

**Statement of Daniel N. Baker**  
Broad Reach Endowed Chair of Space Sciences  
Professor, Department of Physics and Department of Astrophysical and Planetary Sciences  
Director, Laboratory for Atmospheric and Space Physics  
University of Colorado, Boulder

**Before the Subcommittee on Space and Aeronautics  
Committee on Science, Space, and Technology  
U.S. House of Representatives**

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Mr. Chairman, Ranking Minority member, and members of the Committee, I want to thank you for the opportunity to testify today at the hearing on “National Priorities for Solar and Space Physics Research and Applications for Space Weather Prediction.” My name is Daniel Baker and I am a professor of astrophysical and planetary sciences at the University of Colorado. I am also the Director of the Laboratory for Atmospheric and Space Physics at CU-Boulder. The Laboratory is a research institute that has more than 60 teaching and research faculty in the several disciplines of space and Earth sciences. My institute, which we call LASP for short, receives some \$60+ million per year to support experimental, theoretical, and data analysis programs in the Space and Earth Sciences. The majority of these resources come from NASA. But increasing support comes from NOAA, NSF, and other federal agencies. LASP presently supports some 130 engineers as well as dozens of highly skilled technicians and support personnel. We are very proud, as well, that LASP has nearly 70 graduate students and over 100 undergraduate students each year who are pursuing education and training goals in space science and engineering.

I myself am a space plasma physicist and I have served as a principal investigator on several scientific programs of NASA. I am now a lead investigator in the recently launched Radiation Belt Storm Probe (RBSP) mission that is part of NASA’s Living With a Star program. I am also an investigator on NASA’s Cluster, MESSENGER, and Magnetospheric Multi-Scale (MMS) missions. I recently served as Chair of the National Research Council’s Committee on Solar and Space Physics and as a member of the NRC Space Studies Board. I am testifying today in my capacity as chair of the NRC Committee for a Decadal Strategy for Solar and Space Physics (Heliophysics), which recently published the report, *Solar and Space Physics: A Science for a Technological Society* (the “decadal survey”). The report is available online at: <[http://www.nap.edu/catalog.php?record\\_id=13060](http://www.nap.edu/catalog.php?record_id=13060)>. Although my testimony follows the specific recommendations and supporting text in that report; the opinions I express should be attributed to me unless stated otherwise.

The charter for today’s hearing includes 3 overarching questions:

1. What are the [decadal] survey committee’s top recommendations for the coming decade? What is the current state of the solar and space physics programs at NASA and what are the prospects for the foreseeable future to follow the Decadal Survey’s recommendations given that budgets will remain essentially flat?
2. What is the role of the Space Weather Prediction Center at NOAA? To what extent does NOAA work with NASA to develop and disseminate space weather models and forecasts? Where can coordination between agencies improve?

3. The recent solar and space physics decadal survey concluded that “a national, multifaceted program of both observations and modeling is needed to transition research into operations more effectively.” What steps is each agency taking to ensure a solar and space physics research program is effectively maintained and improved?

In my testimony below, I address these questions sequentially; following the testimony, I have appended the Summary of decadal survey report, which provides a more comprehensive review of the decadal survey’s origins, organization, objectives, and recommendations.

### **Background and Overview of the 2013-2022 Decadal Survey in Solar and Space Physics**

From the interior of the Sun, to the upper atmosphere and near-space environment of Earth, and outwards to a region far beyond Pluto where the Sun’s influence wanes, advances during the past decade in space physics and solar physics have yielded spectacular insights into the phenomena that affect our home in space. The decadal survey report, requested by NASA and the National Science Foundation, and carried out with their financial support and with the cooperation of other federal agencies, especially NOAA, presents a prioritized program of basic and applied research for 2013-2022 that will advance scientific understanding of the Sun, Sun- Earth connections and the origins of “space weather,” and the Sun’s interactions with other bodies in the solar system. The report includes recommendations directed for action by the study sponsors and by other federal agencies—especially NOAA, which is responsible for the day-to-day (“operational”) forecast of space weather. Appended to this testimony is the executive summary of the decadal survey, which provides details on all of the survey report’s recommendations.

The present decadal survey is the second NRC decadal survey in solar and space physics. Like all NRC decadal survey reports, this decadal survey was conducted with the assistance of a broad swath of the solar and space physics community; the final report represented the efforts of more than 85 solar and space physicists and space system engineers working over an 18-month period. In developing its recommendations, the survey committee also drew on over 300 “white papers” that were submitted by the community in response to a broadly-distributed survey request for concepts and new ideas to advance the discipline. The survey committee also sponsored numerous town-hall meetings and workshops prior to the formal start of its deliberations.

Per the study statement of work, the survey’s top-level tasks were to:

1. Provide an overview of solar and space physics science and provide a broad survey of the current state of knowledge in the field;
2. Identify the most compelling science challenges;
3. Identify the highest priority scientific targets for the interval 2013-2022; and
4. Develop an integrated research strategy.

