The 2023 Senior Review of the Heliophysics System Observatory Missions

July 1, 2023

Submitted to:
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Executive Summary

During April and May of 2023, the 2023 Heliophysics Senior Review (SR) Panel reviewed 12 operating missions with the NASA Heliophysics Systems Observatory (HSO) fleet. The following 13 missions were invited to submit an Extended Mission proposal: AIM, GOLD, Hinode, IBEX, ICON, IRIS, MMS, New Horizons, SDO, STEREO, THEMIS, TIMED, and Voyager. New Horizons did not respond to the call. After submission of proposals but before the SR panel meeting, ICON and AIM suffered technical failures/anomalies. The panel was instructed by the Heliophysics Division (HPD) to evaluate these two missions according to a subset of criteria (Criteria A: Factor A-1, and Criteria C: Factor C-1) in order to inform end-of-mission reviews and milestones. All of the HSO missions operating in their extended mission phases contribute valuable observations. These missions continue to make discoveries and significant progress while addressing their compelling science investigations.

The overall findings of the panel are:

10 of the 12 missions being reviewed are in excellent health. These missions proposed exciting, timely, and compelling extended mission science investigations. The missions study the Sun, the heliosphere upstream of Earth and around the Moon, the Earth's mesosphere, thermosphere, ionosphere and magnetosphere, the outer heliosphere, and the local interstellar medium. All of the HSO missions reviewed contribute significantly to NASA Heliophysics Strategic Goals and those goals set forth by the 2013 Solar and Space Physics Decadal Survey.

All reviewed missions contribute to understanding the heliophysics system in addition to supporting the scientific objectives proposed by each of the mission teams. However, the SR panel found that the individual extended mission proposals 1) needed more system-level coherence, and 2) perpetuated closed communities. The SR panel recommends that the HPD develop a strategy and implementation plans for a more coordinated HSO mission portfolio. This recommendation can be supported by assisting the mission teams in communicating and collaborating via enabling shared expectations around Open Science and IDEA efforts in order to fulfill the scientific potential of the HSO. To facilitate this coordination, an HSO Program Scientist (PS) would enable tremendous scientific opportunities to understand the entire system and coupling between the systems' components.

The 2023 SR was the first to require an Inclusion, Diversity, Equity and Accessibility (IDEA) plan as part of the proposal. There was a wide range of interpretations by the mission teams on what a quality IDEA Plan should include, how actively the mission team has to participate in IDEA activities, and how it should be reflected in a specific implementation plan and budget. The SR recommends that the

IDEA Plan be part of the overall evaluation score of the mission for all future SRs. The HSO PS could facilitate professional development workshops and training and could provide access to NASA IDEA resources.

The HSO missions' adherence to NASA Policy Directives around Open Science (including open access to publications, open access to data, open-source software, and enabling reproducibility) are much improved from the 2020 Heliophysics SR. However, many of the HSO missions are still slow in archiving. The Heliophysics Data Resources Library (HDRL) has the potential to take a more proactive role within the Heliophysics Science Observatory (HSO) by assessing compliance with NASA policies and by providing resources and support to ensure that legacy missions are fully compliant.

List of Acronyms

2D	two-Dimensional
3D	three-Dimensional
3DP	three-Dimensional Plasma and energetic particle investigation
AACS	Attitude and Articulation Control Subsystem
AC	Alternating Current
ACE	Advanced Composition Explorer
AGU	American Geophysical Union
AIA	Atmospheric Imaging Assembly
AIM	Aeronomy of Ice in the Mesosphere
AIMI	Atmosphere-Ionosphere-Magnetosphere Interactions
AIRS	Atmospheric InfraRed Sounder
ALMA	Atacama Large Millimeter/submillimeter Array
APL	Applied Physics Laboratory
AR	Active Region
ARC	Ames Research Center
ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun
ASCII	American Standard Code for Information Interchange
ASI	All-Sky Imager
AU	Astronomical Unit
AURIC	Atmospheric Ultraviolet Radiance Integrated Code
AWE	Atmospheric Waves Experiment
BRG	Business Resource Group
CCMC	Community Coordinated Modeling Center
CDAWeb	Coordinated Data Analysis Web
CDE	Cosmic Dust Experiment
CDF	Common Data Format
CEDAR	Coupling Energetics and Dynamics of Atmospheric Regions
CIPS	Cloud Imaging and Particle Size
CIRCUIT	Cohort-based Integrated Research Community for Undergraduate Innovation and Trailblazing
CLPS	Commercial Lunar Payload Services
CMAD	Calibration and Measurement Algorithms Document

CME	Coronal Mass Ejection
Co-I	Co-Investigator
COFFIES	Consequences Of Fields and Flows in the Interior and Exterior of the Sun
COR1	Inner Coronagraph (SECCHI)
COR2	Outer Coronagraph (SECCHI)
COSMIC	Constellation Observing System for Meteorology Ionosphere and Climate
CRS	Cosmic Ray Subsystem
CY	Calendar Year
D&I	Diversity and Inclusion
DART	Data Assimilation Research Testbed
DARTS	Data ARchive and Transmission System (Japan)
DC	Direct Current
DEI	Diversity, Equity, and Inclusion
DEIA	Diversity, Equity, Inclusion, and Accessibility
DKIST	Daniel K. Inouye Solar Telescope
DQI	Data Quality Indicator
DRIVE	Diversify, Realize, Integrate, Venture, Educate
DRMS	Data Record Management System
DSCOVR	Deep Space Climate Observatory
DSN	Deep Space Network
DYNAMIC	DYnamical Neutral AtMosphere-Ionosphere Coupling
EFI	Electric Field Instrument
EIA	Equatorial Ionization Anomaly
EIS	Extreme-ultraviolet Imaging Spectrometer
EM	Extended Mission
ENA	Energetic Neutral Atom
EOVSA	Expanded Owens Valley Solar Array
EPB	Equatorial Plasma Bubble
EPO	Education and Public Outreach
ERG	Exploration of energization and Radiation in Geospace
ESA	Electrostatic Analyzers
ESA	European Space Agency
EUV	Extreme UltraViolet
EVE	Extreme ultraviolet Variability Experiment
FAC	Field Aligned Currents

FG	Filter-Graph
FGM	FluxGate Magnetometer
FIP	First Ionization Potential
FISM	Flare Irradiance Spectral Model
FOXSI	Focusing Optics X-ray Solar Imager
FPI	Fast Plasma Instrument
FTE	Full-Time Equivalent
FURST	Full-sun Ultraviolet Rocket SpecTrograph
FUV	Far UltraViolet
FY	Fiscal Year
GBOs	Ground-Based Observatories
GCM	General Circulation Model
GCRs	Galactic Cosmic Rays
GDC	Geospace Dynamics Constellation
GDF	Globally Distributed Flux
GEM	Graduate Degrees for Minorities in Engineering
GITM	Global Ionosphere Thermosphere Model
GLIDE	Global Lyman-alpha Imager of the Dynamic Exosphere
GMAGS	Ground-based fluxgate MAGnetometerS
GOES	Geostationary Operational Environmental Satellite
GOLD	Global-scale Observations of the Limb and Disk
GSFC	Goddard Space Flight Center
GUVI	Global UltraViolet Imager
GW	Gravity Wave
HBCU	Historically Black Colleges and Universities
HDMC	Heliophysics Data Model Consortium
HDRL	Heliophysics Digital Resources Library
HDS	Heliophysics Decadal Survey
HEO	High-Earth Orbit
HI	Heliospheric Imager
HMI	Helioseismic and Magnetic Imager
HPD	Heliophysics Division
HQ	Headquarters
HSO	Heliophysics System Observatory
IBEX	Interstellar Boundary EXplorer

ICD	Interface Control Document
ICME	Interplanetary Coronal Mass Ejection
ICON	Ionospheric CONnection explorer
IDEA	Inclusion, Diversity, Equity, and Accessibility
IDEAL	Inclusion, Diversity, Equity, and Access in a Learning Environment
IDL	Interactive Data Language
IG	In-Guide (budget)
IMAP	Interstellar Mapping and Acceleration Probe
IMPACT	In-situ Measurements of Particles And CME Transients
IMU	Inertial Measurement Unit
IRIS	Interface Region Imaging Spectrograph
IRU	Inertial Reference Unit
ISAS	Institute of Space and Astronautical Science
ISTP	International Solar-Terrestrial Physics
IT	Ionosphere Thermosphere
ITM	Ionosphere Thermosphere Mesosphere
JAXA	Japan Aerospace eXploration Agency
JHU/APL	Johns Hopkins University/Applied Physics Laboratory
JPL	Jet Propulsion Laboratory
JSOC	Joint Science Operations Center
KSAT	Kongsberg SATellite Services
L2-CPE	L2 Charged Particle Environment
LASCO	Large Angle and Spectrometric COronagraph
LASP	Laboratory for Atmospheric and Space Physics
LECP	Low Energy Charge Particle
LISM	Local InterStellar Medium
LISMF	Local InterStellar Magnetic Field
LMSAL	Lockheed Martin Solar and Astrophysics Laboratory
MAGIXS	Marshall Grazing Incidence X-ray Spectrometer
MAVEN	Mars Atmosphere and Volatile EvolutioN
MHD	MagnetoHydroDynamic
MIGHTI	Michelson Interferometer for Global High-resolution Thermospheric Imaging
MLT	Mesosphere, Lower Thermosphere
MLTI	Mesosphere, Lower Thermosphere and Ionosphere
MMS	Magnetospheric MultiScale

MO&DA	Mission Operations and Data Analysis
MOC	Mission Operations Center
MSG	Major Science Goal
NASA	National Aeronautics and Space Administration
NLC	NoctiLucent Cloud
NO	Nitric Oxide
NOAA	National Oceanic and Atmospheric Administration
NSBP	National Society of Black Physicists
NSF	National Science Foundation
NSPIRES	NASA Solicitation and Proposal Integrated Review and Evaluation System
NSSDC	National Space Science Data Center
NuSTAR	Nuclear Spectroscopic Telescope ARray
NUV	Near UltraViolet
ODEO	Office of Diversity and Equal Opportunity
OOI	Office Of Inclusion
PDMP	Project Data Management Plan
PI	Principal Investigator
PLASTIC	PLAsma and SupraThermal Ion Composition
PLS	PLasma Science
PMC	Polar Mesospheric Clouds
PS	Project Scientist
PSG	Prioritized Science Goal
PSP	Parker Solar Probe
PUNCH	Polarimeter to UNify the Corona and Heliosphere
PW	Planetary Waves
PWS	Plasma Wave Subsystem
RAA	Rayleigh Albedo Anomaly
RADYN	RAdiative-hydroDYNamic
REEs	Relativistic Electron Enhancements
REU	Research Experience for Undergraduates
RF	Radio Frequency
RFA	Research Focus Area
ROSES	Research Opportunities in Space and Earth Sciences
RTG	Radioisotope Thermoelectric Generator
SABER	Sounding of the Atmosphere using Broadband Emission Radiometry

SACNAS	Society for Advancement of Chicanos/Hispanics & Native Americans in Science
SAO	Smithsonian Astrophysical Observatory
SC	Solar Cycle
SCM	Search Coil Magnetometers
SDAC	Solar Data Analysis Center
SDO	Solar Dynamic Observatory
SECCHI	Sun Earth Connection Coronal and Heliospheric Investigation
SEE	Solar Extreme ultraviolet Experiment
SEP	Solar Energetic Particle
SG	Science Goal
SHIELD	Solar wind with Hydrogen Ion charge Exchange and Large-Scale Dynamics
SIM	Spectral Irradiance Monitor
SITL	Scientist-In-The-Loop
SMD	Science Mission Directorate
SMEX	SMall EXplorers
SO	Science Objective
SOC	Science Operations Center
SOFIE	Solar Occultation For Ice Experiment
SOHO	SOlar and Heliospheric Observatory
SolO	Solar Orbiter
SOT	Solar Optical Telescope
SPASE	Space Physics Archive Search and Extract
SPDF	Space Physics Data Facility
SPEDAS	Space Physics Environment Data Analysis Software
SPICE	SPectral Imaging of the Coronal Environment
SSMO	Space Sciences Mission Operations
SQ	Science Question
SR	Senior Review
SR2020	Senior Review 2020
SR2023	Senior Review 2023
SST	Solid State Telescopes
STA	STEREO-Ahead
STB	STEREO-Behind
STE	SupraThermal Electron
STEM	Science, Technology, Engineering, and Mathematics

STEREO	Solar TErrestrial RElations Observatory
STIX	Spectrometer/Telescope for Imaging X-rays
SunRISE	Sun Radio Interferometer Space Experiment
SW	Solar Wind
SWFO	Space Weather Follow-On
SWPC	Space Weather Prediction Center
SwRI	Southwest Research Institute
TDISK	GOLD retrieval algorithm
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIDI	TIMED Doppler Interferometer
TIEGCM	Thermosphere-Ionosphere-Electrodynamics General Circulation Model
TIMED	Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics
TRACERS	Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites
TREx	Transition Region Explorer
TSIS	Total and Spectral Solar Irradiance Sensor
UCB	University of California, Berkeley
UCLA	University of California, Los Angeles
UiO	University of Oslo
UK	United Kingdom
UKMet	United Kingdom Meteorological
ULF	Ultra-Low Frequency
URM	Under Represented Minorities
US	United States
UV	UltraViolet
VIM	Voyager Interstellar Mission
VLA	Very Large Array
VLISM	Very Local InterStellar Medium
VM	Voltage Management
VSO	Virtual Solar Observatory
WYE	Work-Year Equivalent
XRT	X-Ray Telescope

Overview

Introduction

NASA's Science Mission Directorate (SMD) conducts reviews of its operating missions on a three-year cycle in order to maximize the scientific return from these missions within finite resources. This review is undertaken per Title 51 U. S. Code §30504, as modified by the NASA Transition Authorization Act of 2017 (P.L. 115-10), which reads in part:

> (1) *The Administrator shall carry out triennial reviews within each of the Science divisions to assess the cost and benefits of extending the date of the termination of data collection for those missions that exceed their planned missions' lifetime.*
>
> (2) *In conducting an assessment under paragraph (1), the Administrator shall consider whether and how extending missions impacts the start of future missions.*

The 2023 Heliophysics Division (HPD) Senior Review assessed the operating missions within the Heliophysics System Observatory (HSO), including the balance of the portfolio and the scientific merits and performance of the missions. HPD invited 13 missions to submit extended mission proposals to the 2023 Senior Review: AIM, GOLD, Hinode, IBEX, ICON, IRIS, MMS, New Horizons, SDO, STEREO, THEMIS, TIMED, and Voyager. New Horizons did not respond to the Call for Proposals and was not assessed. The Senior Review panel was instructed on April 12, 2023 that ICON and AIM should be assessed only against Factor A-1 and Factor C-1 (the findings for which NASA will then use in end-of-mission reviews and activities). The remaining 10 missions were assessed against the full set of evaluation criteria.

This 2023 HPD Senior Review assessment will cover extended mission operations in the period of FY2024-FY2028. NASA will use the results of this review to rebalance HPD mission allocations within the operating mission portfolio. These allocations drive mission budget allocations in the near-term (FY2024, FY2025, and FY2026) and inform the planning for levels of support in later years (FY2027 through FY2028). Each mission team invited to this Senior Review shall propose a mission extension either as a Science Investigation or Heliophysics System Observatory Infrastructure.

The Senior Review panel formed by NASA Headquarters (HQ) assessed these proposals, supplemented by presentations from the mission teams. This assessment submitted to the Heliophysics Division at NASA HQ will be used as input for decisions on the HSO portfolio. The potential outcomes for missions are summarized as one of the following:

- Funded for an extended science mission (for Science Investigation proposals)
- Funded for an extended mission as HSO Infrastructure (for HSO Infrastructure proposals or

Science Investigation proposals)
- Termination

Missions selected for an extended science mission should expect to be included in the next Senior Review. Missions selected for infrastructure operations will not be invited to the next Senior Review but will undergo programmatic review on a similar schedule.

Within the finite resources available, HPD strives to maintain a scientifically well-balanced portfolio consisting of both new and continuing missions. As in previous Senior Review cycles, the mission teams invited to participate in this Senior Review should be cognizant of the constrained and dynamic budget space the Agency is working with as well as the HPD missions that are in development.

Missions Under Review

As shown in the table below, 10 missions were fully reviewed by the Senior Review panel. ICON and AIM were evaluated against Factor A-1 and C-1 only (see the next section for review criterion
Each mission team was asked to provide a detailed in-guide budget with separated Mission Operations, Science Operations, and Science Investigation in terms of budget and level of effort (FTE or WYE). Each mission team was also invited to present an under-guide and over-guide budget. The over-guide budget science investigations were evaluated but not rated. None of the mission teams submitted an under-guide budget.

Charge to the Heliophysics Senior Review Panel

The Senior Review panel assessed the following based on the mission proposal and mission presentation:

- the scientific benefit of continuing each individual mission (Criteria A-C) via completion of previous extended mission science, compelling nature of proposed science investigations, contribution to the Heliophysics System Observatory
- the technical implementation (Criterion D) via health of the mission, including spacecraft, instruments and ground systems, cost and ability to continue within in-guide budget, and sufficiency of management plan
- the IDEA Plan (Criterion E)
- Under-guide and over-guide requests (Criterion F)

The Senior Review panel was also charged with the following:

- Produce and deliver the final Senior Review report
- General Findings: Top-level findings and trends across the missions

- Findings on SSMO and HDRL participation in SR

Evaluation Criteria

The Senior Review panel assessed the proposal content against the following criteria:
Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:** Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)
- **Factor A-2:** Performance of addressing any findings in the previous Senior Review. (The 2023 Senior Review panel will have access to the previous Senior Review report for a mission and other information from that review as needed.) This factor will only be assessed for missions returning to the Senior Review.

Criterion B: Overall Evaluation of the Proposed Investigation (Science Investigation only)

- **Factor B-1:** Scientific merit and impact of the proposed in-guide science investigation.
- **Factor B-2:** Implementation merit of the proposed in-guide science investigation.
- **Factor B-3:** Relevance of the proposed in-guide science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.
- **Factor B-4:** Cost reasonableness of the proposed in-guide science investigation.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:** Quality of the archival mission science data products and associated documentation.
- **Factor C-2:** Synergy with and benefit to the Heliophysics System Observatory. This factor applies only to the planned observations and not any previous scientific return or proposed mission-funded science investigation.

Criterion D: Technical Implementation

- **Factor D-1:** Health of the mission and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory. For this factor, the mission includes the spacecraft, instruments, and project-managed ground systems.
- **Factor D-2:** Cost reasonableness of the mission's operations model. This factor includes the ability to continue healthy operations within the in-guide budget.

- **Factor D-3:** Sufficiency of the management plan and, if applicable, necessity for the succession plan.

Criterion E: Inclusion, Diversity, Equity, and Accessibility

- **Factor E-1:** Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan. This factor applies to the mission's ideal state of IDEA including mission activities, mission team structure, movement of individuals in/out of and within the mission team, and succession planning. This factor includes any tailoring of institutional IDEA strategies to the mission team's plan.
- **Factor E-2:** Recent progress against the mission team's IDEA Plan. This factor assesses the mission's recent actions that have addressed and made progress against the mission IDEA strategy. This factor applies only to those missions that have developed an IDEA strategy before this Senior Review.
- **Factor E-3:** Planned progress against the mission IDEA Plan. This factor assesses the mission team's plan to advance toward its ideal state of IDEA by the next Senior Review. This includes planned metrics and milestones, the ability for upcoming actions to meet those metrics/milestones, and the ability to enable further progress after the next Senior Review.
- **Factor E-4:** Cost reasonableness of the mission team's IDEA activities.

Criterion F: Under-guide and Over-guide Requests (Informational Only)

- **Factor F-1:** Scientific merit and impact of any proposed over-guide science investigation.
- **Factor F-2:** Implementation merit of any proposed over-guide science investigation.
- **Factor F-3:** Scientific merit and impact of any proposed under-guide science investigation.
- **Factor F-4:** Implementation merit of any proposed under-guide science investigation.
- **Factor F-5:** Merit and impact of any proposed over-guide for mission operations.
- **Factor F-6:** Merit and impact of any proposed over-guide for the mission team's IDEA Plan.

The evaluation of each mission will consider the following points:

- Criteria A-D are rated and weighted to provide an overall proposal rating.
    - For Science Investigations, the criteria are weighted as follows: Criterion A, 25%; Criterion B, 30%; Criterion C, 20%; Criterion D, 25%.
    - For Heliophysics System Observatory (HSO) Infrastructure, the criteria are weighted as follows: Criterion A, 25%; Criterion C, 50%; Criterion D, 25%. As HSO Infrastructure proposals do not have a science investigation, they are not

evaluated against Criterion B.

- Criterion E is rated and tracked separately from the overall proposal rating. (Note: This criterion may be incorporated into the overall proposal rating in the next Senior Review.)
- Criterion F is informational and unrated. This criterion does not contribute to the overall proposal rating.
- Each evaluation criterion above will be assigned an adjectival rating based on the number and significance of the strengths and weaknesses. These ratings are described in the following table:

Adjectival rating	**Basis**
Excellent	A thorough and compelling proposal of exceptional merit that fully responds to the objectives of this Call for Proposals as documented by numerous or significant strengths and no major weaknesses.
Very Good	A competent proposal of high merit that fully responds to the objectives of this Call for Proposals. Strengths fully out-balance any weaknesses, and none of those weaknesses constitute fatal flaws.
Good	A competent proposal that represents a credible response to this Call for Proposals. Strengths and weaknesses essentially balance each other.
Fair	A proposal that provides a nominal response to this Call for Proposals. Weaknesses outweigh any strengths.
Poor	A seriously flawed proposal having one or more major weaknesses that constitute fatal flaws.

NASA will use individual mission evaluations when considering the continuation decisions in this Senior Review. This process will include the following:

- The assessment of the missions under consideration
- The overall strength and ability of the Heliophysics System Observatory—including missions in operation and in development—to fulfill the Heliophysics Division priorities from

FY2024 through FY2026, as represented by the 2020 SMD Science Plan and in the context of the 2013 Heliophysics Decadal Survey

Senior Review Process

Senior Review Panel

There were a total of 16 panel members including the Chair, Co-Chair, and three IDEA Panelists. Each mission had a primary reviewer and two secondary reviewers. In addition, the IDEA Plans were evaluated independently and had additional primary and secondary reviewers. The reviewers evaluated each mission against the review criteria and identified major and minor strengths and weaknesses, which were then shared with the panel and discussed openly. Each reviewer developed a list of questions that were shared with the mission teams before each team's presentation. Additional questions were sent to mission teams after their presentations. Responses were requested to be returned within 24 hours. The submitted Extended Mission proposal, the Senior Review Presentation, and the answers to the Senior Review questions were considered to be the full extended mission proposal. The panel evaluation was based on all of the submitted information.

Senior Review Panel Meeting

The Senior Review Chair and Co-Chair had a virtual meeting with the HPD Program Executives and Program Scientists facilitating the 2023 Senior Review on March 8, 2023 to discuss the conflict-of-interest policy and the review process including the timeline. The full panel had a virtual orientation kickoff meeting on March 14, 2023 to discuss the review criteria and the Senior Review process and charge. The Senior Review met in a hybrid mode during April 17-21, 2023 (i.e., two panelists participated remotely and missions presented virtually). The first day included an abbreviated discussion of the Charge and a reading of all conflicts of interest and potential biases. The panel was instructed on how to mitigate any issues during the panel discussion. During the remainder of the first day, the Senior Review panel received four mission presentations. Each mission team had 20 minutes to present highlights from its proposal, any updates to the proposal, and answers to questions submitted to the mission team. Guidance on the format and content of the presentation was provided to the mission teams in the Call for Proposals (though not all mission teams adhered to this guidance). The Senior Review panel then discussed the presentation and evaluation for 15 minutes before meeting with the mission team for a 15-minute question and answer session.

On the second day, the Senior Review panel heard a presentation from Goddard Space Flight Center

(GSFC) Space Science Mission Operations (SSMO) on the nine SSMO-managed missions regarding the state of health of the missions' spacecraft, instruments, and ground segments. This presentation did not include Voyager (managed and operated by JPL), GOLD (a mission of opportunity instrument onboard a commercial geosynchronous spacecraft managed by GSFC's Heliophysics Science Division), and Hinode (operated by JAXA with management for the US contribution by Marshall Space Flight Center). This independent assessment of mission health provided a "stop light" green/yellow/red format for different components of the mission including the Flight Systems, Ground Systems, and the Communication Network.

The Heliophysics Digital Resources Library (HDRL) also gave a presentation. HDRL is a federation consisting of the Heliophysics Data and Model Consortium (HDMC), the Space Physics Data Facility (SPDF), and the Solar Data Analysis Center (SDAC). HDRL collaborates with the Coordinated Community Modeling Center (CCMC) and the Center for HelioAnalytics (CfHA). The HDRL presentation provided highlights of the data and services that have been developed. This presentation mentioned how HSO mission data are currently being archived, curated, and accessed. The importance of "Open Science" was emphasized in the context of reproducibility of published research.

The remainder of the second day and all of the third day were devoted to hearing from the other eight missions, following the same format used on day 1. The fourth day was spent discussing and writing the findings for each mission and voting upon each criterion (A-E). The Senior Review panel then discussed general findings regarding the Senior Review process, the HSO, and common themes that emerged from the individual missions. On the final day, the panel continued with overall discussions and preparation for a debrief with HPD leadership. The Draft Report was finalized within one week of the meeting by the Chair and Co-Chair and distributed to the rest of the Senior Review panel for comment before being presented to the HPD leadership on May 5, 2023. The Final Report was delivered on May 12, 2023.

Senior Review Findings

Overview

The Senior Review panel found that all 12 assessed missions made progress in addressing previous extended mission science investigation and making data accessible as part of their contributions to the HSO. 10 of the 12 missions being reviewed are in excellent health and have proposed exciting, timely, and compelling extended mission science investigations. All missions are currently in Extended Mission. None were proposed for HSO Infrastructure. Since the Senior Review proposals were submitted, ICON and AIM have suffered failures/anomalies. The Senior Review panel evaluated these missions in terms of Factors A-1 and C-1 only.

AIM presented a revised short Extended Mission proposal (through FY25), anticipating a few months of additional science at the end of CY2024. The spacecraft is expected to recover from safe mode during the full-sun season (beginning in Oct 2024), but there is a 60% probability of re-entry by that time. This represents a high risk for a relatively small science return.

ICON proposed an extended Phase F close-out plan (end of Phase E plus two years). This extension will enable support of current ICON science investigations, full support of GOLD-ICON Guest Investigator projects, and support of final revision and publication of all seven Level 2 products. No updated budget was presented.

General Findings

Recommendations for the Senior Review Proposal and Evaluation Process

A number of changes to the Senior Review process are recommended to strengthen the value of the evaluations for both the mission teams and HPD.

The SR panel found that the individual extended mission proposals lacked system-level coherence and perpetuated closed communities. The HPD portfolio would be significantly strengthened and the broader community would be engaged by undertaking the following:

- Develop opportunities for HSO science working groups
- Expand HSO Guest Investigator funding opportunities
- Expand HSO community frameworks to share and leverage development of code, team science efforts, and coordination with HDRL

To facilitate this coordination, a NASA Headquarters (HQ) HSO Program Scientist (PS) would enable tremendous scientific opportunities to better understand the heliophysics system and coupling between the system's components. The PS would enable annual accountability of Extended Mission objectives, NASA Open Data initiatives, community-wide IDEA Professional development, and shared programming and resources (e.g., connections to HPD DEIA lead and professional development opportunities).

