The 2015 Senior Review of the Heliophysics Operating Missions

June 11, 2015

Submitted to:
Steven Clarke, Director Heliophysics Division, Science Mission Directorate
Jeffrey Hayes, Program Executive for Missions Operations and Data Analysis

Submitted by the 2015 Heliophysics Senior Review panel: Arthur Poland (Chair), Luca Bertello, Paul Evenson, Silvano Fineschi, Maura Hagan, Charles Holmes, Randy Jokipii, Farzad Kamalabadi, KD Leka, Ian Mann, Robert McCoy, Merav Opher, Christopher Owen, Alexei Pevtsov, Markus Rapp, Phil Richards, Rodney Viereck, Nicole Vilmer.

Executive Summary

The 2015 Heliophysics Senior Review panel undertook a review of 15 missions currently in operation in April 2015. The panel found that all the missions continue to produce science that is highly valuable to the scientific community and that they are an excellent investment by the public that funds them.

At the top level, the panel finds:

- NASA's Heliophysics Division has an excellent fleet of spacecraft to study the Sun, heliosphere, geospace, and the interaction between the solar system and interstellar space as a *connected system*. The extended missions collectively contribute to all three of the overarching objectives of the Heliophysics Division.
    - Understand the changing flow of energy and matter throughout the Sun, Heliosphere, and Planetary Environments.
    - Explore the fundamental physical processes of space plasma systems.
    - Define the origins and societal impacts of variability in the Earth/Sun System.

- All the missions reviewed here are needed in order to study this *connected system.*

- Progress in the collection of high quality data and in the application of these data to computer models to better understand the physics has been exceptional.

- The funds invested in the Mission Operation & Data Analysis (MO&DA) budget are providing an excellent return in terms of our better understanding the geospace environment in which our technological society functions.

The review noted a few serious problems within the portfolio.

- For various reasons some of the missions are not being funded at an adequate level (the total MO&DA budget is unfortunately low, such that there is not enough money to do the science proposed).

- For the Voyager mission, there are multiple problems regarding data access and archival storage that need to be addressed. In addition, the performance of the magnetometer team is seriously deficient.

- The SDO mission has financial and management problems that need to be addressed at the NASA HQ level.

Contents

1. Overview

1.1 Introduction

The spacecraft operating under NASA's Heliophysics division and the science being accomplished with the data from these missions are impressive. We now have a fleet of spacecraft that allow us to study the interior of the Sun, its generation of magnetic fields, the measurement of those fields, their evolution (both slow and fast), the generation of solar/heliospheric storms, their evolution through the heliosphere, their interaction with the Earth's magnetosphere and ionosphere, and their interaction with interstellar space. The data produced by these spacecraft are being used extensively in computer models to help us better understand the physics of space.

NASA's Science Mission Directorate (SMD) periodically conducts comparative reviews of Mission Operations and Data Analysis (MO&DA) programs to maximize the scientific return from these programs within finite resources. The acronym MO&DA encompasses operating missions, data analysis from current and past missions, and supporting science data processing and archive centers. NASA uses the findings from these comparative reviews to define an implementation strategy and give programmatic direction and budgetary guidelines to the missions and projects concerned for the next 5 fiscal years (matching the Federal government's budget planning cycle).

Additionally, from the NASA Authorization Act of 2005 (Public Law 109-155), Section 304(a): "The Administrator shall carry out biennial 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 have exceeded their planned mission lifetime."

The 2015 Heliophysics MO&DA review, referred to as the Senior Review, was conducted in March through June of 2015. The Senior Review considered the comparative scientific merit of the various flight programs comprising the Heliophysics System Observatory (HSO) along with the data analysis and archiving programs. The review compared expected scientific returns and contributions to the system observatory relative to program costs under the pressure of reduced resources for the MO&DA program. A set of findings consistent with the most recent SMD Science Plan and 2012 Decadal Strategy for Solar and Space Physics was developed by the Senior Review panel to help prioritize the resources of the MO&DA program for FY16 and FY17 along with forward-looking findings for FY18–20. This report presents the findings of the 2015 Senior Review.

In general the panel was very favorably impressed with the status of the Heliophysics MO&DA program. There is a strong fleet of spacecraft to do coordinated Heliophysics and space weather research. Science accomplished since the last senior review by PI teams and the community is impressive, as is the new science proposed in the mission proposals. There is very good coordination between various missions to develop comprehensive datasets that can guide and be used for modeling.

There are areas of serious concern pointed out in the panel findings. One relates to the data availability from an important mission. The other relates to the general problem of insufficient MO&DA funds and the impact this has primarily (but not solely) on one particular mission.

Despite these problem areas, the panel is very favorably impressed with the management of the Heliophysics spacecraft system and its future direction.

1.2 Missions Considered

The following missions, with their launch dates, in-guide budgets in $K (thousands dollars) for 2016, requested budgets, and their differences considered in this review are shown in the following table:

Spacecraft	launch	FY 2016 in Guide	FY 2016 Request	Delta
ACE	1997	3,000	3000	0
AIM	2007	3036	3036	0
CINDI	2008	600	900	-300
Hinode	2006	7250	7250	0
IBEX	2008	3400	3400	0
IRIS	2013	7715	7295	420
RHESSI	2002	1900	1900	0
SDO	2010	9487	13303	-3,816
Stereo	2006	9500	9500	0
Themis	2007	4600	4904	-304
TIMED	2001	2670	2670	0
TWINS	2008	615	615	0
VanAllen	2012	15521	15521	0
Voyager	1977	5674	5774	-100
Wind	1994	2150	2150	0
Total		77,118	81218	-4,100

It was made clear to the panel that there would be no extra money available and that some of the missions, especially SDO (as can be seen in the above table), are requesting significantly more than allocated. The THEMIS mission had an over-guide request ranging from $0.6–1.4M depending on their science goals.

1.3 The Charge to the Heliophysics Senior Review Panel

The objectives of the 2015 Heliophysics Senior Review for MO&DA were to assess the science merits and performance of the 15 missions invited to participate in the review. These missions are (in alphabetical order): ACE, AIM, CINDI, Hinode, IBEX, IRIS, RHESSI, SDO, STEREO, THEMIS, TIMED, TWINS, Van Allen Probes, Voyager, and Wind.

The performance factors that were to be evaluated included mission scientific productivity, technical status, budget efficiency, data quality and accessibility, and contribution to the *Heliophysics System Observatory* (HSO). The period for this Senior Review covered FY16 to FY20.

Each mission that was invited to this Senior Review submitted a proposal outlining how its science investigations would benefit the Heliophysics research objectives. These objectives and focus areas are described in the Science Plan for NASA's Science Mission Directorate 2014 (the SMD Science Plan). Proposals outlined descriptions of the project's proposed science investigations, in a prioritized manner, the project's most recent accomplishments, the technical status relating to the ability of the project to conduct the proposed science investigations, Mission Archive Plans, and a high-level budget for the proposed investigations.

Project teams were requested to submit plans that had a set of *Prioritized Science Goals* (PSGs) for the next 5 years, thus allowing NASA flexibility in planning within a dynamic budgetary environment (*e.g*., reaction to a 5% budget reduction; planning for a flat budget without inflation, or if there should be a 5% increase). These PSGs will also allow subsequent senior reviews to assess and measure the success of each mission in achieving its stated goals. In addition, proposals were expected to show progress against the PSGs that they proposed in the 2013 Heliophysics Senior Review.

From the proposals submitted by the projects, the panel was charged to make their assessments in four broad areas.

(1) In the context of the research objectives and focus areas described in the SMD Science Plan, rank the scientific merits of the expected returns from the projects reviewed during the period FY16 through FY20. The scientific merits include relevance to the research objectives and focus areas, scientific impact, and promise of future scientific impact, as well as contributing to the system science of heliophysics. It is understood that predicting the science productivity of a mission over such a long period is speculative, but missions are asked to assume the *status quo* operationally; hence, the need for *Prioritized Science Goals* (PSGs) in the proposal.

(2) Assess the cost efficiency, data availability and usability, and the vitality of the mission's science team as secondary evaluation criteria. Assess how the missions did in meeting their PSGs (where applicable).

(3) From the assessments above, provide findings on an implementation strategy for the MO&DA portfolio for FY16 through FY20, based on the Extension Paradigm (described elsewhere), which could be one of the following:

- *Continuation of projects as currently baselined;*
- *Continuation of projects with either enhancements or reductions to the current baseline;*
- *Project termination.*

(4) Provide on overall assessment of the strength and ability of the MO&DA portfolio to meet the expectations of the HSO from FY16 through FY20, as represented in the 2014 SMD Science Plan and in the context of the recent Heliophysics decadal survey.

The panel was *not* asked to evaluate or assess the current utility of real-time data for operational or commercial users. However, the relevance of ongoing or new science investigations that may transition from research to operation in the future was within the purview of the Senior Review and the panel was invited to comment as appropriate.

2. Senior Review Panel Findings

2.1 Overview of Findings

Given the funds available for the missions and the proposed science, there is not enough money in the MO&DA budget to provide the quality of data necessary to accomplish the proposed science. We do not mean in this statement that only the science cannot be accomplished, but also that the quality of the data would be compromised such that the quality of science cannot reach its full potential. However, even within the current budget constraints, good science can be accomplished that will advance the field.

The funding for the less expensive missions is sufficiently small that there is little to be gained from cutting them. Cutting the more expensive missions does serious damage to the data quality. The specifics of this will be discussed more fully below.

2.1.1 Findings on 2015 Senior Review Process

In general the findings process went very well. Before the meeting the panel had weekly telephone meetings to discuss issues of concern, with questions being sent to the proposal teams for response. The proposers were then able to come into the meeting with prepared responses to common issues. Naturally, in some cases new questions were raised during the presentation. Some were answered on the spot, but in other cases the proposal teams were given a few days to provide a formal response.

The most severe impediment to readily evaluating the proposals involves the non-uniform and often obscure way the proposals relate the science proposed to the manpower breakdowns. In the current process there was no breakdown as to what would be done by the team in-guide, what could be done over-guide, or what would be covered in another program. All proposals described great science that could/would be done in the next funding period, but it was not generally clear to the panel how much would be done by the teams themselves, and how much is expected to be done under other funding, through engagement of the national and international communities with the mission data sets or related activities. For future Senior Reviews we would like to see the following categories broken down by instrument on each mission:

- Engineering/technical FTE to operate spacecraft and capture data
- Technical FTE to process data to level 0
- Science FTE to process to level 1
- Technical FTE to process to level 1
- Science FTE to do the basic science that ensures the data are useful and what that science includes
- Science FTE contributing directly to the accomplishment of the overall science return promised within the proposal. In other words we expect to be able to see what proposed

science the mission teams will do themselves within-guide, what they would like to do themselves with an over-guide, and what they expect to be done by proposals to SR&T or other national and international funding opportunities

2.2 Broader Relevance to the Science Mission Directorate

The entire fleet of spacecraft reviewed is an extremely valuable asset to the nation in terms of understanding space weather. When the NASA space weather program was initiated, there was a vision of a fleet of spacecraft dispersed throughout the Sun/space/Earth environment to better our understanding of the physics of space weather. The current fleet comes quite close to fulfilling that vision. What we, the science community, are learning from this fleet is impressive.

While we have not solved all of the problems related to space weather, we are making significant progress. We are learning much about the generation and evolution of magnetic fields below and on the Sun's surface. We are able to observe the initiation of solar storms and measure many of the physical parameters necessary to model them (temperature, density, velocity, magnetic field). We are able to track their evolution through the heliosphere as they travel to the Earth, and measure their physical characteristics as they approach Earth. We can measure their interaction with the magnetosphere and the interaction with the ionosphere. As an unexpected bonus we are seeing a significant feedback between the ionosphere and the Earth's lower atmosphere.

The 2015 Senior Review revealed abundant evidence that the recent discoveries facilitated by NASA Heliophysics (HP) extended mission measurements have scientific value beyond the realm of solar and space physics. The science garnered from the current constellation supports the overarching goals of the SMD and addresses some of the specific goals of the three other component SMD divisions. A few examples of these contributions are highlighted below.

The Voyager and IBEX extended missions epitomize SMD's "great journey of discovery" in their exploration of the structure of the outer heliosphere and its boundary with the interstellar medium. The occurrence of magnetic reconnection inferred from recent Voyager measurements calls into question the entire concept of the heliopause as a well-defined boundary separating the heliosheath and the local interstellar medium. IBEX measurements for the first time revealed that the charged particles in the solar wind are nudged into a new orientation that is aligned with the magnetic field orientation of the local interstellar medium as they move away from the Sun's magnetic influence.

Many HP extended missions provided fundamental insight into the ubiquitous magnetic reconnection process that occurs in magnetized plasmas throughout the universe. Coordinated SDO and Hinode observational analysis revealed, for the first time, the rate at which the emerging solar field is reconnected with the pre-existing fields in a steady, quiescent fashion with resultant coronal heating that is comparable to large M-class flares extending over 45 hours, and thought to be produced by plasma turbulence. THEMIS measurements indicate that reconnection fronts are even more important than the reconnection X-point itself, since they represent the sites where lobe magnetic energy is converted to particle kinetic energy or waves as flux tubes shrink and move away from the reconnection point.

AIM demonstrated that water vapor injections into the upper mesosphere and lower thermosphere (MLT) from space traffic potentially affect polar mesospheric cloud properties and compensate for stronger water vapor photolysis during increased solar activity. Observational evidence from AIM and TIMED signal decreases in MLT composition and temperature during the last decade, indicating possible anthropogenic cooling effects due to rising concentrations of the greenhouse gas CO_2. Insights like these into the sources of natural and human induced changes in the Earth system address a primary science theme of the Earth Science Division.

Galactic cosmic rays (GCR) and high-energy charged particles are two of the hazards in the solar system environment that affect the extension of human presence in space. Identifying and better understanding such hazards is one of the overarching goals of the Planetary Science Division. The HP extended missions provided insight into the origins and variability of GCR and high-energy charged particles. The combination of Voyager and ACE GCR observations allowed researchers to disentangle GCR spatial dependences from solar-cycle variations that propagate to the outer heliosphere, and to affirm that solar cycle modulation of GCRs is sensitive to particle energy. ACE abundances dominated by primary GCR allowed for the derivation of source composition. Evidence points to massive star associations and the superbubbles they produce as the environment where fractionation and acceleration occur.

A complement of HP extended missions diagnosed the origin and evolution of hazardous solar energetic particles and elucidated the complex physics underlying magnetic reconnection, the acceleration of particles to high energies, and their explosive eruptions. SDO surface field measurements and coronal extreme-ultraviolet imaging provided estimates of the amount of energy available for flares and coronal mass ejections (CMEs). These SDO diagnostics combined with chromospheric measurements made by IRIS, STEREO and SoHO coronagraph observations, and RHESSI hard X-ray measurements collectively provided new insight into the energetics associated with the initiation and evolution of solar eruptions. Van Allen Probes made several new discoveries during its just completed prime phase, revealing how populations of high-energy charged particles within Earth's radiation belts respond to solar variations and evolve in space environments.

SDO observations also supported the Planetary Science Division's MAVEN mission in its exploration of the solar impacts on the Martian atmosphere. Measurements from ACE enabled identification of material emitted from comets, as well as providing insight into charge exchange reactions occurring between the solar wind and cometary atmospheres. IBEX made the first measurements of energetic neutral atoms (ENAs) emanating from the moon and revealed that they are solar wind ions that scatter and neutralize through interaction with lunar regolith.

HP extended missions also contributed to further understanding of how the universe works, an overarching goal of the Astrophysics Division. STEREO contributed longitudinal surveys to determine the flow direction and speed of interstellar neutrals by establishing the focusing cones and pickup ion crescent distributions aligned along the inflow direction of the local interstellar medium. SDO made transit observations of Venus in 2012 providing benchmark data to compare with exoplanet transits, including information on the background signals above which exoplanet signals are sought. Wind data provided information on the evolution of interstellar and interplanetary dust on day to solar cycle timescales. Wind measurements of dust impact direction indicate that the interplanetary dust population at 1 AU is primarily isotropic and modulated by an interstellar dust component.

The panel thus sees this entire fleet of spacecraft as being a very significant national asset.

2.3 Findings of Special Concern

The Senior Review has identified a few issues that need to be addressed as very high priority:

2.3.1 Voyager

Voyager is an important and ground breaking mission. As stated in the last Senior Review, "The Voyager spacecraft continue to make groundbreaking discoveries in the outer heliosphere at its interface with interstellar space. The unique nature of the Voyager measurements, from a region that is unlikely to be explored again for many decades, means that it is critical that the data be provided to the scientific community in a timely and useable manner. These data represent a unique scientific legacy for all humanity."

The Panel welcomed efforts by most Voyager instrument teams to distribute data. However, while acknowledging challenges in calibrating the magnetometer data, the Panel is distressed with the slow and patchy distribution of these measurements by the magnetometer team, and the fact that data recorded several years ago are still not available. The Panel is also concerned with plans to distribute only averaged data products; the non-reproducible nature of this type of distributed Voyager magnetometer data means that all measurements must be made available for future analysis, which might use methods not yet imagined.

Given the lack of response to the same finding by previous Senior Reviews, we find that NASA has not done what is necessary to rectify the problem with respect to the magnetometer, including replacing the PI. We point out the following:

- High quality magnetometer data needs to be available for current and future science in a timely manner.
- Due to underperformance of the magnetometer team over many senior reviews we find that replacing the current PI may be the first step to accomplish this goal.
- It has been made known to the Panel that there is a team at NASA/GSFC that is capable and willing to take on this task.
- NASA are needed to achieve the above objectives.

The integrity of all Voyager data also seems to be a problem:

- We find that the data storage, access, and documentation are not to modern standards; the archive data should be safely stored and made easily available to interested scientists. The knowledge to process the data from level zero to usable science data must be well documented.

- We find that NASA leadership is needed to provide the resources and direction to achieve these goals, in a timely fashion, since critical personnel involved may soon retire.

2.3.2 SDO

SDO is gathering, processing and distributing data that enables excellent scientific results. A large scientific research community is using SDO data resulting in a very large number of research papers per year. The problem primarily lies with the request for a significant over-guide budget and stated priorities. Funds for over-guide are not available in the MO&DA budget. The panel finds:

- SDO is a very expensive mission in part because of the need for a dedicated ground station, high data rate, and stringent data loss tolerance to achieve the prime-mission science. Allowing for more data loss may be a reasonable means to achieve some reduction in the over-guide request for the extended mission phase.
- The SDO proposal indicates that one negative consequence of an in-guide budget will be the disruption of data flow to SAO and hence to the VSO and community, causing a delay of data availability to the community. This may not be a serious problem for the research component of SDO. Of note, however, the proposal states that the in-guide budget would mean all near-real-time data would cease.
- Another negative consequence, as stated in the proposal, is that a planned EVE calibration under-flight will not be performed. If a calibration rocket flight is needed, NASA may want to consider completing it under another program.
- An issue of concern is that key personnel are leaving the HMI project and are not being adequately replaced. This is weakening the team's ability to produce high quality data and brings to question the ability to perform key tasks.
- Some of the over-guide budget is requested for the HMI team for scientific research. The panel agrees that team members need to be involved in research as a means by which to identify and correct instrument calibration issues. In the context of the prime and extended-prime phase performance and prioritizations, and the presentation of the prioritized science goals, the panel finds that a significant portion of this research component could be achieved outside the MO&DA budget, i.e., by competing at least some of the science lost by the in-guide budget.
- There is no easy solution to the large over-guide request, and the panel supports some of the justification presented. A possible remedy might be for NASA HQ to negotiate with the SDO team to develop a plan that will ensure that the bulk of the data that this mission is providing continue—without taking funds from other missions.

3. Mission Grades

	Mission Median	Science Std Dev
IBEX	9	1.6
IRIS	9	1.3
Van Allen	9	1.5
AIM	8	1.2
Hinode	8	1.2
RHESSI	8	1.0
STEREO (2)	8	1.2
TIMED	8	1.2
Voyager	8	1.6
ACE	7	1.5
SDO	7	1.5
STEREO (1)	7	1.4
THEMIS	7	1.8
TWINS	7	1.3
Wind	7	1.2
CINDI	7	1.2

	HSO Median	Science Std Dev
ACE	9	1.9
SDO	9	1.5
Hinode	9	1.8
IBEX	8	1.2
IRIS	8	1.2
STEREO (2)	8	1.1
THEMIS	8	1.3
Wind	8	1.3
RHESSI	8	1.6
STEREO (1)	8	1.5
Voyager	7	1.6
AIM	7	1.3
TIMED	7	1.9
TWINS	7	1.3
Van Allen	7	1.4
CINDI	6	1.2

The mission grades are as follows: Grades (scale of 0 to 10, 10 is best)

10–8 Future contributions promise to be compelling

7–4 Excellent, but less compelling

3–0 Future contributions relatively modest

4. Extended Mission Assessment

Missions are listed in alphabetical order.

4.1 ACE

Overview of the Science Plan

For 17 years, ACE has measured key parameters of the solar wind from the first Lagrangian orbit point (L1) which is about 1% of the way toward the sun on the sun-Earth line. The ACE instruments measure the Interplanetary Magnetic Field (IMF) as well as the elemental, isotopic, and ionic charge state composition of the energetic nuclei in interplanetary space from the low energies of the solar wind up to the high energies of the galactic cosmic rays. These data are used to study the origins and acceleration of the particles in interplanetary space.

The ACE related research proposed for the 2016–2020 era focuses on five topic areas: (1) solar wind, (2) solar energetic particles, (3) heliospheric and interstellar medium, (4) space weather, and (5) supporting the heliospheric systems observatory. There are four Prioritized Science Goals (PSGs) proposed for the next phase of the ACE mission. These are: (1) Discover the nature and consequences of the changes in the space environment in this unusual solar cycle; (2) Determine where and how energetic particle populations are accelerated; (3) Determine the spatial variations of particles and field in the inner heliosphere with multi-spacecraft studies; and (4) Develop new space weather warnings using L1 data. These topic areas and PSGs are all consistent with the goals and objectives of NASA science and heliophysics research.

The proposal justifies the request for continued operations in several ways. There is the need to better understand the consequences of the declining phase of the solar cycle and a very low solar minimum (as is anticipated) on the acceleration and transport of solar energetic particles and GCRs in the heliosphere. There is new science that can be accomplished with three solar wind satellites near L1. For ACE there is the additional and compelling justification of providing context and supporting data to nearly all other solar, heliosphere, magnetosphere, and ionosphere/thermosphere missions both current and planned.

ACE Science Strengths

The proposed science goals are important in understanding fundamental processes in heliophysics environment. The research objectives in the ACE extended mission proposal emphasize observations that are specific to the ACE mission capabilities and cannot be accomplished by any of the other satellites at L1. The ACE measurements of the isotopes and energetic particles of the heliosphere will be used to better understand the source regions and acceleration processes of energetic particles. In addition three satellites measuring the solar wind and IMF near L1 provide a unique opportunity to measure angles of CME shock fronts and off-axis propagation which have significant consequences on the strength and arrival time of the shocks at Earth.

Several of the proposed research goals require continuous observations into the next solar minimum. These observations will not only provide critical data on GCRs during solar minimum but also new insight into the 11-year solar cycle. The ACE observations will also provide context for observations from other observing platforms that are either currently in operation or will be launched in the 2016–2019 time frame.

