Senior Review 2008 of the Mission Operations and Data Analysis Program for the Heliophysics Operating Missions

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Submitted to:

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1. Overview

1.1 Introduction

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. Performance factors include scientific productivity, technical status, budget efficiency, and participation in the "Heliophysics Great Observatory." NASA uses the findings from these comparative reviews to define an implementation strategy and give programmatic direction to the missions and projects concerned for the next two to four fiscal years.

1.2 Missions Considered

The 2008 Heliophysics (HP) Senior Review considered the following twelve missions (in alphabetical order): ACE, AIM, Cluster, FAST, Geotail, RHESSI, SOHO, STEREO, THEMIS, TIMED, Voyager, and Wind. Nine missions already are in extended mission phases: ACE, Cluster, FAST, Geotail, RHESSI, SOHO, TIMED, Voyager, and Wind.

The THEMIS science team proposed a bifurcation of the primary mission into THEMIS-Low and ARTEMIS (relocating two of the THEMIS spacecraft to lunar orbit) during an extended mission phase. The Panel has made separate evaluations.

1.3 Instructions to the Senior Review Panel

The instructions given to the Senior Review panel by NASA Headquarters are given below:

(1) In the context of the HP research objectives and focus areas described in the SMD Science Plan, rank the scientific merits—on a "science per dollar" basis—of the expected returns from the projects reviewed during FY09 and FY10. The scientific merits include relevancy to the HP research objectives and focus areas, scientific impact, and promise of future scientific impact.

(2) Assess the cost efficiency, data availability and usability, and vitality of the mission's science team as secondary evaluation criteria, after science merit.

(3) Drawing on (1) and (2), provide comments on an implementation strategy for the HP MO&DA program for 2009 and 2010, which could include a mix of Continuation of projects "as currently baselined;" Continuation of projects with either enhancements or reductions to the current baseline;

Mission extensions beyond the prime mission phase; and Project terminations.

(4), (5) and (6): Make preliminary assessments equivalent to (1), (2), and (3) for the period 2011 and 2012.

(7) Provide an overall assessment of the strength and ability of the HP MO&DA program to meet the expectations of the HP Great Observatory (HPGO) during 2009 to 2012 as represented in the SMD Science Plan and in *The Heliophysics Science and Technology Roadmap 2005–2035*.

The panel was not asked to evaluate or assess the utility of HP mission data to operational or commercial users.

1.4 Methodology

The 2008 HP Senior Review Panel met on 8–11 April 2008. There were eleven panel members, with expertise in solar, heliospheric, and geospace science. The twelve missions submitted their proposals by 21 February 2008, and these proposals were distributed to the panel members for review in March prior to the meeting of the panel. During the panel meeting, each project made an oral presentation followed by an opportunity for the panel members to ask questions and ask for clarification. The Education/Public Outreach (E/PO) and Mission Archive Plan (MAP) are considered separately. The panel assessed the scientific merit of each mission.

The mission proposals contained budgets for their MO&DA programs for FY09–FY12 at *Guideline/Minimal* and *Optimal* levels. In total, the Minimal levels were approximately \$62M, \$59M, \$61M, and \$59M, with shortfalls from the Headquarters Guidelines of approximately \$1.5M, \$1.8M, \$1.2M, and \$1.0M. The numbers for the Optimal levels were \$78M, \$70M, \$72M, and \$79M, which lead to shortfalls from the Guidelines of \$8.9M, \$14.4M, \$17.9M, and \$21.5M.

The panel assessed the merit of each mission according to several primary goals, including: impact of scientific results to date as evidenced by citations, press events, etc.; promise of future impact and productivity (due to uniqueness of orbit and location, solar cycle phase, other operating HPGO assets); relevance to the goals of the Heliophysics Division; and spacecraft and instrument health. Secondary goals included cost efficiency, broad accessibility and usability of the data, and productivity and vitality of the science team.

1.5 Summary

1.5.1 Mission Grades

The twelve proposals were graded by the panel according to two criteria: their overall scientific merit; and their contribution to HP/SMD goals as given in *The New Science of the Sun-Solar System Connection, Recommended Roadmap for Science and Technology 2005–2035*. Each proposal was graded on a score from 0 to 10 using the following broad categories:

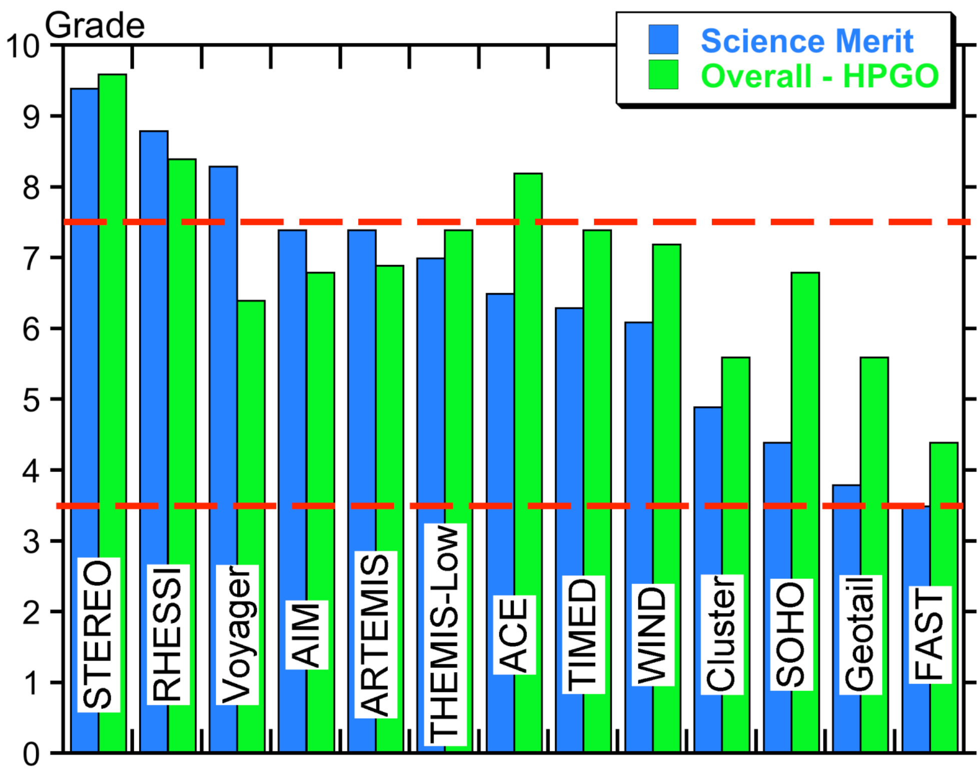
10–8 Future contributions promise to be compelling

7–4 Future contributions are rated excellent, but less compelling

3–0 Future contributions appear to be relatively modest.

The merged results of the scoring by the panel members are given graphically below.

1. The figure makes clear that the panel found that all of the missions reviewed could be expected to make excellent contributions to the HD/SMD enterprise.



The merged panel scores are presented both for science merit and for overall contributions. THEMIS has been divided into the two proposed extended mission segments. The red dashed bars indicate the boundaries of the three grade categories specified above.

2. In terms of science merit, the panel found that the missions fell into three broad groupings with STEREO, RHESSI, and Voyager receiving grades above 8, six missions (AIM, ARTEMIS, THEMIS-Low, ACE, TIMED, and WIND) getting grades above 6, and four missions with grades below 5 (Cluster, SOHO, Geotail, and FAST).
3. Those missions found to have a lower intrinsic science merit still will make major contributions to the HP Great Observatory by supplying crucial measurements in other, and multiple locations. This assessment by the panel can be seen by the substantially higher grades given to these missions in the overall category.

1.5.2 Guest Investigator Program (GIP)

The panel received a briefing on the Guest Investigator Program from a Headquarters Discipline Scientist. The panel was told that the planned annual GIP budgets for the time period FY09–FY12 was $15.8M, $15.5M, $16.2M, and $18.0M. This is a marked increase from the FY06–FY08 budgets of $10.0M, $11.5M, and $11.9M. The panel enthusiastically supports this increase in GIP funding. The present senior review panel, like those in years past, believes that the Guest Investigator Program is an extremely effective means of enhancing the scientific return from operating NASA missions. As has been pointed out before, the impact of the Guest Investigator Program is particularly great for younger researchers, and is an obvious way to enable talented workers to remain in our research fields.

1.5.3 Summary of Key Findings

The opportunities for major advances in heliophysics science over the next few years are unprecedented. With the two STEREO spacecraft in 1 AU orbit well ahead and behind the Earth, SDO in operation, and the flotilla of near-Earth spacecraft remaining in nominal operation, each with its unique sensors and locations, NASA truly will have a Heliophysics Great Observatory during the current rise to solar maximum. The panel recognizes fiscal pressures, but still must note that increased funding, at a level very modest in comparison to the cost of fielding the Great Observatory, would allow a substantially larger scientific gain.

The exploration by STEREO of the structure and propagations of CMEs and ICMEs and associated energetic particle production is central to HP research objectives and focus areas and to NASA strategic objectives. STEREO observations are critically important for determining the three-dimensional structure of the solar atmosphere and heliosphere as they evolve during the rise to solar maximum. Understanding this science lies at the very core of the Living With a Star and HPGO Programs.

RHESSI has been extremely productive in terms of fundamental breakthrough science and in terms of publications. RHESSI remains an extremely valuable mission, with an extended phase that now will occur during the rising phase of the solar cycle when the Sun's global magnetic field is changing in ways that may affect the processes that lead to flare production. Complementary measurements by the Hinode and STEREO missions will provide context observations, vector magnet fields, and detailed plasma diagnostics that were not available during the prime mission. Knowledge of the context in which solar flares are observed by RHESSI will allow the development of a comprehensive description of the reconnection process in the solar atmosphere that will help resolve, revise, and differentiate between the competing theories for energetic particle production and acceleration.

The Voyager spacecraft, over 30 years after liftoff, continue on their voyage of discovery. The panel finds that the Voyager Interstellar Mission proposal offers superb science, tremendous discovery opportunities, and the undisputed fact that nothing like the VIM can be repeated in any form for the next 30+ years; this is a mission that is absolutely imperative to continue. The panel believes that funding near the optimal level and increased DSN support is warranted.

The panel congratulates the THEMIS science team on their innovative plan to drastically reposition the five THEMIS probes at the conclusion of the prime THEMIS mission. The extended mission, which will then consist of THEMIS-Low and the lunar-orbiting ARTEMIS, is highly compelling, both for the individual scientific goals and what will undoubtedly be their excellent contributions to the HPGO.

The panel strongly supports the continuation of the two ITM missions under review: TIMED and AIM. TIMED provides crucial observations of the energy input into and out of the ITM system and ties the phenomena observed by the solar and magnetospheric components of the Great Observatory to their impacts on Earth. AIM, still in its prime mission, with an extended mission should make major advances in our understanding of the solar cycle impact and other effects on polar mesospheric clouds.

