Scientific Assessment of NASAâ€™s SMEX-MIDEX Space Physics Mission Selections

Committee on Solar and Space Physics, Committee on Solar-Terrestrial Research, Commission on Physical Sciences, Mathematics, and Applications, Commission on Geosciences, Environment, and Resources, National Research Council

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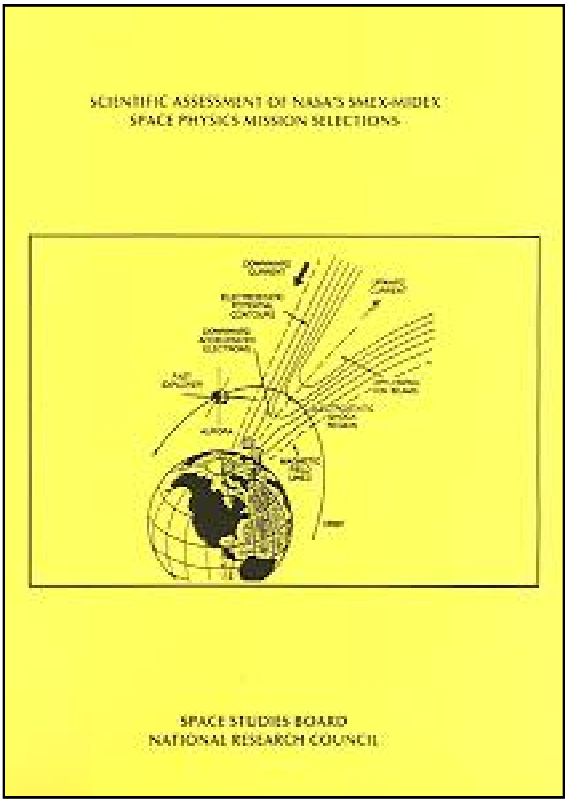

Committee on Solar and Space Physics
Committee on Solar-Terrestrial Research

Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications

Board on Atmospheric Sciences and Climate
Commission on Geosciences, Environment, and Resources

National Research Council

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The cover figure displays the main features of the Earth's auroral acceleration region that were known priot to the launch of the FAST (Fast Auroral Snapshot) spacecraft in August 1996. One in a series of NASA Small Explorer (SMEX) spacecraft, FAST was designed to study the detailed plasma physics of the Earth's auroral regions. From its 400 x 4000 km altitude near-polar orbit, instruments on the FAST spacecraft are providing high temporal and spatial resolution data on particles and fields in the regions where electrons are energized to form the aurora, and where ions are accelerated out of the ionosphere into the magnetosphere. These data are being analyzed to better understand the interaction of the solar wind with the Earth's magnetosphere.

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Scientific Assessment of NASA's SMEX-MIDEX Space Physics Mission Selections

Foreword

One of the recognized strengths of NASA's Explorer program, and arguably the reason for its long record of excellent science, is the fact that missions are selected competitively by peer review. Beyond specifying broad areas of research that will be considered, there are no restrictions on the scientific topics that the review committees could recommend for selection.

Therefore, it is only when NASA officials choose the winner from among top-category proposals that consideration is given to how a particular Explorer mission might address the long-range scientific strategy in a given discipline.

This report is a retrospective study of recent Explorer program selections in space physics. It concludes that the chosen missions do in fact address some high-priority goals of the field. It goes further to consider the degree to which the space physics strategic research goals can be realized by small and moderate Explorer class missions, and it raises issues that can affect the future health and vitality of the program. Now that NASA is relying on "smaller, faster, cheaper" spacecraft to accomplish much of its science program, the findings of the report, and of several other recent studies dealing with small spacecraft,[1] are particularly significant.

Claude R. Canizares, *Chair*
Space Studies Board

[1]Space Studies Board, National Research Council, *The Role of Small Missions in Planetary and Lunar Exploration* (1995), *Assessment of Recent Changes in the Explorer Program* (1996), and *Lessons Learned from the Clementine Mission* (1997), National Academy Press, Washington, D.C.

Scientific Assessment of NASA's SMEX-MIDEX Space Physics Mission Selections

Executive Summary

In this report, the Committee on Solar and Space Physics (CSSP) and the Committee on Solar-Terrestrial Research (CSTR) assess how relevant recent Explorer mission selections are to the priority science goals identified in the National Research Council (NRC) report produced by the committees, *A Science Strategy for Space Physics* (SSB, 1995). Briefings by participants in a variety of Explorer missions, including the recent selections, Transition Region and Coronal Explorer (TRACE) and Imager for Magnetopause-to-Aurora Global Exploration (IMAGE), were made to the committees in June 1996. This report summarizes the committees' findings and recommendations resulting from their deliberations. In addition, it addresses the broader issue of how well the present cost-capped Explorer program can meet the overall goals of the NRC Science Strategy report in this new era of "faster, cheaper, better" missions for the National Aeronautics and Space Administration (NASA).

This report reviews the scientific objectives of TRACE and IMAGE and concludes that both missions will address high-priority goals of the NRC Science Strategy report for the Sun-Earth Connections research program.

