or other significant non-science activities.*

### **Major Strengths**

**The proposal convincingly demonstrated that LRO would provide critical mission support data for a variety of planned lunar exploration programs, including Artemis and CLPS.** The LRO mission is uniquely qualified to continue in the role of mission support for a variety of lunar exploration missions. As an orbital asset, LRO offers the capability of monitoring real-time surface lander activities from a unique vantage point, while the data it provides can put surface observations into a broader geologic context. EM6 activities would also support surface operations planning in evolving illumination conditions, which would be particularly important under the polar illumination planned for Artemis 3.

**The proposed Diviner Polar Off-Nadir campaigns would support the analysis of candidate Artemis landing sites near the South Pole.** Off-nadir observations will provide novel insights regarding the range of temperatures at sub-Diviner spatial scales. Diviner can leverage the slow rotation of LRO's orbit tracks near the Artemis zone to obtain high-temporal resolution coverage of specific areas by slewing off-nadir to make repeat observations of the same target for several orbits.

### **Minor Strengths**

LRO provides the only way for the United States to monitor and potentially support lunar surface missions by other space agencies and commercial space companies.

## **Major Weaknesses**

None noted.

## **Minor Weaknesses**

The proposal did not adequately describe how the LRO team would balance time commitments for supporting CLPS and Artemis (particularly in their Overguide 1 request) versus the proposed scientific investigations. The science objectives and lunar exploration program support requests would need to be prioritized, given possible time and observational constraints. The expected time/instrument commitments for the Artemis program needs were not sufficiently explained.

## **5. Scientific productivity of the mission team in the current phase**

### **Major Strengths**

**The proposal successfully demonstrated that the LRO science team has remained productive.** During EM5, the LRO team produced ~28.7 publications per year, which compares favorably with a historical average of 29.8 publications per year since 2010. These recent peer-reviewed publications are in well-respected field-specific journals (e.g., EPSL, PSJ, GRL, Icarus, JGR Planets). Recent papers were also published in Science Advances/Nature, demonstrating that broad-interest, high-impact results are still emerging from the team, even though the spacecraft has been operating for over a decade.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **6. Performance of the mission in archiving data to the PDS in the current phase**

### **Major Strengths**

**LRO continues to provide the lunar science community with a wealth of data products and PDS-archived data supporting a wide range of lunar science investigations.** The volume of LRO's archived data takes up ~60% of the total PDS data volume or 1.662 petabytes. These data are consistently delivered to the PDS on time, according to the LRO PDS Mission Report Card.

**All LRO legacy data have been successfully migrated to the new PDS4 format.** All new data being acquired are also being delivered to the PDS in the PDS4 format by the LRO instrument teams.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

The most recent LAMP RDRs and DIVINER data releases have been delayed, according to the LRO Mission Report Card provided to the panel by the PDS, but are "in progress".

## **Secondary Evaluation Criteria (7 – 10)**

## **7. Extent to which the science community beyond the mission science team utilizes data and conducts published research**

### **Major Strengths**

**The proposal demonstrated that the lunar science and exploration communities have benefited enormously from the data provided by LRO.** The number of non-member publications has more than doubled in the past 4 years relative to the preceding decade (an average of 120.5 publications/year since 2021 compared to 49.6 per year from 2010-2020). The recent increase in publications reflects a renewed

interest in data relevant to lunar science and exploration, which LRO is uniquely suited to provide.

### **Minor Strengths**

QuickMap is a widely used online map interface that allows users to quickly browse and analyze LRO data. The LRO mission provides data to the operators of this site. The site continues to be a valuable and useful resource for the scientific community and the interested public and is complementary to the formal data archived by the PDS.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **8. Intrinsic merit of science data to be acquired and archived but not analyzed.**

### **Major Strengths**

**LRO continues to make observations with a suite of instruments that build on the archive of data collected during all prior mission phases.** Some proposed EM6 scientific objectives require a number of targeted observations to be made by multiple instruments; however, the spacecraft would also continue to collect data from all the instruments in a passive or untargeted mode. This unique dataset is being used extensively by planetary scientists and represents a wealth of information to be mined by future planetary scientists.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

The proposal did not adequately address the types, amounts, and characteristics of new data that would be collected. These new data were not placed into context with the large amount of data LRO has already collected.

## **9. Demonstrated capabilities and expertise of key personnel**

### **Major Strengths**

**The LRO team is composed of experienced and highly qualified experts in science, instrumentation, and mission leadership and management.** There is also broad expertise for each instrument team that spans a range of career levels, supporting new ideas and approaches.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **10. Expected effectiveness of the proposed Professional Development Plan (PDP) in training future mission leaders, and demonstrated progress toward the goals of the PDP in the current mission phase**

### **Major Strengths**

None noted.

## Minor Strengths

The proposal described how several early- and mid-career scientists were selected as theme leads for the development of this proposal and stated the same individuals would support the project science team and instrument teams in accomplishing science goals.

The proposal described some opportunities for existing team members to learn about mission operations through open mission science meetings.

## Major Weaknesses

**The proposal did not present a substantive professional development plan.** The proposal did not provide an adequate description of how future mission leaders would be trained, nor did it provide sufficient details regarding how progress toward meeting the goals of the PDP proposed for EM6 have been made.

## Minor Weaknesses

None noted.

## 11. Comments on Budget

*The panel will not perform a detailed cost analysis of the proposal. However, please give any comments about the details and appropriateness of the baseline budget presented. Budget comments do not contribute to the mission's overall score.*

The proposed mission budget was consistent with that of EM5. The proposal provided adequate justification for the requested funding at this level.

## 12. Budget Overguides (OGs)

*Missions may propose optional OGs to their budgets. Please provide comments about OGs here, including an assessment of their potential merit, risk, and/or value.*

**Overguide #1: CLPS Landing Site Analysis**

**Overguide #1 Score:** Excellent/Very Good

**Overguide #1 Comments**

Overguide #1 requested funding for LRO to acquire multi-instrument data that target landing sites to support CLPS (and international missions) before, during, and after these landings. These data would provide valuable resources to aid in scientific investigations while providing information for placing surface observations into a

broader geologic context and potentially providing data that would aid in operational planning. This information would be valuable to the success of the CLPS program.

### **Overguide #2: Return-to-the-Moon Website**

**Overguide #2 Score:** Good

#### **Overguide #2 Comments**

Overguide #2 requested funding to create a website that would combine all relevant LRO observations and data products related to each CLPS mission location. However, the request did not convincingly present the need to develop this new website. The proposal did not provide sufficient detail regarding what data would be provided, nor did it sufficiently justify the need for a new website rather than just an update to the existing QuickMap website.

### **Overguide #3: Mini-RF Reprocessing**

**Overguide #3 Score:** Excellent/Very Good

#### **Overguide #3 Comments**

Overguide #3 would fund the redevelopment of the bistatic processor to add the capability for ingesting and reprocessing Mini-RF monostatic X-band observations of the South Pole region. These reprocessed data would provide new insights into the cm-scale surface roughness of regions identified for future Artemis missions as well as CLPS missions to the South Pole area. They would also represent valuable datasets for scientific analyses of this southern region of the Moon.

### **Additional Comments for the Mission**

*Comments here may include suggestions or feedback about portions of the proposal that were not covered by the evaluation criteria. None of these comments affect the score.*

The mission should consider restarting the LRO workshops that were held previously at conferences during the nominal LRO mission phase. These workshops provided useful information about instrument operations, the types of data that they collected, as well as how to use and process these data. Specific workshops for educators also explained how our understanding of the Moon has changed since Apollo. Because it has been over a decade since these workshops were held, these new workshops would benefit younger and even mid-career scientists and educators who have matured during the life of LRO.

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## 6.3 Mars Odyssey

### 2025 NASA Planetary Mission Senior Review Panel Evaluation

**Proposal** 25-PMSR25-0001  
**Title** 2001 Mars Odyssey Tenth Extended Mission  
**Principal Investigator** Jeff Plaut / JPL

#### Summary of Proposal

The Odyssey spacecraft arrived at Mars in October 2001, began acquiring scientific observations in early 2002, and is currently conducting its ninth extended mission (E9). The spacecraft carries the Thermal Emission Imaging System (THEMIS), the Gamma Ray Spectrometer (GRS) instrument suite, and the Mars Radiation Environment Experiment (MARIE). The GRS instrument suite includes the GRS sensor head, the High-Energy Neutron Spectrometer (HEND), and the Neutron Spectrometer (NS). Although MARIE failed in 2003 and the GRS sensor head failed in 2009, THEMIS, HEND, and NS are still operational today. The proposed tenth extended mission (E10) will continue Odyssey's scientific and programmatic activities through FY28. E10 would continue leveraging the current near-terminator orbit to advance THEMIS investigations of the surface and the atmosphere. E10 THEMIS investigations focused on the surface and subsurface will address ancient and modern habitability, recent impact processes, geological and surface processes, thermophysical properties of the surface, polar and high-latitude processes, and subsurface ice mapping, and will assess rock abundance and shape. Furthermore, E10 will continue the long-term characterization of the seasonal and spatial variations of the atmospheric state, including limb retrievals of atmospheric dust and water ice. The ongoing collection and archiving of HEND and NS data would facilitate monitoring the thickness of seasonal CO<sub>2</sub> frost, mapping sub-surface hydrogen abundance, inferring the depth of water, and monitoring the radiation field on Mars. Programmatic support includes data relay for two Mars Exploration Program (MEP) surface assets (Curiosity and Perseverance).

#### **Overall Rating:** Excellent / Very Good

*This reflects all criteria for the guideline proposed mission. The Primary criteria carry a greater weight in the overall rating than the Secondary criteria.*

## Primary Evaluation Criteria

### 1. Intrinsic merit of the proposed science investigations to be undertaken during the EM

#### Major Strengths

**The proposed E10 atmospheric observations would enable the continued long-term characterization of the seasonal and spatial variations of the atmospheric state, increasing our understanding of the current Martian climate.**

The planned atmospheric temperature, dust, and water ice observations would add to the existing extended temporal baseline of THEMIS observations. Limb retrievals of dust and water ice obtained during the four planned E10 campaigns would provide additional constraints for atmospheric models. These observations would complement ongoing investigations by the Mars Reconnaissance Orbiter (MRO) Mars Climate Sounder (MCS) instrument and observations acquired by the Emirates Mars Mission (EMM) Emirates Mars Infrared Sounder (EMIRS) and Emirates eXploration Imager (EXI) instruments.

**During E10, THEMIS would continue to fill coverage gaps at mid and high latitudes with post-sunset observations, permitting additional thermophysical assessments of higher latitude surfaces.** Thermal inertia is a key input parameter for subsurface models and for models of the atmosphere and surface/atmosphere interactions and ice stability. Currently, there are gaps in coverage at northern mid-latitudes where there is a prevalence of low thermal inertia units and ice, so this mapping effort is of high scientific importance.

**The proposed E10 studies of fan-shaped deposits are well-justified and could provide additional insight into Hesperian-Amazonian water-driven sediment transport processes and habitability.** Proof of concept results were recently published in three E9 papers, emphasizing the utility of these measurements. These early results indicate that inferred granulometry and cementation states of measured Martian fans are generally inconsistent with terrestrial debris-dominated fans and that the Martian fans may have formed under lower-energy flow conditions. The planned THEMIS thermal inertia and emissivity observations can be paired with high-resolution imagery from HiRISE to deduce the grain size, induration state, and morphological properties of additional alluvial fan deposits on Mars.

#### Minor Strengths

Mars Odyssey would continue to monitor for thermal “hot spots” (volcanic or hydrothermal), the detection of which would represent a transformative result in our understanding of modern Martian geological activity and habitability. Although there is a low likelihood of a positive hot spot detection (given the null results throughout the mission to date), the E10 campaign would include targets identified by the InSight

mission as regions of marsquake epicenters that may be associated with local volcanic activity.

Mars Odyssey's E10 investigation of chlorides could provide improved estimates of the abundance of salt within the deposits, which may provide additional constraints on formation mechanisms and thus advance understanding of both habitability and climate evolution. The proposed investigation would use a novel approach that includes thermal modeling of off-nadir observations, creating synthetic mixtures, and comparing their properties to THEMIS observations (i.e., forward modeling spectra for different salt abundances and comparing them to derived THEMIS spectra).

### **Major Weaknesses**

**The proposal did not convincingly demonstrate that all the planned E10 scientific investigations would be scientifically significant and require new observations.**

For example, while the proposal claimed that analyzing the thermophysical properties of explosive volcanic deposits (Section 4.1.4) could constrain a variety of deposit properties and emplacement conditions, it did not clearly explain how the new data could be used to support these inferences. Additionally, the proposal did not offer compelling evidence that more observations are needed to complete the rock abundance map (Section 4.1.8), particularly since the PDART program is already funding efforts to produce such global maps (discussed in Section 3.1.6). Furthermore, the proposal did not substantiate the claim that rock shape (i.e., sphericity) can unambiguously indicate the emplacement process (see, for example, Craddock and Golombek, *Icarus*, 274, 2016). Similarly, the proposal did not adequately justify the utility of the crater degradation campaign (Section 4.1.4), and it overlooked several potential issues that would influence degradation rates at these scales (e.g., geologic heterogeneity, contamination by primary craters, local environmental conditions).

### **Minor Weaknesses**

None noted.

## **2. Responsiveness of the proposal to goals described in the 2023 Decadal Survey “Origins, Worlds, and Life”**

*Missions may optionally also refer to goals in Vision and Voyages for Planetary Science in the Decade 2013-2022 (2011), and/or New Frontiers in the Solar System: An Integrated Exploration Strategy (2003), depending on when the mission was originally proposed. The proposal should make clear from which Decadal Survey each goal is taken. Goals from later Decadal Surveys should be prioritized over earlier ones. Proposals may mention goals from other Decadal Surveys (e.g., from other science divisions at NASA), but these will not contribute to the mission's evaluation.*

### **Major Strengths**

**The proposal demonstrated that many of the proposed E10 investigations are aligned with many of the Origins, Worlds, and Life (OWL) Planetary and Astrobiology Decadal Survey questions and subquestions.** The proposed investigations were mapped to multiple subquestions related to OWL Priority Questions 4 (impacts and dynamics), 5 (solid body interiors and surfaces), 6 (solid body

atmospheres, exosphere, magnetospheres, and climate evolution), and 10 (dynamic habitability).

#### **Minor Strengths**

None noted.

#### **Major Weaknesses**

None noted.