Although ACE has been in orbit for more than a decade, its central role in heliophysics research remains undiminished. The newer missions will enhance the value of ACE data by providing unprecedented understanding of the solar context and the first detailed multi-viewpoint observations of large-scale interplanetary phenomena. Wind, also stationed at L1, is an important complement to ACE. The Wind instrument suite makes measurements different from those of the ACE investigations; there is no real duplication. ACE and Wind both are critical components of the Heliophysics Great Observatory. The panel strongly endorses the continuation of the ACE and Wind missions as essential in achieving SMD/HP objectives during the rise to solar maximum over the next few years.

Cluster is a four-satellite mission designed to explore the micro- and meso-scale dynamics of the Earth's magnetosphere and environs. The topics of the Cluster investigations are identified as critical in the Roadmap and whose exploration requires physics input from other missions as part of the Great Observatory. The Panel therefore endorses continued support for the mission. To maximize the impact of this mission, however, the Panel feels that it is important that the mission leaders carefully craft a subset of critical problems and marshal resources appropriately to address these issues.

The Geotail mission continues to provide an excellent science return, and at a modest cost. Because of its orbit and instrumentation, Geotail will provide invaluable correlative information to the THEMIS-Low, ARTEMIS, and Cluster mission science, and thus also is a valued member of the Heliophysics Great Observatory. The panel strongly supports the proposed Geotail extended mission.

The panel finds that limited operation of SOHO is critical to the ongoing effort to understand the solar influence on the heliosphere and geospace because SOHO's coronagraph (LASCO) remedies the lack of a Sun-Earth aligned coronagraph. The SDO mission does not carry such a coronagraph, and thus the SOHO instrument is irreplaceable in the near term. Continuing SOHO operations to collect, disseminate, and archive data from LASCO is therefore essential.

FAST provides high-quality particle and fields data from a magnetospheric vantage point not accessible to other spacecraft in the HP Great Observatory. In particular, FAST directly supports the THEMIS primary mission science by making important substorm-phenomena measurements that neither the THEMIS satellites nor the GBOs can make, and therefore the panel supports extension of the FAST mission.

2. Evaluations of Missions

2.1 Advanced Composition Explorer (ACE)

Science Strengths

The ACE extended-mission proposal outlines a broad program of research, ranging from fundamental processes in space physics to the development of new models of radiation hazards affecting spacecraft and astronauts. ACE is in orbit about the L1 point and carries a magnetometer and a comprehensive set of instruments measuring particle composition over a broad range of energies, from the solar wind to galactic cosmic rays. Since the 2005 Senior Review, ACE has delivered many significant results, including the following:

(1) Identification of coronal structures associated with ^{3}He-rich impulsive particle events (in collaboration with SOHO, RHESSI, STEREO, and Hinode). Since their discovery in 1970, the distinctive type of particle acceleration exhibited in these events has been one of the most puzzling phenomena in space physics.

(2) The first direct evidence that magnetic reconnection commonly occurs in the solar wind. Subsequent multi-spacecraft observations of reconnection outflows (in collaboration with Wind, Geotail, and STEREO) have shown that reconnection in the solar wind is quasi-stationary and occurs over extended distances, rather than being patchy in space and time. Perhaps surprisingly, to date, these observations have revealed no evidence of particle acceleration in association with the reconnection.

(3) Measurements of the intensity, spectral shape, composition, and variability of suprathermal ions that are now known to play a key role as seed particles for large SEP events that potentially endanger robotic and human explorers.

(4) Through collaboration with Wind, examination of interplanetary shock-fronts as a function of spacecraft separation, in terms of both shock characteristics and the time-intensity profiles of the associated energetic particles. Such studies are important for efforts to build global models of particle-acceleration by CME-driven shocks, and more progress can be expected in the future, when the STEREO spacecraft will make it possible to examine the same issues over larger spatial scales.

(5) Precise and comprehensive measurements of the isotopic composition of galactic cosmic-rays (GCR), which may have definitively identified OB associations within superbubbles as the likely source of at least a substantial fraction of GCRs.

In terms of capabilities, it should be noted that ACE provides the most sensitive measurements ever made for solar energetic heavy ions below ~1 MeV/nucleon and above ~10 MeV/nucleon. (Intermediate energies, which have proven to be particularly powerful in SEP transport studies, are measured more precisely and more thoroughly on Wind.)

Relevancy to HP Research Objectives and Focus Areas

ACE has been highly responsive to the stated objectives of the Heliophysics Roadmap. ACE contributes to all 12 of the Research Focus Areas in the Roadmap and to 34 Priority Investigations.

Value to the HP Great Observatory

The ACE mission remains a major asset to the HP Great Observatory by all measures. The data are of high quality and reliability and are readily available. In that ACE has already observed for a complete solar cycle, it is not necessarily expected that ACE alone will lead to fundamental new discoveries. The ACE data play a key role in many multi-platform studies that are at the heart of the HPGO concept. In the coming rise to Solar Maximum, the combination of observations from ACE and from new missions (STEREO, Hinode, and SDO) should serve to answer long-standing questions that go to the heart of Heliophysics objectives. ACE also enables and extends the science return from other ongoing missions, for example, by providing interplanetary solar-wind observations upstream of the Earth. The ACE team are well regarded as leaders in heliophysics research, and without ACE and the ACE team, many of the HPGO objectives would be unachievable.

Spacecraft/Instrument Health and Status

All spacecraft systems are operating within nominal limits, and spacecraft anomalies have been rare and inconsequential. Power output and fuel reserves are judged to be adequate until ~2025. Spacecraft commanding has been uninterrupted. To date, large on-board data recorders have delivered science data without loss in more than 10 years of operation. In order to conserve fuel, ACE discontinued some occasional orbital maneuvers that were designed to minimize telemetry loss during transit of the Solar Exclusion Zone. These transits will occur again in 2011–2013 during solar maximum. However, based on the experience since 2001, the ACE team expects minimal data loss during this period.

ACE carries a complement of nine instruments, all but one of which continue to return excellent science data. Five instruments (CRIS, SIS, SWICS, SWIMS, and MAG) are operating as designed or with very minor degradations in their performance. Three instruments (ULEIS, EPAM, and SWEPAM) have suffered some decrease in resolution and/or sensitivity, but in no case have these problems significantly diminished the instrument's science return. The SEPICA instrument began to malfunction in 2000 and appears to have delivered no useful data since 2005. Overall, the stability and reliability of the ACE instruments have proven to be very impressive.

Data Operations (Accessibility, Quality Control, Archiving)

The ACE data management and accessibility are exemplary and deserve the highest commendation. The quality control and archiving plans are also thorough and well designed. The ACE instrument teams are to be commended for their sustained efforts to maintain and improve instrument calibrations and to deliver the best-possible data to the science community.

Proposal Weaknesses

The proposal itemizes more than 80 specific data analysis projects that will be undertaken, or at least started, in the coming three years. Most of these projects are described with too little detail for the panel to offer any technical assessment. Given the quality of the ACE data, the strong collaborations with other Heliophysics missions, and the track record of the ACE team, one can nevertheless confidently expect progress on many, if not all, of these tasks. The proposal notes that the one-sixth reduction in science support reflected in the guideline budget would "limit the number of studies undertaken." But the proposal gives no information on which projects will be lost due to this budgetary limitation. However, the science return from all SMD missions is limited by budgetary constraints. The proposal gives the Panel inadequate information to make a judgment on the relative merit of ACE's request for the optimal budget.

Overall Assessment and Findings

Although ACE has been in orbit for more than a decade, its central role in heliophysics research is undiminished. Rather than replacing ACE or lessening its contributions, the newer missions will enhance the value of ACE data by providing unprecedented understanding of the solar context and the first detailed multi-viewpoint observations of large-scale interplanetary phenomena. The continuation of the ACE mission is emphatically not "more of the same." Rather, the combination of ACE and other HP missions has the potential for new, transformative insights into central science challenges of the Heliophysics Division. The Panel strongly endorses the continuation of the ACE mission as an essential tool for achieving HP objectives.

2.2 Aeronomy of Ice in the Mesosphere (AIM)

Science Strengths

AIM is the first satellite mission that probes the basic physics of Polar Mesospheric Clouds or Noctilucent Clouds (PMCs/NLCs) on a global scale with high spatial resolution, and makes measurements that can provide information on how these clouds form and vary. These clouds, which occur at high latitudes (>50^o) in both hemispheres at altitudes near 83 km, were first observed in 1885. It is still uncertain why they form. Their brightness and frequency have increased over time, and clouds are now being seen at lower latitudes; this is significant since it may be related to global change.

AIM was launched on 25 April 2007, and already has provided measurements for the 2007 northern hemisphere season and the 2007–2008 southern hemisphere season. AIM instruments have provided data on PMCs/NLCs and ice properties, and on their variability. This is again significant since PMC changes may be related to global change.

The first PMC images, obtained soon after the start of the northern hemisphere cloud season in 2007, revealed that PMCs observed from orbit exhibit a very complex structure. Previous ground-based observations of these clouds (NLCs when observed from the ground) had suggested significant structure, but earlier satellite observations had been unable to confirm this. Indeed, the first AIM observations showed that structured PMCs are a global high-latitude phenomena and confirmed that our present understanding of these clouds is poor. The full range of measurements and derived quantities that will be provided by AIM, particularly when combined with other international assets, offers the scientific community an unparalleled opportunity to understand the physics and chemistry of PMCs and their behavior and their possible relationship to global change.

The early CIPS images show that the PMC brightness over small regions is much more variable (10 times) than previously anticipated. This may indicate small-scale upwelling, an unexpected feature in the MLT region at this scale size. The striking similarity between PMCs and tropospheric cloud signatures hints that mesospheric "weather" (the cloud-like, patchy signatures) may be driven by dynamical processes similar to those in the troposphere. Indeed, AIM observations, combined with those from TIMED, has yielded an exciting new view of mesosphere/lower thermosphere (MLT) dynamics. The unprecedented resolution afforded by CIPS provides impressive maps of gravity wave (GW) observations over the polar cap region; the interpretation of these GW will be important for studies of their influence on PMC formation and dissipation.

AIM has made the first observations of very small ice particles that indicate a strong connection between water vapor content and ice particle size and shape over a range of MLT altitudes, and provided observations of the very small smoke particles, 1 to 3 nm, that are currently believed to be the nucleation sites for PMC ice particles. This is an important finding since the wavelengths involved imply that the observed extinctions must be a true absorption. This represents important new science.

The most far-reaching goal for the AIM extended mission is to address the possible relationship between PMCs and global change. The extended mission affords an opportunity to test this "Miner's Canary" hypothesis.

The modeling community has developed a PMC module for WACCM that offers a major opportunity to compare the AIM measurements with very advanced atmospheric models. In particular, there is some evidence that PMCs may decrease after SPEs. The extended mission will allow AIM to sample some of these effects and compare the AIM measurements, together with those from other assets, with those suggested by models. A quantitative understanding of interhemispheric PMC differences and solar cycle dependence is essential if PMCs are to be used as an indicator for natural or human-induced change.