All four of the PSGs have strong societal relevance. Better understanding of SEP events and their temporal and spatial extent can improve the forecasts of such events which are relevant to astronauts, satellite operators and commercial airlines. Similarly, better understanding and estimates of the GCR levels expected during unusually low solar minima will be very relevant to extended space exploration as well as to the long term radiation exposure expected by airline passengers and crew. Understanding the spatial and temporal nature of CMEs can improve our estimates of the impacts of these events on the magnetosphere and the resulting geomagnetic storms. And finally, improving the space weather warnings at L1 will provide direct benefit to specification and forecasting of space weather at Earth.

Ace Relevant Strengths to Heliophysics Research Objectives

All of the research objectives and research topic areas directly support the primary Heliospheric Research Objectives. Better understanding of the sources and acceleration of the solar wind is critical to understanding the fundamental physical processes of the space environment. Exploring the acceleration and propagation of solar energetic particles and galactic cosmic rays also has implications on the safety and productivity of human and robotic exploration of space. And nearly all of the ACE PSGs have direct or indirect implications for improving our ability to specify and forecast space weather. The proposal provides a good balance between ACE-specific research and support for broader research activities beyond the heliosphere. The number of publications that reference or use ACE data but do not have an ACE scientist as a primary author is a strong indication of how the ACE data continue to be important to the broader heliophysics research community.

ACE Value to the Heliophysics System Observatory

ACE observations contribute to nearly every aspect of heliophysics research making these observations some of the most important to the HSO. The observations at L1 are used to validate models of the acceleration and propagation of CMEs and SEPs. They provide key monitoring of the solar wind and the IMF which in turn feed the models of the magnetosphere and the near-Earth space environment. Every other mission within the senior review references ACE data as important or even critical to their mission. And the ACE data will provide the context for all of the upcoming missions from Solar Probe and Solar Orbiter, the MMS mission in the magnetosphere, and down to the ICON and GOLD missions in the ionosphere and thermosphere. ACE data have been used extensively by other non-ACE scientists in research areas that span the entire HSO system. Models of solar wind, CMEs and coronal holes, use ACE data for validation. Models of the magnetosphere and the ionosphere/thermosphere system use ACE solar wind and IMF data as input drivers. The importance of solar wind and IMF data at L1 cannot be over stated.

The importance of L1 solar wind monitors cannot be over emphasized as is evident by the newly launched DSCOVR spacecraft which will provide operational solar wind and IMF data for the NOAA Space Weather Prediction Center and other operational space weather forecast entities around the world. Having three solar wind monitors as L1 (WIND, ACE, and DSCOVR) emphasizes the importance of the observations but de-emphasizes the contribution of any single observation of these key parameters. However, the research objectives that will be addressed by ACE in the coming years are unique to ACE or they take advantage of the multi-spacecraft constellation that now exists at the L1 point. In addition, ACE solar wind and IMF data will be critical for cross-calibration of the DSCOVR solar wind sensors during the first few years of the DSCOVR mission.

ACE Spacecraft / Instrument Health and Status

For the most part, the ACE spacecraft and the ACE sensors continue to perform well and have exceeded expectations for a 17-year-old satellite. Several of the sensors and detectors have either been adjusted or simply turned off to compensate for this degradation. There has been degradation to the sensitivity of SWEPAM (the primary solar wind sensor) however, through modified procedures and periodic spacecraft maneuvers, the impact of this degradation has been minimized. The operation and analysis of SWICS data had to be modified significantly but since the modifications were performed, SWICS has provided excellent solar wind composition information. There are no issues with the ACE satellite or with the sensors that would degrade the value and utility of these data for the research that is proposed.

ACE Data Operations (accessibility, quality control, archiving)

The ACE program is doing an excellent job insuring that the ACE data are readily available to the research and operational communities. ACE data are accessible at various cadences through NASA’s Coordinated Data Analysis Web (CDAWeb), Virtual Observatories, and the ACE Science Center. ACE data are a key data set in the NASA Space Physics Data Facility OMNI data archive. And the real-time data are available through the NOAA Space Weather Prediction Center and the NOAA National Center for Environmental Information (formerly the National Geophysical Data Center). It is possible that when DSCOVR replaces ACE as the primary real-time solar wind monitor at L1, the ACE real-time beacon data would no longer be collected or archived. This will have no impact on the collection, processing, storage, archive, and dissemination of the ACE science data. The number of requests for ACE data is impressive and highlights the importance of these data to the broad community of space environment researchers.

The ACE program has developed an extensive Mission Archive Plan (MAP) with a dedicated web site describing various levels of data processing and where these data are stored and made available. Unfortunately, the section of the MAP that describes that actual archiving of the data and delivery to CDAWeb is not yet complete (as stated on the web page itself) so it is difficult to assess the plan for long-term archive of the full ACE mission data.

Ace Proposal Weaknesses

This proposal has no serious weaknesses. A few of the research objectives do not have strong requirements for continued operations. This research could likely be addressed with data that has already been collected. One suggestion for enhancing the importance of ACE science is to take advantage of the three solar wind monitors orbiting the L1 point. The proposal mentions the prediction of ICME speeds from non-radial shock normal, but does not mention the use of WIND and DSCOVR in this section (an oversight?). There is ongoing research in this area and initial results indicate that this field of study could improve ICME specification and forecasts and provide additional justification for continued real-time ACE observations.

ACE Overall Assessment and Findings

ACE continues to be one of the most important missions in the fleet of satellites collecting data in the heliosphere. Not only does ACE provide context for nearly all of the other HSO missions (both current and planned) but it continues to collect important data for and emerging scientific problems on topics ranging from solar wind and ICMEs to energetic particles and galactic cosmic rays. The combine data from the ACE, WIND, and DSCOVR satellites will provide new and critical information on the three-dimensional structures within shocks and ICMEs. In this new era with three solar wind monitors at the L1 point, the ACE-unique measurements of high energy particles allow ACE to remain a viable and important mission. One of the more compelling data sets will be the observations of cosmic rays during the next minimum of this unusual solar cycle.

The ACE budget is within guidelines and fully reasonable for supporting the operations, mission services, and science data analysis required to maintain the integrity of these critical data sets. The ACE data are highly reliable and readily available. ACE data are some of the most important and widely used data in the HSO and will likely remain so in spite of adding DSCOVR to the fleet of L1 satellites. The ACE data will be very important in providing the context and the drivers for all of the upcoming missions such as Solar Probe, Solar Orbiter, Magnetosphere Multi-Scale, ICON, and GOLD.

ACE and Space Weather Operations

It should be noted that ACE has provided long and reliable service as the real-time solar wind monitor for NOAA space weather operations. With the launch of DSCOVR, the real-time ACE beacon data will be less critical. However, there have been recent requests to keep the ACE real-time data streams available to support other missions. These requests include one from NASA's Associate Administrator for Space Science, Dr. John Grunsfeld, who recently sent a letter to NOAA senior administrator, Kathy Sullivan, requesting that NOAA/SWPC continue to acquire and processes the real-time EPAM data from ACE in support of the Chandra mission. SWPC has replied that their ground network of collection antennas has no redundancy. They can collect continuous real-time data from only one satellite at a time. SWPC has however offered to process and disseminate the data if NASA (or some other entity) were to establish an alternate ground network to collect the real-time data and send it to SWPC for processing.

The ACE extended mission proposal received a 7/10 median Panel score for the Overall Scientific Merit, placing it solidly in the group of "Excellent" proposals. Its median Panel score of 9/10 for contributions to the HSO places it solidly in the Compelling category. The Panel supports the continued operation of the ACE mission.

4.2 AIM

Overview of the Science Plan

AIM was launched in 2007 as the first satellite mission dedicated to studying Polar Mesospheric Clouds (PMCs). These are water-ice clouds that occur in the summertime at high latitudes, in a thin layer between about 80 and 90 km that were first recorded in 1885. There is considerable evidence that they are getting brighter and spreading to lower latitudes (presumably due to anthropogenic temperature and water vapor changes). Thus PMCs are a subject of great interest as sensitive indicators of climate change.

The main achievement during the first 8 years of the mission has been to gain a significantly better understanding of the microphysical processes governing PMCs. Beyond these original aims, the AIM science team has been highly successful in making both breakthrough observations as well as very important contributions with regard to additional objectives. Among the breakthrough observations, there is the first global observation of meteoric smoke particles (MSPs) as well as the discovery that PMC ice particles contain MSPs. MSPs are not only thought to play an important role for the nucleation of PMCs but have long been speculated to be involved in many other so far unexplained phenomena such as the formation of Nitric Acid Trihydrate (NAT)-particles forming polar stratospheric clouds (which are decisively involved in the formation of the ozone hole) or the existence of an unexpected water vapor maximum at 70 km altitude which was first seen in HALOE-observations on UARS. As additional important contributions to understanding the middle atmosphere and its role in the ITM system, AIM has produced compelling evidence for teleconnection patterns connecting middle atmosphere dynamics in different hemispheres as well as within one hemisphere (inter- and intra-hemispheric coupling), and it has been a versatile tool to characterize gravity waves in the summer mesopause region at spatial scales inaccessible to any other current mission. AIM has produced very high quality observations of nitric oxide and its descent from the thermosphere into the stratosphere thereby forming the likely most important coupling mechanism by which solar energy is transferred from the MLT to the lower atmosphere with potentially Strong implications for surface climate.

As a NASA HSO mission, it is the role of the AIM mission (in combination with TIMED as well as ICON and GOLD in the future) to characterize the ionosphere-thermosphere interface between the magnetosphere and the underlying neutral atmosphere and study how the bi-directional coupling in terms of energy and momentum fluxes between these two systems work.

The Solar Occultation for Ice Experiment (SOFIE) uses the technique of satellite solar occultation to measure vertical profiles of limb path atmospheric transmission within 16 spectral bands between 0.29 and 5.32 µm. SOFIE measurements are used to retrieve profiles of PMC extinction at 11 wavelengths (0.330 to 5.01 µm), temperature, meteoric smoke extinction, and five gaseous species (O3, H2O, CO2, CH4, and NO). All 16 channels are functioning nominally. SOFIE temperatures are validated from 15 to 88 km altitude, and measurements of H2O, NO, and O3 all agree satisfactorily with other established techniques.

The Cloud Imaging and Particle Size (CIPS) experiment is a wide-angle imager consisting of four cameras that provides images of PMCs with a spatial resolution of 1×2 km in the nadir and about 5 km at the edges of the forward and aft cameras. The ability to image PMCs at a large range of scattering angles enables the ice particle size to be determined. The retrieved parameters include PMC presence, albedo, particle size, and ice water column content (IWC), with 25 km^2 resolution covering the summer polar region (latitudes from ~55–84°). CIPS data contain the first spaceborne daytime images of small-scale Gravity Waves (GW), which largely account for energy and momentum deposition in the mesosphere and lower thermosphere (MLT). CIPS imagery has also now been used outside the summer polar region to detect GW signatures in Rayleigh-scattered sunlight above the ozone layer at 50 km altitude.

Notably, due to orbital precession, the AIM orbit will be changing considerably during the extended mission allowing for a total of 18 months of global coverage of CIPS and SOFIE observations in the 2017–2018 timeframe. Consequently, the AIM team plans to concentrate on these novel possibilities (i.e., global orbital coverage, new observables like gravity wave signatures at 50 km altitude) and open up to even broader compelling science objectives than before. These objectives include the characterization of the global distribution of medium and small scale gravity waves at the bottom of the mesosphere as well as the inference of the global residual mesospheric circulation from MSP observations—both of which are key inputs to understanding the dynamical coupling of the MLT with above and below. In addition, as an extension to its original science goals on the role of PMCs as climate change indicators, they will investigate the drivers of mid-latitude PMC occurrence (and its potential role as climate change indicators) and finally clarify the relative roles of anthropogenic and solar forcing on general PMC occurrence.

AIM Science Strengths

The AIM science team has been very successful in achieving the science goals posed in the 2013 senior review process.

They have successfully used CIPS and SOFIE to study gravity and planetary wave activity and they have successfully combined these with observations from ground-based networks, other satellites, and modeling.

They have been able to identify a 27-day signature associated with the rotation of the solar atmosphere in the ice water content of PMCs and they were able to study the solar sensitivity of ice water content.

They have further been successful in gaining first indications of decadal scale temperature and corresponding ice water content variations in the polar summer mesopause region indicating a possible long term cooling due to rising concentrations of the greenhouse gas CO2. Since we are now entering the declining phase of solar cycle 24 there is great promise that additional years of observation will strengthen the case for an anthropogenic cooling of this altitude range of the atmosphere.

They have been able to demonstrate a correlation between the seasonal variation of meteoric smoke and the meridional circulation of the atmosphere (the latter based on model data) indicating that meteor smoke observations are a versatile tool for studying the residual large scale circulation of the atmosphere.

They have also been able to make the case that water vapor injections from space traffic after the space shuttle era into the MLT-region have the potential to affect PMC properties and compensate for stronger water vapor photolysis during increased solar activity.

Finally, they have been able to study the effect of photochemically active species (like HOx and NOx) produced by energetic particle precipitation on PMCs but found no effect. The explanation for this finding is that other natural variability of the PMC environment is too large to allow the detection of small effects due to energetic particles.

Based on the results of the past years, the AIM science team is proposing new compelling science questions for the extended mission for which they will likely be able to make significant progress in the next years.

AIM has developed the ability to observe new variables which allow them to study scientific objectives of broader significance than before. This includes both new observables such as the ability to image gravity waves at an altitude of 50 km from Rayleigh-scattered sunlight just above the ozone layer as well as new orbital coverage allowing AIM to obtain global coverage during a total of 18 months in the 2017–2018 timeframe.

In addition, even though significant progress has been made to address the original AIM objectives, surprises have emerged and these can best be addressed by accumulating further data over the declining phase of Solar Cycle 24. These results—particularly the cooling in the MLT and increase in PMCs toward solar maximum—show that fundamental uncertainties remain.

There are four Prioritized Science Goals (PSGs) for the extended mission:

- PSG1: How does dynamical variability in the lower atmosphere couple to geospace weather? How do the fluxes of gravity waves at 50 km vary with latitude and season?
- PSG2: What governs the occurrence of mid-latitude PMCs?
- PSG3: What are the roles of solar and anthropogenic forcings on PMCs and the structure of the mesosphere?
- PSG4: Can the latitude variation of meteoric smoke be used to better understand the global mesospheric circulation?

PSG1, PSG2 and PSG4 make direct use of the evolving orbit of AIM allowing the mission to obtain global fields of the corresponding observables thus enhancing the scientific return greatly.

PSG1 and PSG4 are highly compelling addressing the issue of vertical coupling between different regions of the geospace system. They make both use of the evolving orbit of AIM as well as new measurement capabilities such as the ability to observe gravity waves with CIPS at ~50km altitude and to detect meteoric smoke particles.

PSG2 and PSG3 are both very important science goals whose answers will greatly help clarifying whether PMCs are indeed suitable indicators for climate change as has been proposed more than 25 years ago.

AIM Relevant Strengths to Heliophysics Research Objectives

PSG-1 and 4: The role of gravity waves in atmospheric circulation has been a subject of various Heliophysics roadmaps, as well as the National Research Council's 2012 Decadal Survey Report (DSR) ("Solar and Space Physics: A Science for a Technological Society," released by the National Academy of Sciences) Goal No. 3, to "determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs."

PSG-2 and 3: Relevant to NASA Heliophysics Roadmap Research Focus Area (RFA) H3 "Understanding the role of the Sun and its variability in driving change in the Earth's atmosphere."

AIM Weaknesses

None noted.

AIM Value to the Heliophysics System Observatory

AIM focuses on solar-terrestrial science in the Earth's stratosphere, mesosphere, and lower thermosphere, and thus operates at one of the boundaries of the HSO. Its value lies in providing important new information about solar impacts on the dynamics and chemistry of these regions, and the role of solar variability in the Earth's climate. AIM is complementary to TIMED observation both regarding its ability to image the horizontal extent and evolution of gravity wave fields in the summer mesopause region and globally at 50 km, while SABER on TIMED observes gravity waves in vertical profiles and can thus deliver information on propagation directions of the waves. Also, SOFIE observations on AIM allow the community to quantify CO2 concentrations below 75 km while SABER on TIMED has better quality above that altitude. The combined data set will allow the community to study the atmosphere's transition from a well-mixed state to a state determined by molecular diffusion which is one of the longest standing open questions of aeronomy.

AIM Spacecraft / Instrument Health and Status

SOFIE and CIPS are operating nominally with no issues to consider. The spacecraft receiver stopped working a few days after the launch of the mission, but this failure has been fully mitigated resulting in a data reception recovery of close to 100%.

AIM Data Operations (accessibility, quality control, archiving)

The AIM mission provides an extensive set of products in NetCDF format and makes them readily available through instrument web sites coordinated through a Science Data System (SDS). Documentation that includes calibration information is provided for all the products, and is easy to find.

AIM Proposal Weaknesses

No weaknesses were identified.

AIM Overall Assessment and Findings

The Panel noted the very successful accomplishments in the first 8 years of the mission. The Panel was also impressed with the broadening of the original goals of AIM following the successful measurement of several originally unplanned parameters—meteoric smoke, gravity waves, and various gas-phase constituents. Also the panel welcomes the approach to utilize the evolving AIM orbit for better latitudinal and seasonal coverage of several observables.

The proposal makes a well-argued science case for extension of the mission. All four PSGs are either highly compelling or very important and hence certainly all worth pursuing.

AIM Overall Grade

The AIM extended mission proposal received an 8/10 median Panel score for the Overall Scientific Merit, placing it solidly in the group of "Compelling" proposals. Its median Panel score of 7/10 for contributions to the HSO places it solidly in the Excellent but less compelling category with significant value for HSO science. The Panel supports the continued operation of the AIM mission.

4.3 CINDI

Overview of the Mission

CINDI is a NASA Mission of Opportunity that flies on the Communication/Navigation Outage Forecasting System (C/NOFS) satellite. CINDI consists of two instruments: the Ion Velocity Meter (IVM) that measures ion density, temperature, composition and velocity, and the Neutral Wind Meter (NWM) that measures neutral atmosphere pressure and wind. CINDI measurements cover a range of altitudes over the equator and low latitudes (13-degree inclination orbit). As part of the operational C/NOFS program, the Air Force supports CINDI instrument operations, data access and distribution, and satellite orbit and position data.

The CINDI IVM sensors include an ion drift meter (IDM) and retarding potential analyzer (RPA). The IVM instruments have been and are continuing to perform as expected since their initial turn on. The NWM measures neutral atmosphere pressure and wind with two sensors that include the cross-track sensor (CTS) and the ram wind sensor (RWS). The latter is designed to extract neutral density and wind variations along as large a portion of the satellite track as is possible. These NWM instruments were designed to fly during solar maximum conditions. Launch delay combined with the comparatively weak recent solar maximum has to date compromised the implementation and scientific return of these instruments. CINDI produced excellent wind and density results while C/NOFS perigee was near 350 km. These combined with the continuing downward progression of CINDI with altitude confirm that there will be more extensive NWM data collection and analysis during this proposal period.

Overview of the Science Plan

The Coupled Ion Neutral Dynamics Investigation (CINDI) science team proposes a focused study addressing the following fundamental questions:

(1) How are variations in neutral density and winds near the equator related to energy inputs from above and below?

(2) What is the role of atmospheric waves on the dynamics of the ionosphere at equatorial latitudes?

(3) How does solar activity affect how equatorial plasma irregularities evolve in time?

These compelling science questions directly address a number of research focus areas that are aligned with the priorities detailed in the Decadal Survey for Solar and Space Physics, the SMD Science Plan, and the Heliophysics Roadmap.

CINDI Science Strengths

The CINDI extended mission plan is well conceived and addresses compelling science topics that are uniquely facilitated by the measurements that CINDI will make during the next year as C/NOFS descends prior to reentry into the Earth's atmosphere. Additional data and operations are clearly required to accomplish the proposed science objectives. CINDI will continue to be the only mission providing coincident information on the dynamic state of the ionosphere and thermosphere as the solar cycle declines. This makes it an important data set for achieving system science of the effect of the Sun and magnetosphere on the Earth atmosphere.

Among CINDI accomplishments during its initial extended mission phase is the demonstration that longitude variations in the ionosphere and thermosphere are well aligned, suggesting that ion drag influences the distribution of the neutral species. The CINDI team also showed significant thermospheric density responses to variable solar flux and magnetic activity.

The CINDI mission and science team costs are low relative to the unique science return.

CINDI Relevant Strengths to Heliophysics Research Objectives

The CINDI mission clearly addresses priority investigations in the 2014–2033 HP Science and Technology Roadmap which are aligned with the science objectives laid out in the 2013 Decadal Survey for Solar and Space Physics. Two of the key science objectives in the Roadmap are, RFA F3, "understand ion-neutral interactions" and, RFA H3 "understand the coupling of the Earth's magnetosphere-ionosphere-atmosphere system, and its response to external and internal forcing." CINDI is one of the few HSO missions that can directly address these topics and the only mission making in situ measurements of the ionosphere and thermosphere. As such, CINDI also contributes to RFA W4 to "understand, characterize, and model the space weather effects on and within terrestrial and planetary environment. " The particularly relevant proposal element is the plan to diagnose ionospheric and thermospheric coupling processes in the region where plasma perturbations are born and subsequently evolve into depletions that penetrate through the F region. In this regard CINDI should provide insight into the underlying physics governing these phenomena which impacts radio communications.

CINDI Value to the Heliophysics System Observatory

CINDI's in situ measurements of the ionosphere and thermosphere constitute unique contributions to the HSO. They provide perspectives on how the geospace system responds to variable solar and geomagnetic forcing as well as the impacts of the lower atmosphere on the thermosphere-ionosphere. Any interpretation of CINDI data requires a detailed description of the external drivers. CINDI represents an important component of the HSO, enabling the inclusion of the connected ionosphere and thermosphere system in a coherent study of the geospace environment.

There is also an emerging synergy between CINDI in situ winds and the TIMED upper thermospheric remote sensing wind measurements that will be deduced from TIDI red-line emissions as described in the TIMED proposal plan.

CINDI Spacecraft / Instrument Health and Status

The state of the C/NOFS satellite and CINDI IDV instrument performance is excellent and the NWM performance is improving as the orbit allows for viable thermospheric measurements near perigee. All indicators suggest that satellite and instrument performance will continue to be excellent until the satellite reentry, which is anticipated to occur sometime in 2016. The letter of support from the Air Force Research Laboratory that accompanies the proposal indicates their commitment to continued operation of the satellite until reentry of the vehicle.

The team addressed the previous Senior Review battery-charging concern related to the angle between the Sun and C/NOFS's precessing orbit, since they demonstrated no impact on the operation of CINDI instruments.

CINDI Data Operations (accessibility, quality control, archiving)

The CINDI team is doing a good job of making data available to the community in a timely fashion and in useful formats. They responded to the 2013 Senior Review findings to make the data available in netCDF format on the SPDF and provide SPASE metadata for the CINDI data products. The data are also being delivered on a timely basis through the project website. However, as pointed out in the assessment of CINDI's MAP, the project needs to do a better job linking and preserving its documentation of the data products.

CINDI Proposal Weaknesses

The panel found no major CINDI mission weaknesses.

CINDI Overall Assessment and Findings

CINDI has a clear extended mission plan addressing compelling science topics. During the initial extended mission CINDI established the responses of the ionosphere and thermosphere to variable solar, geomagnetic and lower atmospheric forcing. This provides a clear context for the proposed extended mission science. CINDI will be the only mission providing coincident information on the dynamic state of the ionosphere and thermosphere during the declining solar cycle and is therefore valuable to the HSO. The CINDI mission strongly addresses priority investigations in the Heliophysics Science and Technology Roadmap. The CINDI mission costs are comparatively low relative to the science return. The health and safety of the C/NOFS satellite is good with the Air Force intending to continue operations of the spacecraft until reentry. The CINDI team is doing a good job of making data available in a timely fashion and in useful formats.