### **Survey Recommendations**

The survey report’s recommendations are shown in the report summary that is appended to this testimony. The recommended actions include completion of projects in NASA and the National Science Foundation's (NSF's) current program, creation of a new "mid-scale" projects line at NSF, augmentation of NASA and NSF "enabling" programs, and acceleration and expansion of NASA's Heliophysics Explorer Program. For later in the decade, the report recommends beginning new moderate-size NASA missions to address high-priority science targets, and a multiagency initiative to address pressing needs for improved forecasts of space weather and predictions of its impacts on society.

*A key element of the survey is that its recommended program was fit to resources anticipated in a challenging fiscal environment.* To ensure that the costs of the recommended NASA program were realistic, the NRC contracted with the Aerospace Corporation, who conducted an independent cost and technical evaluation (CATE) of selected reference mission concepts. In addition, the survey committee provided “decision rules” that can be employed to maintain the vitality of the program should the recommended program need to be adjusted because of unanticipated technical problems, cost overruns, or budget shortfalls. At the request of NASA, decision rules specific to the flagship mission Solar Probe Plus were also provided.

Four scientific goals inform the survey committee’s recommendations:

1. Establish the origins of the sun's activity and predict the variations of the space environment;
2. Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs;
3. Understand the interaction of the sun with the solar system and the interstellar medium; and
4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Considering cost, schedule, and complexity, the decadal survey provides a number of research recommendations to reach these goals. It also considers challenges that could impede achievement of the recommended program, including budget issues, the necessity to coordinate activities across multiple agencies, and the limited availability of appropriately-sized and affordable space launch vehicles.

The report’s first recommendation is to continue support for the key existing program elements that comprise the Heliophysics Systems Observatory and for successful implementation of programs in advanced stages of development. Second in priority is the establishment of a new, integrated multiagency initiative—“DRIVE”—that will more effectively exploit NASA and NSF scientific assets. Fully exploiting available resources is always a priority; in the highly constrained budgets anticipated in the foreseeable future, it is a necessity.

The DRIVE initiative has five components:

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

As shown in Figure 1, below, the survey committee recommends a gradual implementation of the elements of DRIVE (because of budget constraints); in addition, elements of DRIVE are sequenced to take advantage of the implementation of new programs later in the decade survey interval. For example, Mission Operations and Data Analysis (MO&DA) augmentation begins in 2016, at a time when the Solar Dynamics Observatory (SDO) will have moved out of its prime mission phase, thus adding greatly to data covered by the general Guest Investigator (GI) program. The NASA portion of DRIVE is fully implemented by 2022, amounting to an augmentation to existing program lines that is equivalent to approximately \$33 million in current (2013) dollars. Note: In developing the DRIVE run-outs, the survey committee assumes a 2.7% rate of inflation, which is what NASA currently assumes as the inflation factor to be used for its new starts.