The principal findings of the committees are as follows:

1. Both the most recently selected Small Explorer (SMEX) and Mid-size Explorer (MIDEX) missions (TRACE and IMAGE, respectively) address high-priority scientific issues fully consistent with the current primary science goals of the solar and space physics discipline, as identified by the NRC *Science Strategy* report (SSB, 1995).

2. Although the Explorers do an excellent job of focusing on specific scientific objectives, most of the broader top-priority objectives summarized in the NRC *Science Strategy* report can only be accomplished with larger, more scientifically capable missions.

3. To succeed within their severe cost constraints, Explorer missions cannot afford instruments that require lengthy development or space qualification

cycles. Therefore, the use of instruments and/or instrument subsystems that have been developed for previous missions is essential. The present funding cap on SMEX and MIDEX could well prove too restrictive for building scientifically first-rate missions without such instrument "heritage." Lessons learned from the space physics Explorers demonstrate the importance of instrument and spacecraft heritage in meeting science goals while remaining within cost and schedule limits.

4. The committees support NASA efforts to make the Explorer program more responsive to "missions of opportunity." However, they are concerned that relaxing current launch vehicle constraints on the Explorer program could attract suborbital and Shuttle-based missions that would previously have been funded under a different line. This could place additional strain on maintaining sufficient Explorer funding.

5. The current operation and management styles of the SMEX program—including mutually beneficial cooperation between NASA and non-NASA participants, reduction of documentation, and flexibility in that class—are fostering opportunities for excellent, high-priority science.

6. The extremely low selection rate (2/50) among the large number of proposed Explorer missions results in much effort spent fruitlessly in proposal preparation. This extra work puts a significant burden on the research community and their industrial partners.

7. As with many other flight missions, Explorer missions can often continue to provide important scientific knowledge well after the scheduled mission termination if appropriate funding is available.

The committees recommend that NASA consider the following:

1. Establish a line of larger missions, such as Solar-Terrestrial Probes, because most of the broader, top-priority science objectives can only be accomplished with more capable missions. Explorer mission science could then be properly placed in the context of a coherent overall science program. This would include a balance of larger and smaller missions, suborbital projects, and research and analysis (R&A), all working synergistically to accomplish identified scientific objectives.

2. Adapt some of the management style and procedures associated with the SMEX program, as discussed in Finding No. 5 above, in other science programs. Recent spacecraft–Principal Investigator (PI) mode space physics Explorers (such as Solar and Magnetospheric Particle Explorer [SAMPEX] and Fast Auroral Snapshot Explorer [FAST]) successfully demonstrate how high-priority science can be carried out in "faster, cheaper, better" ways.

3. Within NASA's R&A program, provide for some instrument development opportunities in addition to the suborbital program of rockets and balloons, because of the importance of instrument heritage to the success of

many Explorer experiments.

4. With respect to Explorer program proposals, consult the advisory groups before the final-stage proposal review process for a broad range of inputs and suggestions regarding candidates for membership on its all-important technical proposal review panel. This process could have a better chance of finding expert peer reviewers free of conflicts of interest.

1
Introduction

NASA's Explorer line has for decades provided opportunities for many small to medium-size, community-inspired missions. The Explorer missions generally supplemented and complemented larger agency or division programs and goals. These opportunities gave rise to such space physics successes as the Atmospheric Explorer (AE), the Interplanetary Monitoring Platforms (IMPs), the International Sun-Earth Explorer (ISEE), the Active Magnetospheric Particle Tracer Explorer (AMPTE), and the Dynamics Explorer (DE) missions of the 1960s, 1970s, and 1980s. The early Explorer missions were all conducted in the mode of open solicitation of individually competed and selected instruments, with individual PIs for each experiment. More recent Explorer missions, such as SAMPEX and FAST, have a single PI for the entire spacecraft project. The Advanced Composition Explorer (ACE), TRACE, and IMAGE are now being readied for flight, all in the one-PI/ spacecraft mode of an integrated suite of instruments.

Recent pressures to downsize total spacecraft and mission costs have led to a new focus on the Explorer line. In particular, three cost categories of Explorers have now been established, with the MIDEX the newest and largest, capped at $76 million; the SMEX at less than $38 million; and the University Explorer Class (UNEX), similar to the NASA/University Space Research Association (USRA) Student Explorer Demonstration Initiative (STEDI) missions, at less than $4 million. Furthermore, all of these Explorers are now restricted to Med-Lite or smaller launch vehicles. Previously, Explorers costing up to several hundred million dollars were acceptable, with Delta-class launches the norm.

The space physics community had hoped that a dedicated Solar-Terrestrial Probe (STP) class of missions would be approved to fill the need for what are now considered larger missions—over $70 million, with more ambitious payloads and scientific goals. Though the Thermosphere-Ionosphere-Mesosphere Explorer (TIMED) is now an approved mission of this class, there is still no dedicated STP line in NASA mission planning. As a result, the Explorer line has become essential for continuing progress in the field. The large number of proposed Explorer missions reflects the richness of the field and the creativity of its community. However, in the last year, only 2 out of 50 Explorer mission proposals were selected for development.