These science management activities are appropriate Headquarters functions. However, there are additional lower-level program management functions that could be but currently are not within the scope of SSMO and HDRL. In the absence of other options, the HSO PS could also fill those functions and oversight. These functions include, but are not limited to,

- guiding missions in the transition from prime to extended operations (e.g. first proposal to the Senior Review),
- monitoring execution of direction that results from the Senior Review process (e.g. development of succession plans, implementation and management of the IDEA Plan, adherence to the Heliophysics Data Policy), and
- guiding missions in their addressing findings and concerns from the Senior Review process.

The first two bullets are within the scope of HPD Program Scientist responsibilities and SSMO and HDRL are fulfilling some of those program management responsibilities, but gaps exist. This HSO Program Scientist could also provide their insights and assessment to the Senior Review panel, similar to the SSMO overview

The SR panel recommends that an independent assessment of mission health for all missions, not only those that are managed by SSMO, be provided in future SRs.

Despite clear guidance in the Call for Proposals, the Senior Review proposals varied in a general format and how specific evaluation criteria were addressed. This variance was particularly notable in the way that the individual mission teams addressed previous SR findings (Factor A-2). The SR panel recommends adding a required section in the Proposal Content to directly address previous SR findings, to aid in the evaluation of Factor A-2.

The definition of "mission science team" with respect to understanding the work directly supported by the mission and the broader community was not used consistently. The definition of "science team" often included those people currently unfunded by the project and potentially funded by other ROSES grants. An estimate of how the extended mission-funded science investigation *directly* contributed to addressing the previous and proposed science objectives should be provided in the narrative and in the description of the publications. In other words, "science team" should not include those people who are unfunded directly from the extended mission, even if these people have historically been integrated into the mission. For missions with significant international participation, it is important to separate tasks and science contributions between US and non-US mission teams. This separation can be simply accomplished by only including papers with co-authors who are directly funded by the mission during the Prime or Extended Mission and "science team" contributions.

Several Senior Review mission proposals interchanged Science Objectives and Science Goals as defined in Appendix A.2 of the Call for Proposals. Those investigations therefore proposed very broad Goals that are not able to be achieved in the three-year extended mission. It is essential to include a list of well-defined *new* Science Objectives (SO) that are different from the previous Senior Review proposal. If the SOs are identical, the proposal should explain the differences from the previous tasks (i.e., what new science will be done).

Factor D-3 refers to the strength of the management plan and "if applicable, necessity for a succession plan." The SR2023 panel recommends that a succession plan should be required for any mission moving into their second extended mission and that this plan be discussed as part of the mission team's IDEA Plan.

The SR panel evaluates the reasonableness of the cost to accomplish the proposed science investigation per Factor B-4. In general, very little detail is provided on how the team's budget ranged between Science Operations and Science Investigations, and the proportion of the overall budget devoted to Science Investigation activities. All but two missions (GOLD and IBEX) devoted the majority of funds to operations.

IDEA Plans

The 2023 Senior Review was the first Senior Review that requested an IDEA Plan. The following instructions were provided to each mission regarding the IDEA Plan within the Call for Proposals.

A11. Required Document: Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan (up to 5 additional pages)

One of the strategic goals of the NASA 2022 Strategic Plan is fulfilling Presidential Executive Orders 13985 and 14041 through supporting participation by underserved communities in its technology programs and executive orders. NASA will continuously promote the incorporation and transformation of Inclusion, Diversity, Equity, and Accessibility (IDEA) into HPD culture and business practices.

The mission IDEA Plan is a strategy describing planned efforts to increase inclusion, diversity, equity, and accessibility. The Plan must include the following elements:

- *Description of the mission's ideal IDEA state, including but not limited to the following:*
    - *Mission team structure and activities*
    - *Mission team participation, including movement of individuals into, out of, and within the team*
- *Description of actions taken since the last Senior Review to make progress on the mission IDEA strategy, if a mission IDEA strategy was developed before this Senior Review.*
- *Metrics and milestones for mission activities to make progress on the mission IDEA strategy. These metrics and milestones shall include expected dates and outcomes for steps taken to make progress on the IDEA strategy.*
- *A narrative on the implementation of the mission's IDEA strategy within the in-guide budget, and justification of any requested over-guide budget.*

Where a mission draws upon a participating organization's IDEA strategy, the Plan shall tailor that overarching strategy to the mission and provide mission-specific details for the other required elements.

It is understood that missions are at various stages of maturity regarding an IDEA Plan and the plan's accompanying implementation. Mission teams should assess their situations and present a plan including metrics and milestones for progress. It is not expected that a mission could reach its ideal state before the next Senior Review, but specific methods for progress shall be planned.

NASA expects to periodically review mission IDEA Plans (including but not limited to future Senior Reviews) in order to assess the achievement of the milestones described.

Each mission was evaluated against Criterion E. The panel rated each of the missions except for AIM and ICON. The median rating for Criterion E is given in the following table.

Mission	Criterion E
AIM	
GOLD	Fair
Hinode	Very Good
IBEX	Good
ICON	
IRIS	Very Good
MMS	Very Good
SDO	Very Good
STEREO	Very Good
THEMIS	Very Good
TIMED	Excellent
Voyager	Fair

One mission earned an Excellent rating. Three missions presented IDEA Plans with significant weaknesses. Most missions included the IDEA Plan activities in the over-guide budget and stated that the activities would not be implemented otherwise. To signify to the community the importance of changing culture through implementing IDEA Plans, the Senior Review panel recommends funding some of the modest requests that were evaluated as being highly effective.

It was common for mission teams to submit institutional IDEA Plans or initiatives from their specific institutions, but there was very little tailoring with respect to the mission team (as was required by the SR CFP) and often neglected plans for implementation across institutions. Many missions included a

Code of Conduct. However, the provided Code of Conduct and IDEA Plan were often not tailored to the specific mission. There was little or no discussion of how these plans will be implemented and enforced, and who in the mission team will be responsible. Strong IDEA Plans assigned specific team members to implement the IDEA Plan.

Although leveraging and partnering with existing programs at the mission institutions is often valuable, many mission teams simply "name dropped" the program and did not describe how the mission would engage with the activities. For K-12 outreach programs, multiple missions engaged with the same small number of school districts. This arrangement resulted from many missions being led by a few institutions (e.g., Lockheed-Martin's programming with the Palo Alto Unified School District) with little indication of coordination.

Several mission teams discussed efforts to quantify their demographics and measure their impact. Demographic surveys and statistics can be helpful but miss other key elements of IDEA. The SR panel suggests the use of climate surveys (that assess perceptions of the missions and institutions climate including quality and extent of team interactions) with clear plans of action to respond to findings. These surveys are most effective if outside experts are brought in to develop, distribute, track, and interpret the results.

As NASA moves toward requesting IDEA Plans from future missions and in future Senior Reviews, NASA HPD should coordinate across SMD regarding how IDEA Plans should look in proposals, and how the plans should be evaluated. The evaluation of these plans should be included as part of the overall rating.

Though the IDEA Plan is a stand-alone part of the SR proposal, the components of the plan itself should be integrated into the entire proposal because it should be integrated into the entire mission. IDEA speaks to *how* we collaborate, do good science, mentor, and build our future. As part of the Review Criteria, the teams should describe *how* IDEA is integrated into the entire proposal by showing how it is integrated into the team's culture.

Cross-Mission Findings

There were several common concerns and opportunities across the HSO that were identified by the Senior Review panel. Some of these areas have to do with the development of new NASA policies around Open Science and the IDEA Plan. Others were identified by the wide range of mission and science operations costs, the adoption of automation, and other efficiencies over the long, extended missions.

The first finding was that several legacy missions use proprietary software (e.g., the TIMED use of the AURIC model), international partner software (e.g., the IRIS use of Bifrost from UiO), or commercial software (e.g., Hinode's use of IDL SolarSoft) for calibration and the generation of data products. In these cases, the proprietary software is not accessible to the community. Future SR proposals should identify software that is not compliant with NASA's Open Science requirements. These proposals should plan to transition to Open Source Code or other mechanisms in order to enable reproducibility.

Another finding was that there is a wide range of mission and science operation efficiencies developed by HSO missions to maximize science during the transition from prime mission to the extended mission. This occurrence is reflected in the wide range of Mission Operation (MO) costs and the percentage of the total budget devoted to science investigations. Senior Review proposals should be required to examine mission and science operation processes in order to identify cost savings and to identify trade studies for reduction of costs through *required* under-guide budget proposal and narrative.

Overall Mission Evaluation Ratings

Each mission was evaluated on its progress toward achieving science objectives from its previous extended mission proposal as indicated by the team's publications (Factor A-1) and how well the mission team addressed the findings from the SR2020 (Factor A-2). The SR panel also evaluated the strengths and weaknesses of the proposed future extended mission including the science merit (Factor B-1), implementation (Factor B-2), relevance to Heliophysics Divisions Strategic Objectives and the Decadal Survey (Factor B-3), and the cost-reasonableness of the in-guide science investigation (Factor B-4). The SR panel evaluation includes contributions to the HSO, particularly the quality of the archival mission data products and documentation (Factor C-1), the synergy with HSO, and benefit to the HSO (Factor C-2). The basis of the overall evaluation was formed by the Technical Implementation including the health of the mission (Factor D-1), the cost reasonableness of the mission operation's model (Factor D-2), and the sufficiency of the management plan including the succession planning process (Factor D-3). The SR panel also evaluated the quality of the Inclusion, Diversity, Equity and Accessibility (IDEA) Plan with respect to an ideal mission's state (Factor E-1), recent progress (Factor E-2), planned progress (Factor E-3), and the cost reasonableness of the IDEA activities (Factor E-4).

Ratings for all Criterion (A-E) were voted separately. Factors A-D were compiled into an overall score using the following weights: Criterion A, 25%; Criterion B, 30%; Criterion C, 20%; Criterion D, 25%). Criterion E was rated and tracked separately but was not part of the Overall Rating.

The table below summarizes the Overall rating. ICON and AIM were only evaluated on Factor A-1 and C-1; therefore, these two missions did not include an Overall rating. The individual Criterion evaluation as well as the general and specific findings for each mission appear in the ensuing sections.

Mission	Criterion A	Criterion B	Criterion C	Criterion D	Overall
AIM	Good		Excellent/VG		
GOLD	Good	Very Good	**Excellent**	Excellent/VG	Very Good
Hinode	Excellent/VG	Very Good	**Excellent**	Very Good	Excellent/VG
IBEX	Very Good	Very Good	Good	Very Good	Very Good
ICON	Good		Very Good		
IRIS	**Excellent**	**Excellent**	**Excellent**	Very Good	**Excellent**
MMS	Very Good	Very Good	**Excellent**	Very Good	Very Good
SDO	Very Good	Very Good	**Excellent**	Good	Very Good
STEREO	Good	Very Good	Very Good	Very Good	Very Good
THEMIS	**Excellent**	**Excellent**	**Excellent**	Excellent/VG	**Excellent**
TIMED	Very Good	Very Good	Very Good	**Excellent**	Excellent/VG
Voyager	Very Good	Very Good	Good	Good	VG/Good

Extended Mission Assessment

AIM

Mission Synopsis

The Aeronomy of Ice in the Mesosphere (AIM) mission was launched in 2007 to primarily study the morphology of Polar Mesospheric Clouds (PMCs) or NoctiLucent Clouds (NLCs) that form around 83 km in Earth's mesosphere. AIM has three instruments on board: Solar Occultation for Ice Experiment (SOFIE), Cloud Imaging and Particle Size Experiment (CIPS), and the in-situ dust collector Cosmic Dust Experiment (CDE). CDE was not operational eight months after the beginning of the mission. Recently, AIM has focused more on studies of atmospheric coupling due to gravity waves (GWs).

The Science Objectives (SOs) from the 2020 extended mission were:

1. What is the morphology of GWs entering the MLT?
2. How does planetary wave (PW) activity influence PMCs and composition in the mesosphere?
3. How do anthropogenic and extra-terrestrial forcing impact the polar mesosphere?

In SO-1, CIPS Rayleigh Albedo Anomaly (RAA) measurements in conjunction with other satellite and re-analysis data sets were studied to investigate the rare Antarctic sudden stratospheric warming in 2019. RAA measurements were analyzed to illustrate the lower mesospheric gravity wave response to tropospheric convection during the southern hemisphere monsoon season. In SO-2, it was found that planetary waves in the summer stratosphere and mesosphere affect the PMC season start and end and affect the longitudinal distribution of PMCs during mid-season. In SO-3, the mesosphere was shown to cool at most altitudes by 1-2 K per decade in response to greenhouse gas increases.

Recently, AIM has experienced technical anomalies and failures. It is expected that the natural decay of AIM's orbit will lead to reentry as early as March 2024 (10% probability of reentry). Current predictions by GSFC Flight Dynamics Facility show a 60% chance that AIM will reenter by October of 2024, which is when the spacecraft will next experience full Sun.

Overall Assessment

AIM's SOs and sub-questions have been compelling. The effort to address those SOs has significantly advanced the understanding of mesospheric dynamics in general and has more specifically advanced the understanding of PMC formation and variability around the mesopause, which is the coldest region of Earth's atmosphere. In later mission extensions, observations have helped to better understand gravity wave activity and interactions with the mean flow. A large number of publications in peer-reviewed journals has demonstrated the productivity of the mission.

Recently the AIM spacecraft has encountered technical anomalies that led to the end of scientific measurements.

Focused Findings

AIM has significantly improved our understanding of PMCs, atmospheric waves, and large-scale background atmospheric variations. AIM has provided substantial insight into PMCs, mesospheric gravity waves, how planetary waves influence the mesosphere, and how anthropogenic and extraterrestrial forcing impacts the mesosphere at various time scales.

While there has been some scientific progress, Science Objective (SO) 1 ("What is the morphology of GWs entering the MLT?") is not directly addressed. SO-1b ("How do GWs in the summer mesosphere affect PMCs?") does not contribute towards addressing SO-1. The connection of the new observations to the previous research findings is not always clearly demonstrated. Some aspects of the findings of the mission were already presented in previous studies by others outside the team. The observed results are thus not clearly put into the context of the current state of knowledge of mesospheric dynamics. For example, the fact that the decline in GW activity after the sudden stratospheric warming that coincided with weakening of the zonal wind was caused by wind filtering, wave saturation, and disruption of the polar night jet has already been studied.

There is an unknown degree of expectation that the spacecraft will recover from safe mode during the full-sun season (Oct 2024), but there is a 60% probability of reentry by that time. This appears to represent a high risk for a relatively small science return.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**

  Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

Major Strengths

AIM has significantly improved our understanding of Polar Mesospheric Clouds (PMCs), atmospheric waves, and background atmospheric variations. AIM has provided substantial insight into PMCs, mesospheric Gravity Waves (GWs), how Planetary Waves (PWs) influence the mesosphere, and how anthropogenic and extraterrestrial forcing impact the mesosphere. SOFIE temperature and nitric oxide concentrations are being used in the latest version of the Mass Spectrometer Incoherent Scatter (MSIS) model, improving the quality of empirical models. AIM has provided insight into the solar cycle and longer-term variations in mesospheric temperature and composition and effects of rocket exhaust on PMCs.

Minor Strengths

AIM demonstrates synergy with other missions. Coincident measurements by AIM, AIRS, and TIMED can potentially advance the characterization of the middle atmosphere.

Major Weaknesses

Some of the previous science objectives are not completed, or the associated efforts provide only incremental progress. While there has been some scientific progress, SO-1 (“What is the morphology of GWs entering the MLT?”) has not been directly addressed. SO-1b (“How do GWs in the summer mesosphere affect PMCs?”) does not contribute towards addressing SO-1. Some aspects of the findings of the mission were already presented in previous studies by others outside the team. For example, the fact that the decline in GW activity after the sudden stratospheric warming that coincided with weakening of the zonal wind was caused by wind filtering, wave saturation, and disruption of the polar night jet has already been studied.

Minor Weaknesses

The proposal does not adequately support the claim that AIM observations help improve models. It is not demonstrated that comparing simulations of the Tonga eruption to data from AIM/CIPS and other instruments as stated in the proposal will provide significant insight into the strengths and deficiencies of the models, enabling critical improvements to the treatment of GWs in next-generation weather and climate models. No evidence is provided that waves observed by AIM/CIPS have an impact on the thermosphere-ionosphere. It is stated that CIPS shows GWs with horizontal wavelengths of 23–600 km and vertical wavelengths >15 km, and that these scales encompass most of the convectively generated GWs at 50-55 km altitude and include those GWs that are most likely to impact the overlying ionosphere-thermosphere-mesosphere system. However, no supportive evidence has been provided.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**
Quality of the archival mission science data products and associated documentation.

Major Strengths

AIM provides high-quality mesospheric data that significantly contributes to the Heliophysics System Observatory. The mission has demonstrated the capability to gather high-quality data. Recent data updates have increased data quality. The currently operational PMC retrieval version, v5.20, was applied after the last Senior Review to all data collected since launch, and the updated retrieval method improves cloud detections and error reporting. CIPS data from the current PMC season are archived after they have been validated. Level 2 data (i.e., higher-order data products and auxiliary data) have been archived at the SPDF and are available to the public through the instrument SDCs. Data documentation for each instrument is archived at the SPDF and SDCs.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

GOLD

Mission Synopsis

Global-scale Observations of the Limb and Disk (GOLD) was launched in 2018. The primary goal of the mission is to determine how the Ionosphere Thermosphere (IT) system responds to drivers on a global-scale, which is essential to our physical understanding of coupling between the space environment and the Earth's atmosphere.

GOLD provides full-disk imaging of thermospheric temperature and composition from its geostationary orbit with a high cadence (as fast as 30 minutes). GOLD makes global-scale images of two critical state variables (thermospheric temperature and composition) on the dayside. GOLD makes global-scale images of ionospheric densities in the low latitudes at night. In addition to the daytime and nighttime disk images, GOLD's limb observations provide exospheric temperatures that are derived from N2 Lyman-Birge-Hopfield (LBH) emission profiles and O2 density profiles that are derived using stellar occultations.

The GOLD instrument is an imaging spectrograph measuring Earth's airglow emissions from 135 to ~162 nm. The instrument is hosted on a commercial communications satellite under an agreement with SES Government Solutions. The instrument is healthy, is performing well and has successfully operated on-orbit since October 2018 while observing daytime thermosphere and nighttime ionosphere in the American hemisphere every day. Data are validated by an experienced science team. Data are available to the scientific community through the Space Physics Data Facility and the GOLD Science Data Center. GOLD's prime two-year mission was completed in October 2020. The team proposed a three-year extended mission to operate through October 2023.

The mission extension proposal includes the following in-guide science objectives:

- SO-B.1 How does the solar cycle change the nighttime EIA morphology and EPB generation and characteristics?
- SO-B.2 How do thermospheric composition and temperature behave during the recovery phase of a geomagnetic storm?
- SO-B5: B.5 How much does the wave-induced variation in composition and temperature in the middle thermosphere change with increasing solar UV flux?

Overall Assessment

GOLD results have led to significant gains in understanding the Equatorial Plasma Bubbles (EPBs) variations, Equatorial Ionization Anomaly (EIA) morphology and evolution, and the storm-time thermospheric dynamics.

GOLD science objectives cover a range of scientific topics that are central aspects of ionosphere-thermosphere dynamics including the I-T variations during the recovery phase and the dependence on solar activities of EPBs and EIA morphology.

GOLD observations provide excellent context and situational awareness for all other ITM observations and the community for determination of the response of the I-T system to different forcing during solar maximum.

The proposed methodology is feasible and adequate for implementation of the in-guide SOs (1, 2 and 5) with GOLD measurements leveraged with other observations and simulations.

GOLD is overall strongly relevant to the scientific goals of the Heliophysics Division. GOLD's synergies with concurrent and upcoming NASA missions in the HSO increase the scientific return of the entire observatory.

The mission has demonstrated the capability to gather high-quality data. GOLD spacecraft, instruments, and ground operation systems are all operating nominally.

Focused Findings

The methodology to distinguish different waves and their corresponding sources is unclear. It is not clear how the small-scale and medium-scale waves are distinguished from each other and what is the nature of these thermospheric waves. Some of the findings regarding the effects and sources of waves are rather speculative without clear evidence about the sources. As indicated in the proposal text, GOLD is not able to distinguish between the sources of waves: "The low phase speed and latitudes over which this wave is seen (10 – 30°N) indicates that it is either a primary or secondary wave of lower atmosphere origin." Indeed, the wave can either be coming from below or can be generated in situ.

The methodology has not been described in sufficient detail. For example, SO2a will use GOLD data and a thermospheric GCM to study how the recovery of ΣO/N2 and TDISK differ and how recovery differs in solar maximum and solar minimum. Sufficient detail is not provided regarding how the recovery will be characterized in order to understand the underlying physical processes and understand how the diagnostic analysis will be conducted with the GCM models.

The GOLD IDEA Plan depends heavily on institutional IDEA activities with limited tailoring and limited participation of GOLD team members. The proposal states that during the GOLD mission formulation and during execution, the PI and deputy-PI implemented mentoring and inclusive practices for the team. The team includes several early-career scientists, students, and individuals from underrepresented groups. However, the roles of these individuals relative to the GOLD mission was unclear. The plan speaks of LASP scientists' activities to broaden the participation of underrepresented groups in NASA heliophysics projects, but there is no indication of GOLD team members actively participating in these activities. Meanwhile, it was unclear how the GOLD IDEA

Plan would make advances towards its ideal state of IDEA. The desired outcomes of the proposed activities and how these outcomes would enhance or support IDEA goals were not provided.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**

Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

Major Strengths

GOLD results have led to significant gains in understanding SO1 and SO2 subjects of interest including the Equatorial Plasma Bubbles (EPBs) variations, Equatorial Ionization Anomaly (EIA) morphology and evolution, and the storm-time thermospheric dynamics. Specifically,

1. GOLD observations of EIA and bubble morphology have been successful beyond expectations, including coordination and comparison with other data sources (COSMIC-2, ICON) and modeling efforts. Summary plots showing trends in bubbles are an excellent example of how GOLD is transforming understanding of bubble occurrence. This understanding whets interest for what may be in store during solar maximum.
2. Storm-time observations illustrate how well GOLD can depict the storm phases and provide excellent ground truth for the interpretation and analysis of models. Correlations between GOLD and ICON winds during the Tonga eruption and analysis of O/N2 recovery times during eclipses highlight GOLD's ability to capture thermospheric dynamics.

Minor Strengths

Observation of "small-scale" waves and interactions with planetary waves using staring mode has shown promising results, although the methodology might not identify "sources."

O2 lack of seasonal dependence is intriguing and may lead to some new scientific understanding.

Major Weaknesses

The methodology for SO3 to distinguish different waves and their corresponding sources is unclear, and SO4 is not completed. In SO3, it is not clear how the small- and medium-scale waves are distinguished from each other and what is the nature of these thermospheric waves. Some of the findings regarding the effects and sources of waves are rather speculative without clear evidence about the sources. As indicated in the proposal text, GOLD is not able to distinguish between the sources of waves: "The low phase speed and latitudes over which this wave is seen (10

– 30°N) indicates that it is either a primary or secondary wave of lower atmosphere origin." Indeed, the wave can either be coming from below or generated in-situ. Meanwhile, the proposal states that SO4 is not completed and both of the two sub-objectives are ongoing.

Minor Weaknesses

The proposal argues that observations of O/N2 variations are a compelling line of investigation, but does not discuss the potential advances in the context of previous investigations. A large day-to-day variation of the O/N2 ratio has been shown even during quiet time in GOLD measurements. This phenomenon has been investigated by a number of previous studies. The described GOLD findings may not be discoveries. Rather these findings may be validation or extension of previous studies.

The sporadic nature of the stellar occultation measurements makes the statistical spread quite large. It can be challenging to accurately identify tidal, planetary signatures and seasonal variations.

- **Factor A-2:**
Performance of addressing any findings in the previous Senior Review. (The 2023 Senior Review panel will have access to the previous Senior Review report for a mission, and other information from that review as needed.) This factor will only be assessed for missions returning to the Senior Review.

Major Strengths

The GOLD team has made a definitive effort to address those concerns raised by the previous Senior Review panel including concern that the GOLD team was focused on gathering data rather than addressing science questions. The GOLD team has shown how the observations, trends, and climatology derived from GOLD measurements have direct application to the science questions. These applications have been shown particularly in the case of EPBs and also O/N2.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The proposal does not clearly address the questions from SR 2020 and specifically does not show

how each issue raised by SR 2020 has been addressed.

Findings 2 and 5 from SR 2020 have not been fully addressed. For example, data assimilation efforts are still not adequately described.

Criterion B: Overall Evaluation of the Proposed Investigation (Science Investigation only)

- **Factor B-1:**
  Scientific merit and impact of the proposed in-guide science investigation.

Major Strengths

GOLD science objectives cover a range of scientific topics that are central aspects of ionosphere-thermosphere dynamics including the I-T variations during the recovery phase and the dependence of EPBs and EIA morphology on solar activities. Specifically,

- It has been a major challenge for the community to accurately describe and predicate the I-T status during the recovery phase due to the complex processes. SO2 would strongly enhance our capability to address this problem. Meanwhile, GOLD's wide longitudinal coverage and 2D disk images provide an unprecedented opportunity to separate local time variation from spatial variations.
- Observations of EPBs and EIA morphology at solar maximum are highly anticipated. The GOLD team has demonstrated the ability to analyze both trends for insight into general behavior as needed for models, unique events and features (e.g., plasma blobs, EIA features at higher latitudes), and changes with geomagnetic activity.

GOLD observations provide excellent context and situational awareness for all other ITM observations and the community for determination of the response of the I-T system to different forcing during solar maximum. The combination of GOLD with models, other satellite measurements, and ground-based measurements would provide a complete specification of ITM conditions.

Minor Strengths

Given that the solar and magnetic activity is expected to increase during the extended mission, GOLD measurements would provide an opportunity to characterize the thermosphere at high solar activity. Results can be compared to low solar activity variations in order to characterize solar cycle variations.

Major Weaknesses

None noted.

Minor Weaknesses

Wave and planetary wave studies planned with GOLD data may not lead to a better understanding of wave processes, as O/N2 and TDISK observations are not relatable to sources.

Coordinated observations with other instruments (SABER, AWE, etc.) are necessary to understand wave processes.

- **Factor B-2:**

Implementation merit of the proposed in-guide science investigation.

Major Strengths

The proposed methodology is feasible and adequate for implementation of the in-guide SOs (1, 2 and 5) with GOLD measurements leveraged with other observations and simulations. It is timely to study the dependence of the I-T system on the solar and geomagnetic conditions, since the next extended period will cover solar maximum and greater geomagnetic activity conditions. GOLD provides a unique opportunity to characterize the thermosphere-ionosphere system at various scales, especially in the storm recovery phase.

Minor Strengths

The operational considerations with both special mode and storm mode will provide important datasets during solar flares and geomagnetic events with increased observing duration and temporal resolution.

Major Weaknesses

The methodology has not been described in sufficient detail. For example, SO2a will use GOLD data and a thermospheric GCM to study how the recovery of $\Sigma O/N2$ and TDISK differ and how recovery differs in solar maximum and solar minimum. Sufficient detail is not provided regarding how the recovery will be characterized in order to understand the underlying physical processes and understand how the diagnostic analysis will be conducted with the GCM models.

Minor Weaknesses

The baseline case may need to be studied in a more systematic way. The accuracy of the baseline may impact the difference field, which has been used to represent the effects of geomagnetic storms or Tonga eruption.

- **Factor B-3:**

Relevance of the proposed science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.

Major Strengths

GOLD is overall strongly relevant to the scientific goals of the Heliophysics Division. GOLD observations are essential for addressing the four Atmosphere-Ionosphere-Magnetosphere Interactions (AIMI) challenges in the 2013 Heliophysics Decadal Survey (DS). GOLD observations are also essential for answering NASA's charge to the Heliophysics Division per the 2015 Roadmap to "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs" (DS, Goal 2) and to "…predict the variations of the space environment" (DS, Goal 1).