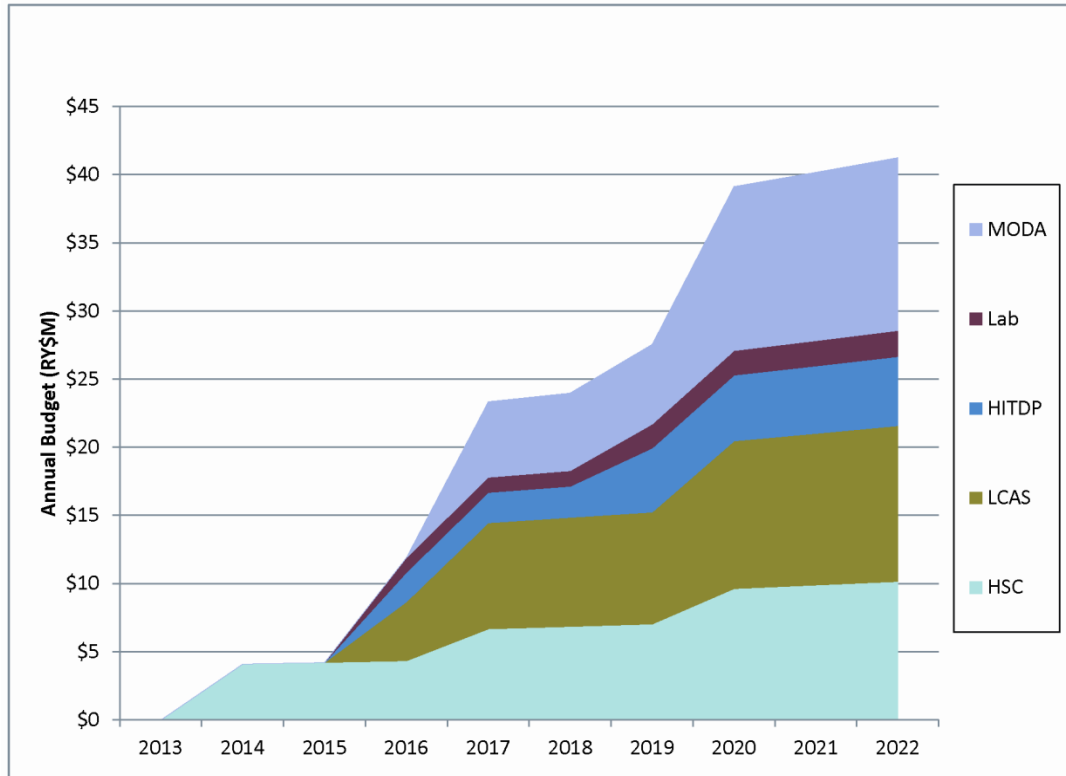


Figure 1: NASA DRIVE implementation: For the cost of a small mission, the DRIVE initiative recommends augmentations to NASA mission-enabling programs that have been carefully chosen to maximize the effectiveness of the program overall. Six of the DRIVE sub-recommendations have cost impact for NASA. Of these, *NASA Mission Guest Investigator* would require a cost allocation within STP and LWS missions of ~2% of total mission cost for a directed guest investigator program. The other five, *NASA LCAS Microsatellites (LCAS)*, *MO&DA augmentation (MODA)*, *Heliophysics Science Centers (HSCs)*, *Heliophysics Instrument and Technology Development Program (HITDP)*, and *Multi-agency Laboratory Experiments (Lab)*, are shown in the figure.

Third, the report recommends that NASA accelerate and expand the Heliophysics Explorer program, which provides frequent flight opportunities to enable the definition, development and implementation of mission concepts. Informing this recommendation was the recognition that the solar and space physics community has done much of its best and most innovative research with Explorers, a program which had been reduced during the previous decade. A key objective for the next survey interval—2013–2022—is to restore the number of Medium and Explorer class missions such that, in combination with competitively selected Instrument Opportunities on hosted payloads (MOOs), a higher cadence can be achieved that is capable of maintaining the vitality of the science disciplines. Augmenting the current program by \$70 million per year, in fiscal year 2012 dollars, will restore the option of mid-size Explorers and allow them to be offered in alternation with small explorers every 2 to 3 years. As part of the augmented Explorer program, it is also recommended that NASA support regular selections of Missions of Opportunity, which allow the research community to respond quickly and to leverage limited resources with interagency, international, and commercial flight partnerships. For relatively modest investments, such opportunities can potentially address high-priority science aims identified in this survey.

A highly constrained budget and the need to complete missions already in advanced stages of development postpones any new moderate- or large-class starts until midway in the survey interval of 2013–2022. Figure 2, below, shows a proposed implementation of the core NASA program, in which each

of the assets required to achieve the goals of the solar and space physics program are implemented at what is considered a proper cadence and within a budget profile that should be attainable. The recommended program addresses in a cost effective manner many of the most important and interesting science objectives, but the anticipated budget significantly constrains what can be accomplished. Built on top of the existing research foundation, the core program recommended here ensures that a proper distribution of resources is achieved. In particular, it restores a balance between small, medium, and large missions.

As detailed in the survey report, 3 new moderate- and 1 large-class mission starts are recommended later in the decade to investigate space physics at the edge of heliosphere, where the sun's influence on interstellar space is no longer dominate; the effects of processes in Earth's lower atmosphere on conditions in space; fundamental questions related to the creation and transport of plasma in Earth's ionosphere and magnetosphere; and how the Earth responds globally to magnetic storms from the sun.

**A key recommendation of the survey committee is that NASA's Solar-Terrestrial Probes program be restructured as a moderate-scale, competed, principal-investigator-led (PI-led) mission line that is cost-capped at approximately \$520 million per mission in fiscal year 2012 dollars including full life-cycle costs.** NASA's Planetary Science Division has demonstrated success in implementing mid-size missions as competed, cost-capped, PI-led investigations via the Discovery and New Frontiers programs. These are managed in a manner similar to Explorers and have a superior cost-performance history relative to that of larger flagship missions. The committee concluded that STP missions should be managed likewise, with the PI empowered to make scientific and mission design trade-offs necessary to remain within the cost cap. With larger-class LWS missions, which the committee recommends to continue to be Center-led, and smaller-class Explorers and Missions of Opportunity, this new approach will lead to a more balanced and effective overall NASA HPD mission portfolio that is implemented at a higher cadence and provides the vitality needed to accomplish the breadth of the survey's science goals. The eventual recommended minimum cadence of STP missions is one every 4 years.