With these considerations in mind, the committees undertook a short study to assess the potential of missions in the Explorer class to execute the high-priority space physics investigations recommended in their report, *A Science Strategy for Space Physics* (SSB, 1995). Toward this end, the committees were briefed on a number of recent Explorer programs. In addition to the recently selected TRACE (SMEX) and IMAGE (MIDEX), the committees examined the SAMPEX and FAST missions as representative of already launched SMEX Explorers. CSSP/CSTR also considered two space physics-oriented STEDI missions to assess using the future UNEX class to enhance the Explorer line capability in solar and space science.

The primary task of this brief study is an assessment, from the perspective of the NRC *Science Strategy* report, of the science capabilities of the recent Explorer selections TRACE and IMAGE and of expectations of this program in the future. In the strategy report, five general topics in space physics were identified as key areas for study in the next decade. They are listed here, not according to priority:

1. Mechanisms of solar variability;

2. Physics of the solar wind and the heliosphere;

3. Structure and dynamics of magnetospheres and their coupling to adjacent regions;

4. Middle and upper atmospheres and their coupling to regions above and below; and

5. Plasma processes that accelerate highly energetic particles and control their propagation.

Prioritized lists of research activities were recommended for each of these topics. In addition, the NRC *Science Strategy* report promoted four themes within the five topics, listed here in prioritized order:

1. To complete currently approved programs;

2. To exploit existing technologies and opportunities to get new results in a cost-effective manner;

3. To develop the new technology required to advance the frontiers of space physics; and

4. To support the theory and modeling activities vital to space physics.

Below is a summary of the presentations made to the committees and the findings drawn from them and subsequent discussions. These findings include brief descriptions of what was learned from various team representatives about the space physics Explorer mission experience, the Explorer mission science goals in light of the NRC *Science Strategy* report priorities, and the challenges faced by the newest space physics Explorers. Because of the integral link between the Explorer program's attributes and its scientific productivity, the committees' assessments could not isolate its science aspects. This report is therefore as much a commentary on the Space Physics Explorer Program as an analysis of mission accomplishments. The Space Studies Board conducted a more general review of the overall Explorer program with a complementary emphasis (SSB, 1996). This report includes specific recommendations to NASA based on the committees' findings.

2
Recently Launched Space Physics Explorers: SAMPEX and FAST

SAMPEX

SAMPEX is an approximately 350-kg spacecraft that carries a complement of in situ particles and fields instruments in a high-inclination orbit that ranges between 675 km and 550 km. SAMPEX was selected as a SMEX mission in April 1989. It was launched on July 3, 1992, on a four-stage Scout expendable launch vehicle.

The overall SAMPEX science goal is to study highly energetic charged particles of both magnetospheric and cosmic ray origin. This research includes particles trapped in Earth's magnetosphere and those that enter the magnetosphere from interplanetary space over the magnetic poles. One specific SAMPEX science goal addresses the composition and charge state of anomalous cosmic rays (ACRs), so identified because they are not of solar or traditional galactic or extragalactic origin and have unusual species abundances and solar cycle dependencies. Using the Earth's magnetic field as a spectrometer, SAMPEX data have been used to determine charge state by accurately measuring masses and energies of cosmic rays as a function of their location in the magnetosphere. Another specific SAMPEX science goal is to measure magnetospheric particle precipitation patterns over the entire globe and to relate these patterns to various atmospheric effects as well as to spacecraft anomalies. SAMPEX recently completed its nominal three-year prime mission and is now in an extended mission phase.

SAMPEX science goals touch on many of the objectives noted in the NRC Science Strategy report. For example, SAMPEX has already contributed to a fundamental understanding of anomalous cosmic rays. SAMPEX data show definitively that anomalous cosmic rays are mostly singly ionized. In addition, based on their composition, they are ordered by their first ionization potential in a way that confirms their origin from interstellar neutrals entering the heliosphere. Other studies have shown that the interstellar neutrals approaching the Sun become ionized through charge exchange with solar wind ions, are accelerated at the heliospheric termination shock, and diffuse into the inner solar system. The higher-energy population has been shown to be doubly charged, suggesting that it is a subpopulation that has been charge exchanged a second time after an initial acceleration to approximately 100 keV, eventually attaining about twice the energy of the singly charged component. These results enhance our understanding of astrophysical mechanisms leading to the acceleration of cosmic rays to extremely high energies. Another SAMPEX result bearing on particle acceleration processes is that the relative abundances of various isotopes of, for example, oxygen and neon are different in the lower-energy solar cosmic ray range than in the higher-energy range.

SAMPEX has also mapped magnetospheric energetic electron fluxes as a function of the magnetospheric coordinate L, as well as temporal changes and local time. Moreover, SAMPEX data have shown that upper-atmosphere NOx changes with the level of flux of precipitating energetic electrons. The effect is still poorly defined but intriguing in its potential implication for Sun-Earth connections of significance to humankind. With its extended mission, SAMPEX will be able to observe changes associated with the solar cycle. These observations are essential to understand both the NOx result and the implications of the ACRs.