CINDI Overall Grade

The CINDI extended mission proposal received “Excellent, but less compelling” rankings for both the extended mission science (median panel score 7/10) and CINDI’s contribution to the Heliophysics Systems Observatory (median panel score 6/10). The comparatively lower HSO ranking stems from the low impact that CINDI data have on other elements of the HSO. The panel supports the continued operation of the CINDI extended mission.

The panel considered the in-guide and over-guide proposal options and found that the CINDI team proposed excellent science in their modest over-guide proposal. Nevertheless, it was low priority in the context of the highly constrained budget available for the HP extended missions. The panel points out that the team could submit a proposal to the Heliophysics Guest Investigator or Supporting Research programs to pursue their over-guide objectives.

4.4 Hinode

General Overview of the Mission

The joint US/UK/Japanese *Hinode* mission was launched in 2006 and now enters its third extended mission phase. *Hinode* consists of three instruments which act as a comprehensive observatory. The Extreme-ultraviolet Imaging Spectrometer (EIS) obtains high spectral and spatial resolution images and spectra in two wavelength regimes: 17.0–21.0 nm and 25.0–29.0 nm, enabling sampling over temperatures 0.1–20 MK. An X-ray telescope (XRT) images the solar corona with good spatial resolution, high cadence (8s) and with a wide dynamic range and temperature sensitivity that enables studies from coronal holes to flares. The Solar Optical Telescope (SOT) Focal Plane Package (FPP) includes a high-resolution (0.2") high-cadence (< 2s capable) multi-filter narrow- and broad-band imaging system (NFI, BFI) for photospheric and chromospheric data. The SOT also includes the Spectro-Polarimeter (SP), a scanning-slit instrument which obtains polarization spectra of magnetically sensitive photospheric spectral lines. XRT is a full-disk imager, while the EIS and SOT instruments have limited fields-of-view. *Hinode* is a complex mission in many aspects: the multiple instruments, the limited fields of view of two instruments, and the multi-national cooperation and coordination which is required for successful scientific return make the NASA necessary costs difficult to assess.

Overview of the Science Plan

The proposed science investigations span a wide range of topics and scales, from the description of ubiquitous small-scale magnetic features on the Sun to the stellar analogies of solar-cycle coronal behavior. The team has proposed four Prioritized Science Goals:

- Study 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 proposal outlines recent advances in these topics and future investigations. The justification for continued operation and observations center on the unique observational capabilities of the *Hinode* instruments, including polar-cap magnetic field transport characterization during the decline of the activity cycle and beginning of the next cycle, determining the source of the slow solar wind in the context of declining activity, and understanding the high-temperature coronal emission during cycle minimum.

Hinode Science Strengths

The *Hinode* instrument suite has enabled paradigm-defining science in a number of topics. An impressive summary was given in the proposal, of which only a few are noted here as examples. The solar polar magnetic field structure and dynamics has been intently studied, confirming the dominance of small but strong-field unipolar elements, in the context of coincident flux-balanced weak elements. Pre-eruption brightenings have been observed in the chromosphere which are consistent with small reconnection events; the seemingly benign emergence of a new active region has been seen in light of the energy transferred into the solar corona, now estimated as comparable to large flares but manifest as gradual small reconnection processes. Instrument coordination has led to the identification of the source of the slow solar wind during an active Sun, and the possibility of an activity-cycle-independent dynamo process has been identified, which generates the ever-present weak component of the photospheric magnetic field. With respect to a broad scientific impact beyond the heliophysics, the panel notes that a large fraction of the spectra lines observed in EIS/*Hinode* data are as of yet unidentified.

Further mission extension is supported by many lines of argument. For example, the unique ability of *Hinode*/SP to quantitatively study the polar magnetic fields for the next few years presents the opportunity to gather critical information relevant to understanding the driver(s) of the solar cycle during the transition to solar minimum and a period of stronger polar influences on heliospheric topology. The hints of pre-event reconnection phenomena, the energetics of emerging magnetic field, and quantitative DEM tests of flare Standard Models must be confirmed and statistically verified. Extended observations by XRT will help quantify the behavior of the hottest component of the solar corona during the transitions between phases of the activity cycle. For an extended mission period, new improved numerical modeling capabilities are now producing new observationally testable predictions that will be especially constrained in the light of recent additions to the HSO fleet (see below).

The *Hinode* mission has fostered broad community science involvement, but also strong team science: more than 900 refereed journal articles have been published using *Hinode* data; of those, 1/3 have a first author with some support from mission (2/3 led by scientists from the outside-mission community). *Hinode* also demonstrates encouraging young-scientist involvement in the US, Japan, and the UK. The proposal cites statistics that approximately 40% of *Hinode* publications are led by a student or early-career scientist; over 90 graduate student theses rely upon *Hinode* data.

Hinode Relevant Strengths to Heliophysics Research Objectives

The PSGs map well to the Research Focus Areas in the 2014 Heliophysics Roadmap and to the goals outlined in the 2012 Decadal Survey. The proposal responds directly to the Heliophysics Science Goals from 2014 NASA Science Mission Directorate strategic plan to "Explore the physical processes in the space environment from the Sun to the Earth and through the solar system." The *Hinode* mission prioritized science goals dovetail well with National Research Council Decadal Survey Priorities, in particular (a) Determine the origins of the Sun's activity and predict the variations of the space environment and (d) Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe. The proposal demonstrated the strong links between these nationally-defined science goals and both the achievements thus far and the plan for future investigations.

Hinode Value to Heliophysics System Observatory

Hinode instruments provide data in unique parts of parameter space that complement other solar missions. XRT presents a unique bridge between SDO/AIA and RHESSI, especially for studies of high-energy events that can severely impact the heliosphere with sudden energetic particle flux, and the influence of X-ray plasma on the more local considerations of the near-Earth environment. XRT presently represents the sole HSO capability for imaging the hottest coronal plasmas. EIS spectral coverage complements the IRIS observing capability, and is itself complemented by SDO/AIA for context. The SOT package, in particular the SP, provides a standard by which other magnetic field data are judged, and its high sensitivity enables an understanding of the "true" structure of the photospheric magnetic field which, for example, is viewed in only an averaged sense with SDO/HMI.

In light of reduced funding yet increased opportunity for synergistic observations, the *Hinode* instrument teams have developed new observing modes to contribute uniquely to HSO system science and coordinate with other missions, yet reduce planning and operations requirements. New modes have been developed for the SP to enable high cadence vector magnetic observations of a narrow FOV co-aligned with IRIS. EIS now routinely takes full-disk spectroscopic observations to identify and investigate solar wind sources-boundary condition information for HSO system science.

The *Hinode* mission has undertaken not only coordinated observations with other HSO missions, it is actively sought after for coordinated observations with ground-based facilities both in the US and internationally. New ground- and space-based facilities such as ALMA, NuSTAR, are beginning to coordinate observing plans.

Hinode Spacecraft / Instrument Health and Status

The instruments and spacecraft continue to perform well. Spacecraft attitude systems are functioning nominally, and available fuel is sufficient for orbit maintenance and debris avoidance maneuvers for approximately ten additional years in the present 680km-high orbit.

SOT/FPP: Four NFI filters are working well, two have been damaged, one of which (630.2nm) has some redundancy with another which is working well (525.0nm); the Hα (656.3nm) filter is damaged but data are obtained still for morphological information. The previously identified instrumental effect (so called "bubbles," "snail trails") is either absent or mitigated. For the BFI absolute intensity calibration software was developed and is distributed through SolarSoft. The SP has shown some light-level decrease and CCD contamination, with corresponding increase in noise, but detectors, mechanical systems, and in-flight processing and electronics are working well and normal mitigating efforts (bake-outs, flat-field and calibration sequences) are achieving desired effects.

XRT: As reported for previous SR cycles, there have been some contamination/residue issues which are minimized by bakeouts and flat-field modeling, and new calibration algorithms to remove scattered light from the 2012 appearance of a pinhole which are being finalized. Temperature issues (too high at times upstream, too low during eclipse seasons downstream) have, in recent tests, appeared to effectively cancel each other out, so that the filter-wheel #1 preventative suspension during eclipse seasons is no longer being applied.

EIS: Although the number of warm pixels is still increasing, the rate of increase has slowed, and the number/location/effect of monitored continuously; the instrument sensitivity degradation also continues, but is very slow. Both issues are of minimal impact to the science. When the number of warm pixels begins to negatively impact spectral fitting, the EIS team will consider carrying out bakeout procedures. Second-order calibration efforts and improvements to the seasonal alignment errors are underway, with the goal of EIS and IRIS coordinated observing commands to be coaligned within a few arcseconds. Notes and results from investigations are documented through SolarSoft Software Notes, in addition (where appropriate) in the peer-reviewed literature.

Overall: The *Hinode* mission remains scientifically viable and critical to the system science.

Hinode Data Operations (accessibility, quality control, archiving)

In response to the 2013 SR and in anticipation of extended support, new observing strategies are being developed to (1) accommodate decreased extended-phase budget constraints, (2) support and coordinate with new complementary capabilities by other missions and ground-based facilities, (3) test new results from modeling efforts not available during prime phase or even earlier extended phases.

The *Hinode* mission operations have been optimized to reduce the cost without loss of efficiency. International participation occurs at the scientific, operational, and data reduction/analysis levels. Spacecraft operations are still performed at JAXA; Chief Observers for XRT and SOT are a 50% US burden, for EIS the US COs handle about a third of the duties. NASA responsibility for Chief Planner duty has been reduced by almost 40%.

The Mission Archive Plan report finds that due to multiple resident archive sites, the data should be well preserved – but that there is a lack of a cohesive plan for data archival overall. The community enjoys access through a variety of tools; there is concern that the Final Archive will be able to maintain full utility of the data, in particular with regards to the coalignment database.

Hinode Proposal Weaknesses

While the scientific achievements from *Hinode* data were compelling and fully exploited the possibility of "system" science, the panel found the presentation of the science to be somewhat fragmented. The proposal adequately describes the links between PSGs, the 2014 Heliophysics Roadmap Research Focus Areas and 2012 Decadal Survey Challenges, but the narrative could have better mirrored the "system science" approach to bring continuity between at times seemingly disparate investigation topics.

Hinode Overall Assessment and Findings

The 2015 Senior Review panel finds that the scientific return in recent years from *Hinode* is exceptional. The mission returns data in a unique niche of HSO data space, and the mission is in fair overall health with adequate data archiving efforts. Continuing the *Hinode* mission would ensure that a unique HSO asset is supported. The panel finds the proposal to demonstrate an excellent outlook for future collaborative work with other HSO missions (in particular, with IRIS, RHESSI, and SDO). The proposal meets the in-guide budget, and the team has developed new operating modes to be able to operate in an efficient manner while continuing to enable broad scientific discovery.

The Panel notes that the proposal includes approximately $2.6M/year for Science Data Analysis, which in our opinion should include funding both for routine data quality analysis and to perform relevant scientific investigations by the team. The Panel was surprised upon comments from the presenters that for the preceding extended mission phase, no mission-related science was performed under extended-phase funding. The Panel is concerned that this approach is the result of a misinterpretation of the 2013 Senior Review findings, and wishes here to clarify that there is no restriction on using part of that SDA funding to support *Hinode*-related science research by the team. This appears to be common practice across the other mission teams, with the caveat that this has to be balanced with the priority to meet data production commitments under a constrained overall budget which is likely to reduce with time.

The panel found that the major concerns raised in 2010 and 2013 SR cycles have been addressed: costs have been reduced, the instrument teams have developed new, efficient observing modes to further streamline operations while ensuring that high-quality data are obtained. There is still some minor concern regarding a high cost/science ratio in light of the contributions from international partners. The proposed science available to additional *Hinode* operations is compelling, and there is recognition that this is an extremely complex mission. The panel praises the *Hinode* team's proactive engagement in cross-mission collaborations. The scientific output has been very satisfactory, especially in the context of addressing fundamental outstanding questions and testing model predictions, with generally quantitative methods and results.

The Hinode extended mission proposal received an 8/10 median score for extended mission science, and 9/10 median score for contributions to Heliophysics Systems Observatory; both scores are in the highest, "compelling" category. The panel finds that continuing the *Hinode* mission would ensure continued systems-approach research to outstanding topics in solar and heliospheric physics.

4.5 IBEX

Overview of the Science Plan

The Interstellar Boundary Explorer (IBEX) measures energetic neutral atoms (ENAs) coming from the far outer heliosphere. The goal is to use these data to deduce information about the global structure of the heliosphere, the spectrum of energetic particles in the outer heliosphere, the interaction of the heliosphere with the interstellar medium, and properties of local interstellar medium (LISM). In the extended mission (EM) the IBEX team also proposes to focus on the global structure of the Earth's magnetosphere and its dynamic interaction with the solar wind and ENA emission from the other solar system objects. In the prime mission phase IBEX has made a number of important discoveries related to the structure of the outer heliosphere. A surprise was the discovery that ENAs of around 1keV peak along a band, called the "IBEX ribbon" that seems to be defined by the ring where the line of sight is normal to the local, possibly draped, interstellar magnetic field. The ribbon exhibits structure that varies with time. The source of the ribbon remains uncertain and is a major focus of the EM. Peaking of the highest-energy ENAs in the polar regions where the solar wind speed is the highest suggest that the source of ENAs is linked to the solar wind speed. Consistent with this idea, the spectra of ENAs are harder near the poles than the equator. Because of the time delay in the propagation of the solar wind, the present measurements correspond to solar minimum so a major goal of the EM is to study the variation of ENAs and the structure of the global heliosphere with the phase of the solar cycle. Further measurements of neutral H and He from the LISM will establish the direction of the flow of the LISM. Because the orbital radius extends out to around 50 RE IBEX has been able to image ENA emission from Earth's global magnetosphere, including the magnetopause, the cusps, and the tail regions. Time resolution is sufficient to image the dynamics of the magnetosphere during its interaction with CMEs during solar maximum although spatial resolution is limited. IBEX has been able to measure ENAs backscattered from the lunar surface during its interaction with the solar wind. During the extended mission IBEX will also seek to measure scattering from comets and cometary tails.

IBEX Science Strengths

The interaction of the solar wind with the interstellar medium, the primary goal of IBEX, is a priority of NASA's SMD and the 2012 Solar and Space Physics Decadal Survey. Because of the presence of the Voyager spacecraft in the outer heliosphere, the EM IBEX measurements will provide critical measurements on the global structure of the heliosphere that can be compared with *in situ* Voyager measurements. The recent observations of a tilted heliotail will provide additional information on the orientation of the LISM magnetic field. The EM will cover the period of solar maximum and combined with the earlier data at solar minimum will complete the exploration of the structure of the outer heliosphere over the complete solar cycle. Particularly important is to explore the impact of changing solar wind velocity and dynamic pressure on the distribution of ENAs in the outer heliosphere. This additional information should enable the IBEX team to pin down the source of the ribbon and to understand the distribution and spectral shape of the globally distributed ENA flux and its implications for understanding particle heating and acceleration in the outer heliosphere. It is now well accepted that the ENA emission from the ribbon is related to the local interstellar magnetic field giving an important constraint on models of the global heliosphere—despite the fact that we do not actually know, at present, what causes the ribbon. The study of emissions from the heliospheric tail will provide a valuable check on the overall structure of the heliosphere and help determine the validity of the recently proposed "jet" model of the heliosphere. The variation of the flux of neutral H over the upcoming solar minimum will provide important data for understanding the role of interstellar pickup particles in the dynamics of the solar wind. Global imaging of the interaction of the Earth's magnetosphere with the dynamic solar wind, with resolution times on the order of minutes or less, will produce key data for benchmarking global magnetospheric models and for assisting in the interpretation of local measurements by satellites in the local geospace environment. Understanding the impact of solar disturbances on the geospace environment is a top priority of NASA's SMD and the Decadal survey. The proposed study of the structure of the heliospheric tail will help to determine the validity of the recently proposed "jet" picture of the heliosphere.

IBEX Relevant Strengths to Heliophysics Research Objectives

IBEX has significant synergy with other heliospheric missions. The Voyager 1 spacecraft is in the VLISM and Voyager 2 is in the inner heliosheath and approaching the heliopause. Comparison with IBEX is a unique opportunity because local measurements in the outer heliosphere will not be available for decades at best after the Voyager mission comes to a close. The heliopause encounters by Voyager will enable IBEX to benchmark estimates of the thickness of the inner heliosheath based on integrated fluxes of ENAs. Enhanced activity in the heliosheath associated with the propagation of solar disruptions into the outer heliosphere during solar maximum might be identifiable with both Voyager and IBEX. Comparisons of the IBEX ribbon with Cassini's Imaging-Neutral Camera (INCA) measurements of a similar band are ongoing and will continue. Global imaging of the Earth's magnetosphere with IBEX will produce a unique global view of how CMEs impact the Earth space environment while existing satellites within the magnetosphere—Cluster, THEMIS, the Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS), Artemis, Van Allen Probes—and the upcoming MMS mission produce local measurements.

IBEX Value to the Heliophysics System Observatory

The interaction of the solar wind with the interstellar medium, the primary goal of IBEX, is a priority of NASA's SMD and the 2012 Solar and Space Physics Decadal Survey. The IBEX EM will provide data that will facilitate planning for the IMAP mission, which was identified as a priority of the 2012 Decadal Survey. The interaction of solar wind with the Earth's magnetosphere, which controls space weather in geospace, is also a priority of SMD and the 2012 Decadal Survey. In this vein, the committee finds that encouraging closer collaboration between Voyager and IBEX will significantly increase the scientific return. Perhaps this can be furthered by a GI program.

IBEX Spacecraft / Instrument Health and Status

The spacecraft subsystems are healthy with ample consumables present. IBEX has two instruments that measure ENAs with energies in the range of 10eV–2keV (IBEX-LO) and in the range of 380eV–6keV (IBEX-HI). ENAs are not deflected by magnetic fields and therefore are able to offer global views of heliospheric structure and dynamics. The measurements, because they are line-of-sight integrals, complicate the interpretation and typically require a parallel modeling effort for interpreting the results. Both the IBEX-HI and IBEX-LOW instruments are operating normally.

IBEX Data Operations (accessibility, quality control, archiving)

Data from the IBEX mission are served from the SPDF, and are readily available. Many forms of higher-level products are available, along with the original data. Data are all described in SPASE and listed in the HDP. Overall, the IBEX archive is in good shape. Interpretation and utilization of ENA image data are heavily dependent on analysis process so completion of the stand-alone data package for the non-expert scientists, described in the plan, is essential for the long-term utility of the data. It is important that the mission dedicates resources to this aspect of the project. The MAP assessment panel praised the mission for "The plan for data archiving is exemplary in its completeness in terms of data, software, and documentation."

IBEX Proposal Weaknesses

No significant weaknesses.

IBEX Overall Assessment and Finding

The IBEX mission, along with the Voyager spacecraft, is playing a key role in our evolving understanding of the structure of the outer heliosphere and its dynamics. The IBEX measurements are unique in their ability to explore the global structure of the heliosphere and its evolution over the solar cycle. The evolution of the ribbon and the spectra of the global distribution of ENAs over the solar cycle should help in unraveling the source of the ribbon and the spectrum of ENAs. A well-supported modeling effort will be key element in maximizing the scientific return on the IBEX investment. Overall the IBEX extended mission proposal is compelling and the IBEX team has been highly productive during the PM stage of the mission.

The large number of publications in top journals and the positive press that has come out of the IBEX mission support the conclusion of the Senior Review panel that the productivity of the IBEX science team has been high and will remain so in the EM phase.

IBEX Overall Grade

The IBEX extended mission proposal received a 9/10 median panel ranking for Overall Scientific Merit, placing its science merit in the upper end of the Compelling category. It received a ranking of 8/10 for Value to the HSO, placing it in the Compelling category here also. The Panel finds that the operation of the IBEX extended mission should be continued.

4.6 IRIS, Interface Region Imaging Spectrograph

General Overview of the Mission

The Interface Region Imaging Spectrograph, IRIS, provides spectra and images from the solar photosphere into the low corona. It is designed to make spectroscopic observations of the Sun at high spatial, spectral, and temporal resolution. The spacecraft carries a 20-cm UV Cassegrain telescope that feeds a dual range UV slit spectrograph and slit-jaw imager. IRIS has an effective spatial resolution between 0.33 and 0.44 arcseconds, and a maximum field of view of 120 arcseconds. The far-UV channel covers the 133.0–141.0 nm range, with a $4x10^{-3}$ nm spectral resolution. The near-UV channel covers the 278.0–284.0 nm range, with an $8x10^{-3}$ nm spectral resolution. The slit-jaw imaging covers similar ranges in the far-UV (4.0 nm bandpass) and near-UV (0.4 nm bandpass). IRIS has a very high data rate, that allows images to be taken every 5–10 s and spectra every 1–2 s. IRIS travels in a polar sun-synchronous orbit (twilight orbit) that allows for eight months of continuous observations per year and maximizes eclipse-free viewing of the Sun.

Overview of the Science Plan

The IRIS mission deliberately combines unprecedented observations of the solar chromosphere and transition region with advanced numerical simulations, including the development of publicly available sophisticated radiative transfer codes. During its prime mission phase IRIS has already achieved significant milestones in reaching its primary objective of understanding the processes that energize the solar atmosphere. For example, the detection of non-thermal electrons in coronal nano-flares provides new insight into mechanisms behind non-thermal energy generation specifically which dominate in the chromosphere and corona. The IRIS high-resolution spectra have shown for the first time the existence of regions of very dense plasma in the photosphere and low chromosphere that are rapidly accelerated and heated to 80,000 K. This discovery has pushed numerical simulations to explore specific reconnection processes that will explain these newly observed features and their impact regarding the mass and energy supply for the corona. One of the most challenging problems in solar physics today is to better understand the nature of solar flares and coronal mass ejections (CMEs). IRIS has provided critical data that demonstrate, for example, the important role played by electron beams in the chromosphere during flares (which challenges some flare models) and evidence for tether-cutting magnetic reconnection as a trigger for both flares and associated CMEs.

The IRIS Science Plan for its extended phase is quite compelling. It is focused on five prioritized science goals: 1) Study the fundamental physical processes in the solar atmosphere; 2) Investigate the (in)stability of the magnetized atmosphere; 3) Analyze the energy and mass transfer between photosphere, chromosphere, and corona; 4) Quantify the variations of far and near ultraviolet solar radiation over the solar cycle; 5) Explore the solar-stellar connection. The accomplishment of these goals will provide a new insight into basic physical processes and improve the current numerical models.

The IRIS mission fully addresses the type of crucial research listed on each of the four Key Science Goals of the Solar and Space Physics Decadal Survey, all four of the Science Challenges of "The Sun and the Heliosphere" panel of the Decadal Survey, as well as many of the Research Focus Areas of the Heliophysics Roadmap: Energy transport and dissipation through waves, effects and diagnostics of non-thermal particles in the solar atmosphere, mass and energy transport through jets, chromospheric heating and diagnostic, and dynamics of flares and coronal mass ejections.