Relevancy to HP Research Objectives and Focus Areas

AIM is primarily relevant to HP objective H, "to understand the nature of our home planet;" in particular, it addresses RFAs H2 and H3.

AIM also bridges HP objectives to Earth Science objectives because it is relevant to atmospheric composition and climate variability and change, *i.e.*, can PMCs/NLCs be used as a "Miner's Canary" for climate change?

Value to the HP Great Observatory

AIM probes the basic physics and morphology of NLCs in the polar gateway between the geospace environment and Earth's atmosphere. It is synergistic with TIMED and other HP Great Observatory assets, and its value to the Great Observatory can be rolled up as "when the sun chooses to exhibit some major change, e.g., the Halloween storms of 2003, the resulting energy flow interacts with the Earth's atmosphere and the effects are important to everyone."

Spacecraft/Instrument Health and Status

The spacecraft is healthy and fully functional; over 99% of data are captured on the ground. An uplink problem has been addressed by adding full autonomy to the spacecraft and instruments, enabling 24 days worth of command loads (maximum outage has been 6 days so far). The effect upon science operations has been minimal.

AIM carries three instruments. Two of the three, SOFIE and CIPS, are performing nominally, while the third, CDE, has had modest issues that have had a minimal impact upon the science return. One question seems to be whether it can operate in the autonomous mode.

Data Operations (Accessibility, Quality Control, Archiving)

Accessibility: Data are available from all three instruments. It is promptly processed. The heritage from earlier missions for the instrument teams is obviously paying dividends.

Uncertainties: There are no SOFIE errors given (in v01.01 on the web page), and there are no obvious error tables for the different instruments. This is, however, not unusual considering the early stage of the AIM mission.

Minimum/Optimum Budget

The proposed staff reductions assume that spacecraft operation is established and data processing algorithms are fully operational. Considering the solved problems with the spacecraft uplink, this may be a risk. Typically there is a need for algorithm improvements due to unexpected data flaws or degradation as the mission proceeds.

Proposal Weaknesses

There are no real weaknesses in the proposal, although the new science of the proposed gravity waves study compared to the similar AIRS/AURA data was not made sufficiently clear.

Overall Assessment and Findings

The Senior Review is reviewing the proposal for an extended AIM mission, although it is less than one year into its prime mission. The initial results are very exciting and have already yielded some seminal findings. The mission offers potential for major advances in our understanding of PMCs/NLCs. There is every likelihood that the extended mission will make a major contribution to solving the questions related to an improved understanding of these clouds. The Senior Review was satisfied that the AIM extended mission offers the potential for major advances in our understanding of solar cycle impact and other effects on PMCs. These clouds represent the interface between the atmosphere and space.

The Senior Review strongly endorses the continuation of the AIM mission into an extended phase as it addresses the "Miner's Canary" and global change, probably the most important question for humankind.

2.3 Cluster

Science Strengths

The Cluster team and collaborators have published over 700 papers and made groundbreaking contributions in a number of areas. Over the proposed extended mission, the four-spacecraft Cluster constellation will continue to operate in a configuration that will facilitate the study of micro- and meso-scale dynamics of critical magneospheric phenomena, including: the Earth's bow shock; the magnetopause and dayside reconnection; the dynamics of the tail current sheet; the auroral zone; and the plasmasphere and inner magnetosphere. To facilitate these multiscale studies, three of the spacecraft are separated by 10,000 km in a triangular configuration with the fourth spacecraft perpendicular to this plane with a variable spacing from 20 to 10,000 km. Spacecraft 3 is scheduled to be rotated by 45° to facilitate measurement of 3-D electric fields since at present all three spacecraft measure common 2-D spin-plane fields.

The mission will continue to explore the structure and dynamics of the bow shock and its role in producing energetic ions and electrons, a problem with fundamental scientific applications in space and astrophysics. The increased spacecraft separation of this extended mission will allow spacecraft to examine the macroscale structure of this shock, including the cross coupling of regions with quasi-parallel and quasi-perpendicular geometry and correlation lengths of large-scale structures. The dynamics and role of density holes and field-aligned beams on shock structure will be studied.

The magnetopause is a region of critical importance in understanding magnetic reconnection and the flow of plasma from the magnetosheath into the magnetosphere. In this region, a new Grad-Shafranov technique will be exploited to measure the development and structure of magnetic islands (FTEs), including the Hall fields, effective resistivity, and slow-mode shocks. The EDI instrument will be used to measure fine-scale Hall electric fields, although the ability of Cluster to measure non-gyrotropic electrons seems questionable. The role of magnetopause or magnetosheath reconnection in producing electron solitary waves (ESWs), a proposed dissipation mechanism for reconnection, will be explored. See below for further discussion of magnetopause reconnection measurements.

A new focus of the Cluster mission now will be the inner magnetosphere and plasmasphere, where a variety of waves are possible mechanisms for the acceleration, transport, and loss of energetic electrons during storms and substorms. This topic is of obvious importance for the science of space weather. For example, the stability and dynamics of whistler chorus and equatorial noise will be explored with multiple satellites to establish the spatial localization of source regions and dependence on geomagnetic activity.

The Cluster orbital parameters now will facilitate the exploration of the auroral zones in the range of 1–2 Earth radii. This is a critical region where magnetospheric currents flow into and out of the ionosphere, and parallel electric fields produce intense electron beams and associated turbulence. This is the first multi-spacecraft exploration of this region and complements the measurements of FAST at lower altitude. The structure of double layers and dispersive Alfven waves and associated distribution functions will be measured. Conjunctions once every twelve days with THEMIS will enable the study of the coupling of auroral processes with substorms.

The Cluster orbit in the magnetotail will evolve so that measurements can be taken from 7 to 19 Earth radii down the tail. This changing orbit will allow Cluster to explore the critical near-Earth region where it has been suggested that turbulence can cause a disruption of the cross-tail current sheet, initiating substorms. This information will facilitate the study of substorm onset as part of the THEMIS mission. In addition, ongoing studies of the properties of turbulence in the magnetotail and source regions of O^+ will be completed with new data closer to the Earth. Electron acceleration in magnetic islands, including the role of entrained Hall electric fields and the structure of slow shocks, which may also act as particle accelerators, also will be explored.

Relevancy to HP Research Objectives and Focus Areas

The Cluster mission will address many of the goals laid out in the Roadmap. These include the physics of reconnection, the structure of shocks and their role in the production of energetic particles, the initiation of substorms that play an important role in the injection of particles into the inner magnetosphere, and the physical mechanisms responsible for the abundant energetic electron population in the outer radiation belt.

Value to the HP Great Observatory

Cluster will continue to play a key role in the exploration of magnetic reconnection and associated particle acceleration. Cluster, along with THEMIS and supported by FAST and Geotail, will provide critical information on the dynamics of substorms. Operating in concert with the fleet of Great Observatory spacecraft, including RHESSI, SOHO, STEREO and Hinode, as well as with in-situ measurements by the magnetospheric satellites in the GO, Cluster will fulfill a vital role in studies of the full cycle of space weather from the initiation of flares and CMEs to their impact on the geospace system, including space weather issues such as the radiation environment.

Spacecraft/Instrument Health and Status

Several of the instruments aboard the four Cluster satellites have had problems, and some instruments have failed. The multiple spacecraft, of course, provides redundancy in those cases where proper operation on all four spacecraft is not required for the science. The proposal is not clear on the science limitations imposed by these failures.

Data Operations (Accessibility, Quality Control, Archiving)

The Cluster Active Archive (CAA) provides public access to carefully prepared and calibrated Cluster data with high resolution. By the end of 2008, the expectation is that the CAA will contain data through 2007. This major effort is being funded by ESA and their member states. The CAA is becoming an exceptional tool for the HP science community. The creation of the CAA reduces the pressure on the individual instrument teams in the area of broad data dissemination. Integration of data from the WBD investigation into the CAA is an issue because of the magnitude of the data collected.

Proposal Weaknesses

The proposal presented a long list of scientific studies that would be carried out over the next several years. Each of these topics is interesting. The proposal, however, seems less than the sum of its parts. The proposers were less than successful in defining a more limited number of compelling problems that could serve to define success for the extension of this mission. The Earth's bow shock is an important laboratory for the exploration of collisionless shock physics and associated particle acceleration, yet the proposed measurements of mesoscale correlation lengths do not seem likely to produce breakthroughs of a substantial nature.

The Cluster mission, with its four-spacecraft constellation, seems ideally suited for exploring the mesoscale structure of the reconnection dissipation region in preparation for and complimenting the goal of the MMS mission to explore electron-scale structure of the dissipation region. Cluster has already made substantial contributions in this area, producing the first estimates of the length of the electron diffusion region, yet no follow-up on this work is proposed. Proposed studies on reconnection that were discussed in the proposal were not always well conceived. A new technique for identifying the electron diffusion region was presented based on the structure of the Hall electric fields and electron temperature anisotropies calculated in symmetric, 2-D PIC simulations. The proposal to use these same signatures to explore magnetopause reconnection with no discussion of the strong asymmetries that are typically present at the magnetopause seems questionable.

A substantial section of the proposal was devoted to work related to the inner magnetosphere and plasmasphere, and electron acceleration in the outer radiation belts. However, the Cluster orbit, because of its high inclination, is much less desirable for studying electron acceleration in the radiation belts as the equatorial orbits of the THEMIS constellation, or those planned for RBSP. Furthermore, the particle instrumentation, RAPID and PEACE, for example, of course, were not designed for operation in the intense radiation-belt environment, and therefore have serious limitations for carrying out radiation belt science.

An extensive discussion of substorm onset in the proposal was presented (Sec. 2.5.4), *yet within this discussion,* there was no mention of cross comparisons with THEMIS, a surprising oversight given the substantial resources that THEMIS is expending on this topic.

The proposal states that *the costs of validating (Cluster) data have not decreased* (since launch) and requests an augmentation of $1M/yr *solely to support … acquisition and validation tasks*. The panel did not understand why data validation costs do not decrease after almost a decade into the mission; instrument performance and idiosyncrasies should be well explored by now. In any event, the proposal does not provide an explanation or justification.

Overall Assessment and Findings

Cluster is a four-satellite mission that is designed to explore the micro- and meso-scale dynamics of the Earth's magnetosphere and environs, including: the solar wind and entrained turbulence; the bow shock and its mesoscale structure; reconnection at the magnetopause and in the magnetotail; the plasma sheet, associated turbulence and its role in triggering substorms; the auroral zone particle acceleration and associated radiation and oxygen outflows; and the ring current. All of these topics are identified as critical in the Roadmap and whose exploration requires physics input from other missions as part of the Great Observatory. The Panel therefore endorses continued support for the mission.