The science accomplishments of SAMPEX are a function of both the scope of the instrumentation and the specifics of the orbit. Many of the goals concerning precipitation of particles and ACR charge states require a polar low Earth orbit. (Even with its more advanced complement of instruments, ACE will not be able to achieve many of these measurements from its L1 orbit.) SAMPEX addresses many of the NRC *Science Strategy* goals in the area of acceleration and propagation of highly energetic charged particles, as well as some areas concerning the effects of these particles on the upper atmosphere and spacecraft. Areas addressed incompletely or not at all include an understanding of the acceleration mechanisms for CRs and ACRs. Though some mechanisms are hinted at and others may perhaps be ruled out for ACRs, these are inferences that are neither definitive nor comprehensive. Similarly, SAMPEX has addressed elemental abundances but only for the more commonly occurring species and over a limited energy range. The issue of how much time has elapsed between element synthesis and acceleration of the particles is largely unaddressed. Finally, although some work has been done on the correspondence between atmospheric chemistry and energetic particle precipitation, progress in this area will not be enough to resolve questions on the consequences.

Nevertheless, the SAMPEX mission has been and continues to be highly relevant to the priority goals outlined in the NRC *Science Strategy* report. The presentation to the committees on SAMPEX indicated that the Explorer process in place at the time had generally worked well. The oversight by NASA/Goddard at the instrument level was modest; coordinated efforts with the Goddard spacecraft engineers were positive and constructive. Notably, the funding was never reduced; SAMPEX was funded in full, as originally proposed. Rapid contracting helped the schedule. The single central data processing unit (DPU) for all instruments designed for SMEX worked to the mission's advantage. Much of the schedule risk was reduced because so much of the instrument payload had been developed and/or used in earlier missions. Several of the instruments flew in 1989 on a shuttle "get away special" (GASCAN), so they were systems that had already been developed, built, and tested. Others had been built for the U.S. spacecraft in the Solar Polar mission, which was cancelled. This high level of heritage was considered critical in meeting both costs (the spacecraft, at $22 million, was well below the SMEX limit) and schedule.

Today, the SAMPEX mission operates in an extended mission phase designed to continue exploration of some of the science issues raised here and, in particular, to measure solar activity effects during the approach to the upcoming solar maximum (expected in 2001). A particularly noteworthy attribute of the extended mission is its cost effectiveness: operating costs are only $1.5 million per year for Goddard Space Flight Center (GSFC) operations and $1.2 million per year for science.

FAST

FAST, the second SMEX Explorer, was launched on a Pegasus-XL in 1996. The spacecraft was designed to explore the microphysics of the auroral acceleration region by making a comprehensive set of particles and fields measurements at unprecedented time resolution. FAST is addressing a specific goal of the NRC *Science Strategy* report: understanding the small-scale physical processes (microphysics) in the magnetosphere and ionosphere (an essential element of the report's section "Structure and Dynamics of Magnetospheres and Their Coupling to Adjacent Regions"). The 187-kg FAST spacecraft operates only in the auroral zone above approximately 65º and 75º magnetic latitude, where it samples the plasma and field conditions at altitudes of 400 to 4,200 km (above the regions rockets can directly probe). Its particle instruments are designed to determine as full a coverage of the time-dependent distribution functions of the local ions and electrons as possible. Very high temporal resolution is achieved through a specially developed data system with large radiation-hardened memory (1 gigabit) and fast write capability. These high data rates allow detailed analysis of wave-particle interactions and electron gyro-period phenomena. For example, particle distribution functions can be correlated with wave fields seen while in an especially high-rate burst mode of operation, which can be triggered by fluctuating fields.

It is hoped that FAST will establish the origins and roles of parallel electric fields in the auroral acceleration regions called inverted Vs; of wave-particle interactions in the creation of upward-moving ion beams of auroral arcs and the fine structure within them; of electrostatic double layers; and of field-aligned currents, auroral kilometric radiation, and kinetic Alfven waves potentially critical in solar wind-magnetosphere-ionosphere coupling. FAST can resolve spatial scales to much smaller dimensions than most imaging systems. For global context, it relies on ground-based observatories, the POLAR satellite, or DOD satellites (the Defense Meteorological Satellite Program [DMSP] or Midcourse Space Experiment [MSX] spacecraft) for simultaneous auroral imaging. FAST also takes advantage of conjunctions with ground-based and suborbital observations for more detailed correlative data analyses. In fact, the FAST prime mission plan includes "campaigns" with these other facilities during which FAST can be commanded into specified mode sequences in real time.

The FAST data system required custom design and construction. On board, the data rates are too high for the SMEX standard systems and so, data are simply passed directly to the memory through the instrument DPU. On the ground, data passes through the Goddard Operations Center at University of California–Berkeley, which provides most of the data system functions. Launch of FAST was delayed by problems with the Pegasus-XL launcher. FAST hardware was, in fact, ready for launch 2 years before problems with the Pegasus-XL were resolved. FAST investigators told the NRC committees that they were very pleased with the support they received from GSFC. In particular, the new GSFC engineering team took the initiative to provide the special capabilities needed for mission success. The FAST experience with Goddard support was quite positive.