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-4:**

Cost reasonableness of the proposed science investigation.

Major Strengths

None noted.

Minor Strengths

The proposed in-guide budget is reasonable for the completion of most of the science objectives. As the proposal notes (Section B.8), the completion of Science Objectives B.3 and B.4 requires the granting of Overguide 1, and the production of data products in Science Objective B.6 requires the granting of Overguide 2.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**

Quality of the archival mission science data products and associated documentation.

Major Strengths

The mission has demonstrated the capability to gather and archive high-quality data. Specifically,

1. Data is quality-checked on a biweekly basis before being released publicly. Data with significant issues (large data gaps, geolocation errors, etc.) are withheld from public release.
2. All Level 2 data products have both file-level and pixel-level Data Quality Indicators (DQIs) that are set to non-zero values when certain conditions are met.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The TDISK data has a low signal-to-noise issue at high solar zenith angle.

- **Factor C-2:**

Synergy with and benefit to the Heliophysics System Observatory. This factor applies only to the planned observations and not any previous scientific return or proposed mission-funded science investigation.

Major Strengths

GOLD's synergies with concurrent and upcoming NASA missions in the HSO increase the scientific return of the entire observatory. Specifically,

1. GOLD has a unique capability within the HSO, providing global-scale context for observations from satellites in low-earth orbit observing the T-I system (e.g., ICON, TIMED, AIM, COSMIC-2) and for ground-based observations.
2. NASA missions investigating wave effects at lower altitudes (e.g., ICON, TIMED, AIM) are also synergistic with GOLD.
3. Data assimilation capabilities (WACCM-X+DART) that have already been developed by

the team are available to others and allow wider use of GOLD TDISK.

4. SDO provides and upcoming NASA missions TRACERS and EZIE will provide information on solar and magnetospheric forcing that GOLD needs in order to understand the forcing effects on the I-T system.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion D: Technical Implementation

- **Factor D-1:**
  Health of the mission and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory. For this factor, the mission includes the spacecraft, instruments, and project-managed ground systems.

Major Strengths

The GOLD spacecraft, instruments, and ground operation systems are all operating nominally. Specifically,

1. The GOLD Science Operations Center monitors instrument health and safety in near real-time and generates command loads for the instrument. All GOLD flight components are operating nominally with no anomalies observed to date. Spacecraft performance and operations are nominal.
2. Instrument spectroscopic, imaging, and radiometric performance confirm laboratory measurements. Detectors exhibit a moderate gain reduction in the 135.56 nm component of the OI doublet. This was anticipated during instrument development and is managed in flight using a combination of flatfield correction lamps and a mechanism that displaces the spectrum on the detector.
3. Ground operations and flight data processing at the mission Science Operations Center and Science Data Center are nominal.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-2:**
  Cost reasonableness of the mission's operations model. This factor includes the ability to continue healthy operations within the in-guide budget.

Major Strengths

None noted.

Minor Strengths

The proposed funding level for operations is reasonable.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-3:**
Sufficiency of the management plan and, if applicable, necessity for the succession plan.

Major Strengths

None noted.

Minor Strengths

All GOLD team-member organizations and responsibilities remain the same as the current extended mission. Processes and implementation procedures are unchanged.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion E: Inclusion, Diversity, Equity, and Accessibility

- **Factor E-1:**

Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan. This factor applies to the mission's ideal state of IDEA including mission activities, mission team structure, movement of individuals in/out of and within the mission team, and succession planning. This factor includes any tailoring of institutional IDEA strategies to the mission team's plan.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The GOLD IDEA Plan depends heavily on institutional IDEA activities with limited tailoring and limited participation of GOLD team members. The proposal states that during the GOLD mission formulation and during execution, the PI and deputy-PI implemented mentoring and inclusive practices for the team. The team includes several early-career scientists, students, and individuals from underrepresented groups. However, the roles of these individuals relative to the GOLD mission was unclear. The plan describes LASP scientists' activities to broaden the participation of underrepresented groups in NASA heliophysics projects, but there is no indication of GOLD team members actively participating in these activities.

- **Factor E-2:**

Recent progress against the mission team's IDEA Plan. This factor assesses the mission's recent actions that have addressed and made progress against the mission IDEA strategy. This factor applies only to those missions that have developed an IDEA strategy before this Senior Review.

The mission did not have an IDEA Plan before the 2023 Senior Review to measure progress against.

- **Factor E-3:**
Planned progress against the mission IDEA Plan. This factor assesses the mission team's plan to advance toward its ideal state of IDEA by the next Senior Review. This includes planned metrics and milestones, the ability for upcoming actions to meet those metrics/milestones, and the ability to enable further progress after the next Senior Review.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

It was unclear how the GOLD IDEA Plan would make advances towards its ideal state of IDEA. GOLD plans to advance broad science objectives with three activities including the following:

- Informal gatherings with each of the early-career scientists and with student mission operators
- Hosting a guest speaker for students in the American Indian, Black, Hispanic, Asian, and Women engineering societies
- GOLD investigators attending at least one Diversity and Climate Committee meeting and two relevant training courses.

The desired outcomes of these activities and how these outcomes would enhance/support IDEA goals were not provided.

- **Factor E-4:**
Cost reasonableness of the mission team's IDEA activities.

Major Strengths

None noted.

Minor Strengths

The proposal includes adequate support for outreach activities within the in-guide budget.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion F: Under-guide and Over-guide Requests (Informational Only)

- **Factor F-1:**
  Scientific merit and impact of any proposed over-guide science investigation.

Major Strengths

The first over-guide request would provide support for existing early-career science team members and funding for the training of new students that is needed in the I-T community. The I-T community has not had many recent missions that could support the training of the next generation of scientists. This request would commit funds for the training of new students, training them both on this science and in the use of this recent I-T mission's data.

The second over-guide request would support the delivery of new data products that would be beneficial to the science community. It would fund Science Objective B.6, which includes new data products.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-2:**
  Implementation merit of any proposed over-guide science investigation.

Major Strengths

None noted.

Minor Strengths

The implementation of the over-guide objectives are clearly described and continue in line with existing GOLD activities..

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-3:**

Scientific merit and impact of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-4:**

Implementation merit of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-5:**

Merit and impact of any proposed over-guide for mission operations.

No over-guide for ops was proposed.

- **Factor F-6:**

Merit and impact of any proposed over-guide for the mission team's IDEA Plan.

No over-guide for IDEA was proposed.

Hinode

Mission Synopsis

Hinode is an international solar mission led by JAXA (Japan) with major contributions from NASA, the UK Space Agency, and ESA. Hinode carries three main instruments. The Solar Optical Telescope (SOT) provides measurements of photospheric vector magnetic fields with unparalleled signal-to-noise. The Extreme UltraViolet (EUV) Imaging Spectrometer (EIS) provides extensive spectroscopic observations of the solar upper atmosphere. The X-Ray Telescope (XRT) provides unique imaging of high-temperature coronal plasma.

The overall objectives of the mission are:

- Understand the sources and evolution of highly energetic dynamic events.
- Characterize cross-scale magnetic field topology and stability.
- Trace mass and energy flow from the photosphere to the corona.
- Continue long-term synoptic support to quantify cycle variability.

The Hinode mission continues to be a cornerstone of the Heliophysics System Observatory (HSO). Hinode provides comprehensive observations of the solar photosphere, chromosphere, transition region, and corona with an unprecedented combination of spatial, spectral, and temporal resolution.

Overall assessment

The team has made significant progress related to scientific objectives from the previous review. The Hinode data have been used to diagnose energy release and transport in study of solar flares, to study plasma abundances and compositions in solar flares in order to determine the sources of different Solar Energetic Particle (SEP) populations, to investigate the role of small-scale eruption events in coronal heating and solar wind acceleration, and to study other phenomena. The previous investigation has been very productive. From the beginning of 2020 to the proposal submission, 194 papers using Hinode data have appeared in the peer-reviewed literature, and about one third of these papers are led or contributed by the US team. The previous efforts have also included science meetings that are open to the community. These meetings have garnered significant interest and participation.

The science theme of the extended mission is compelling. The proposed investigations include plans for combining Hinode data with other space and ground-based observatories in order to apply tighter constraints and diagnostics to the science goals.

All three instruments on Hinode are unique and complementary to other missions. Hinode will provide highly complementary data to the HSO in coordination with Solar Orbiter, particularly in understanding the sources of solar wind and coronal heating. Hinode will also perform coordinated observations during each front-side encounter of Parker Solar Probe. Hinode will continue coordination with IRIS. The combined capabilities of Hinode, along with IRIS, SolO, PSP, SDO, STEREO, DKIST, etc. permit an overview of heliophysics science investigations. Hinode will also continue to enhance rocket campaign science.

Focused Findings

Overall, the mission continues to operate effectively with no major anomalies or critical failures. The star tracker anomaly interrupted the science observation from December 2021 to February 2022. Operational procedures were developed to mitigate the need for the star tracker. Data products are acquired by carefully considering different factors in order to successfully mitigate the performance reduction from the 2008 loss of the X-band telemetry system. Sufficient stationkeeping and spacecraft maneuver fuel is available to continue observations for at least ten additional years in the current orbit. Several anomalies or degradations are noted, but a mitigation strategy has been developed for each issue in order to correct the change. These minor anomalies were presented: i) The star tracker, which controls the spacecraft roll, experienced an anomaly. ii) The loss of SOT's Filter-Graph (FG) in 2016 due to a camera anomaly. iii) Temperatures in the forward end of the XRT have been higher than expected.

Hinode is currently observing the rising phase of Solar Cycle 25, which is key to several mission objectives. Hinode will continue to coordinate closely with IRIS and other new assets of the HSO, notably including PSP and ESA's SolO.

A detailed implementation plan for each science objective is in place. The plan accounts for the uniqueness of the Hinode data and its synergy with other HSO data from SolO, PSP, DKIST, MUSE, IRIS, et cetera that are likely to be available.

The team made a major effort to archive all of the instrument data on NASA servers with the data analysis routines. This effort addresses a finding from the 2020 Senior Review. All of the Level 0 data and much of the higher-level data are publicly available on SDAC or mirrored to the SDAC. Much of the data can be analyzed by open-sourced Python-based codes on GitHub.

The science return from the NASA investment in Hinode is enhanced by substantial leveraging of mission support by the international partners.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**

Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

Major Strengths

The team has made significant progress on scientific objectives from the previous review. The Hinode data have been used as important diagnostics of energy release and transport in studying solar flares. The data has also been used to study plasma abundances and compositions in solar flares to determine the sources of different Solar Energetic Particle (SEP) populations. The Hinode data has also been used to investigate the role of small-scale eruption events in coronal heating and solar wind acceleration. The previous investigation has been very productive. From the beginning of 2020 to the proposal submission, 194 papers using Hinode data have appeared in the peer-reviewed literature. About one third of these papers are led or contributed by the US team. The previous efforts have included science meetings open to the community. These meetings have garnered significant interest and participation.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor A-2:**

Performance of addressing any findings in the previous Senior Review. (The 2023 Senior Review panel will have access to the previous Senior Review report for a mission, and other information from that review as needed.) This factor will only be assessed for missions returning to the Senior Review.

Major Strengths

The proposal made significant progress in improving data accessibility. The previous Senior Review findings suggested that data archive and data analysis tools needed to be updated. Use has required the user to perform the calibration from Level 0 to Level 1 and/or Level 2, doing so within SolarSoft and IDL. Some of the data analysis routines are not available on NASA servers. The mission team made a major effort to archive all of the instrument data on NASA servers with the data analysis routines. All of the Level 0 data and much of the higher-level data are publicly available on SDAC or mirrored to the SDAC. Much of the data can be analyzed by open-sourced Python-based codes on GitHub.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion B: Overall Evaluation of the Proposed Investigation (Science Investigation only)

- **Factor B-1:**
  Scientific merit and impact of the proposed in-guide science investigation.

Major Strengths

The proposed investigations combine Hinode data with other space and ground-based observatories in compelling studies to apply tighter constraints and diagnostics to the first three science goals. These goals include "Measure Plasma Properties in Large-Scale Eruptive Events," "Characterize cross-scale magnetic field topology and stability," and "Trace mass and energy flow from the photosphere to the corona." These goals directly address fundamental solar physics questions that are directly relevant for understanding transient solar events. Detailed forward work areas are noted with US participation institutions identified.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-2:**
  Implementation merit of the proposed in-guide science investigation.

Major Strengths

The implementation of the science objectives is appropriate and feasible. A detailed implementation plan for each science objective is in place. The plan accounts for the uniqueness of the Hinode data and its synergy with other HSO data from SolO, PSP, DKIST, MUSE, IRIS, et cetera that are likely to be available.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-3:**

Relevance of the proposed science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.

Major Strengths

The proposal's science goals and related objectives align well with the 2014 Heliophysics Roadmap Research Focus Areas (RFAs) and the 2013 Heliophysics Decadal Survey Heliospheric Major Science Goals (MSGs). The proposal clearly connects the science goals to the RFAs and MSGs in Table 1.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-4:**

Cost reasonableness of the proposed science investigation.

Major Strengths

The proposal presented a very detailed explanation in the budget narrative. The proposed in-guide budget covers mission operations support and limited data analysis in order to ensure high-quality science return.

Minor Strengths

The science return from the NASA investment in Hinode is enhanced by substantial leveraging of mission support by the international partners.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**

Quality of the archival mission science data products and associated documentation.

Major Strengths

HINODE data are available through the Solar Data Analysis Center (SDAC) and can be accessed directly from the SDAC or the VSO. This access is in addition to the data available from mission websites.

The Hinode Science Center is located at the JAXA Institute of Space and Astronautical Science (ISAS) and serves as the primary archive for all Hinode data. Analysis software is provided by each instrument team primarily through SolarSoft. This multi-mission software library is used extensively within the solar physics community and enables cross-mission data analysis. The primary source of ancillary data products for the Hinode mission is the SIRIUS Database that is maintained as part of the Mission Operations Center at ISAS. These data include all operational data and engineering data and reports that are shared between the operations and instrument teams. These data and reports are made available online. Each instrument team provides software for analyzing their own data. Also provided are the most current calibration data and the software required to calibrate the Hinode instrument science data. Final Level-0 telemetry files are archived by the resident archives for each instrument team as well as the Solar Data Analysis Center (SDAC) at GSFC.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

Although Hinode provides raw data along with the calibrated data and is a legacy mission, the use of IDL SolarSoft does not adhere to the new NASA Data Policy.

- **Factor C-2:**

Synergy with and benefit to the Heliophysics System Observatory. This factor applies only to the planned observations and not any previous scientific return or proposed mission-funded science investigation.

Major Strengths

All three instruments on Hinode are unique and complementary to other missions. Hinode will provide highly complementary data to HSO in coordination with Solar Orbiter, particularly in understanding the sources of solar wind and coronal heating. Hinode will also perform coordinated observations during each front-side encounter of Parker Solar Probe. Hinode will continue coordination with IRIS. The combined capabilities of Hinode, along with IRIS, SolO, PSP, SDO, STEREO, DKIST, et cetera permit an overview of heliophysics science investigations. Hinode will also continue to enhance rocket campaign science.

Hinode is currently observing the rising phase of Solar Cycle 25, which is key to several mission objectives. Hinode will continue to coordinate closely with IRIS and other new assets of the HSO, notably including PSP and ESA's SolO.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion D: Technical Implementation

- **Factor D-1:**
  Health of the mission and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory. For this factor, the mission includes the spacecraft, instruments, and project-managed ground systems.

Major Strengths

Overall, the mission continues to operate effectively with no major anomalies or critical failures. The star tracker anomaly interrupted the science observation from December 27, 2021 to February 2022. Operational procedures were developed to mitigate the need for the star tracker. Data products are acquired by carefully considering different factors in order to successfully mitigate the performance reduction from the 2008 loss of the X-band telemetry system. Sufficient stationkeeping and spacecraft maneuver fuel is available to continue observations for at least ten additional years in the current orbit. Several anomalies or degradations are noted, but a mitigation strategy has been developed for each issue in order to correct the change. These minor anomalies were presented: i) The star tracker, which controls the spacecraft roll, experienced an anomaly. ii) The loss of SOT's Filter-Graph (FG) in 2016 due to a camera anomaly. iii) Temperatures in the forward end of the XRT have been higher than expected.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-2:**
  Cost reasonableness of the mission's operations model. This factor includes the ability to continue healthy operations within the in-guide budget.

Major Strengths

The proposed mission's operations model is appropriate and feasible. The proposal presents the continued mission using cost reductions in Focused Mode Operations. Focused Mode includes the reduction of timeline creation from three times per week to once per week. Following two years of engineering tests and adjustments, Focused Mode has been successfully integrated into the annual operations schedule since the 2015 Senior Review.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-3:**

Sufficiency of the management plan and, if applicable, necessity for the succession plan.

Major Strengths

The high-level organizational structure is explained with the interconnection between JAXA and NASA clearly described. The management structure is described for the US institutions under the Hinode Project Office (HPO), with defined roles and responsibilities.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion E: Inclusion, Diversity, Equity, and Accessibility

- **Factor E-1:**

Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan. This factor applies to the mission's ideal state of IDEA including mission activities, mission team structure, movement of individuals in/out of and within the mission team, and succession planning. This factor includes any tailoring of institutional IDEA strategies to the mission team's plan.

Major Strengths

The Hinode team shows a strong commitment to mentorship of the next generation of scientists. This mentorship occurs through the SAO REU program and the LMSAL partnership with Palo Alto Unified School District. Both programs have resulted in students' presentations at major conferences, which indicates that the students were substantially involved in the project.

Minor Strengths

Summer internships at the University of Alabama-Huntsville for students from "local historically under-served schools" are likely valuable, but too few details are provided (e.g., number of students and internship outcomes) to make a definitive assessment.

The Hinode team's commitment to the training of new personnel is essential for the success of a complex, international project and is beneficial for the professional growth of junior scientists.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor E-2:**

Recent progress against the mission team's IDEA Plan. This factor assesses the mission's recent actions that have addressed and made progress against the mission IDEA strategy. This factor applies only to those missions that have developed an IDEA strategy before this Senior Review.

Major Strengths

The Hinode mission has demonstrated a commitment to team diversity. Instrument teams regularly train new personnel and scientists from a broad and diverse range of backgrounds. The

Hinode NASA Project Scientist is a female and early-career at the time of assignment. The team overcomes hiring policies for international students by hiring post-doctoral students and by providing mission-level training.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor E-3:**

Planned progress against the mission IDEA Plan. This factor assesses the mission team's plan to advance toward its ideal state of IDEA by the next Senior Review. This includes planned metrics and milestones, the ability for upcoming actions to meet those metrics/milestones, and the ability to enable further progress after the next Senior Review.

Major Strengths

None noted.

Minor Strengths

In the Hinode mission team's oral presentation, the team stated that they will continue to participate in SAO's REU program and LMSAL's partnership with Palo Alto Unified School District.

Major Weaknesses

The proposal states that "[t]he ideal state of the *Hinode* project is to provide meaningful experience of a wide variety of essential mission functions to a broad array of community members with diverse backgrounds," but does not provide specific objectives and discrete milestones. The proposal also states that "[t]he teams will strive to capture a more complete set of information by the next Senior Review" but does indicate which metrics will be measured and how.

Minor Weaknesses

Although the Hinode mission has handled multiple leadership transitions (see Table 3), the mission team provided no clear plan for succession or explanation of how IDEA goals could be incorporated into such a plan.

- **Factor E-4:**
Cost reasonableness of the mission team's IDEA activities.

Major Strengths

None noted.

Minor Strengths

The use of external funding sources (e.g., NSF funding for the SAO REU program) provides for efficiency and enhanced return in the broader implementation of mentorship programs and IDEA initiatives.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion F: Under-guide and Over-guide Requests (Informational Only)

No under-guide or over-guide requests were submitted.

IBEX

Mission synopsis

The NASA Small Explorer (SMEX) mission Interstellar Boundary Explorer (IBEX) was launched in 2008 and began science operations in February 2009. Ever since, its two neutral atom instruments have scanned a great circle in the sky once every 15 seconds from High-Earth Orbit. Combined with the orbital motion of Earth, IBEX produces a complete all-sky map of neutral count rates in energies ranging from 10 eV to 6 keV every six months. IBEX is dedicated to observing both interstellar neutral atoms entering the heliosphere and Energetic Neutral Atoms (ENAs) from the boundaries of the outer heliosphere. IBEX also observes neutral atoms from Earth's magnetosphere and from the Moon when these two objects come into the field of view.

The overarching science goals of the IBEX mission are to explore and map the complex boundary between the heliosphere and the Local InterStellar Medium (LISM) and to characterize the LISM from a remote vantage point, treating neutral atoms as messengers from these regions and boundaries. IBEX discovered a novel neutral signal dubbed the Ribbon. The exploration of the behavior of this feature and its physics have joined the original set of science goals. The cumulative observations through the current extended mission (EM4) complete one solar cycle of data. Time-dependent phenomena of the heliosphere-LISM system are coming increasingly into focus for science investigations.

In the proposed extended mission EM5, IBEX will continue to discover the evolving properties of interstellar interactions. This process will stimulate fundamental controversies and contribute to their resolution. The scientific objectives for EM5 again focus on the three science goals of determining the origin of the Ribbon, determining the properties of the global heliosphere and the underlying physical processes, and determining the properties of the LISM on a global scale. The specific science objectives proposed for EM5 rely on time-dependent processes and the detailed analysis of time lags in neutral responses to changes in the outer heliosphere. These changes in turn depend on the solar wind changing over the past Solar Cycle (SC) and into Cycle 25.

Overall assessment

IBEX has made numerous fundamental discoveries, many of which were not anticipated. IBEX provides an unprecedented picture of the global structure of the heliosphere and its evolution over the solar cycle. IBEX characterizes the properties of the LISM and puts ever more stringent constraints on their time variability. Continued observations of the Ribbon are integral to the study of the microphysics that are present in the outer heliosheath outside the heliopause where the Ribbon ENA are created.

IBEX is unique in that it is the only member of the HSO that detects neutral atoms. These atoms are either of interstellar origin or are messengers of remote plasma regions pertaining to the outer heliosphere. Hence, IBEX enables fundamental and vigorous progress in science investigations of the outer heliosphere, the global heliosphere, and the LISM. IBEX's focus on the outer heliosphere and the LISM is only matched by the Voyager Interstellar Mission (VIM) whose twin spacecraft are now taking in-situ measurements at the edge of the LISM, which is a region relatively close to the heliopause that is thought to be the source of the Ribbon ENA.

The proposal makes a strong science case for a further extended mission. The objectives focus on the time-dependent responses of neutral signals to the time-dependent heliosphere, extending the analyses into the next solar activity cycle. The objectives thus refine the investigations of the Ribbon mechanism and source region, of the sources of Globally Distributed Flux (GDF) in both upwind and heliotail regions, of the 3D structure of the global heliosphere, and of the characteristics of the LISM including the strength and orientation of the interstellar magnetic field. As the mission proceeds, testable predictions are pursued in order to contribute to the resolution of unsettled science questions concerning the global heliosphere and interstellar interactions.

The productivity of the larger IBEX science team remains high, with 51 new IBEX science papers published since the last Senior Review. The launch of the IBEX mission has invigorated the science of the outer heliosphere. The continued success of IBEX has sustained this new era of vigorous activity and tremendous progress, which was further boosted by the entrance of the Voyagers into the LISM during the last decade.

Focused Findings

IBEX achieved substantial progress on the current EM4 science objectives, with data from a complete solar cycle as the basis for the analyses. Highlights from a variety of science investigations connected to open science questions ("controversies"). These investigations include timing studies establishing constraints on the distance of the source region of Ribbon neutrals, thus discarding a variety of competing proposed Ribbon mechanisms in favor of the now leading theory involving secondary neutrals. Highlights also include the first model-independent reconstruction of the 3D structure of the global heliosphere and a refined determination of parameters in the LISM.

The proposal makes a strong science case for a further extended mission. The objectives focus on the time-dependent responses of neutral signals to the time-dependent heliosphere, extending the analyses into the next solar activity cycle. The objectives thus refine the investigations of the Ribbon mechanism and source region, studies of the sources of Globally Distributed Flux (GDF) in both upwind and heliotail regions, of the 3D structure of the global heliosphere, and investigations of the characteristics of the LISM. The compilation of long-term observations is putting ever tighter constraints on the theories and modeling associated with the science objectives. Examples include investigating the structure of the heliotail with its very distant ENA source regions, or studying the Ribbon response to pressure pulses in the LISM. The proposed science investigations are achievable with the type of data and derived products that the IBEX team produces on a routine basis. This includes control of the instrument backgrounds, including establishing standardized “good times” lists and “super good times” lists. Implementation will be additionally helped by an improvement of count statistics as the return ENA signal rises in response to the end of SC 24.

There are unique and important synergies between IBEX and the Voyager Interstellar Mission (VIM). Both Voyagers are now taking in-situ measurements in a region of local interstellar space that is thought to be the source region of the Ribbon ENA. The Ribbon neutrals reach IBEX with a delay that is dictated by their energy, and the proposed EM5 capitalizes on continued measurements into SC 25 to connect the Ribbon flux with the Voyager in-situ measurements. The rise of SC 25 during the proposed EM5 follows the solar minimum that occurred at the start of the current EM4. This rise will make this Voyager-IBEX connection even more important because of the related increase in both solar activity and ENA fluxes.

The EM proposal also emphasizes that continued operation of IBEX allows for a unique overlap with the Interstellar Mapping and Acceleration Probe (IMAP) to be launched in 2025. IMAP will have neutral instruments onboard that derive from IBEX instruments. The IBEX EM offers the opportunity to have uninterrupted coverage of heliospheric and interstellar neutral fluxes at 1 AU for potentially more than two decades, assuming that IMAP enjoys a similar longevity as IBEX. Moreover, a period of time when both IMAP and IBEX are operational simultaneously allows invaluable and unique possibilities for cross-calibration. This activity will help to distinguish between local and non-local background sources for both missions.

Many of the recommendations of the 2020 Senior Review regarding issues with data release and archiving were addressed. The CMAD was authored and is a very comprehensive and useful document. The CMAD is a standalone 260-page document that describes in great detail the mission, instruments, procedures, methods, and algorithms, including calibration of instruments and validation. This will remain a very useful document accompanying IBEX data. The PDMP was substantially revised and updated in 2019 and received an update in the current proposal. The PDMP is a comprehensive document describing the mission, its operation, data, and data products. Following a recommendation by the prior Senior Review panel, 11 years of raw data were made public in May 2022 and are available on the mission website (https://ibex.princeton.edu/RawDataReleases). SPDF ingestion will follow. Information related to IBEX’s orbit, ephemeris, and attitude information was included in this release as well. SPDF houses the data releases and their associated documentation. Some data handling software and scripts are offered at the mission website.

The quality of published and archived IBEX data is very high. However, producing Level 3 data products requires a lot of careful analysis and also involves the aid of modeling. This effort seems to create an archiving bottleneck that slows the flow of data into the public domain, resulting in time lags of several years. Data release #17 (Level 3 data) and Raw Data release #1 were the only data releases during EM4 to date. These releases continue to be the latest IBEX data available. Their data end in

December 2019, making three years' worth of further data (all levels) pending to be publicly available at either the mission's website or on the official, public-facing NASA data repositories such as SPDF.

While listing the connections of IBEX to other key members of the HSO, the proposal does not include explicit plans to actively reach out to HSO missions for synergistic collaboration. Moreover, neutral fluxes at IBEX are akin to a line-of-sight integral of distributed neutral production. The deconvolution of the fluxes to achieve global heliospheric interpretations has to involve modeling and theory. The proposal does not mention actively contacting the broader community of heliosphere scientists and modeling groups.