Nevertheless, the proposal is not successful in defining a limited set of key scientific goals that can be used to define the success of the mission. To maximize the impact of this mission, however, the Panel feels that it is important that the mission leaders carefully craft a subset of critical problems and marshal resources appropriately to address these issues. In light of the upcoming MMS mission and the increasing magnetospheric activity associated with solar cycle 24, one of these focus areas should be reconnection. The spacing of the four spacecraft will enable Cluster to measure the mesoscale structure of reconnection at the magnetopause and in the magnetotail, complimenting MMS's focus on microscale processes. The inner magnetosphere topics might also constitute a focus area if it is carried out in conjunction with the proposed extension of the THEMIS mission. The inner THEMIS cluster is proposed to have an equatorial orbit that complements the more polar Cluster orbit.

If the WBD data cannot be seamlessly integrated into the CAA, there is a good possibility that these data will be little used, leading to questions concerning the utility of continuing WBD operations.

The proposed budget enhancement to fund a Cluster focused GI program has not been convincingly justified, and is therefore not supported by the Panel.

2.4 Fast Auroral SnapshoT Explorer (FAST)

Science Strengths

FAST was launched twelve years ago and was the second SMEX mission. FAST has been highly productive during its prime mission and subsequently. The FAST science team proposes to extend their mission to support the HP Great Observatory over the next few years. Although the electric fields investigation is no longer operational due to radiation damage effects, the rest of the experiments and support equipment is functioning well.

FAST, in its relatively low, high-inclination orbit, measures particles and fields near the foot of the magnetic field lines traversed by both the THEMIS and Cluster spacecraft that are at much higher altitude, often near the equatorial plane. Thus, FAST is able to examine in detail the particles and fields near the loss cone. This simply cannot be done by the high-altitude satellites. Such data are and will be highly valuable in the interpretation of THEMIS and Cluster observations.

The low-altitude FAST orbit results in a short orbital period and thus provides a rapid revisit to all L values, giving a temporal resolution that is impossible with the THEMIS and Cluster spacecraft.

THEMIS has GBO (Ground Based Observatories) as a central part of the mission. However, the GBO only cover a modest fraction of the Earth, whereas FAST gives a global view, and at all times. FAST thus will provide vital additional data that will directly support the THEMIS space and ground observatories.

In addition, coincident observations between the GBO and FAST will be used to do auroral science even in the absence of simultaneous THEMIS observations. The THEMIS/GBO provide a serendipitous opportunity for FAST to continue auroral research without incurring additional costs for quality, ground-based facilities.

FAST scientists have recently reported the first direct observations of flare prompt-phase photoelectrons. Photoelectrons are very important for Earth's upper atmosphere, for the complicated thermospheric chemistry (and, for instance, the E-layer ionization), and because they heat the thermal electrons and the neutral gas. Photoelectrons are a good tracer for energy deposition during solar flares because they are very sensitive to the magnitude and wavelength of EUV. FAST photoelectron observations will be directly used to validate and improve EUV irradiances (SEE/TIMED or later SDO) that are parameterized for solar flares (i.e., in the FISM model).

The FAST team has been highly productive over the long life of FAST; there can be no doubt that they can carry out the proposed program. The fact that many of the FAST team are part of the THEMIS investigation ensures that effective collaboration can be, and, in fact, already has been achieved.

Relevancy to HP Research Objectives and Focus Areas

The FAST mission directly addresses three research focus areas: F2—understand the plasma processes that accelerate and transport particles; F3—understand the role of plasma and neutral interactions in nonlinear coupling of regions throughout the solar system; and H2—determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.

Value to the HP Great Observatory

FAST is the only operational or planned mission that can provide low-altitude particle and field measurements, near the atmospheric loss cone, on magnetic field lines connected to the THEMIS and Cluster spacecraft, and provide such data at a frequent cadence.

FAST will also provide measurements of photoelectrons resulting from solar flare EUV in support of the interpretation of TIMED and SDO EUV observations.

Spacecraft/Instrument Health and Status

The spacecraft and most of the instrumentation continue nominal operation some twelve years after launch. The exception is the electric-field investigation that is no longer in operation due to radiation damage. The telemetry has been reconfigured to enhance high time resolution particle measurements.

Overall Assessment and Findings

FAST provides high-quality particle and fields data from a magnetospheric vantage point not accessible to any other spacecraft in the HP Great Observatory fleet. In particular, FAST directly supports the THEMIS primary mission science by making important substorm-phenomena measurements that neither the THEMIS satellites nor the GBOs can make; therefore, the panel supports extension of the FAST mission.

2.5 Geotail

Science Strengths

Geotail is a low-cost mission that will provide a highly valuable contribution to the Heliophysics Great Observatory. The Geotail orbit is ideal for measuring the mid-tail dynamics, including the field and flow properties associated with near-Earth and distant reconnection. The 9x30 Re orbit also allows Geotail to spend a significant amount of time skimming the dayside magnetopause and measuring dayside reconnection, and skimming the dawn and dusk boundary layers that are key regions of magnetosheath plasma entry and energy coupling with the solar wind. In addition, when apogee is in the dayside regions, Geotail will spend 35% of its time in the solar wind, enabling the accurate measurement of the solar wind conditions that are driving the magnetosphere.

The most significant contribution from Geotail will be through its complementary measurements to those of THEMIS and ARTEMIS. When the prime mission of THEMIS ends, Geotail will be the only satellite measuring the dawn-dusk mid-tail plasma sheet. These measurements will be valuable in assessing the location of reconnection, both down the tail and across the tail, that will establish the larger scale context of the energy-transfer processes that THEMIS will be measuring with a finer-scale satellite configuration nearer the Earth.

Geotail and ARTEMIS will be valuable for assessing the relationship between near-Earth and distant reconnection, determining the temporal relationship between reconnection occurring in these two regions as well as the cross-tail extent. During conjunctions along the tail flanks, the coordinated Geotail and ARTEMIS measurements will provide valuable constraints on the down-tail extent and effectiveness of plasma entry into the magnetosphere through processes such as Kelvin-Helmholtz waves and high-latitude, northward-IMF reconnection. The role of deep-tail reconnection in capturing the flank plasma is an important outstanding question that these coordinated observations will help to resolve.

Relevancy to HP Research Objectives and Focus Areas

The Geotail mission supports the understanding of fundamental processes of the space environment (Open the Frontier to Space Environment Prediction). Geotail provides accurate measurements of the near-Earth solar wind conditions, a key factor in space weather. These data contain information on solar-wind shocks that can abruptly change the Earth’s radiation environment.

Value to the HP Great Observatory

Multipoint observations are crucial in the quest to understand and predict the geospace environment. Geotail is well positioned to support the THEMIS prime mission and Cluster science. And in the THEMIS extended mission time period, Geotail will be the only Great Observatory asset in the mid-tail because three THEMIS probes will have apogees of only 12 Re, and the two other THEMIS probes will become ARTEMIS in lunar orbit. Geotail also has instrumentation not on board THEMIS

Spacecraft/Instrument Health and Status

The spacecraft performance remains nominal after 15 years of operation. All residual hydrazine was dumped in order to alleviate any risk of freezing during eclipses. There is no reason to believe that the spacecraft cannot operate for many more years. All instruments, with the exception of the high-energy particle instrument, continue to provide excellent data.

Data Operations (Accessibility, Quality Control, Archiving)

Geotail data are readily available via CDAWeb, the Japanese DARTS, and US Web sites. The Japanese have developed a Conjunction Event Finder providing ready access to Geotail and other, related data.

Proposal Weaknesses

The Geotail proposal contains no significant weaknesses.

Overall Assessment and Findings

The panel finds that the Geotail mission is still providing excellent science. The Geotail orbit is ideal for measuring magnetotail dynamics, dayside magnetic reconnection, magnetopause boundary layers, and the entry of solar wind plasma in the magnetosphere. Geotail will also make accurate measurement of the solar wind conditions that are driving the magnetosphere during part of its orbit. Because of its orbit and instrumentation, Geotail can provide invaluable correlative information to the THEMIS-Low, ARTEMIS, and Cluster mission science. Geotail makes a highly valuable contribution to the Heliophysics Great Observatory. The panel strongly supports the proposed Geotail extended mission.

2.6 The Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI)

Science Strengths

RHESSI addresses the primary focus areas of the Heliophysics Program, namely understanding magnetic reconnection and its role in the processes that accelerate and transport particles though the solar atmosphere and into interplanetary space. RHESSI makes unique measurements of the magnetic-field reconnection events that explosively release the energy that powers solar flares and CMEs. It does this by directly observing and imaging the hard X-rays from the reconnection region produced by bremsstrahlung from the electron population released in the event using energy-sensitive detectors that assign both an energy and a spatial location to each detected photon. Spatial localization of the events allows the reconnection event to be related to the structure and evolution of the magnetic field structure.

Interpretation of the electron energy spectrum derived from the hard X-ray emission provides insight into the physics of the reconnection process, while the spatial/temporal variation of the emission suggests how the flow of energy from the reconnection site evolves.

Among RHESSI's accomplishments are:

- Identification of the two sources of the hard X-rays: bremsstrahlung and albedo.
- Demonstration that neither the thick nor thin target model of energy deposition accurately describes the observations that suggest the possibility of continuous acceleration during the energy release process.
- HXR emission observed along the entire length of the flare ribbons rather than simply at the footpoints, suggesting that the energy release is occurring above the arcade. This is possibly a universal phenomenon that is prevented from

observation through the limited dynamic range of the observing technique.

- The high percentage of the total flare energy observed in keV electrons strongly suggests that electron acceleration and the energy release process are closely related rather than being accelerated in the associated shock front. Simulations of magnetic reconnection suggest that magnetic islands are formed and are rapidly compressed. As this happens, the electrons contained within the islands undergo Fermi acceleration.
- Flares observed at the limb show two different behaviors, namely the hard X-rays are co-spatial with the thermal emission or they lie above it. Comparison of future events of this type with STEREO imagery will provide the magnetic context that may differentiate between the two types of event.
- HXR emission from rising flux tubes (loops) suggests that the energetic electrons contained within the magnetic loop structure are being advected upward.
- Gamma-ray emission suggests that ions are accelerated in the flare process and not by CME shocks.
- The observations indicted that almost all the flare energy is released as energetic electrons or ions.

For the next phase of the solar cycle during the proposed extended mission, the rise to maximum, RHESSI has been joined by two new missions that will add new dimensions to the analysis of the RHESSI data. Hinode will add coronal context; vector magnetic field measurements; and density, temperature, and velocity diagnostics of the pre- and post-reconnection flare plasma. Together these measurements will enhance our understanding of the specific conditions that are a prerequisite for reconnection to occur in the solar atmosphere with a goal of establishing a set of necessary and sufficient parameters for reconnection and the associated particle acceleration.

RHESSI has also observed flares that originate behind the limb. These observations provide a method for observing weaker emissions from higher in the solar atmosphere that can be masked by the stronger emissions from the flare foot points. The results show that the non-thermal radiation is not always co-spatial with the thermal radiation but can appear higher in the atmosphere. Because the flare originates behind the limb, the relationship to the underlying conditions, the magnetic structure, is unknown. Observations from STEREO will solve this problem and lead to insight into why a separation between the thermal and non-thermal emission occurs in some but not all limb flares.