FAST instrumentation was originally highly developed under the sounding rocket program. Each of the four instruments also has extensive heritage from a spaceflight program: the electron analyzer from AMPTE, GIOTTO, WIND, MO, and CLUSTER missions (see the appendix for a list of acronyms and abbreviations); the ion mass spectrometer from CLUSTER; the electric field experiment from S3-3, ISEE-1, CRRES, POLAR, and CLUSTER; and the magnetometer from Pioneer Venus, ISEE-1 & -2, and POLAR. This heritage was considered crucial to the mission's success in budgeting, scheduling, and technical risk.

FAST is now in orbit with all instruments functioning. Preliminary results suggest that it will fulfill its promise of elucidating the microphysics of Earth's auroral acceleration region.

3
The Newest Space Physics Explorers: TRACE and IMAGE

The most recently selected space physics Explorers are TRACE, a SMEX, and IMAGE, one of the first MIDEX missions. These missions were conceived under the new, more highly constrained guidelines for Explorers. Although it has not yet flown, TRACE is well into development and therefore illustrates the scientific potential that may be possible under the new guidelines. IMAGE, the newest space physics MIDEX, illustrates the scope of what might be termed a maximum science agenda deemed achievable within the current Explorer program. Of course, any test of achievement must await the mission itself.

TRACE

The TRACE Small Explorer was selected in September 1993 and is scheduled for launch in the fourth quarter of 1997 on a Pegasus-XL. This 224-kg spacecraft, destined for a 600- to 700-km dawn-to-dusk, Sun-synchronous orbit, is essentially dedicated to a single high-resolution telescope for continuously observing the Sun at ultraviolet (UV) and extreme ultraviolet wavelengths (EUV). TRACE represents a low-risk, cost-effective approach to addressing important solar physics concerns identified in the NRC Space Strategy report. In planned conjunction with the operating experiments on the Solar and Heliospheric Observatory (SOHO), TRACE will provide key data to help us understand the processes that lead to solar variability. TRACE's open data policy and Yohkoh-based data dissemination system should ensure an immediate impact within the space physics community.

Data from TRACE will produce a set of solar images of a portion of the solar surface coaligned through filters that select different spectral features. By comparing the temporal evolution of events as seen through different filters, investigators will gain critical information about the origin and evolution of local energy-release processes and rearrangement of coronal structures like coronal holes. Because the spectral features measured by TRACE span the major parts of the transition region between the chromosphere and corona, the direction in which energy releases move can be determined from the time lags. The science capability of TRACE will also be greatly enhanced by the availability of simultaneous SOHO data, including SOHO's global perspectives. Coordinated ground-based and suborbital observations, though not part of the TRACE mission, are expected to enhance the TRACE science accomplishments.

While recognizing the value of the TRACE mission, the committees note that some major objectives in the area of solar physics will remain unsatisfied. For example, the TRACE/SOHO combination does not measure vector magnetic fields, and the longitudinal magnetic field measurements are not made continuously. The spatial resolution in the white light band is modest, and the study of small magnetic structures cannot be carried out with this instrument. Although the data access will be open, the problems investigated will be constrained by how observing sequences are defined, and it is unclear how the community will participate in those decisions. Nevertheless, TRACE is a substantial step forward in the study of the mechanisms of solar variability.

The management experience from the TRACE perspective seems positive. The GSFC SMEX team was responsive to the novel requirement for the guide telescope to drive the attitude control system. The parts program and quality assurance were left largely up to the experiment team. However, cost constraints allowed for little redundancy. Fortunately, the instruments for the TRACE mission required little development because of extensive heritage from the rocket program and from SOHO (especially the experiments with the Extreme Imaging Telescope [EIT] Michaelson-Doppler Interferometer [MDI]). The data system draws heavily on Yohkoh heritage. Without this heritage (and its spare parts), TRACE could not have been done as a SMEX (with a $35 million funding cap), nor could it have been carried out on such a short schedule. It should also be recognized that the nominal cost of the mission does not reflect the full cost associated with Goddard civil service salaries, which is also true for SAMPEX and FAST.

IMAGE

The IMAGE mission was selected as one of two prime missions in the recent NASA MIDEX selection. As mentioned previously, MIDEX is a new flight opportunity program within the Explorer line. Capped at $70 million per mission, it represents the largest flight program routinely available to the space physics community.

The MIDEX program has an aggressive schedule with a relatively rapid hardware development phase of about 36 months. The IMAGE spacecraft is being procured through the PI's institution, Southwest Research Institute (SRI), and is scheduled for launch in January 2000 on a Med-Lite launcher (Delta).

IMAGE has a 2-year prime mission lifetime. Like FAST, IMAGE features a fully integrated payload. However, a recent change from a Taurus to a Delta launch has ameliorated the need for the expensive FAST power system. It will also allow a higher perigee and a longer lifetime through solar maximum, thereby significantly enhancing the expected science return.

The scientific goals of IMAGE are to do the following: (1) identify the method of entry of solar wind plasma into the magnetosphere; (2) determine the extent and location of ionospheric plasma sources; (3) discover how and where energetic plasmas are accelerated, transported, and lost during substorms and storms; (4) determine the direct effects of solar wind forcing on the magnetosphere; and (5) measure coronal mass ejection (CME)-related neutral atom fluxes and radio emissions as forecasting tools for geomagnetic storms (Burch, 1995, pp. 1–2).