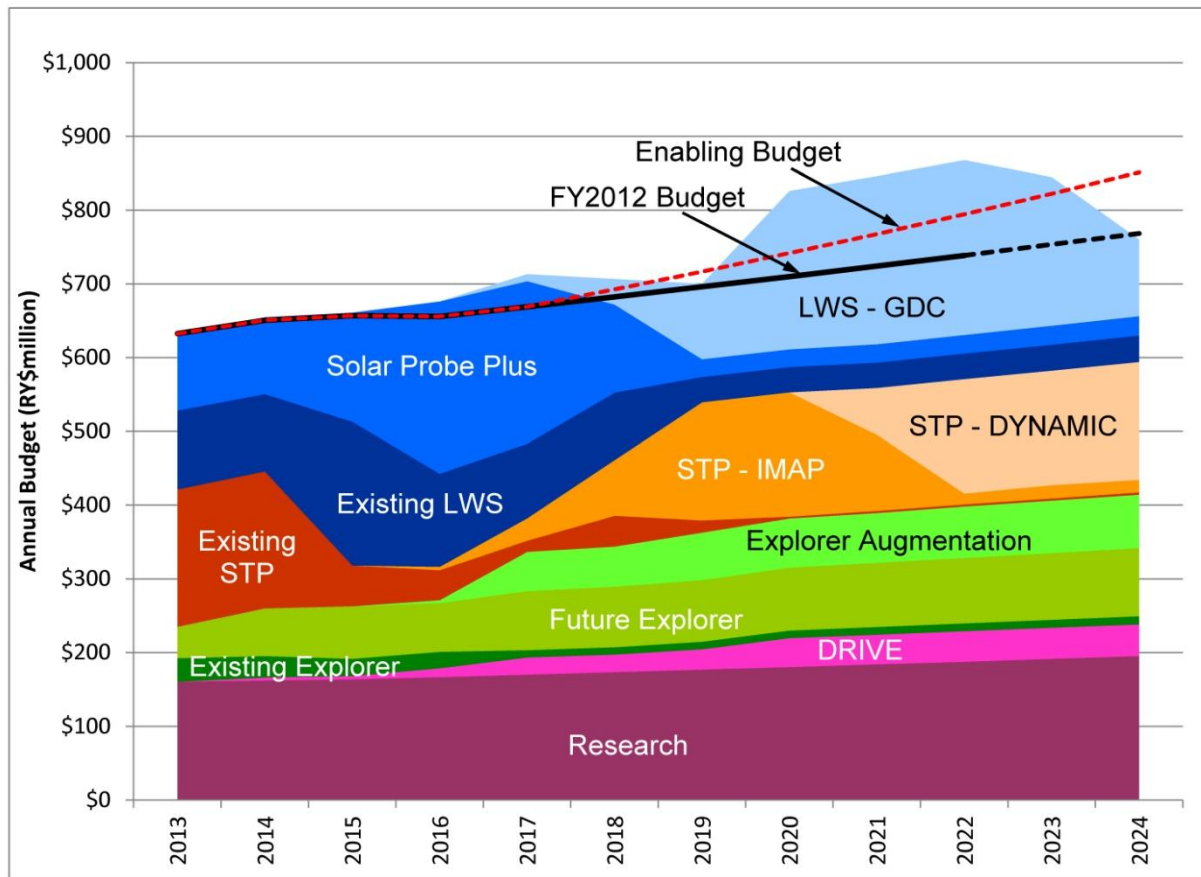


Figure 2: Heliophysics budget and program plan by year and category from 2013 to 2024. The solid black line indicates the funding level from 2013 to 2022 provided to the committee by NASA as the baseline for budget planning, and the dashed black line extrapolates the budget forward to 2024. After 2017 the amount increases with a nominal 2 percent inflationary factor. Through 2016 the program content is tightly constrained by budgetary limits and fully committed for executing existing program elements. The red dashed “Enabling Budget” line includes a modest increase from the baseline budget starting in 2017, allowing implementation of the survey-recommended program at a more efficient cadence that better meets scientific and societal needs and improves optimization of the mix of small and large missions. From 2017 to 2024 the Enabling Budget grows at 1.5 percent above inflation. (Note that the 2024 Enabling Budget is equivalent to growth at a rate just 0.50 percent above inflation from 2009.) GDC, the next large mission of the LWS program after SPP, rises above the baseline curve in order to achieve a more efficient spending profile, as well as to achieve deployment in time for the next solar maximum in 2024. Note: LWS refers to missions in the Living With a Star line and STP refers to missions in the Solar-Terrestrial Probes line.

### Enabling Effective Space Weather and Climatology Capabilities

NASA research satellites, such as ACE, SOHO (with ESA), STEREO, and SDO, designed for scientific studies, provide critical measurements essential for specifying and forecasting the space environment system, including the outward propagation of eruptive solar events and solar wind conditions upstream from Earth. While these observational capabilities have become essential for space environment operations, climatological monitoring, and research, NASA currently has neither the mandate nor the budget to sustain these measurements into the future.