Relevancy to HP Research Objectives and Focus Areas

Understanding the origin, causes, and effects of explosive events on all spatial and energy scales in the Sun's lower atmosphere is a (the most) critical element of HP research. The

CMEs that are a consequence of this explosive release of energy give rise to major disturbances across interplanetary space, and are frequently accompanied by solar energetic particle events. By relating the point of energy release to the vector magnetic field determined from other space-based observations, e.g., Hinode, remains the best hope for developing predictive methods for CME.

Although not directly related to the HP research objectives, collaborations with the GLAST observatory may prove to be productive for observing the highest energy emissions.

Value to the HP Great Observatory

RHESSI is the only operational or planned mission that can provide "spectral" images of the initial stages of energy release in flares. The observations identify the location of the energy release. Subsequent comparison with vector magnetic field measurements from Hinode and SDO and 3-D modeling may lead to a predictive capability.

Spacecraft/Instrument Health and Status

Following annealing, the effective area of all but one detector returned to near their original values. The cryo-cooler suffered some degradation after the annealing process that has required an increase in the input power, but it is still able to maintain the detectors in the operating range.

Data operations (Accessibility, Quality Control, Archiving)

The data are difficult for non-experts to use. The team has addressed this problem by developing a technique (visibilities) that converts the count data into electron data that can then be inputted directly into the reconstruction algorithms. The Senior Review Panel approves the team's efforts to educate other scientists in the data analysis techniques appropriate for RHESSI through workshops, and encourages the team to continue these efforts.

Proposal Weaknesses

Although not really a proposal weakness, the panel notes that recent gamma-ray spectroscopy studies have been compromised by issues with the rear detector response, and encourages the RHESSI instrument team to resolve this problem as soon as possible.

Overall Assessment and Findings

RHESSI remains an extremely valuable mission that has been extremely productive in terms of both publications and fundamental breakthrough science. RHESSI's extended phase will occur during the rising phase of the solar cycle when the Sun's global magnetic field is changing that may affect the processes that lead to flare production.

Complementary measurements by the Hinode and STEREO missions will provide context observations, vector magnet fields, and detailed plasma diagnostics that were not available during the prime mission. Knowledge of the context in which solar flares are observed by RHESSI will allow the development of a comprehensive description of the reconnection process in the solar atmosphere that will help resolve, revise, and differentiate between the competing theories for energetic particle production and acceleration. The Senior Review complements the RHESSI team on their past achievements and looks forward to the exciting results that they expect from the extended mission.

The RHESSI Team is requesting a GI Program beyond their present proposal "to stimulate . . . understanding of high energy solar events." The "accessibility" of the data to the scientific community remains a concern of this panel. The panel finds that the practice of holding RHESSI workshops in conjunction with scientific conferences is a most useful method for educating users who then can compete successfully in the general GI solicitations.

Costs for an extended mission are modest.

2.7 Solar and Heliospheric Observatory (SOHO)

Science Strengths

SOHO has been a mainstay of Heliophysics research for the last decade. Its broad observational coverage and easy access to the data has made collaboration between the instrument teams and with the rest of the community the gold standard for such efforts. SOHO's observations have led to numerous discoveries that have advanced many areas of Heliospheric physics, including helioseismology, meridional flow, and waves and flows in the Sun's atmosphere. SOHO is credited in over 3,000-refereed publications to date (over 600 since the last Senior Review) and tens of graduate dissertations per year. SOHO has been the major source of knowledge of the origin and propagation of CMEs.

The LASCO coronagraph on board SOHO is both irreplaceable (in the short term) and crucial to the Heliophysics Great Observatory. Visible (white-light) and polarization brightness images of the corona were called out as high priority needs for the follow-on mission, the Solar Dynamics Observatory, but descoped from that mission during development.

The SOHO baseline proposal is to extend the life of the spacecraft to provide critical Earth-Sun line visible light images of the solar corona. The baseline requested mission does not, itself, include any science—it is merely to maintain, collect, and archive data to enable science that is funded via other sources. In addition, several autonomous, European-operated instruments would continue collecting synoptic data at no cost to

NASA. The optimal funding request includes a modest augmentation for a single targeted campaign to study origins of solar energetic particles.

CELIAS is a solar wind monitor with capability to separate isotopes and energies of minor ions in the solar wind. The SOHO baseline request includes approximately $400k/year funding to maintain and operate the CELIAS instrument (According to the team's answers in the question period of their presentation, this is primarily for the SEM EUV irradiance monitor; but SEM is mentioned only in passing in the written proposal, and not at all in the prepared presentation).

EIT is a full-disk EUV imager that pioneered full-disk monitoring of the solar corona in the EUV. The SOHO baseline request includes a period of intercalibration between EIT and SDO/AIA, and then ongoing occasional synoptic image sets from EIT. Ongoing occasional synoptic image sets were mentioned, but not justified, in the SOHO proposal.

LASCO is a visible light coronagraph that images the solar corona at altitudes between 2 Rs and 30 Rs. It is capable of producing coronal images in polarized and in unpolarized visible light. The LASCO synoptic dataset has yielded most of the current understanding of CME acceleration and ICME origin, and is an irreplaceable part of the Heliophysics Great Observatory.

UVCS is the only operating coronagraphic spectrograph. A recent breakthrough provides a strong indication that UVCS is capable of detecting the difference between thermal and slightly perturbed line profiles that are quite possibly a key signature of the seed populations of solar energetic particles. Using these signatures, it may be possible to distinguish between the different models of SEP acceleration. However, confirmation of this process requires collecting further synoptic observations with UVCS in a new operating mode, at least through the rise phase of the next solar cycle (2009–12). The optimal funding profile request includes approximately $400k/year to operate UVCS through 2012.

Relevance to HP Research Objectives

LASCO is the only space-based coronagraph located close to the Earth-Sun line. It is a crucial piece of the HP Great Observatory, both for its ability to observe Earth-bound CMEs as "halos" and for providing a second or third view to the STEREO heliospheric imagers in heliocentric orbits. Earth-Sun line coronagraph data are important to at least RFAs F1, F3, H1, H3, and J1 from the 2005 Roadmap.

The science contemplated for UVCS—probing broad spectral profiles in coronal features for signs of suprathermal ions that may serve as SEP seed populations—is directly relevant to the goals laid out in the Roadmap since it may lead directly to an understanding of SEP formation and therefore to an improved ability to forecast SEPs. In particular, understanding SEP precursors and seed populations would be a breakthrough advance for RFAs F2 and J2 in the 2005 Roadmap.

Spacecraft/Instrument Health and Status

Many of the instruments are showing their age; however, they are still able to provide excellent data. There are known issues with the SOHO high-gain antenna and gyro systems, but these issues have been worked around and do not affect the revised mission plans reviewed by the Senior Review. Fuel and power reserves are sufficient for over 30 years of reduced-mission operation.

Data Operations (Accessibility, Quality Control, Archiving)

The SOHO data system is exemplary. Data are processed into well-documented forms and made available to everyone via the SOHO archive. Most imaging data, including LASCO images, are distributed in uncalibrated form only ("Level 0"), along with software (written in IDL) to calibrate the data. LASCO images are also processed into background-subtracted quick-look movies. The calibration process is well understood. UVCS data are made available in uncalibrated form, together with the IDL software needed to calibrate them. SOHO data are indexed both via mission-specific search tools and via the Virtual Solar Observatory.

Historically, UVCS data have been considered difficult to retrieve and interpret, and this view was reinforced by the presentation to the Senior Review panel. Particularly, as the mission winds down and instrument-specific expertise is lost to other projects, the SR panel finds that the UVCS team needs to take active steps to broaden the investigator base among interested outside parties. Complete documentation of the analysis process for a specific set of spectral questions, including a full description of all steps taken to reduce the raw data and arrive at the final published plots, would be helpful to this goal.

Proposal Weaknesses

SOHO is intended to be operated in a large observatory mode, and hence has a high fixed cost of operation. Retiring most of the SOHO instruments thus greatly increases the cost per unit data from the remaining instruments. Nevertheless, Sun-Earth line coronagraph data are of particularly high value, and maintaining SOHO is, in the short term, the most cost-effective way to continue collecting them.

Continued funding of CELIAS was not well defended. The main use of CELIAS' requested funding—maintaining the SEM module of the instrument—was not mentioned in the proposal nor in the prepared presentation. The CELIAS science effort of $400k/yr in the baseline request is approximately equal to the well-defended UVCS science effort for the augmented proposal, but there was no clear and compelling justification given for the use of those funds.

Overall Assessment and Findings

Continued limited operation of SOHO is critical to the ongoing effort to understand the solar influence on the heliosphere and geospace because SOHO's coronagraph (LASCO) both remedies the lack of a Sun-Earth-aligned coronagraph on the SDO mission and is irreplaceable in the near term. Continuing SOHO operations to collect, disseminate, and archive data from LASCO is therefore essential.

Recently identified science would be enabled by targeted UVCS operations and would lead to a compelling scientific return. These operations would be at a minimal incremental cost to NASA given continued operation of SOHO. Operating UVCS through the next solar maximum will yield otherwise unobtainable first exploration of suprathermal seed populations in the solar corona that give rise to SEP events. The panel finds that the U.S. portion of the CELIAS program should be terminated and EIT operations should be terminated after intercalibration with SDO/AIA. The relevant funds should be used instead to address the proposed UVCS science, within the baseline proposal budget.

2.8 Solar TErrestrial RElations Observatory (STEREO)

Science Strengths

The STEREO twin spacecraft are providing new perspectives of the Sun and heliosphere from orbits that carry the spacecraft in opposite directions from the Sun-Earth line at a separation rate (relative to Earth) of ~23^{o} per year. STEREO is well on its way to meeting its four primary scientific goals. Significant results include 3-D reconstructions of coronal loops, polar jets, and erupting twisted filaments, as well as the identification of an extremely long reconnection X-line in the solar wind. These findings have important implications for determining coronal magnetic topologies, vertical density scale heights, absolute flow speeds, and reconnection at the Sun and in the heliosphere. STEREO has helped determine the steadiness of heliospheric structures and provided observations of ions streaming off Earth's bow shock over very large distances (up to 3800 R_E).

STEREO observations have also produced unexpected science results, such as observations of magnetic reconnection between comet ion tails and ICME magnetic fields, the discovery of obliquely propagating whistler-mode waves in the radiation belt, measurements of stellar variability, and studies of interplanetary dust distributions.

