Geospace Sciences:

The study of the space environment of Planet Earth

A document by the Geospace Section of the Division of Atmospheric and Geospace Sciences

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The space environment has had a profound role in shaping the conditions for life on Earth and continues to influence the sustainability of modern technologically reliant societies. The evolution of the primordial atmosphere is a result of complex interactions involving solar radiation and the matter in the solar system. Even the evolution of life on Earth was influenced by mutations caused by cosmic radiation. In modern times, technological systems are increasingly affected by physical processes that take place in the Sun-Earth system, while space exploration and space tourism exposes humans directly to the space environment. The space environment also serves as a laboratory in which to probe basic plasma physics processes that are otherwise inaccessible to experimental investigations.

Although research in geospace science and "space weather" has progressed dramatically over the past decade, many of the most important and intriguing phenomena at the Sun, in the solar wind, and in the Earth space environment cannot yet be fully explained or adequately predicted. We have now advanced to a point where further progress requires understanding of both basic space plasma physics and the way in which physical processes are coupled over a vast variety of temporal and spatial scales. We call this science that includes all aspects of the fundamental research needed to understand the Sun-Earth system "Geospace science."

I. Overarching Goals

In the past decade, the research arena for the Geospace research community has expanded to include global change, space weather, and space situational awareness. These studies that have been enabled by new technologies, such as cyberinfrastructure, advanced communications, major research instrumentation, major research facilities, and distributed instrumentation, among others. With these tools, the community seeks answers to broader, more encompassing questions that involve the integrative role of the upper atmosphere in the entire planetary system. The focus is now on gaining a global perspective, where the geospace environment is analyzed as an entire system in order to fully understand its response to external and internal stresses and its subsequent impact on other parts of the whole Earth system.

A. Fundamental Scientific Understanding

The main challenge facing Geospace science is that it involves complex physical processes that must be understood. Major outstanding science questions include:

- How magnetic reconnection works and operates in the solar atmosphere, within the solar wind, at the dayside magnetopause, and in the magnetotail to initiate and facilitate energy transfer between the different regions of the space environment
- How particles are accelerated at the Sun, in the interplanetary medium, and in the near-Earth space environment
- How mass, energy, and momentum are transported through the heliosphere, magnetosphere, ionosphere, and atmosphere
- How plasma waves and irregularities are produced in the ionosphere, magnetosphere, solar wind, and solar corona.
- Understanding the space environment of Earth in the context of other planets.

B. Linking Science with Societal Needs

To confront the remaining challenges in space weather specification and forecasting, an integrated systems approach is essential, which takes advantage of the modeling and instrumentation advances described above. Space weather phenomena are recognized as natural hazards for which improved understanding, prediction, and mitigation are high priorities. The National Space Weather Program, initiated more than 15 years ago, has highlighted the importance of space weather and addresses fundamental research questions needed for better understanding of the space environment on all spatial and temporal scales. Ensuring that advances in knowledge in this area are used to their full potential for solving pressing societal needs sets some specific objectives for geospace science:

- A robust systems approach to understanding and predicting space weather.
- Development of large-scale, global space environment models suitable for space weather specification and forecasting.
- Make current space weather forecasting take better advantage of the rapid. developments in space weather research, observations, and modeling by transforming the existing relationship between research and operations.

II. Approaches

Through its core programs of Solar Physics, Magnetospheric Physics, Aeronomy, Facilities, and Space Weather GS supports the in-depth research needed for fundamental understanding of space phenomena. GS special programs, such as CEDAR, GEM, SHINE, and Space Weather modeling provide targeted research support guided by community input. GS strives to enable advancement of all aspects of geospace science, seeking an integrated understanding of the space environment. This includes the impacts of geospace phenomena on society. Since these and other basic science questions in space physics are interdisciplinary in nature, strong cross-disciplinary efforts are required to resolve them. In addition, the scientific approach to these challenging problems requires carefully planned and coordinated efforts in modeling and observations as discussed below.