IRIS Science Strengths

IRIS provides the highest spectral resolution observations of the chromosphere and transition region in the far-UV and near-UV ranges of any mission. The subarcsecond spatial resolution combined with the very high temporal cadence of the observations makes IRIS a unique instrument for detailed studies of the magnetic field reconnection and its thermodynamic effects in flares. IRIS has a strong program of coordinated observations with Hinode and SDO. IRIS chromospheric and transition region spectra and images form a perfect complement to Hinode's high-resolution photospheric magnetograms and coronal spectra and images, and to SDO's contextual full-disk magnetograms and coronal images. The synergy with Hinode and SDO allows studies of how the magnetic field drives and mediates dynamics and heating in the coronal and solar wind. The high quality of the data and the new research opportunities offered by this mission are confirmed by 31 refereed papers published in the 16 months since the data became public, a rate similar to the corresponding phase of other Heliophysics missions. IRIS observations are being used by at least 25 PhD students worldwide.

IRIS Relevant Strengths to Heliophysics Research Objectives

The research topics outlined in the proposal are highly relevant to the heliophysics research objectives. During its extended phase the IRIS mission will focus in further developing advanced numerical simulations to improve the diagnostic value of its observations, and further strengthening collaborations with other space- and ground-based observatories. IRIS science goals for the next five years will address a broad range of unsolved questions pertinent to the physics of the solar chromosphere and low corona, such as which physical processes dominate the heating of the chromosphere, which mechanisms drive white light flares and initiate coronal mass ejections, and how jets supply mass to the corona and to the fast/slow solar wind. The transition layers of the solar atmosphere are crucial to understand in terms of the basic physics of our star, but they are so highly structured and dynamic that only the unique capabilities of the IRIS mission are presently poised to provide answers.

IRIS Value to the Heliophysics Systems Observatory

IRIS is a great asset to the Heliophysics Systems Observatory. It has an excellent track record of coordinating with HSO missions. The current synergy with Hinode, SDO and RHESSI is an example of a system's approach to build up a better understanding of such a complex system as the solar atmosphere. Future collaboration/coordination plans include ground-based instrumentation that will soon be operational, such as the Atacama Large Millimeter/submillimeter Array (ALMA), the German GREGOR 1.6m telescope, and the NSF-funded 4m Daniel K. Inouye Solar Telescope (DKIST). IRIS observations will be used to investigate solar abundance details and provide physical insight into the cyclic- and feature-driven variability of the solar UV output—both of which have far-reaching impact in heliospheric and astrophysical science.

IRIS Spacecraft / Instrument Health and Status

The IRIS spacecraft contains no consumables, and has performed almost flawlessly on orbit for nearly two years. No subsystem shows signs of significant degradation.

IRIS Data Operations (accessibility, quality control, archiving)

The IRIS data are available to the science community in each level of reduction as soon as they are available at SDO ISOC, where they are archived and processed. Calibrated data are available within seven days of the observations, while preliminary calibrated quick-look images are provided within hours of the observations. The Heliophysics Coverage Registry provides a specific search engine that enables easy co-temporal/spatial IRIS and Hinode data comparison. In addition, the modeling output are considered part of the IRIS mission data and made available for community analysis through the same distribution channel.

IRIS Proposal Weaknesses

None.

IRIS Overall Assessment and Findings

The panel found the IRIS proposal to well-summarize this outstanding mission, which addresses compelling science. The proposed investigation for the extended phase of the mission is well defined. An important component of the requested budget is played by the cost of the downlink X-band passes. For FY16 this cost is covered by ESA, resulting in a total budget that is under the in-guide amount. The somewhat over-guideline budget for FY17–20 is mostly due to charges by NASA for downlink capability. However, if ESA support for this capability continues beyond 2016 the saving for NASA will be significant, bringing the actual requested budget under the guideline.

IRIS Overall Grade

The IRIS extended mission proposal has been graded by the Panel as compelling in both its science merits (median panel score 9/10) and value to the HSO (median panel score 8/10). The Panel supports the continued operation of the IRIS extended mission.

4.7 RHESSI

General Overview of the Mission

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) is an imaging spectrometer which provides high resolution X-ray and gamma ray imaging spectroscopic observations over the range of energy from 3 keV to 17 MeV. This range covers soft X-rays emitted by hot thermal plasma, hard X-ray and gamma-ray bremsstrahlung emitted by energetic electrons, and nuclear gamma-ray lines produced by energetic ions. RHESSI was launched in February 2002, has a few arcsec angular resolution, and 1–few keV spectral resolution. It is presently in a 510km roughly circular orbit (at an inclination of 38º), with expected operations through at least 2017 (see below).

RHESSI Overview of the Science Plan

For the next mission extension, the RHESSI team proposes to collaborate extensively with the other HSO missions, in particular with the newer missions such as IRIS. RHESSI's overall science goal of understanding solar flare energy release and particle acceleration is elucidated through four Primary Science Goals: (1) the evolution of solar eruptive events (SEEs), (2) the acceleration of electrons, (3) the acceleration of ions, and (4) the origin of the thermal plasma. Two additional objectives are listed which take advantage of RHESSI's capabilities for observing (5) the optical Sun and (6) X-ray and gamma-ray sources of both terrestrial and astrophysical origin. As the sole mission to observe high-energy solar emissions, the RHESSI science plan focuses on the expectations of this declining solar cycle phase. Additionally, in the past three years RHESSI data have been used to challenge the basic thick target flare model, dating from the 1970s and heretofore the essential description of the dominant non-thermal processes in the impulsive phase of a flare. Evidence has emerged for bulk acceleration in the corona, and, unexpectedly, the presence of non-thermal particles in the lowest layer of the solar atmosphere, close to the photosphere itself. The proposal anticipates major revisions to this paradigm, facilitated by new complementary data becoming available

RHESSI Science Strengths

RHESSI observations are both unique and highly complementary to data sets from other instruments in the HSO; this includes not only SDO, STEREO and *Hinode* but most recently, IRIS; astrophysics missions such as Fermi/LAT have also been recently involved with coordinated observing efforts. The proposal additionally describes ample motivation to coordinate with ground-based facilities, as well—in particular with radio observations due to the very complementary diagnostics they provide. The proposal well demonstrates the progress made in the PSGs since the 2013 Senior Review, a few of which we highlight here. RHESSI observations and the analysis of RHESSI data have been key to recent challenges of the thick-target model; recent publications have also concerned estimating the global energetics of solar flares (performed in coordination with SDO in particular), and numerous aspects of flare electrons (generation, acceleration, propagation and trapping). A well observed recent limb event by both RHESSI and SDO/AIA identified a coronal source of electron acceleration, and the first observations of an X-ray source affiliated with the eruption of a quiescent filament brings these types events into focus, especially regarding their triggering mechanism.

For the next extension, the RHESSI PSGs will be addressed with particular emphasis on coordinated observations with new resources, such as IRIS, and the solar-dedicated EOVSA. These new resources and the physical insight gained by their combination with additional RHESSI observations, provide a key impetus for a further extension of the RHESSI mission.

The RHESSI team and the collaborations it fosters have been incredibly productive, in the contexts both of publications and citations and the dissemination of data and analysis techniques to the broad community. Over 500 citations per year presently arise from roughly 400 annual refereed publications that contain RHESSI data. Over 100 theses (Master's and PhD) have relied upon RHESSI data.

RHESSI Relevant Strengths to Heliophysics Research Objectives

The maturity of the RHESSI mission does provide an extensive database of observations over more than a full solar cycle, and its continued operation should provide additional observations of larger events which sometimes occur in a cycle's declining phase, as in the next extension. As the first and only imaging spectroscopic instrument in its energy range, and especially now with a number of additional observational resources and facilities with which to collaborate (highlighted above), there is very high expectation of further breakthroughs in topics of high priority for Heliophysics research. While the overall theme of RHESSI research focuses on solar flares and energetic events, the proposal does outline additional non-flare (and non-solar) topics that again, will benefit from another mission extension due to the availability of new complementary observing facilities.

RHESSI Value to the Heliophysics System Observatory

RHESSI occupies a unique vantage in the HSO with its high-energy imaging spectroscopy capability that is optimized for solar energetic event data acquisition. Understanding the role of energetic particle production in flares and propagation in the heliosphere thus benefits greatly from the RHESSI data. The energetics of CMEs, now extending to the eruption of quiescent filaments, is key to fully tracing the solar impacts through the heliosphere, and RHESSI data play a demonstrated key part of pursuing that understanding.

RHESSI Spacecraft / Instrument Health and Status

Although the proposal demonstrates conclusively that RHESSI is currently capable of continued productive activity, it is unlikely that this will continue without severe degradation until the next review cycle. There is no clear and unambiguous set of criteria provided to determine objectively when degradation will render the data effectively useless. The primary issue is the need for detector annealing, which strains the cryocooler, and can probably not be repeated.

RHESSI Data Operations (accessibility, quality control, archiving)

The RHESSI data archive, containing both Level-0 telemetry and various quick-look and housekeeping data, reside at both GSFC and at FHNW in Switzerland. The data reduction algorithms are complex, but relevant software and documentation are available through SolarSoft. Spectral analysis capabilities have been enhanced through collaboration with Fermi GBM and LAT. Substantial effort has been invested in tools and data presentation so as to encourage collaborative studies, such as the availability now of SDO/AIA cutout image FITS files and movies for every RHESSI flare post-2010.

The RHESSI Mission Archiving Plan is well developed and carefully thought out, although it is noted that the "visibilities" approach may be expensive.

RHESSI Proposal Weaknesses

No major weaknesses noted. The tie-ins between the RHESSI PSGs and the 2014 Heliophysics Roadmap Research Focus Areas, and the Decadal Survey Challenges were very weak, with little explanation regarding how each PSG would address specific topics in those documents.

RHESSI Overall Assessment

The RHESSI extended mission proposal received an 8/10 median ranking from the panel for "Overall Scientific Merit" which corresponds to an evaluation of "compelling." Its median Panel ranking for "Value to the HSO" is also 8/10, again translated as "compelling." The Panel finds that continued operation of the RHESSI extended mission is warranted until such time as the imaging capability is lost, at which time a re-evaluation may be warranted

4.8 SDO Solar Dynamics Observatory

General Overview of the Mission

The Solar Dynamics Observatory (SDO) is a flagship mission of the Living With a Star program, with three instruments on-board. The Helioseismic and Magnetic Imager (HMI) obtains full-disk images of Doppler velocity and polarization with which helioseismic analysis and magnetic field estimates (both line-of-sight and vector) can be obtained. The native spatial sampling is 0.5", with cadence of 45s (Dopplergrams and line-of-sight magnetic field maps) and 12 min (vector magnetic field maps). HMI is a full-disk imaging instrument. The Extreme-ultraviolet Variability Experiment (EVE) provides EUV spectral irradiance measurements in the Soft X-ray (0.1–10nm) and EUV (10–122nm) wavelength intervals, with up to 0.25s cadence and moderate spectral resolution; EVE also includes a low-resolution Solar Aspect Monitor (SAM) that provides full-disk context images. The Atmospheric Imaging Assembly (AIA) captures full-disk coronal images in 8 wavelength regimes every 12 seconds at 1" resolution, alternating two chromospheric-wavelength images. The SDO is in a geosynchronous orbit with a continuous science downlink; there are two fairly short eclipse seasons annually.

SDO Overview of the Science Plan

The prioritized goals presented in the Solar Dynamics Observatory (SDO) proposal emphasize several broad areas of particular importance in solar physics. The "Subsurface flows and structure" PSG is aimed at developing a better understanding of the large and small scale sub-photospheric flows, their relationship with the local features (e.g., sunspots) and events (flux emergence, waves, flares), and the role of the large-scale flows in the solar cycle. The temporal changes in the level of solar activity and the understanding of the origin of the solar cycle will be explored in the framework of the PSG titled "Magnetic Variability and the Solar Cycle," and the causes of solar eruptive events is targeted for study under the PSG "Characterizing the Eruptive Potential of Active Regions." The latter also includes the development of a forecasting method, which, eventually may lead to improvements in Space Weather forecasts. The proposed activities include a continuation of routine observations with all SDO instruments, as well as comprehensive data analysis and state-of-the art modeling by both the SDO instrument teams and in collaboration with broader community. The SDO proposal also identifies two more targeted goals to address specific questions under "Collaborative Studies of Solar Eruptive Events (SEEs)" and "Global-Scale Coronal Dynamics Driving the Heliosphere and Magnetospheres." The team proposes additional activities (not identified as PSG) to pursue special observing campaigns aimed at unique observing opportunities for rare events, as well as broader initiatives providing observational support to the Heliophysics System Observatory (HSO) and its research community, and for cooperative research with the astrophysics and planetary sciences communities. During prime phase, the SDO observed the rising phase and peak of cycle 24. The extended mission will cover the declining phase of cycle 24. Taken together, these observations will provide critical information about the physics of the solar cycle, and allow for a better understanding of changes in properties of solar active phenomena with the phase of cycle. The proposed PSGs will be addressed via a combination of research conducted by the team members, the research by broader research community (both US and international), and via direct collaboration between SDO team and researchers from broader heliophysics and astrophysics communities.

SDO Science Strengths

The SDO instruments provide a combination of imaging and spectral data that sample the Sun from its interior to the outer corona. These instruments provide a cadence and uniform quality of data that well characterize the photospheric magnetic fields (both longitudinal and vector), represent the thermal structure in the chromosphere and corona, allow the probing of different depths in the solar convection zone and summarize the broad UV spectral irradiance changes due to both long-term and very short-term solar activity variation. High data quality and uniformity combined with physically-appropriate time cadence and full disk coverage make the SDO data indispensable for studies of large-scale connectivity in the solar atmosphere. The general availability of many SDO data products with minimal latency allows for complementary usage in the context of space weather situational awareness and forecasting efforts. Some SDO data will also be used to develop important synergy between solar and stellar astrophysics. The science impact from this complex mission has been major. Recent science results cited from the SDO prime mission phase include breakthroughs in coronal seismology, developing a better understanding of evolution of magnetic fields in solar upper atmosphere decoding the importance of helicity and global connectivity to the eruption of magnetic systems, and establishing the hierarchy of organized flows in the convection zone. SDO science data have been used in about 1800 refereed journal articles including 17 Ph.D. dissertations. The science goals for the next extension are important.

SDO Relevant Strengths to Heliophysics Research Objectives

The research topics outlined in the proposal are highly relevant to the heliophysics research objectives as outlined by both the Heliophysics Roadmap Research Focus areas, and the Decadal Survey Challenges. Topics are proposed for exploring fundamental mysteries of heliophysics (by exploring the physical processes in solar atmosphere and its interior), advancing the understanding of the connections between the Sun and the Earth, to developing the knowledge of solar phenomena that will enable better Space Weather forecasts.

SDO Value to the Heliophysics Great Observatory

SDO is a great asset to the HP System Observatory. Of note, its full-disk imaging and high-cadence irradiance data combine to provide context observations for many heliophysics missions in the Heliophysics Systems Observatory. Planning operations for several space-borne (e.g., IRIS, Hinode) and ground-based (e.g., NSO, BBSO) observatories utilize near real time data from SDO; the combination of SDO/AIA and STEREO's imagers enabled the first-ever global view of the Sun; magnetosphere/ionosphere missions (e.g., TIMED, AIM, CINDI and future missions: GOLD, ICON) utilize the SDO/HMI data to assist their data analysis.

As a contribution to improving space weather specification and forecasting, the panel notes that the SDO EVE irradiance observations will be critical to cross-calibration of the GOES R EXIS sensor which will be launched in March 2016. The SDO AIA and HMI data are used in the analysis of solar active region complexity which leads to improved probabilistic flare forecasts. The SDO EVE sensor provides a proxy to the GOES solar X-Ray Sensor (XRS) which has been critical during satellite eclipse periods especially during 2012–2014 when NOAA GOES satellites had only one operating XRS.

SDO Spacecraft / Instrument Health and Status

With one exception, all instruments are in a good health and expected continue taking a good quality of data. EVE/MEGS-A has failed, and there are no expectations for this instrument to provide further solar irradiance data in the 5–38nm band. HMI reboots of the flight software and anomalous upsets have not affected the science data significantly due to their low occurrence rate. All SDO spacecraft subsystems are operating nominally with two exceptions, neither of which interferes with SDO's ability to continue normal operations for at least five more years.

SDO Data Operations (accessibility, quality control, archiving)

Data accessibility appears to be adequate. The Joint Science Operations Center Instrument Operations Center (JSOC-IOC) ingests and makes most data products searchable and exportable. Near-real time data are available with a latency depending on data product, which ranges from a few minutes (AIA, HMI line-of-sight data) to a few hours (the near-real-time HMI vector field data, far-side images from helioseismology).

Quality control is generally adequate, but the panel notes that there are occasions of problem data (mostly applicable to HMI) not being caught. Developing a mechanism for the users to report issues with the data, may be an important new feature for the team to consider implementing. Due to the large size of the database, the long-term/final archiving of SDO data will present a future challenge. SR finds that is important that the SDO team develop plans for addressing this future challenge. Additional details on data archiving are included into MAP report attached to this SR report.

SDO Proposal Weaknesses

While in general the science goals presented in the proposal are noble and worth pursuing, neither the proposal nor the presentation provided adequate description or justification for the majority of the PSGs as to why the related research should be undertaken under an SDO budget. Most PSGs descriptions lack adequate details regarding what exactly the team is proposing to do within that PSG's framework. The PSGs presented in the proposal cover a very broad swath of solar physics, and the SDO team may not have the best expertize to advance research in some of the proposed areas. The panel agrees that the best approach to addressing some proposed PSG topics may be via a targeted GI program element. Some PSGs as described appear to be part of SDO routine data processing. All PSGs are presented in a framework of “two-year” or “five-year” plans, both of which require the over-guide budget request. The proposal provides no details on which PSGs can be achieved with the in-guide budget, only a broad statement that with the “in-guide funding level, few of the science tasks detailed in the two- and five-year plans can be completed.” The “two-year” above-guide plan targets PSG-related tasks identified as relevant for primary data validation, and as such crucial for success in the extended phase. However, the panel finds again a lack of adequate justification or description in the proposal regarding these tasks, their role in validation, and the team's direct involvement or responsibility for the alluded-to science investigations.

The proposal offered no acknowledgement of existing issues with the SDO/HMI data (i.e., related to orbital motions) and no evaluation of resulting potential impacts on the proposed PSGs. The Panel emphasizes that such an evaluation is necessary to determine the source of, and mitigate the effects of, the temporal variability in the data from both Doppler and Vector HMI cameras. Overall, the panel was not convinced that providing over-guide funding would result in significant improvements to the HMI data.

SDO Overall Assessment and Findings

- SDO is a valuable asset to the Heliophysics System Observatory. It provides a breadth of observational information that will enable cutting-edge investigations; the data are presently used by many NASA Heliophysics missions, as well as for near-real-time space-weather forecasting by US and international agencies.
- The panel expresses concerns that while the additional funds are requested for an extensive research element for the SDO mission, several known issues with the HMI data will not be addressed. The quality of data is adequate for some PSGs but the known problems will impede if not preclude the usefulness of HMI data for research projects required in support of other PSGs. The Panel finds that a clear and thorough assessment of the orbital effects on all HMI data products is needed, accompanied by a plan for testing possible mitigation algorithms and evaluating the results. As the attempts by the team have thus far not been successful, the panel believes that bringing expertize from outside the team will find the resolution to this issue. It is understood that bringing the community expertize will require additional targeted funding. The Panel finds the PSG topics to be broad in scope, and success in addressing the PSGs would often require expertise beyond that available within the SDO team. The Panel additionally found the expected efforts regarding in-house science unclear. As such, the Panel finds that dedicated GI-program funding for SDO-related research may be an astute funding pathway to engage the broader research community in the proposed PSG topics.
- While the panel finds that the in-guide budget for SDO is inadequate, it is unconvinced that a significant increase in funding is justifiable for SDO-team-led science. There is a concern regarding stated negative impacts on spacecraft operations, data acquisition, data calibration and data processing described in the proposal under in-guide funding levels. While the mission's funding in the extended phase is expected to gradually decline, the decrease in SDO funding level appears to have been too steep to ensure a healthy mission. These considerations are important to be taken into account when the SDO funding level is determined. The SDO mission was designed and built to an extremely tight data capture and quality specification dating from circa 2001. Now that SDO has been operating for more than five years, a review of this specification, in light of NASA's extended mission paradigm, could highlight areas of cost savings in mission operations and ground system maintenance and at the same keep the data quality at acceptable levels scientifically.
- The SDO extended mission proposal received a 7/10 median ranking from the panel for "Overall Scientific Merit" which corresponds to an evaluation of Excellent. Its median Panel ranking for "Value to the HSO" is 9/10, which translated as compelling. The Panel finds that continued operation of the SDO extended mission is warranted, but a compromise needs to be found to ensure continuation of data flow with the constraints of the available budget.

4.9 STEREO

General Overview of the Mission

The STEREO mission is based on twin spacecraft providing new perspectives on the Sun and the heliosphere from multiple longitudinal viewpoints near 1 AU. The mission completed its prime phase in January 2009 after nearly two years of operations. The STEREO spacecraft were launched on a single Delta II vehicle in October 2006 and inserted into heliocentric orbits in December 2008 (Ahead) and January 2009 (Behind). The two spacecraft drift away from the Sun-Earth line by 22° per year. They were in opposition in February 2011 and approached the Sun-Earth line on the far side of the Sun until superior conjunction (2015 January–July). The mission is now at superior conjunction. Contact with STEREO-B was lost in October 2014 and two scenarios for the extension of the mission have been proposed and discussed (one or two spacecraft operations).

Both spacecraft carry a combination of remote sensing and in situ instruments (SECCHI, IMPACT, PLASTIC and SWAVES). The STEREO mission is one of the missions which provide real-time data that are used directly in the NOAA Space Weather Forecast Office. Each of the STEREO instrument teams involves US as well as European scientists and one of the STEREO instruments (SWAVES) has both US and French PIs. Data from the mission are freely available via the STEREO Science Center and the instrument team websites. A large number of STEREO publications have appeared in the refereed literature (more than 900) with around 170 publications per year in 2013 and 2014.

Overview of the Science Plan

The strong potential of the STEREO mission is to be able to study and understand the initiation, propagation and evolution of space weather events across the heliosphere. The combination of several remote sensing instruments (EUV imager, coronagraphs, heliospheric imager) allows the follow of the propagation of CMES from their onset at the Sun to 1 AU and in combination with in situ experiments to measure the parameters (velocity, temperature, density...) of the associated perturbations at 1AU. Observations from STEREO from two different vantage points in combination with e.g., observations from SOHO/LASCO provide unique input for determining the conditions of the solar wind and perturbations at the encounter of other planets of the solar system as well as at the boundaries of the heliosphere. The STEREO observations are also used for space weather applications at the NOAA Space Weather Forecast Office.

The two spacecraft are currently at superior conjunction after having probed since launch a complete range of angles with the Sun-Earth axis. A major current concern is the potential loss of STEREO-B. Thus the proposal presented two versions for the science of the extended mission and for the budget (in case STEREO-B is recovered or not). In the context of the senior review, the discussion of the extension and the evaluation was done considering the two options.

The scientific analysis of the data is organized in ten prioritized scientific objectives (PSGs) grouped in three goal sets, based on the unique vantage points and complete instrumentation of the STEREO spacecraft:

- Characterizing space weather throughout the inner heliosphere.
- What can we learn from 360° coverage of the solar corona?
- What can we learn from coverage of the full heliosphere?

Since the last senior review, significant progress has been made on the PSGs (see next subsection).

The science plan also has strong links with the science to be achieved in the context of the Heliophysics System Observatory due to the unique perspective on the solar phenomena which can be achieved with the STEREO spacecraft (even in the case of the loss of STEREO B). STEREO data are used to monitor and study space weather through the inner heliosphere and the mission therefore also has a strong synergy with planetary missions such as MESSENGER and VENUS-Express.