A further surprise was the ability of the SECCHI instrument to remotely image the propagation of co-rotating interaction regions. This capability bodes well for the prime mission objective of STEREO to take advantage of large angle separation between the two spacecraft and Wind, ACE, and SOHO to map CME propagation from the sun to the Earth as solar cycle 24 develops. Given the importance of ICMEs as sources of solar energetic particles, scientific discovery in this area is expected to be a highlight of the mission. The increasing separation of these spacecraft combined with Wind and ACE is also central to helping pin down the spatial extent of magnetic reconnection in the solar wind, a result that will have broad scientific impact in the heliosphere and beyond.

Relevance to HP Roadmap

The overlap of the STEREO science program with the Roadmap has been well documented in the Scientific Objectives section of the proposal. Briefly, the separation of the STEREO spacecraft from other spacecraft in the HPGO will facilitate critical multipoint observations of the structure and propagation of CMEs and ICMEs, which is critical for developing models for energetic particle production and assessing space weather hazards. Such multipoint observations are also key for understanding the spatial development of reconnection, a priority of the Roadmap. The spacecraft locations relative to other HPGO spacecraft and the potential for unusual aspects of impending solar cycle 24 make the strong case for potentially large scientific return from both the primary and the extended mission.

Value to HP Great Observatory

STEREO is an essential component of the HPGO. The unique orbits are providing new and unprecedented views of the Sun and heliosphere. By 2011, STEREO A & B spacecraft will be 180° apart and will be able to view the entire solar disk for the first time, providing unparalleled, continuous observations of the evolution of solar structures as well as a global view of the structure of the heliosphere, including CIRs and ICMEs during the rise of solar activity. STEREO observations have enhanced the scientific return of observations from other spacecraft in the HPGO, including SOHO, Hinode, RHESSI, TRACE, ACE, WIND, and Geotail. STEREO observations will be needed by Messenger to provide contextual information about the presence of flaring or ICME activity that may impact the environment of Mercury. STEREO science will both enhance and be profited by upcoming missions such as SDO and IBEX.

Spacecraft/Instrument Status

All STEREO spacecraft systems are healthy. There was a failure of the X-axis inertial measurement unit of the Ahead spacecraft in late spring of 2007. The backup unit is running flawlessly, and the system is operational. In the event that the backup unit fails, the spacecraft attitude can be maintained using the SECCHI guide telescope. The spacecraft thrusters have fuel for more than 100 years. Only two instrument problems have occurred, and neither are serious: (1) Effective loss of the STE-U resulted in a decreased sensitivity to electrons in the few keV range; however, the gap is partially filled by backscattering and some overlap with SWEA. (2) There is interference in the S/WAVES instrument on the Behind spacecraft associated with the IMPACT boom. This limits S/WAVES's ability to do 3-antenna direction finding below 100 kHz on all but the strongest events. STEREO utilizes the WIND/WAVES direction finding to help fill the missing capability. The SECCHI instrument suite is fully operational and providing a wide variety of exceptional observations. With the exception of part of the STE-U suprathermal electron instrument, all of the in-situ particle instruments on STEREO appear to be working well and are returning excellent data. The very large SEP events of December 2006 fortuitously provided an opportunity to cross-calibrate the STEREO particle instruments with each other and with ACE and Wind while all the spacecraft were still near the Sun-Earth line. Since then there have been no other gradual SEP events. However, CIR events have provided additional opportunities to compare particle measurements and are yielding interesting new insights in themselves. The most important comparative particle measurements still lie in the future when the rate of events will rise.

Data Operations

STEREO data are being used in many science investigations, with over 70 publications appearing in just the first year of the mission. All STEREO science data, as well as a number of data tools, are accessible via the Internet through the STEREO Science Center (SSC) archive and PI sites. Over 11 terabytes of data have been served in 2007. However, the Level 2 data are not yet fully available. Work remains to fully implement this section of the archive. Fortunately, there appears to be funds in the FY08/09 budget to address this deficiency. An augmentation is requested for FY10 through FY12 to provide more than ”bare-bones data handling.” It is stated that otherwise ”no new data products could be developed.” The development of new data products continues to occur even in the case of other very old missions, often without specific support or within limited budgets. STEREO will eventually have to make the same transition.

Proposal Weaknesses

Downlinks drop with STEREO distance to DSN, resulting in telemetry dropping by 60% in August 2009 and down to 20% of current rate by October 2010. The team notes that a change in cadence and/or data compression algorithms will be required, but no specifics are provided. An assurance is given that this will “in no way” limit STEREO mission primary science goals. It would be more reassuring if a basic plan had been provided by the team to support this claim.

Overall Assessment and Findings

In spite of the absence of substantial solar activity prior to the start of solar cycle 24, STEREO has produced a wealth of interesting results, including the 3-D structure of magnetic loops and polar jets, the propagation of co-rotating interaction regions, and the spatial development of magnetic reconnection. As with other well-designed missions, the STEREO team has quickly taken advantage of unexpected events, such as the observations of the disconnection of comet tails. The exploration of the structure and propagations of CMEs and ICMEs and associated energetic particle production is central to HP research objectives and focus areas and to NASA’s strategic objectives. The first year has produced many exciting new insights as well as unexpected discoveries of interest to the broader astrophysical community. During the extended phase of the mission, STEREO will be in a position to provide continuous observations of the full solar disk coinciding with the expected rise to solar maximum activity that will lead to a greater understanding of the eruption and evolution of magnetic flux, primarily in the form of active regions, into the solar atmosphere. STEREO observations are critically important for determining the three-dimensional structure of the solar atmosphere and heliosphere as they evolve in response to the newly emerging flux from solar cycle 24. Understanding this response lies at the very core of the Living With a Star, and HPGO Programs. The number of CME and SEP events is expected to rise dramatically during the extended mission, providing STEREO with numerous opportunities for discovery. During this phase, the STEREO coronagraphs will be ideally situated for imaging Earth-directed CMEs, providing more accurate observations for space weather forecasts. STEREO, ACE, and Wind combined will provide unprecedented measurements on the large-scale longitudinal structure of SEP intensity, spectra, and composition. These measurements are expected to have a major impact on long-standing questions about SEP acceleration and transport, and to lead to major improvements in our ability to model these important space-radiation hazards.

The spacecraft and instrument health status is, with few exceptions, nominal, and is expected to continue for many years. Data operations are adequate and will be much improved with the availability of Level 2 data, which will become fully accessible at the end of 2008.

The large spatial separation of the STEREO spacecraft will not be repeated for many years and, with other HPGO spacecraft, provides key information on the 3-D structure of the corona and solar wind. Current budget reductions in FY10 through FY12 would negatively impact science productivity at a time of high interest in STEREO data that coincides with the rise to maximum solar activity in cycle 24. However, funding for modeling efforts could be carried out under the Guest Investigator, Theory and R&A programs.

2.9 Time History of Events and Macroscale Interactions During Substorms (THEMIS)

The THEMIS extended mission proposal consists of a bifurcation of the original mission into two parts called THEMIS-Low, using the current inner three satellites, and ARTEMIS, which will use the two outer satellites in lunar orbit.

Science Strengths: THEMIS-Low

The orbits of the three lower-altitude THEMIS probes will be configured to address scientific issues requiring smaller probe separations than available in the baseline mission, and separations both within and perpendicular to the equatorial plane. The apogees are to be ~12 Re, allowing the detailed investigation of the near-Earth plasma sheet and the dayside equatorial magnetopause as well as the radiation belts. With this new orbit configuration, THEMIS-Low will be able to answer important questions regarding magnetotail dynamics; dayside reconnection; and radiation belt acceleration, transport, and loss as the THEMIS-Low orbits precess around the Earth.

In the magnetotail, the smaller probe separations will be used to investigate the stability and dynamics of the near-Earth current sheet, particularly as it thins in association with storms and substorms. These measurements, together with numerical simulations and complementary measurements from other satellites and ground-based instruments, will give important new knowledge of the physical processes at the core of energy storage and release in space plasma. Specific areas of investigation include current carrier evolution, current diversion and filamentation, growth of tail instabilities, and the role of turbulence in the dissipation of fast earthward plasma sheet flows.

In the inner magnetosphere, the string-of-pearls configuration of the probes will give the particle and field measurements needed to determine the role of waves in storm-time electron acceleration and loss, and the role of large electric fields in the ring current, sub-auroral polarization drifts, and plasmaspheric evolution. The results of these studies will form an important foundation upon which the upcoming RBSP mission will build.

At the dayside equatorial magnetopause, the three-probe configuration will measure the structure of magnetic reconnection, including the asymmetric inflow regions (magnetosheath and magnetosphere) and the outflow region (separated in the Z direction).

Science Strengths: ARTEMIS

The ARTEMIS mission involves moving the two higher THEMIS probes into lunar orbits where they will become the ARTEMIS pair. At this location, roughly 60 Re from Earth, ARTEMIS will study the distant magnetotail, shock acceleration upstream from the magnetosphere, and the kinetic properties of the lunar wake. In the magnetosphere, ARTEMIS will be situated to determine the cross-tail extent of magnetotail reconnection. Together with Cluster, Geotail, and THEMIS-Low, ARTEMIS will determine the evolution of reconnection jets and plasmoids from near Earth to the distant magnetotail. ARTEMIS will also investigate the drivers and effects of turbulence in the magnetotail, and determine the role of turbulence in controlling the diffusion of plasma across the magnetopause, particularly under northward IMF conditions when the closed magnetospheric boundary may retreat inside the lunar orbit.

In the solar wind, ARTEMIS will measure the spatial properties of the bow shock and interplanetary shocks as well as the e-folding distance of the accelerated particles. This will yield constraints on particle acceleration models and improve our understanding of diffusive acceleration in foreshocks. Together with Wind, Geotail, and Cluster, ARTEMIS will improve our understanding of the small- and large-scale properties of low-shear reconnection in the solar wind.

In the lunar wake, ARTEMIS will determine the three-dimensional structure of the wake, identify the plasma acceleration processes in and around the wake, and study these processes under a variety of solar wind and magnetospheric conditions.

Science Strengths: Overall

The extended mission satellite configurations of THEMIS-Low and ARTEMIS will yield important science discoveries on the key processes at the core of solar wind–magnetosphere–ionosphere coupling, and they will contribute strongly to the HP Great Observatory. The importance of THEMIS-Low and ARTEMIS is particularly high as we approach solar maximum, and the strength and frequency of geoeffective solar activities increase.

In the new inner magnetosphere orbits, three of the THEMIS probes will give radially and vertically separated measurements in the near-Earth current sheet, at the dayside magnetopause, and through the ring current and radiation belt regions. These satellites will determine the mechanisms for the dissipation of fast earthward flows associated with storms and substorms in the inner magnetosphere and ionosphere, the thickness and dynamics of the near-Earth current sheet, the physics of asymmetric reconnection and particle acceleration at the dayside magnetosphere, and the role of waves and large electric fields in the inner magnetosphere.