A growing literature has documented the need to provide a long-term strategy for monitoring in space, and elucidated the large number of space weather effects, the forecasting of which depend critically on

the availability of suitable data streams.<sup>1</sup> An example is the provision of measurements of particles and fields at the L1 Lagrange point (or, using technologies such as solar sails, closer to the Sun on the Sun-Earth line), which is critical for short term forecasting of harmful space weather effects such as radiation, GPS accuracy reduction, and potentially deleterious geomagnetically induced currents on the power grid. The decadal survey steering committee found that the existing ad hoc approach towards the provision of these capabilities was inadequate.

A new plan is also needed that synthesizes and capitalizes on the strengths of the agencies participating in the NSWP as well as on opportunities in the commercial sector, such as the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) that uses the Iridium constellation of communications satellites to measure the electric currents that link Earth's atmosphere and space. The committee sees a need for a clearinghouse for coordinating the acquisition, processing, and archiving of underutilized real-time and near real-time ground- and space-based data needed for space weather applications. For example, highly valued energetic particle measurements made by GPS and LANL GEO satellites for specification of the radiation belts are not now routinely provided. Likewise, model development has been supported by individual agencies rather than being coordinated across relevant stakeholders.

In the survey report, the committee articulates a vision for an enhanced national commitment by partnering agencies for continuous measurements of critical space environment parameters, analogous to the monitoring of the terrestrial environment NASA is conducting in collaboration with a number of other agencies, for example, NOAA and the U.S. Geological Survey (USGS). The committee anticipates the criticality of such a program growing in priority relative to other societal demands and envisions that NASA utilize its unique space-based capabilities as the basis for a new program that could provide sustained monitoring of key space environment observables to meet this pressing national need. In addition to ensuring the continuity of critical measurements, robust space environment models capable of operational deployment are also necessary for the prediction and specification of conditions where observations are lacking.

The committee anticipates that it will take decades to achieve a space environment weather and climatology infrastructure equivalent to current capabilities in the modeling and forecasting of terrestrial weather and climate; thus, it is necessary to start immediately. The committee's vision for achieving critical continuity of key space environment parameters, their utilization in advanced models and application to operations is a major endeavour that will require unprecedented cooperation among agencies in areas where they have specific expertise and unique capabilities.

### **Space Weather-Related Recommendations**

The following recommendations were made by the survey committee to help fulfill its vision of an effective program in space weather that meets national needs—one that advances the fundamental science that underpins understanding of space weather phenomena and its effects on society and the evident need for effective vehicles to translate newly gained knowledge towards societal benefit:

**Recharter the National Space Weather Program:** The survey committee recommends that, to coordinate the development of this plan, the National Space Weather Program should be rechartered under the auspices of the National Science and Technology Council and should include the active participation of the Office of Science and Technology Policy and the Office of Management and Budget.

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<sup>1</sup> See, for example, National Research Council, *Severe Space Weather Events—Understanding Societal and Economic Impacts: A Workshop Report*, The National Academies Press, Washington, D.C., 2008, and D.N. Baker and L.J. Lanzerotti, A continuous L1 presence required for space weather, *Space Weather* 6:S11001, doi:10.1029/2008SW000445, 2008.

The plan should build on current agency efforts, leverage the new capabilities and knowledge that will arise from implementation of the programs recommended in this report, and develop additional capabilities, on the ground and in space, that are specifically tailored to space weather monitoring and prediction.

**Work in a multi-agency partnership to achieve continuity of solar and solar wind observations:** The survey committee recommends that NASA, NOAA, and the Department of Defense work in partnership to plan for continuity of solar and solar wind observations beyond the lifetimes of ACE, SOHO, STEREO, and SDO. In particular:

- Solar wind measurements from L1 should be continued, because they are essential for space weather operations and research. The DSCOVR and IMAP STP missions are recommended for the near term, but plans should be made to ensure that measurements from L1 continue uninterrupted into the future.
- Space-based coronagraph and solar magnetic field measurements should likewise be continued.

Further, the survey committee concluded that a national, multifaceted program of both observations and modeling is needed to transition research into operations more effectively by fully leveraging expertise from different agencies, universities, and industry and by avoiding duplication of effort. This effort should include determining the operationally optimal set of observations and modeling tools and how best to effect that transition. With these objectives in mind, the committee recommends that:

- **The space weather community should evaluate new observations, platforms, and locations that have the potential to provide improved space weather services. In addition, the utility of employing newly emerging information dissemination system for space weather alerts should be assessed.**
- **NOAA should establish a space weather research program to effectively transition research to operations.**
- **Distinct funding lines for basic space physics research and for space weather specification and forecasting need to be developed and maintained.**

Implementation of a program to advance space weather and climatology will require funding well above what the survey committee assumes will be available to support its research-related recommendations to NASA. The committee emphasizes that implementation of an initiative in space weather and climatology should proceed only if it does not impinge on the development and timely execution of the recommended research program.