STEREO Science Strengths

The combination of remote sensing and in situ instruments on STEREO, the new possibilities of observations provided by the heliospheric imagers and the unique 3D perspective of the phenomena provided by the mission led to new and sometimes intriguing results in the field of solar and heliospheric physics. The unique vantage points and complete instrumentation have provided and will continue to provide significant capabilities to address the 10 discussed in the proposal. Prioritized Science Goals based on the three major topics were stated in the previous section.

Important results were obtained since the last review on the large scale structures of CMEs (using multiple point measurements of ICMEs), the propagation of CMEs in the IP medium (interaction with the ambient medium, with other CMEs, deflection), and on the source and propagation of solar energetic particles (unexpected results were obtained on the angular extension at which SEPs are observed). New results were also obtained on the production of radio bursts from electron beams or shocks using the TDS mode of SWAVES.

STEREO far side observations combined with Earth side observations provide new views on the connections between CMEs, EUV waves, shocks and the occurrence of sympathetic events. Far side observations are also crucial to understand the lifetime of active regions, coronal holes as well as to estimate the amount of open flux from coronal holes.

STEREO observations with PLASTIC and IMPACT also provided interesting results on interstellar pickup ions and allow the building of longitudinal surveys of He+, O+ and Ne+, which are quite useful to determine the direction and the speed of the flow of interstellar neutrals. New and important results were also obtained on the dust in the inner heliosphere (decrease with time of the nano dust flux as the solar cycle evolves).

The STEREO data are used to monitor and study space weather through the inner heliosphere and are also used as inputs to simulations of the propagation of CMEs (such as the ENLIL models). The STEREO data are widely distributed and used by a large community outside the instrument teams. A lot of services use STEREO data in their browsers, web sites. In addition to science data, STEREO provides instantaneous beacon data to the space weather community used directly in particular by the NOAA Space Weather Forecast Office. In particular, the STEREO coronagraphs have greatly enhanced the ability to quantify CME parameters which improves the forecast of geomagnetic storms. The STEREO particle and EUV imaging data are also used in the preparation of the 1–3 day forecasts of co-rotating interaction regions and of solar irradiance and F10.7 radio flux.

New Opportunities in the Extended Phase of the Mission

The STEREO mission started at a period when the Sun was relatively quiet. During the extension of the mission, there is still a good chance of catching large solar events which occur in the declining phase of the cycle and to study with the combined instrumentation the characteristics of extreme events which cannot be observed from the Earth's perspective.

Potential Loss of STEREO-B

The loss of science if STEREO-B is not recovered has been evaluated by the team and discussed at the senior review panel. It was argued by the team that nearly all of the science PSGs for which two senior reviews have decided to extend the mission previously could still be accomplished at least partly with one spacecraft. For the scientific objectives needing longitudinal coverage (e.g., PSG 2.2: lifetime of active regions, coronal holes), the loss of STEREO-B will not greatly affect the scientific return, due in part to the combination of STEREO data with SDO. However, there will be a loss of the EUV coverage of the west limb and an increased uncertainty in the 3D fitting of CME propagation. The combination with SOHO/LASCO can however still provide good coverage of CME propagating along the sun-earth's axis (space weather application). The major impact on the loss of STEREO-B will be for studies linked to radio bursts (longitudinal extent of type III bursts) and to the loss of observations of SEPs propagating in the direction of STEREO-B and which are the ones that are best connected to the earth (this would last until 2019). For space weather oriented objectives, there will be of course also a loss of the possibility to triangulate the CMEs which leads to a loss of accuracy in propagation angle and arrival time predictions. However, the combination of STEREO-A observations with SOHO/LASCO can still provide good coverage (see above).

STEREO Relevant Strengths to Heliophysics Research Objectives

The STEREO mission allows the monitoring and study of space weather from the Sun through the inner heliosphere. The mission therefore has a strong synergy with many missions of the heliophysics observatory as well as with some planetary missions such as MESSENGER and VENUS Express. Work has been done to be able to provide the solar wind conditions at the location of these spacecraft based in particular on the STEREO measurements. The research topics outlined in the STEREO proposal are highly relevant to the heliophysics research objectives since they are strongly linked to the understanding of the initiation, propagation and evolution of space weather events across the heliosphere.

STEREO Value to the Heliophysics Great Observatory

Due to its unique vantage point and its combination of remote sensing and in situ instrumentation, the STEREO mission has a major value to the Heliophysics Great Observatory and will continue during the extension of the mission, even if STEREO-B is lost.

New Opportunities in the Extended Phase of the Mission

With the launch of MAVEN, the extension of the STEREO mission will provide new opportunities to continue the exploration of CMEs, SEPS and space weather throughout the inner heliosphere up to 1.5 AU. STEREO-A can also act for some time as a test bed for the design of an L5 sentinel mission dedicated to space weather applications (early warning of perturbations arriving at the earth).

Therefore, in the extended phase, the mission will still have a very strong impact in the field of solar and heliospheric physics in combination with the other HSO missions (solar physics and interplanetary missions at 1 AU but also heliospheric missions such as IBEX and Voyager) as well as with planetary missions such as MAVEN.

STEREO Spacecraft / Instrument Health and Status

The main concern is the potential loss of STEREO B in October 2014.

The only other major spacecraft subsystem failures are the loss of the primary inertial measurement unit on STEREO-A (in April 2007) and the degradation of the same unit on STEREO B (starting in 2012). Backups were then used but the backup IMU also failed on STEREO B in January 2014. As a result, the pointing accuracy during scientific observations is now performed using the star trackers and the SECCHI guide telescopes. Instruments have continued to function nominally until superior conjunction.

STEREO Data Operations

The STEREO mission has produced a comprehensive set of coronal images and in situ time series data that are served from the mission archive at SDAC in addition to (for in situ products) both mission sites and the SPDF. The instruments are well documented, but specific data product documentation is difficult to find.

STEREO Proposal Weaknesses

In the case of the loss of STEREO B, the DSN contact time allocated to the two STEREO spacecraft is proposed to be used for STEREO-A alone which leads to the provision of observations with improved temporal and spectral sampling, improved imaging spatial resolution and less data compression. Doubling the contact time for the one spacecraft will allow new possibilities for science such as the study of the early triggering of CMEs, a better knowledge of the pitch angle distribution of particles, an increased possibility to study high frequency waves and turbulence, and new possibilities of 3D studies of jets and spicules in combination with SDO and IRIS. This would result in a marginal decrease of the budget.

The in guide budget is $9500 k. In the case of a two spacecraft mission, the proposed cost is unchanged for the PI team and project management except for inflation. The budget is under-guide for 2016–2018, over-guide for 2019–2020 and UNDER-GUIDE in total for the next 5 years. In the case of a single spacecraft mission, the budget would be under-guide for the extended period, but the savings would be marginal (in the case the same telemetry is used for only one spacecraft, which permits better quality data and the achievement of additional scientific goals).

STEREO Overall Assessment and Finding

Below are summarized the main strengths and weaknesses of the STEREO mission.

Strengths

- Unique measurements capabilities (measurements away from the Sun-Earth's axis, combination of in situ and remote sensing observations, heliospheric imager)
- Extremely productive scientifically
- Used for space weather applications (beacon mode)
- Constraints for models of the IP medium (such as ENLIL)
- Highly complementary to other missions of HSO
- Very active collaborations (international as well)

Weaknesses

The potential loss of STEREO-B would have a significant impact to the scientific productivity of the mission, but the expected science return of the mission is still high (see above), in particular in combination with the other HSOs.

STEREO Conclusions

The science return from the STEREO mission's instruments has been excellent in the past years. Future scientific returns of the mission by itself have been evaluated in the hypothesis of a one spacecraft and two spacecraft mission. The panel has found that if STEREO B is recovered, the contribution of the mission promise to be compelling (mean grade 8/10) for overall scientific merit although in the case of a single STEREO spacecraft the mean grade is down to 7 (excellent but less compelling).

The STEREO mission has a strong impact in the Heliophysics Great Observatory (even in the case of the loss of STEREO B). Even with only one spacecraft, the mission provides unique data (obtained at a unique vantage point) that largely contributes to our understanding of the whole heliosphere and brings a valuable contribution for many solar, planetary and interplanetary missions. This is revealed in the grade and ranking given to STEREO in the context of HSO contributions (median rate 8/10 for both one or two spacecraft missions, e.g., future contribution promise to be compelling).

4.10 THEMIS

General Overview of the Mission

THEMIS is a MIDEX mission consisting of a five-satellite constellation. It was launched in February 2007 into carefully planned orbits of varying apogee which resulted in the spacecraft regularly becoming radially-aligned at distances between 12 R_E and 30 R_E, with particular focus on the terrestrial magnetotail in order to target the key regions and underlying physics driving substorm dynamics. A key additional planned element of the mission was for the THEMIS probes alignments to occur when Canada was in the midnight sector in order to take advantage of a dedicated network of ground-based observatories which have provided highly valuable additional data to help address the mission science goals. After successfully completing this prime mission in 2010, the THEMIS proposed and implemented a split into three Earth-orbiting (THEMIS "low, " inside of 15 R_E) and two lunar orbiting (ARTEMIS) spacecraft groups to optimize its ongoing scientific return. Both parts of the mission have since contributed to the advancement of knowledge of geospace processes, for example by answering longstanding questions regarding the origin of discrete and pulsating aurora, electromagnetic energy conversion in the magnetosphere, magnetic reconnection, upstream transients, the elusive origin of plasmaspheric hiss, the propagation and effects of morning chorus, the lunar wake and exosphere and many others. The THEMIS probes continue to be a primary asset for wide-ranging studies of magnetospheric dynamics.

Overview on the Science Plan

The THEMIS science plan aims to build on several of the recent high-profile scientific discoveries from this mission. The science plan presents a coherent approach which proposes to derive results to further our understanding of physical processes occurring in, and coupling between, the regions of geospace that are visited by the 5 spacecraft as their orbits precess during the year. The plan has a high probability of success and the results promise to be high impact, addressing important outstanding scientific questions. The proposal includes a novel (over-guide) element to the plan which employs a new orbital configuration and embraces a strategy for optimal coordination between multiple missions in the Heliophysics System Observatory (HSO). In particular, this would be achieved through orbital maneuvers which maximize the science returns from combining THEMIS measurements with those from the Magnetospheric Multi-Scale (MMS) mission.

Recent observations in the nightside magnetotail provide new details of the presence of intense electric fields associated with fast Earthward flows and the generation of current systems which couple to the auroral ionosphere. The THEMIS guide-level science implementation plan involves raising of the apogee of the 3 near-Earth spacecraft in order to sample, with multi-point measurements, the region of the magnetotail beyond 12 R_E. These observations will allow the THEMIS science team and the extensive THEMIS science community to address science questions relating to how energy flux coupled from the interaction with the solar wind and/or from reconnection activity further tailward is rapidly transported through and/or dissipated in this region. Observations of such injections, whether they subsequently extend into near-Earth space and thus how they relate to physical processes occurring in the radiation belts (e.g., generation of the various waves which play a role in particle acceleration) provide a potential systems level connection to the Van Allen probes which directly sample this region.

Under this same orbital strategy, THEMIS will, at times when apogee is located on the dayside, directly sample transient phenomena such as hot flow anomalies, foreshock waves, pressure pulses and the effects of dayside reconnection. Of particular interest is determining the observational characteristics and downstream consequences of foreshock bubbles, a phenomenon whose occurrence was recently confirmed by THEMIS, following predictions derived from simulations. In this orbital phase, THEMIS will also seek to identify factors controlling the magnetopause reconnection rate, such as the presence of plasmaspheric plumes just inside of the magnetopause or the effects of merging outflow jets from multiple reconnection sites. These studies are again motivated by recent THEMIS results and will build significantly on them.

Next, we note that THEMIS science has continued to benefit from the powerful array of ground-based observatories built-up during the mission at high latitudes, and particularly in Canada. The coupling of magnetospheric flows into the high latitude ionosphere is detectable with these observations and thus they provide a more global picture of the magnetospheric dynamics. Recent GB observations suggest that small scale flows may rapidly cross the polar cap from day-to night-side. Seeking to understand the magnetospheric counterpart and drivers for these flows motivates, at least in part, the over-guide request for funding to control the orbits of the 3 near-Earth THEMIS probes in order to keep them optimized with both the Canadian sector GB assets AND the newly launched MMS mission. In particular, this over-guide science implementation plan seeks to coordinate the THEMIS orbit with maneuvers along track such that they remain in opposition to MMS at apogee. Thus THEMIS will be located in the nightside plasma sheet, magnetically conjugate within the GB arrays, when MMS is sampling the dayside magnetopause. Conversely, THEMIS will be at the magnetopause when MMS is positioned to observe reconnection sites in the tail. This coordinated approach represents a significant capability under the concept of the HSO with the potential to enhance both THEMIS and MMS science. For the relatively small additional operational cost proposed, the science return arising from this optimization of the orbits between THEMIS and MMS is expected to be significant. The configuration will, for example, enable the community to answer questions relating to how the driving of the system and global dynamics are affected by processes such as reconnection, which operate on the microscale but which can now be targeted by the very fast MMS observations of very small scales.

Finally, we note the contribution of the 4^{th} and 5^{th} THEMIS probes which remain in orbit about the moon (formerly operated as the ARTEMIS mission). Over a period of 4 days per month these spacecraft cross the more distant magnetotail (~60 R_E) and thus contribute to the HSO-related science questions above by observing the exhaust regions and/or providing a means to monitor the changing flux content of the magnetotail associated with the dynamics observed closer in. For the remainder of the month these probes sample the exterior solar wind plasma, contributing very significantly to our ability to monitor the direct and clean solar wind inputs from the region immediately upstream and which are responsible for driving magnetospheric dynamics. Such measurements from *directly* upstream of the Earth are not routinely available from the solar wind monitors which orbit the L1 Lagrange point. These spacecraft also sampling the foreshock region providing important information about how solar wind inputs are processed by the bow shock in advance of their impact on the magnetopause, including the effects of hot flow anomalies and other pressure structures which are generated as a result of this interaction.

THEMIS Science Strengths

THEMIS continues to be an exceptionally scientifically productive mission currently producing around 150 refereed papers per year, 2/3 of which are led by researchers outside of the THEMIS team and from around the world:

- THEMIS is a core mission for the magnetospheric community. The nature of the THEMIS orbit within the magnetosphere means that the spacecraft regularly sample key regions in the chain linking the solar wind, outer and inner magnetosphere and ionosphere. THEMIS thus forms a key element of the HSO. Data from the mission can hence be used to address a very broad range of topics, which is reflected in the published scientific return described in the proposal.
- The 5 instruments on each spacecraft remain healthy and can support full science for foreseeable future. Similarly all 5 spacecraft are working nominally and have sufficient fuel reserves to support the required orbital maneuvers in the proposed mission extension and beyond.
- The THEMIS team is both experienced in understanding/handling the instruments and generous in sharing their knowledge with external researchers (they have collaborated on a significant fraction of the papers published).
- Strong existing synergy/collaboration exists with a host of ground based assets, particularly in Canada but also further afield—this provides strong M-I coupling information and a means of establishing global links to the in situ data and which the THEMIS team have demonstrated can provide an exceptional integrated data set with which to drive scientific discovery;

THEMIS Relevant Strengths to Heliophysics Research Objectives

THEMIS addresses each of the 2014 SMD goals for Heliophysics:

a) Heliophysics Goal 1: “Explore the physical processes in the space environment from the Sun to Earth and throughout the solar system.” THEMIS makes key observations of fundamental physical processes, such as collisionless shocks, magnetic reconnection, particle acceleration, turbulence, wave-particle interactions, in the context of the geospace environment. The multi-spacecraft aspect of the mission allows these processes to be examined in multiple dimensions, on several scales and with the separation of temporal from spatial effects.
b) Heliophysics Goal 2: “Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system.” THEMIS provides a critical set of measurements in the chain of observations needed to establish the connections between the solar wind, magnetosphere, radiation belts and the

ionosphere. This is also critical to our broader interpretation and understanding of planetary, exoplanetary and astrophysical environments.

c) Heliophysics Goal 3: “Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.” THEMIS observations are relevant to addressing the physical processes which drive the ‘Space Weather’ phenomena which are increasingly understood to represent a risk to both human health and technology in space.

Moreover, the THEMIS over-guide proposal directly responds to the view expressed in the HPS Decadal Survey and NASA’s Science Plan that implementation of an Optimized HSO is imperative for the field of Heliophysics (see section 4 below).

However, it also provides strong potential synergy with the Van Allan Probes, TWINS, (Cluster, Geotail), IBEX and a host of ground-based observatories in the magnetospheric context, and with Wind and ACE in the context of the proposed studies of upstream transients, as well as with the solar observing missions (especially SDO, Stereo and Hinode) which provide monitoring of the solar source of the drivers of geomagnetic activity including coronal mass ejections and fast solar wind streams which can drive magnetic storms in geospace.

THEMIS Value to the Heliophysics Great Observatory

The in-guide science implementation plan provides for a number of potential synergistic observations between THEMIS and MMS, the Van Allan Probes, TWINS (Cluster, Geotail), IBEX and a host of ground-based observatories in the magnetospheric context, and with Wind and ACE in the context of the proposed studies of upstream transients. Solar observing missions, especially SDO, Stereo and Hinode, provide monitoring of the solar source of the drivers of geomagnetic activity. These provide opportunities in which chains of observations may occur to help understand the fundamental plasma physics processes shaping geospace in response to solar wind forcing, determine the factors controlling them, and to observe the global consequences of these processes, including the ‘Space Weather’ effects which are becoming of increasing concern to society at large.

However, as noted above, this extended mission proposal provides an explicit plan for active coordination between HSO assets, in particular with MMS. This over-guide element provides a high level of scientific return at modest cost and the panel ranks this very highly. This panel finds this to be a high priority for implementation. Indeed, this represents a significant level of engagement with the HSO concept—the highest priority goals are depending upon or benefitting from HSO coordination, in particular though aligning THEMIS science operations primarily with those of MMS, as well as with the Van Allen Probes. Specifically, the proposal details:

- Pro-active advance orbit planning and coordinated operations which maximize appropriate conjunctions as part of the HSO, rather than relying on fortuitous and coincidental conjunctions and a post-facto comparison of datasets which is the more common and less inventive and less scientifically productive approach.
- A comprehensive plan of orbital maneuvers/changes which place THEMIS probes in regions which have potential scientific value due to their connection with other regions

simultaneously sampled by MMS and the Van Allen Probes. Changes would be made to reflect developments in the MMS prime mission orbital plan including changes in the along-track orbital motions to ensure MMS and THEMIS reach apogee at the same time. Appropriate control of separations and configuration of the 3 THEMIS probes is also proposed, including apogee raise maneuvers, to best meet science goals.

- An overall proposed optimization of the THEMIS/MMS/GBO assets resulting system level coordination. The result will be the operation of a significant part of the HSO in which explicit planning for mission conjunctions will allow regular periods of powerful global coverage and dedicated data gathering campaigns for SW-magnetosphere-ionosphere coupling studies.

Finally we note that the THEMIS data analysis software (TDAS) is being developed into a more global tool for the community in the form of the Space Physics Environment Data Analysis Software (SPEDAS) under the leadership of the THEMIS team. This is beginning to become adopted as a standard for other missions (Van Allen Probes, MMS), promising enhancing capacity for inter-comparison of datasets within this part of the HSO concept.

THEMIS Spacecraft / Instrument Health and Status

All 5 of the THEMIS/ARTEMIS probes remain healthy and operating nominally. There are sufficient fuel reserves, including those required for de-orbit, to undertake the series of maneuvers proposed to place THEMIS in the optimum orbits for active coordination with the MMS mission, and for the scientific investigations necessitating a raising of the apogees of the near-Earth probes. The mission team report in the proposal all subsystems are effectively performing as good as new. Some minor technical issues (micrometeoroid severage of one of P1's EFI wire boom spheres in 2010, a helium bubble in a P4 tank and oxidization of the EFI spheres on P5) have appeared during the mission lifetime, but these have been resolved with workarounds and without any science degradation.

THEMIS Data Operations (accessibility, quality control, archiving)

THEMIS data operations continue to be the exemplar for prompt dissemination of data products to the community, high quality of the data products, ease of access and data archiving. In addition, the dedicated THEMIS mission-developed software is being rolled out and used by other missions. Testament to the outstanding efficiency of the THEMIS data operation overall is provided by the scientific return from the worldwide community, which is currently running at around 150 THEMIS-based papers per year in the refereed scientific literature.

THEMIS Proposal Weaknesses

This senior review panel had some difficulties with the format of the THEMIS proposal. The proposal documented an outstanding science return since the last senior review. It argued in general that these results motivated the proposed future activity and generally promised compelling operations in conjunctions with other missions within the HSO. However, the proposal did not adequately set out science questions as Prioritized Science Goals (PSGs), as every other extended mission proposal had done. The panel felt that the PSGs addressed by the

THEMIS proposal were, in fact, rather more 'prioritized methodologies' and 'prioritized spacecraft operations'. Although science targets were presented within the achievements section and within the context of the proposed operational plans, the details of the prioritization of the underlying target scientific questions, and the motivation and timeliness were not presented very clearly. The panel would have appreciated a more explicit development of the future science case and more details of how the proposed (and costed) mission operations would lead to closure of priority science questions.

THEMIS Overall Assessment and Findings

The panel noted the ongoing high level of impact and exceptional scientific output of the THEMIS mission, the strong involvement of the community in pursuing THEMIS mission science, and the core role which the THEMIS mission plays within the geospace element of the HSO, in particular for understanding the processing, input, transport and dissipation of energy from the solar wind into the magnetosphere and ionosphere. The panel noted the importance of funding for the THEMIS team to continue to support and coordinate community research. The panel also noted the strong commitment of the THEMIS team to the SPEDAS effort which is being prioritized and led by the team towards this goal.

The panel noted that the preferred implementation of the extended mission proposed by the THEMIS team in their science plan represents a significantly over-guide bid. At the same time, the panel noted that the guide level itself represents a fairly large cut from the present level of funding awarded to the team, but understood that the previous THEMIS mission budget had been awarded over-guide in recognition of the finding of the previous Senior Review which encouraged the coordination of THEMIS operations with the then upcoming MMS mission in the context of the HSO. This remains highly valued by this panel as an activity for the upcoming extended mission phase, since the panel find that the over-guide plan of the THEMIS team to deliver coordinated operations with MMS is likely to lead to significant returns at modest cost. The panel further noted that the team has already absorbed significant reductions below the 'two thirds of prime mission costs funding level' specified by NASA's extended mission paradigm, and the proposed in-guide budget would represent a further significant reduction to THEMIS funding in that context, with a detrimental impact on the science return.

The panel also recognized that in a cost constrained environment, funding for extended mission phases should reflect an increasing proportion of the scientific return being derived from researchers outside the mission science team, especially in the later years of extended mission operations. However, the panel acknowledges that an award at the guide level would necessitate a further and very significant (~50%) reduction to an exceptionally productive science team which would have a very detrimental effect on the scientific output from the mission and which is not considered desirable. Moreover, the proposal also indicates that implementation at the new guide level would place the unique opportunities for valuable coordination with the newly-launched MMS mission at risk.