ARTEMIS, the two-satellite mission in lunar orbit, will give multipoint measurements in the magnetotail, in the solar wind, and in the lunar wake. In the magnetotail, these measurements will provide new information on the azimuthal extent of magnetic reconnection, the plasma flows and particle acceleration associated with tail reconnection, the structure of plasmoids, and the temporal relationship between the reconnection in the deep tail and near-earth storm and substorm dynamics. In the solar wind, the 1–20 Re spacing of the probes will enable the determination of the structure of low-shear reconnection and of particle acceleration at shocks. The ARTEMIS measurements in the solar wind will be an excellent complement to those of STEREO, WIND, and ACE. Within the lunar wake, the two ARTEMIS probes will enable new studies of the kinetic processes responsible for particle acceleration and the formation and filling of the wake; however, the panel found these studies less compelling than the other proposed ARTEMIS investigations.

Relevancy to HP Research Objectives and Focus Areas

The THEMIS extended mission will address several aspects of HP research objectives, including such central issues as the physics of reconnection, particle acceleration process, the manner in which solar activity affects the Earth, and several space weather issues.

Value to the HP Great Observatory

Both parts of the proposed extended THEMIS mission, THEMIS-Low and ARTEMIS, would be exceptionally valuable elements of the HP Great Observatory. ARTEMIS will provide important multi-point observations in the outer magnetotail and in the solar wind, while the THEMIS extended mission will determine the related physical processes occurring at the key locations (dayside magnetopause and near-Earth plasma sheet) where the energy transfer that drives the coupled solar wind-magnetosphere-ionosphere system is occurring.

Spacecraft/Instrument Health and Status

The five THEMIS probes and their instruments have operated nominally since launch. The THEMIS ground systems have performed well also.

Data Operations (Accessibility, Quality Control, Archiving)

The THEMIS team has also done a superb job of making the data available to the international scientific community, and has held public workshops to ensure that interested scientists have access to the necessary software to utilize the data.

Overall Assessment and Findings

The THEMIS prime mission has proven to be highly successful, cost effective, and a vital element of the HP Great Observatory. With its strategically placed five-satellite constellation and its effective collaborations with other satellites and with an extensive array of ground-based instruments, THEMIS is providing answers to key, outstanding questions on how energy is released during geomagnetic storms and substorms.

Overall, the panel finds that the proposed THEMIS extended mission, consisting of THEMIS-Low and ARTEMIS, is highly compelling, both for their individual scientific goals and what will undoubtedly be their excellent contributions to the HP Great Observatory.

2.10 Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED)

Science Strengths

TIMED explores the ionosphere-thermosphere-mesosphere (ITM) region that links the Sun, heliosphere, and magnetosphere with Earth's environment. TIMED measurements during the descending phase of solar cycle 23 showed that the response of the ITM system on time scales ranging from minutes to decades is not simply the linear superposition of the effects of individual drivers (solar, magnetic, tropospheric weather, human-induced) but a result of complex, nonlinear interactions and preconditioning. The

3D data from TIMED allowed, for the first time, the cause-and-effect chain that governs the ITM response to external system drivers during different solar activity levels to be followed, and the determination of the basic roles of dynamics, radiative forcing, and chemistry.

The groundbreaking TIMED observations during the past six years raised many new science questions that are fundamental to understanding the nonlinear interaction of the various ITM drivers. Therefore, two new objectives are identified for the extended mission. They are to understand and characterize: (1) the solar-cycle-induced variability of the ITM region, and (2) the human-induced variability and change of the ITM region.

A long-baseline, uniform dataset covering a full solar cycle is essential to achieve these compelling science goals, particularly to separate and identify effects from the solar cycle, secular trends, and other natural and anthropogenic influences that remain a key question in atmospheric physics. Quantitative measures of the complex interactions between radiatively important species (NO, CO_2, O, H_2O, O_3, OH), dynamics (wave activity, turbopause behavior, QBO, ENSO), and energetics (solar irradiance, airglow) are crucial for this purpose. SABER data processing is maturing and can now provide reliable temperatures and O and CO_2 densities that are a key requirement for the extended mission objectives. The TIDI wind data have proven to be extremely valuable in the study of the dynamical wave coupling of the lower atmosphere with equatorial electrodynamics and thermospheric composition. These studies will increase in importance during the extended mission because the longer dataset will provide an unprecedented opportunity to separate solar cycle effects from QBO (Quasi-Biennial Oscillation) and ENSO (El Nino/Southern Oscillation) driven effects.

There has been no strong ENSO event since the TIMED launch. ENSO-related variability in the troposphere and stratosphere, however, is expected to have a dramatic impact on the ITM because it changes the heat balance and wave activity of the entire atmosphere. There is a good chance to observe a strong ENSO event within the extended mission because it occurs every few years.

The magnetic activity in the rising phase of the solar cycle is generally more infrequent and isolated than in the descending phase. TIMED observations in the rising phase therefore provide a special opportunity to study an ITM driven more strongly by solar irradiance changes. This will allow for a more robust separation of the different drivers, and is very important to test next-generation first principle and predictive models. If an observed temperature change is a strictly solar effect, then the ITM should be warming in the next few years; and if it is a strictly terrestrial effect, then the ITM should be cooling. The TIMED observations are capable of distinguishing between these two cases.

TIMED observations are also an important baseline for studies of the polar ITM that is particularly responsive to global change. Significant linkages and synergies with the AIM mission have been identified. The combination of the forthcoming SDO/EVE data with

SEE will allow study of the ITM solar forcing at an unprecedented time resolution. Together with TIMED observations of changes in magnetic energy inputs and thermospheric composition (i.e., nitric oxide abundance in the GUVI spectrographic mode), this will provide a new view of the processes by which energy is converted and processed in Earth's upper atmosphere. The UV spectral measurements made by the TIMED/SEE instrument are complementary to the measurements that will be made by the EVE instrument on SDO. The SEE observations cover a wider spectral range, albeit with less spectral resolution, and are considered to be useful but not essential for EVE.

Relevancy to the HP Research Objectives and Focus Areas

The TIMED mission contributes to all three broad Roadmap objectives. It has a vital role in "understand the nature of our home in space" because it is the only mission that provides a comprehensive view of the ionospheric and atmospheric changes and physics identified in this objective. The specific TIMED science goals are particularly relevant for RFAs H2.1-H2.3, H3.1-H3.3, and H4.1-H4.3.

Similarities of Earth's atmosphere with that of Mars make TIMED also relevant for "safeguard the journey of exploration" (particularly RFAs J4.2-J4.4) because there are no missions at Mars that can study its atmospheric dynamics, chemistry, and thermal balance in a comparable way. Mars' atmosphere, for instance, is highly influenced by CO_2 non-LTE effects in a way similar to the Earth's upper atmosphere. TIMED's long-term solar irradiance observations and solar cycle studies contribute to RFAs J1.1 and J2.2.

TIMED also makes important contributions to "open the frontier to space environment prediction" because it is the only mission that examines, in detail, the plasma/neutral interaction in a planetary atmosphere (RFA F2.4) and the resulting atmospheric response (RFAs F3.1, F3.2), ionosphere/thermosphere interactions (F3.3), and their role in the terrestrial dynamo (F4.4).

Value to the HP Great Observatory

TIMED is the terrestrial anchor of the HP Great Observatory. The mission ties the phenomena observed by the solar and magnetospheric components of the Great Observatory to the impacts on Earth, and links solar-driven processes in the lower atmosphere to geospace.

TIMED complements measurements made by other Great Observatory missions. One example is the combination of TIMED and AIM, the latter mission studying PMC physics and their potential use as a global change indicator. Other examples include the combination of TIMED with SDO data to study the solar forcing of the ITM, and with FAST to study ionosphere-magnetosphere coupling. The TIMED mission also bridges the gap between the HP Great Observatory and NASA's Earth Science missions.

Spacecraft/Instrument Health and Status

The Guidance and Control subsystem suffered a reaction wheel failure in early 2007. The spacecraft is now under three-wheel control, and uses its two star cameras for pointing. As a backup for another reaction wheel failure, a two-wheel scheme has been developed, tested, and uploaded.

Two instruments, SABER and SEE, continue to perform in a nominal fashion. A third instrument, TIDI, has suffered from ice on the optics and a light leak since the beginning of the mission. TIDI can be expected to perform during an extended mission much as it has in the past.

The fourth instrument, GUVI, suffered a serious failure on 7 December 2007 when the scan mirror ceased moving. Statistical comparisons with DMSP data indicate that GUVI now views parallel to the satellite ground-track with an offset of 300 km. Because of this failure, GUVI is now operated in a spectrographic mode that uses telemetry bandwidth previously dedicated to cross-track imaging to download the full FUV airglow spectrum instead of the five colors previously used.

As a result of this failure, GUVI lost cross-track scanning as well its profiling and limb imaging capabilities. Thus, GUVI is restricted to making the important O/N_2 ratio and EUV/FUV energy flux measurements only along the offset ground track. However, the spectrographic mode will provide new and scientifically valuable measurements, including NO column density, and enhanced time and spatial along-track resolution.

Data Operations

The data are readily available and described on the mission and instrument web pages. GUVI, SABER, and SEE cover quality and validation issues well. All instruments report on precision and accuracy in the literature. GUVI, SEE, and TIDI provide uncertainties in the data files. This information is missing in the SABER files.

The TIDI vector winds on the instrument web page are flagged to not use them due to "serious issues." This warning has been in place for several months although this problem is said to have been solved. The panel finds this situation a concern.

Proposal Weaknesses

The proposal did not explain in sufficient detail the scientific impact of the loss of GUVI's scanning capability. The fact that the spectroscopic mode was not used in the past suggests that the impact might be substantial.

Overall Assessment and Findings

The panel strongly supports the continuation of the TIMED mission. TIMED provides crucial observations of the energy input into and out of the ITM system. This region is at the interface where solar and magnetospheric energy is first deposited into Earth's environment and where these drivers from above compete and interact with radiative forcing and dynamical influences from below. TIMED is the terrestrial anchor of the HP Great Observatory and ties the phenomena observed by the solar and magnetospheric components of the Great Observatory to their impacts on Earth.

The panel finds that an extension of the TIMED mission will significantly further the understanding of the relative effects of the solar cycle, lower atmospheric variability, and human-induced changes upon the ITM region. Significant parts of these effects and their interactions are neither known nor understood and are crucial for testing the next generation of first principle and predictive models for the magnetosphere-ionosphere system, and for the neutral atmosphere including climate modeling.

The TIMED extended-mission proposal suggests that TIMED/SEE might be turned off as a cost saving measure some time after SDO/EVE data are available. Before this action is taken, the panel feels that an independent comparison of the two datasets should be made to ensure that no critical information will be lost.

2.11 Voyager Interstellar Mission (VIM)

Science Strengths

Both the Voyager 1 and 2 spacecraft now have crossed the heliospheric termination shock, providing measurements of a region that is unlike any found elsewhere in the heliosphere. The VIM continues to be a remarkable mission of discovery, yielding results that are both unexpected and sometimes confirming of theoretical expectations. The VIM is unique in that there is no possibility in the foreseeable future to have corresponding in-situ measurements of the outermost region of our heliosphere and the boundaries between the solar wind and the local interstellar medium. The science return, although based on aging instrumentation that was not optimized for far outer heliospheric observations, is absolutely extraordinary, and will essentially guide much of our thinking about the global heliosphere (and how other cool G-class type stars interact with their interstellar environment), its structure, and its basic physics.