A. Observations

Space physics by its nature is data starved. The continued development and operation of modern observatories and instruments are essential to secure the acquisition of the unique measurements that are critical for science and space weather purposes. A broad spectrum of radio, optical, in-situ, and remote sensing techniques is needed to provide the continuous, simultaneous observations dictated by the unique characteristics of Geospace and the complexity of the processes taking place. In addition, the science requires both long-term synoptic and short-term, targeted measurements to better understand processes occurring on a broad range of spatial and temporal scales.

1. Continuous and Global Observations

The vast spatial extent of Geospace and the dynamic nature of the phenomena occurring require a strategically deployed network of observational instrumentation. GS supports multiple strategies in providing the requisite data, including:

- Development and fabrication of robust, cheap, and easily deployed instruments to facilitate global ground-based observational networks including magnetometers, passive optical instruments, lidars, and radars.
- Pursuit of cost-effective and innovative space-based observational capabilities to complement the broad portfolio of large, traditional space missions sponsored by NASA.
- Studies to determine the optimum type and placement of large observatories and instruments to make better use of limited resources and overcome logistical limitations.
- Development and implementation of new incoherent scatter radar technologies to modernize, maintain, and expand the existing ISR network.
- Expansion of the existing array of ground-based solar observatories to better understand the drivers of Geospace phenomena and origins of space weather disturbances.

2. Campaigns

Experimental campaigns are extremely effective in enabling focused studies of fundamental physical processes taking place in localized or transient Geospace phenomena. Carefully planned and coordinated sets of observations from ground-based sensor networks and satellites will lead to major breakthroughs in our understanding of Geospace. To facilitate experimental campaigns and maximize the scientific benefits from coordinated measurements, GS supports:

- Development of small, easily transportable observing instruments and modular platforms that can be easily and quickly deployed.
- Implementation of advanced sensor technology, including smart sensors and networks of instruments that can be remotely operated and reconfigured.
- Utilization of collaboration technology that facilitates the execution of large, complex field campaigns, as well as the subsequent analysis of data and scientific research.

B. Modeling

The complexity of the Sun-Earth system, and of the physical processes occurring in the space plasma physics that comprise it, necessitates the use of highly advanced numerical models to develop and test scientific understanding. Major space weather modeling efforts have been funded through NSF's Science and Technology Center CISM (The Center for Integrated Space Weather Modeling) and the DoD's Multidisciplinary University Research Initiatives. Support for large-scale collaborative modeling efforts continue through the NASA/NSF Partnership for Space Weather Modeling Collaborations. Important development needs for Geospace science modeling include:

- Improved modeling techniques to handle multi-scale phenomena
- Community access to adaptable, modular modeling framework to facilitate modifications and updates with science advances and utilization of new computer technology.
- Improved data assimilation techniques to generate more physically realistic models even when data are sparse.

C. Capacity Building

GS supports innovative approaches to education through its major programs, all of which provide opportunities for students at the undergraduate and graduate levels.

1. Student Development

The CEDAR, GEM, and SHINE programs conduct annual workshops with substantial student participation, including special workshops for students, poster prizes, and representation on steering committees. The Cubesat Program is particularly successful in engaging student interest in space science and technology. GS also funds focused schools to provide educational training in areas not included in traditional undergraduate and graduate curricula, for example, space weather, incoherent scatter radar, and radio science.

2. Post-doctoral Opportunities

The CEDAR, GEM, and SHINE programs all have annual solicitations for post-doctoral fellowships. These programs have not only produced a steady stream of highly qualified young scientists, but also produced outstanding scientific results. Post-doctoral support from NSF has been strengthened through requirements for mentoring plans in all proposals requesting funds for post-doctoral researchers. For those seeking academic careers, the GS disciplinary programs fund CAREER awards on a nearly annual basis. In addition, to strengthen the presence of space weather researchers in university academic departments, GS supports the Faculty Development in Space Science (FDSS) Program. This highly successful initiative, so far, has resulted in the creation of more than eight new faculty positions for young space scientists. All eight have now received tenure.

III. GS Strategic Priorities

GS strategic priorities are set to meet the major goals and objectives outlined in the previous section. They are organized within five distinct thrusts as follows: Basic Research; Advanced Facilities and Instrumentation; Integrated and Coupled Models; Effective Education and Training; and Strengthening the Geospace Section.