The IBEX team recognizes and leverages well-established IDEA policies and plans through the PI's institution. However, the IDEA Plan has limited tailoring to the mission itself, and there is no Code of Conduct implemented. Extensive EPO efforts in earlier phases of the mission were very effective. The current involvement of the IBEX team with partnerships relevant to IDEA initiatives should have been outlined in more detail. The proposal details clear metrics and milestones including determining whether sub-institutions have a written DEI/DEIA plan, sharing best practices for recruitment and retention, and ensuring that any openings get advertised widely.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**
Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

Major Strengths

The IBEX science team achieved substantial progress on the three Science Objectives from the previous Senior Review. The additional data from the latest EM completes one solar cycle of data, and time-dependent heliospheric phenomena are coming into focus. Substantial progress has been yielded in a variety of science investigations, connected to open science questions ("controversies") and objectives. Highlights include timing studies establishing stringent constraints on the distance of the source region of ribbon neutrals, thus discarding a variety of competing proposed ribbon mechanisms in favor of the now leading theory involving secondary neutrals. Highlights also include the first attempt of a model-independent reconstruction of the 3D structure of the global heliosphere and a refined determination of parameters in the Local Interstellar Medium.

The productivity of the IBEX science team remains high. 51 new IBEX science papers have been published since the last Senior Review by the core team.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor A-2:**
Performance of addressing any findings in the previous Senior Review. (The 2023 Senior Review panel will have access to the previous Senior Review report for a mission, and other information from that review as needed.) This factor will only be assessed for missions returning to the Senior Review.

Major Strengths

Many of the recommendations of the 2020 Senior Review regarding issues with data release and archiving were addressed. As requested, 11 years of lower-level and raw data were made public May 2022 and are available on the mission website (https://ibex.princeton.edu/RawDataReleases). SPDF ingestion will follow. SPDF houses data releases 1-14 and their associated documentation (and as of April 2023, releases 15-17) as well as some data handling software and scripts. Archiving of lower-level and raw data from recent years is still in progress.

The mission responded to the 2020 Senior Review finding on the Calibration and Measurement Algorithm Document (CMAD) by delivering a comprehensive and useful document for data end users. The CMAD is a stand-alone 260-page document that describes in great detail the mission, instruments, procedures, methods, and algorithms, including calibration of instruments and validation. The CMAD will remain a very useful document accompanying IBEX data.

Minor Strengths

The PDMP was substantially revised and updated in 2019 and received an incremental update in the current proposal. The PDMP is a comprehensive document describing the mission, its operation, data, and data products.

Major Weaknesses

None noted.

Minor Weaknesses

Not all 2020 findings were addressed in the current proposal (e.g., active outreach to involve HSO mission data and heliosphere researchers outside the IBEX team).

Criterion B: Overall Evaluation of the Proposed Investigation (Science Investigation only)

- **Factor B-1:**
Scientific merit and impact of the proposed in-guide science investigation.

Major Strengths

The proposed scientific investigation is compelling and is likely to result in strong research findings that shape our knowledge of the outer heliosphere, Ribbon, and the LISM. Although the proposed three Science Objectives (SO) are more like Science Goals and are nominally identical to the previous Senior Review's SOs, the proposal focuses on concrete achievable objectives. The onset of solar cycle 25 creates conditions through which more progress in the SO is achievable (e.g., large merged solar wind features that elicit a time-delayed response in the ENA signal). The compilation of long-term observations is putting ever tighter constraints on the theories and modeling associated with the SO (e.g., when investigating the structure of the heliotail with its very distant ENA source regions).

The proposal makes the compelling case for continued IBEX observations concurrent with the Voyager and IMAP missions. As convincingly argued, IBEX the only neutral telescope having covered the period of a solar cycle with consistent observations. For the proposed EM period, IBEX observes Ribbon ENA while the twin Voyager spacecraft move away from the heliopause and carry out in-situ measurements in the source region of the Ribbon ENA. Further, with the impending 2025 launch of IMAP, the IBEX EM offers the opportunity to have an uninterrupted coverage of heliospheric and interstellar neutral fluxes at 1 AU for potentially two decades (assuming that IMAP enjoys a similar longevity as IBEX). Moreover, a period of time when both IMAP and IBEX are operational simultaneously allows invaluable and unique possibilities for cross-calibration. This activity will help to distinguish between local and non-local background sources for both missions.

Minor Strengths

While the SO have nominally remained the same between SR proposals, the current proposal highlights the fact that the large time series of observations has shifted the attention to the time-dependent phenomena of the global heliosphere while constraining the VLISM to be consistent with time-independence.

Major Weaknesses

None noted.

Minor Weaknesses

The proposal does not adhere to the level of specificity of Science Objectives (SO) in the Senior Review Call for Proposals' definition. The proposed three SOs are nominally identical to those of the previous EM period, and are more like Science Goals. The SO as stated are broad enough that each includes a variety of questions that are either unanswered to-date, need a more detailed answer, or need refinement of the description in terms of physics processes.

- **Factor B-2:**
Implementation merit of the proposed in-guide science investigation.

Major Strengths

The proposed science investigations are achievable with the type of data and derived data products that the IBEX team has a good track record of producing on a routine basis. This activity includes control of the instrument backgrounds including establishing standardized "good times" lists and "super good times" lists. Implementation will be additionally helped by an improvement of count statistics as the return ENA signal rises in response to the end of SC 24.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-3:**
Relevance of the proposed science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.

Major Strengths

The SO and the proposed detailed investigations connect directly to the NASA and community science goals. These goals were formulated in the most recent 2014 Science Plan for NASA's Science Mission Directorate (SMD) as well as the most recent 2013 Solar and Space Physics Decadal Survey. These connections were detailed explicitly in the proposal. IBEX's focus on the outer heliosphere and the VLISM in terms of ENAs and interstellar neutrals is unmatched. IBEX's focus on the outer heliosphere and the VLISM in general is only shared by the Voyager Interstellar Mission (VIM).

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-4:**

Cost reasonableness of the proposed science investigation.

Major Strengths

The proposed science investigation and its implementation can be fully supported with the in-guide resources. The science investigation budget supports approximately between seven and eight FTEs. The science team was very productive in the past, and the labor allocation will allow this to continue.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**

Quality of the archival mission science data products and associated documentation.

Major Strengths

The data archiving is proceeding at a rate that supports science investigations. Archiving comprises raw data as well as curated data products of Level 2 and Level 3. Level 3 products are highly processed data products that are at the heart of high-quality science investigations.

Minor Strengths

The CMAD is a very comprehensive and useful document of 260 pages. The CMAD is a standalone document that describes in great detail the mission, instruments, procedures, methods, and algorithms, including calibration of instruments and validation. The CMAD will remain a very useful document accompanying IBEX data.

Major Weaknesses

Generation of Level 3 data productions seems to slow the flow of data into the public domain, with time lags of several years. The quality of published and archived IBEX data is very high, but producing Level 3 data products requires a lot of careful analysis and also involves the aid of modeling in part. All of the released data currently end at December 2019 (data release #17, raw data release #1), making the time lag longer than three years. Data release #17 and raw data release #1 are the only data releases to date during EM4. The official, public-facing NASA data repositories at SPDF were even further behind than those offered at the mission's website until data releases #15, #16 (both EM3), and #17 (EM4) recently appeared at SPDF in April 2023. The IBEX PDMP states that "Level 2 products are made available to the SPDF and NSSDC approximately one month after each All Sky image is obtained (approximately seven months after data acquisition)," yet these Level 2 data (count rates independent of modeling, and similar data) are seemingly not published outside the Data Releases. These Level 2 data do not appear at SPDF, at NSSDC, or through the mission's website. These Level 2 data hence suffer the same time lag as Level 3 products.

Minor Weaknesses

None noted.

- **Factor C-2:**

Synergy with and benefit to the Heliophysics System Observatory. This factor applies only to the *planned observations and not any previous scientific return or proposed mission-funded science investigation.*

Major Strengths

There is a unique and important synergy between IBEX and the Voyager Interstellar Mission (VIM). The proposal capitalizes on the synergy between IBEX observations of Ribbon ENA and the twin Voyager spacecraft both leaving the immediate vicinity of the heliopause and nearing environments that are thought to be the source region of the Ribbon ENA while making in-situ measurements in that region.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

While listing the connections of IBEX to other key members of the HSO, the proposal does not include plans to actively contact HSO missions for synergistic collaboration. Moreover, neutral fluxes at IBEX are akin to a line-of-sight integral of distributed neutral production. The deconvolution of the fluxes to achieve global heliospheric interpretations has to involve modeling and theory. The proposal does not mention actively contacting the broader community of heliosphere scientists and modeling groups. However, science enabled by IBEX does seem to indicate through the provided reference list that some of this synergy is occurring.

Criterion D: Technical Implementation

- **Factor D-1:**
  Health of the mission and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory. For this factor, the mission includes the spacecraft, instruments, and project-managed ground systems.

Major Strengths

The spacecraft and its instruments are essentially in very good health. There is nominal detector degradation after ~14 years of operations at HEO. The mission operating model is essentially unchanged and has been working very well. A lunar-synchronous orbit has increased mission stability. The contribution to the HSO remains on a high level.

Minor Strengths

The ground system that is responsible for the relatively infrequent data downlinks during IBEX perigee is being updated to bring it into IT security compliance. While the pandemic has slowed this endeavor that started in 2020, switchover is planned for May 2023 according to recent Q&A during the SR panel meeting.

Star tracker outages are related to cosmic ray levels and should become less frequent in the next few years due to Solar Cycle 25. Such outages have no significant effect on the rest of the operations, and recovery is automatic.

Major Weaknesses

None noted.

Minor Weaknesses

The IBEX flight computer experiences random resets on the order of a few occurrences per year, with the associated potential for data loss. This operations issue is mitigated by the spacecraft and flight computers recovering as designed.

- **Factor D-2:**
  Cost reasonableness of the mission's operations model. This factor includes the ability to continue healthy operations within the in-guide budget.

Major Strengths

The IBEX mission operations are streamlined and have reached a well-orchestrated level that is executed with very reasonable costs. Activities include running the mission, ensuring mission health, obtaining data, and executing the data processing pipeline including archiving operations. The execution of these activities are in line with expectations for a mature mission.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-3:**

Sufficiency of the management plan and, if applicable, necessity for the succession plan.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

A succession plan has not been written, despite the IBEX mission duration having now undergone four extended mission periods. There is also no description of how the IDEA Plan will be integrated into the succession planning process.

Criterion E: Inclusion, Diversity, Equity, and Accessibility

- **Factor E-1:**

Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan. This factor applies to the mission's ideal state of IDEA including mission activities, mission team structure, movement of individuals in/out of and within the mission team, and succession planning. This factor includes any tailoring of institutional IDEA strategies to the mission team's plan.

Major Strengths

None noted.

Minor Strengths

The IBEX team recognizes and leverages well-established IDEA policies and plans through Princeton University and the Department of Astrophysical Sciences.

Major Weaknesses

None noted.

Minor Weaknesses

The IDEA Plan has limited tailoring of the Princeton IDEA Plan to the mission itself and there is no Code of Conduct.

Implementation of the IDEA Plan is being managed by the PI with the next level of support by support staff rather than other members of the leadership team.

- **Factor E-2:**

Recent progress against the mission team's IDEA Plan. This factor assesses the mission's recent actions that have addressed and made progress against the mission IDEA strategy. This factor applies only to those missions that have developed an IDEA strategy before this Senior Review.

Major Strengths

In earlier phases of the mission, IBEX completed extensive EPO efforts. These efforts include a planetarium show shown nationally, educational products for the visually impaired and for neurodiverse learners, and work with a Chicago Public Schools after-school program.

Minor Strengths

Departmental partnerships exist with Delaware State University (HBCU), and the department does booth sponsorship at NSBP and SACNAS. However, the proposal does not detail the IBEX team's involvement with these programs.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor E-3:**
Planned progress against the mission IDEA Plan. This factor assesses the mission team's plan to advance toward its ideal state of IDEA by the next Senior Review. This includes planned metrics and milestones, the ability for upcoming actions to meet those metrics/milestones, and the ability to enable further progress after the next Senior Review.

Major Strengths

The proposal details clear and appropriate milestones for the coordination of IDEA activities. Princeton administrators will support IBEX by asking each sub-institution to submit a summary of its IDEA Plan with links to the full policy. Princeton will compile these summaries into a single document to share with the team. Princeton will share recruitment and retention activities across the team and will develop a list of upcoming openings and advertise directly to underrepresented minorities.

Minor Strengths

The team will expand diversity through hiring early-career researchers at universities or research centers. This effort is supervised by IBEX PI, Co-Is, and team members.

The IBEX team will invite current IMAP student collaborators to join IBEX/IMAP science team meetings.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor E-4:**
  Cost reasonableness of the mission team's IDEA activities.

Major Strength

None noted.

Minor Strength

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The proposal does not budget for specific IDEA activities and does describe specific IDEA activities in sufficient detail to drive cost requirements.

Criterion F: Under-guide and Over-guide Requests (Informational Only)

No under-guide or over-guide requests were submitted.

ICON

Mission Synopsis

ICON was launched on 10 October 2019 into a low-Earth orbit to explore the boundary between Earth and outer space and to understand the physical connection between the atmosphere and geospace. ICON payload consists of four instruments:

- MIGHTI is a pair of imaging interferometers that measure the Doppler shift of two emission lines from atomic oxygen (557.7 nm and 630 nm) and three components of the O_2 emission band. These interferometers provide neutral winds and temperatures, respectively, over a wide range of altitudes in the lower and middle thermosphere.
- The Far UV (FUV) range imager gives daytime thermospheric composition and nighttime ionospheric O^+ over a wide range of altitudes.
- A pair of Ion Velocity Meters (IVM-A/B) provide in-situ measurements of the 3D motion of O^+ ions.

ICON had three main scientific objectives in the first mission extension:

1. Find the cause of day-to-day variability in the ionosphere.
2. Determine the key drivers of seasonal changes in the ionosphere.
3. Understand the competing influences of geomagnetic storms as they modify the ionosphere.

In Science Question (SQ) 1, it was demonstrated that large-scale atmospheric waves (i.e., tides and planetary waves) can be successfully retrieved, which revealed short-term variability in tides. In SQ2, diurnal and semidiurnal tides are determined from ICON data and used as an input into an atmospheric general circulation model extending above the mesopause. In SQ3, research results submitted for publication demonstrate that a small geomagnetic disturbance (minimum Dst = −40 nT) was found to be associated with significant, continental-scale changes in thermospheric composition and ionospheric densities.

In late-November 2022, ICON encountered technical anomalies and is currently not functional. ICON proposed an extended Phase F close-out plan (end of Phase E plus two years). This extension is expected to enable support of current ICON science investigations, full support of GOLD-ICON Guest Investigator projects, and support of final revision and publication of all seven Level 2 products. No updated budget was presented.

Overall assessment

ICON has provided valuable observations of ions and neutrals in the Earth's lower thermosphere and middle thermosphere. Historically, thermospheric neutral winds and temperature have been poorly sampled. ICON measurements contribute toward filling the thermospheric measurement gap at low latitudes by providing zonal and meridional winds at high cadence. ICON's measurements are high-quality and are widely available to the scientific community. The activities of the team have led to the generation of new data products.

The global modeling approach to study tides cannot provide an accurate picture of the tidal variability in the thermosphere since the utilized model does not account for the impact of other waves (e.g., gravity waves) on the propagating tides.

Focused findings

Insufficient progress has been made in providing closure to previous science objectives. Minor progress has been recorded for SO2 and no research results have been published for SO3. Recent publications and progress in addressing the science questions have not been included or described here.

Lower-boundary tidal forcing in the upper mesosphere is used as input for the TIEGCM model to generate tides. It is not demonstrated that the implementation of the tidal fields are adequately done. It is not demonstrated that the tides can be realistically propagated in the model above the mesosphere given the lack of small-scale waves in the model. These waves are a major concern in tidal studies. Gravity-wave tidal effects are not accounted in the modeling framework. Realistic tidal wave variations thus cannot be facilitated.

There is no description of the impact of the limitations in orbital coverage on the day-to-day variability of the upper atmosphere.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**
  Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

Major Strengths

ICON contributes toward filling the thermospheric measurement gap at low latitudes. Thermospheric horizontal winds have been poorly sampled due to a lack of global observations. ICON has provided good coverage of low-latitude zonal and meridional winds. This coverage contributes towards filling both the data gap and our understanding of the structure of thermospheric circulation.

ICON has provided new detailed observations at low latitudes to better characterize the mean and variable structure of the ionosphere and thermosphere. ICON enables the determination of the mean behavior of large-scale waves such as tides and planetary waves, wind shear and its modulation by tides, and the wind-driven dynamo. ICON data available over nearly three years provide a detailed view of the large-scale waves.

Minor Strengths

None noted.

Major Weaknesses

The ICON proposal does not show that sufficient progress has been made in providing closure to previous science objectives. The Senior Review proposal does not clearly detail what the original investigation was focused on (e.g., SO1: “Finding the cause of day-to-day variability in the ionosphere”). Only minor progress has been made with regard to SO2 (“Determining the key drivers of seasonal changes in the ionosphere”). Lower-boundary tidal forcing in the upper mesosphere is used as input for the TIEGCM model to generate tides, but it is not demonstrated that the implementation of the tidal fields are adequately done. It is not demonstrated that the tides can be realistically propagated above the mesosphere given the lack of small-scale waves in the model. Gravity waves are known to influence tides significantly, and this important physics is not acknowledged. Gravity-wave tidal effects are not accounted in the modeling framework. Realistic tidal wave variations thus cannot be facilitated. SO3 (“Understanding the competing influences of geomagnetic storms as they modify the ionosphere”) is not completed, given that no research results have been published. One paper on the study of a small geomagnetic disturbance is currently in review. Recent publications and progress in addressing the science questions have not been included or discussed here.

Minor Weaknesses

Challenges in capturing the day-to-day variability of tides are not addressed. ICON has made progress in studying the day-to-day variability of the upper atmosphere. However, a complete sampling in latitude/longitude and in local time is necessary to fully characterize tides. ICON can only determine the mean structure of the tides, considering at least a 35-day sampling window. The day-to-day variability of the tides and their contribution to ionospheric variability cannot be accurately determined. It is stated that ICON can clearly retrieve tides originating in the lower and middle atmosphere. However, in-situ generated tides contribute to ICON observations. These tides cannot be separated from the lower atmospheric ones.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**
Quality of the archival mission science data products and associated documentation.

Major Strengths

ICON has demonstrated the capability to gather high-quality data. The mission data are available both on the mission website (https://icon.ssl.berkeley.edu/Data) and on SPDF, and the archives look complete. The science data products are documented very well. An online Python tutorial specific to ICON data processing is available on the ICON website under the Data tab.

Minor Strengths

The ICON data structure is conveniently presented for data users. Level 2 cardinal wind velocities are reported in both magnetic and geographic coordinates (e.g., magnetic zonal wind) in order to support both georeferenced and electrodynamical studies.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

IRIS

Mission synopsis

The Interface Region Imaging Spectrograph (IRIS) is a solar observatory that provides high spatial resolution, high cadence, seeing-free images, and spectra in the near and far-UV. IRIS is a Small Explorer NASA mission flying in a polar, sun-synchronous orbit. The principal investigator institution is Lockheed Martin (LM) Solar and Astrophysics Laboratory (LMSAL) in LM's Advanced Technology Center, with major contributions from Lockheed Martin Civil Space, NASA Ames, Smithsonian Astrophysical Laboratory, Montana State University, High Altitude Observatory, Stanford University, and the University of Oslo. IRIS is an approved ESA collaborative mission.

The primary goal of the IRIS mission is to understand how the upper layers of the solar atmosphere are energized by tracing mass and energy from the photosphere through the chromosphere, transitions region, and corona. To this end, IRIS provides the community with unique observations of the chromosphere and transition region. These observations continue to challenge our understanding of the physical processes occurring in the upper layers of the solar atmosphere. The IRIS project also provides the community with state-of-the-art numerical simulations, machine learning tools, and inversions. These tools are essential for interpreting IRIS observations.

During the second extended mission that started in 2020, the prioritized science goals were to improve chromospheric diagnostic tools, investigate braiding heating and Alfven waves, nanoflares, flare triggers through machine learning approaches, pre-flare turbulence, and FIP effect.

The science objectives for the next extended mission phase leverage previous findings and aim to improve tools and techniques. These objectives include:

- Investigate the dependence of chromospheric parameters on physical parameters in the photosphere and corona.
- Include new heating mechanisms in numerical models and validate 3D MHD simulations with IRIS observations.
- Investigate flare dynamics at unprecedented time cadence.
- Investigate non-thermal electrons during nano-flares.
- Improve IRIS2 data products
- Provide the community with new MHD time-series.

Overall assessment

IRIS is a small mission with focused yet very challenging objectives. IRIS provides unique observations of the chromosphere and transition region that no other observatory can currently provide. The relatively simple instrumentation and flexible observing modes, complemented with state-of-the-art analysis tools and numerical models, have allowed the community to gain new insight into fundamental physical processes such as reconnection, heating, multi-fluid interaction, turbulence, and energy and mass transfer between the solar atmosphere and wind.

The IRIS mission is a fundamental and well-integrated asset of the HSO. Coordinated observations are made with Hinode, SDO, STEREO, NUSTAR, and other missions, as well as ground-based observatories such as ALMA and the Swedish Solar Telescope. These coordinated observations allow the community to investigate the physical processes that connect the photosphere to the upper layers of the solar atmosphere and wind. IRIS will also complement upcoming SoLO and Parker Solar Probe data, as well as future ground-based observations that are acquired with the DKIST, providing unprecedented spatial and temporal resolution. Synergies with SoLO are expected to be particularly strong, as IRIS chromospheric observations complement SoLO/Spice observations of the Transition Region and corona.

The proposed in-guide budget is reasonable overall and is suitable for both operations and science. The ESA advisory structure has confirmed support for space communications until 2028.

The IRIS mission is in very good health. It is likely that IRIS will continue operating through the next extended mission.

Focus Findings

The IRIS team has proposed a compelling science investigation that has the potential to significantly enhance our comprehension of the physical processes taking place in the upper layers of the solar atmosphere. Proposed research topics are centered around crucial aspects such as the understanding of chromospheric heating, flare dynamics, and reconnection. These topics are directly aligned with the objectives laid out in the 2013 Heliophysics Decadal Survey. The proposed study will generate new data and data-products including advanced simulations and diagnostics from IRIS2. These resources will be made publicly available, providing a platform for the wider scientific community to explore and possibly uncover new discoveries in this area.

The IRIS mission continues to provide the scientific community with high-quality and well-documented data and data products. Quick-look tools and analysis tools are readily accessible through LMSAL. IRIS data are available at multiple sites including SDAC. The numerous publications produced by non-affiliated scientists reflect the exceptional support offered by the IRIS team to the scientific community.

While the data reduction software for IRIS is publicly available, this software is currently written in the IDL commercial programming language. To ensure the reproducibility of data, it is important to also provide a version of the data reduction pipeline in a non-commercial language such as Python. This availability will maintain consistency with other data analysis tools developed by the IRIS team.

As noted in the previous Senior Review, the proposal includes a request for high science operation costs. This level of funding is necessary to support the complex observing planning and coordination with other facilities, as well as calibration procedures that can only be partially automated. Although the IRIS team improved the efficiency of some aspects of the calibration pipeline, data reduction and processing remain time-consuming and continue to require human intervention.

The over-guide proposed science investigation is very interesting. One of the main research tasks involves estimating photospheric magnetic fields from multiline inversions of Near-UltraViolet (NUV) IRIS observations. This task has the potential to significantly enhance IRIS data by providing the community with a fundamental diagnostic that is currently only available through complicated, coordinated observations with other facilities. This complexity may lead to uncertainties. This task is high-risk/high-return. The technique has been applied previously on spectral ranges that are different from the NUV range observed by IRIS, and the proposal presents no proof-of-concept.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**

  Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

Major Strengths

The IRIS team has addressed all of the Scientific Objectives from the previous Senior Review. The conducted research projects have yielded highly impactful scientific results, evidenced by the extensive number of peer-reviewed publications. These results have provided the scientific community with new tools for data analysis and interpretation. The specific scientific contributions have greatly enhanced our understanding of long-standing questions including 1) chromospheric heating, 2) chromospheric and coronal heating, 3) non-thermal electrons in both nanoflares and non-flaring regions, 4) flare triggers, 5) pre-flare turbulence, 6) reconnection in supra-arcade regions, and 7) the origins of the FIP effect. The team has made significant progress in improving the speed of IRIS2, which is the inversion code used to invert IRIS spectra. This improvement has enabled the community to access a vast dataset of one-dimensional atmosphere models.

The team has produced a significant volume of publications. The IRIS team has produced 56 refereed publications since the last Senior Review**.**

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor A-2:**

  Performance of addressing any findings in the previous Senior Review. (The 2023 Senior Review panel will have access to the previous Senior Review report for a mission, and other information from *that review as needed.) This factor will only be assessed for missions returning to the Senior Review.*

Major Strengths

The IRIS team fully addressed some comments from the 2020 Senior Review.

- A new dark-current model and an automated way to correct for orbital wobble have been implemented in order to improve the efficiency of the calibration procedure.
- Level 2 and Level 1 data are available on SDAC and are up to date.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The previous Senior Review suggested that the Bifrost code be made publicly available. However, the code was developed by the University of Oslo, and it is not in the IRIS team's authority to provide the Bifrost code publicly. Although understandable as a legacy mission, this still is not consistent with the new NASA Open Data Policies.

Criterion B: Overall Evaluation of the Proposed Investigation (Science Investigation only)

- **Factor B-1:**
  Scientific merit and impact of the proposed in-guide science investigation.

Major Strengths

The proposed investigation is compelling and is likely to produce high-impact results. The proposal describes focused objectives that are likely to improve understanding of the complex phenomena occurring in the chromosphere and of the various physical processes that connect this layer of the atmosphere with the photosphere and corona. These objectives include:

1) Exploit IRIS2 inversions and coordinated observations with other observatories (e.g., SDO, EIS, SPICE) to study how chromospheric parameters depend on other physical parameters in the solar atmosphere. This objective will be accomplished by making use of machine learning approaches.
2) Validate 3D MHD simulations by comparing them with IRIS plage observations. Bifrost and Ebysus include different physical processes. The use of both Bifrost and Ebysus to interpret observed line profiles is likely to provide new clues about the different processes that determine heating in the chromosphere. Of particular relevance is the proposed work of using results from Ebysus to parametrize multi-fluid heating, which is novel and promising.
3) Leverage the new IRIS observing mode to investigate flare dynamics at unprecedented time cadence. Evidence of turbulence energy dissipation and repeated magnetic reconnection will be investigated through automatic clustering algorithms for a range of flare observations. Whenever available, data will be complemented with coordinated observations of the Transition region and corona (e.g., HINODE/EIS, SoLO/SPICE, SoLO/STIX, GOES, VLA, EOVSA) in order to help distinguish between magnetic reconnection and Alfvenic turbulence.
4) Investigate non-thermal electrons during nano-flares by inverting the large statistical sample of nano-flare observations in the NUV from previous mission investigations. Comparison with RADYN simulations will allow us to interpret the relationship among the line parameters observed with IRIS and will allow us to determine the physical properties of the observed heating events.

At the same time, the proposed objectives aim to provide the scientific community with new models and IRIS data products that are likely to foster new scientific discoveries. Two new IRIS2 data products will be released: 1) new atmosphere models obtained from multi-line inversions of IRIS spectra, and 2) integrated radiative losses. These products are important for a variety of applications and are likely to foster new scientific discoveries. New 3D-MHD time-series obtained with the Bifrost code, as well as new atmosphere models from the Ebysus code, will be made available to the community.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-2:**

Implementation merit of the proposed in-guide science investigation.

Major Strengths

None noted.