The mission has a 30-year history of top quality work and discovery science. The proposal lays out the obvious tried and tested science plan/path for the team to continue their mission. The next six years will focus on the science of the inner heliosheath, but there are likely to be several "discovery" results, such as the possibility for observing the 'magnetic wall' and approaching the heliopause. Major mysteries remain unresolved, such as the source of, and acceleration mechanism for the anomalous cosmic rays. Given the time, the VIM should unravel these mysteries. The character of turbulence in the heliosheath appears to be quite different from that of the supersonic solar wind, and besides being intrinsically interesting, is important to cosmic ray modulation (and perhaps ACR energization). The behavior of major solar wind structures downstream of the heliospheric termination shock (current sheet, sector structure, transmitted shocks, etc.) will be examined by the VIM. Disentangling the influence of the local interstellar medium will be a key element of the extended VIM. Finally, the VIM will measure the response of the heliosheath to solar cycle variations.

Relevancy to HP Research Objectives and Focus Areas

The VIM will provide in situ background and support for the upcoming IBEX mission. IBEX will measure energetic neutral atoms (ENAs) at 1 AU, many of which will be created in the inner heliosheath. Voyager 2 will measure thermal particle distributions, and Voyagers 1 and 2 will measure energetic particles in the inner heliosheath, both of which will be key to deconvolving IBEX data. Almost accidentally, STEREO made some very interesting ENA measurements, and the Voyager 2 plasma distributions and Voyager 1 and 2 energetic particle measurements have already been invoked to try to understand these observations.

Value to the HP Great Observatory

Both in terms of science and in being part of the Great Observatory, the VIM is irreplaceable. Unlike other missions, for which it is conceivable (even if unlikely in many cases) that they could be replaced in one form or another, the VIM, and its ability to make in-situ observations of completely unexplored regions, cannot be replaced within a 20–30 year timescale. IBEX will make quite different measurements of the heliospheric boundary region from those that the VIM makes, but VIM will provide valuable observations for deconvolving the IBEX spectra, especially because IBEX integrates over a line-of-sight that can reflect both temporal and spatial effects, and its spatial resolution does not match the small-scale structure that is observed by the VIM. The VIM is extremely relevant to the first of the Heliophysics Research Objectives, Open the Frontier to Space Environment Predictions, since they are the only spacecraft exploring in situ beyond the planets to the interstellar medium. In terms of the specific research focus areas, the VIM addresses directly "plasma processes that accelerate and transport energetic particles," revealing rather surprising results about the acceleration of anomalous cosmic rays, for example, and addressing the modulation boundaries of galactic cosmic rays. This science, which has a history longer than the space age, can be addressed only by the VIM until another mission is launched towards the LISM region.

Spacecraft/Instrument Health and Status

The longevity of the instruments has proven to be excellent, and the instrument operations/health is well understood since the mission has been so long lived. The plasma instrument does not work on V1, and the magnetometer on V2 has had a problem, which makes data analysis arduous. Nonetheless, the instrumentation and spacecraft performance is sufficient to continue meeting the VIM science goals.

Data Operations (Accessibility, Quality Control, Archiving)

With the exception of the magnetometer data, broad accessibility and usability of the VIM data is sufficient, and potential users can readily download the data from the appropriate websites.

As recognized in the proposal itself, there is a need to improve the "quality and timeliness of Voyager MAG data sent to the Voyager Investigators, other scientists, and the NSSDC." The panel was somewhat disturbed by the description provided for the method of reducing the V2 MAG data and the absence of automation. It was also noted that the 48-s data have not been readily available since 1989. Historically, it has been hard to get magnetometer data and reduce it because the S/N is rather low. However, the question of how the magnetometer data access has been improved since the last senior review was not answered to the satisfaction of the panel.

The panel was told that spacecraft problems in 2006 damaged the V2 magnetometer, creating calibration difficulties. The MAG team had to hire a PhD-level programmer full-time to collect zero-point tables. The MAG data can be corrected for the damage, but this has to be done by eye since no automation routines were developed for the task. Since the by-hand accumulation of the zero table is for every 48 seconds of data, this is extremely labor intensive, laborious, and subject to systematic biases. (Voyager 1 does not have this problem.) The guideline budget does not allow funding of the programmer beyond 2010, so it is unclear how the processing of V2 MAG data will continue thereafter. Currently, as a result of the V2 crossing of the termination shock, processing of Voyager 1 MGA data is behind by about a year. The panel expressed concerns about the magnetometer correction method—algorithm vs. person—and when pressed, the Voyager team indicated that there might be a possibility of introducing some automation routines that had been developed before. It's not clear why this has not been implemented given the potential cost savings and the possibility for better accuracy and perhaps less bias than a person-based reduction method. Finally, the panel is concerned that no plans exist to make the 48-s data available at this time.

Proposal Weaknesses

There are no scientific weaknesses in this proposal.

As discussed above, there is a weakness in the MAG operations—in the accessibility of the data, the usability of the data, and the method for reducing the V2 data.

Overall Assessment and Findings

The panel finds that the VIM proposal offers superb science, tremendous discovery opportunities, and the undisputed fact that nothing like the VIM can be repeated in any form for the next 30+ years; this a mission that is absolutely imperative to continue. The VIM observations will define and guide our understanding of the interaction of the Sun with the interstellar medium for decades. The VIM results will determine global heliospheric science for the next 15 years or more, and will complement and provide a baseline for the upcoming IBEX mission by providing, in part, the data that will be needed to deconvolve the ENA atom observations at 1 AU, adding considerable value to both missions.

An issue is the relatively low priority given to the VIM by the DSN, which led to a data gap during the first crossing of the termination shock by V1. (Current tracking support levels were sufficient to capture three of the five shock crossings that V2 experienced.) Because the VIM is a real-time data acquisition mission, the science return is significantly degraded by reductions in DSN tracking support. The Panel believes that it is imperative that DSN support not be further reduced, and further that a strong case can be made for increased DSN support.

The VIM has the potential and perhaps even is expected to continue its mission of discovery to and beyond 2020. The seniority of the CRS and MAG teams suggests that there is a danger of losing critical capabilities before the mission concludes in data processing and analysis, instrument performance and characteristics, etc., especially because Voyager is an older 1970's spacecraft with dated technologies. The panel believes that it is essential for these VIM instrument teams to be supported sufficiently that they can impart this knowledge base to new team scientists before it is lost.

The Panel finds the case for continuation of the Voyager Interstellar Mission truly compelling.

2.12 Wind

Science Strengths

Wind spacecraft is positioned at L1 and therefore, along with ACE, will continue to serve as a solar wind monitor for studies of transient disturbances of the solar wind and the flow of mass and energy into the Earth's magnetosphere. Wind in the extended mission, along with ACE, the two STEREO spacecraft, and MESSENGER, will provide necessary links in the chain of observations needed to define the large-scale structure of global interplanetary disturbances in the inner heliosphere. Differences in location and instrumentation among these spacecraft give each a critical role in advancing the science.

The Wind spacecraft will keep on playing a central role in the study of solar-wind reconnection events because of its unsurpassed, comprehensive, and high-cadence measurements of the plasma distribution functions and the magnetic field. These measurements are essential for identifying the many small to modest size events and especially those associated with weak shear.

Data from Wind will continue to be used to study the mechanisms for the production of energetic particles both locally in interplanetary shocks and in regions remote from the spacecraft. In the range of ~1–10 MeV/nucleon, Wind provides the most sensitive measurements available for solar heavy ions, including angular distributions that are not available from any other spacecraft. These observations are particular important for studies of solar energetic particle transport.

Wind, along with STEREO and ACE, will continue to explore the structure and evolution of interplanetary shocks, coronal mass ejections, and magnetic clouds. The Wind/Waves instrument in combination with similar capabilities on STEREO will enable accurate tracking of interplanetary shocks—the slowing of the propagation with radial distance from the sun has already been documented. High-cadence magnetic field and ion measurements will facilitate the exploration of solar wind turbulence. Critical issues include particle acceleration in interplanetary space and the source of the v^{-5} energetic ion distributions, the role of intermittency, and the coherence and dissipation scales.

Relevancy to the HP Roadmap

The Wind extended mission will continue to address many of the goals laid out in the Roadmap. These include the physics of reconnection and the structure of shocks, and their propagation, dynamics, and role in accelerating energetic particles. In conjunction with RHESSI and STEREO, Wind and ACE can address the transport of energetic particles from the Sun to the Earth and beyond.

Value to the Heliophysics Great Observatory

Wind, along with ACE, will act as a solar wind monitor for magnetospheric satellites. Wind will additionally act as a backup as well as augmentation for ACE and STEREO in providing crucial data for the exploration of the physics of reconnection and general interplanetary disturbances. These studies will be extended to the magnetosphere using observations by Cluster, THEMIS, and Geotail. Combined with RHESSI, ACE, MESSENGER and STEREO, Wind will enable the study of impulsive events on the sun, their propagation through the heliosphere to the Earth, and with Cluster, THEMIS, and Geotail, the resultant impact on the Geospace environment.

Spacecraft/Instrument Health and Status

Most of the instruments on Wind continue to function normally. The gamma-ray instrument, TGRS, is turned off, and the high-energy particle and composition instrument, EPACT, has suffered some failures.

Data Operations (Accessibility, Quality Control, Archiving)

A single project web site has been created for Wind. To facilitate collaboration with STEREO, the Wind data have been converted to the STEREO format. The data are also compatible with the Virtual Heliospheric Observatory.

Proposal Weaknesses

The panel found no significant weaknesses.

Wind no longer makes measurements of energetic ions above 10 MeV/nuc, and thus does not measure ions with energies sufficiently high to be a significant radiation hazard. However, ACE and other assets fulfill this function.

Overall Assessment and Findings

The Panel strongly supports continuation of the Wind extended mission.

The Wind spacecraft is stationed at L1, and as a vital complement to ACE, supplies crucial information on the solar wind upstream of the Earth. In spite of its age, the instruments are healthy, and adequate fuel is available for continued operation. The time resolution of key instruments provides Wind with unique capabilities for exploring solar wind reconnection, the structure of interplanetary shocks and coronal mass ejections, and associated particle acceleration. Combined with other satellite missions such as RHESSI, Hinode, SOHO and STEREO, Wind can track the evolution and transport of disturbances and associated energetic particles from their sources in the solar atmosphere through the heliosphere to the Earth environment. Thus, Wind provides an essential link in the chain of Heliophysics Great Observatory components that is needed to continue the timely progress that is especially imperative at the dawn of solar activity cycle 24, in the development of a predictive capability for destructive disturbances that will affect future human exploration in interplanetary and planetary space.