#### **Minor Weaknesses**

In several cases, the proposal did not convincingly demonstrate a direct link between the proposed investigations and the referenced Decadal Survey subquestions. For example, the proposal did not demonstrate a clear link between rock abundance and shape (Investigation 4.1.8) and the referenced subquestion 5.4b (“Where and how have glacial processes sculpted landscapes?”). As another example, the proposal did not adequately explain how thermophysical studies (Investigation 4.1.5) would meaningfully address referenced subquestion 6.2d (“How does orbital forcing... govern climate change and surface volatile redistribution on... bodies with volatile cycles like modern Mars”).

### **3. Capability of the spacecraft to achieve the proposed science**

#### **Major Strengths**

**The Mars Odyssey team continues to successfully manage a functioning spacecraft and instrument payload.** The health of the hardware is particularly impressive given the age (almost 24 years) of the spacecraft. The team has well-formulated mitigation strategies that have been developed for spacecraft subsystems. For example, with the failure of the X-axis reaction wheel as of December 2013, Odyssey currently does not have reaction wheel redundancy. The proposal included a clear plan for using thrusters for attitude control of the spacecraft in the event of an additional reaction wheel failure.

#### **Minor Strengths**

The THEMIS, HEND, and NS instruments are unmatched in their capabilities by instruments on any other spacecraft at Mars. Those capabilities are key for carrying out the proposed science objectives of this extended mission. The THEMIS instrument is the only infrared camera currently orbiting Mars and offers a unique data set.

#### **Major Weaknesses**

None noted.

## Minor Weaknesses

The proposal did not include an adequate plan for the prioritization of the proposed scientific investigations in the event that E10 could not be completed in its entirety. The low mass of usable propellant (3.2 kg) with its high uncertainty ( $\pm 2.0$  kg [ $3\sigma$ ] or  $\pm 1.33$  kg [ $2\sigma$ ]) represents a risk to the duration and success of the extended mission. This risk could be realized early in the event of a safe-mode event or loss of a reaction wheel, either of which would increase propellant usage. [Note: E10 requires 1.3 kg of propellant for successful completion of all objectives in the absence of any safe mode events or other such realized risks.]

## 4. Merit of any programmatic objectives

*This may include activities such as data relay for other NASA or international missions; science which advances the goals of NASA directorates beyond SMD; international cooperation; or other significant non-science activities.*

## Major Strengths

**Odyssey would continue providing valuable telecom relays between the surface of Mars and Earth for nominal and critical event support.** Based on the relay information provided by MEP, 14% of Perseverance and 13% of Curiosity relay sessions were recently provided by Odyssey. The local time (~6:00 am / pm LMST) of Odyssey's orbit is convenient for the overpass scheduling of NASA's landed rover assets.

## Minor Strengths

The proposed use of the HEND and NS instruments to detect gamma-ray bursts at the solar distance of 1.5 AU represents a valuable cross-divisional activity that supports Astrophysics and Heliophysics program objectives.

## Major Weaknesses

None noted.

## Minor Weaknesses

None noted.

## 5. Scientific productivity of the mission team in the current phase

### Major Strengths

**The proposal clearly demonstrated that the Odyssey team completed and published a variety of important scientific investigations on Mars' surface, subsurface, and atmosphere during E9.** The team averaged approximately 6 publications per year. A significant number (e.g., more than half in 2024) of those publications were led by students or post-doctoral researchers.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

## **6. Performance of the mission in archiving data to the PDS in the current phase**

### **Major Strengths**

**The Odyssey team has a demonstrated record of rigorous preparation and timely delivery of validated data archives to the PDS, and a well-developed plan has been established for E10.** The proposal indicated that the instrument teams have updated their data delivery pipelines to the new PDS4 standards. Deliveries to the PDS of raw and higher-level products, consisting of data acquired during the period 9 to 6 months prior to the delivery date, would be made every three months.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **Secondary Evaluation Criteria**

### **7. Extent to which the science community beyond the mission science team utilizes data and conducts published research**

### **Major Strengths**

**A considerable number of outside publications showcase the community's use of Odyssey data.** In 2024, there were more than 20 publications led by non-team members that made use of Odyssey data, continuing a trend of high usage that dates back to 2003.

**The team provides THEMIS data to planetary scientists and the public in an easy-to-access form through the JMARS tool, which has significantly increased community usage of these data.** As such, the PDS download statistics may significantly underestimate the use of these data by the broader community.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **8. Intrinsic merit of science data to be acquired and archived, but not analyzed**

### **Major Strengths**

**Although no funding is included in E10 for HEND/NS science analysis, continued collection and archiving of the unique HEND/NS data are of high scientific value for the community and could be useful for supporting future landed human missions.** The proposal identified multiple avenues of high-value scientific research that could be addressed with HEND/NS data, including monitoring the thickness of seasonal CO<sub>2</sub> frost, mapping sub-surface hydrogen abundance and inferring the depth of water, and monitoring the radiation field at Mars.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

Based on the titles of the papers listed in Appendix A4, it is not clear that the community is using THEMIS data from terminator (~6:00 am / pm local time) orbits. It is therefore not clear that these data will prove to be of high intrinsic value for the community.

## **9. Demonstrated capabilities and expertise of key personnel**

### **Major Strengths**

**The longevity of the team over more than 23 years in flight demonstrates effective leadership, management, and cohesion to meet the evolving demands of the mission in terms of engineering and science.** Longstanding partnerships between JPL, LMSS, and other team institutions provide confidence that continued working relationships for the benefit of the mission will continue to be successful.

### **Minor Strengths**

None noted.

## **Major Weaknesses**

None noted.

## **Minor Weaknesses**

Although likely beyond their control, the Odyssey team did not have a permanent project manager at the time of their proposal or presentation to the panel. The absence of a permanent PM represents a risk to Odyssey's E10 overall success. Filling this position would quickly resolve this issue.

### **10. Expected effectiveness of the proposed Professional Development Plan (PDP) in training future mission leaders, and demonstrated progress toward the goals of the PDP in the current mission phase**

#### **Major Strengths**

None noted.

#### **Minor Strengths**

The proposal identified several team members who have historically gained the necessary experience on the Odyssey team to transition to leadership roles, either on Odyssey or on other missions. For example, Karl Harshman has become the PI of GRS (2024, during E9), Laura Kerber has become the Deputy Project Scientist of Odyssey (2018), and Victoria Hamilton has become the THEMIS Deputy PI (2016).

#### **Major Weaknesses**

None noted.

#### **Minor Weaknesses**

The proposal did not adequately describe a formal "Professional Development Plan". Instead, it discussed the history of successful career training and opportunities provided by the Odyssey mission. Although historical evidence suggests success in the future, a documented plan would strengthen the likelihood of successfully training the next generation of scientists and engineers.

### **11. Comments on Budget**

*The panel will not perform a detailed cost analysis of the proposal. However, please give any comments about the details and appropriateness of the baseline budget presented.*

#### **Major Strengths**

**Although the budget has remained flat, the Odyssey team has a demonstrated record of producing high-value science for NASA and the community and a well-developed plan for continuing to do so in E10.** The team has demonstrated that they have the range of expertise and the FTEs necessary to undertake the proposed extended mission.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **12. Comments on Budget Overguides (OGs)**

*Missions may propose optional OGs to their budgets. Please provide comments about OGs here, including assessment of their potential merit, risk, and/or value.*

**Overguide #1:** Reprocess and Convert Previously Acquired THEMIS Data from PDS3 to PDS4

**Overguide #1 Score:** Excellent

### **Overguide #1 Comments**

This overguide budget request would fund the Odyssey team to reprocess and convert all previously acquired THEMIS data to PDS4 format. This activity is well justified and important, given the high intrinsic scientific value of the THEMIS dataset and the high demand for these data by the broader science community. Converting Odyssey data to PDS4 would maximize the useability of THEMIS data for future scientists and engineers. The proposal makes a convincing case that it is important to complete this data reprocessing and archiving now by the Odyssey team, who have intimate knowledge of the data, rather than waiting until a time when the project has ended and team members have dispersed.

### **Additional Comments for the Mission**

*Comments here may include suggestions, or feedback about portions of the proposal which were not covered by the evaluation criteria. None of these comments affect the score.*

None noted.

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## 6.4 Mars Reconnaissance Orbiter

### 2025 NASA Planetary Mission Senior Review Panel Evaluation

**Proposal** 25-PMSR25-0003  
**Title** Exploring a Changing Mars – MRO EM7  
**Principal Investigator** Richard Zurek / JPL

#### Summary of Proposal

The proposed science objectives for the Mars Reconnaissance Orbiter (MRO) 7th Extended Mission (EM7) are extensions of science objectives and accomplishments from EM6, and continue to build a long temporal database that records surface and atmospheric changes on Mars. For EM7 the MRO team proposes 15 science investigations to address four goals: (1) Explore the climate record of Early Mars, using High-Resolution Imaging Science Experiment (HiRISE), Context Imager (CTX), and Shallow Radar (SHARAD) observations of ancient sedimentary and volcanic deposits, and constrain remanent magnetism through ionospheric measurements during solar events, (2) Explore climate change of Late Mars by studying polar ice, glacial terrains, ice-filled craters, and stacked lava flows using HiRISE, CTX, and SHARAD, (3) Explore surface, volatile, and aeolian changes on Modern Mars, by observing gullies and dunes, and by quantifying the current rate of impact cratering using HiRISE and CTX, (4) Explore diurnal and longer atmospheric changes on Modern Mars, by extending the daily weather record to a second decade of Mars years and by observations of the movement and loss of water vapor within the atmosphere using Mars Color Imager (MARCI) and Mars Climate Sounder (MCS). The spacecraft remains healthy, its orbit is appropriate, and it has sufficient reserves to conduct the proposed investigations. Instruments would utilize new observing modes that require frequent and sometimes very large spacecraft rolls. MRO would also continue to provide programmatic support for surface rover missions by relaying data and commands, as well as conducting site reconnaissance and environmental measurements as needed.

#### **Overall Rating:** Excellent/Very Good

*This reflects all criteria for the guideline proposed mission. The Primary criteria carry a greater weight in the overall rating than the Secondary criteria.*

## **Primary Evaluation Criteria**

### **1. Intrinsic merit of the proposed science investigations to be undertaken during the EM**

#### **Major Strengths**

The proposed HiRISE, CTX, and SHARAD observations that explore climate change of Early Mars (Goal 1) and ice, volcanics, and related climate change of Late Mars (Goal 2) would further advance the record and documentation of Mars history, which is fundamental to understanding drivers and effects on habitability.

Although ancient Mars magmatism has been extensively investigated, more recent volcanism remains a largely understudied area. Towards that end, the proposed mapping of crosscutting strata, rootless cones, and lava flow margins in the youngest terrains (the proposal's Investigation 8 in Goal 2) could lead to significant insights into recent volcanism and the later thermal history of the planet.

Continued monitoring and characterization of active geologic processes of Modern Mars (Goal 3) has the potential to better define volatile and sediment movements on gully slopes and in dunes, and to help quantify current impact rates.

Continued monitoring to refine trends, cyclic patterns, and inter-seasonal variability in weather and dust storm activity using MARCI and MCS would aid in understanding atmospheric changes on Modern Mars (Goal 4).

The use of very large spacecraft rolls (to 120 degrees) gives the radar altimeter a less obstructed view of the planet and would allow SHARAD to probe deeper into the subsurface, and improve signal-to-noise ratio, which provides for substantial enhancement in discerning layering in radargrams. The new data would relate to and improve upon the understanding of paleoclimate and recent reactivation of subsurface volatiles.

Well-described synergies in data among the MRO instruments would further the accomplishment of the proposed investigations. As one example, the combination of HiRISE, CTX and SHARAD observations improves the likelihood of detection of near-surface ice deposits. Another example is the combined use of MCS and MARCI to provide weather reports at landing sites for missions on approach to Mars.

#### **Minor Strengths**

The proposal demonstrated an innovative use of SHARAD Total Electron Content to improve the spatial resolution (~100 km) of magnetic anomalies in the ancient Martian crust. High-resolution mapping could reveal shorter-wavelength variations in magnetic field strength than were resolvable from previous orbital measurements. The merit of this investigation would rise in priority if these data lead to new insight about the timing or mechanisms of magnetization (and demagnetization).

Further quantifying the distribution of gravity waves using cross-track observations of the atmospheric limb over the full MRO orbit would allow higher sensitivity to the detection of gravity waves and aid in the investigation of gravity wave sources.

Synergies with other Mars missions through joint observations could increase the value of any single mission's data. As one example, the MCS team proposes to work with rover, TGO, and MAVEN teams to quantify the movement of water vapor between the surface and varying levels of the atmosphere.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

The proposal and discussion did not convincingly demonstrate how the identification of alteration minerals that had been best addressed by CRISM measurements in the primary and prior extended missions, given that CRISM is no longer operable, could be realized by other MRO instruments. The proposal states that "HiRISE color and albedo based assessments will complement and extend spectral results from nearby CRISM data taken previously, as CRISM is no longer operating." The HiRISE color data alone cannot confidently identify alteration minerals.

Many of the proposed observations are not described as tests of scientific hypotheses, but instead involve repeated observations for building a longer temporal baseline. Examples are continued monitoring of weather and new impact craters. The proposal provides no indication of how many of these additional observations would be needed to address various science objectives.

Many of the proposed investigations depend on HiRISE observations; however, the potential loss of additional CCDs and/or increasingly frequent bit-flip errors in HiRISE data comprise the greatest risks to completing the science goals. The proposal does not adequately clarify the effects that changes in HiRISE capability would have on the various investigations.

## **2. Responsiveness of the proposal to goals described in the 2023 Decadal Survey “Origins, Worlds, and Life”**

*Missions may optionally also refer to goals in Vision and Voyages for Planetary Science in the Decade 2013-2022 (2011), and/or New Frontiers in the Solar System: An Integrated Exploration Strategy (2003), depending on when the mission was originally proposed. The proposal should make clear from which Decadal Survey each goal is taken. Goals from later Decadal Surveys should be prioritized over earlier ones. Proposals may mention goals from other Decadal Surveys (e.g., from other science divisions at NASA), but these will not contribute to the mission’s evaluation.*

### **Major Strengths**

The Science Traceability Matrix demonstrates that the proposal addresses priority science questions in the Decadal Survey: Origins, Worlds, and Life. The fact that the proposers are responsive to the most current Decadal, rather than an earlier one in effect when the MRO mission concept was developed, demonstrates the continued usefulness of this mission's data.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **3. Capability of the spacecraft to achieve the proposed science**

### **Major Strengths**

Most instruments and spacecraft sub-systems are rated as good to excellent. All are healthy, or healthy enough, to collect the proposed datasets during EM7. The proposal clearly described the overall mission health and status of instruments and subsystems, including problems and failures of specific MRO instrument and spacecraft components, providing confidence that a thorough assessment has been completed and objectives of the extended mission have a high probability of being met.