A. Basic Research Priorities

i. Maintaining the integrity of core disciplinary programs through careful management and planning of new activities that potentially impact core budget levels.
ii. Ensuring that targeted programs such as the CEDAR, GEM, and SHINE remain at the cutting edge of science frontiers.
iii. Exploring the full scientific potential of the upcoming ATST facility.
iv. Promoting innovative approaches to space science research, particularly system science approaches that effectively integrate studies of the entire Earth-Sun system.
v. Encouraging cross-disciplinary efforts that enhance scientific understanding and facilitate the application of research results to societal problems.

B. Advanced Facilities and Instrumentation Priorities

i. Expanding the section to include all ground-based solar facilities, particularly the ATST. Three recent community panel reports (2006 National Space Weather Program Assessment and the 2008 and 2011 GS COVs) have recommended that responsibility for solar physics at the NSF be consolidated under one Division and the ATST must reside in the Division that funds solar science.
ii. Pursuing the recommendations of two NAS/NRC committees for an integrated suite of solar instrumentation to meet challenges during the coming decade and beyond, including the ATST, FASR, and COSMO.
iii. Taking advantage of the innovative AMISR radar technology through relocation of existing systems to other locations and the construction of new systems, particularly in the southern hemisphere where observations are seriously lacking.
iv. Funding a broad spectrum of instrumentation for space science research, including not only ground-based instrumentation but also innovative space-based projects such as AMPERE and the CubeSat program.
v. Working closely with the community in developing strategies for supporting these new observational capabilities.
vi. Exploiting new technologies for developing smart sensors that can be widely distributed and easily operated.

C. Integrated and Coupled Models Priorities

i. Strengthening inter-agency collaborations with NASA, AFOSR, DOE, and other partners to fund a new generation of coupled space weather models.
ii. Continuing to assist the transition of space weather research into operations. For example, the Community Coordinated Modeling Center is funded jointly by GS and NASA. GS recognizes the CCMC as an increasingly important resource both for space physics and space weather research and for the transition of research models into operational space weather forecasting.
iii. Ensuring that space science and space weather priorities are considered and included in all appropriate Directorate and NSF-wide new initiatives, such as FESD, SEES, etc.

D. Effective Education and Training Priorities

i. Expanding the Cubesat program, which sustains the career development of students and researchers while producing a talented future cadre of trained professionals for the United States.
ii. Promoting the training of students to view the space environment as a strongly coupled system, a system that is intimately linked to Earth's lower atmosphere, and ultimately to the land and oceans of our planet.
iii. Maintaining the FDSS program by funding one or two faculty positions every two or three years.
iv. Continuing to support student attendance at meetings such as GEM, CEDAR and SHINE, which has proven to be a successful tool to increase student participation in research.
v. Making education of and outreach to under-represented groups a special priority.
vi. Continuing the highly successful practice of supporting the participation of graduate students and undergraduate students in research projects.
vii. Increasing the use of RET supplements for awards, which has proven a highly effective way to extend space science education and outreach to the high-school level.

E. Strengthening the Geospace Section

To accomplish the goals and objectives outlined in this document GS must continue to be a community leader in geospace science and the National Space Weather Program and ensure that the geospace research community is well served administratively and organizationally within NSF. Specific GS priorities to strengthen its leadership role are:

i. Continuing to pursue collaborations with other NSF offices and directorates.
ii. Continuing to pursue inter-agency partnerships as a way to leverage GS efforts and fulfill its goals. For example, GS partners with the Dept. of Energy to enhance fundamental plasma physics research (the NSF/DOE Partnership for Basic Plasma Science and Engineering).
iii. Working with the space science community to take advantage of opportunities for cross-cutting funding such as MRI, STC, EPSCOR, Hazards SEES, INSPIRE, several big data initiatives, and others.

IV. Relation to Solar and Space Physics Decadal Survey

The Decadal Survey on Solar and Space Physics (National Academies, 2012) has as it's top recommendation the implementation of a new, integrated, multiagency initiative (DRIVE—Diversify, Realize, Integrate, Venture, Educate) that will develop more fully and employ more effectively the many experimental and theoretical assets at NASA, NSF, and other agencies. The following sections summarize the way the GS Strategic Plan addresses the imperatives within the DRIVE initiative.