Thank you again for the opportunity to bring to your attention the results of the 2<sup>nd</sup> National Research Council decadal survey in solar and space physics. At your request, I've focused my remarks on several questions that have particular relevance to NASA and its Science Mission Directorate; however, as the discussion of space weather indicates, multiple federal agencies have vital interests how we organize the nation's efforts in solar and space physics research and applications. In summary, our report:

- Fits the current fiscal boundary;
- Focuses on research and its societal impact;
- Empowers the community to innovate;
- Takes advantage of the unique constellation of missions and data available today and studies the coupled domains of heliophysics *as a system*;

- Builds the community's strength and facilitates development of cost-effective PI-class missions;  
and
- Recommends exciting missions of historical significance that hold tremendous promise for new discoveries.

# Solar and Space Physics: A Science for a Technological Society

## Summary

From the interior of the Sun, to the upper atmosphere and near-space environment of Earth, and outward to a region far beyond Pluto where the Sun's influence wanes, advances during the past decade in space physics and solar physics—the disciplines NASA refers to as heliophysics—have yielded spectacular insights into the phenomena that affect our home in space. This report, from the National Research Council's (NRC's) Committee for a Decadal Strategy in Solar and Space Physics, is the second NRC decadal survey in heliophysics. Building on the research accomplishments realized over the past decade, the report presents a program of basic and applied research for the period 2013-2022 that will improve scientific understanding of the mechanisms that drive the Sun's activity and the fundamental physical processes underlying near-Earth plasma dynamics, determine the physical interactions of Earth's atmospheric layers in the context of the connected Sun-Earth system, and enhance greatly the capability to provide realistic and specific forecasts of Earth's space environment that will better serve the needs of society. Although the recommended program is directed primarily to NASA (Science Mission Directorate–Heliophysics Division) and the National Science Foundation (NSF) (Directorate for Geosciences–Atmospheric and Geospace Sciences) for action, the report also recommends actions by other federal agencies, especially the National Oceanic and Atmospheric Administration (NOAA) those parts of NOAA charged with the day-to-day (operational) forecast of space weather. In addition to the recommendations included in this summary, related recommendations are presented in the main text of the report.

## RECENT PROGRESS: SIGNIFICANT ADVANCES FROM THE PAST DECADE

As summarized in Chapter 3 and discussed in greater detail in Chapters 8-10, the disciplines of solar and space physics have made remarkable advances over the last decade—many of which have come from the implementation of the program recommended in the 2003 solar and space physics decadal survey.<sup>2</sup> Listed below are some of the highlights from an exciting decade of discovery:

- New insights, gained from novel observations and advances in theory, modeling, and computation, into the variability of the mechanisms that generate the Sun's magnetic field, and into the structure of that field;
  - A new understanding of the unexpectedly deep minimum in solar activity;
  - Significant progress in understanding the origin and evolution of the solar wind;
  - Striking advances in understanding both explosive solar flares and the coronal mass ejections that drive space weather;
  - Groundbreaking discoveries about the surprising nature of the boundary between the heliosphere—that is, the immense magnetic bubble containing our solar system—and the surrounding interstellar medium;
- New imaging methods that permit researchers to directly observe space weather-driven changes in the particles and magnetic fields surrounding Earth;

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<sup>2</sup> National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003; and National Research Council, *The Sun to the Earth—and Beyond: Panel Reports*, The National Academies Press, Washington, D.C., 2003.

- Significantly deeper knowledge of the numerous processes involved in the acceleration and loss of particles in Earth’s radiation belts;
- Major advances in understanding the structure, dynamics, and linkages in other planetary magnetospheres, especially those of Mercury, Jupiter, and Saturn;
- New understanding of how oxygen from Earth’s own atmosphere contributes to space storms;
- The surprising discovery that conditions in near-Earth space are linked strongly to the terrestrial weather and climate below;
- The emergence of a long-term decline in the density of Earth’s upper atmosphere, indicative of planetary change; and
- New understanding of the temporal and spatial scales involved in magnetospheric-atmospheric coupling in Earth’s aurora.

It is noteworthy that some of the most surprising discoveries of the past decade have come from comparatively small missions that were tightly cost-constrained, competitively selected, and principal investigator (PI)-led—recommendations in the present decadal survey reflect this insight.

Enabled by advances in scientific understanding as well as fruitful interagency partnerships, the capabilities of models that predict space weather impacts on Earth have also made rapid gains over the past decade. Reflecting these advances and a society increasingly vulnerable to the adverse effects of space weather, the number of users of space weather services has also grown rapidly. Indeed, a growing community has come to depend on constant and immediate access to space weather information (Chapter 7).