EM7 would include a new cadence of roll operations - utilizing frequent changes in spacecraft attitude (small and large rolls, up to 30 degrees) - to adjust to changes in instrument capabilities. The team has ample experience in conducting these rolls, and they have the necessary resources to take on the increased planning activity. The new application of very large rolls (up to 120 degrees) of the spacecraft (on a roughly monthly cadence) to expand SHARAD observations would be an innovative use of the spacecraft in this extended mission.

The Mars Exploration Program at JPL conducted a Mars Projects Operational Risk Review and found that known risks present low-probability threats to the EM7 program, and none of the risks were classified as “high.” Known risks include limited remaining operational lifetime of the Inertial Measurement Unit (IMU-1), failed Ka band component of the Deep Space Transponder, and HiRISE loss of additional charge-coupled device memory modules. In addition, the project has mitigation plans in place in case any of the risks are realized.

### **Minor Strengths**

Project Management is stewarding its resources to extend the mission lifetime. For example, spacecraft propellant reserves are high and would be sufficient to support spacecraft operation through EM7 and beyond. The proposal also describes resiliency in addressing engineering and operational challenges. As one example, IMU-B is in good health, but the IMU-A Y axis has begun to degrade. To mitigate this risk the project has developed an All-Stellar Mode (ASM) that uses the star trackers. The ASM is currently used ~93% of the time, allowing the IMUs to be off, thus limiting the laser degradation so that the IMUs can be used during specific critical operations.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

The X-Band TWTA is nearing its end of life and is a single-string failure point for the communication system. The project demonstrated that the risk of TWTA failure during EM7, however, is minimal.

## **4. Merit of any programmatic objectives**

*This may include activities such as data relay for other NASA or international missions; science which advances the goals of NASA directorates beyond SMD; international cooperation; or other significant non-science activities.*

### **Major Strengths**

During EM7, MRO would continue to support ongoing landed missions. MRO serves as a significant and reliable UHF communications relay for rover missions, HiRISE imagery continues to be used for rover traverse planning, and MARCI and MCS provide weather watches for *Curiosity* and *Perseverance* operations.

### **Minor Strengths**

SHARAD observations contribute to the characterization of the Martian radiation environment, which is relevant for future human exploration.

The proposal discussed how the environmental data sets can be further exploited as NASA’s Moon to Mars (M2M) program shifts attention to missions sending humans to Mars. For example, specific objectives in M2M applied science that could be

addressable with MRO data include: characterizing modern environments with respect to weather, impacts, and dust; coordinating orbital and surface platforms to optimize science; and characterizing accessible resources on Mars to enable in situ resource utilization.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **5. Scientific productivity of the mission team in the current phase**

### **Major Strengths**

Team-led publications in peer-reviewed journals (68 papers in the last three years) demonstrate high scientific productivity during EM6. This high productivity has continued for many extended missions, despite steadily decreasing science funding.

### **Minor Strengths**

The continued addition of new Co-Is contributes to maintaining science productivity. A significant number of team publications are led by early-career scientists.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **6. Performance of the mission in archiving data to the PDS in the current phase**

### **Major Strengths**

The MRO Team archives an impressive quantity of data (>56.5 TB) every quarter to the PDS, with instrument teams providing validation prior to submission. MRO data products have been delivered on time, as indicated by the report from the PDS regarding performance in archiving data over the past cycle.

### **Minor Strengths**

Conversion of data products to PDS4 format is ongoing, and the proposal adequately describes the varying status among the different instruments. HiRISE, CRISM, CTX, and MARCI have made significant progress in producing PDS4 label templates and

products during EM6. This conversion work is supported by an overguide proposed and funded in the previous PMSR.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

SHARAD deliveries to the PDS are slightly delayed, and Italian EDR and RDR products remain in PDS3 format, apparently due to contracting delays. Conversion of MCS data products to PDS4 format has been delayed, due to changes in team membership and necessary response to engineering challenges.

## **Secondary Evaluation Criteria**

### **7. Extent to which the science community beyond the mission science team utilizes data and conducts published research**

#### **Major Strengths**

Non-team publications (478 in three years) demonstrate an impressive use of MRO data (especially HiRISE, CTX, and SHARAD) by the broader scientific community.

During each quarter of the last three years, a significant quantity of data were downloaded from the PDS Geosciences Node (SHARAD, CRISM, Gravity), the Planetary Cartography and Imaging Node (HiRISE, CTX, MARCI), and the Atmospheres Node (MCS).

#### **Minor Strengths**

HiRISE maintains a list of targets for individuals who are not part of the MRO team (HiWish). These targeting requests are not necessarily tied to Decadal Survey priorities, but they constitute a useful public outreach function.

#### **Major Weaknesses**

None noted.

#### **Minor Weaknesses**

None noted.

### **8. Intrinsic merit of science data to be acquired and archived, but not analyzed**

#### **Major Strengths**

None noted.

### **Minor Strengths**

There is intrinsic scientific value in global data sets, and some portion of that value cannot be foreseen. Some EM7 data to be acquired and archived (but not analyzed) would likely be of high scientific value to future investigators. Previous applications of such data have addressed wide-ranging scientific topics well beyond those described in prior extended mission proposals.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **9. Demonstrated capabilities and expertise of key personnel**

### **Major Strengths**

The named key personnel are capable and experienced. Generational changes in the position of Project Scientist and in three instrument PIs (HiRISE, MCS, SHARAD) are now required, and the individuals identified in the proposal for these new appointments have experience as deputies in these roles and are well qualified for these higher-level positions.

### **Minor Strengths**

The project has exceptional continuity in the proposed organizational structure from previous extended missions.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **10. Expected effectiveness of the proposed Professional Development Plan (PDP) in training future mission leaders, and demonstrated progress toward the goals of the PDP in the current mission phase**

### **Major Strengths**

The proposal demonstrates a robust and resilient PDP, highlighting the record of progression of Co-Is to deputy team leaders and Deputy PIs, and eventually to Project

Leads. Also, other Co-Is have gone on to key positions on other spacecraft missions such as *VERITAS*, *Perseverance*, and *Lunar Trailblazer*.

New leadership at both the project and team investigation levels is fostered by the recognition of high-performing science investigation team staff such as Co-Is, mentoring of new science team members, and involving students in research and observation planning.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **11. Comments on Budget**

*The panel will not perform a detailed cost analysis of the proposal. However, please give any comments about the details and appropriateness of the baseline budget presented. Budget comments do not contribute to the mission's overall score.*

Overall planned costs for EM7 meet the PMSR25 guideline. Science costs vary from year to year, but at best are basically flat funded. Increases in project costs during EM7 will be incurred because of growth in flight system costs (8%) and mandated cybersecurity requirements for the ground data system (6%).

The increase in flight system cost was not explained in the proposal, but clarification from the project indicated the increase is due to anticipated cost growth in a flight system contract with LMSSC to be negotiated for EM7.

## **12. Budget Overguides (OGs)**

*Missions may propose optional OGs to their budgets. Please provide comments about OGs here, including assessment of their potential merit, risk, and/or value.*

### **Overguide 1: Low-Density Parity Check for Electra**

**Overguide #1 Score:** Very Good

#### **Overguide #1 Comments**

Overguide funding is requested for a Low-Density Parity Check software upgrade to the Electra communication system. *Perseverance* and *Curiosity* would benefit from a ~40% increase in relay throughput to MRO, and a future *Mars Sample Return Lander* or other landed asset also would benefit. Increased relay volume would not affect MRO operations, nor impact MRO's relay to the DSN.

The Electra upgrade would not address or affect MRO science goals in EM7.

#### **Additional Comments for the Mission**

*Comments here may include suggestions, or feedback about portions of the proposal which were not covered by the evaluation criteria. None of these comments affect the score.*

None noted.

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## **6.5 MAVEN**

### **2025 NASA Planetary Mission Senior Review Panel Evaluation**

**Proposal**                      **25-PMSR25-0006**  
**Title**                          **MAVEN Planetary Mission Senior Review [EM6]**  
**Principal Investigator** **Shannon Curry / University of Colorado**

### **Summary of Proposal**

The Extended Mission 6 (EM6) proposal for the MAVEN mission includes 12 investigations under four goals that would advance the understanding of how dust storms, extreme solar activity, and crustal magnetic fields affect Martian atmospheric evolution and climate history. Goal 1 centers on a coordinated campaign of in situ and remote sensing investigations of the atmosphere to characterize the reservoir in the upper atmosphere for escape. MAVEN would characterize the abundance of water in the upper atmosphere, investigate aurora, and examine the effects of dust storms on atmospheric variability. Goal 2 focuses on the physical processes governing the acceleration of ions from the exobase. The investigations include examining the initial energization, measuring the effects of dust, and studying the role of electric currents in escape. Goal 3 assesses the response of the atmosphere to heating expected from intense solar storms during the declining phase of the solar cycle. These investigations include establishing the atmospheric response to solar flares and radiation, the coupled ionosphere-magnetosphere response to high-energy particles, and opportunistic observations during alignments of Earth and Mars. Goal 4 also focuses on the effects of intense solar storms, with an emphasis on atmospheric escape. MAVEN would characterize ion escape in the plume and tail, photochemical escape, ion precipitation, and sputtering.

The proposed investigations are linked to the 2022 “Origins, Worlds, and Life” Decadal Survey questions 6 (Solid Body Atmospheres, Exospheres, Magnetospheres and Climate Evolution) and 10 (Dynamic Habitability). The MAVEN spacecraft and its instruments are operating nominally, with fuel remaining for EM6 and beyond. In order to fulfill Mars Exploration Program Office requirements to manage fuel and orbit evolution to maintain MAVEN as a communications relay, the MAVEN team plans to raise periapsis in 2028. The proposal includes a professional development plan that outlines succession for instrument lead roles and offers growth opportunities for early career team members. In addition to its science investigations, MAVEN serves as a relay for landed assets on Mars

## **Overall Rating: Excellent**

*This reflects all criteria for the guideline proposed mission. The Primary criteria carry a greater weight in the overall rating than the Secondary criteria.*

### **Primary Evaluation Criteria (1 – 6)**

#### **1. Intrinsic merit of the proposed science investigations to be undertaken during the EM**

##### **Major Strengths**

**MAVEN's EM6 investigations on characterizing the response of the Martian system to solar storms during the declining phase of Solar Cycle 25 would be extremely valuable, and would provide a unique opportunity to study both how escape processes evolve through the solar cycle and how escape processes are affected by particularly strong solar activity.** The likelihood of observing strong solar events during EM6 is high given how much stronger Cycle 25 maximum was than Cycle 24 maximum, and that particularly strong solar activity occurs during the declining phase of the solar cycle. This observation is important for characterizing atmospheric escape through Mars's history with a changing Sun because escape during intense solar events may be similar to the rapid atmospheric loss during early Solar System history when the Sun was more active (this behavior also is applicable to close-in exoplanets). This study is appropriately prioritized by EM6 Goals 3 (Determine the atmospheric response to heating from solar storms) and 4 (Measure how atmospheric escape varies over a full solar cycle).

**The proposed prioritization of *in situ* measurements of the martian atmosphere below 200 km altitude is a valuable and timely focus for EM6, given that a periapsis raise in 2028 (to save propellant to extend its presence around Mars as a communications relay into the early 2030s) is expected to preclude these measurements after EM6.** For the first time, MAVEN would be able to make sustained observations in the exobase region between 150 and 200 km altitude where ion energization takes place, which is critical to understanding ion escape from Mars.

**MAVEN's improvement of spatio-temporal coverage would be important to move towards a physical understanding of the processes involved in atmospheric escape from Mars.** The evolution of periapsis would add to coverage over specific Martian locations in the southern hemisphere at local noon during expected dust storm seasons during EM6, which would allow local and global understanding of the impact of dust storms on water loss processes (e.g., Stone et al. *Science* 2020, Holmes et al. *EPSL* 2021)

**Although MAVEN has been in orbit at Mars for a decade, the new observational campaign that co-locates *in situ* and remote sensing observations of the atmosphere in EM6 would offer significant science advances in understanding**

**the inventories of gases within the reservoir for escape.** Investigation 1 would observe the altitude profile of water in the atmosphere of Mars to understand the exchange from lower to higher altitude, where escape to space becomes possible. This approach would better align observations from Imaging Ultraviolet Spectrograph (IUVS) and Neutral Gas and Ion Mass Spectrometer (NGIMS), resolving discrepancies in H<sub>2</sub>O density measurements. Below 160 km, IUVS data show densities 2 to 3 orders of magnitude higher than those predicted by a Planetary Circulation Model. Additionally, the density decreases by about 4 orders of magnitude between 160 km and 190 km, where NGIMS observations begin. The methodology to make co-located observations was developed during EM5, but has yet to be applied to make new scientific observations.

**During EM6 the MAVEN team would collaborate with those operating a range of spacecraft, allowing the mission to significantly enhance and broaden the science return from MAVEN and other NASA and international missions.** For EM6, the mission proposes additional coordinated measurements in collaboration with Mars Reconnaissance Orbiter (MRO), the ExoMars Trace Gas Orbiter (TGO), Mars Express (MEX), Odyssey, Mars Science Laboratory (MSL), the Emirates Mars Mission (EMM), and Solar Orbiter. These coordinated observations of solar wind conditions and their effects on the induced magnetosphere and ionosphere would be particularly valuable during periods of enhanced solar activity expected in EM6. Successful past examples of collaborative observations include MAVEN and MEX making simultaneous measurements of the solar wind and its impact on the Martian induced magnetosphere and ionosphere (Stergiopoulou et al., 2022); vertical profiling of water density, transport, and escape in the Martian atmosphere using TGO and MAVEN (Chaffin et al., 2021); coordinated observations of the Martian aurora by MSL during the May 2024 solar storm (<https://www.nasa.gov/solar-system/planets/mars/nasa-watches-mars-light-up-during-e-pic-solar-storm/>); and joint observations of the Martian aurora and solar wind by EMM and MAVEN (Lillis et al., 2024).

## **Minor Strengths**

During EM6, MAVEN would monitor the solar wind at Mars during the declining phase of the solar cycle, which would be beneficial for heliophysics and comparative planetology. The alignment of the Sun-Earth-Mars described in Investigation 9 presents an opportunity both to get better upstream measurements of the solar wind headed towards Mars and to perform comparative planetology. Even when Mars is not in alignment with Earth, MAVEN's data would continue to improve the understanding of the evolution of interplanetary coronal mass ejections and the interplanetary magnetic field from the Sun to Mars.