Accomplishing these goals will require instrumentation measuring radio waves, ultraviolet photons, and neutral atoms to construct images of magnetospheric plasmas. It includes not only core magnetospheric plasmas but also the sharp density gradients at the several plasma/field boundary layers. The IMAGE spacecraft will be placed into a 500 km x 7 Earth Radii (RE) altitude polar orbit that will permit the imagers to view the magnetosphere globally and thereby reconstruct three-dimensional images.

The IMAGE mission has a clear scientific focus highly relevant to the third research topic identified in the NRC *Science Strategy* report, magnetospheric-ionospheric physics. The second-highest priority in that research topic (after reaping the full scientific potential of the International Solar–Terrestrial Physics [ISTP] program) was to "simultaneously image the plasma and energetic particle populations in the aurora, plasmasphere, ring current, and inner plasma sheet to study the global structure and large-scale interactions of magnetospheric and ionospheric regions during different levels of geomagnetic activity" (SSB, 1995, p. 74). This high-priority research activity is precisely the area targeted by the IMAGE mission, which is thus highly relevant to a principal scientific goal set forth in the report.

Moreover, the second-highest priority, cross-cutting emphasis in the NRC *Science Strategy* report, involved the use of existing technologies to obtain rapid results cost effectively. To a large degree, the IMAGE instrumentation, though fresh in design, is based on similar currently available experiments. Several of these concepts were developed in the course of the definition of the Inner Magnetospheric Imager (IMI) mission, originally intended as one of NASA's first Solar-Terrestrial Probe missions. IMAGE will address the need outlined in the NRC Science Strategy report for "spacecraft and instrument technology . . . to complement point-by-point in situ measurements of the magnetosphere with global imaging" (SSB, 1995, p. 77). In addition, the IMAGE mission incorporates the modeling required to interpret the measured images, consistent with recommendations made in the NRC *Science Strategy* report.

As mentioned previously, IMAGE benefits to a certain extent from heritage derived from IMI development efforts. This raises an interesting paradox: Ideally, an Explorer mission should be a pathfinder for a subsequent, more comprehensive, second-generation mission such as IMI. (This was expressed as the third-priority emphasis in the NRC *Science Strategy* report—namely, the development of new technologies where second-generation instruments could be identified for magnetospheric imaging with greater sensitivity and greater energy, angle, and mass resolution.) However, the selection of IMAGE as an Explorer has essentially eliminated IMI from the Solar-Terrestrial Probe queue. It was unclear from the presentation made to the committees how much of the IMI science could be accomplished with the smaller, cheaper, faster IMAGE version.

Overall, IMAGE expects to provide a low-cost, fast-track mission for global imaging, one of the highest-priority science goals of the NRC Science Strategy report. At the same time, it raises the broader issue of how much "smaller, cheaper, faster" methods can replace a more comprehensive approach to the science (e.g., with a solar-terrestrial probe mission).

4
STEDI Missions:
Models for the UNEX Explorer Line

The Student Nitric Oxide Experiment (SNOE)

SNOE, the STEDI mission at the University of Colorado scheduled for launch in December 1997, addresses the role nitric oxide (NO) plays as a major source of neutral cooling in the lower thermosphere. Understanding the distribution of NO is critical in deciphering the thermal structure of the atmosphere and its variations with solar and magnetic activity. The transport of thermospheric NO to mesospheric altitudes on the nightside also plays an important role in mesospheric ozone chemistry. This is a specific component of the much broader objective of understanding the causes of mesosphere/lower-thermosphere structure and variability, cited in "The Middle and Upper Atmospheres and Their Coupling to Regions Above and Below," Chapter 4 in the *Science Strategy* (SSB, 1995).

Past measurements have clearly indicated a variation in NO with solar and magnetic activity. However, the exact nature of this relationship and the relative importance of inputs associated with each of these types of variability are not known. SNOE's prime scientific focus is to resolve this question by making simultaneous observations of NO abundance, solar emissions, and magnetic activity (as inferred from auroral imaging).

TERRIERS

TERRIERS is the Boston University–based STEDI mission with an ionospheric focus. Scheduled for launch in January 1998, it is intended to provide a global view of ionospheric structure and variability by using tomographic techniques to deconvolve the ionospheric profile down to an altitude as low as 100–120 km, depending on the strength of the signal. This is a new technique with the potential for further scientific applications. One focus is on the equatorial ionosphere, with major advances expected in understanding large-scale equatorial irregularities like spread-F and equatorial bubbles.

The NRC *Science Strategy* report identifies the low-altitude ionosphere, which is highly structured, as an underexplored region with strong electrodynamic coupling between the atmosphere and the near-space environment. Further progress in understanding large-scale electrodynamic coupling to the magnetosphere requires a global survey of the ionospheric plasma distribution as it responds to changing conditions. Recent spacecraft could provide only point measurements at the satellite altitude, whereas ground-based facilities produce time sequences of ionospheric profiles but only over limited geographical areas. Tomographic imaging of the ionosphere on a global scale down to low altitudes would contribute critical information to the science objectives identified in the NRC Science Strategy report.