## SCIENCE GOALS FOR THE NEXT DECADE

The significant achievements of the past decade set the stage for *transformative* advances in solar and space physics for the coming decade. Reports from the survey’s three interdisciplinary study panels (Chapters 8-10) enumerate the key scientific opportunities and challenges for the coming decade; collectively, they inform the survey’s four overarching science goals, each of which is considered of equal priority:

***Goal 1. Determine the origins of the Sun’s activity and predict the variations in the space environment.***

***Goal 2. Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.***

***Goal 3. Determine the interaction of the Sun with the solar system and the interstellar medium.***

***Goal 4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.***

## GUIDING PRINCIPLES AND PROGRAMMATIC CHALLENGES

To achieve these science goals, the survey committee recommends adherence to the following principles (Chapter 1):

- To make transformational scientific progress, the Sun, Earth, and heliosphere must be studied as a coupled system;

- To understand the coupled system requires that each subdiscipline be able to make measurable advances in achieving its key science goals; and
- Success across the entire field requires that the various elements of solar and space physics research programs—the enabling foundation comprising theory, modeling, data analysis, innovation, and education, as well as ground-based facilities and small-, medium-, and large-class space missions—be deployed with careful attention both to the mix of assets and to the schedule (cadence) that optimizes their utility over time.

The committee’s recommendations reflect these principles while also taking into account issues of cost, schedule, and complexity. The committee also recognizes a number of challenges that could impede achievement of the recommended program: the assumed budget may not be realized or missions could experience cost growth; the necessity to coordinate activities across multiple agencies; and the limited availability of appropriately sized and affordable space launch vehicles, particularly medium-class launch vehicles.

## RECOMMENDATIONS—RESEARCH AND APPLICATIONS

The survey committee’s recommendations are listed in Tables S.1 and S.2; a more complete discussion of the “research” recommendations—the primary focus of this survey—is found in Chapter 4 along with a discussion of the “applications” recommendations, while Chapter 7 presents the committee’s vision, premised on the availability of additional funds, of an expanded program in space weather and space climatology. The committee’s recommendations are prioritized and integrated across agencies to form an effective set of programs consistent with fiscal and other constraints. An explicit cost appraisal for each NASA research recommendation is incorporated into the budget for the overall program (Chapter 6); however, for NSF programs, only a general discussion of expected costs is provided (Chapter 5).

### Research Recommendations

#### Baseline Priority for NASA and NSF: Complete the Current Program

**The survey committee’s recommended program for NSF and NASA assumes continued support in the near term for the key existing program elements that constitute the Heliophysics Systems Observatory (HSO) and successful implementation of programs in advanced stages of development.**

NASA’s existing heliophysics flight missions and NSF’s ground-based facilities form a network of observing platforms that operate simultaneously to investigate the solar system. This array can be thought of as a single observatory—the Heliophysics System Observatory (HSO) (see Figure 1.2). The evolving HSO lies at the heart of the field of solar and space physics and provides a rich source of observations that can be used to address increasingly interdisciplinary and long-term scientific questions. Missions now under development will expand the HSO and drive scientific discovery. For NASA, these include the following:

- The Radiation Belt Storm Probes (RBSP, Living With a Star (LWS) program, 2012 launch) and related Balloon Array for RBSP Relativistic Electron Losses (BARREL; first launch 2013) will determine the mechanisms that control the energy, intensity, spatial distribution, and time variability of Earth’s radiation belts.
- The Interface Region Imaging Spectrograph (IRIS; Explorer program, 2013 launch) will deliver pioneering observations of chromospheric dynamics just above the solar surface to help determine their role in the origin of the heat and mass fluxes into the corona and wind.

- The Magnetospheric Multiscale mission (MMS; Solar-Terrestrial Probe (STP) program, 2014 launch) will address the physics of magnetic reconnection at the previously inaccessible tiny scale where reconnection is triggered.

Compelling missions that are not yet in advanced stages of development but are part of a baseline program whose continuation NASA asked the survey committee to assume include the following:<sup>3</sup>

- Solar Orbiter (European Space Agency-NASA partnership, 2017 launch) will investigate links between the solar surface, corona, and inner heliosphere from as close as 62 solar radii.
- Solar Probe Plus (SPP, LWS program, 2018 launch) will make mankind's first visit to the solar corona to discover how the corona is heated, how the solar wind is accelerated, and how the Sun accelerates particles to high energy.

With these new investments, the powerful fleet of space missions that explore our local cosmos can be significantly strengthened. However, implementation of the baseline program will consume nearly all of the resources anticipated to be available for new starts within NASA's Heliophysics Division through the midpoint of the overall survey period, 2013-2022.

For NSF, the previous decade witnessed the initial deployment in Alaska of the Advanced Modular Incoherent Scatter Radar (AMISR), a mobile facility used to study the upper atmosphere and to observe space weather events, and the initial development of the Advanced Technology Solar Telescope (ATST), a 4-meter-aperture optical solar telescope—by far the largest in the world—that will provide the most highly resolved measurements ever obtained of the Sun's plasma and magnetic field. These new NSF facilities join a broad range of existing ground-based assets that provide an essential global synoptic perspective and complement space-based measurements of the solar and space physics system. With adequate science and operations support, they will enable frontier research even as they add to the long-term record necessary for analyzing space climate over solar cycles.