Minor Strengths

The proposed objectives are feasible for execution within presented plan. The objectives are built upon recent developments to the observation and simulation techniques.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-3:**

Relevance of the proposed science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.

Major Strengths

The scientific objectives are all major science goals of the Heliophysics Decadal Survey. Understanding heating mechanisms in the chromosphere and understanding physical processes that occur during flares and flare precursors are objectives of the Heliophysics Decadal Survey.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-4:**

Cost reasonableness of the proposed science investigation.

Major Strengths

The in-guide budget is reasonable for the proposed science investigation. The proposal reasonably allocates different portions of the science budget to the different projects. The requested number of FTEs and the estimated standard billing units are sufficient to achieve the science goals.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**

Quality of the archival mission science data products and associated documentation.

Major Strengths

The IRIS data management plan is consistent with the Senior Review requirements. IRIS data, data products, and documentation are available at multiple locations including SDAC and the Heliophysics Data Portal. The mission data is searchable through the Heliophysics Events Knowledgebase. Documentation is available in SPASE. Links to documentation is available at the LMSAL and SDAC. The PDMP and CMAD are complete and current. Extensive documentation and tutorials are available on the LMSAL website for IRIS data, IRIS tools, and Bifrost simulations. Reduction and analysis codes are included in Solarsoft and SunPy.

The quality of the archival data products is demonstrated by the high community use of IRIS data. The publication rate (~65/year) on peer-reviewed journals of scientific results obtained with IRIS data has remained roughly constant since the last Senior Review. This rate demonstrates that IRIS observations are still in high demand from the community and continue to foster new discoveries.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

Calibration routines are available in IDL, which is a commercial programming language and therefore has a barrier to entry for users.

- **Factor C-2:**

Synergy with and benefit to the Heliophysics System Observatory. This factor applies only to the planned observations and not any previous scientific return or proposed mission-funded science investigation.

Major Strengths

The proposal provides a detailed and convincing description of the relevance of the IRIS mission within the HSO. The proposal lists several science cases that will benefit from coordinated observations of IRIS measurements with the HSO facilities and ground-based observatories as well as science cases that will complement measurements obtained from HSO assets. These science cases include understanding energy mass transfer, CME initiation, reconnection events, source and connection with the solar wind, solar irradiance variations, and solar-stellar studies. The proposal provides convincing evidence of the key role that IRIS will play in addressing all of these issues. IRIS will continue prioritizing coordinate observations with rocket flights (e.g., FURST, FOXSI, MAGIXS, etc.) and with HINODE. IRIS + SoLO/SPICE will provide unprecedentedly spectrally-pure and contiguous thermal coverage from the photosphere to the hottest regions of the corona. IRIS observations provide key context for downstream observations with PSP (e.g., sources of solar wind and switchback) and will provide key context in the future with PUNCH.

Minor Strengths

The proposal provides convincing evidence that coordination with ground-based observatories (e.g., ALMA, Goode, SST) is extremely beneficial for the scientific community. Coordination with DKIST will be of particular importance for studying the chromosphere and its connections with the photosphere and transitions region.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion D: Technical Implementation

- **Factor D-1:**

  Health of the mission and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory. For this factor, the mission includes the spacecraft, instruments, and project-managed ground systems.

Major Strengths

The spacecraft, instruments, and project-managed ground systems all appear to be in good health. Data quality is continuously monitored, and data calibration procedures are updated accordingly. The loss of sensitivity in the FUV is monitored daily and is mitigated by intercomparison with radiometric data from TIMED/SEE and TSIS/SIM, as well as comparison with the FISM model.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-2:**

  Cost reasonableness of the mission's operations model. This factor includes the ability to continue healthy operations within the in-guide budget.

Major Strengths

The cost is reasonable for the operations model. There does not seem to be any special operations that may not be achieved within the in-guide budget.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-3:**
  Sufficiency of the management plan and, if applicable, necessity for the succession plan.

Major Strengths

The proposal describes a well-defined management plan. Key personnel have been identified in the major areas of expertise (e.g., Science Lead, Instrument Lead, Operations Lead, etc.). Each member of the key personnel has lengthy, well-demonstrated expertise in their respective areas.

The proposal describes a well-defined succession plan. Deputy positions in the major areas of expertise have been created in order to train early-career scientists in leading positions within the project. All deputies have been taking increasing responsibility. Some deputies are expected to assume key roles during the next few years.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion E: Inclusion, Diversity, Equity, and Accessibility

- **Factor E-1:**

Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan. This factor applies to the mission's ideal state of IDEA including mission activities, mission team structure, movement of individuals in/out of and within the mission team, and succession planning. This factor includes any tailoring of institutional IDEA strategies to the mission team's plan.

Major Strengths

None noted.

Minor Strengths

The IRIS team shows a significant commitment to mentorship of the next generation of diverse scientists. This commitment is demonstrated through partnerships with minority-serving institutions and participation in an REU program that is committed to "recruiting traditionally underrepresented groups of students."

The proposal cites specific demographic statistics for the IRIS mission and compares these statistics to those of comparable groups. These statistics focus primarily on gender identity (and, to a lesser extent, race/ethnicity), and measures of inclusivity (e.g., climate surveys) are not proposed or discussed.

Major Weaknesses

None noted.

Minor Weaknesses

Although the proposal's descriptions of the "four pillars" align with the overall IDEA goals, the description lacks details and specific examples regarding the IRIS team.

The proposal presents noteworthy goals but does not define the metrics for those goals. For example, the proposal notes the ARC's Office of Diversity and Equal Opportunity office but doesn't detail how often or in what way the office will be consulted.

- **Factor E-2:**

Recent progress against the mission team's IDEA Plan. This factor assesses the mission's recent actions that have addressed and made progress against the mission IDEA strategy. This factor applies only to those missions that have developed an IDEA strategy before this Senior Review.

Major Strengths

The proposal describes several past IDEA activities that made progress on the IRIS IDEA strategy. These include representative advertising, investments in MSIs, an REU program with SAO, the prioritization of early-career and female scientists, and accessibility to IRIS data.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor E-3:**

Planned progress against the mission IDEA Plan. This factor assesses the mission team's plan to advance toward its ideal state of IDEA by the next Senior Review. This includes planned metrics and milestones, the ability for upcoming actions to meet those metrics/milestones, and the ability to enable further progress after the next Senior Review.

Major Strengths

The plan includes well-defined, reasonable future milestones. These milestones include the selection of an IRIS DEI contact person to oversee the implementation of the IDEA Plan, the establishment of a baseline for individual behavior, a regularly reassessed IRIS Code of Conduct, and annual IDEA seminars for IRIS members. The appointment of an IRIS DEI contact person significantly increases the likelihood of the successful completion of the stated milestones.

Minor Strengths

IRIS will leverage the longstanding efforts of the Lockheed Martin Business Resource Groups.

Major Weaknesses

None noted.

Minor Weaknesses

The proposal does not detail in what capacity and how often the BRGs and the Ames ODEO will be consulted.

- **Factor E-4:**

Cost reasonableness of the mission team's IDEA activities.

Major Strengths

The four over-budget requests (Milestones 5 through 8) are modest and specific while supporting meaningful activities. Each request stands a significant chance of improving the IDEA state of the IRIS mission and the heliophysics community overall.

Minor Strengths

Milestones 1 through 4 can be feasibly implemented within the specified schedule at no cost.

The proposal leverages external funding (especially NSF funding of REU programs). This leverage provides for efficiency and enhanced return in the implementation of mentorship programs and IDEA initiatives more broadly.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion F: Under-guide and Over-guide Requests (Informational Only)

- **Factor F-1:**
  Scientific merit and impact of any proposed over-guide science investigation.

Major Strengths

The over-guide science investigation has compelling science merit and impact. The proposed over-guide projects include (1) magnetic field measurement via multiline inversions, (2) studying flare loop top dynamics, and (3) studying coronal heating that is associated with spicules.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-2:**
  Implementation merit of any proposed over-guide science investigation.

Major Strengths

None noted.

Minor Strengths

The first two proposed Science Objectives are feasible.

Major Weaknesses

The third Science Objective to estimate magnetic field strength through multi-line inversions of photospheric NUV lines is not clearly shown to be implementable due to the differences between this application and previous uses of the technique. Existing literature proved the proposed technique on spectral ranges that are different from the ones observed by IRIS. However, this ~~high-risk~~ objective has the potential high reward of providing IRIS with magnetic field measurements that are currently available only through coordinated observations.

Minor Weaknesses

None noted.

- **Factor F-3:**

Scientific merit and impact of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-4:**

Implementation merit of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-5:**

Merit and impact of any proposed over-guide for mission operations.

No over-guide for ops was proposed

- .**Factor F-6:**

Merit and impact of any proposed over-guide for the mission team's IDEA Plan.

Major Strengths

Milestones 1 through 4 can be feasibly implemented within the specified schedule at no cost.

The four over-budget requests (Milestones 5 through 8) are modest and specific while supporting meaningful activities. Each request stands a significant chance of improving the IDEA state of the IRIS mission and the heliophysics community overall.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

MMS

Mission Synopsis

Launched in 2015 as part of the NASA Solar-Terrestrial Probes program, the Magnetospheric MultiScale (MMS) mission consists of four identically instrumented spacecraft in a high-altitude eccentric orbit. Each spacecraft carries a suite of instruments to provide in-situ measurements of fields and charged particles in space. These suites include plasma analyzers, energetic particle detectors, electric and magnetic field instruments, as well as an active spacecraft potential control device. The instruments provide three-dimensional electric and magnetic fields with unprecedentedly high time resolution (millisecond) and accuracy. Scientifically, the mission has used the high time resolution and small inter-spacecraft spacing of its tetrahedron (tens of km) to study microphysics within (and resulting from) magnetic reconnection.

The scientific objectives for the proposed extended mission are the following:

- Understand the role of kinetic physics in the strongly driven magnetosphere during intense space weather events near solar maximum.
- Discover how the electron-kinetic dynamics that enable magnetic reconnection couple to the larger-scale geospace environment.
- Understand particle acceleration processes in the magnetotail and their relationship to magnetic reconnection.
- Understand the fundamental nature of kinetic-scale turbulence, including its coupling to larger scales.
- Understand the role of kinetic physics in bow shock structure and interplanetary shocks.

Within the extended mission, the MMS team will modify the spacecraft orbital configurations into (a) a logarithmic-spaced string-of-pearls formation (electron-scale, ion-scale, MHD scale), and (b) multi-scale tetrahedron spacing.

Overall Assessment

The MMS science teams made significant progress in addressing these goals from the 2020 Senior Review:

- Understand how reconnection works in all boundary regions in Geospace.
- Determine the nature of kinetic-scale turbulence and its roles in reconnection and particle acceleration.
- Understand particle acceleration processes at bow shock and their possible relationship to magnetic reconnection and turbulence.
- Heliophysics System Observatory Science

The mission has substantially addressed each of the proposed Science Objectives. The science outcomes have been significant in impact and quantity. Major discoveries and advancements include electron-only reconnection, turbulence generation, and particle acceleration at Earth's bow shock and magnetosheath. The team has also developed and utilized novel techniques. These techniques include evaluating the individual terms of generalized Ohm's law and assessing how the turbulent electric fields dynamically arise from MHD to electron scales. The team has also demonstrated and utilized novel measurement techniques for quantifying reconnection rates with in-situ spacecraft measurements.

Data from the mission are used widely as part of the HSO. The team actively supports the HSO by modeling spacecraft conjunctions and incorporating these into operations planning and determining time windows for burst data telemetry. Data from all four spacecraft are available at the mission website and SPDF with quick-look measurements that are typically provided to the community within days of observation. IDL and Python SPEDAS tools are readily available to the community for accessing and visualizing data.

The spacecraft remains in good health. Spacecraft subsystems continue to behave nominally with sufficient fuel for proposed operations and orbital maneuvers during the extended mission. The science instruments remain in good condition. In 2018, component failure on the MMS4 FPI instrument occurred, limiting electron measurements to one half-sky. All other instruments and data products are nominal.

Focused Findings

Data from the MMS mission are of high quality and scientific value. The mission provides well-calibrated, extremely high time resolution measurements. These measurements are used to study the microphysics of reconnection and a wide variety of other topics ranging from shock microphysics to energetic particle acceleration in Earth's magnetotail. The high-quality dataset enables a broad range of new discoveries in fundamental science.

The proposed extended mission's Science Objectives have some overlap with Science Objectives from the previous extended mission. Although this overlap may limit distinct applications, the mission is still anticipated to make significant progress in addressing the Science Objectives.

The extended mission implementation plan is compelling and enables novel measurements that are well-suited for the planned science objectives. The team proposes to change the measurement tool provided by MMS through modifying the spacecraft orbital configurations. These newly enabled spatial and temporal sampling configurations will sample different target regions as the orbits precess in local time. These configurations are anticipated to enable a rich array of new science.

The previous senior review identifies minor discrepancies between the statements in the PDMP document and the implemented archiving activities. The Level 3 data described in the PDMP is still not publicly available through the NASA CDAWeb archive. This availability should be a priority for the team.

The previous Senior Review noted that the CMAD and PDMP documents did not offer an easy introduction for MMS data users to provide an overview of the different types of data products. The CMAD document and software tools have been sufficiently improved.

The MMS team provides an opportunity for early-career team members to submit proposals to the mission for one-year grants. This opportunity provides a platform for early-career researchers to gain experience writing proposals and develop project management skills. Although this program provides some benefits, the internal nature of the program is not consistent with the best practices of IDEA. The insular nature does not provide the opportunity for inclusion of individuals or ideas beyond the current team. It is recommended that this early-career award activity be made transparent and open to the broader community.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**

Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

The mission defined four Science Objectives in the previous Senior Review:

SO1. Understand how reconnection works in all boundary regions in Geospace.

SO2. Determine the nature of kinetic-scale turbulence and its roles in reconnection and particle acceleration.

SO3. Understand particle acceleration processes at bow shock and their possible relationship to magnetic reconnection and turbulence.

SO4. Heliophysics System Observatory Science

Major Strengths

The mission has substantially addressed each of the previous Senior Review Science Objectives. The science outcomes have been significant both in impact and quantity. Major discoveries and advancements include electron-only reconnection, turbulence generation, and particle acceleration at Earth's bow shock and magnetosheath. The team has also developed and utilized novel techniques. These techniques include evaluating the individual terms of generalized Ohm's law and assessing how the turbulent electric fields dynamically arise from MHD to electron scales. The team has also demonstrated and utilized novel measurement techniques for quantifying reconnection rates with in-situ spacecraft measurements.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

Although significant progress has been made on Science Objective 1, the Objective is too general and broad for well-defined closure to demonstrate an understanding over all dimensions of reconnection within geospace.

- **Factor A-2:**
Performance of addressing any findings in the previous Senior Review. (The 2023 Senior Review panel will have access to the previous Senior Review report for a mission, and other information from that review as needed.) This factor will only be assessed for missions returning to the Senior Review.

Major Strengths

None noted.

Minor Strengths

The previous Senior Review comments that the Science Objectives defined were too broadly to demonstrate well-defined closure. The Science Objectives in the 2023 Senior Review have become more specific, where closure will be more readily demonstrated.

The previous Senior Review noted that the CMAD and PDMP documents did not offer an easy introduction for MMS data users to provide an overview of the different types of data products. The CMAD document and software tools have been sufficiently improved.

Major Weaknesses

None noted.

Minor Weaknesses

The previous Senior Review identifies minor discrepancies between the statements in the PDMP document and the implemented archiving activities. This discrepancy has not been sufficiently addressed. The Level 3 data described in the PDMP is not publicly available through the NASA CDAWeb archive. At the time of the 2023 Senior Review, the Level 3 data was not publicly available through CDAWeb.

Criterion B: Overall Evaluation of the Proposed Investigation (Science Investigation only)

- **Factor B-1:**
  Scientific merit and impact of the proposed in-guide science investigation.

Major Strengths

The proposed Science Objectives are compelling and address major objectives of heliophysics with broad application to plasmas throughout the universe including the physics of turbulence, reconnection, and shocks. The coupling from small/electron scales to ion and MHD scales for the targeted Science Objectives represents coverage of major gaps in the community's understanding. Focused study of these areas is expected to lead to major advancement.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The proposed Science Objectives have some overlap with Science Objectives from the previous Senior Review. Although this overlap may limit distinct applications, the mission is still anticipated to make significant progress in addressing the Science Objectives.

- **Factor B-2:**
  Implementation merit of the proposed in-guide science investigation.

Major Strengths

The implementation plan is compelling and enables novel measurements that are well-suited for the planned Science Objectives. The team proposes to change the measurement tool provided by MMS through modifying the spacecraft orbital configurations into (a) a logarithmic string-of-pearls formation and (b) multi-scale tetrahedron spacing. These newly-enabled spatial and temporal sampling configurations will sample different target regions as the orbits precess in local time. These configurations are anticipated to enable a rich array of new science.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-3:**
  Relevance of the proposed science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.

Major Strengths

None noted.

Minor Strengths

The MMS Extended Mission Science Objectives are well-aligned with the goals of the 2013 Heliophysics Decadal Survey as well as the 2020 NASA SMD Science plan. The goals are in-line with the Decadal Survey Priority: "Establish how magnetic reconnection is triggered and how it evolves to drive mass, momentum, and energy transport." The goals are also in-line with the SMD Science Plan to discover (G1) the fundamental physics governing how the universe works, (G2) what the coupled solar-terrestrial system teaches us about the habitability of planets in other stellar systems throughout the universe, and (G3) the physics that helps protect our technology and astronauts in space from the impacts of space weather.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-4:**
  Cost reasonableness of the proposed science investigation.

Major Strengths

None noted.

Minor Strengths

The proposed in-guide budget covers science and mission support to ensure the quality of the instruments and data products in order to allow continuous monitoring of the instrument's state-of-health and performance.

Major Weaknesses

None noted.

Minor Weaknesses

The project brings significant carryover in FY23 and FY24, demonstrating divergence in the spending plan from what was proposed.

With both the in-guide and over-guide proposed budgets, all science investigations by the mission team would be terminated after FY26. MMS is a complex mission with operational control of four spacecraft and 100+ instrument components onboard. The high cost-to-science ratio is concerning and methods to lower the cost of operations should be explored.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**

Quality of the archival mission science data products and associated documentation.

Major Strengths

The mission employs a robust calibration program, and the products meet Level-1 science requirements. Cross-calibrations utilize independently computed parameters from different instruments. These parameters include currents or densities that enhance confidence in data accuracy. Plasma distributions and moments are well-calibrated throughout different plasma regimes including the outer magnetosphere, magnetotail, magnetosheath, and foreshock. MMS data are of extremely high quality. The mission continues to produce plasma distribution measurements with time resolution that are orders of magnitude finer than any other mission.

Minor Strengths

Data products and documentation are well archived at the MMS Science Data Center and SPDF. Data analysis codes are publicly available through Space Physics Environment Data Analysis Software (SPEDAS) in IDL and Python. The CMAD is readily available through the MMS science data center.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor C-2:**

Synergy with and benefit to the Heliophysics System Observatory. This factor applies only to the planned observations and not any previous scientific return or proposed mission-funded science investigation.

Major Strengths

Strong opportunities for conjunctions with other missions including TRACERS, Arase, THEMIS, and Cluster exist and are planned to be targeted by the MMS team, and these conjunctions will result in significant science advancements. These conjunctions provide opportunities for major HSO contributions to the understanding of shock physics, radiation belt evolution, magnetopause dynamics, and the mapping of local magnetopause reconnection physics to the cusps. When planning burst mode windows, the SITL takes into account the crossing of boundaries as well as predicted conjunctions through mapping magnetic field lines. It is anticipated that these conjunctions will provide significant science return from assets in the HSO.

Minor Strengths

The mission has demonstrated active coordination with the Cluster team in order to support future planning beyond independent conjunction predictions.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion D: Technical Implementation

- **Factor D-1:**

  Health of the mission and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory. For this factor, the mission includes the spacecraft, instruments, and project-managed ground systems.

Major Strengths

The spacecraft and instrumentation components are in good health and continue to meet Level 1 science requirements. Some of the instruments have minor limitations, but calibration steps have mitigated effects of these limitations on the usefulness for science discovery.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-2:**

  Cost reasonableness of the mission's operations model. This factor includes the ability to continue healthy operations within the in-guide budget.

Major Strengths

None noted.

Minor Strengths

The mission team provides a reasonable plan for mission operations to enable the new orbital configurations and the instrument support within the in-guide budget.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-3:**

Sufficiency of the management plan and, if applicable, necessity for the succession plan.

Major Strengths

The mission presents a strong plan to transition several of the leadership roles to new members, and the mission has taken active steps to enact this plan. Each team member to be transitioned into a new role has served as part of the team in the past and has been trained for the advanced role by the previous leader.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion E: Inclusion, Diversity, Equity, and Accessibility

- **Factor E-1:**

  Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan. This factor applies to the mission's ideal state of IDEA including mission activities, mission team structure, movement of individuals in/out of and within the mission team, and succession planning. This factor includes any tailoring of institutional IDEA strategies to the mission team's plan.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor E-2:**

  Recent progress against the mission team's IDEA Plan. This factor assesses the mission's recent actions that have addressed and made progress against the mission IDEA strategy. This factor applies only to those missions that have developed an IDEA strategy before this Senior Review.

Major Strengths

The MMS team has awarded five-to-10 one-year Early-Career Grants to early-career researchers that increase visibility and provide training in project leadership.

Minor Strengths

The team deliberately invites early-career team members to be teleconference leaders.

All key positions were assigned deputies for succession planning and for the training of future PIs and Project Scientists.

Major Weaknesses

The MMS Early-Career Grants are not awarded through an open competition, which is contradictory to IDEA principles. This opportunity is restricted to just individuals that have been selected to be on the MMS science team rather than being competed through a call open to anyone. This opportunity is not transparent.

Minor Weaknesses

None noted.

- **Factor E-3:**

Planned progress against the mission IDEA Plan. This factor assesses the mission team's plan to advance toward its ideal state of IDEA by the next Senior Review. This includes planned metrics and milestones, the ability for upcoming actions to meet those metrics/milestones, and the ability to enable further progress after the next Senior Review.

Major Strengths

The proposal suggests the addition of short IDEA training "posts" as part of regular telecons and workshops. This suggestion includes a goal of at least 12 per year. These "easy-to-absorb training modules" are modeled after the GSFC Heliophysics Division IDEA newsletter.

The MMS team proposes to develop a written Code of Conduct that will be disseminated when participants register for meetings. The Code of Conduct will address conflict resolution, steps to ensure that all voices are heard, and cultural awareness. The Code of Conduct will be created in conjunction with professionals at GSFC and SwRI. The proposal notes who will manage the Code of Conduct.

Minor Strengths

The MMS team will continue the Early-Career Grants into FY23 with in-guide funding and into FY24 if over-guide funding is received.

The MMS team proposes to develop a short, online post-workshop "satisfaction" survey that focuses on inclusion factors and indicators of psychological safety.

The MMS team proposes to develop an online anonymous feedback box that will act as a "pulse survey" to gauge the team's climate.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor E-4:**

Cost reasonableness of the mission team's IDEA activities.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The proposal does not budget for specific IDEA activities and does describe specific IDEA activities in sufficient detail to drive cost requirements.

Criterion F: Under-guide and Over-guide Requests (Informational Only)

- **Factor F-1:**
Scientific merit and impact of any proposed over-guide science investigation.

Major Strengths

None noted.

Minor Strengths

The over-guide budget supports enriched science analysis that addresses the same Science Objectives but in more ways or in more detail.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-2:**
Implementation merit of any proposed over-guide science investigation.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-3:**

Scientific merit and impact of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-4:**

Implementation merit of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-5:**

Merit and impact of any proposed over-guide for mission operations.

- No over-guide for ops was proposed.**Factor F-6:**

Merit and impact of any proposed over-guide for the mission team's IDEA Plan.

No over-guide for IDEA was proposed.

SDO

Mission Synopsis

SDO is one of NASA's large strategic missions aimed at addressing multiple strategic priorities in science. SDO has three instruments onboard. The Helioseismic and Magnetic Imager (HMI) imager takes full-disk Doppler and magnetograms (longitudinal and vector) that provide helioseismic and magnetic field information. The Atmospheric Imaging Assembly (AIA) captures full-disk coronal images in seven wavelength bands and two chromospheric images alternating between 12 second cycles. The Extreme Ultraviolet Variability Experiment (EVE) provides EUV spectral irradiance measurements in the Soft X-ray and EUV wavelengths. SDO is in a geosynchronous orbit with near-continuous science downlink. The science objectives emphasize five broad areas of particular importance in solar physics:

1) Track subsurface flows and structures as activity rises.
2) Unmask magnetic variability of the solar cycle.
3) Explore magnetic connections from the Sun throughout the heliosphere.
4) Reveal the fundamental physics of solar atmospheric dynamics and eruptive events.
5) Understand space weather and space climate for Earth and other planets.

The fourth extended mission will continue in-depth exploration of the objectives with new questions posed by recent research. Data from all three SDO instruments are routinely provided to space weather monitoring and prediction users including NOAA and the US Air Force as well as to NASA for space weather and mission planning purposes.

Overall Assessment

The SDO science teams made significant progress in addressing all goals from the 2020 Senior Review, making continued progress in understanding of the following:

1) Properties of the sub-photospheric flows that are critical for the operations of the solar dynamo
2) Energy flow and wave propagation through the atmosphere
3) Fundamental physics of solar eruptive events
4) The solar drivers for space weather

Activities facilitated by the SDO have led to creation of new data products, have created a seminar series highlighting early-career scientist accomplishments, and are supporting the HelioCloud project. SDO data are utilized in a significant number of publications including more than 500 refereed papers and an additional 200 non-refereed papers each year. The cumulative number of SDO citations within the refereed literature exceeds 60,000. The total volume of AIA and HMI data now exceeds 22 Petabytes, and 130 TB are downloaded by all users each month. EVE data is downlinked an average of 780 times a month by users.

The objectives described in the proposal are both compelling and realistic. These objectives capitalize on the fact that SDO will be observing its second solar cycle, which makes it possible to contrast the two. This comparison will allow, for example, investigation of the physical reasons for the (expected) differences in dynamo processes as a function of rotation rate and meridional circulation. An improved rind-diagram helioseismology pipeline will enable comparison with Time-Distance helioseismology in order to determine how flows change with depth, particularly at high latitudes. The proposal has clearly identified key questions upon which the mission will focus in order to reach the science objectives. The proposal provides a clear implementation plan and task list. The proposed objectives contribute to the research focus areas listed in the 2013 Heliophysics Decadal Survey and the NASA Heliophysics Division's strategic objectives. The in-guide budget is sufficient to ensure continuation of observations, calibration and validation for these observations, and about 50% of the proposed science investigations.

The SDO team provides excellent access to the data at both the JSOC and the EVE pages at CU LASP. The PDMP has been updated and the draft CMAD is near completion. Archive data has begun to flow into the NASA SDAC archive. The SDO team is putting the mission code into GitLab repositories that will meet the needs of open-source availability and will enable easy transition to a future archive.

The spacecraft and all instruments are in excellent health. The plans for continued operations are clear. Degradation of all three instruments is within the expected range. The proposal presents realistic plans for evaluation and mitigation of continuing instrument degradation. The SDO team put considerable effort into better understanding of the source of the 24-hour variations in Doppler and magnetic field measurements, eliminating several potential causes but with additional steps outlined.

The SDO team strongly supports community engagement by organizing special events and scientific conferences and through implementation of a highly successful public outreach program. The team has an established IDEA Plan that outlines team interactions and interactions with the community. The team has also implemented a Code of Conduct.