Summary of STEDI Missions

STEDI appears successful in providing hands-on educational opportunities for both undergraduate and graduate students in engineering and software development, which makes the students highly marketable after graduation. STEDI investigators are staunch advocates of the program in its current format. The final test of the technical, management, and scientific success of the STEDI missions awaits their launch, which is normally on Pegasus vehicles.

5
Findings and Recommendations

Findings

1. Both the most recently selected SMEX and MIDEX Explorers (TRACE and IMAGE, respectively) address high-priority scientific issues fully consistent with the current primary science goals of the solar and space physics discipline, as identified by the NRC *Science Strategy* report (SSB, 1995).

Discussion: TRACE will observe the Sun with sufficient temporal and spatial resolution to allow, for the first time, detailed studies of the magnetic coupling of the corona to the photosphere. These observations have long been identified as essential to advance understanding of the sources of solar variability. IMAGE will carry out comprehensive global imaging of the Earth's magnetosphere. Such measurements have been identified by the scientific community as having the highest priority in advancing magnetospheric physics.

2. Although the Explorers do an excellent job of focusing on specific scientific objectives, most of the broader top-priority objectives summarized in the NRC Science Strategy report can only be accomplished with larger, more scientifically capable missions.

Discussion: Certain challenges will require instrumentation beyond Explorer capabilities. These include very-high-resolution observations of small-scale structures (<100 km) on the solar surface, such as flux tubes, that may play a decisive role in solar activity; measurements of the composition of cosmic rays at very high energies; and tests for elements heavier than nickel. In situ observations of the solar wind acceleration region or of the heliospheric boundary and interstellar medium cannot be accomplished with Explorer launch vehicles. The required spacecraft technology is beyond what the Explorer program could support. Magnetospheric studies of Mercury for comparison with those of Earth are also beyond the scope of Explorers, both in their required launch capability and their need for comprehensive measurements.

Space physics thus has a critical need for an external line of Solar-Terrestrial Probes (such as TIMED), together with occasional use of larger Frontier Probes, to carry out its science program. The Explorer program can be successful only in such a context.

3. To succeed within their severe cost constraints, Explorer missions cannot afford instruments that require lengthy development or space qualification cycles. Therefore, the use of instruments and/or instrument subsystems that have been developed for previous missions is essential. The present funding cap on SMEX and MIDEX could well prove too restrictive for building scientifically first-rate missions without such instrument heritage. Lessons learned from the space physics Explorers demonstrate the importance of instrument and spacecraft heritage in meeting science goals while remaining within cost and schedule limits.

Discussion: Instrument heritage derives both from R&A funding (e.g., Supporting Research and Technology [SR&T] and the suborbital program) and from development undertaken for major flight programs. The TRACE mission is a good example: It uses multilayer telescopes first developed in the laboratory by NASA SR&T funding and subsequently used in two rocket programs that obtained the first EUV normal-incidence solar images. TRACE has borrowed heavily from technology developed for the Extreme Imaging Telescope (EIT) and Michaelson-Doppler Interferometer (MDI) experiments on SOHO. Neither TRACE's cost cap nor its rapid schedule could have been met without this heritage. This cost-effective strategy could be jeopardized by the upcoming expected dearth of large flight programs.

4. The committees support NASA efforts to make the Explorer program more responsive to "missions of opportunity." However, they are concerned that relaxing current launch vehicle constraints on the Explorer program could attract suborbital and Shuttle-based missions that would previously have been funded under a different line. This could place additional strain on maintaining sufficient Explorer funding.

Discussion: The key attribute of the Explorer program is that, given reliable launch vehicle options, it makes rapid access to space possible. This goal has consistently been the top recommendation of numerous science advisory panels to NASA. The agency is to be commended for addressing this challenge. The Office of Space Science (OSS) is now planning to modify the Explorer program so that it more closely resembles the Discovery program—for example, by including the Space Shuttle as an acceptable launch vehicle. Although the committees support the general concept of making the Explorer program more responsive to "missions of opportunity," less restrictive policies on launch vehicle options might have the unintended effect of reducing the funding available for Explorer missions.

5. The current operation and management styles of the SMEX program—including mutually beneficial cooperation between NASA and non-NASA participants, reduction of documentation, and flexibility in that class—are fostering opportunities for excellent, high-priority science.

Discussion: The small Explorer programs were widely praised by the investigator teams interviewed by the committees. The SAMPEX, FAST, and TRACE teams considered the SMEX program at GSFC to be well managed, with a high level of technical competence and a minimum of red tape. The SMEX program was a good example of a case where a "cheaper, faster, better" method has existed within the agency for some time (SSB, 1996). Because the MIDEX program has only just begun, the committee cannot comment on any distinctions between it and the SMEX program, but we strongly support the same approach.

6. The extremely low selection rate (2/50) among the large number of proposed Explorer missions results in much effort spent fruitlessly in proposal preparation. This extra work puts a significant burden on the research community and their industrial partners.