## **Major Weaknesses**

**The proposal stated that MAVEN's new observations in EM6 would help answer critical questions that will advance our understanding of Martian atmospheric evolution and climate history; however, the proposal did not provide sufficient detail on how the proposed investigations would be applied to progress knowledge of the four larger goals of the proposal, or to the cited Decadal Survey questions.** Mars' complicated atmospheric system has many factors that affect escape rates and other processes, and the proposal did not sufficiently describe the expected influence of integrating the outcomes of the investigations on the knowledge of the evolution of the atmosphere. For example, the proposal stated in Investigation 4, "Observation of these features close to the 'extremes' . . . will provide important constraints on the sources and fates of these suprathermal tails and associated processes," but the proposal did not sufficiently describe the expected significance of the superthermal tails to quantifying the processes. Also, the proposal stated in Goal #4 that "A central theme of the MAVEN mission is to extrapolate present day loss process into the distant past," and argued that extreme solar conditions are more similar to average conditions early in Martian history. However, the proposal did not sufficiently explain how the effects of high solar activity on the present-day Martian atmosphere would relate to the effects of similar drivers on the early Martian atmosphere.

### **Minor Weaknesses**

**The proposal did not clearly present a path to reach closure on some of the individual science investigations.** For example, the proposal states that for Investigation 4, "Determine which processes control the initial energization of escaping ions," extended sampling at constant altitude would be key to revealing processes governing initial ion energization, but the proposal does not sufficiently explain what analysis would reveal those processes. Investigation 11, "Characterize photochemical escape during a stronger solar cycle maximum", would investigate how photochemical escape rates respond to intense flares and CME shock impacts. However, the proposal did not sufficiently explain how such determination would be made from the set of measurements listed in the Science Traceability Matrix.

## **2. Responsiveness of the proposal to goals described in the 2023 Decadal Survey “Origins, Worlds, and Life”**

*Missions may optionally also refer to goals in Vision and Voyages for Planetary Science in the Decade 2013-2022 (2011), and/or New Frontiers in the Solar System: An Integrated Exploration Strategy (2003), depending on when the mission was originally proposed. The proposal should make clear from which Decadal Survey each goal is taken. Goals from later Decadal Surveys should be prioritized over earlier ones. Proposals may mention goals from other Decadal Surveys (e.g., from other science divisions at NASA), but these will not contribute to the mission’s evaluation.*

### **Major Strengths**

**The proposed MAVEN EM6 investigations would directly and compellingly address Decadal Survey questions 6.3 (What processes drive the dynamics and energetics of atmospheres on solid bodies?), 6.5 (What processes govern atmospheric loss to space), and 10.3 (Water availability: what controls the amount of water on a body over time).** For example:

- Investigations 8, 10, and 12 would improve understanding of atmospheric escape in the presence of crustal fields, which is relevant to Decadal question 6.5a “How does the presence or absence of intrinsic or parent body magnetic fields influence the escape of gases from solid planets and satellites?”
- The majority of proposed investigations support Decadal question 6.3f, “How do the structure and dynamics of planetary magnetospheres vary with season and solar inputs?”, including an intensive focus on inputs during solar storms and times of high solar activity.
- Decadal question 10.3, “Water availability: what controls the amount of water on a body over time?”, would be addressed by the study of atmospheric escape (Investigations 10–12) and the characterization of the upper atmosphere (Investigations 1 and 3).

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

**Many of the Decadal questions listed in Table 4.1 were not sufficiently addressed by EM6 investigations or measurements as written in the proposal.** For example:

- It is not sufficiently described how Decadal question 6.2d, “How does orbital forcing, including obliquity and eccentricity changes [...] govern climate change

and surface volatile redistribution [...]” (p. 28), would be addressed by EM6 Investigation 7, “Investigate neutral atmosphere response to flares and increased radiation” (p. 29).

- Decadal question 6.3d is listed on Page 28 as a “Relevant [Decadal] question [...] to MAVEN’s EM6’s objectives” but is not listed in the p.29 table.
- The connection to question 6.3e, “What Determines the Effectiveness of Ion-Neutral Drag on Augmenting Upper Atmospheric Circulation?”, for Investigation 2 is not sufficiently demonstrated.
- Similarly, the proposal did not demonstrate the relevance of question 6.3a, “How Do Horizontally and Vertically Propagating Waves Drive Planetary Atmosphere Dynamics?”, to Investigation 10.

### **3. Capability of the spacecraft to achieve the proposed science**

#### **Major Strengths**

**The MAVEN spacecraft is healthy and operating well.** All scientific instruments are operating nominally with effective accommodations for known issues and can meet EM6 requirements. The amount of fuel remaining is adequate. Gimbals are projected to remain well within their operational lifetime within EM6. Thus MAVEN would be capable of achieving the science objectives in the proposed EM6.

**The team recognizes the hardware risks in EM6 and has a solid risk-management plan that includes effective mitigation measures and contingency plans for potential failures.** For example, the development and use of All-Stellar Mode (ASM) due to “problems with IMU-1” in 2022 demonstrates the team’s capability to maintain spacecraft health given the concern about the laser degradation of the single remaining IMU. As another example, battery life and charging considerations place requirements on minimum orbit period and maximum eclipse duration. The MAVEN team’s description of their battery management approach showed that this issue is well understood and managed. As a third example, the team is monitoring the performance of the Articulated Payload Platform (APP) and presented a plan for preparing for and responding to any evidence of gimbal degradation.

#### **Minor Strengths**

The team has tailored the science investigations to take advantage of the evolution of MAVEN’s trajectory, which has been dictated partially by NASA. For example, the proposed study of the global response to atmospheric heating during dust storms leverages the observations near the source zone for dust storms during the dust storm season. Likewise, the team plans to focus on processes occurring in the exobase while the orbital characteristics are such that MAVEN’s trajectory skims through the exobase, providing minutes of sustained observations.

## Major Weaknesses

None noted.

## Minor Weaknesses

None noted.

## 4. Merit of any programmatic objectives

*This may include activities such as data relay for other NASA or international missions; science which advances the goals of NASA directorates beyond SMD; international cooperation; or other significant non-science activities.*

### Major Strengths

**MAVEN plays a critical role in the Mars Relay Network, providing 23% of the data relay of NASA surface assets at Mars.** MAVEN's work as a relay for surface assets is valuable, not only for the number of bits transmitted, but by increasing the number of overflight passes for decisional data, which adds flexibility and resilience for rover planning.

**MAVEN has cross-mission collaboration with other Mars missions, mutually increasing the value of the programs.** Some examples include:

- MAVEN reduces mission risk to assets at Mars. MAVEN currently sends alerts notifying Mars assets of increased solar activity that can affect spacecraft operations and hardware. These notifications are done in coordination with the Community Coordinated Modeling Center (CCMC) and Moon to Mars (M2M) Space Weather Analysis Office within the NASA GSFC Heliophysics Science Division.
- MAVEN enhances the science return of other missions by notifying them of significant events. Recently, MAVEN received an ICME warning from CCMC and sent the Mars alert out, and subsequently Mars 2020 had time to adjust their Supercam observations to observe a visible aurora on Mars for the first time. This science opportunity was possible only because the Mars 2020 team was informed that the storm was coming. A paper describing the observations has been submitted to *Science*.
- MAVEN's collaborations with ExoMars TGO (ESA), Mars Express (ESA), and Emirates Mars Mission (UAE) are particularly notable because they help to build international ties.

**MAVEN has a cross-divisional link with heliophysics and astrophysics and a cross-directorate link with human exploration.**

- Multi-point measurements significantly enhance the understanding of space physics phenomena, which demonstrates MAVEN's synergy with the NASA Heliophysics Division. Simultaneous observations from MAVEN and other

spacecraft at Mars and throughout the heliosphere provide opportunities to understand the evolution of the solar wind, coronal mass ejections, comets, and the martian space environment.

- There is commonality between investigating atmospheric escape at Mars and exoplanet research on atmosphere loss (e.g., validating models of stellar wind stripping of atmosphere from exoplanets). The 170 astrophysics papers that cite MAVEN or use MAVEN data demonstrate the extensive influence MAVEN data have on astrophysics studies.
- Additionally, MAVEN results are relevant to human exploration in that MAVEN monitors space weather at Mars and quantifies the space environment. Together with Curiosity's Radiation Assessment Device (RAD), MAVEN is a valuable asset for monitoring and understanding the radiation hazard on the Mars surface (e.g., during solar storms), which is perhaps the single greatest hazard for human missions to Mars (Guo et al. 2018, *Astronomy & Astrophysics*, 611, A79).

### **Minor Weaknesses**

None noted.

## **5. Scientific productivity of the mission team in the current phase**

### **Major Strengths**

**The mission team remains engaged in the analysis and interpretation of MAVEN data and the advancement of scientific findings, including in response to major solar system events.** The team continues to publish at a rate of ~45 publications/year, which is comparable to other productive spacecraft teams. The amount of productivity is consistent across MAVEN's instrument teams as well, demonstrating broad productivity. The team continues to seek high-impact outlets for their publications, for example, as demonstrated by including a recent *Science Advances* paper that is in review (Clarke et al. 2024). In addition, the team also makes their results accessible to the public through engaging visualizations and frequent press releases.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

## **Minor Weaknesses**

None noted.

## **6. Performance of the mission in archiving data to the PDS in the current phase**

### **Major Strengths**

**The MAVEN team has met all of its PDS release dates in EM5, achieving 100% on-time delivery.** The team's long-term performance in PDS delivery demonstrates a track-record of similar successes. The mission has archived all of the data in PDS4 format since the beginning of the mission.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **Secondary Evaluation Criteria (7 – 10)**

## **7. Extent to which the science community beyond the mission science team utilizes data and conducts published research**

### **Major Strengths**

**There is a long and continuing pattern of the science community utilizing MAVEN data for scientific research.** The rate at which the community beyond the MAVEN team is publishing results from MAVEN data has increased, sustaining numbers exceeding 50/year since 2022, which demonstrates that MAVEN data continue to add to our scientific understanding. Annual non-team publications have exceeded the number of team publications since 2020, demonstrating substantial usage of MAVEN

data by the broader scientific field, including publications in high-impact journals (e.g., Gunnell et al. *Science Advances* 2023, Y. Ye et al. *Nature Astronomy* 2024; Kleinböhl et al. *Nature Astronomy* 2024). The team's practice of inviting researchers who are not team members to team meetings has been an effective means to ensure that community members both understand and utilize mission data. The team also makes their curated data available in accessible public websites (MAVEN Science Data Center, <https://lasp.colorado.edu/maven/sdc/public/>), further encouraging data dissemination in the field. Also, the Rules of the Road and Best Practices for Data Usage by Non-MAVEN-Team Members documents make it very clear how to collaborate on analysis of MAVEN data and ensure that nuances in the data are communicated to users. These approaches are a leading example for how space mission teams should interact with the greater science community.

**MAVEN data have an impact in other scientific disciplines beyond those related to their primary mission objectives related to Mars' atmosphere.** MAVEN's primary objective is to understand the evolution of Mars' atmosphere in response to external and planetary drivers. It is notable that MAVEN data have an impact in other scientific disciplines. MAVEN papers are frequently cited by a wide range of science communities, including heliophysics and astrophysics. The proposal states that, "In Astrophysics, over 170 papers have been published using or referencing MAVEN data."

#### **Minor Strengths**

None noted.

#### **Major Weaknesses**

None noted.

#### **Minor Weaknesses**

None noted.

### **8. Intrinsic merit of science data to be acquired and archived, but not analyzed**

#### **Major Strengths**

**MAVEN's untargeted, near-continuous data collection for more than one complete solar cycle would be valuable for understanding the solar wind at Mars' orbital distance and differentiating the impacts of solar activity, latitude, local**

**time, geographic features, atmospheric dust loading, etc. on atmospheric processes and escape.** The data would be especially valuable considering how they can be combined with data from current and future missions to Mars to understand processes in the space environment around Mars. MAVEN's unique position at Mars allows it to produce solar wind data differentiated from other probes throughout the solar system. Given the armada of spacecraft presently at Mars and planned for the future, MAVEN data are likely to continue to be of high importance for interpreting data from other missions.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **9. Demonstrated capabilities and expertise of key personnel**

### **Major Strengths**

**MAVEN introduced a new Principal Investigator in 2021, demonstrating the team's commitment to providing meaningful leadership opportunities to develop team scientists.** The new PI brings enthusiasm to the mission and has successfully led the team through EM5. The team continues to work together effectively under the new PI as demonstrated by their seamless and successful production of interdisciplinary and multi-instrument papers.

**This long-running mission has leadership that strikes an appropriate balance between maintaining institutional knowledge through original personnel and augmenting the staff with new personnel.** Because of this approach, the MAVEN team has personnel with extensive knowledge of the science, the spacecraft, and programmatic needs, as well as personnel bringing fresh ideas and different techniques to the project. This approach enables the team to simultaneously innovate while efficiently managing and operating the MAVEN spacecraft and analyzing and interpreting mission data.

### **Minor Strengths**

The team has multidisciplinary expertise that spans from heliophysics to atmospheres.

This diversity is important to advancing the scientific understanding of the evolution of Mars' atmosphere, as the team responds to drivers from space and processes occurring in the atmosphere.

MAVEN maximizes collaboration through cross-instrument working groups. For example, The Rules of the Road (Appendix B) state, "Cross-instrument and interdisciplinary science will be the norm rather than the exception and will be the primary means by which the science team reaches its major scientific conclusions."

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

## **10. Expected effectiveness of the proposed Professional Development Plan (PDP) in training future mission leaders, and demonstrated progress toward the goals of the PDP in the current mission phase**

### **Major Strengths**

**The MAVEN team has a track record of ensuring career progression for mission staff and scientists through distinct professional development efforts.** The succession plan is thoughtful and well laid out. For example, the team has a plan for succession that names deputy leads for the instruments and gives them opportunities to train under a mentor. The proposal states that three Deputy Instrument leads will be promoted to Instrument PI in 2025; this would represent a significant leadership progression. The relatively recent (2021) handover of the mission PI-ship from Jakosky to Curry provides demonstrated evidence of commitment to leadership progression within the MAVEN team. Also, the designation of early career scientists to lead the science session in the Project Science Groups will both develop leadership skills for those scientists and promote them through increased visibility. These efforts help NASA build a cohort of people with leadership experience who can become mission PIs on future missions.

### **Minor Strengths**

None noted.

## Major Weaknesses

None noted.

## Minor Weaknesses

None noted.