FIGURE 4.1 A relatively small, low-cost initiative, DRIVE provides high leverage to current and future space science research investments with a diverse set of science-enabling capabilities. The five DRIVE components are as follows:

- Diversify observing platforms with microsatellites and mid-scale ground-based assets.
- Realize scientific potential by sufficiently funding operations and data analysis.
- Integrate observing platforms and strengthen ties between agency disciplines.
- Venture forward with science centers and instrument and technology development.
- Educate, empower, and inspire the next generation of space researchers.

Diversify: Diversify Observing Platforms with Microsatellites and Mid-Scale Ground-Based Assets

Recommendation: The National Science Foundation should create a new competitively selected mid-scale project funding line in order to enable mid-scale projects and instrumentation for large projects.

Recommendation: NSF's CubeSat program should be augmented to enable at least two new starts per year. Detailed metrics should be maintained, documenting the accomplishments of the programs in terms of training, research, technology development, and contributions to space weather forecasting.

The GS Strategic Plan addresses the "Diversify" mandate of the Decadal Survey through its broad approach to enabling geospace research. The expansion of geospace observing capabilities has been on-going for many years and has been the cornerstone of the focused programs: CEDAR, GEM, and SHINE. Observing facilities supported by GS now include single-site observatories, such as the six incoherent scatter radars, networks, such as SuperDARN, the Consortium for Resonance and Rayleigh Lidars, and the Low-Latitude Ionospheric Sensor Network. Space-based capabilities, such as AMPERE and the Cubesat missions provide complementary coverage of geospace properties. The continued support for these efforts are given high priority in the GS Strategic Plan (III.B.iv, III.B.v, and III.B.vi). The GS-supported observing capabilities are well integrated with data handling and modelling activities, as well. The CEDAR database continues to be a repository of measurements from an extensive array of observational assets. Community-driven modelling efforts include the end-to-end space weather models funded through the NASA/NSF strategic partnership, the Center for Integrated Space Weather Modeling, and the Community Coordinated Modeling Center.

GS continues to explore opportunities to diversity its facility portfolio through on-going efforts to fund mid-scale projects such as FASR and COSMO (III.B.ii and III.B.v). The next decade will see new observations from AMISR sites constructed at or moved to new locations to meet emerging scientific priorities (III.B.iii). Finally, GS is involved with negotiations for the transfer of the Advanced Technology Solar Telescope into the Section to consolidate the facility support with the associated research support (III.B.i).

Realize: Realize scientific potential by sufficiently funding operations and data analysis

Recommendation NSF should provide funding sufficient for essential synoptic observations and for efficient and scientifically productive operation of the Advanced Technology Solar Telescope (ATST), which provides a revolutionary new window on the solar magnetic atmosphere.

The recommendation is achieved in the GS Strategic Plan by careful management of the core budget of the STR Program as well as ensuring that the full scientific utilization of the ATST is a top priority (III. A.i, III.A.iii, III.B.i, and III.B.ii).

Integrate: Integrate Observing Platforms and Strengthen Ties Between Agency Disciplines

Recommendation: NSF should ensure that funding is available for basic research in subjects that fall between sections, divisions, and directorates, such as planetary magnetospheres and ionospheres, the Sun as a star, and the outer heliosphere. In particular, outer-heliospheric research should be included explicitly in the scope of research supported by the AGS section at the NSF.

The GS Strategic Plan addresses the Integrate initiative in several ways. GS already is involved in joint programs that cross disciplines with NASA, AFOSR and DOE (III.C.i, III.C.ii, and III.E.ii) and within NSF (III.A.v, III.E.i, and III.E.iii). For example the GS Section is working with the NASA Heliophysics Division to jointly develop strategic capabilities for the NSF Space Weather program and the NASA Living with a Star program. Within NSF, GS and Plasma Physics as part of the NSF/DOE Partnership for Basic Plasma Science and Engineering have a joint program in basic plasma physics research (III.E.ii). The Geospace Sciences Strategic Plan explicitly calls for participation in new Directorate and NSF-wide initiatives that cross disciplines and support investigation of the entire Sun-Earth system (sections III.A.iv, III.A.v and III.C.iii). Comparative studies of planetary magnetospheres and ionospheres are important for understanding the magnetosphere and ionosphere system at the Earth and are supported under the base program (section III.A.i and III.A.v).