Focused Findings

SDO addresses key science questions about the origin and evolution of solar activity and provides vast amounts of observations that enable cutting-edge research and public outreach. SDO is the only space-based mission delivering full-disk magnetograms of the solar photosphere. SDO provides high-resolution imaging data of the solar corona and solar irradiance measurements. SDO will be probing the interior of the Sun during the upcoming solar maximum. The magnetograms are widely used by HSO for context, for direct comparison, and in the modeling of various solar and heliospheric phenomena.

The in-guide budget risks the ability of the mission to achieve repair and replacement of the aging ground communication facilities, delivery of high-quality data to the research community and space weather users, and the ambitious scientific goals. These facilities are maintained and operated by the mission, in contrast to many missions with downlink services that are provided by NASA without financial implications to the projects.

The in-guide budget is only supporting 50% of the proposed science tasks. This level of support seriously impacts the expected progress on three of the science objectives and represents a reduction from 75% in the previous extended mission. Because of the wide use of SDO data, this level of support still represents a large effort to assist users and the public with access to the SDO data and its interpretation. The SDO team needs to find ways to reduce this effort in order to ensure that more funding can be applied to the proposed science. Efficiencies in the calibration and validation efforts would enable more science as well. The in-guide budget is insufficient to support a succession plan.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**

Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

Major Strengths

Significant advancements were realized in all of the broad Science Objectives and all of the funded science tasks in the previous extended mission. Multiple examples of discoveries from all three instruments covering different aspects of each Science Objective are detailed in the proposal. The Science Objectives of the mission are:

1) Track subsurface flows and structures as activity rises.
2) Unmask magnetic variability of the solar cycle.
3) Explore magnetic connections from the Sun throughout the heliosphere.
4) Reveal the fundamental physics of solar atmospheric dynamics and eruptive events.
5) Understand space weather and space climate for Earth and other planets.

Highlighted results include the following:

- Observations of an EUV wave, the resulting loop oscillations, and identifying the various wave modes and non-wave components
- Utilizing machine learning in combination with time-distance helioseismology to infer the far-side unsigned magnetic flux
- Understanding the degradation of front-facing EUV filters through the mechanism of UV-induced oxidation
- Identification of a large systematic cross-equator effect in association with meridional circulation

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The tasks of calibrating data, validating data, and assisting users with access to and interpretation of the data are listed as science goals. These activities enable science but are not science investigations.

- **Factor A-2:**
Performance of addressing any findings in the previous Senior Review. (The 2023 Senior Review panel will have access to the previous Senior Review report for a mission, and other information from that review as needed.) This factor will only be assessed for missions returning to the Senior Review.

Major Strengths

The team made substantial progress in addressing the findings of the previous Senior Review. The PDMP was updated with the Data Product Inventory and is nearing approval. Draft CMADs were provided to the Senior Review panel and are nearing completion.

Minor Strengths

SDO Level 0 data is in the process of being transferred to the SDAC. Final details regarding which data will be archived and available from the SDAC still need to be confirmed in an ICD that is in progress. Mission source code is publicly available for AIA and HMI, and this code is being transferred to a GitLab repository in order to enable an easy transition to the SDAC. EVE mission code is in the process of being made available publicly in a GitLab repository.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion B: Overall Evaluation of the Proposed Investigation (Science Investigation only)

- **Factor B-1:**
  Scientific merit and impact of the proposed in-guide science investigation.

Major Strengths

The science objectives "Measure and Interpret Internal Dynamics and Structures as Activity Peaks" and "Analyze Magnetic Variability Across Many Time Scales" contain many tasks that will address the objectives in a substantive way. Improvements in the HMI ring-diagram helioseismology pipeline will enable investigations of near-surface flows on global scales and local scales for comparison to time-distance helioseismology. These improvements will also enable further characterization of low-latitude and long-living vorticity, which is revealed as Rossy waves. The task to explore the relationship between energy and helicity in active regions and solar eruptions will expand on an earlier study to enable firm conclusions about predicting solar eruptions from emerging active regions. A collection of tasks centered around solar-cycle scale variations involve the relationship of photospheric flows, investigates how flux emergence constrains the mechanisms of the solar cycle, and provides constraints on dynamo modeling.

Minor Strengths

None noted.

Major Weaknesses

Minimal overall progress on the remaining three science objectives can be expected as most of the identified tasks have no in-guide funding. In the task to "Investigate Magnetic Connections from the Sun Throughout the Heliosphere," only one of three tasks is funded. It is acknowledged that this one funded task to better understand how MHD waves transport energy in the photosphere, chromosphere, and lower corona is important to study. In the objective to "Reveal the Fundamental Physics of Solar Atmospheric Dynamics and Eruptive Events," 75% of the tasks are unfunded. In the objective to "Understand Impacts of Solar Variability on Earth and Other Planets, and Sun as a Star," none of the tasks will be funded.

Minor Weaknesses

None noted.

- **Factor B-2:**
  Implementation merit of the proposed in-guide science investigation.

Major Strengths

The implementation of each of the planned tasks is well described and clear paths to closure are identified. The work is largely based on expanding initial results or utilizing techniques that were developed during the previous Extended Mission in order to attack new science problems. Ring-diagram helioseismology will be improved by a simultaneous multi-ridge fitting technique and the computation of higher resolution (5°) tiles.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-3:**
  Relevance of the proposed science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.

Major Strengths

The proposed science investigations have high relevance to the scientific goals of the Heliophysics Division. Even with the reduced in-guide funded science objectives, all three goals of the NASA Heliophysics Division in the 2014 Science Plan are addressed either as an essential part of that goal or as a contributor to that goal. These investigations also are essential to or contribute to all four goals of the 2013 Heliophysics Decadal Survey, the Decadal Survey Atmosphere Ionosphere Magnetosphere Interactions Challenge 4, the Solar and Heliophysics Challenges 1 through 3, and the Solar Wind Magnetosphere Interaction Challenge 4.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-4:**

Cost reasonableness of the proposed science investigation.

Major Strengths

None noted.

Minor Strengths

The in-guide tasks that the proposal states will be funded by the project require an average FTE/WYE cost that is reasonable.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**

Quality of the archival mission science data products and associated documentation.

Major Strengths

The SDO team has ensured that the data products are of the highest possible quality, and easy access to the data is provided. Excellent access to data is available from project repositories. Extensive efforts to ensure the data are calibrated and validated have been undertaken. This observation is supported by the extreme number of papers written by the community each year with a dependence on SDO data. The data are regularly used for machine-learning-based work and artificial-intelligence-based work, which require well-calibrated and validated data. In 2022, a monthly average of 130 TB of data were downloaded by users. The JSOC averages 70,000 requests for 10.4 million files per month. EVE downlinks more than 780 requests per month. A typical year sees more than 500 papers. The latest full year of 2021 saw more than 700 refereed papers that used SDO data. Extensive online documentation for retrieving and interpreting SDO data is available from the mission repositories. SDO team members are substantially involved in development of SunPy, which enables low-cost access to software for data analysis. Images from SDO are annotated in near-real-time as part of the Heliophysics EventKnowledge Database, facilitating easy searches for data of interest.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The proposal's discussion implies the need to further improve data documentation before archiving. Science Objective 3 ("Assist science users and the public with access to and interpretation of SDO data") mentions the need to use substantial time each week helping users to identify, transfer, and analyze the data.

- **Factor C-2:**

Synergy with and benefit to the Heliophysics System Observatory. This factor applies only to the planned observations and not any previous scientific return or proposed mission-funded science investigation.

Major Strengths

The planned science objectives have significant synergy and benefits to the HSO research goals and identify collaborations with a large number of missions. The proposal details 10 specific planned activities that will benefit HSO as well as other NASA divisions and ground-based observatories. The in-guide science goals include collaborations with SolO, PSP, IMAP, STEREO, IRIS, and MAVEN. Given the large numbers of papers utilizing SDO data, the synergy and benefits to HSO are clear.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion D: Technical Implementation

- **Factor D-1:**

  Health of the mission and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory. For this factor, the mission includes the spacecraft, instruments, and project-managed ground systems.

Major Strengths

The spacecraft, instruments, and ground systems are all in excellent condition. The SDO Ground System is being proactively maintained with plans for the replacement of many subsystems.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

Continued maintenance of the SDO Ground System requires over-guide funding, which puts the ability to provide large volumes of data at risk. Delay from previous over-guide funding needs to be addressed with NASA.

- **Factor D-2:**

  Cost reasonableness of the mission's operations model. This factor includes the ability to continue healthy operations within the in-guide budget.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-3:**

Sufficiency of the management plan and, if applicable, necessity for the succession plan.

Major Strengths

None noted.

Minor Strengths

The existing management team has extensive knowledge and experience with SDO and with related missions.

Major Weaknesses

The over-guide budget is required to engage successors for key personnel or to move current team members into these elevated roles. This requirement puts the program at significant risk should an increased budget not become available.

Minor Weaknesses

None noted.

Criterion E: Inclusion, Diversity, Equity, and Accessibility

- **Factor E-1:**
Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan. This factor applies to the mission's ideal state of IDEA including mission activities, mission team structure, movement of individuals in/out of and within the mission team, and succession planning. This factor includes any tailoring of institutional IDEA strategies to the mission team's plan.

Major Strengths

The SDO team has an established ideal IDEA Plan that outlines team interactions and interactions with the community. The team shows a strong commitment to mentorship with local high schools and the NASA GEM program.

The SDO team has already implemented a formal Code of Conduct for its science workshops. This Code of Conduct includes a process for reviewing complaints and taking action if necessary.

Minor Strengths

The participation of senior personnel (Project Scientist and instrument PI) in the NASA Science Mission Directorate's Inclusion Plan Best Practices Workshop demonstrates genuine interest in improving the mission's state of IDEA.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor E-2:**
Recent progress against the mission team's IDEA Plan. This factor assesses the mission's recent actions that have addressed and made progress against the mission IDEA strategy. This factor applies only to those missions that have developed an IDEA strategy before this Senior Review.

Major Strengths

None noted.

Minor Strengths

The team currently recruits a diverse set of young researchers at the student and postdoctoral levels.

The team is cognizant of choosing meeting speakers to balance gender and career level. However, concern could be added to other diversity factors within IDEA.

The team encourages short-term researchers and community interactions.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor E-3:**
Planned progress against the mission IDEA Plan. This factor assesses the mission team's plan to advance toward its ideal state of IDEA by the next Senior Review. This includes planned metrics and milestones, the ability for upcoming actions to meet those metrics/milestones, and the ability to enable further progress after the next Senior Review.

Major Strengths

The team proposes to meet regularly with the Heliophysics DEIA Lead in order to provide the team with outside expertise in IDEA. This person will be able to help identify training and educational opportunities.

The team proposes for future workshops to have attendees agree to a Code of Conduct as part of the meeting registration process. The team will also use surveys to solicit feedback.

Minor Strengths

The team will utilize existing partnerships and tools (Lockheed Martin, LASP/CU Space Weather Summer School, and Stanford IDEAL) for training. The team will utilize existing partnerships (GSFC Research Practicum at Eleanor Roosevelt HS, LMSAL's Palo Alto Unified School District program, and COFFIES Science) for outreach opportunities.

Major Weaknesses

None noted.

Minor Weaknesses

The proposal provided insufficient details about the evaluation methodology of the surveys. For example, no information is given regarding how the surveys will be developed and distributed. There is inadequate description of the timeline and milestones that will be used for analyzing and taking action in response to the survey results. The team member(s) who will oversee this process are not identified.

The proposal does not adequately describe how the AIA team would recruit its new junior scientist. Although the proposal identifies a "preference of women and minorities," the proposal does not describe actionable steps that will be taken to affect that preference (e.g., direct solicitations or targets of opportunity).

- **Factor E-4:**

Cost reasonableness of the mission team's IDEA activities.

Major Strengths

None noted.

Minor Strengths

External funding (e.g., GEM funding and NSF funding of REU programs) provides for efficiency and enhanced return in the implementations of mentorship programs and IDEA initiatives more broadly.

Using IDEA funding to support additional students and other personnel could effectively diversify the team.

Major Weaknesses

None noted.

Minor Weaknesses

Criterion F: Under-guide and Over-guide Requests (Informational Only)

- **Factor F-1:**
Scientific merit and impact of any proposed over-guide science investigation.

Major Strengths

The SDO over-guide would enable the completion of the proposed science by accounting for ~50% of the proposed investigations. The mission team addresses three of the five overarching science objectives and relates to all three Heliophysics Division science goals, Decadal Survey goals 1 through 4, and 5 of the Decadal Survey challenges. These objectives and goals would include collaborations with all missions mentioned related to in-guide activity plus TIMED, GOLD, ICON, MAVEN, and Hinode.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-2:**
Implementation merit of any proposed over-guide science investigation.

Major Strengths

None noted.

Minor Strengths

The proposal clearly demonstrates the basic tools and techniques for achieving closure of the tasks that are in hand or are achievable.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-3:**
Scientific merit and impact of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-4:**
Implementation merit of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-5:**
Merit and impact of any proposed over-guide for mission operations.

Major Strengths

The over-guide request will allow the replacement of aging elements of the Ground System at White Sands such as the Antenna Control Assembly, and the request maintains the highly effective systems engineering team and flight software team in FY25 and FY26 to levels at which these teams have demonstrated success at maintaining the state of health and resilience of the flight system. The over-guide request will allow the replacement of aging elements of the JSOC data center. The demand for SDO data continues to grow, so the updating of data distribution system hardware will allow the team to continue serving science requests from the community without major interruptions to access.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-6:**
Merit and impact of any proposed over-guide for the mission team's IDEA Plan.

Major Strengths

The over-guide request will enable the team to involve early-career scientists in the mission and involve minority-serving institutions in SDO science. The IDEA Plan will directly provide funding for several new students and scientists from underrepresented minority backgrounds.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

STEREO

Mission Synopsis

The STEREO spacecraft were launched on October 25, 2006 and inserted into heliocentric orbits. Subsequently, the two spacecraft were allowed to drift in opposite directions from the Earth-Sun line by 22 degrees per year. The spacecraft subsystem failures include the loss and aging of the Inertial Measurement Units (IMUs) and the loss of STEREO-B in 2014 due to IMU failure after nearly eight years of successful operation. Thus, the STEREO mission presently consists of only the STEREO-A spacecraft. Over the period covered by this proposal, STEREO-A will move through the Earth-Sun line in August 2023, providing unique opportunities in cooperation with other solar imaging missions.

The mission instrumentation consists of the following:

- The Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) is a remote-imaging suite that images from the Sun to 1 AU and beyond with a combination of a solar EUV imager, two coronagraphs, and two heliospheric imagers.
- The In-situ Measurements of Particles And CME Transients (IMPACT) suite samples the 3D distribution of solar wind plasma electrons, the characteristics of Solar Energetic Particle (SEP) ions and electrons, and the local vector magnetic field.
- PLAsma and SupraThermal Ion Composition (PLASTIC) measures the properties of the bulk solar wind. In particular, PLASTIC measures the plasma characteristics of protons, alpha particles, and heavy ions.
- STEREO/WAVES (S/WAVES) is an interplanetary radio burst tracker that traces the generation and evolution of traveling radio disturbances from the Sun to the orbit of Earth.

Overall Assessment

The STEREO mission continues to provide important data as part of the HSO, although the proposed science objectives for the next extended mission are very broad.

Focused Findings

The team proposes to continue the studies as STEREO crosses the Sun-Earth line in 2023 and moves through the L4 Lagrangian point ahead of Earth, reaching a separation of 70 degrees in September 2026. This near-Earth encounter will provide exciting new science related to the solar activity near solar maximum. Parker Solar Probe and Solar Orbiter will further enhance the possibilities for research based on multi-point observations in conjunction with STEREO.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**

Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

Major Strengths

Several science objectives grouped in three categories have been substantially accomplished. These categories include: 1) the structure and magnetic morphology of CMEs, active regions, and the solar wind as revealed by multi-point measurements; 2) applying STEREO observations toward evaluating off-L1 location for space weather research; and 3) understanding the effects of solar cycle variations on the corona and heliosphere. The STEREO team has done excellent work on these topics, resulting in more than 2000 based theses and publications in the refereed literature. The STEREO team has provided freely available data and data analysis software to the community.

Minor Strengths

None noted.

Major Weaknesses

It has not been adequately demonstrated that the team has accomplished Previous Science Objective B3. Team-led work still appears to be primarily focused on the large-scale CME structures without addressing the proposed objective of the best indicator of SEP occurrence and severity.

Minor Weaknesses

None noted.

- **Factor A-2:**

Performance of addressing any findings in the previous Senior Review. (The 2023 Senior Review panel will have access to the previous Senior Review report for a mission, and other information from that review as needed.) This factor will only be assessed for missions returning to the Senior Review.

Major Strengths

None noted.

Minor Strengths

The proposal addresses most of the earlier findings from the last Senior Review.

Major Weaknesses

The proposal does not address the 2020 Senior Review's finding of the project not having clear and focused objectives that can reach closure. The previous Senior Review noted that the science objectives are broad in nature, leading to difficulty in assessing closure. It has been demonstrated that significant research progress was made regarding most of the objectives. However, while it is said that "we endeavored to be more focused in our objectives," there are four categories and 12 sub-objectives proposed in this senior review. The objectives are therefore still very broad and the in-guide budget effort is insufficient to support their accomplishment.

Minor Weaknesses

None noted.

Criterion B: Overall Evaluation of the Proposed Investigation (Science Investigation only)

- **Factor B-1:**
  Scientific merit and impact of the proposed in-guide science investigation.

Major Strengths

The proposed science objectives (A) and (B) are compelling. The team proposes to pursue science enabled by STEREO-Ahead's (STA's) unique location in the heliosphere combined with the upcoming solar maximum. The location of STA enables studies of solar transients with relatively close azimuthal separation. STEREO will further extend studies of the evolution of the solar dipolar field, solar wind features, and how these phenomena affect the heliosphere. STA provides a vital location of observation in conjunction with recent and upcoming missions near Earth and throughout the solar system.

The proposed specific objectives include the following: (A) leveraging the inferior conjunction of STA to uncover the multi-scale nature of the heliosphere at solar maximum; (B) multi-dimensional studies for the new multi-spacecraft era; (C) space weather research during Solar Cycle 25 maximum; (D) solar cycle science.

STA is uniquely located upstream of L1 as it crosses the Sun-Earth line. Studies of fine-scale radial variations will therefore be enabled. As STA continues to approach L4, studies of longitudinal variations of solar wind structures and stereoscopic observations will be enabled.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

Other than the location across the Sun-Earth line, all other observations appear to be a continuation of previous observations for the purpose of increasing statistics.

- **Factor B-2:**
  Implementation merit of the proposed in-guide science investigation.

Major Strengths

The implementation for most science objectives is appropriate as long as data collection is normal. As most observations are continuations of previous ones, these observations can be implemented with existing methodology.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The implementation plan is not clear for several science objectives, as elaborated below. Objective B2 (the role of microphysics in radial evolution) proposes to utilize the STA-PSP radial alignment. However, it is not clear how the radial alignment would contribute, and there are no references demonstrating the feasibility of wave observations during radial alignment between two spacecraft of large separation. For D3 (variation of small-scale solar wind sub-structures), it is not demonstrated whether the proposed machine-learning technique is capable of studying interplanetary field enhancement structures.

- **Factor B-3:**
Relevance of the proposed science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.

Major Strengths

The science investigations are relevant to 2013 Heliophysics Decadal Survey goals. The science objectives address Goal 1 ("Determine the origins of the Sun's activity") and Goal 4 ("Discover and characterize fundamental physical processes…"). Objective D addresses the goal to "Determine how the Sun generates the quasi-cyclical variable magnetic field that extends throughout the heliosphere." Objective A addresses the goal to "Determine how the Sun's magnetism creates its dynamic atmosphere." Objectives A through D address the goal "Determine how magnetic energy is stored and explosively released."

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-4:**
Cost reasonableness of the proposed science investigation.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

The science objectives listed in the proposal are too broad in nature to be accomplishable within the proposed budget. This breadth leads to difficulty in assessing how science closure will be achieved and demonstrated during the period from FY2023 to FY2026. It is unclear how the team will accomplish all of the objectives based on the science investigation budget.

Minor Weaknesses

None noted.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**

Quality of the archival mission science data products and associated documentation.

Major Strengths

The data product and the documentation are archived at the STEREO Science Center and within SDAC and SPDF. New CMADs have been produced and are publicly available. Quick-look products are available to the public.

Minor Strengths

None noted.

Major Weaknesses

It is not clear what the remaining products are and what the timeline is for their completion. The proposal mentions that "SPASE description for the handful of remaining products are underway." However, the identity of the remaining products and the timeline for their completion are not adequately described. The required budget, risk, and timeline are not shown for new data products including heavy ions and ICME information.

Minor Weaknesses

Data analysis software is openly available, but it is not clear whether the instrument documentation includes the software documentation. It is not clear whether there is software that does not use the proprietary IDL.

- **Factor C-2:**

Synergy with and benefit to the Heliophysics System Observatory. This factor applies only to the planned observations and not any previous scientific return or proposed mission-funded science investigation.

Major Strengths

STEREO contributes to HSO by measuring variations in conjunctions with L1 missions. The heliospheric imagers continue to provide a unique view of the inner heliosphere, benefiting PSP and SolO. Small angular separations with Earth are ideal for active region tomography and also for triangulation of eruptions near the solar surface. Reaching the L4 location in 2026 is important for measurements of SEP and for imaging active regions. This location provides a unique perspective that is valuable for heliospheric model selection, heliospheric model validation, and space weather studies of other planets. This location provides important resources for upcoming missions including SWFO-L1, IMAP, SunRISE, and PUNCH.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion D: Technical Implementation

- **Factor D-1:**

Health of the mission and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory. For this factor, the mission includes the spacecraft, instruments, and project-managed ground systems.

Major Strengths

The spacecraft, instruments, and project-managed ground system are all in good health. Instruments continue to work nominally. Abnormalities in IMPACT and PLASTIC are resolved or mitigated. The ground system has been upgraded.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-2:**

Cost reasonableness of the mission's operations model. This factor includes the ability to continue healthy operations within the in-guide budget.

Major Strengths

The cost of the proposed mission operations is reasonable and is within the in-guide budget.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-3:**

Sufficiency of the management plan and, if applicable, necessity for the succession plan.

Major Strengths

None noted.

Minor Strengths

The management plan is sufficient assuming that current staff remain in their roles.

Major Weaknesses

None noted.

Minor Weaknesses

The succession plan is vague. The proposal states, "We have commenced nominating mid-career scientists as new Co-I's." However, there is no clear timeline for the planned succession.

Criterion E: Inclusion, Diversity, Equity, and Accessibility

- **Factor E-1:**
  Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan. This factor applies to the mission's ideal state of IDEA including mission activities, mission team structure, movement of individuals in/out of and within the mission team, and succession planning. This factor includes any tailoring of institutional IDEA strategies to the mission team's plan.

Major Strengths

The proposal identifies clear and appropriate ways to address concerns regarding implementing IDEA initiatives within a large team. It acknowledges the large, multi-institutional STEREO team and the difficulties this can cause in implementing IDEA initiatives. The STEREO project scientist will work with institutional PIs. IDEA activities will be incorporated into existing programs including annual meetings.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor E-2:**
  Recent progress against the mission team's IDEA Plan. This factor assesses the mission's recent actions that have addressed and made progress against the mission IDEA strategy. This factor applies only to those missions that have developed an IDEA strategy before this Senior Review.

The mission did not have a*n* IDEA Plan before the 2023 Senior Review to measure progress against.

- **Factor E-3:**
  Planned progress against the mission IDEA Plan. This factor assesses the mission team's plan to advance toward its ideal state of IDEA by the next Senior Review. This includes planned metrics and milestones, the ability for upcoming actions to meet those metrics/milestones, and the ability to enable further progress after the next Senior Review.

Major Strengths

The proposal provides a clear timeline with specific milestones for implementing IDEA initiatives. Effort has already been made to research survey options and the demographics of comparable groups of researchers.

The proposal emphasizes that the STEREO D&I Plan will be “dynamic” and states how the results of demographics and climate surveys will be used to inform the next steps. The team has already identified target metrics and points of comparison for these metrics. Examples include the demographics of federal STEM workers.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

Although the proposal states that the “STEREO project will work with institutional PIs to delineate clear succession plans,” few details are provided. Additionally, reference is made to “turn-over related to retirements” without any assessment of how these personnel changes have been handled.

- **Factor E-4:**

Cost reasonableness of the mission team’s IDEA activities.

Major Strengths

None noted.

Minor Strengths

The proposal states that no additional funding is requested to implement the STEREO D&I Plan. Although IDEA initiatives may require some additional effort on the part of the mission leadership, the utilization of existing annual meetings and web resources makes this implementation more feasible.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion F: Under-guide and Over-guide Requests (Informational Only)

- **Factor F-1:**
  Scientific merit and impact of any proposed over-guide science investigation.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

The machine-learning component in the over-guide budget is not sufficiently demonstrated to be essential to the achievement of the proposed scientific investigation objectives.

Minor Weaknesses

None noted.

- **Factor F-2:**
  Implementation merit of any proposed over-guide science investigation.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-3:**

Scientific merit and impact of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-4:**

Implementation merit of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-5:**

Merit and impact of any proposed over-guide for mission operations.

- No over-guide for ops was proposed.**Factor F-6:**

Merit and impact of any proposed over-guide for the mission team's IDEA Plan.

No over-guide for IDEA was proposed.

THEMIS

Mission Synopsis

Launched in 2007, THEMIS consists of five identical probes (i.e., A, B, C, D, and E) with 20 ground-based observatories. After completing its prime mission in 2010, the set was split into three Earth-orbiting (THEMIS) probes and two lunar orbiting (ARTEMIS) probes. The three Earth-orbiting THEMIS probes (C, D, and E) have low-inclination orbits that are ideal for studying the equatorial magnetosphere.

Each THEMIS probe carries five sensors including an Electric Field Instrument (EFI; for DC electric fields), a Fluxgate Magnetometer (FGM; for DC magnetic fields), Search Coil Magnetometers (SCM; for AC magnetic fields), ElectroStatic Analyzers (ESA; for plasma electrons and ions), and Solid State Telescopes (SST; for energetic electrons and ions up to MeV). In addition to the flight sensors, the mission also supports Ground-Based Observatories (GBO) consisting of a network of 20 All-Sky white-light Imagers (ASI) and nearly two dozen Ground-based fluxgate MAGnetometerS (GMAGS) based in North America.

Much of the community accesses and analyzes THEMIS data through the Space Physics Environment Data Analysis Software (SPEDAS) IDL software, which has also been adopted by other missions. This software has been ported to Python for even wider open-access use. This access is especially important since THEMIS is used for numerous correlative studies with other missions such as MMS, PSP, Cluster, ERG, GOES, and (after launch) TRACERS and IMAP.

In the proposed extended mission, the orbits of the three Earth-orbiting probes will be modified to provide near-equilateral triangular configurations residing approximately in the XZ plane in the magnetotail and in the XZ, XY, or YZ planes on the dayside. These configurations will be used for observations of dayside and nightside phenomena. These configurations allow the separation of spatial and temporal features at least in one plane in order to serve three overarching science objectives:

1) Identify what powers the storm-time ring current.
2) Reveal how storm-time relativistic electron enhancements are powered and what makes them so geoeffective.
3) Resolve the relative importance of dayside transients for powering the storm-time ring current and relativistic electron enhancements.

Overall Assessment

THEMIS has been a high-impact mission since the last Senior Review, and the mission has successfully addressed its prioritized science goals. The highly compelling new proposed science investigation will take advantage of well-coordinated assets (THEMIS, ARTEMIS, GBOs) in addition to a combination of NASA, NOAA, and other international assets. These assets will be used to advance our understanding of "what drives the dominant space weather phenomena at Earth: storms and relativistic electron enhancements." The proposed effort will utilize these assets to obtain coordinated observations from the sources to the sinks of the energy in order to investigate the ultimate driver of storms and the most damaging Relativistic Electron Enhancements (REEs) that occur. The THEMIS data are widely used by the community and play a broad role in the HSO. The THEMIS mission data archives are thorough and complete at the appropriate NASA and mission data websites, and these archives are accompanied by high-quality documentation. Many of the algorithms and code that were first developed by the THEMIS team have been adopted by other mission teams as a result of the openness and willingness to share and advance the community. All (minor) sensor anomalies have been recovered or are using a successful workaround plan so that the sensors are returning to full science capability on all probes.