The panel finds that it is imperative to fund ~50% of the over-guide request of $600k for science team activities, in mitigation of the risk to the vitality of the team, and to secure the continuation of the exceptional scientific output from the highly successful THEMIS mission. Consistent with the finding of the previous Senior Review, the panel also is convinced that a coordinated approach to science activities with MMS within the HSO remains highly compelling. The panel finds that a means to award this over-guide element ($300k) of the proposed program would be very highly desirable.

However, the proposal did not make a sufficiently compelling case for the other elements of the over-guide bid. The panel is enthusiastic about the development of the SPEDAS software for integrating multi-mission data but does not support the mission's over-guide request for continuing the development of this tool in the current MO&DA financial climate. The panel notes however that there are competitive grants programs that could be the source of funds for continuing the development of SPEDAS. Thus this and the other elements of the over-guide proposal are not considered as high priority and the panel finds that these should be met, as currently, on a best efforts basis and without the award of the associated additional resources.

THEMIS Overall Grade

Overall, the panel rated the proposed extended mission for THEMIS as 7 (excellent) for future mission science and 8 (compelling) for contribution to the Heliophysics System Observatory.

4.11 TIMED

General Overview of Mission

The Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) spacecraft was launched in 2001 into low earth orbit to make remote sensing measurements of the solar extreme- and far-ultraviolet forcing and the response of the Earth's ionosphere, thermosphere and mesosphere (ITM). TIMED contains a solar flux monitor (SEE) and three earth oriented remote sensing instruments (SABER, GUVI and TIDI) to measure the temperature, composition, dynamics and energetics of the ITM. The PIs describe TIMED as the "terrestrial anchor" of NASA's Heliophysics System Observatory (HSO). TIMED has accumulated a significant database of solar and ITM measurements from the second half of SC-23 up through the peak of SC-24. The experiment team proposes to continue their observations through 2020, which will allow characterization of the declining phase of solar cycle SC-24. The mission has amassed an important and unique database (altitude profiles and column densities) of the following state variables of the upper atmosphere and ionosphere:

Instrument	Sensed Parameters
GUVI Global Ultraviolet Imager	Daytime thermospheric temperature, O, N_2, O_2, O/N_2, precipitating particles, characteristics energy and fluxes, and effective solar EUV fluxes
SABER Sounding of the Atmosphere using Broadband Emissions Radiometry	Temperature, pressure, density, O_3, H_2O, CO_2, O, H densities and mixing ratios; CO_2 15.4 and 4.3 µm, O_3 9.6 µm, NO 5.3 µm, H_2O 6.8 µm, OH 2.0 and 1.6 µm emission rates, solar and chemical heating rates, IR cooling rates
SEE Solar EUV Experiment	Solar spectral irradiance from 0.1 to 194 nm
TIDI TIMED Doppler Interferometer	Horizontal vector winds, $O_2(1\Sigma)$ airglow emission rates

Overview of the Science Plan

For the extended mission the experiment team has developed the following PSGs:

1. Characterize, compare, and study the ITM drivers and response differences between SC-23 and SC-24,
2. Determine and understand the ITM long-term decadal-scale changes and discern between anthropogenic and natural forcings,
3. Investigate the whole atmosphere hydrogen budget and transport, and
4. Gain new insights into the ITM response to geomagnetic storms through collaborative studies with GOLD, ICON and other HSO missions.

PSG (3) is a new goal from the previous Senior Review. This proposal has more explicit plans to coordinate with GOLD and ICON, as their launch dates come closer and this proposal shifts the focus to geomagnetic storms. For each PSG they have identified a good list of Key Science Questions to help focus their investigation. The TIMED PSGs are closely coupled to all four Atmosphere-Ionosphere-Magnetosphere Interactions (AIMI) areas of the 2012 Heliophysics Decadal Strategy (HDS) which include:

- AIMI-1: Understand how the ionosphere thermosphere system responds to, and regulates, magnetospheric forcing over global, regional and local scales.
- AIMI-2: Understand the plasma-neutral coupling processes that give rise to local, regional, and global scale structures and dynamics in the AIM system.
- AIMI-3: Understand how forcing from the lower atmosphere via tidal, planetary, and gravity waves, influences the ionosphere and thermosphere.
- AIMI-4: Determine and identify the causes for long-term (multi-decadal) changes in the AIM system.

TIMED Science Strengths

The close alignment between TIMED capabilities, PSGs and the HSG AIMIs is seen a strength of the mission. Observations from the mission so far have helped separate the difference between solar and terrestrial forcing (gravity waves, tides, sudden stratospheric warmings, etc.) on the upper atmosphere and ionosphere during a time of unusually low solar activity. This has been fortuitous for TIMED since the solar forcing normally dominates forcing form the lower atmosphere. SC-24 continues to be unusually low which will allow additional comparisons and characterization of the anthropogenic effects which is the focus of PSG 2. SABER CO_2 and NO measurements and calculated cooling and heating rates provide valuable insights into the global thermal balance of the upper atmosphere.

The SABER measurements of waves and tidal structures have firmly established a strong connection between the lower atmosphere and upper atmosphere including: El Nino effects, sudden stratospheric warmings, quasi-biennial oscillation, and others.

PSG 3 focusing on hydrogen and hydrogen escape is synergistic with AIM and TWINS and should provide insights into space hydrogen in the upper atmosphere and polar mesospheric clouds.

There should be great value in coordinated measurements and science between TIMED, GOLD and ICON. Like TIMED, ICON is closely aligned with the HDS AIMI goals. TIMED can measure a number of state variables important to ICON and GOLD consistent with PSG 4.

TIMED Relevant Strengths to Heliophysics Research Objectives

The relevance of TIMED to the HP Research Objectives continues to be high and the PSGs are closely aligned with the HDS AIMI goals.

TIMED has continuing value to the HP Great Observatory and the experiment team's claim that their mission is the "Terrestrial Anchor of the Heliophysics System Observatory." TIMED observations have synergy with almost all of the HSO missions (except Voyager).

TIMED Spacecraft / Instrument Health and Status

The spacecraft and all four instruments are functional although not as healthy as earlier in the mission. Overall, the instrument suite capability appears to be sufficient to meet the PSGs as proposed. The SABER instrument appears to be in the best health and is clearly the "Jewel in the Crown" of TIMED mission. The GUVI scan mirror has been inoperable since 2007 making this instrument a fixed staring spectrograph looking at 30 degrees off nadir. The GUVI team has taken advantage of this abnormality and now NO column densities from GUVI spectra have been added as a measureable to the mission list. The proposal only showed one global map of NO column density but it was difficult to determine the value of GUVI NO measurements, especially compared to SABER NO measurements. There are still references to GUVI measurements of scintillation regions, i.e., measurements of airglow depletions from ionospheric bubbles, but it is hard to assess the quality of this data contribution to the mission without a scan mode. The GUVI instrument appears to still be capable of providing information on thermospheric density variability.

Apparently the TIDI performance has improved from what it was early on in the mission. The proposal refers to several examples of TIDI measurements in collaboration with other data but the PSGs do not depend strongly on it.

The SEE instrument measures the solar EUV and FUV flux daily but only has a 3% duty cycle.

TIMED Data Operations (accessibility, quality control, archiving)

The TIMED spacecraft has been operational for more than a dozen years and data acquisition and processing appears to be autonomous. JHU/APL operates the TIMED Mission Operations on site and data are processed and archived in accordance with the TIMED Mission Archive Plan (MAP) discussed in their Appendix I. Most of the labor is invested in processing and archiving SABER data. Science products from each of the instruments are produced on a continual basis and the plan is to transition all the data to the SPDF within 150 days after the end of the mission. It is not clear from what functionality will be preserved at that time. Additionally, there is an issue with their NetCDF formats and how the data can be used in the future.

TIMED Proposal Weaknesses

This mission is becoming a one-sensor mission with SABER as the dominant sensor. The role of the other instruments, TIDI, SEE and GUVI is limited. SEE has only a 3% duty cycle and it is not clear of the importance of SEE data to the overall mission. GUVI can only view at a single look angle and its value to the mission is limited.

TIMED Overall Assessment and Findings

During its lifetime the TIMED mission has produced an important set of state variables (density, temperatures, dynamics, composition and energetics) of the mesosphere, thermosphere and ionosphere and has produced a number of discoveries in multiple areas. The mission has helped established connections between the lower and upper atmosphere in comparison to solar forcing. The low activity in SC-23 and SC-24 has really helped make this possible. The experiment team claim that they are the “terrestrial anchor” of the HSO is valid—at least until GOLD and ICON complete much of their science. The TIMED science is providing important insights into the thermodynamics of the upper atmosphere and climate change.

The publication rate is good and dominated by investigators outside the TIMED experiment team. The number of publications increased significantly from the previous senior review indicating the use of a new algorithm to assess publication productivity. The overall publication rate is about 180 papers per year and has steadily increased since launch and may have reached a steady state.

The median panel score for the TIMED extended mission was 8/10 for Overall Scientific Merit, placing it in the group of “Compelling” proposals. TIMED’s median panel score was 7/10 for contributions to the HSO placing it in the "Excellent, but less compelling" category. The Panel supports the continued operation of the TIMED mission.

4.12 TWINS

Overview of the Science Plan

The TWINS extended mission for 2016–2020 aims to continue 3D imaging of global ion dynamics, composition, and densities from two spacecraft on two separated orbits that each perform Energetic Neutral Atom (ENA) imaging and Lyman-alpha imaging of exospheric hydrogen atoms. The TWINS science plan continues a program of 10 overlapping science investigations covering 6 science topics. The science topics are divided into two categories: broad and targeted (3 broad and 3 targeted). Each topic comprises specific Prioritized Science Goals (PSGs) for a total of 16 PSGs. These Science plans are summarized below:

Broad Topic A. The Global 5-Dimensional Ring Current (RC)

- A-1. Determine the global (3D spatial) distribution of RC ion intensity and pitch angle (PA).
- A-2. Determine the relative importance of different physical mechanisms governing RC formation and decay.
- A-3. Determine how physical processes and evolution of the RC are important for other particle populations such as electrons of the Van Allen Belts.

Broad Topic B. Ring Current and Plasma Sheet Energization

- B-1. Determine how the RC & plasma sheet respond differently to different types of storms (CIR and CME-driven).
- B-2. Determine how the RC & plasma sheet response vary throughout the solar cycle.
- B-3. Reveal the average and extremes of the high-altitude, high-latitude ring current, plasma sheet, and cusp.

Broad Topic C. Ion Precipitation

- C-1. Determine the global distribution of ion precipitation (from the ring current, plasma sheet, and cusp).
- C-2. Uncover the causal relationships linking the dynamics and energetics of precipitating and trapped ions.

Targeted Topic E. Ion Temperature

- E-1. Determine the local time and radial dependence of magnetospheric ion temperature (RC and plasma sheet).
- E-2. Determine whether particle transport explains global temperature features.
- E-3. Discover the global dynamical connection between plasma sheet and RC temperature.

Targeted Topic F. Neutral Hydrogen Exosphere

F-1. Determine the global 3D spatial dependence of exospheric H atoms as revealed by geocoronal (Ly-alpha) imaging.
F-2. Discover whether the observed antisunward-pointing geocoronal tail ("geotail") can be populated by solar wind ions penetrating the magnetopause and undergoing charge stripping.
F-3. Determine the relative contributions of ballistic, orbiting, and escaping atoms to the exospheric distribution.

Targeted Topic G. Ion Composition

G-1. Discover the altitude (trapped vs. precipitating) dependence of ion composition.
G-2. Determine the dynamic linkages among ionospheric, RC, and plasma sheet ion composition, and what these linkages reveal about the responsible physical mechanisms.

TWINS Science Strengths

TWINS' unique observational configuration and measurements provide the capability to address important questions articulated in its 16 PSGs. In particular, TWINS will enable investigation of the distribution of the extended neutral hydrogen (H) exosphere and the relative contributions of hydrogen and oxygen to the terrestrial ring current (RC) and plasma sheet, i.e., basic properties of key components of geospace. TWINS will specify the 3D spatial, energy, and pitch angle distributions of the RC, whose dynamics defines geomagnetic storms. The extended mission will elucidate how the RC and plasma sheet are energized during different phases of the solar cycle. It will also enable studying the global dynamic linkages between magnetospheric (high-altitude) and precipitating (low-altitude) ions.

TWINS Relevancy Strengths to Heliophysics Research Objectives

TWINS' simultaneous imaging of a broad region of geospace can advance our understanding of the global connectivities and causal relationships between processes in different regions of the magnetosphere at a wide range of spatial and temporal scales. TWINS quantifies ring current processes (energization and heating, precipitation, and composition) across large portions of the magnetosphere, from the magnetotail into the inner magnetosphere and down to the ionosphere. The ring current's global evolution is a basic defining characteristic of the Sun-Earth interaction as manifested by geomagnetic storms and space weather. The proposed science objectives map to two of the Heliophysics Decadal Survey science goals: TWINS determines the dynamics and coupling of Earth's magnetosphere, ionosphere, and exosphere, and their response to solar inputs; TWINS imaging helps explore two fundamental (and universal) physical processes in the space environment: particle acceleration/transport, and charge exchange. Furthermore, TWINS develops knowledge and capability to detect and predict variability and extremes of the space environment, through investigations that target the dependence on storm type, storm phase, season, and solar cycle.

TWINS Value to the Heliophysics Great Observatory

TWINS' global ENA imaging capability has synergy with other HP Great Observatory missions that perform in situ (single-point or multi-point) measurements by providing synoptic contextual information that amplify the value of local (single-point or multi-point) measurements by placing them in a global macroscopic context in relation to the many coupled geospace phenomena. Embedded within some of the science investigations of the TWINS extended mission are a number of multi-mission collaborative studies that include other members of the HSO.

Synergistic studies using TWINS, THEMIS, Van Allen probes, and MMS can achieve cross-scale knowledge of reconnection, ring current and radiation belts, gaining insight into the relationship between RC seed populations and outer belt energization. This constellation enables simultaneous measurement of the solar wind input and the global and local geospace response, tracking the flow of energy from the dayside to the nightside and into the inner magnetosphere and ionosphere. Van Allen probes can extend this multi-scale, multi-region knowledge to include composition. Inclusion of MMS data can reveal the timing and energetics of dayside input with respect to the magnetospheric response. Correlation of TWINS inner magnetospheric imaging with IBEX imaging of the day-side magnetosheath, magnetosphere and cusp, and the night side plasma sheet from tens of RE outside the magnetosphere can provide additional information regarding the timing and causal linkages governing ion transport and energization.

TWINS Spacecraft / Instrument Health and Status

The 2 TWINS host spacecraft are expected to continue to perform nominally through the 5-year horizon of this Senior Review. The ENA sensors on both spacecraft are operating well and continue to return high quality data. A temporary anomaly encountered in the TWINS 2 actuator motion was resolved in early 2014 by a routine recovery procedure. During the period 2013–2014, the TWINS 2 LAD response degraded. TWINS 1 LAD continues to function nominally and is fully adequate to support continued science.

TWINS Data Operations (accessibility, quality control, archiving)

TWINS data are primarily accessed via the web-page http: //twins.swri.edu, in the form of either summary browse plots/images, or a custom plotting/downloading interface. The Level 1 TWINS data are also hosted by CDAWeb. The TWINS Legacy Mission Archive Plan has been implemented since 2013. Required data products (science data, software, and documentation) are delivered and/or routinely archived, and all data are prepared for Final Archival at the end of the mission. Simultaneous hosting/serving of TWINS data at both the TWINS page and CDAweb is intended to continue for as long as the TWINS Science Operations Center (SOC) exists.

In response to the 2013 Senior Review, ENA inversions (a Level 2 data product) are provided to the broader community "as available." However, this data product appears to be provided on a per-request-basis only, rather than a systematic, documented product describing the algorithms and assumptions. This panel notes that such important information needs to be made explicitly available as part of the Level 2 data product. Also, the panel finds that it is important that the TWINS team dedicate efforts to ensure that the reduced support for science operations data quality checks, implemented after the 2013 Senior Review, will not impact the data quality deleteriously.

In 2014 the TWINS mission began hosting the TWINS Storm Catalog at http://twinsstorms.swri.edu/, where members of the science community can access TWINS plots from an ensemble of large CIR and CME driven storms.

TWINS Proposal Weaknesses

While TWINS continues to provide unique and highly valuable observations of the geospace environment, the scientific productivity resulting from the mission appears relatively meager compared to other heliophysics missions of similar scope and seems confined mostly to the efforts of the mission science team. This is also apparent from the relatively low number of dissertations resulted from TWINS and a small number of educational institutions involved with scientific analysis of TWINS data. The expansion of the broader scientific community involvement in utilizing the TWINS data more extensively might be best realized through a Guest Investigator program.

TWINS Overall Assessment and Findings

The TWINS extended mission was ranked Excellent in Overall Scientific Merit by the Panel with a median score of 7. The combination of the relatively low cost of operation together with the great value of its unique and synergistic observations highly justify continuation of the extended mission. The median panel ranking for the value to the HSO is 7. Both scores place TWINS in the lower half of the Excellent category. The panel supports the continued operation of the TWINS extended mission.

Given the value of the TWINS dataset, but noting the already very constrained TWINS in-guide budget, the panel is supportive of increasing the TWINS science budget (increase of $100k) in order to provide the resources necessary to address the routine availability and usability of fully processed TWINS data products. Therefore the panel finds it important that NASA HQ to find additional funds to address this need in the TWINS program.

4.13 Van Allen Probes

General Overview of Mission

The Van Allen Probes two spacecraft mission operates from a low inclination orbit in the inner magnetosphere. Each spacecraft carries an extensive suite of in situ particle instruments spanning a wide range of energies, together with electric and magnetic field sensors, to examine the wave-particle interactions which control the acceleration transport and loss of energetic particles in the Earth's ring current and radiation belts. The mission completed its two year prime phase on 31st October 2014, having met all level 1 requirements. Following the declaration of Mission Success on 26th March 2014, the mission was granted a bridging phase to align the program with the schedule for this Senior Review. This is the mission's first proposal for extended phase operations.

Van Allen Probes Overview of the Science Plan

The Van Allen Probes team describes a focused science plan targeting the understanding of the dynamics of the inner magnetosphere and radiation belts for the extended phase operations of the two NASA Van Allen Probes. The proposal outlines three Prioritized Science Goals (PSG) addressing high profile and high impact science targets which build upon and exploit the already impressive discoveries obtained using mission data thus far. As defined in the proposal these PSGs focus on developing understanding of:

i. The relative roles of local verses transport mechanisms of particle acceleration and the role that nonlinear mechanisms play in the acceleration process.
ii. The relative importance of precipitation and magnetopause losses of energetic particles in the inner magnetosphere and provide more definitive information about the causes and consequences of the precipitation.
iii. The relative roles of global-scale transport processes and mesoscale dynamic injections in the inner magnetosphere and their relative roles in the production of geo-effective waves.

Each of these PSGs was further broken into two specific questions, on each of which there promises to be a high likelihood of successful closure during the extended mission.

The satellites and instrument suites are all in excellent health, with sufficient fuel for optimization of orbits during the extended mission operations and for maintaining the required sun-pointing alignment of the spacecraft spin axis. The team proposes a careful and fuel-efficient approach to maximizing scientific returns from optimized probe orbits, including separating the probes further in azimuth for the diagnosis of wave and shock propagation interactions. The proposed change in apogee will increase the probe lapping rate thereby increasing the frequency of close conjunctions. The team will also minimize the distances of closest approach along the same field line through careful along-orbit phasing. Overall, the operations planning will enable new scientific discoveries in the new mission configuration utilizing new data collection and burst modes and increased data bandwidth to the ground.

The upcoming declining phase of the solar cycle is also expected to provide new and additional information about the solar cycle dependence of inner magnetosphere dynamics, especially from the expected changing conditions from CMES to CIR solar wind drivers arising from solar trans-equatorial coronal holes in the transition from solar maximum to the declining phase. The unusual solar asymmetry in the dynamics of coronal holes and active regions in the northern and southern hemispheres of the Sun during this solar cycle maximum also represent important and unusual conditions which may change the way the radiation belts respond during the solar cycle. Overall, the team presented a truly compelling science case for the extended phase operation of a mission which has already delivered a fantastic science return from data of uniquely high quality, cleanliness and energy resolution.

The team also proposes clear and significant interactions with other mission assets in the Heliophysics System Observatory (HSO), as well as with ground-based arrays during the extended mission. Moreover, coordination with a number of upcoming cube satellite missions which are scheduled to fly during this period will provide critical new information about particle precipitation into the atmosphere. Despite the expected availability of precipitation data from such cube satellite missions, however, the panel also noted the teams stated desire to seek "*more definitive information about the causes and consequences of precipitation.*" Since the loss cone is too small to resolve in Van Allen Probe data, particle dynamics related to the transition from trapped trajectories to entry into the loss cone cannot be measured directly. The team does propose to use modeling of the dynamical variations of particle distributions during wave-particle interactions to infer the causative action of scattering loss into the atmosphere. However, as the team note in their proposal: "*For precipitation losses, we need more opportunities than those afforded by the two 1-month BARREL campaigns to obtain coordinated near-equatorial and precipitating flux.*" The panel is supportive of meeting this need during extended mission; however, the panel noted that flights like those of the BARREL balloon campaigns which were available during the prime mission phase are not currently base-lined for the extended mission.

Finally, the expected launch of the Japanese ERG satellite in the summer of 2016 provides further opportunities not only for multi-point characterization of inner magnetosphere dynamics, but will provide important complimentary measurements from higher magnetic latitudes.

Van Allen Probes Science Strengths

- There has been excellent, high impact and extensive scientific productivity from the mission team, producing scientific discoveries which address all of the prime mission science objectives in over 150 scientific publications to date.
- The mission team proposes follow-on extended mission science which has excellent traceability to new targeted priority science goals and which build on earlier high profile discoveries arising from the prime mission phase.
- The science case for the extended mission is well-made and compelling. It exploits the new scientific knowledge developed in the prime mission, and promises significant and high-impact science returns in this first extended phase of mission operations.
- The mission subsystems and payloads are all operating optimally and returning spectacular data. The data from the energetic particle instruments are especially significant being of un-paralleled resolution and cleanliness.
- The team proposes careful use of limited fuel resources to maximize close conjunctions and periods with increased azimuthal probe separation to deliver an unprecedented characterization of wave-particle and shock-stimulated particle interaction processes.
- Strong synergy with other HSO assets, especially those operating in geospace (e.g. MMS and THEMIS), as well as with those monitoring both solar activity (e.g., Stereo, SDO and Hinode) and the incident solar wind (ACE and Wind). The Van Allen Probes orbit enables data collection from a key region which serves as a pathway for energy transport and a reservoir for energy storage in energetic particle populations in the inner magnetosphere. The ultimate loss of these trapped energetic particles through precipitation into the atmosphere also represents a key element of the energy budget for ionospheric and atmospheric dynamics.

Van Allen Relevant Strengths to Heliophysics Research Objectives

The Van Allen Probes provide a strong contribution which addresses each of the 2014 SMD goals for Heliophysics:

Heliophysics Goal 1: “Explore the physical processes in the space environment from the Sun to Earth and throughout the solar system.” The Van Allen Probes represents a voyage of discovery to the inner magnetosphere, targeting the wave-particle interactions responsible for controlling the dynamics of the energetic particle populations in the radiation belts and ring current. The mission seeks to discover, ideally to the point of predictability, the dominant physical processes which control the transport, acceleration and loss of energetic particles of up to relativistic energies.