Venture: Venture Forward with Science Centers and Instrument and Technology Development

Recommendation: NASA and NSF together should create heliophysics science centers (HSCs) to tackle the key science problems of solar and space physics that require multidisciplinary teams of theorists, observers, modelers, and computer scientists, with annual funding in the range of $1 million to $3 million for each center for 6 years, requiring NASA funds ramping to $8 million per year (plus increases for inflation).

The GS Strategic Plan promotes innovative approaches to space science research, particularly system science approaches that effectively integrate studies of the entire Earth-Sun system and encourages cross-disciplinary efforts that enhance scientific understanding and facilitate the application of research results to societal problems (Section III.A.iv and III.A.v). NSF support for larger collaborative research projects, at the level recommended, on critical space science and space weather topics is currently provided through Directorate and NSF-wide initiatives, such as FESD and SEES (Section III.C.iii). However, the GS Strategic Plan specifically calls out the need for strengthening inter-agency collaborations with NASA, AFOSR, DOE, and other partners to fund a new generation of coupled space weather models (section III.C.i)

Educate: Educate, empower, and inspire the next generation of space researchers

Recommendation: NSF Faculty Development in Space Sciences (FDSS) program should be continued and be considered open to applications from 4-year as well as PhD-granting institutions as a means to broaden and diversify the field. NSF should also support a curriculum development program to complement the FDSS program and support its faculty.

Recommendation: A suitable replacement for the NSF CISM Summer School should be competitively selected, and NSF should enable opportunities for focused community workshops that directly address professional development skills for graduate students.

The GS Strategic Plan addresses the Educate component of the Decadal Survey DRIVE initiative through the priorities in Section III.D. It highlights continued efforts to train the next generation of space scientist through proactive efforts within the GEM, CEDAR, and SHINE Programs (III.D.iv). The annual workshops for these programs feature involvement of students in workshops, tutorials, poster sessions, and steering committees. These programs, along with the Center for Integrated Space Weather Modeling and the Community Coordinate Modeling Center, have recently emphasized the importance of a system level understanding of the coupled space weather domains (III.D.ii). This has created a cadre of young space scientists with the depth and breadth to explore and uncover the hidden linkages that characterize the complex Sun-Earth system.

GS continues to encourage Research Experiences for Undergraduates through both formal and informal programs at universities, laboratories, centers, and facilties (III.D.v-vii). The Cubesat program has also been highly successful in attracting student participation in hands-on, end-to-end space science mission development (III.D.i). The multi-disciplinary aspects of these missions have broadened participation at the undergraduate and graduate levels, while the university-industry partnerships offer career opportunities that effectively attract and retain students (III.D.v).

The GS supports early career scientists through the NSF CAREER program, with funding from the core programs. Additional opportunities for young space scientists seeking academic positions has been provided through the Faculty Development in Space Science Program, which has created eight new space science faculty positions in the last five years (III.D.iii). This program will be continued on a rolling basis beginning in FY2014.

The GS also supports a variety of informal education and outreach programs designed to promote awareness of space weather. This includes continued support for AGU's Space Weather Journal, and sponsorship of workshops, such as Space Weather Week and the Space Weather Enterprise Forum (III.D.v).

V. Conclusion

Space science is entering a new era. With new coupled models taking advantage of high-speed computing, powerful new observational platforms coming into existence and being planned, and a new synergistic view of the space environment, we are now posed to begin truly understanding the entire Sun to Earth system. Balancing this intellectual breakthrough, we have the dramatic rise in the appreciation of the relevance of geospace on today's technologically dependent society.

GS has been trend setting and forward looking; but now it is required to step up and assume new responsibilities to meet a wide array of challenges.