Focused Findings

THEMIS proposes exciting science, provides a valuable contribution to the HSO, and supports the lunar program through its ARTEMIS component. THEMIS's near-Earth portion is critical to the function of the HSO as it can routinely provide simultaneous three-point information with mesoscale spacing (~several R_E).

The proposed in-guide budget is reasonable and appropriate for the mission operations and the proposed science. Involvement and support for THEMIS/ARTEMIS to participate in the Artemis and the Lunar Gateway is a compelling application for NASA. The over-guide budget would enhance the main science investigation and HSO support by funding a broader team of scientists in order to provide the Artemis and Lunar Gateway science teams with near-real-time MeV ion measurements. Over-guide support makes sense on two fronts for this application: 1) the potential science and operational outcomes are tremendous, and 2) the cost to continue the mission collaboration is far smaller than the cost to launch another pair of instrumented spacecraft to the moon to replace ARTEMIS in order to serve in this collaborative role.

The proposal clearly describes data archiving and software efforts that are consistent with the Senior Review requirements. The substantial community productivity by scientists unaffiliated with the mission demonstrates THEMIS' user-friendly software tools, high data quality, and the responsiveness of THEMIS' staff and instrument scientists.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**

Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

Major Strengths

The THEMIS mission has continued to significantly contribute to our understanding of heliophysics and has successfully addressed all of the Science Objectives and Science Questions in the previous extended mission. Over the last two years, THEMIS has determined the mechanism by which energy is converted from magnetic to plasma and the mechanism which drives auroral acceleration at localized energy conversion regions at the inner edge of the plasma sheet and the dayside magnetosphere. It also revealed that these energy conversion regions proliferate and intensify during increased solar wind electrodynamic conditions and compressional driving conditions. Those conditions are also responsible for causing magnetic storms and relativistic electron enhancements. The THEMIS team has provided major advancements in the community's understanding of heating from tail reconnection exhaust. The mission has also discovered the major driver of Field Aligned Currents (FAC) through "embedded FAC." These embedded FAC are smaller spatially in nature than the traditional FAC that result from two cell convection patterns but carry far more current than previously understood. The team and mission have made compelling progress in the study of dayside transients and how these transients may impact the solar wind-magnetosphere coupling. The team provided specific contributions in the relative occurrences of magnetosheath jets that can compress the magnetopause boundary and cause rotations in the magnetic field to enhance or decrease geoeffectivity. The THEMIS mission team has made major progress on the acceleration of particles within these varying plasma environments, highlighting the role of wave particle interactions from whistler waves, ULF resonance in the radiation belts, and Fermi acceleration in the foreshock.

Minor Strengths

Important progress was made in the understanding of the mechanisms of energy conversion from magnetic to plasma and then conversion from plasma to magnetic as energy is transferred radially inward on the nightside. This progress has come as a result of experimental work as well as numerical modeling.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor A-2:**

Performance of addressing any findings in the previous Senior Review. (The 2023 Senior Review panel will have access to the previous Senior Review report for a mission, and other information from that review as needed.) This factor will only be assessed for missions returning to the Senior Review.

There were no corrective actions requested in the 2020 Senior Review findings.

Criterion B: Overall Evaluation of the Proposed Investigation (Science Investigation only)

- **Factor B-1:**
  Scientific merit and impact of the proposed in-guide science investigation.

Major Strengths

The proposed Science Objectives are highly compelling, addressing major outstanding science questions within heliophysics. THEMIS will utilize its well-coordinated mission assets, will leverage an unparalleled distributed observatory, and will take advantage of the combination of NASA, NOAA, and other international assets in order to understand "what drives the dominant space weather phenomena at Earth: storms and relativistic electron enhancements (REEs)." The proposed effort will utilize these assets to obtain coordinated observations from the sources to the sinks of the energy in order to investigate the ultimate driver of storms and the most damaging REEs that occur. Using mesoscale spacing of the THEMIS spacecraft and statistics, the team will make major progress in understanding the spatial or temporal local impact of dayside transients at the magnetopause and within the magnetosphere. Understanding how these kinetic structures affect the total energy budget to the extent that they impact or fuel storms, causing the cascade of energy transfer that creates REEs remains a major gap in the community's understanding. Similarly, a compelling science objective is the quantification of how local acceleration in upstream regions such as the foreshock, as well as within the magnetosphere, due to dayside transients impact the development of storms. The emergent Solar Cycle 25 is predicted to be more intense than any other period in the lifetime of THEMIS. This solar cycle will allow the team to continue to mature our understanding on transient phenomena during storm times in the next few years, while also addressing the SR2023 primary objectives.

Minor Strengths

A focused effort by the THEMIS mission is anticipated to provide important advancement in the understanding of the role of nightside injections versus radial diffusion in the production of relativistic electrons.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-2:**
  Implementation merit of the proposed in-guide science investigation.

Major Strengths

The proposed science investigation is well-aligned with an appropriate and feasible implementation plan. The proposed effort will utilize evolving inner-probe spacing in order to provide triangle configurations with extension close to the XZ plane. This configuration will be in place as the apogee processes over local times allowing sampling of the dayside, flanks, and nightside magnetosphere and will enable the mission to address the dayside and nightside science questions. THEMIS has implemented similar configurations in previous years, providing high confidence that the mission will successfully address the science objectives.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-3:**
  Relevance of the proposed science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.

Major Strengths

The proposal's science goal and related objectives are compelling and in-line with the goals of the 2013 Heliophysics Decadal Survey. The proposed goals are particularly aligned with the Decadal Survey's Key Science Goals 2 and 4. Key Science Goal 2 is to "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs." Key Science Goal 4 is to "Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe."

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-4:**
Cost reasonableness of the proposed science investigation.

Major Strengths

The proposed in-guide budget is reasonable and covers instrument and mission support by scientists to ensure the quality of the instruments and data products. This budget enables continual monitoring of the instrument state-of-health and performance, which is critical for assurance of measurement data quality.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**
  Quality of the archival mission science data products and associated documentation.

Major Strengths

The THEMIS mission data archives are thorough and complete at the appropriate NASA and mission data websites, and these archives are accompanied by high-quality documentation. All data are publicly available from NASA's Space Physics Data Facility (SPDF) and CDAWeb archive in addition to the mission website and other mirror websites at UCLA, France, and elsewhere. The data are ISTP-compliant and SPASE-compatible. There are widely distributed data ingestion, analysis, and visualization tools (open-source) in IDL-based code (through SPEDAS) and in Python-based code. All project-originated code is either described in the CMAD or is released as part of the open-source THEMIS Data Analysis System code. The mission code is available as open-source software on the mission website and as a plug-in to SPEDAS. The software comes complete with documentation, YouTube sessions, online tutorials, and webinars. The THEMIS mission rapidly places data online, usually within less than a week. Summary plots are available within days. This rapid availability is highly useful for all researchers, especially those conducting active experiments such as ground-based radar or rocket experiments. The THEMIS team goes beyond the effort offered by other missions and provides regular training sessions at the NSF/GEM meeting.

The substantial community productivity by scientists who are unaffiliated with the THEMIS mission provides evidence of THEMIS' user-friendly software tools, high data quality, and the responsiveness of THEMIS' staff and instrument scientists. The THEMIS mission provides analysis and calibration code in an easy-to-access format. Many of the algorithms and code first developed by the THEMIS team have been adopted by other mission teams due to the mission team's openness and willingness to share for advancement of the community. This example that the THEMIS mission has set for the community is a significant Major Strength.

The mission data can be telemetered to the ground in different resolutions depending on the target science, providing the opportunity for a diverse set of HSO science by the broader community.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor C-2:**

Synergy with and benefit to the Heliophysics System Observatory. This factor applies only to the planned observations and not any previous scientific return or proposed mission-funded science investigation.

Major Strengths

THEMIS's near-Earth portion is critical to the function of the HSO as it can routinely provide simultaneous three-point information with mesoscale spacing (~several R_E). These observations include the radiation belts, ring currents, and their drivers from the outer magnetosphere (day and nightside) in a string-of-pearls configuration. The spacecrafts' mesoscale spacing provides a valuable tool used by community members who seek to address large-scale and system-level objectives that are highly valuable investigations in current magnetospheric study.

THEMIS will continue to be highly engaged in correlative studies with other Heliophysics missions. These missions include PSP, MMS, Cluster, ERG, GOES, and (after launch) TRACERS and IMAP. THEMIS is the only NASA near-Earth equatorial mission covering the entire near-Earth space. THEMIS is the only mission observing the mid-tail and solar wind. ARTEMIS provides solar wind data that are synergistic with ACE, Wind, and DSCOVR. The data will also be synergistic with the IMAP observations at L1. THEMIS provides the largest coverage of the ionosphere in GBOs including All Sky Imagers and >20 ground magnetometers. THEMIS is a key complement to NASA's TRACERS and the Canadian TREx program. The ARTEMIS spacecraft data are highly relevant as solar wind and charged particle probes for the upcoming CLPS experiments and science experiments to be deployed on the lunar surface in the next several years. A number of these payloads address science objectives within the heliophysics mission.

Minor Strengths

The THEMIS GBO contributes valuable magnetometer and all-sky imaging to the community datasets.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion D: Technical Implementation

- **Factor D-1:**

Health of the mission and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory. For this factor, the mission includes the spacecraft, instruments, and project-managed ground systems.

Major Strengths

The THEMIS instruments and spacecraft continue to operate effectively with no major anomalies or critical failures. Propellent resource requirements for operations remain low, with margin remaining for re-entry. Three minor anomalies are presented with strategies implemented for operational, characterization/calibration, and software mitigation in order to maintain full science operations capability. No major degradations are present. Several anomalies or degradations are noted, but a ground-calibration strategy has been developed to correct for the change in each case.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

One spacecraft (THEMIS-D) periodically experiences lockups of the bus that are attributed to space weather events. The lockup requires a hard reset from the ground, which results in a loss of science data between a lockup event and the next ground pass when the reset command can be transmitted. This duration can sometimes be 10-20 hours. This lockup situation occurs "every couple of weeks" but is not anticipated to impact closure on the science objectives.

- **Factor D-2:**

Cost reasonableness of the mission's operations model. This factor includes the ability to continue healthy operations within the in-guide budget.

Major Strengths

The proposed cost is reasonable for the mission's operations model. The experienced THEMIS operations team operates the five highly maneuverable satellites. The team collects and processes data from the satellites and from 20 ground stations. Approximately seven FTEs operate the mission and spacecraft including GBOs. Approximately three FTEs conduct science operations including GBOs. Science validation and project management enable efficient reallocation of resources to address potential issues and to re-optimize science when necessary. This approach results in very high productivity and community support. Science funding is allocated only on a partial basis for non-students. Student funding is also very efficient, with fellowships and non-THEMIS project support being sought (and obtained) to maximize yield.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-3:**
Sufficiency of the management plan and, if applicable, necessity for the succession plan.

Major Strengths

The THEMIS management structure, key personnel, and roles are clearly defined and well-established. The Project Scientist, PI, and Mission Operations Manager have decades of experience with NASA project management. These key personnel have been involved in hundreds of scientific and technical publications related to space science and technology.

The proposed effort has a well-defined succession plan that will provide opportunities for early-career scientists. THEMIS intends to formally propose to NASA to replace Deputy PIs with two new Deputy PIs in order to create growth opportunities for other early-career scientists. A succession plan is provided. Qualified mid-career researchers are planned to succeed senior researchers in the Deputy PI roles for magnetospheric science and lunar science.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion E: Inclusion, Diversity, Equity, and Accessibility

- **Factor E-1:**

Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan. This factor applies to the mission's ideal state of IDEA including mission activities, mission team structure, movement of individuals in/out of and within the mission team, and succession planning. This factor includes any tailoring of institutional IDEA strategies to the mission team's plan.

Major Strengths

The proposal includes a well-articulated IDEA Plan, a THEMIS-ARTEMIS Code of Conduct, and mentorship training plans. The proposal includes a clearly identified IDEA Representative with the responsibility to ensure that the IDEA initiatives are established and followed across institutions. The appointment of an IDEA Representative to oversee IDEA initiatives for the entire project significantly increases the likelihood of these initiatives being successfully implemented. The Code of Conduct provides clear guidelines and examples of constructive and unacceptable behavior. The proposal also provides a means to report any complaints to the IDEA Representative in order to address any harassment or misconduct and to provide accountability.

Minor Strengths

The proposal includes specific demographic statistics, but these statistics are limited to race/ethnicity and gender identity (excluding, for example, metrics on climate). The methodology for collecting these statistics is not described.

The proposal states that the team "aim[s] to increase racial/gender/ethnicity representation with future hiring," but specific policies/procedures are not addressed.

The proposal states that the THEMIS team will work with new UCLA DEI personnel to "build stronger partnerships with local high schools and community colleges in the next four years, as well as develop pathways for recruiting students from minority-serving institutions and historically black colleges and universities across the country." However, specific objectives and milestones are not provided.

The ongoing development of the "Heliophysics Audified: Resonances in Plasmas" shows a significant interest by the THEMIS team in increasing the accessibility of space physics data.

Major Weaknesses

None noted.

Minor Weaknesses

The Code of Conduct does not seem to be fully tailored to the THEMIS team. Terms such as "project maintainer" and "contributor" do not seem to apply. Some of the text in the "Our Responsibilities" section seems more appropriate for a software development project.

- **Factor E-2:**

Recent progress against the mission team's IDEA Plan. This factor assesses the mission's recent actions that have addressed and made progress against the mission IDEA strategy. This factor applies only to those missions that have developed an IDEA strategy before this Senior Review.

The mission did not have an IDEA Plan before the 2023 Senior Review to measure progress against.

- **Factor E-3:**

Planned progress against the mission IDEA Plan. This factor assesses the mission team's plan to advance toward its ideal state of IDEA by the next Senior Review. This includes planned metrics and milestones, the ability for upcoming actions to meet those metrics/milestones, and the ability to enable further progress after the next Senior Review.

Major Strengths

The proposal provides a well-defined IDEA Plan for advancing to an ideal state of IDEA by the next Senior Review. The proposal cites demographics for current THEMIS personnel, which is significantly more diverse than the national Heliophysics workforce (see: NAP2022). Among the graduate students that comprise the next generation of STEM professionals, the distribution is significantly improved. As mission personnel retires or new positions become available, the THEMIS team aims to increase racial/gender/ethnicity representation with future hiring. The over-guide budget includes eleven additional personnel, of which three are women of Asian descent and one is a Latino male. THEMIS leadership positions are assigned to a diverse group of individuals including women and LGBTQ members of the community. The proposed effort demonstrates a commitment to providing opportunities for science research and exposure to graduate and undergraduate students in addition to planning outreach events for K-12 students.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The proposal does not specify policies, procedures, and hiring strategies to achieve the desired diversity metrics.

- **Factor E-4:**

Cost reasonableness of the mission team's IDEA activities.

Major Strengths

None noted.

Minor Strengths

The THEMIS plan does not require additional NASA resources, but could be augmented through other venues. If successful, the pursuit of external funding (e.g., NSF funding for an REU program) will provide for efficiency and enhanced return in the implementation of mentorship programs and IDEA initiatives more broadly.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion F: Under-guide and Over-guide Requests (Informational Only)

- **Factor F-1:**
Scientific merit and impact of any proposed over-guide science investigation.

Major Strengths

The THEMIS engagement with the ARTEMIS and Lunar Gateway science teams is compelling and will lead to important heliophysics science return. ARTEMIS and the Lunar Gateway will provide three points in space around the moon. These assets can be used to probe structures across the magnetotail in order to simultaneously study tail reconnection and its lobe drivers. These assets can also be used to probe structures in the solar wind in order to study the 3D structure of shocks and particle acceleration within these shocks.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-2:**
Implementation merit of any proposed over-guide science investigation.

Major Strengths

Over-guide support for THEMIS/ARTEMIS to participate in ARTEMIS and the Lunar Gateway is a well-founded and cost-effective activity. The cost to continue the mission collaboration is far smaller than the cost to launch another pair of instrumented spacecraft to the moon to replace ARTEMIS in order to serve in this collaborative role. An added element of this collaboration is the potential to get real-time data from the ARTEMIS spacecraft.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-3:**

Scientific merit and impact of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-4:**

Implementation merit of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-5:**

Merit and impact of any proposed over-guide for mission operations.

No over-guide for ops was proposed.

- **Factor F-6:**

Merit and impact of any proposed over-guide for the mission team's IDEA Plan.

Major Strengths

None noted.

Minor Strengths

The proposed over-guide budget includes eleven additional personnel who enhance team diversity. Three of these personnel are women of Asian descent and one is a Latino male.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

TIMED

Mission Synopsis

The TIMED mission was launched in 2001, with the primary goal of determining the basic states and energy balance of the Mesosphere, Lower Thermosphere and Ionosphere (MLTI) by making observations covering altitudes between 60 km and 180 km. The TIMED instrument suite consists of four instruments: The Global UltraViolet Imager (GUVI), a far-ultraviolet spectrograph observing composition and temperature; The Solar Extreme Ultraviolet Experiment (SEE), a sun-pointing spectrograph/photometer combination measuring solar radiance from the soft X-rays to the far ultraviolet; The TIMED Doppler Interferometer (TIDI), a limb sounding interferometer measuring wind and temperature profiles; and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER), a multichannel limb-scanning radiometer measuring broadband infrared emission in order to obtain altitude profiles of temperature, pressure, geopotential height, volume mixing ratios for a number of trace species, and atmospheric cooling and heating rates. The overall objectives of the TIMED two-year, nominal mission were to perform a comprehensive, global study of the MLTI region and to establish a baseline against which to compare future measurements. TIMED has delivered quality science data since early 2002. Despite more than 20 years on orbit, TIMED is still able to routinely produce most of its original data products as well as some additional products that were added over the course of the mission. The mission started at the declining phase of Solar Cycle 23. The current mission extension will cover five years of the increasing solar activity phase of Solar Cycle 25.

The mission extension proposal includes the following science objectives:

1) Assess long-term change in the MLT associated with increasing CO_2 and varying solar activity.
2) Fill knowledge gaps in the storm-time dynamics of thermospheric composition.
3) Understand how the MLT is affected by short-lived and localized episodic disturbance events.

Overall Assessment

The TIMED science teams made significant progress in addressing goals from the 2020 Senior Review:

1) Understand the causes for the hemispheric and longitudinal variations in storm-time neutral response.
2) Investigate how middle atmospheric meteorological disturbances influence the thermosphere.
3) Determine the ongoing effect of weaker solar cycles on the thermal structure, composition, and dynamics of the Ionosphere-Thermosphere-Mesosphere (ITM) region

Results from these investigations and Emerging Topic investigations motivated the compelling Science Objectives proposed for the current mission extension. The science value of the TIMED mission continues to be significant, with almost 400 publications using TIMED data. These publications were produced both by TIMED science team members and the external science community. TIMED provides unique measurements that enhance the GOLD mission. These measurements include cross-mission calibration of the O/N2 products that are essential to the study of I-T structures and internal coupling processes that affect the I-T system.

The TIMED spacecraft and instruments are in relatively good health considering their 20+ years on-orbit. GUVI continues to be limited to its spectrographic mode due to a failure of the scanning mechanism in 2007. Contingency plans are in place in the event of a second reaction wheel failure (e.g., two-wheel concept of operations).

Focused Findings

TIMED observations constitute a highly valuable, long-term dataset for conducting high-priority MLT research. The measurements complement GOLD, providing new opportunities to study both the temporal and spatial response of the I-T system to external inputs. With the loss of ICON, TIMED continues to be the primary source of data for MLTI science, providing context and continuity for current and future HSO missions (e.g., GDC, DYNAMIC, AWE, GLIDE, EZIE, IMAP).

The proposed Science Objectives are mostly timely and compelling. However, Science Objective 1 ("Assess long term change in the MLT associated with increasing CO2 and varying solar activity") does not reference the extensive body of literature that is associated with this topic. This lack of connection makes it difficult to assess the impact of the proposed effort on the current state of knowledge.

The efforts to improve the TIDI wind measurements should be a high priority for the team, as closure of the Science Objectives may suffer from lack of accurate thermospheric winds measurements in the absence of ICON.

The PDMP and CMAD should be completed and provided to SPDF. The extensive TIMED database needs to be fully documented in order to ensure that current and future users understand the data products. This availability will become even more important as new data users are drawn to TIMED data products during the waxing phase of Solar Cycle 25. The accuracy of solar cycle trends using TIMED data needs to be verifiable.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**

Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

Major Strengths

The TIMED team has substantially addressed the broad Science Objectives in the previous extended mission. Significant results include (1) identification of the relationship between solar inputs and CO_2 in creating the extremely low mesospheric temperatures observed during two consecutive solar minimum periods, (2) characteristics of the hemispheric asymmetry of the thermospheric response to geomagnetic storms, (3) exploration of NO cooling during the 2020 Solar Eclipse Event, and (4) intercomparison and cross-calibration of GUVI, GOLD and ICON O/N_2 products. The team also collaborated on multiple Emerging Science Topics, including assessment of the thermospheric density enhancement that led to the loss of the Starlink satellites, the thermospheric response to the Tonga volcanic eruption, and techniques to detect larger-scale gravity waves in the thermosphere using TIMED/GUVI data. Intercomparisons between winds measured by TIMED/TIDI and ICON/MIGHTI demonstrate promise in improving TIDI wind products, helping to resolve systematic errors induced by telescopes' misalignment and light leaks. The scientific production by the team members continues to be impressive (17 publications from the team, 377 external), considering the small budget allocated (see Figure 14).

Minor Strengths

Although the more broadly defined previous SOs were not addressed in full, the investigations revealed new insights into the storm-time thermospheric response and the middle atmospheric trends via data/modeling studies. The effort lays the groundwork for future comparisons with GOLD and (heritage) ICON data in order to better quantify the complex competition between drivers.

Major Weaknesses

None noted.

Minor Weaknesses

The previous SO related to longitudinal and hemispheric asymmetry of the storm-time response was only partially addressed. The proposal did not clearly indicate the contributions of the TIMED team.

- **Factor A-2:**

Performance of addressing any findings in the previous Senior Review. (The 2023 Senior Review panel will have access to the previous Senior Review report for a mission, and other information from that review as needed.) This factor will only be assessed for missions returning to the Senior Review.

Major Strengths

The proposal addressed many findings from the previous Senior Review. All mission data to date has been archived in SPDF. The Senior Review 2020 panel also noted the significance of coincident observations with GOLD and ICON; the TIMED team met those expectations with its efforts to understand cross-calibration issues between GUVI, ICON, and GOLD O/N_2 measurements.

Minor Strengths

The continued TIDI operations and comparisons to ICON/MIGHTI measurements demonstrate the viability of the TIDI instrument, in direct response to comments concerning the potential loss of TIDI data if those operational funds were redirected to support science investigations.

In response to comments concerning the ability to close the broad science questions, the proposal provides adequate information about the importance of the achieved results and their role in improving our understanding of the complex physical processes that determine the properties of the ITM. Given the limited funding, the choice to focus on data/modeling comparisons for closure (e.g., WACCM-X, GITM) was appropriate.

Major Weaknesses

The proposal did not specifically address the finding of the previous Senior Review concerning the broad nature of the Science Objectives and the likelihood of closure. Although the proposal described a substantial number of relevant investigations, the proposal did not clearly describe how those results close the previous SOs.

Minor Weaknesses

The PDMP was not completed, apparently due to a lack of funding in FY22 and FY23 dedicated to that task. The CMAD was also not completed for similar reasons. The previous panel noted that some TIMED data processing uses proprietary commercial code packages (e.g., AURIC). The

TIMED team has stated that the CMAD will not include these codes, but it is unclear how this issue will be resolved.

Criterion B: Overall Evaluation of the Proposed Investigation (Science Investigation only)

- **Factor B-1:**
  Scientific merit and impact of the proposed in-guide science investigation.

Major Strengths

The team's results from the previous Science Objectives and Emerging Science Topics provide excellent motivation for the proposed science investigation. Timely and compelling Science Objectives include "Fill knowledge gaps in the storm-time dynamics of thermospheric composition" and "Understand how the MLT is affected by short-lived and localized episodic disturbance events."

The TIMED mission will provide synergistic science observations with GOLD to study storm-time temporal and spatial changes in the O/N_2 that can only be disambiguated using these data. The proposed study of transient events such as volcanic eruptions, rocket launches, and solar eclipses on the ITM is novel and timely, as the next solar eclipse will see current instrumentation favorably positioned to study the effects of decreased solar irradiance on Earth's atmosphere and SpaceX and Artemis launches are scheduled in the next three years. The proposal also describes a detailed investigation using both SEE and SABER observations to quantify the relationship of the EUV inputs and thermal response of the I-T, including an assessment of the relevance of F10.7 as a proxy for solar inputs.

Minor Strengths

Proposed Science Objectives flow from, but do not replicate, previous Science Objectives. Team efforts with respect to Emerging Science Topics have motivated the transient event study. Much of the groundwork necessary for inter-instrument comparisons has already been laid during the previous mission extension.

Major Weaknesses

None noted.

Minor Weaknesses

The Science Objective to "Assess long term change in the MLT associated with increasing CO2 and varying solar activity" does not reference the extensive body of literature that is associated with this topic. This lack of connection makes it difficult to assess the impact of the proposed effort on the current state of knowledge.

Closure of the proposed Science Objective related to future episodic events including the upcoming solar eclipses would have been enhanced with ICON/MIGHTI winds. This loss of data may be mitigated somewhat by the use of TIDI winds, but the effort to improve and re-validate TIDI thermospheric winds is only included as an over-guide Science Objective. While the TIMED team could not have anticipated the loss of ICON data, the failure to prioritize TIDI wind improvements as part of the primary investigation is a weakness.

- **Factor B-2:**
Implementation merit of the proposed in-guide science investigation.

Major Strengths

The in-guide mission science objectives are clearly articulated and aligned with appropriate and feasible investigation methodologies and tasks. This approach provides high confidence that the proposed investigation will accomplish the tasks and successfully address the proposed science objectives.

Minor Strengths

The modeling effort is appropriate and builds on previous experience with SD-WACCM-X. The TIMED team is also involved in an NSF joint investigations program to model the I-T response to the 2023 and 2024 eclipses.

Major Weaknesses

None noted.

Minor Weaknesses

The rocket launch impacts aspect of the Science Objective is primarily observational. It is not clear how the TIMED data are to be used in the investigation of I-T effects due to SpaceX and Artemis launches.

- **Factor B-3:**
Relevance of the proposed science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.

Major Strengths

The SOs are well-motivated by Goals 2 and 4 of the 2013 Heliophysics Decadal Strategy (HDS) report and by compelling science that can be addressed using complementary data from the GOLD mission, from the heritage ICON mission, and from other ongoing and to-be-deployed HSO assets. SO#1 is directly relevant to Heliophysics Decadal Survey Challenge AIMI-4: (Determine and identify the causes for long-term [multi-decadal] changes in the AIM system). SO#2 is directly relevant to Heliophysics Decadal Survey Challenge AIMI-1 (Understand how the IT system responds to, and regulates, magnetospheric forcing over global, regional, and local scales). SO#3 is directly relevant to 2013 Heliophysics Decadal Survey Challenge AIMI-3.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-4:**
Cost reasonableness of the proposed science investigation.

Major Strengths

None Noted.

Minor Strengths

None noted.