## 11. Comments on Budget

*The panel will not perform a detailed cost analysis of the proposal. However, please give any comments about the details and appropriateness of the baseline budget presented. Budget comments do not contribute to the mission's overall score.*

Most proposed WBS funding levels are flat between EM5 and EM6, indicating the request is consistent with the past cost of mission operations. However the Ground Data System budget more than doubles between FY24 and FY25, and remains higher than in FY23 and 24 throughout EM6. The project's presentation to the panel provided the rationale for this increase. It is due mainly to the transition from the JPL Flight LAN to the LM Mission Operations Network (MONET), including out-year recurring costs, which were reasonable.

## 12. Budget Overguides (OGs)

*Missions may propose optional OGs to their budgets. Please provide comments about OGs here, including assessment of their potential merit, risk, and/or value.*

No overguides proposed.

## Additional Comments for the Mission

*Comments here may include suggestions, or feedback about portions of the proposal which were not covered by the evaluation criteria. None of these comments affect the score.*

A summary paper (Jakosky et al., 2018) aggregated the results of MAVEN for extrapolating processes of atmospheric escape back through time. Given that the mission has been active for more than a decade, a new reevaluation of the range of atmospheric escape rates for various processes and an updated synthesis paper along the lines of that of Jakosky et al. (2018), with integrations over time, would be particularly timely and would help address fundamental questions about the history and evolution of the Martian atmosphere.

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## 6.6 Mars Science Laboratory

### 2025 NASA Planetary Mission Senior Review Panel Evaluation

**Proposal** 25-PMSR25-0004  
**Title** Mars Science Laboratory Extended Mission 5:  
Investigating the Habitability on Aeolis Mons  
**Principal Investigator** Kathya Garcia / JPL

#### Summary of Proposal

The proposed EM5 traverse would bring Curiosity over one vertical kilometer from its landing site to where the continuous strata of lower Mount Sharp end. The work to be done in EM5 would complete the construction of a key "reference section" that would establish a stratigraphic and environmental history of Early Mars. The rover's climb would be bookended by two high-priority investigations. The first would begin at a site that has high promise for assessing subsurface habitability. A field of decameter-sized, cemented fractures (the "Boxwork") is hypothesized to record ancient habitable environments sustained by groundwater, where rapid mineralization may have preserved organic molecules. The second high-priority investigation is planned for Curiosity after an extended traverse and climb through the Mg-sulfate-bearing unit (Mg-SBU). After the climb, Curiosity would be at a hypothesized major erosional unconformity between the Mg-SBU (a unit formed with intermittent water and aeolian activity) and the overlying Yardang unit (that likely represents purely aeolian sedimentation) and would study the hypothesized significant environmental change from wet to dry that the contact signifies. During EM5, Curiosity would also make measurements of atmospheric composition and meteorology, ultraviolet and high-energy radiation, and investigate cycles of water vapor and dust.

#### **Overall Rating: Excellent / Very Good**

*This reflects all criteria for the guideline proposed mission. The Primary criteria carry a greater weight in the overall rating than the Secondary criteria.*

#### **Primary Evaluation Criteria**

##### **1. Intrinsic merit of the proposed science investigations to be undertaken during the EM**

##### **Major Strengths**

The scientific merit of the proposed investigations in EM5 is high. EM5 investigations follow in the path of the ground-breaking science of MSL over the primary and earlier

extended mission phases. The principal theme is to investigate the persistence of habitability markers recorded in the strata of Mount Sharp. The high-priority goals for EM5 are anchored by I) a quantitative investigation of a geologic formation termed the “Boxwork” structure early in EM5, and II) exploration of the apparent environmental transition, at a geologic contact, from the conditions recorded in the Mg-SBU to those in the stratigraphically higher Yardang unit.

Four significant investigation strengths were identified:

**1) Investigation of the Boxwork structure**

The Boxwork structure has been identified from orbital data and has been a target for MSL since EM3. However, orbital data have not revealed why the fractures have formed preferentially in this elevation interval, or the composition and mineralogy of the ridges, or any association of salts or alteration products with the fractures. The geologic structure is now within reach of the rover. MSL was not able to reach this structure in EM4, but it is a priority for EM5. The science goals are very important for constraining the nature and duration of subsurface fluid flow on Mars at the elevation on Mount Sharp. The investigation would obtain measurements fundamental to assessing and determining the details of possible habitability in ridges of the boxwork, hypothesized to be inverted mineralized fracture zones. Because the boxwork target is much bigger than the vein complex investigated at the Garden City deposit during EM1, there is a higher potential for rigorous sampling.

**2) Investigation of the contact between the Yardang unit and the underlying Mg-sulfate-bearing unit (Mg-SBU)**

The proposed investigation of the Yardang unit and hypothesized basal unconformity is a very important target and ultimately would take the rover to the critical geologic transition that has been a significant puzzle for Gale crater for 15 years. The rover would be able to access the contact between the Mg-SBU and the overlying Yardang unit and determine the composition and texture of the rocks at this critical boundary.

**3) Investigations of the Mg-SBU**

The proposed EM5 investigation seeks to climb over 360 vertical meters to systematically assess changes in depositional environment and chemical and mineralogical composition in the Mg-SBU. This focus is a strong response to the significant science discoveries thus far in EM4 involving iron carbonates and diagenesis related to Mars’ paleoenvironment.

The proposed investigation of the Mg-SBU is well described and would leverage the considerable experience the MSL team has built exploring the lower sections of Mount Sharp. Basic characteristics about the depositional environment of the sulfates (such as grain sizes/shapes and sedimentary structures) can be readily gleaned from the MSL instrument suite and integrated to determine the extent to which aeolian, lacustrine, fluvial, or other processes were important in the deposition and creation of the Mg-SBU.

#### **4) Investigations of Mars' atmosphere**

The continued investigation of Mars's present-day atmosphere and environment would extend an already highly valuable dataset. Local investigation of how the aerosol distribution and surface energy budget varies with elevation would further constrain models of Mars's atmosphere and climate. Further study of argon, CO<sub>2</sub> isotopes and CH<sub>4</sub> would yield additional insights into atmospheric circulation and the still-unresolved methane paradox. Passive atmospheric monitoring provides long-term, key atmosphere records on Mars.

#### **Minor Strengths**

The investigation involving radiation environment monitoring by RAD is significant because of the uniqueness of the measurements and the length of the record obtained thus far.

#### **Major Weaknesses**

MSL EM5 would bookend their two high-priority investigations (the Boxwork structure and the hypothesized unconformity at the base of the Yardang unit) with a long-distance and long-operational-time (28 months) traverse through the medium-priority Mg-SBU. Given the priority of the Yardang investigation, the mission traverse plans, resource commitments, and operational timelines are not aligned with the team's stated priorities. The proposal did not exhibit a sense of urgency in the operations to accomplish the investigation of hypothesized unconformity at the base of the Yardang unit within the constraints of time and resources.

#### **Minor Weaknesses**

The value of the rover for "atmospheric composition and meteorology, cycles of water vapor and dust, and ultraviolet and high-energy radiation to eight Mars years" (p. 1) is reduced, because the Dynamic Albedo of Neutrons (DAN) experiment can only operate in passive mode and the Rover Environmental Monitoring Station (REMS) wind sensor is no longer functioning. While DAN can detect hydrogen in passive mode the results are less robust. The lack of the REMS wind sensor means there are no additional in situ wind detections.

The disconnect between orbital and in situ measurements of CH<sub>4</sub> (from TGO and MSL, respectively) was emphasized in the EM4 PMSR22 report. However, the EM5 proposal provided only cursory discussion of how the project plans to follow up and potentially resolve this discrepancy, including the possibility of contamination during rover measurements. The proposal did discuss what has been done in EM4 (section 3.4.1) and described the post-sunset measurements planned in EM5 to test which of three modeled mechanisms is the likely control on the observed methane patterns (section 4.6.2). Nevertheless, given the importance of methane, sufficient explanation of the specifics of related investigations was missing in the proposal, acknowledging for example that methane seepage might vary as a function of facies/geology changes along the traverse.

## **2. Responsiveness of the proposal to goals described in the 2023 Decadal Survey “Origins, Worlds, and Life”**

*Missions may optionally also refer to goals in Vision and Voyages for Planetary Science in the Decade 2013-2022 (2011), and/or New Frontiers in the Solar System: An Integrated Exploration Strategy (2003), depending on when the mission was originally proposed. The proposal should make clear from which Decadal Survey each goal is taken. Goals from later Decadal Surveys should be prioritized over earlier ones. Proposals may mention goals from other Decadal Surveys (e.g., from other science divisions at NASA), but these will not contribute to the mission’s evaluation.*

### **Major Strengths**

The investigations proposed for EM5 are responsive to, and very well aligned with, the priorities given in the Origins, Worlds, and Life (OWL) Decadal Strategy (National Academies, 2023). The proposal clearly stated that the investigations would address questions 5, 6, 10 and 11 in OWL, and it broadly showed which particular measurements from the EM5 investigations would be most significant to the strategy goals.

### **Minor Strengths**

None noted

### **Major Weaknesses**

None noted

### **Minor Weaknesses**

None noted

## **3. Capability of the spacecraft to achieve the proposed science**

### **Major Strengths**

The core capabilities of the rover remain intact and the instruments continue to provide high-quality data. As presented in the proposal, the spacecraft and instruments during the EM5 transect (e.g., SAM pumps, HGA actuators, drive actuators, the drill mechanism, and brush) appear to be able to support EM5 operations despite the fact they are well over their life metrics. While wheel integrity and grouser components continue to degrade, the state of degradation does not yet appear to be critical and related activities will be engaged in tasks and subject to conditions that have already been experienced. The proposal explained clearly the current status of the rover and its instruments and subsystems, and the team appears to understand the likely extent of further wear on the units during EM5. Thus, it is highly likely that the rover and related instruments would be able to achieve the EM5 science goals from start to finish, though the level of optimism conveyed in the proposal may be a little high (see weakness below).

The team is resourceful and has provided workaround solutions to unexpected challenges in rover and instrument operations. This flexibility is demonstrated by the efforts to minimize wear and tear on the wheels, and to continue to acquire color data

with the MastCam instrument despite its field of view being occluded by the now-inoperable filter wheel. The careful power management by the engineering team demonstrates that they have a strong understanding of the power challenges expected in EM5.

### **Minor Strengths**

As explained in the proposal, the range of rover operations is limited primarily by funding for planning cycles (i.e., workforce) and not by MMRTG power output. The MMRTG capability is sufficient for the proposed EM5.

### **Major Weaknesses**

The proposal provided an overly optimistic scenario concerning the rover and its key components looking forward to all of what is proposed for EM5. As one example, the team shared that the Pyro 2, inner ring SAM oven was unable to reach the desired temperature. While there is a workaround to enable EM5 plans, it is evidence of aging systems that could impact planned rover activity and science measurements. Furthermore there are many signs of wear on the drill, turret and wrist solenoids. There is a significant risk that these may fail completely in EM5, impacting their ability to carry out proposed science.

The proposal is overly optimistic about the future availability of Sun-synchronous, timely relays that would enable a good cadence of planning operational activities. ODY is one of the two Sun-synchronous relay orbiters and the only one in a near-terminus orbit, so it is important and convenient for MSL operations planning. However, it is low on fuel and its proposed EM10 (2025-2028) may be its last. The risk of losing a key end-of-day orbital relay spacecraft makes it imperative to move expeditiously to get to the Yardang unit.

### **Minor Weaknesses**

The wheels continue to degrade and as noted in the proposal, which leads to slower drives as the team seeks to mitigate further damage.

The left MastCam color imager has an obscured field-of-view; the team has developed a workaround that retains color imaging, but at the expense of additional time and image frames for navigation. The loss of the filter wheel eliminates multispectral mapping and mineralogic insight from the 14-filter multispectral imaging.

## **4. Merit of any programmatic objectives**

*This may include activities such as data relay for other NASA or international missions; science which advances the goals of NASA directorates beyond SMD; international cooperation; or other significant non-science activities.*

### **Major Strengths**

Radiation environment monitoring by MSL's Radiation Assessment Detector (RAD) instrument provides the only surface-based measures of radiation levels, and is intended to be utilized for future human exploration as part of NASA's Moon-to-Mars

strategy. RAD's measurements of surface radiation are also important for understanding in situ resource utilization (ISRU) shielding potential when near elevated features, timing for future human missions, and radiation variability. All of these measurements are critical for planning future missions. They are complementary to those documented in orbit by Mars Odyssey's High Energy Neutron Detector/Neutron Spectrometer (HEND/NS) detectors.

### **Minor Strengths**

Joint meteorological observations between MSL and Perseverance have demonstrated examples of scientific returns that could be generated by a meteorological network on Mars.

### **Major Weaknesses**

None noted

### **Minor Weaknesses**

None noted

## **5. Scientific productivity of the mission team in the current phase**

### **Major Strengths**

The team's productivity is exceptional, with over 90 team-led publications from the beginning of EM4 through the time of proposal submission.

Through EM4 the mission was able to characterize climate and environmental change recorded in the clay-sulfate transition, which represents a variable transition from wetter to drier conditions during a pivotal period in Mars' history. The science findings have been published broadly.

The Mg-SBU preserves a complex record of environments that includes aeolian deposition overprinted by flooding by a rising water table. Variability within the unit was identified and findings are highly relevant to the EM4's central theme of habitability.

### **Minor Strengths**

The fortuitous discovery of elemental sulfur on the martian surface is a major result with important implications for our understanding of early surface and atmospheric chemistry.

The potential evidence for a lake existing under ice-free conditions is particularly noteworthy, if the wind-driven wave ripples interpretation turns out to be correct.

New iron carbonate (siderite) discoveries are adding depth and nuance to our understanding of atmosphere-surface interactions and a changing climate during the time period recorded in the Gale stratigraphy.

## **Major Weaknesses**

Methane was a topic that was specifically addressed in the publicly available review of MSL's proposal submitted to PMSR22:

*“Major Weakness: EM4 would provide opportunity for further testing of previous, tantalizing, but tentative observations about atmospheric methane levels; however, the proposal and subsequent discussion lacked description of protocols to resolve discrepancies between orbiter and rover observations and to eliminate doubts about possible internal sources of methane on MSL”*

The review recommended more study during EM4, in particular, additional comparisons to methane measurements by Trace Gas Orbiter (TGO). Given the importance of CH<sub>4</sub>, the status of these CH<sub>4</sub> investigations and explanations of any followup was inadequately addressed.