Heliophysics Goal 2: “Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system.” The Van Allen Probes mission samples the critical region of the inner magnetosphere which is coupled to solar wind drivers though the higher altitude magnetosphere and magnetotail; the precipitation of energetic particles from the Van Allen belts into the ionosphere and atmosphere as a result of wave-particle scattering into the loss cone also represents an important component of the energy budget in those regions.

Heliophysics Goal 3: “Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.” The primary goals of the Van Allen Probes mission is focused on understanding, ideally to the point of predictability, the dynamics of highly penetrating relativistic particles which constitute the population of particular radiation which is trapped in the Van Allen belts. The extremes of radiation levels in the belts represent a threat to the operation of electronic systems and subsystems on satellites and spacecraft, as well as a threat to astronaut health.

Van Allen Probes Value to the Heliophysics Great Observatory

Van Allen Probes is very evidently driving new scientific discoveries from the assets in the HSO. There are clear connections and strong synergies with important supporting HSO observations such as those from ACE and Wind (and DSCOVER) in the upstream solar wind, those monitoring of the driving conditions at the Sun (e.g., Stereo, SDO, Hinode), as well as those making in situ observations elsewhere in the magnetosphere such as with THEMIS and MMS. The Van Allen Probes mission focuses on the scientific processes which control the transport, acceleration, storage and loss of energetic particles trapped in the ring current and radiation belts, which are strongly coupled to different plasma and particle populations in the magnetosphere. Thus concurrent observations of, for example, the plasma sheet, which can act as the source particle population for the radiation belts and ring current, are highly valuable at system level. Furthermore, other HSO assets in elliptical orbits offer additional high-cadence passes through the inner magnetosphere, thereby providing not only higher temporal cadence cuts through the inner magnetosphere but also additional MLT coverage. Similarly, tail and magnetopause dynamics may control the generation and entry of source populations, and shocks and waves which propagate through the system and influence energetic particle dynamics. All of these benefit from the availability of multi-point measurements from the geospace fleet of satellites in the HSO. Finally, precipitation of energetic particles into the atmosphere can affect ionospheric and atmospheric dynamics, for example through their impacts on NOx and HOx pathways. Despite the importance of the Van Allen Probes within the HSO network, and its value for monitoring the energy flow though the solar-terrestrial system, the Van Allen Probes will have their greatest impact through driving new scientific discoveries relating to radiation belt science within the HSO.

The team's proposal mentions that the high geometric factor MMS particle instruments will provide data to be used to target local monitoring of magnetopause shadowing losses at energies of up to 1 MeV. If the MMS instruments indeed have sufficient cadence and sufficient energy coverage that intervals of radiation belt particle impacts on the magnetopause, and thereby direct magnetopause shadowing loss, can be resolved then this could offer significant new additional science return for the Van Allen Probes mission within the HSO.

The panel also noted the value of the Van Allen Probes data for space weather, including the broadcast of the real-time space weather beacon from the spacecraft. The scientific focus of the Van Allen Probes mission on relativistic and ultra-relativistic particles is also of great interest for the space weather goal of forecasting the harsh space radiation environments – not least because these can impact the operations, and in some cases can cause the total failure, of satellites as a result of space radiation effects.

Van Allen Probes Spacecraft / Instrument Health and Status

Both Van Allen Probes remain extremely healthy and all instruments are operating nominally. There are sufficient fuel reserves for the proposed maneuvers during the extended mission as well as to maintain the spacecraft spin axis pointing towards the Sun. This is the first extended mission for the Van Allen Probes, following the successful completion of their prime mission, and the data from the mission continues to deliver scientific discovery of the highest quality with a payload functioning as it did immediately after launch.

Van Allen Probes Data Operations (accessibility, quality control, archiving)

The data from the mission are of extremely high quality, and the high-energy particle data is exceptionally clean and of very high energy resolution representing probably the best radiation belt data ever collected. The extensive scientific output from the mission is testimony to the high caliber of the data, and the quality control within the team is exemplary. Following the successful commissioning and calibration of the instruments in the prime mission, the Van Allen Probes team has applied considerable effort to deriving the best possible calibration and cross-calibration of the instruments. This included cross calibration between the probes, as well as inter-calibration between the particle instruments across energy boundaries, especially between MAGEIS and REPT.

The data are being made widely and openly available from all of the instruments through a broad range of platforms, including from the mission instrument team web sites, through CDAWeb at SPDF, and increasingly through SPEDAS and the relevant VxOs, etc. As a result, the data are being widely used to drive scientific discovery. However, the panel noted that many of the individual instrument teams are using their own different preferred data analysis platforms and that the analysis of data from multi-instruments would be aided by a more coordinated approach. Ideally, this would enable single point data access in formats easily integrated and analyzed with a common analysis package. The panel notes that the Van Allen team is aware of this need and is taking steps to rectify it. Nonetheless the panel believes that the Van Allen Probes team needs to undertake additional efforts in the extended mission phase to make all instrument data easily accessible from a single location. This should be in a form that can be easily ingested into a common data analysis platform for all of the instruments in the payload. More information and the availability of more extensive documentation about the content of data files and processing options at the mission web site would also be valuable.

Van Allen Probes Proposal Weaknesses

None noted.

Van Allen Probes Overall Assessment and Findings

The panel noted the great impact and exceptional scientific returns derived from the Van Allen Probes mission in its prime mission phase. The panel further noted the compelling science proposed for the extended mission phase, which both builds on the extensive scientific discoveries from the prime mission and which utilize new and optimized orbital configurations including new data and burst modes and benefit from increased data rates to the ground. Together with existing and new assets in the HSO, as well as through coordinated operations with a number of upcoming cube satellites and the Japanese ERG mission the panel finds the proposal compelling and expects a significant ongoing level of high impact science returns from the mission.

The panel finds that additional balloon campaigns during the extended mission would deliver a significant scientific return at a modest cost, perhaps using the operational, planning and hardware designs, and infrastructure developed during prior BARREL campaigns,. The panel encourages NASA HQ to work with the Van Allen Probes and BARREL teams to examine the possibility for further coordinated balloon flights during the extended mission. Although the Van Allen Probes team highlights the possible use of data from upcoming cube satellite missions towards the precipitation science goal, the panel finds that additional information, which could be derived from X-ray measurements characterizing electron precipitation on high altitude balloons, would be extremely valuable during the extended mission phase.

The panel also noted that the mission operations and management budget appears to be comparatively large. However, the panel also recognizes that the basis of these operational costs may been defined to a significant degree by the operational design implemented for the mission prime phase amd are projected to be carried over into the extended phase. The panel believes that a focused review by a panel of experts of the mission’s work breakdown for operations, engineering, management, etc., would help to clarify areas of the mission that may contain potential for more efficient work and commensurate lower costs during future mission extensions. Such analysis recognizing that design decisions made for implementation of the prime mission may constrain the savings that can be achieved during the extended mission phase as well.

Van Allen Probes Overall Grade

Overall, the panel rated the proposed extended mission for Van Allen Probes as Compelling (median score 9) for future mission science and Excellent (median score 7) for contribution to the HSO.

4.14 Voyager

General Overview of the Mission

The Voyagers continue to surprise and excite scientists with new discoveries as they continue their exploration of the distant heliosphere and now the local interstellar medium. The consensus is that, from the end of September 2013 Voyager 1 (V1) is past the ultimate boundary of the solar system and the interstellar medium, the heliopause and now is exploring the local interstellar medium as influenced by the heliosphere. Voyager 2 (V2) is still in the heliosheath (HS)—the region between the termination shock and heliopause (HP) and is expected to cross the HP within the next couple of years. The Voyagers measure plasma, high-energy charged particles over a wide energy range, magnetic fields, and plasma waves. They provide real-time *in situ* data. V1 is making the first direct *in situ* measurements of the local interstellar medium (LISM) although without the working plasma instrument is not measuring directly the plasma characteristics. When V2 will cross the HP we will have the first *in situ* measurements of the plasma characteristics (density, speed, temperature) of the LISM.

In 2010 V1 entered an unexpected region where solar wind flow speeds were near zero. This quasi-stagnation region ended when V1 crossed a very sharp boundary in August 2012 at 122 AU, the *heliocliff*. The heliospheric particle counts had two dips, then dropped to background levels. At the same time the galactic cosmic ray (GCR) intensities increased by 12% and the magnetic field magnitude increased by a factor of 1.8. These observations were those expected for a HP crossing, except that the magnetic field direction did not change. Initially (at the time of the 2013 Senior Review) the *heliocliff* was interpreted as the boundary of a new region of open magnetic field lines. Since then the plasma wave data showed that electron densities beyond the heliocliff are 0.06–0.11 cm^{-3}, consistent with LISM densities. While particle observations across the heliocliff were consistent with expected LISM populations, the absence of directional changes in the magnetic field and pressure balance estimates predicting that the HP should be at ~140 AU were initially powerful arguments that V1 remained in the heliosheath. The plasma densities of 0.06–0.11 cm^{-3} derived from plasma waves observations, 40 times the heliosheath value, convinced many that V1 was in the LISM.

The LISM has proved to be a much more active region than expected, with shocks driven by solar activity generating plasma waves and modulating the Galactic Cosmic Rays (GCRs) intensities and anisotropies.

The heliosheath characteristics at V2 are very different from those observed at V1. Whereas V1 observed a slowdown of the flow and entered a quasi-stagnation region before encountering the HP, the flow at V2 has turned tailward but maintained a constant average speed. Data from different heliosheath locations are critical for understanding the global morphology of the heliosheath plasma and energetic particle flows. The working plasma instrument on V2 will provide a much more complete picture of the heliosphere interaction region.

In addition to crossing of the HP by Voyager 1, the V1 and V2 heliosheath observations have provided many other surprises that are still not understood. Outstanding problems are the acceleration mechanism and source location of the anomalous cosmic rays (ACRs) and the role of reconnection both in the heliospheric current sheet and at the HP. V2 data from a different region of the heliosheath should help resolve these issues. The current solar maximum now reaching the Voyagers and the next declining phase of the solar cycle will provide opportunities to observe the effect of interplanetary coronal mass ejections and merged interaction regions (MIRs) on the heliosheath and the LISM.

Overview of the Science Plan

New measurements to be made by the Voyagers in the extended mission will address many basic, long-standing questions about the plasma and magnetic properties of the outer heliosphere and LISM, the nature of the termination shock (TS) and its role in the acceleration of ACRs, the role of the heliosheath in the modulation of GCRs, the spectra of low-energy interstellar GCRs, and the source and location of heliospheric radio emissions. With the crossing of the HP by V1 it also become clear that another surprise is the width of the HS that is much smaller than all the models predict.

The proposal lists the following prioritized science goals that can be addressed directly by the spacecraft instruments:

- Determine the characteristics of the energetic particles, solar wind plasma, and magnetic field in the heliosheath at V2, and identify the underlying physical processes that produce the observed spatial and temporal variability and control the width of the heliosheath.
- Search for precursors of the heliopause at V2, determine its location, and observe the nature of the heliopause region.
- Determine accurate energy spectra, gradients, and anisotropies of low energy cosmic rays and energetic particles in the LISM.
- Determine the strength, direction, draping and turbulence in the local interstellar magnetic field; search for the predicted magnetic sector crossing that would indicate if V1 were still in the HS.
- Determine the radial dependence of the plasma density beyond the heliopause at V1 and the speed, temperature, and density of the local interstellar plasma at V2. Identify sources of electron plasma oscillations and kilohertz radio emissions in the interstellar medium during the upcoming period of solar activity.
- Determine the effects of solar cycle progression on the HS and on the generation of transients and shocks in the LISM.

- Provide in situ observation in support of the Heliospheric System Observatory Studies of global heliospheric processes and mappings of the heliospheric interaction with the local interstellar medium.

V1 and V2 Measure

(a) The properties and radial evolution of thermal plasma with the Plasma Science Investigation (PLS) (Voyager 2 only). The instrument measures the characteristics of the solar wind, and will also measure, for the first time, the cold and dense interstellar plasma when Voyager 2 crosses the heliopause.
(b) The energy spectrum and angular distribution of suprathermal, energetic ions and electrons from tens of keV to tens of MeV with the Low-Energy Charged Particles (LECP) collector; this instrument also measures the intensity and angular distribution of GCRs with energies greater than 200 MeV.
(c) The energy spectrum and anisotropy of ACRs and GCRs with the Cosmic Ray Subsystem (CRS).
(d) The heliospheric and interstellar magnetic field intensity and direction with the Magnetometer (MAG).
(e) The electrical field components of plasma waves from tens of Hz to 56 kHz with the Plasma Wave Subsystem (PWS).

Voyager Science Strengths

- The Voyager Interstellar Mission explores the farthest reaches of the Sun's influence *in situ*. This is likely the only opportunity for such measurements for many decades to come.
- The V2 will likely reach the HP and enter the interstellar medium during its operational lifetime. V1 already the crossed the HP and its probing for the first time the LISM, the region influenced by the heliosphere and galactic cosmic rays (GCR).
- The nature of the HP is still being debated. Several measurements from few months before the cross, as the disappearance of the solar wind electrons in May 2012; to the several dropouts where ACR and energetic particles dropped while GCR increased; before the final drop, needs to be explained. Several suggestions have been proposed to explain the data from time dependent phenomena (e.g., interchange instability); to reconnection processes.
- The width of the heliosheath, the distance between the TS and HP crossings, was 28 AU for V1. Steady-state MHD-kinetic simulations give widths of 55–65 AU. Explaining the thin heliosheath is another challenge to be explained.
- Voyager 1 has entered a new frontier, the local interstellar medium. V1 measures interstellar magnetic fields, plasmas and particles but still observes disturbances that are produced by the Sun and transmitted through the HP. V1 measures both the nature and strength of these disturbances and the small-scale fluctuations in the magnetic field and set limits on the turbulence in the LISM.
- V1 is measuring for the first time galactic cosmic rays in the pristine LISM. There is a question if there will be any modulation near the HP and how it will vary as V1 adventures into the LISM. These issues will be resolved in the next couple of years.

- V1 and V2 provide important local measurements of energetic particles that interact with neutral particles to create energetic neutral atoms that are imaged by IBEX. The combination of local and integrated line-of-sight measurements provides important information about the structure of the heliosphere. Moreover the global ENA images by IBEX probe regions not accessible to V1.

Voyager Relevant Strengths to Heliophysics Research Objectives

The 2015 Senior Review panel finds that the Voyager mission is highly relevant to the goals and objectives of NASA's Heliophysics Research program. Voyager makes measurements that directly address two of the four overarching goals from the most recent Heliophysics decadal survey: (1) Determine the interaction of the Sun with the solar system and the interstellar medium; and (2) Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe. In addition, along with measurements from other Heliophysics space missions, Voyager also addresses a third overarching goal of the decadal survey: Determine the origins of the Sun's activity and predict the variations of the space environment: the Voyager spacecraft are playing a unique role in developing an understanding of the entry and modulation of GCRs as they propagate toward Earth's space environment.

Moreover, Voyager science addresses two of NASA Heliophysics strategic goals: (1) Open the Frontier to Space Environment Prediction: by increasing our understanding of the space environment from the Sun to Earth, to other planets, and beyond to the interstellar medium; (2) Understand the Nature of Our Home in Space: by measuring the boundaries of the heliosphere, which lead to variations in cosmic rays at Earth that are affected by solar activity.

The Voyagers are the only components of the Great Observatory that are, for now and in the foreseeable future, making *in situ* measurements of the furthest region of the heliosphere. As such, the mission addresses directly a number of important science challenges and goals outlined in the Heliophysics decadal survey.

V1 and V2 measure variations in the heliospheric plasma due to solar disturbances, which are measured by other Heliophysics spacecraft, thereby measuring the extent of the Sun's influence.

V1 and V2 provide important local measurements of energetic particles that interact with neutral particles to create energetic neutral atoms that are imaged by IBEX. The combination of local and integrated line-of-sight measurements provides important information about the structure of the heliosphere.

Voyager Value to the Heliophysics System Observatory

Voyager benefits from measurements from other Heliophysics spacecraft closer to the Sun that monitor solar disturbances that propagate to the outer heliosphere. Merged interaction regions and interplanetary shocks can influence the location of the heliospheric boundaries and flows within the heliosheath. Because we are currently at the maximum in the sunspot cycle, solar transients from the increased solar activity are anticipated.

In addition, the Voyagers establish “ground truth” at two points within the heliosheath. The Voyagers measure ionized particle populations locally while the IBEX instruments measure neutral atoms produced by the interactions of lower-energy neutral particles with these higher-energy charged-particle populations. The resulting images produced by IBEX are integrations along lines of sight (LOS) many tens of AU in length. Voyager measurements can provide *in situ* information that relate to the distribution of the energetic protons along these LOS.

The following science goals will be addressed with its instruments and those made by other Heliophysics spacecraft mission instruments:

1. Determine the effects of the solar cycle progression on the heliosheath and on generation of transients in the LISM.
2. Provide *in situ* observations in support of HSO studies of global heliospheric processes and mappings of the heliospheric interaction with the LISM.

Voyager Spacecraft / Instrument Health and Status

The currently operating instruments are in good health and all five will continue to operate until 2020; afterward some instruments will have to be turned off to ensure that enough power is available to make measurements until 2028. The complement of instruments does not include the plasma instrument on V1, which has not been operational for many years. The typical uncertainty in the magnetic field is of the order of 0.03nT, making measurements of very weak magnetic fields in the heliosheath uncertain; although V1 is presently measuring stronger magnetic fields with much smaller relative uncertainties. The instruments are fully capable of making measurements of the heliosheath plasma and ionized component of the interstellar medium, as well as high-energy charged particles, plasma waves, and magnetic fields in these regions in order to achieve the science goals of the mission. Currently, five investigator teams are supported, though data are collected for one additional instrument—Voyager 1's Ultraviolet Spectrometer (UVS).

Voyager Data Operations

The Voyager team is doing a reasonable job of making most data available to the scientific community in a timely manner; however, there are concerns that very important high-quality, up-to-date magnetic-field data are not readily available. The panel believes that there should be an immediate action item related with this issue and it is addressed in section 2.3.1

We note that in general the Voyager data are not being stored in a coherent and modern manner, as can be expected from a mission of this age. However, the Panel finds that the current storage and documentation efforts are unacceptable for a mission of this importance. The panel supports the assessment that NASA needs to work with the PIs such that the data and processing software are properly stored and documented for access by current and future researchers. These issues are discussed more fully in the Voyager MAP attached to this report.

The Deep Space Network (DSN)

The DSN provides 6–8 hours of downlink time per spacecraft per day for the Voyager Interstellar Mission (VIM). Because VIM does not store data onboard, this means large data gaps exist. The Voyagers have discovered boundaries of the heliosphere, e.g., the termination shock and the heliopause (during the periods of the dropouts), that were remarkably thin. A lack of data during this, or any other, boundary crossing would be extremely unfortunate and would give an incomplete picture. The Senior Review panel finds it imperative that the downlink time allotted for VIM from the DSN not be reduced.

Voyager Proposal Weaknesses

The lack of up-to-date, high-quality magnetic-field data is a weakness of the proposal. Since the heliopause will likely be crossed during the operational lifetime of the V2 spacecraft, having accurate data from all instruments in a timely manner is very important. The Senior Review panel notes that NASA must address this problem as discussed in section 2.3.1 above.

The Senior Review panel is concerned that key personnel on the VIM science team have retired and have not been replaced. The Senior Review panel finds it critical for the continued success of the VIM that there be an efficient continuity of mission operations and production of usable data for the scientific community.

Voyager Overall Assessment and Finding

The 2015 Senior Review panel finds the continuation of the Voyager Interstellar Probe mission to be very compelling. The Voyagers explore a region of space that will not be explored again in the foreseeable future. Moreover, the spacecraft continue to make new and exciting discoveries as they have since their launch (although the scientific emphasis changed from planetary encounters to understanding the solar wind / LISM interaction). The instrument team is very active and works closely with guest investigators—primarily modelers and theorists—to help interpret the unique observations.

Voyager has revealed surprise after surprise since their crossings of the termination shock several years ago, including observations within the past years of the crossing of the HP by V1 that entered the interstellar medium. V1 spacecraft is returning the first *in situ* measurements of the local interstellar medium—this alone provides a truly compelling reason to continue the mission. V2 is expected to cross the HP and enter the interstellar medium with a working plasma instrument what again, alone provides a truly compelling reason to continue the mission.

The panel noted the importance of the Voyager and IBEX teams to work more closely together. Both set of observations complement each other. Furthermore, given the unique opportunity of the crossing of the Heliopause by Voyager 1 (e.g., with the critical findings of the width of the heliosheath, strengths and direction of the magnetic field outside the HP) and the imminent crossing by Voyager 2.

Therefore, the 2015 Panel believes that a dedicated Guest Investigator (GI) program for the Outer Heliosphere community will help achieve this goal. However, the panel would not find it acceptable to fund this GI program from the current mission budgets for Voyager and IBEX as they are already at a "bare bones" level.

Voyager Overall Grade

The Voyager extended mission proposal received an 8/10 median ranking from the Panel for Overall Scientific Merit, placing its intrinsic science contributions in the Compelling category. Its value to the HSO received a median panel ranking of 7/10 and solidly in the Excellent category. The panel supports the continued operation of the Voyager extended mission.

4.15 Wind

Overview of the Science Plan

Wind was launched in November 1994 to the Earth's L1 Lagrange point where it spent a number of years before performing maneuvers to move to other vantage points. It executed a number of magnetospheric petal orbits to examine high latitudes. Between 2000 and 2002 Wind moved away from the Sun-Earth line reaching 350 RE in the east-west direction. In 2003 it completed an L2 campaign taking it 500 RE downstream of ACE. Since 2004, Wind has been back at L1 where it is currently in an L1 halo orbit upstream of the Earth, spin stabilized with spin axis aligned with the ecliptic south, which is perpendicular to that of ACE. Wind carries 8 instrument suites that measure thermal to energetic solar particles, quasi-static fields to high frequency radio waves, and gamma rays.

The spacecraft and instruments are in overall good health and Wind continues to be a remarkably productive mission scientifically. By acting as a near-Earth measurement point and reference for comparison with other spacecraft in terms of solar wind and energetic particle data, Wind enables multipoint ICME analyses and studies of energetic particle acceleration processes. In addition, the mission's long-term solar wind and field data sets have recently been reanalyzed by the instrument teams, producing groundbreaking discoveries regarding fundamental plasma processes such as instabilities, wave-particle interactions, shocks, and reconnection, which are directly relevant to NASA's heliospheric research objectives.

The Wind project's Prioritized Science Goals for 2016–2020 are: 1) Continuation of studies of the long-term variation of solar wind abundances and energetic particles over two solar cycles; 2) A new investigation of solar wind magnetic and particle structure with the help of ACE and DSCOVR; 3) A new study to determine kinetic signatures of heating and acceleration; and 4) Continued studies of dust particles in interplanetary space. These topic areas and PSGs are all consistent with the goals and objectives of NASA science and heliophysics research.

The proposal justifies the request for continued operations in several ways. There is the need to better understand the consequences of the declining phase of the solar cycle and an expected very low solar minimum on the acceleration and transport of solar energetic particles and dust in the heliosphere. There is new science that can be accomplished with three solar wind satellites near L1. For Wind and ACE there is the additional and compelling justification of providing context and supporting data to nearly all other solar, heliosphere, magnetosphere, and ionosphere/thermosphere missions both current and planned.

WIND Science Strengths

The high quality Wind data continue to be useful in a remarkably wide range of studies and are used by a large community, as evidenced by over 1 million data downloads from CDAWeb in 2013–2014. Of particular note are the high time resolution field measurements and high precision and high cadence measurements of thermal and suprathermal plasma populations. These full 3-D distributions of protons and electrons from the bulk population to those at higher energies are the best available measurements for undertaking studies of fundamental space plasma physics processes such as reconnection, shocks, turbulence, and instabilities.