Major Weaknesses

The proposal does not clearly demonstrate that completing the investigation is feasible with the in-guide budget. The listed goals are ambitious considering the small budget, especially with the large amount of data to be analyzed. The over-guide request compensates for overall cuts starting in FY26; however, the proposal does not clearly describe whether a non-restoration of the cut funds would impact the in-guide investigation. The proposal also did not discuss how the lack of the TIDI over-guide funding would impact the in-guide science objectives.

Minor Weaknesses

While the 20-year-old instruments are still producing good data and the team has prepared for many operating contingencies, any deviation from the current operating status may be difficult to accommodate at current funding levels.

TIDI wind improvement is an over-guide item. It is not clear how the absence of TIDI data may impact the in-guide science objectives if the over-guide is not funded.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**

  Quality of the archival mission science data products and associated documentation.

Major Strengths

All TIMED data are publicly available from NASA's Space Physics Data Facility (SPDF) and CDAWeb archive. The instrument teams maintain documentation, tools for quick-look and analysis, and data products at the institutional websites.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The PDMP and CMAP documents on SPDF have not been updated. These documents date back to 2020. The Project Data Management Plan (PDMP) and Calibration and Measurement Algorithm Documents (CMAD) completion are dependent on additional funding. These documents were not completed in the last funding cycle due to the over-guide funding not being provided in FY22 and FY23.

- **Factor C-2:**

  Synergy with and benefit to the Heliophysics System Observatory. This factor applies only to the planned observations and not any previous scientific return or proposed mission-funded science investigation.

Major Strengths

TIMED provides unique measurements to the study of I-T structures and internal coupling processes that affect the I-T system. The TIMED measurements will also complement future missions such as GLIDE, AWE, and EZIE. TIMED will continue as the sole provider of calibrated solar irradiance measurements over the Far-UltraViolet (FUV) range (115-200 nm) during the ramp-up to the maximum of Solar Cycle25.TIMED will be the only ITM mission providing polar observations prior to the anticipated launches of the GDC and DYNAMIC missions. The data acquired by SABER will be fundamental to understand and characterize the long-term effects of increasing CO_2 levels in the atmosphere. TIMED will be the principal source of the data on H_2O and H in the mesosphere that are relevant to the GLIDE mission.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion D: Technical Implementation

- **Factor D-1:**

Health of the mission and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory. For this factor, the mission includes the spacecraft, instruments, and project-managed ground systems.

Major Strengths

The spacecraft and instruments are healthy, and there are no life-limiting concerns related to extending the TIMED mission for five more years. Three minor anomalies are presented: i) one string of solar cells has failed, ii) a reaction wheel has failed, and iii) there is subsequent slow degradation of the laser intensity in the Inertial Reference Units (IRUs). All anomalies have operational, characterization/calibration, and software mitigation strategies that are implemented in order to maintain full science operations capability.

Minor Strengths

Data quality is constantly monitored, and intercomparison with data from other instruments is crucial and shows high stability overall over time. In particular, SEE relies on rocket launches for calibration.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-2:**

Cost reasonableness of the mission's operations model. This factor includes the ability to continue healthy operations within the in-guide budget.

Major Strengths

None noted.

Minor Strengths

The proposed mission's operations model is appropriate and feasible based on the significant experience and expertise in operating the TIMED spacecraft, instruments, and ground stations.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-3:**
  Sufficiency of the management plan and, if applicable, necessity for the succession plan.

Major Strengths

The TIMED management structure, key personnel, and roles are clearly defined and well-established. The proposed effort describes plans to gradually release some leadership duties to early-career scientists and engineers throughout the project. This approach includes the APL Project Scientist position, adding a Deputy PI and two Co-PIs to the SABER instrument team.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion E: Inclusion, Diversity, Equity, and Accessibility

- **Factor E-1:**

Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan. This factor applies to the mission's ideal state of IDEA including mission activities, mission team structure, movement of individuals in/out of and within the mission team, and succession planning. This factor includes any tailoring of institutional IDEA strategies to the mission team's plan.

Major Strengths

The TIMED IDEA Plan demonstrates a genuine effort to create an environment that is conducive to growth, development, and innovation. The TIMED team shows a significant commitment to mentorship of the next generation of diverse scientists through continued participation in "internship programs that specifically target student[s] with disadvantaged backgrounds and underrepresented minorities (URM) communities." The TIMED team has a code of conduct that applies "[w]hen members join the mission team in any capacity," including a clear process for investigating and managing concerns.

Minor Strengths

Succession planning and utilization of institutional IDEA practices are incorporated into the IDEA Plan and citizen science programs. The TIMED mission has implemented clear succession plans for the mission overall and for the instrument team. These succession plans involve transition periods and the direct mentorship of the new leaders. The TIMED team's involvement with multiple citizen science programs shows a commitment to science outreach to a broad community.

The proposal leverages APL undergraduate internship programs that specifically target students with disadvantaged backgrounds and UnderRepresented Minorities (URM) communities in order to integrate diversity and inclusion within the overall TIMED efforts.

Major Weaknesses

None noted.

Minor Weaknesses

There is no discussion of how new team members will be recruited or selected in a manner that promotes and increases diversity.

- **Factor E-2:**
Recent progress against the mission team's IDEA Plan. This factor assesses the mission's recent actions that have addressed and made progress against the mission IDEA strategy. This factor applies only to those missions that have developed an IDEA strategy before this Senior Review.

Major Strengths

Minor Strengths

TIMED has demonstrated an effective benefit to graduate students and early-career scientists. 84 graduate students, 21 masters students, and 63 PhD students have benefited from the TIMED program worldwide. This record provides confidence that the team will continue to engage with next-generation scientists.

The TIMED team has recently increased diversity along some dimensions in a key position and in team membership. IDEA goals are supported by addition of a mid-career female scientist as a Deputy Project Scientist and addition of a part-time, early-career female scientist to one of the instrument teams.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor E-3:**
Planned progress against the mission IDEA Plan. This factor assesses the mission team's plan to advance toward its ideal state of IDEA by the next Senior Review. This includes planned metrics and milestones, the ability for upcoming actions to meet those metrics/milestones, and the ability to enable further progress after the next Senior Review.

Major Strengths

The proposal presents a detailed, multi-pronged IDEA Plan for the TIMED mission that addresses multiple IDEA goals. The proposal presented five new objectives related to IDEA in this extended mission proposal: Succession, Mentoring, Public Engagement, Citizen Science, and Codes of Conduct. There are plans to utilize existing institutional programs to hire four URM each year starting winter of 2024. There are plans to recruit an underrepresented graduate student for one of the instrument teams. Timelines and deliverables were included in the plan.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

Some of the proposal's description of timelines and deliverables is vague. For example, the proposal specifies "scientific sessions and peer-to-peer networking opportunities at CEDAR workshop and AGU Fall meeting," but the proposal does not provide details such as the number, type, and topics of sessions.

- **Factor E-4:**
Cost reasonableness of the mission team's IDEA activities.

Major Strengths

None noted.

Minor Strengths

The funds requested to support the TIMED IDEA Plan are reasonable. The leveraging of external funding (e.g., NSF funding of REU programs) provides for efficiency and enhanced return in the implementation of mentorship programs and IDEA initiatives more broadly. Although the request for over-budget funding to support IDEA initiatives is significant, the expansion of TIMED undergraduate internships could enhance the team's diversity. The team has a clear recruitment plan through the APL CIRCUIT program, which supports the current budget request.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion F: Under-guide and Over-guide Requests (Informational Only)

- **Factor F-1:**
Scientific merit and impact of any proposed over-guide science investigation.

Major Strengths

The focus of the efforts related to over-guide mission SEO request #2 is on enhancing collaboration and preparation for current and future missions including GOLD, SDO, and GLIDE. The SEO related to Flare Irradiance Spectral Model (FISM) is well-defined, relevant (SDO), and includes a graduate student as part of the IDEA objectives.

SEOs include early-career scientists and some transition planning.

Minor Strengths

The GUVI-derived H trends from over-guide SEO #3 have synergy with the upcoming GLIDE measurements. GUVI measures H below ~600 km, while GLIDE will measure H above ~600 km.

Major Weaknesses

None noted.

Minor Weaknesses

Two of the proposed projects (improvement of FISM and improvement of TIDI wind measurements) are more "data enhancement" than science related.

- **Factor F-2:**
Implementation merit of any proposed over-guide science investigation.

Major Strengths

None noted.

Minor Strengths

The implementation tasks for the science enhancement over-guide activities are outlined and are appropriate.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor F-3:**
Scientific merit and impact of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-4:**
Implementation merit of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-5:**
Merit and impact of any proposed over-guide for mission operations.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The proposal did not clearly explain why over-guide support was necessary for the required task of completing/updating the CMADs. The requested 0.8 FTE per year per instrument (as requested in the budget narrative) is significant, and it is not clear that the budget narrative is consistent with the budget table.

- **Factor F-6:**
  Merit and impact of any proposed over-guide for the mission team's IDEA Plan.

Major Strengths

None noted.

Minor Strengths

The over-guide request is consistent with the proposed IDEA Plan's intention to a student for the improvement of FISM.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Voyager

Mission Synopsis

The twin Voyager space probes were launched in 1977, making the pair the longest-operating space mission of all time. After completing encounters with the giant planets of the solar system, the program was refocused as the Voyager Interstellar Mission (VIM) with a primary objective to study the plasma and energetic particle environment of the distant solar wind, heliosheath, and the Local InterStellar Medium (LISM). Voyager trajectories took the spacecraft past the solar wind termination shock and eventually past the heliopause (i.e., the magnetic boundary of the solar system). This occurred in 2012 for Voyager 1 and 2018 for Voyager 2. The VIM has produced a multitude of discoveries that greatly advance our understanding of the outer heliosphere and the Sun's interstellar environment. The Voyagers are the only man-made platforms outside the heliosphere. Given the large cost and long transit times of proposed future missions, the Voyagers will remain humanity's only source of in-situ information about interstellar space for decades to come. Each space probe currently operates five instruments. The Cosmic Ray Subsystem (CRS) measures high-energy ions and electrons including galactic and anomalous cosmic rays. The Low Energy Charged Particle (LECP) detector detects lower-energy ions mainly of heliospheric origin. The Fluxgate MAGnetometer (MAG) measures magnetic field. The PLasma Science Instrument (PLS; only operational on Voyager 2) measures thermal plasma. The Plasma Wave Subsystem (PWS) detects high-frequency radio and plasma waves. Forced by the decline in power outputs from the Radioisotope Thermoelectric Generators (RTGs), the mission plans to gradually switch off instruments and the respective heaters in order to ensure that at least one instrument on each spacecraft is operational. The spacecraft has sufficient power to operate all instruments until the late 2020s. Through creative engineering, the team has managed to extend the lifetime through the mid-2030s when the instruments will be turned off serially.

The Voyager mission has delivered outstanding science since the last Senior Review. Voyager 1 and Voyager 2 are continuing their exploration of the space around the heliopause. Voyager 1 is currently at 158 AU (36 AU into the VLISM), exploring the VLISM since 2012. The Voyagers are a source of unique data and are an irreplaceable part of the HSO fleet.

While the mission provided an in-guide budget, two additional important areas are succession and archiving. The implementation of a succession plan will need extra funds. This need is particularly critical for Voyager since the infusion of additional personnel and early-career hires will transfer knowledge from the scientists or technicians who may retire in the next few years.

The Senior Review panel recommends additional funding for different instruments as well as data recalibration due to heater turn-off for CRS and LECP. In particular:

- Early-career funding for CRS, PWS, PLS, and LECP science and data processing
- Funding for technical subsystem experts to evaluate, design, and implement novel operating

modes
- Funding to complete the support of AACS anomaly investigation

DSN asset use is increasing and Voyager's tracking requirements are frequently in jeopardy of being reduced. The 70-meter antenna is a single-point failure for both Voyager spacecraft.

- As of November 2022, due to the increasing spacecraft range, DSS-43 (70 m) in Canberra is now required for uplink to both Voyager 1 and Voyager 2. DSS-43 is the only 70-m antenna with a 100 kw S-Band transmitter. The other 70-m antennas have 20 kw transmitters. DSS-43 is therefore a potential single-point failure for both Voyager spacecraft.

The Senior Review panel recommends that Voyager DSN needs upgrade support for the S-band in order to remediate the 70-m antenna as the potential single-point failure.

The current mission science objectives are aimed at closing the understanding gaps on the following:

1) Determine the characteristics of the energetic particles, solar wind plasma, and magnetic fields in the VLISM and identify physical processes that produce these characteristics.
2) Determine the density, speed, temperature, and variations of the ionized component of the VLISM.
3) Determine the effects of solar-induced disturbances on the VLISM and how these vary with the solar cycle.
4) Investigate why the magnetic field did not change directions at the heliopause crossing, and what the implications are for the global structure and draping of the VLISM magnetic field.

Overall Assessment

The Voyager mission has delivered outstanding science since the last Senior Review. Voyager 1 and Voyager 2 are continuing their exploration of the space around the heliopause. Voyager 1 is currently at 158 AU (36 AU into the VLISM), exploring the VLISM since 2012 (nearly a complete solar cycle). Voyager 2 is at 132 AU, 13 AU beyond its heliopause crossing. Voyager 1 and Voyager 2 explore different regions of the VLISM, and therefore both are valuable.

Several new discoveries were made. These discoveries include detection of thermal emission lines at the plasma frequency that provides a continuous profile of the VLISM plasma density at Voyager 1, quasi-periodic oscillations in GCRs, and large pressure fronts in the VLISM. The reasons for these phenomena are not yet fully understood.

Exciting puzzles arise from new measurements and the revisiting of old data. The plasma flow speeds based on Compton-Getting on CRS agree with LECP but disagree with PLS speeds. The direction of the magnetic field at Voyager 1 is rotating away from the direction predicted by IBEX.

Focused Findings

The mission spacecraft are in good health considering their age, and major efforts were undertaken to extend their lifetime. The Voyagers can provide invaluable data with in-guide funding. The panel strongly recommends additional funding to implement succession personnel for different instruments as well as data recalibration due to heater turn-off for CRS and LECP. In particular:

- Early-career funding for CRS, PWS, PLS, and LECP science and data processing
- Funding for technical subsystem experts to evaluate, design, and implement novel operating modes
- Funding to complete the support of AACS anomaly investigation

The mission team provided specific plans to train early-career scientists and transfer knowledge from other scientists or technicians who may retire in the next few years. Plans are also included for training new individuals on the processing, calibration, and archiving of instrument data. The team also provided specific plans for Technical Subsystem Expertise and AACS Anomaly Support.

Voyager observations throughout the heliosphere and out of the heliosphere will be unique, at least for the next five decades. If sufficient efforts and investments to recover these data are not made now, there is a danger that the information might be lost or might become unusable. Continued interest and understanding of the unique series will require financial and intellectual investments in succession planning and education of the younger generation for future leadership positions.

DSN support is critical. Each Voyager spacecraft requires 10 hours of tracking coverage per day, either on a 70-m antenna or an array of 34-m antennas. This use averages 10.1 hours/day for Voyager 1 and 8.5 hours/day for Voyager 2. However, competition for DSN assets is increasing, and Voyager's tracking requirements are frequently in jeopardy of being reduced. The 70-meter antenna is a single-point failure for both Voyager spacecraft.

- Due to the increasing spacecraft range as of November 2022, DSS-43 (70 m) in Canberra is now required for uplink to both Voyager 1 and Voyager 2. DSS-43 is the only 70-m antenna with a 100 kw S-Band transmitter. The other 70-m antennas have 20 kw transmitters. DSS-43 is therefore a potential single-point failure for both Voyager spacecraft .
- The Project is investigating options with the DSN for implementing the capability for high-power S-band transmission in the northern hemisphere. However, no funding currently exists for this upgrade.
- The Project and DSN are also investigating options for PWS high-rate playback past 2026 when the five-antenna array is no longer sufficient to return the data.

The Senior Review panel recommends that Voyager DSN needs upgrade support for the S-band in order to remediate the 70-m antenna as the potential single-point failure.

Criterion A: Scientific Success in Previous Mission Investigation

- **Factor A-1:**

Success of previous science investigation. (Achievements of Science Objectives in the previous extended mission period for missions returning to their second or later Senior Review; or achievements of prime mission Science Objectives for mission teams proposing for their first extended mission. Missions transitioning to management under the Heliophysics Division from another organization will be assessed only on their Division-relevant investigation objectives.)

Major Strengths

The Voyager mission has delivered outstanding science since the last Senior Review. Voyager 1 and Voyager 2 are continuing their exploration of the space around the heliopause. Voyager 1 is currently at 158 AU (36 AU into the VLISM). Voyager 1 has been exploring the VLISM since 2012, which is still highly influenced by the heliosphere. Voyager 1 has been exploring the VLISM for nearly a solar cycle. Voyager 2 is at 132 AU, 13 AU beyond its heliopause crossing. The Voyagers continue to take unprecedented discovery data in the VLISM in the form of energetic particles, plasma, and magnetic fields.

The proposal clearly shows how all of the Science Objectives from the previous Senior Review have been addressed. Furthermore, three major discoveries were made: 1) the detection of thermal emission lines at the plasma frequency that provides a continuous profile of the VLSIM plasma density, 2) quasi-periodic oscillations were discovered in GCR ions and electrons, and 3) a large pressure front was encountered by Voyager 1. Many of the Science Objectives consisted of gathering new data. Namely:

- Continuing to gather information about energetic particles, plasma, and magnetic fields up to 158 AU (Voyager 1) and 132 AU (Voyager 2)
- Determining GCR rare elements, isotopes, and electrons of a broader energy range for an additional three years
- Providing in-situ observations in support of the HSO
- Obtaining measurements of the magnetic field in the VLISM

Other objectives were focused on analyzing data and comparing the data with models, such as:

- Determine the effects of solar disturbances on the VLISM and how these vary with the solar cycle
- Investigating why the magnetic field did not change at the HP crossing, as expected from IBEX measurements
- Determine the effect of transient shocks on GCRs
- Investigate the origin of a region of depressed plasma density

Many of these discoveries challenge current models.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor A-2:**
  Performance of addressing any findings in the previous Senior Review. (The 2023 Senior Review panel will have access to the previous Senior Review report for a mission, and other information from that review as needed.) This factor will only be assessed for missions returning to the Senior Review.

Major Strengths

The team addressed the finding to focus on their science objectives. The previous Senior Review outlined how Science Objectives were more a list of items than scientifically driven objectives. The proposal does a reasonable job in linking the proposed tasks (still presented as a list of items) to the scientific content and specific problems. However, in many cases there is not a clear connection between the tasks and the scientific objectives.

Minor Strengths

The mission partially addressed the 2020 Senior Review findings on succession planning. The mission has a new Project Scientist (Linda Spilker) after Ed Stone had to suddenly step down. The team also brought in Jamie Rankin as Deputy Project Scientist. The team also took steps to name Alan Cummings as PI for the CRS instrument with Jamie Rankin as Deputy PI. The team is taking firm steps to bring in early-career scientists, but some of this effort will need additional funding.

Major Weaknesses

None noted.

Minor Weaknesses

The Voyager mission made an effort to make the most recent data available (e.g., MAG data), but data archiving is still incomplete (e.g., the Voyager 1 LECP electron data). The team is making an effort to transition to SPDF. However, not all data are available in the SPDF archive and the

PDMP documentation does not include a consistent level of information for each instrument.

Criterion B: Overall Evaluation of the Proposed Investigation (Science Investigation only)

- **Factor B-1:**
  Scientific merit and impact of the proposed in-guide science investigation.

Major Strengths

The proposed science goals constitute an outstanding investigation that would significantly advance the field. These goals aim to continue to characterize and understand the VLSIM, which continues to challenge our understanding. Continued observations in the VLSIM will lead to better understanding of transient events such as shocks and pressure fronts and processes that shape the global heliosphere.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-2:**
  Implementation merit of the proposed in-guide science investigation.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The heating instruments have been gradually turned off, which means the instruments are operating in very different conditions. This is a risk, although the team is dedicating great effort to maintaining the data quality.

- **Factor B-3:**

Relevance of the proposed science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.

Major Strengths

The science goals of the team are closely aligned with the 2013 Heliophysics `Decadal Survey. The proposed investigation addresses the following Decadal Survey goals: "Determine the interaction of the Sun with the solar system and the interstellar medium." "Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe."

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor B-4:**

Cost reasonableness of the proposed science investigation.

Major Strengths

The proposed in-guide budget will permit achieving the essential data collection objectives. However, as the mission moves forward, retaining this workforce will consume an increasing part of the available funding.

Minor Strengths

None noted.

Major Weaknesses

The in-guide budget, as stated by the proposal, is inadequate to maintain research and plan for the future science team membership. The proposal clearly states that the in-guide budget does not support full scientific utilization, implementation of a program management succession plan, and implementation of the management succession plan for PLS and CRS instruments. As the operations costs increase in future years, even less funds will be available for project-funded research.

Minor Weaknesses

None noted.

Criterion C: Contribution to the Heliophysics System Observatory

- **Factor C-1:**

Quality of the archival mission science data products and associated documentation.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

Voyager data archiving is not consistent with the Senior Review requirements and is not complete. The mission team has been making a major effort to digitize the data, but it is not yet complete. The team is making an effort to transition to SPDF; however, low-level data are not generally available in the SPDF archive and the PDMP documentation does not include a consistent level of information for each instrument. Voyager 1 LECP electron data is not currently available and the plan to post to the APL website (before transition to SPDF) will not include all of the electron channels. The JPL Voyager data access page links to a number of different pages that do not include adequate explanations or provide information in an easily accessible format.

Minor Weaknesses

The CMAD is still in draft form and the Voyager team is awaiting additional input from the science community.

- **Factor C-2:**

Synergy with and benefit to the Heliophysics System Observatory. This factor applies only to the planned observations and not any previous scientific return or proposed mission-funded science investigation.

Major Strengths

The Voyagers provide unique measurements of the VLISM. These measurements provide the boundary for measurements and models of the whole heliosphere. Voyager observations are complementary and fundamental to understanding IBEX observations, Cassini observations, and future IMAP observations. Further, the Voyager data are key inputs used in community-led research activities, such as Heliophysics Division’s DRIVE Science Center studying the outer heliosphere, Solar wind with Hydrogen Ion charge Exchange and Large-Scale Dynamics (SHIELD).

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

Criterion D: Technical Implementation

- **Factor D-1:**

Health of the mission and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory. For this factor, the mission includes the spacecraft, instruments, and project-managed ground systems.

Major Strengths

The team uses a very creative approach to manage power and extend the life of the mission while maintaining the science return. On Voyager 2, the spacecraft transitioned from power management to "Voltage Management" (VM) on March 31, 2023. The voltage regulator is bypassed in this state, which allows the spacecraft access to draw more power from the RTGs. This can be viewed as using "safety net" power. The VM mode of operations should delay the next instrument turn-off by at least two years, allowing additional science from all instruments.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The proposal's statement on powering of the instrument means that some measurements could be lost towards the end of this Senior Review cycle. The Voyager team states that all instruments should be able to remain powered until the late 2020s, with the magnetometer and plasma wave instruments possibly being powered longer. A planned mitigation for the power situation is to turn the instruments off serially in order to extend the spacecraft lifetime beyond 2030.

- **Factor D-2:**

Cost reasonableness of the mission's operations model. This factor includes the ability to continue healthy operations within the in-guide budget.

Major Strengths

None noted.

Minor Strengths

The operations model is feasible and adequate within the in-guide budget. While there are over-guide requests for operations, they are enhancing rather than necessary.

Major Weaknesses

None noted.

Minor Weaknesses

None noted.

- **Factor D-3:**

Sufficiency of the management plan and, if applicable, necessity for the succession plan.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

The succession plan with in-guide support lacks specificity in some instruments. The initial in-guide budget was stated to support succession planning for CRS, LECP, and PWS. However, the budget did not state how the succession training would be accomplished. In response to questions provided during the Senior Review process, the mission provided an over-guide budget.

Minor Weaknesses

None noted.

Criterion E: Inclusion, Diversity, Equity, and Accessibility

- **Factor E-1:**

Mission Inclusion, Diversity, Equity, and Accessibility (IDEA) Plan. This factor applies to the mission's ideal state of IDEA including mission activities, mission team structure, movement of individuals in/out of and within the mission team, and succession planning. This factor includes any tailoring of institutional IDEA strategies to the mission team's plan.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

The proposed IDEA Plan's heavy reliance on the JPL Office Of Inclusion (OOI) presents a serious concern for a mission as decentralized as Voyager. It is unclear whether employees at institutions other than JPL have access to OOI resources, or whether OOI programs will be implemented at those other institutions. The proposal does not adequately describe how a potential conflict (e.g., a case of harassment) involving team members from multiple institutions would be addressed.

Minor Weaknesses

The proposal does not adequately address the current relationship between Voyager and JPL with respect to IDEA. The proposal does not adequately describe how often Voyager personnel work with the OOI, and who within the mission interacts with OOI.

- **Factor E-2:**

Recent progress against the mission team's IDEA Plan. This factor assesses the mission's recent actions that have addressed and made progress against the mission IDEA strategy. This factor applies only to those missions that have developed an IDEA strategy before this Senior Review.

Major Strengths

None noted.

Minor Strengths

The Voyager mission proposal describes reasonable succession planning that would diversify its science and engineering teams along multiple dimensions.

Major Weaknesses

None noted.

Minor Weaknesses

While Voyager's partnership with the SHIELD DRIVE team would provide access to outreach efforts, the proposal does not provide any specific details on Voyager team members' participation in those efforts.

- **Factor E-3:**
Planned progress against the mission IDEA Plan. This factor assesses the mission team's plan to advance toward its ideal state of IDEA by the next Senior Review. This includes planned metrics and milestones, the ability for upcoming actions to meet those metrics/milestones, and the ability to enable further progress after the next Senior Review.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

The proposal's IDEA Plan does not identify specifics objectives for these efforts, clearly trace the chain of responsibility in implementing actions to complete those objectives, or detail the metrics referenced to track IDEA activities. Although aspirational goals are stated (e.g., "creat[ing] an inclusive environment where different perspectives are valued"), the proposal does not specify either the performance targets or the specific actions that would be taken to achieve these goals. While some tasks are discussed, they are not accompanied by specific team members (by name or by role) tasked to lead or manage them. For specific tasks, such as the reference to the collection and tracking of IDEA metrics, the Plan does not demonstrate that those metrics would be sufficient in scope or in target for their stated purpose. The proposal inadequately details challenging metrics (e.g., assessing whether "team members [are] feeling respected and heard"), the format or frequency of project team measurements, and how the JPL annual employee survey would be used to "evaluate the effectiveness of IDEA efforts" with regards to non-JPL employees.

Minor Weaknesses

None noted.

- **Factor E-4:**
  Cost reasonableness of the mission team's IDEA activities.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

The proposal does not budget for specific IDEA activities and does describe specific IDEA activities in sufficient detail to drive cost requirements.

Criterion F: Under-guide and Over-guide Requests (Informational Only)

- **Factor F-1:**

Scientific merit and impact of any proposed over-guide science investigation.

No over-guide science was proposed.

- **Factor F-2:**

Implementation merit of any proposed over-guide science investigation.

No over-guide science was proposed.

- **Factor F-3:**

Scientific merit and impact of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-4:**

Implementation merit of any proposed under-guide science investigation.

No under-guide science was proposed.

- **Factor F-5:**

Merit and impact of any proposed over-guide for mission operations.

Major Strengths

None noted.

Minor Strengths

None noted.

Major Weaknesses

None noted.

Minor Weaknesses

There was no specific request for an over-guide, and the presentation's list of potential additional funded items did not provide adequate details of the work that would be conducted or the impact it would have on the mission operations.

- **Factor F-6:**

Merit and impact of any proposed over-guide for the mission team's IDEA Plan.

No over-guide for IDEA was proposed.