## **Minor Weaknesses**

None noted

## **6. Performance of the mission in archiving data to the PDS in the current phase**

### **Major Strengths**

The project has done a commendable job in meeting all its delivery objectives in EM4 and has delivered 48.7 terabytes of data (23.3 million files), on time, to the PDS through Release #36. The MSL project is also working to back-convert all earlier deliveries from PSD3 to PDS4.

### **Minor Strengths**

None noted

### **Major Weaknesses**

None noted

### **Minor Weaknesses**

None noted

## **Secondary Evaluation Criteria**

### **7. Extent to which the science community beyond the mission science team utilizes data and conducts published research**

#### **Major Strengths**

A metric that quantifies how the community beyond the science team has used MSL data is measured in the number of publications by the scientific community outside the MSL team. This publication rate is, in the aggregate, directly comparable to the total number of team-internal publications.

#### **Minor Strengths**

The new data products produced in EM4 – the Mastcam Photometry Cubes and MAHLI Technical Reports in the PDS, and the MSL Solid Sample Library (non-PDS) – are innovative and valuable for new science applications.

#### **Major Weaknesses**

None noted

#### **Minor Weaknesses**

None noted

### **8. Intrinsic merit of science data to be acquired and archived, but not analyzed**

#### **Major Strengths**

The data that would be collected and archived would be of high scientific value to the planetary science community. The MSL mission has been exceptional in gathering science data that is widely used in diverse planetary science disciplines and publications. The fundamental metrics in support of this estimation are the high rate of ground-breaking publications from data gathered by the MSL team, and the significant use of MSL data by the broader community.

#### **Minor Strengths**

None noted

#### **Major Weaknesses**

None noted

#### **Minor Weaknesses**

None noted

## **9. Demonstrated capabilities and expertise of key personnel**

### **Major Strengths**

MSL has an outstanding leadership team. The team is experienced and has shown great capacity to adjust to the changing environment on Mars and changes in the operational capabilities of MSL. This experience is well demonstrated in the proposal and in the project's response to questions.

### **Minor Strengths**

None noted

### **Major Weaknesses**

None noted

### **Minor Weaknesses**

None noted

## **10. Expected effectiveness of the proposed PDP in training future mission leaders, and demonstrated progress toward the goals of the PDP in the current mission phase**

### **Major Strengths**

MSL has been exemplary in training junior team members and later promoting them to positions of leadership and authority. Examples include current CheMin PI and Deputy (Tom Bristow and Elizabeth Rampe), ChemCam PI and Deputy (Nina Lanza and Olivier Gasnault), SAM PI and Deputy (Charles Malespin and Amy McAdam), and MAHLI PI and Deputy (Aileen Yingst and Michelle Minitti), all of whom grew into those roles from within the MSL science team, as did the Project Scientist (Ashwin Vasavada) and Deputy (Abigail Fraeman). The forward-looking professional development plan is excellent, and gives high confidence in the implementation of their PDP given past progress in training and appointing new instrument PIs.

### **Minor Strengths**

None noted

### **Major Weaknesses**

None noted

### **Minor Weaknesses**

None noted

## 11. Comments on Budget

*The panel will not perform a detailed cost analysis of the proposal. However, please give any comments about the details and appropriateness of the baseline budget presented.*

From the proposal, the project appears well managed within the constraint of a flat-line budget and projected ability to carry out successful operations and generate scientific results regarding their high-priority targets.

## 12. Comments on Budget Overguides (OGs)

*Missions may propose optional OGs to their budgets. Please provide comments about OGs here, including assessment of their potential merit, risk, and/or value.*

### Overguide #1: Additional Planning Cycles

**Overguide #1 Score:** Good

#### Overguide #1 Comments

Overguide #1 is the overguide request as proposed by the MSL project. The description of the overguide request in the proposal did not make a strong case for how the additional planning cycles and the resulting changes to mission operations during the overguide would enable unique investigations, address new science problems, or increase the science return of EM5 beyond achieving a more rapid rate of progress toward upper Gediz Vallis. The proposed overguide would take the rover to near the top of Gediz Vallis, where it would be ready to initiate objectives to be proposed next review cycle in EM6, including a search for the origin of the elemental sulfur. The proposal and the project's presentation emphasized that the advantage to MSL from the overguide is that the extra planning cycles would strategically place MSL in an optimum position to begin a potential EM6. The proposal did not clearly identify how the overguide would increase the opportunities to investigate the topics central to the current EM5 proposal, such as detailed analyses of the contact between the Mg-SBU and the Yardang unit, the Boxwork structure, or the Mg-SBU itself.

### Overguide #2: Panel-Revised Strategy for Utilizing Additional Planning Cycles

The proposal made a strong case that the Mg-SBU/Yardang unit contact is a compelling target for EM5, and a science and traverse plan more closely linked to the importance and study of this contact and the Yardang unit would increase the scientific merit of the recommended overguide investigation. The panel suggested, discussed, and voted on a revised overguide investigation, here termed "Overguide #2."

**Overguide #2 Score:** Excellent/Very Good

#### Overguide #2 Comments

Overguide #2 would include additional planning cycles primarily utilized to enable

investigation of specific targets strongly linked to the EM5 science goals, rather than to prepare for a not-yet-proposed EM6. A key target to be addressed would include a more thorough investigation of the Mg SBU/Yardang contact in areas that appear to be accessible (apparently within reach based on Figure 4.1).

This revised investigation would travel to and engage the Yardang as quickly as possible and conduct a sequence of operations along the traverse during the approach the Mg-SBU/Yardang contact and study it carefully and systematically. Due to the expected strong science return from the investigation of the Yardang/Mg-SBU contact and the Yardang unit itself, it is recommended that the MSL team develop a modified overguide. A revised overguide investigation that specifies targets along the rover traverse path to the end of EM5 and incorporates more study of the contact at the base of the Yardang unit and shows how the targets fit into the science investigations is strongly encouraged. Setting MSL up for EM6 is not compelling.

### **Additional Comments for the Mission**

*Comments here may include suggestions, or feedback about portions of the proposal which were not covered by the evaluation criteria. None of these comments affect the score.*

The panel felt very strongly that the pace of operation should be weighted toward traveling to and substantially completing the characterization of the Yardang unit and the postulated unconformity at its base during EM5. While the allocation of remaining instrument measurement resources in the proposal seems appropriate, and no near-term technical failures appear imminent, the rover and the supporting relay assets will degrade and face additional risk over time. The panel sensed a lack of urgency on the part of the MSL team to achieve more operational efficiency during EM5, even specifically calling out interesting science to be done later in a future (and hypothetical) EM6. The panel also felt adaptability to any “extra science opportunities within SBU” (as proposed by the mission for EM6) should be de-prioritized and coordinated with the Mars Exploration Program office for approval of any related delays in progress of the rover toward the Yardang unit.

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## 7. Evaluations of Project Data Management Plans (PDMPs)

### 7.1. PROJECT DATA MANAGEMENT PLAN EVALUATION – Juno

**Mission Team: Juno**

**Proposal Number: 25-PMSR25-0002**

**Proposal Title: Juno 2<sup>nd</sup> Extended Mission**

#### **PROJECT DATA MANAGEMENT PLAN SUMMARY**

The proposal provided a detailed accounting of the data that have been archived, including both science data and engineering products. The proposal also clearly described how data would be handled through all stages of the data lifecycle. In addition, the mission has submitted all required data to the Planetary Data System (PDS), the archive is current, and PDS pages are well organized and easy to navigate. Finally, the proposal included a clear description and plan for the conversion of data from PDS3 to PDS4 formats and the delivery of EM2 data in both PDS3 and PDS4 formats.

#### **PROJECT DATA MANAGEMENT PLAN MERIT**

##### **Major Strengths**

**The proposal provided a detailed accounting of the data that have been archived, including both science data and engineering products. The proposal also clearly described how data would be handled through all stages of the data lifecycle.** The proposal included a detailed data management plan that provided a thorough and structured overview of how Juno mission data were received, processed, stored, validated, and archived. The document also listed all instruments and the Planetary Data System (PDS) science discipline nodes responsible for archiving. The data management plan also demonstrated compliance with NASA requirements and data product validation. NASA's SPD-41 Scientific Information Policy requirements were referenced and clear explanations for how the Juno data archive meets these requirements were given. The plan also followed and clearly described standard PDS archiving, peer review, and validation procedures for data integrity. Finally, the responsibilities of Juno mission members were clearly discussed. The responsibility scheme is complex, involving the Juno Project members, JPL and several PDS nodes, and was described in detail.

**The mission has submitted all required data to the Planetary Data System (PDS), the archive is current, and PDS pages are well organized and easy to navigate.** Data delivery to the PDS was delayed on occasion during the Primary Mission, but recent data deliveries have been on time and the archive is complete. The Juno archive pages in the PDS (notably the Atmospheric and Imaging node pages) are

well-organized and easy to navigate, with links to each instrument collection. For example, the microwave radiometer has a clear and thorough description of the instrument and the data holdings, including information such as antenna beam patterns and contribution functions for sounding the atmosphere. In addition, the proposal described how the mission proactively and collaboratively engaged with PDS archiving nodes, helping to ensure a high-quality data archive with maximum benefit to the science community. Representatives from the PDS are on working groups to discuss data archiving and are part of conversations on how to address any liens identified in data reviews.

**The proposal included a clear description and plan for the conversion of data from PDS3 to PDS4 formats and the delivery of EM2 data in both PDS3 and PDS4 formats.** The proposal described a reasonable plan to convert PDS3 data to PDS4 and considered the needs of the science community. For example, the mission would provide PDS4 wrappers for PDS3 Waves data so that both formats are available for EM2 data. Notably, some PDS4 data has been converted proactively to PDS4 format and ahead of a requirement to do so. These data included the MWR, UVS, JIRAM, and Gravity investigations due to migration efforts during the prime mission and EM1 by the PDS Atmospheric node (ATM).

### **Minor Strengths**

The Juno mission has properly archived data and at times went above and beyond their Project Data Management Plan requirements. For example, in the original Juno proposal, the SRU and ASC were considered engineering subsystems. However, SRU and ASC observations led to major scientific discoveries reported in a number of publications, illustrating the potential impact for scientific discovery. These data are now archived as standard data products in the PDS.

The proposal demonstrated that data from the mission is used widely by community members outside the mission team. Throughout the mission, papers lead by non-team authors were roughly equal in number to those published by the mission team. In addition, the proposal illustrated that the publication rate by the community has been consistent throughout the mission.

The Juno mission demonstrated a clear commitment to supporting the community in using Juno data. The Juno mission has conducted workshops for non-Juno scientists to demonstrate how to use Juno PDS data, enhancing the accessibility of the data to the wider community.

### **Major Weaknesses**

None noted.

## **Minor Weaknesses**

The Juno mission roles and responsibilities for software and tool development, including software maintenance, was not clearly described or addressed in detail.

In the proposal description of the migration of data from PDS3 to PDS4, there is no discussion of the effort required to reformat the remaining datasets. In addition, there is no discussion of potential risks or contingency plans, such as if the peer review process identifies major issues, if there are delays in the conversion process or reviews, or if there is missing telemetry or information for PDS4 labels.

## **NOTES TO PROPOSERS**

None noted.

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## 7.2. PROJECT DATA MANAGEMENT PLAN EVALUATION – LRO

**Mission Team:** Lunar Reconnaissance Orbiter

**Proposal Number:** 25-PMSR25-0005

**Proposal Title:** Lunar Reconnaissance Orbiter: Extended Science Mission 6

### **PROJECT DATA MANAGEMENT PLAN SUMMARY**

All data archived previously and planned for the extended mission would be of high technical merit and quality. With successful deliveries every 3 months for the past decade and a half, resulting in > 60% of the data in the PDS, the proposal established the performance of archiving past mission data. The scientific community has made extensive use of LRO data since the mission launched, including LRO images, thermal data, and laser altimetry data. The PDMP would archive all new data in PDS 4 format. The mission is in the process of converting all archival data to PSD 4.

### **PROJECT DATA MANAGEMENT PLAN MERIT**

#### **Major Strengths**

**All data archived previously and planned for the extended mission would be of high technical merit and quality.** The mission uses a peer review process to ensure high data quality. The Project Data Management Plan (PDMP) details the data pathways from the Mission Operations Center and Science Operations Center to the Planetary Data System (PDS). The Lunar Reconnaissance Orbiter (LRO) data management team has an established process that accounts for all data from each LRO payload. The mission would continue to archive all science data during the proposed extension. They would execute a plan to archive the non-required Radio Science data on a best effort basis.

**With successful deliveries every 3 months for the past decade and a half, resulting in > 60% of the data in the PDS, the proposal established the performance of archiving past mission data.** Although a couple instruments were delayed for Data Release 60 and the Mini-RF releases were delayed between 6 and 18 months for Data Releases 54-57, the proposal met most milestones in archiving data to the PDS in the previous cycle.

**The scientific community has made extensive use of LRO data since the mission launched, including LRO images, thermal data, and laser altimetry data.** The large number (~1000) and large fraction (~2/3) of external publications implies that data is being used by scientific community members beyond the mission team. The number of non-member publications has more than doubled in the period past 4 years relative to the preceding decade (an average of 120.5 publications/year since 2021 compared to 49.6 per year from 2010-2020). The recent increase in publications reflects a renewed

interest in data relevant to lunar science and exploration, which LRO data is uniquely suited to providing. LRO data is a core component of science and exploration activities of the lunar community, as highlighted in the Decadal Survey and Scientific Context for the Exploration of the Moon Report. Commercial Lunar Payload Services also make use of LRO products.

**The PDMP would archive all new data in PDS 4 format.** The proposal stated that all newly acquired data is being delivered to the PDS in PDS 4 format, except for the non-required Radio Science data, which would be delivered on a best effort basis. The mission team completed the improvements to the Miniature Radio-Frequency (Mini-RF) instrument data to enable delivery in PDS 4 format on time.

### **Minor Strengths**

None noted.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

None noted.

### **NOTES TO PROPOSERS (OPTIONAL)**

None noted.

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### 7.3. PROJECT DATA MANAGEMENT PLAN EVALUATION – ODY

**Mission Team:** Mars Odyssey

**Proposal Number:** 25-PMSR25-0001

**Proposal Title:** 2001 Mars Odyssey Tenth Extended Mission

#### **PROJECT DATA MANAGEMENT PLAN SUMMARY**

The Odyssey mission consistently delivers instrument data on time to the PDS nodes for planned data releases. During E9 all deliveries to the assigned PDS nodes have either been on time or early. The Odyssey THEMIS and GRS instruments have completed a transition plan to the PDS4 standard and will begin delivery of newly acquired data in PDS4 formats to the PDS starting in 2025 (during E9). However, the Odyssey mission is not planning to update their delivery schedule to the 3-6 months after data acquisition required by SPD-41 and will continue to deliver data to the PDS 6-9 months after acquisition.