Wind's ability to remotely detect shock waves using radio waves is unique in near-Earth space and is particularly useful in conjunction with data from radio receivers on the STEREO spacecraft.

Wind's Energetic Particle Acceleration, Composition, and Transport (EPACT) measurements of solar energetic heavy ions in the 1–10 MeV range, complementing those from ACE, are important for studies of particle transport from the Sun into the heliosphere.

Wind's ability to make an absolute measurement of the local plasma density allows precise calibration of plasma instruments, not only on Wind itself but also on ACE and NOAA's Deep Space Climate Observatory (DSCOVR).

Unlike some detectors, Wind's plasma instruments do not saturate during high particle fluxes, meaning that it can take continuous measurement during the passage of the most extreme coronal mass ejections and interplanetary shocks.

The realization that Wind can detect the arrival direction of micron-sized dust particles at the spacecraft has enabled the study of the dynamics of interplanetary dust and dust streams, an area that is of growing interest.

The high quality and long database from 1994 is important because it has enabled and will enable future studies of phenomena that occur infrequently.

Wind is currently experiencing a resurgence in scientific productivity as a direct result of the instrument teams (particularly MFI, 3DP and SWE), both from their own research efforts and their release of newly calibrated data products used by other researchers worldwide.

The proposed science goals are important in understanding fundamental processes in Heliophysics.

WIND Relevant Strengths to Heliophysics Research Objectives

All of the research objectives and research topic areas directly support the primary Heliospheric Research Objectives. Better understanding of the sources and acceleration of the solar wind is critical to understanding the fundamental physical processes of the space environment. Wind contributes directly to a wide range of Heliophysics research objectives. Wind's detailed measurements of particles and fields helps the understanding of magnetic reconnection and the processes that accelerate and transport particles. Wind measures coronal mass ejections and other solar transients, both remotely and locally, and provides important information on the state of the solar wind upstream of the Earth. Wind's measurements of solar energetic particles characterize the variability and extremes of the space environment that will be encountered by human and robotic explorers. Its entire instrument complement provides input into studies to help develop the capability to predict the propagation and evolution of solar disturbances.

WIND Value to the Heliophysics System Observatory

Wind contributes several unique measurements to the HSO. Its sensitive radio measurements make it possible, in combination with measurements from the STEREO spacecraft arrayed around the Sun, to triangulate the origin of the emission, remotely probing the motion of coronal mass ejections through interplanetary space. Wind's measurements of solar energetic particles in the important 1–10 MeV energy range, combined with those from ACE nearby and STEREO farther away, make it possible to study particle acceleration and propagation in a global sense in the inner heliosphere. Wind and ACE will also be important for calibrating the DSCOVR space weather satellite that has been launched to L1 by NOAA. Having Wind, ACE, and DSCOVR at L1 will also allow three-point measurements of the solar wind characteristics. Better specification of the solar wind at L1 will greatly benefit geospace missions and models. In the coming years, in the second half of Solar Cycle 24, we can expect several large energetic particle events and Wind will make a vital contribution to their analysis.

Located upstream of the Earth, Wind shares with ACE and DSCOVR the duty as a monitor of the near-Earth solar wind. Studies combining Wind data with those from THEMIS and Van Allen Probes, along with MMS, will continue to provide vital information on the effects of interplanetary plasma, fields, and energetic particles on conditions in near-Earth space.

While ACE and Wind are currently very healthy, they have been in operation for many years. If ACE or Wind should fail, the other can supply most of the crucial measurements needed by the other HSO missions and backup DSCOVR well into the future.

There have been 3600 refereed publications since launch and over 500 since the last Senior Review. There were over one million data downloads in 2013–2014. There have been 8 PhD theses since 2013 with 14 still in progress. In 2014, Wind has produced news releases on NASA homepage news and also on Popular Science and NASA homepage spotlight.

WIND Spacecraft / Instrument Health and Status

Seven of the eight *Wind* instruments, including all of the field and particle suites, remain largely or fully functional. The TGRS γ-ray instrument is the only one that is turned off. The specific degradations in instrument capabilities are the following: the APE and IT detectors of the EPACT instrument, covering the highest energy ranges do not work. The LEMT and STEP telescopes of the same instrument continue to operate normally. On the SMS instrument the SWICS solar wind composition sensor was turned off in May 2000. The SMS MASS sensor is in a fixed voltage mode that allows reduced science data collection.

During the past few years, the spacecraft experienced a few instrument latch-ups and single bit flight software errors most likely due to high energy particle single event upsets. On October 27, 2014, the command and attitude processor suffered two single event upsets that resulted in a complete loss of data from October 27, 2014, until November 7, 2014, and a partial data loss from all instruments between November 7, 2014, and November 20, 2014, after which full functionality to all instruments was recovered.

WIND Data Operations (accessibility, quality control, archiving)

Overall Wind data provision is excellent, with the timely release of high quality data products via CDAWeb and the availability of pertinent documentation. Indeed, the detailed re-analysis of the existing magnetic field, SWE and 3DP data sets by the instrument teams is an exemplar of what can be done to enable new science from existing instruments. These new data releases have made Wind NASA's principal platform for the study of the kinetic processes that occur in plasmas throughout the solar system and indeed the Universe.

The 2013 Panel noted concerns that high energy EPACT data products are not released to the public in as timely a manner as those from other instruments and urged the Wind project to address this issue. The 2015 proposal satisfactorily addressed this issue.

WIND Proposal Weaknesses

The proposal has no serious weaknesses. A few of the research objectives do not have strong requirements for continued operations. This research could likely be addressed with data that have already been collected.

WIND Overall Assessment and Findings

The proposed Prioritized Science Goals were judged by the Panel to represent excellent science, building on the revitalized output of this mission in recent years. Wind continues to be one of the most important missions in the fleet of satellites collecting data in the heliosphere. Wind together with ACE provides context for nearly all of the other HSO missions (both current and planned) and it continues to collect important data for emerging scientific problems on topics ranging from solar wind and interplanetary dust. The combined data from the ACE, WIND, and DSCOVR satellites will provide new and critical information on the three-dimensional structures within shocks and ICMEs.

The panel strongly endorses the proposed 3-point solar wind structure capability and believes that it should be developed into an enhancement to the OMNI dataset which routinely determines the orientation of solar wind discontinuities to provide improved estimation of the time of arrival of geoeffective solar wind events at the dayside magnetopause.

The Wind budget is within guidelines and fully reasonable for supporting the operations, mission services, and science data analysis required to maintain the integrity of these critical data sets. The Wind data are highly reliable and readily available. The Wind data will be very important in providing the context and the drivers for all of the upcoming missions such as Solar Probe, Solar Orbiter, Magnetosphere Multi-Scale, ICON, and GOLD.

WIND Overall Grade
Overall, the panel rated the proposed extended mission for Wind as Excellent (median score 7) for future mission science and Compelling (median score 8) for contribution to the HSO.

5. Mission Archive Plans

The Call for Proposals for the 2015 Senior Review requested each participating mission to append its up-to-date Mission Archive Plan (MAP) to its proposal for continued operations. In particular, “each mission should submit a MAP with an emphasis on describing what final, useful, calibrated, documented products the mission will produce that will form the mission’s active legacy. Missions should also show the progress they have made in serving and documenting their data from the last Senior Review.” Note that IRIS, SDO and Van Allen Probes submitted their initial MAPs to this review.

Following the practice of previous SRs, the MAPs where evaluated by an independent group of data archive experts led by Dr. Aaron Roberts of the Goddard Spaceflight Center. The summary of the reviews by this group is attached.

Appendix 1: Summary Reviews of Mission Archive Plans for the Heliophysics Senior Review of Operating Missions

23 April 2015

Following the provisions of the Heliophysics Data Policy, each mission in extended phase of operations is to prepare and maintain its Mission Archive Plan (MAP). These plans focus "on the content of the data and metadata files at the end of the mission. The MAP will depict the status of the mission's science data (science quality, documentation, formats, standards, and essential data analysis tools) with respect to the mission's planned archival science data. The MAP should show the path to creating the mission's Resident Archive(s) and the subsequent Final Archive(s). The MAP will be updated as the mission progresses into and through its extended mission phase. The MAP review will include an assessment of the adequacy and appropriateness of the planned data products and proposed archival transition."

The Call for Proposals for the 2015 Senior Review requested each participating mission to submit its up-to-date MAP appended to its proposal for continued operations. In particular, "each mission should submit a MAP with an emphasis on describing what final, useful, calibrated, documented products the mission will produce that will form the mission's active legacy. Missions should also show the progress they have made in serving and documenting their data from the last Senior Review." Note that IRIS, SDO and Van Allen Probes submitted their initial MAPs to this review.

Following the practice in previous SRs, the MAPs where evaluated by an independent group of data archive experts led by Dr. Aaron Roberts of the Goddard Spaceflight Center.

General comments:

(1) All missions are providing access to data products through mission web sites and/or HP Data Centers (SDAC and SPDF). Nearly all of the expected products are available, most are easily accessed, and nearly all are available in standard formats (FITS, CDF, and NetCDF). Many missions, especially newer ones, are placing data in the Final Archives from the mission start, thus making "final archiving" straightforward. The situation continues to improve from one Senior Review to the next. As a testimony to the richness of the data environment that the field has achieved, it has become impossible to survey adequately all the missions' datasets in detail for this review.

(2) With few exceptions, documentation of the instruments and products is good. Efforts are being made to preserve the documentation in data centers, but this is not being done systematically. This should not be a difficult problem to solve, but some thought should be given to a systematic approach.

(3) A general issue is the degree to which specialized tools for the visualization and use of the data can be preserved post-mission in the Final Archives. Simple time series or image products are typically very well served by the current Final Archives; more complex products will, in some cases, require more thought to preserve the utility. (The development of tools such as JHelioviewer, Autoplot and SPEDAS should help with this.)

(4) Some missions seem to see the Resident Archive phase as a time to complete analysis and processing over a number of years. This has been done in a few special cases in the past, but this is not the expected mode of operation going forward. In general, as the flow of data and documentation to Final Archives becomes routine, the role of Resident Archives (which have small funding in any case) will decrease, and perhaps disappear. Missions will mostly be expected to use their ramp-down funding to complete their archiving tasks.

(5) Efforts are being made to deal with NetCDF files in Final Archives. As with CDF and HDF, standards for such things as the representation of time would increase the utility of the NetCDF format as a general archival format.

(6) There is considerable dependence on IDL for processing and analysis of data, especially but not solely in the Solar Physics realm. The concern with this is that not all researchers can afford to support the commercial products, and that being dependent on a company that presumably has a finite lifetime presents a risk. Theses issues are being addressed through a number of routes, including the development of Python and other open-source tools and the use of IDL's ability to make stand-alone applications that do not require an IDL license. It is not clear to what extent IDL dependence represents a significant burden or to what extent it represents more of a long-term risk than depending on any other product (e.g., Java-3D is free, but may not be supported long-term).

(7) The most significant potential single new cost to the HP Data Archives is the long-term archiving and serving of SDO data. The SDO team has begun the investigation of the magnitude of the task. The SDO MAP does not, however, provide cost estimates for specific approaches; HQ, the Data Centers, and SDO will need to devise of the most cost-effective approach as well as the means to pay for it.

(8) Not all missions have realized that under the current Heliophysics data policy the NSSDC is not the Final Archive for HP data, but this is a minor point. There is also a fair amount of confusion about SPASE, Virtual Observatories, and the general structure of the HP Data Environment. It is anticipated the planned improvements to the Heliophysics Data Program should help to clear up these issues.

Summary Reviews of Mission MAPs

ACE MAP

The ACE mission has done an exemplary job of producing, providing access to, and documenting data from the mission. In addition to providing data as ASCII and HDF files from the ACE Science Center, the mission provides archival versions of all products to SPDF in CDF, and thus guarantees easy, long-term access to the data. A few products remain to be incorporated into the CDAWeb distribution, but there is a plan to do this in a timely fashion. ACE has done an excellent job of producing what is needed for a lasting Final Archive.

AIM MAP

The AIM mission provides an extensive set of products in NetCDF format and makes them readily available through instrument web sites coordinated through a Science Data System (SDS). Documentation that includes calibration information is provided for all the products, and is easy to find. Both overview graphics and NetCDF files are available, although the route through the various data centers and web pages can be confusing at times. IDL software is provided for reading NetCDF files. The team has worked with SPDF to demonstrate the transfer of data to the Final Archive. It is not clear what the team means by a "Resident Archive" in this case, and in any case the further preparations for final archiving and effective serving of the data long-term should not wait for a Resident Archive stage. The data reduction code to be archived will not be complete, but will be for "future reference." Also, it is not clear why the analysis tools will not be included in the final archive, or the extent to which the products will be useful without those tools. Overall, the AIM mission is doing a very good job of producing and serving a comprehensive set of data products, but it is not clear that the preparations for a final archive will guarantee that the numerical data products will continue to be useful post-mission.

CINDI MAP

The CINDI instrument on the C/NOFS satellite delivers information from an ion velocity sensor (IVM) and a neutral wind sensor (NWM). The high-resolution ion density, composition, temperature, and drift data from the IVM instrument have been archived at SPDF in CDF and HDF format and are available from CDAWeb ftp archive and also from the CINDI Data Distribution Website at the University of Texas at Dallas. The activities during this proposal period are focused on the production and archiving of a viable NWM data product. This sensor provides data only below the exobase (~440 km) and it has not been operated continuously through the mission. It needs a refinement of the post-processing procedures to obtain meridional wind velocity and the neutral number density for periods of operation below the exobase. The CINDI MAP did not discuss the documentation of the instruments or products, but more information is available at the UT Dallas CINDI home page. Preservation of documentation is as important as preserving the data. The CINDI MAP needs to address this deficiency.

Hinode MAP
The Hinode mission provides an extensive set of products, all of which are served both on instrument-based web sites and from the Hinode Science Center (HSC) housed at SDAC, and all of which are in standard FITS format. Access to the products at the HSC is through the Virtual Solar Observatory. The products are also registered in the Heliophysics Events Knowledgebase. The Plan states that the data products will be delivered to NSSDC for final archiving, but the products are already at what the current HP Data Policy designates as the final archive (SDAC). Quick look images are available by instrument at various sites. The co-alignment database is very important, but it is not clear how it would be used as part of the final archive. The MAP does not describe a unification of the various products and documentation in one place, although it does describe the production of final products (independent of SolarSoft) for all but the EIS instrument, including JPEG2000 files for JHelioviewer in the XRT case. There is no timeline for the production of final products. Hinode data are held in Japan in the DARTS system as well in European sites, and thus should be well preserved. Overall, while the mission is providing excellent products in a variety of ways, some further thought is needed on how to bring the data, tools, and documentation together in a more cohesive final archive.

IBEX MAP
The IBEX mission has, from the start, made all data and overview graphics available as quickly as feasible, and they have maintained both mission and Final Archive versions of the data, including both graphical and numerical representations. Many articles that aid in understanding the data and results from it are summarized and posted on the mission web site. One issue, which should be easily fixed, is that the presentation of the data in the HDP and Final Archive is somewhat confusing. For example, it is not immediately apparent that SPDF has the most recent data ("release 8"), but some digging reveals that it does. There needs to be a "guide for the perplexed" that is easily found; the current MAP could serve as a good starting point. The data are currently provided in ASCII, which for such small volumes of data is workable, although CDF versions in a consistently constructed final archive would be desirable. The plan for data archiving is exemplary in its completeness in terms of data, software, and documentation.

IRIS MAP
The IRIS mission is doing an excellent job of producing, providing, and preserving a comprehensive set of data products. While SolarSoft is used for producing Level 3 products (due to volume constraints), fully calibrated products are produced in FITS format that do not require software processing. Data are mirrored at multiple sites, and mirroring at SDAC is planned. Since the mission has been active for a relatively short time, it is not surprising that the plan for Final Archiving is not very detailed, but it includes the transfer of data to SDAC and the continued serving of the data through VSO. Documentation is extensive and easily accessible. Software will presumably persist in SolarSoft, but this should be made explicit. Data volumes are relatively large (100TB total), but not a problem by current standards.

RHESSI MAP
The RHESSI mission provides an excellent set of data, tools, and documentation, and the MAP provides a detailed and well-thought-out plan (including cost estimates) for preserving the missions utility. The current implementation includes extensive tools in SolarSoft in addition to easily used browse tools. There will soon be a set of standardized Level 2 SolarSoft-independent data products that will be easily distributed and contain the information needed by most of the scientists using RHESSI in studies correlating data from multiple wavelength ranges. The post mission plan provides a route to preserving the utility of the data even without the use of SolarSoft. The reviewers of the RHESSI MAP are concerned is that while the production of "visibilities" may be an excellent way to do this, they will be expensive to execute as indicated in the projected budget. Also, more detailed plans should be worked out with SDAC before the mission ends.

SDO MAP
The SDO mission has done a wonderful job of providing a comprehensive set of products in a variety of useful ways. The mission provides high-resolution processed images, level-0 and processed FITS files, search engines, effective browse services, and a cutout service that delivers data for selected regions. They have supported SunPy, a Python-based and therefore open source version of an increasingly complete version of SolarSoft. The most significant potential single new cost to the HP Data Archives is the long-term archiving and serving of SDO data. The SDO team has begun the investigation of the magnitude of the task. The SDO MAP provides a good discussion of some of the possible ways to go about producing a post-mission SDO archive, but it does not provide specific cost estimates for these approaches; HQ, the Data Centers, and SDO need to come to resolve the most cost-effective approach as well as how to pay for it. In the meantime, the SDO project is producing all the material that would be needed for such an archive.

STEREO MAP
The STEREO mission has produced a comprehensive set of coronal images and in-situ time series data that are served from the mission archive at SDAC in addition to (for in-situ products) both mission sites and SPDF. The instruments are well documented, but specific data product documentation is difficult to find. There is little discussion (except for SECCHI) in the MAP of the products that are or will be produced, except to say that a year will be required to do final calibration, validation, and completion of the most recent data. The fact that the data already reside in the Final Archives means that this plan, while not detailed, should be effective. SolarSoft will not be required to use the final SECCHI FITS files. The STEREO MAP needs to specify plans for archiving clear documentation of data products including their production and their caveats.

THEMIS MAP
The THEMIS mission has done an excellent job at producing high quality products that are available both from mission sites and from SPDF via CDAWeb and ftp. The mission has produced IDL-based software, "SPEDAS." that grew out of the needs of a

number of missions. It has become a general analysis tool that includes the use of SPDF Web Services to access all of CDAWeb in addition to providing specific readers and analysis tools for THEMIS and other instruments. Data from all five THEMIS spacecraft and from ground sites are available from various sites, and have been produced as CDF files that are available from the Final Archive (SPDF). The THEMIS mission web site is nicely organized and provides clear routes to extensive documentation.

TIMED MAP

The TIMED mission produces a comprehensive set of products that are generally well documented. Most of the data are in NetCDF, although some are in IDL savesets, which should be converted for long-term archiving. Distribution is through various web sites and VITMO; the route to data is not always straightforward, but files are available for easy downloading. Good browse products exist. Tools for analysis mostly consist of a list of IDL files, documented internally. The MAP deals with the preservation of the data, but does not discuss how useable the data will be post mission. The ongoing discussions with SPDF should be continued with a view to establishing how best to make the final archive useful.

TWINS MAP

The TWINS mission is producing comprehensive sets of calibrated images and other products from neutral-atom imagining instruments on a pair of spacecraft. They are using standard formats for the data products, and working closely with SPDF to make data available through CDAWeb and ftp transfers. References are given for the instrument and processing algorithms, and the fact that the instruments are copies of the MENA instrument on IMAGE means that there is a heritage of other documents, but overall the web site lacked detail on products, what was done to make them, and how to interpret them. It would be a good start to put the information in the MAP onto the web page. The MAP states that SPDF has been provided with documentation, but it is not obvious that there is a route to this. The “enhanced online dynamic plotting and data filtering capabilities” are for users who know the instruments intimately; this should be described without requiring a password. It is not clear how to take advantage of the many views in the PostGRE SQL database or how shutting down the database would degrade capabilities. In summary, the TWINS mission provides open and easy access to a comprehensive set of high quality products, but the documentation of these products could use improvement. The TWINS team is clearly dedicated to providing the highest quality possible long-term archive, but it is not clear exactly what will be lost in moving from current processing capabilities to a Final Archive.

Van Allen Probes MAP

The Van Allen Probes mission does an exemplary job of producing and making available an extensive set of data products. They have worked with the SPDF to provide data in standard CDF format for distribution through CDAWeb, thus accomplishing a major part of the final archiving task. Although a few of their links to some of the quick look and other pages were broken, in general the Science

Gateway provides convenient access to information and documentation, and the "rPlot" tool provides very nice overviews of data. However, the Gateway does not seem to provide very direct links to data files, whether for the mission or for "related data." Data are accessible for all the instruments except RPS (which seems to have only level-0 data), but there was no easy route to obtain multi-instrument, multi-spacecraft data other than as browse plots. CDAWeb can provide this, but it is not an obvious route to the data from either the Gateway or Mission websites. There is considerable documentation of the instruments and data products, but it is difficult to evaluate it as a whole because it is widely distributed at a variety of sites. Overall, the Van Allen Probes mission is doing an excellent job of producing and providing data, but it would be useful to have a more cohesive view into the data and its documentation both for current use by non-team scientists and for the final archiving of the data.

Voyager MAP

The Voyager Interstellar Mission continues to deliver unique data from the instruments still functioning well. The data are in a variety of formats (mostly ASCII and some csv), and are delivered from a diverse variety of sites. Encounter data is stored in PDS, but most of the general mission data have not been placed in Final Archives. It is to be expected that the oldest mission in the Heliospheric System Observatory would have traits reflecting its age, and the following comments are meant to encourage improvements as possible. It is suggested that the LECP data be processed with Excel, although the procedure is simple enough to be done otherwise; calibrated flux products are promised in the MAP, and should be produced. It is not clear why the CRS team is reluctant to produce complete count rate and flux products at the highest possible time resolution, but CRS data in general are well documented and up-to-date. The MAG data are difficult to produce, but it is still unclear exactly what is being produced and provided. The provision of a complete 48s product, as indicated in the MAP, would be very welcome, but no timetable was given. PLS and PWS data are produced routinely. PLS data are stored as ASCII files and are available at SPDF as well as the instrument site. PWS files are only available at the Iowa PDS node, where the full resolution data is in binary form and uncalibrated. Greyscale browse plots exist for the PWS data, but are small and difficult to read. (Note: The NSSDC is no longer the Final Archive for HP data. The final archive for the Voyager Interstellar Mission will be the SPDF.) Coordination between the mission/instrument teams and SPDF would help in producing a cohesive Voyager archive.

Wind MAP

The WIND mission delivers a comprehensive set of high-quality products, primarily through CDAWeb and the SPDF ftp site. The WIND team has teased much more from some of the datasets than was originally anticipated, such as the detailed information now available on proton and Helium anisotropies from SWE. The magnetic field product now provides all the information that is likely possible. The 3DP proton moments, although noisy, provide the highest resolution plasma information available in the solar wind. The MAP notes that there is still more to be done, e.g., with the EPACT and SWE datasets. It is important to complete these data set upgrades. Some datasets are still stored as IDL savesets, and it would be useful to have CDF versions of these. Extensive documentation is nicely referenced on the Wind website.