Discussion: Such a low success rate is also a strong disincentive for the industry to participate in the proposal process. NASA's use of a multistep proposal process should help alleviate this problem. In this process, the initial mission concept proposal involves a smaller initial investment, with emphasis on the proposed science. After the first selection round, development funds are made available to help mould the selected concepts into full mission proposals (SSB, 1996). It is the committees' view that for efforts of MIDEX scope this approach will encourage creativity while minimizing the expense of the proposal process, in both human and economic terms. A second problem arising from the large number of proposed missions is the difficulty of finding expert peer reviewers without conflicts of interest.

7. As with many other flight missions, Explorer missions can often continue producing important scientific knowledge well after the scheduled mission termination if appropriate funding is available.

Recommendations

Based on the information from the briefings, subsequent deliberations, and findings, the committees recommend that NASA consider the following:

1. Establish a line of larger missions, such as Solar-Terrestrial Probes, because most of the broader, top-priority science objectives can only be accomplished with more capable missions. Explorer mission science could then be properly placed in the context of a coherent overall science program. This would include a balance of larger and smaller missions, suborbital projects, and R&A, all working synergistically to accomplish identified scientific objectives. For example, Explorer selections can materially contribute to the development of some of the technology needed for more ambitious missions.

2. Adapt some of the management style and procedures associated with the SMEX program, as discussed in Finding No. 5 above, in other science programs. Recent spacecraft–PI mode space physics Explorers (such as SAMPEX and FAST) successfully demonstrate how high-priority science can be carried out in "faster, cheaper, better" ways.

3. Within NASA's R&A program, provide for some instrument development opportunities in addition to the suborbital program of rockets and balloons, because of the importance of instrument heritage to the success of many Explorer experiments.

4. With respect to Explorer program proposals, consult the advisory groups before the final-stage proposal review process for a broad range of inputs and suggestions regarding candidates for membership on its all-important technical proposal review panel. This process could have a better chance of finding expert peer reviewers free of conflicts of interest.

Scientific Assessment of NASA's SMEX-MIDEX Space Physics Mission Selections

References

Burch, J.L. 1995. Imager for Magnetopause-to-Aurora Global Exploration (IMAGE). Proposal submitted to the National Aeronautics and Space Administration in response to AO-95-OSS-02 (Abstract).

Space Studies Board (SSB) and the Board on Atmospheric Sciences and Climate, National Research Council. 1995. *A Science Strategy for Space Physics*. National Academy Press, Washington, D.C.

Space Studies Board (SSB), National Research Council. 1996. *Assessment of Recent Changes in the Explorer Program*. National Academy Press, Washington, D.C.

Scientific Assessment of NASA's SMEX-MIDEX Space Physics Mission Selections

Appendix
Acronyms and Abbreviations

A B C D E F G H I J K L M
N O P Q R S T U V W X Y Z

ACE Advanced Composition Explorer
ACR Anomalous Cosmic Rays
AE Atmospheric Explorer
AMPTE Active Magnetosphere Particle Tracer Explorer

CLUSTER European Space Agency–NASA multisatellite mission; launch failed, 1996; scheduled for future reflight
CME Coronal Mass Ejection
CRRES Combined Release and Radiation Effects Satellite
CSSP Committee on Solar and Space Physics
CSTR Committee on Solar-Terrestrial Research

DE Dynamics Explorer—NASA magnetospheric-ionospheric mission launched in 1981
DMSP Defense Meteorological Satellite Program
DPU Data Processing Unit

EIT Extreme Imaging Telescope
ESA European Space Agency
EUV Extreme Ultraviolet

FAST Fast Auroral Snapshot Explorer

GASCAN A term derived from Shuttle "get away special" experiments, which were placed in a cylindrical housing

GIOTTO European Space Agency's spacecraft project to encounter Comet Halley
GSFC Goddard Space Flight Center

IMAGE Imager for Magnetopause-to-Aurora Global Exploration

IMI Inner Magnetospheric Imager Mission, proposed for one of the solar terrestrial probes
IMP Interplanetary Monitoring Platforms
ISEE International Sun-Earth Explorer—a NASA-ESA series of three spacecraft launched in 1977
ISTP International Solar-Terrestrial Physics program

L1 Orbit Lagrangian point positioned between Earth and the Sun

MDI Michaelson-Doppler Interferometer
MIDEX Mid-size Explorer
MO Mars Observer
MSX Midcourse Space Experiment (DOD satellite launched in 1995)

NASA National Aeronautics and Space Administration

OSS Office of Space Science

POLAR A NASA contribution to the international Solar-Terrestrial Physics program, launched in 1996

R&A Research and Analysis
RE Earth Radius

SAMPEX Solar and Magnetospheric Particle Explorer
SME Solar Mesosphere Explorer
SMEX Small Explorer
SNOE Student Nitric Oxide Experiment
SOHO Solar and Heliospheric Observatory
SR&T Supporting Research and Technology
STEDI Student Explorer Demonstration Initiative
STP Solar-Terrestrial Probe
SRI Southwest Research Institute

TERRIERS Boston University's Tomographic Experiment using Radiation Recombination Ionospheric EUV (extreme ultraviolet) and Radio Sources
TIMED Thermosphere-Ionosphere-Mesosphere Explorer
TRACE Transition Region and Coronal Explorer

UNEX University Explorer

USRA University Space Research Association
UV Ultraviolet

WIND International Solar-Terrestrial Physics Program Spacecraft