The proposal outlined a plan to convert and re-deliver pre-E9 data from the THEMIS and GRS instruments in the PDS4 format. Generation and delivery of GRS legacy data from the entire Odyssey mission prior to E9 is expected be completed before the beginning of E10.

Although the proposal body did contain updated information, the PDMP (Archive Generation, Validation, and Transfer Plan) has not been updated for the proposal and was a re-submission of the plan which was submitted to support the previous E9 proposal (Revision 2, last updated 12/29/2021).

#### **PROJECT DATA MANAGEMENT PLAN MERIT**

##### **Major Strengths**

**The Odyssey mission consistently delivers instrument data on time to the PDS nodes for planned data releases.** During E9 all deliveries to the assigned PDS nodes have either been on time or early. Mars Odyssey data has been released regularly since the first archive and the quality has remained consistent throughout the extended life of the mission and 90 data releases.

**The Odyssey THEMIS and GRS instruments have completed a transition plan to the PDS4 standard and will begin delivery of newly acquired data in PDS4 formats to the PDS starting in 2025 (during E9).** GRS will begin delivery of newly acquired data in the PDS4 format in 2025. Similarly, THEMIS PDS4 data will begin to be delivered to PDS in January 2025. For both instruments, once delivery begins subsequent deliveries will occur on the nominal schedule. The proposal indicated that for both instruments all E9 data will be archived in PDS4 format by the end of E9. The

publication of new data from THEMIS and GRS in the PDS4 format will be a major benefit to the community in this cycle, enabling the next generation of tools, services, and scientists to use this rich dataset.

### **Minor Strengths**

The proposal explained that for the THEMIS instrument, once the delivery to the PDS of PDS4 formatted data begins, both PDS3 and PDS4 products will be delivered. The continued delivery of PDS3 products will ensure continuity for the community and will allow users the option to select which data set they prefer.

The proposal demonstrated that data from the mission is used widely by community members outside the mission team. During the years 2003-2004, 11 papers using Odyssey data were published by the mission team while 43 were published by the planetary community (a ratio of 1:4). In addition, the proposal showed that the publication rate by the community has held strong throughout the mission and that current community publication rate is about half what was at its peak during 2006 and 2010-2011. The continued publications using Mars Odyssey data demonstrates the continued relevance and importance of the data and science derived from them. As an example, the THEMIS data is utilized by the science community and remains an important dataset for researchers and specifically the THEMIS IR and VIS data is a fantastic resource for context mapping local regions at moderate scales.

### **Major Weaknesses**

**The Odyssey mission currently delivers data to the PDS that has been acquired 6-9 months before the delivery date and is planning to maintain this schedule throughout the proposed E10.** SPD-41 states that for SMD missions “There shall be no period of exclusive access to Mission data. A period after the data have been obtained may be allowed for activities such as calibration and validation of the data. This period shall be as short as practical and shall not exceed six months.” The delivery of data to the PDS that has been acquired 6-9 months previously does not meet the requirements of SPD-41.

### **Minor Weaknesses**

The proposal includes an Archive Generation, Validation, and Transfer Plan that has not been updated for the PMSR25 review. The Archive Generation, Validation, and Transfer Plan, which was submitted in place of a Project Data Management Plan, was submitted as Revision 2 with a last update in 12/29/2021 and stated that this was revised for the E9 proposal. Appendix A5 did not indicate why the plan was not updated for this proposal and simply provided the previous plan revision without commentary. Although the Plan in Appendix A5 did not contain any new information for E10, the

proposal body did include additional relevant information.

The Odyssey mission plans to implement some SPD-41 policies on only a best effort basis during E10. The proposal stated that the mission has already implemented most of the directives of SPD-41 for the duration of the mission, “such as those associated with validation and delivery of raw and higher-level science data products, ancillary data, and documentation” and will voluntarily comply with the SPD-41a requirement to submit publications to the NASA repository. However, a few policies of SPD-41 such as archiving software for pipeline data processing or data analysis will be carried out “on a best-efforts basis.” The mission is planning to address these items during the E10 extended mission “within the constraints of available resources” but the proposal stated that “for the purposes of this proposal they should be considered ‘variances’ to the current policy due to limited resources.”

It is unclear why Table 3-2 misses the PDS4 "raw" data processing level since this corresponds to EDR-level PDS3 data.

#### **NOTES TO PROPOSERS (OPTIONAL)**

None noted.

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## 7.4. PROJECT DATA MANAGEMENT PLAN EVALUATION – MRO

**Mission Team:** Mars Reconnaissance Orbiter (MRO)

**Proposal Number:** 25-PMSR25-0003

**Proposal Title:** 7th Extended Mission Proposal FY26–28: Exploring a Changing Mars

### **PROJECT DATA MANAGEMENT PLAN SUMMARY**

Overall, the PDMP was thoroughly described and included all the necessary components to indicate that the archiving would be successfully executed in EM7. The proposal demonstrated that data from the mission is used extensively by community members outside the mission team. The MRO mission has consistently delivered most data products to the PDS on time in all previous cycles, with some Italian SHARAD data being the minor exception. The Italian SHARAD instrument has had “contracting issues” resulting in delays in delivery to the PDS and a significant delay in the transition to the PDS4 format.

The MRO mission has a well-documented plan to transition to providing newly acquired data in PDS4 format which has most instruments doing so by the end of EM6. The mission has a plan to convert all pre-EM6 products from PDS3 (as originally delivered) to PDS4 format.

### **PROJECT DATA MANAGEMENT PLAN MERIT**

#### **Major Strengths**

**Overall, the PDMP was thoroughly described and included all the necessary components to indicate that the archiving would be successfully executed in EM7.** The project would continue to archive all science data in EM7. The archiving progress and plan for all data types for all instruments was clearly outlined in the proposal (e.g., Table A5-7). The proposal updated the PMDP from the PMSR 2022 document appropriately and indicated that most PDS3 to PDS4 work is proceeding as planned and on schedule. The proposal outlined the timing and reasons for variances from the schedule.

**The MRO mission has consistently delivered mission data products to the PDS on time in all previous cycles, with only minor exceptions.** This is notable given the vast volumes data still being acquired by MRO across all active instruments. All deliveries from the HiRISE, CRISM, CTX/MARCI, MCS, and U.S. SHARAD instruments are being made on time according to the schedule. All instruments, other than CTX/MARCI, have been delivering data within 3-6 months after acquisition for some time now as required by SPD-41, and several datasets are being delivered more quickly. The CTX/MARCI data is transitioning to this delivery schedule as outlined in the EM6 PDMP. In addition, several instruments are already delivering PDS4 products to

PDS and most of the remaining instruments are on schedule to do so according to the EM6 PDMP.

**The proposal indicated that data from the mission is used extensively by community members outside the mission team.** During the year 2023-2024, 40 papers using MRO data were published by the mission team while 287 were published by the external planetary community (a ratio of just over 1:7). In addition, approximately 50TB of MRO data has been downloaded quarterly from the PDS which demonstrates the ongoing criticality of these datasets to the broader community. Both publications and download are a testament to the continuing scientific value of the data products, and the curatorial work that enables scientific studies with no connect to the team to use the data.

**The MRO mission has a well-documented plan to transition to providing data in PDS4 format which has most instruments doing so by the end of EM6.** The HiRISE instrument has developed a data dictionary and PDS4 labels for all data types and have generated sample files that are under review by the PDS. The instrument plans to start delivery of EM6 PDS4 products in early CY25 and will be caught up to the nominal delivery schedule by the end of EM6. The CRISM instrument was not selected for funding for EM6 and is no longer collecting data, therefore the CRISM instrument is not providing delivery of EM6 data in PDS4 format but is converting pre-EM6 files to PDS4. The CTX/MARCI instrument has produced PDS4 label templates for all archived data products and is producing a sample dataset for peer review by the end of CY2024. Delivery of EM6 data in PDS4 format will begin in CY25, although the proposal does not indicate when the instrument will be caught up delivering newly acquired EM6 data to the PDS in PDS4. The MCS instrument has developed PDS4 labels for their EDR data products and their RDR products will have similar label files. EDR and RDR data will be delivered in PDS4 format by the end of EM6. As of Aug. 1, 2024, all pre-EM6 and new deliveries of U.S. SHARAD RDR products are available in both PDS3 and PDS4 formats. U.S. SHARAD Cluttergram products have been delivered in PDS4 format since their inception in 2021.

### **Minor Strengths**

The CTX/MARCI instrument is transitioning to deliver data to the PDS 3-6 months after acquisition. The instrument has been delivering data to the PDS 6-9 months after acquisition according to original mission agreements in the PDMP but will accelerate deliveries to meet requirements in SPD41.

The proposal clearly outlined how data is shared between the mission, instrument teams, and the PDS. The mission central database is maintained at JPL and data is transferred to instrument facilities via a File Exchange Interface (FEI) maintained by the mission. The proposal stated that Interface Control Documents (ICD) exist for each relationship between facilities that provide data and the PDS nodes that receive that data.

The proposal explained that the mission transfers all SHARAD data to both the U.S. SHARAD and Italian SHARAD facilities giving confidence that if Italian SHARAD continues to have contracting issues, the raw spacecraft data will not be lost.

The MRO mission has put in tremendous effort to produce high quality data, including implementing notable improvements to both CRISM and HiRISE calibrations over past cycles. The inclusion of updated calibration in the HiRISE PDS4 conversion process is commended.

The MRO mission has archived many volumes of special products that are beyond their required PDS deliveries, which are of high scientific value (e.g., HiRISE DTMs, CRISM MTRDR, SHARAD DDR). The addition of higher level/derived products to the archival (PDS) deliveries is highly appreciated.

The HiRISE instrument delivers data to the PDS on an accelerated timeline, making high quality data quickly available to community. Rather than delivering quarterly as most PSD mission instruments do, most HiRISE data products are delivered monthly to the PSD. In addition, many products are delivered 1-2 months after acquisition rather than the nominal 3-6 months that is required.

Although specifics were not given, the proposal indicated that the MRO mission maintains a publication database which it will link or transfer to the appropriate NASA repository during EM7 to comply with SPD-41.

The HiRISE instrument has worked with the PDS Imaging node to implement storage of HiRISE data in the Imaging Node cloud service. HiRISE has transferred the entire HiRISE PDS3 archive to the cloud service as a backup and to test this facility for receiving HiRISE uncompressed PDS4 RDRs.

## **Major Weaknesses**

**The Italian SHARAD instrument has had delays in making scheduled data deliveries to the PDS and has delayed delivery of new PDS4 products.** The proposal stated that these delays are “due to contracting issues” without further discussion of the details of the contracting issue, or more importantly, if the issues potentially still exist or will continue to impact data deliveries. During EM6, 5 Italian SHARAD data deliveries to the PDS were delayed for between 2 to 10 months for 2023Q3 through 2024Q3. In addition, the Italian SHARAD EDR and RDR PDS4 data products are delayed 2 years from the schedule outlined in the EM6 PDMP. The PDS4 standard requires 8-bit data, while legacy data is a mix of 4, 6, and 8-bit. The instrument recognizes this but has not yet concluded plans to address the issue in the new PDS4 files. The instrument will re-purpose U.S. SHARAD code to assist with the re-calibration, conversion, and creation of labels in PDS4 format.

## **Minor Weaknesses**

MCS delivery and conversion of PDS4 files is delayed approximately one year from the original EM6 PDMP “due to the loss of a team member doing the work and the instrument responding to MCS actuator anomalies.” The proposal stated that tools for converting the DDR data set would be done the first year of EM7, and that plans for plans for the delivery of the DDR data in PDS4 data would not be made until the last quarter of EM6.

The proposal does not explain why EDR and RDR data from the MCS instrument will not be archived in legacy PDS3 formats after the pipeline to create PDS4 data is completed by the end of EM6. The proposal indicated that newly acquired DDR data after EM6 will be archived in PDS3 and PDS4 formats providing continuity to the community who may primarily use PDS3 formatted data and labels. However, the proposal indicated that EDR and RDR will only be delivered in PDS4 formats and does not explain why this was a reasonable decision.

The proposal provided uneven details across instruments for the transition to archiving newly acquired data in PDS4 formats. For example, the proposal provided detailed information and a schedule for the conversion for the HiRISE instrument while lacking some or all details for the plan and schedule for instruments like Italian SHARAD. A chart showing status and a schedule for each instrument would have been helpful.

The MRO mission is meeting most requirements of SPD-41, such as delivery of data to the PDS 3-6 months after acquisition, however the mission does not plan to archive software. SPD-41, section IV.B, states that “In order to support reproducibility, SMD shall commit to the full and open sharing of information produced by NASA SMD Missions. This includes observations, calibrations, coefficients, documentation, software, algorithms, technical reports, and any ancillary information or work product related to the Mission.” The EM7 proposal states that “Although not required by the PMSR25 call, SPD-41a guidelines also call for archival of software and data, other than PDS deliverables. Due to the tight budget, MRO cannot undertake those tasks at this time.”

## **NOTES TO PROPOSERS (OPTIONAL)**

None noted.

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## 7.5. PROJECT DATA MANAGEMENT PLAN EVALUATION – MAVEN

**Mission Team:** Mars Atmosphere and Volatile Evolution Mission (MAVEN)

**Proposal Number:** 25-PMSR25-0006

**Proposal Title:** MAVEN Planetary Mission Senior Review

### **PROJECT DATA MANAGEMENT PLAN SUMMARY**

The proposal provided a detailed, well-structured accounting of the data that have been archived, including all science data and engineering products and team roles and responsibilities. This detailed description provided significant confidence in the continued effective and timely delivery of MAVEN mission data to the science community. The MAVEN mission also has appropriate configuration management and data error identification and tracking processes established, demonstrating that there are many levels of protection established to ensure the data's fidelity. In addition, the Science Data Management Plan clearly demonstrated a commitment to producing a data archive of the highest quality, maximizing data accessibility, and with an approach of providing a critical service to the science community. Finally, the MAVEN mission has archived data to the PDS in accordance with their nominal delivery schedule and all data deliveries to the appropriate PDS nodes were complete, ensuring rapid community access and dissemination of future scientific outputs. However, a final data delivery to the archive and final archive data peer-review timeline was not discussed, and especially in the context of a possible mission closeout.

### **PROJECT DATA MANAGEMENT PLAN MERIT**

#### **Major Strengths**

**The proposal provided a detailed, well-structured accounting of the data that have been archived, including all science data and engineering products and team roles and responsibilities. This detailed description provided significant confidence in the continued effective and timely delivery of MAVEN mission data to the science community.** This attention to detail was demonstrated by diagrams such as Figure 3-1 and Table 4-2, which illustrated the workflow and data handling through all stages of the data lifecycle from spacecraft operations to data delivery to the Planetary Data System (PDS). For example, the data ground system roles and responsibilities were clearly described, a detailed description of all data products to be archived was supplied, and a detailed description of the end-to-end data processing procedures was provided. Clear guidelines were given for archiving, sharing, and maintaining data in formats that comply with NASA's policies, allowing future researchers to more easily access and reuse the data. In addition, adherence to FAIR (Findable, Accessible, Interoperable, and Reusable) data management principles was evident. Finally, the entire Science Data Management Plan was provided in the

appendix, including the document change log, demonstrating that the SDMP is maintained as a living document and modified as needed throughout the mission.

**The MAVEN mission has appropriate configuration management and data error identification and tracking process established, demonstrating that there are many levels of protection established to ensure the data's fidelity.** The proposal described strong version control processes that were in place for both software and data, in addition to appropriate multi-level labeling for different stages of the data reduction process. Minimum configuration management included versioning systems, release control procedures, issue/defect tracking, and documentation. This system ensured that the MAVEN project delivered to the user community correct, validated, and timely science and calibration data and the software that was used to produce, distribute, and analyze these data. This system also allowed the community to identify, have access to, and use intended data versions and maintains a complete pedigree for each data product produced, facilitating reproducibility of science results. In addition, potential challenges were identified, such as the team being in geographically dispersed areas, and this difficulty was effectively addressed by the use of an effective configuration management system employed at each contributing institution for all science products. Further, a data defect tracking system was also employed, together with a portal by which the science community was able to report any errors.

**The Science Data Management Plan clearly demonstrated a commitment to producing a data archive of the highest quality, maximizing data accessibility, and with an approach of providing a critical service to the science community.** This commitment was demonstrated through thoughtful consideration for how the science community would use these data and the effort and thought dedicated to making the data usable. For example, file formats were selected that were familiar to and convenient for the scientific communities that the MAVEN program would serve. Detailed release notes accompanied all released software and data, and information included in release notes was clearly described. In addition, there were no proprietary periods associated with any of the MAVEN data products, and the scientific community outside the MAVEN team had timely access to the scientifically useful products (Levels 2+) through the PDS. Finally, software tools were hosted on the Science Data Center (SDC) website, the SDC GitHub, and archived in the PDS to facilitate access to, display of, and analysis of MAVEN science data products. Analysis tools that are unique to a specific dataset were developed by appropriate science team members and delivered to the SDC with documentation for using the tools. In addition, IDL virtual machines were developed to provide access to particle and fields resources that would otherwise only be available to IDL users.

**The MAVEN mission has archived data to the PDS in accordance with their nominal delivery schedule and all data deliveries to the appropriate PDS nodes were complete, ensuring rapid community access and dissemination of future scientific outputs.** The data deliveries to the PDS and the community occurred every 3 months, with minimal delays, and in PDS4 format. The data provided also included specific data products generated to facilitate inter-comparisons between instruments.

Data with improved calibrations and new products were also archived and available to the science community.

### **Minor Strengths**

All MAVEN data have been and will be archived in PDS4 format. MAVEN was the first planetary mission to archive in PDS-4 from the outset, and the first to develop and implement a PDS-compliant Common Data Format (CDF) for archiving Particles and Fields data. The use of CDF in PDS4 is an effective practice for particles and fields instruments, is a format quite common in the heliophysics domain, and is especially useful in the context of MAVEN being used for space weather monitoring.

The proposal demonstrated that data from the mission was used widely by community members outside the mission team, and the number of publications led by non-team members has increased throughout the mission. In addition, the proposal illustrated that the publication rate by the community has been consistent throughout the mission.

### **Major Weaknesses**

**A final data delivery to the archive and final archive data peer-review timeline was not discussed, and especially in the context of a possible mission closeout.** The data passed a peer-review early in the mission and data were therefore certified. However, these peer-reviews date from 2014-2019 and most of them were held in the 2014-2016, which was the relatively early phase of PDS4 standard development. In 10 years, the PDS4 standard has evolved, together with more mature discipline dictionaries and archiving guidelines to capture more metadata in the products, making data better documented and more discoverable. A plan for an additional set of "delta" (or final) peer-reviews of the MAVEN data to help obtain a final archive with more metadata and improved calibrations could have significant community benefit and was not described.

### **Minor Weaknesses**

The proposal did not clearly describe whether calibration (in addition to calibrated) data were also archived in the PDS, and if any calibration software would be made available to the community. Some instruments did not archive level 1 data, and therefore the process of re-calibrating the data (if necessary) using calibration data and raw data may not be possible in all cases.

## **NOTES TO PROPOSERS**

None noted.

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## 7.6. PROJECT DATA MANAGEMENT PLAN EVALUATION – MSL

**Mission Team:** Mars Science Laboratory

**Proposal Number:** 25-PMSR25-0004

**Proposal Title:** Mars Science Laboratory Extended Mission 5: Investigating the Habitability on Aeolis Mons

### **PROJECT DATA MANAGEMENT PLAN SUMMARY**

All data archived in Extended Mission (EM) 4 and planned for EM5 would be of high technical merit and valuable to the science community. In the last cycle, the MSL successfully met all milestones for archiving data to the PDS. The large number (~500) and large fraction (50%) of external publications and the download statistics imply that data is being used by scientific community members beyond the mission team. The PDMP clearly described the process for data integration across instruments, accessibility by the community, and maximum use of the archived data through the effective and well-used Analyst's Notebook tool. The mission demonstrated innovation in EM 4 in providing new data products and formats to better serve the community. The PDMP compellingly demonstrate that all new data would be archived in PDS 4 format. The proposal states that the mission is on track to finish the conversion of all archival data to PDS 4 format by the end of EM 4.

### **PROJECT DATA MANAGEMENT PLAN MERIT**

#### **Major Strengths**

**All data archived in Extended Mission (EM) 4 and planned for EM5 would be of high technical merit and valuable to the science community.** The PDMP would deliver high quality data; robust, published calibration; appropriate formats; and significant utility of reduced data record products. In the extended mission, the Mars Science Laboratory (MSL) would continue to archive all science data.

**In the last cycle, the MSL successfully met all milestones for archiving data to the PDS.** The mission has delivered 48.7 terabytes of data (23.3 million files) to the PDS through Release #36. The vast majority of the data archived in EM 4 were delivered on time, with only a small number of delays [e.g., Mars Hand Lens Imager (MAHLI)/Mast Camera (Mastcam)/Mars Descent Imager Experiment Data Record Release 1]. The current MSL data archive is complete and all deliveries are up-to-date.

**The large number (~500) and large fraction (50%) of external publications and the download statistics imply that data is being used by scientific community members beyond the mission team.** External publications based on MSL data have been strong and continuing for 10 years. For the last few years, the rate of external publications has been similar to that of team members. There has been a significant increase in data downloads since 2019.

**The PDMP clearly described the process for data integration across instruments, accessibility by the community, and maximum use of the archived data through the effective and well-used Analyst's Notebook tool.** The MSL Analyst's Notebook is an especially useful interface that goes above-and-beyond in making the PDS-archived data easily accessible to external users. This tool enables users to view and analyze data from multiple instruments along with mission records (e.g., traverse locations). The platform demonstrates the MSL's heavy investment in making the collected data broadly accessible to the larger scientific community.

**The mission demonstrated innovation in EM 4 in providing new data products and formats to better serve the community.** The new data products include the Mastcam Photometry Cubes and MAHLI Technical Reports in the PDS, and the MSL Solid Sample Library (non-PDS). The Radiation Assessment Detector (RAD) data have been converted to a data format used in the Heliophysics community [Common Data Format (CDF)], expanding the pool of potential users.

**The PDMP compellingly demonstrate that all new data would be archived in PDS 4 format.** The mission successfully archived all new data in PDS 4 format during EM 4, as well as converting a significant amount of archival data to EM 4.

### **Minor Strengths**

In the case of instrument or mission closeout, the PDMP included an adequate duration for delivering data to the archive and other products (e.g., software) to long-term storage sites.

The mission has provided valuable non-PDS open repositories for the data, including the Chemistry and Mineralogy (CheMin) Open Data Repository and the Gale Crater Open Data Repository.

### **Major Weaknesses**

None noted.

### **Minor Weaknesses**

Although the mission would deliver the majority of the data within six months of acquisition, some of the planned releases would be beyond 6 months, in violation of SPD-41. SPD-41 indicates that for SMD missions "There shall be no period of exclusive access to Mission data. A period after the data have been obtained may be allowed for activities such as calibration and validation of the data. This period shall be as short as practical and shall not exceed six months."

The PDMP did not include a final peer review of the archive data as part of possible closeout activities. Such a final peer review would be valuable given changes since the initial peer review to the calibration of the data, the documentation of the data, and the type of products generated, and given the conversion of the data to PDS4.

The PDMP did not include a plan to add information available in Analyst Notebooks to the PDS for long-term archiving (e.g., by adding metadata to the MSL PDS4 data products or by creating new PDS4 data products for the mission to preserve the information in the PDS system).

Although the proposal demonstrated a large number of external publications and that data is being accessed, it did not fully demonstrate the extent to which the science community beyond the mission team utilizes mission data (for example, how many users that are not team members are contributing to the downloads in Figure A5-2 and the extent to which this downloaded data is being used in non-team member publications). Some of the external publications have current and/or former MSL team members as co-authors (e.g., Feldman et al., 2024; Z. Chen et al., 2024; Mitra et al., 2024); and/or (b) use general results from MSL, but do not present new analyses of MSL data (e.g., Cogliati and Macey, 2024; Y. Chen et al., 2024; Fifer and Wong, 2024).

The PDS4 data products contain inhomogeneities across instruments. Differences in the level of details captured in the PDS4 product labels vary across instruments, which may make some instrument data (e.g. cameras on the imaging node) more discoverable and documented than others instrument data (having more basic PDS4 labels).

## **NOTES TO PROPOSERS (OPTIONAL)**

When migrating the RAD data to PDS4, consider using the CDF format (converted to PDS4), since this is a possible option to archive data in PDS4 (and meet both the Heliophysics and Planetary Science community's needs).

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## 8. Panel Members

| Panelist                | Institution          | Juno      | LRO      | ODY      | MRO      | MAVEN    | MSL      |
|-------------------------|----------------------|-----------|----------|----------|----------|----------|----------|
| W. James Adams          | NASA HQ (ret.)       | x         | x        |          | x        |          |          |
| William Blackwell       | MIT-LL               | x         |          |          |          |          |          |
| Daniel Britt            | UCF                  |           | x        | x        | x        |          | x        |
| Wendy Calvin            | UNR                  |           |          |          |          |          | x        |
| Ed Cloutis              | U Winnipeg           |           |          | x        | x        |          |          |
| Robert Craddock         | Smithsonian          |           | GC       | x        |          |          |          |
| Tim Dowling             | U Louisville         | x         |          |          |          |          |          |
| Richard French          | Wellesley / SSI      | x         |          |          |          |          |          |
| Antonio Genova          | Sapienza U Rome      | x         |          |          |          |          |          |
| Jupiter Hansen (Cheng)  | U Alabama            |           | x        |          |          |          |          |
| Paul Helfenstein        | Cornell              | x         |          |          |          |          |          |
| Chris Herd              | U Alberta            |           |          |          |          |          | x        |
| Dana Hurley             | APL                  |           |          |          |          | GC       |          |
| Joel Hurowitz           | Stony Brook          |           |          | x        |          |          |          |
| Gordon Johnston         | NASA HQ (ret.)       |           |          | x        |          | x        | x        |
| Melinda Kahre           | NASA ARC             |           |          | GC       |          |          |          |
| Edwin Kite              | U Chicago            |           |          |          |          | x        |          |
| Thomas LaPen            | U Houston            |           |          |          |          |          | x        |
| Timothy Lyons           | UCR                  |           |          |          |          |          | x        |
| Harold McSween          | UTK                  |           |          |          | GC       |          |          |
| David Minton            | Purdue               |           | x        |          |          |          |          |
| John Moores             | York U, Toronto      | x         |          |          |          |          |          |
| Jack Mustard            | Brown                |           |          |          |          |          | GC       |
| Mikki Osterloo          | SSI                  |           |          | x        | x        |          |          |
| Carl Pilcher            | NASA HQ / ARC (ret.) | GC        |          |          |          |          |          |
| Darci Snowden           | Central Wash. U      | x         |          |          |          | x        |          |
| David Southwood         | Imperial College, UK | x         |          |          |          |          |          |
| Michelle Thompson       | Purdue               |           | x        |          |          |          |          |
| Sonia Tikoo             | Stanford             |           | x        |          |          |          |          |
| Marissa Vogt            | PSI                  |           |          |          |          | x        |          |
| Jennifer Whitten        | Smithsonian          |           | x        |          |          |          |          |
| David Williams          | ASU                  |           |          |          | x        |          |          |
| Colin Wilson            | ESTEC                |           |          |          |          | x        |          |
| Paul Withers            | Boston U             |           |          | x        |          |          |          |
| Robin Wordsworth        | Harvard              |           |          |          |          |          | x        |
| Xi Zhang                | UCSC                 | x         |          |          |          |          |          |
| <b>Voting Panelists</b> | <b>36</b>            | <b>11</b> | <b>8</b> | <b>8</b> | <b>6</b> | <b>6</b> | <b>8</b> |

| <b>Panelist</b>                                                                                  | <b>Institution</b> | <b>Juno</b> | <b>LRO</b> | <b>ODY</b> | <b>MRO</b> | <b>MAVEN</b> | <b>MSL</b> |
|--------------------------------------------------------------------------------------------------|--------------------|-------------|------------|------------|------------|--------------|------------|
| Melissa Lane                                                                                     | Fibernetics, LLC   | RC          | RC         | RC         | RC         | RC           | RC         |
| Sean Solomon                                                                                     | Columbia U         | RC          | RC         | RC         | RC         | RC           | RC         |
| Travis Gabriel                                                                                   | USGS               | ES          |            |            |            | ES           |            |
| Sean Hsu                                                                                         | U Colorado         |             |            | ES         |            |              | ES         |
| Eva Stuekeen                                                                                     | St Andrews, UK     |             | ES         |            | ES         |              |            |
| x = Panelist<br>GC = Group Chief<br>RC = Review Chair (non-voting)<br>ES = Exec Sec (non-voting) |                    |             |            |            |            |              |            |