## **R1.0 Implement the DRIVE Initiative**

**The survey committee recommends 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 DRIVE initiative encompasses specific, cost-effective, augmentations to NASA and NSF heliophysics programs. Its implementation will bring existing “enabling” programs to full fruition and will provide new opportunities to realize scientific discoveries from existing data, build more comprehensive models, make theoretical breakthroughs, and innovate. With this in mind, the committee has as its first priority for both NASA and NSF (after completion of the current program) the implementation of an integrated, multiagency initiative comprising the following components:*

- 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

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<sup>3</sup> In accordance with its statement of task, the survey committee did not reprioritize any NASA mission that was in formulation or advanced development. In addition, the study charge specified that Solar Orbiter and Solar Probe Plus would not be included in any prioritization of future mission opportunities.

The five DRIVE components are defined in Chapter 4, with specific and actionable recommendations for each element. Implementation of the NASA portion of the DRIVE initiative would require an augmentation to existing program lines equivalent to approximately \$33 million in current (2013) dollars (see Chapter 6).<sup>4</sup> The cost and implementation of the NSF portion of DRIVE are described in Chapter 5. Although the recommendations for NSF within the DRIVE initiative are not prioritized, the survey committee calls attention to two in particular:

**The National Science Foundation 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.**
- **Create a new competitively selected mid-scale project funding line in order to enable mid-scale projects and instrumentation for large projects.** There are a number of compelling candidates for a mid-scale facilities line, including the Frequency Agile Solar Radiotelescope (FASR), the Coronal Solar Magnetism Observatory (COSMO), and several other projects exemplifying the kind of creative approaches necessary to fill gaps in observational capabilities and to move the survey's integrated science plan forward.

## **R2.0 Accelerate and Expand the Heliophysics Explorer Program**

**The survey committee recommends that NASA accelerate and expand the Heliophysics Explorer program. Augmenting the current program by \$70 million per year, in fiscal year 2012 dollars, will restore the option of Mid-size Explorer (MIDEX) missions and allow them to be offered alternately with Small Explorer (SMEX) missions every 2 to 3 years. As part of the augmented Explorer program, NASA should support regular selections of Missions of Opportunity.**

The Explorer program's strength lies in its ability to respond rapidly to new concepts and developments in science, as well as in the program's synergistic relationship with larger-class strategic missions.<sup>5</sup> The Explorer mission line has proven to be an outstanding success, delivering—cost-effectively—science results of great consequence. The committee recommends increased support of the Explorer program to enable significant scientific advances in solar and space physics. As discussed in Chapter 4, the committee believes that the proper cadence for Heliophysics Explorers is one mission every 2 to 3 years. The committee's recommended augmentation of the Explorer program would facilitate this cadence and would also allow selection of both small- and medium-class Explorers. Historically, MIDEX missions offered an opportunity to resolve many of the highest-level science questions, but they have not been feasible with the current Explorer budget.

Regular selections of Missions of Opportunity will also allow the research community to respond quickly and to leverage limited resources with interagency, international, and commercial flight partnerships. For relatively modest investments, such opportunities can potentially address high-priority science aims identified in this survey.

## **R3.0 Restructure Solar-Terrestrial Probes as a Moderate-Scale, PI-Led Line**

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<sup>4</sup> The survey committee assumes inflation at 2.7 percent in program costs, the same as the percentage used by NASA for new starts.

<sup>5</sup> National Research Council, *Solar and Space Physics and Its Role in Space Exploration*, The National Academies Press, Washington, D.C., 2003, p. 36.

**The survey committee recommends that NASA’s Solar-Terrestrial Probes program be restructured as a moderate-scale, competed, principal-investigator-led (PI-led) mission line that is cost-capped at \$520 million per mission in fiscal year 2012 dollars including full life-cycle costs.**

NASA’s Planetary Science Division has demonstrated success in implementing mid-size missions as competed, cost-capped, PI-led investigations via the Discovery and New Frontiers programs. These are managed in a manner similar to Explorers and have a superior cost-performance history relative to that of larger flagship missions. The committee concluded that STP missions should be managed likewise, with the PI empowered to make scientific and mission design trade-offs necessary to remain within the cost cap (Chapter 4). With larger-class LWS missions and smaller-class Explorers and Missions of Opportunity, this new approach will lead to a more balanced and effective overall NASA HPD mission portfolio that is implemented at a higher cadence and provides the vitality needed to accomplish the breadth of the survey’s science goals. The eventual recommended minimum cadence of STP missions is one every 4 years.

**Although the new STP program would involve moderate missions being chosen competitively, the survey committee recommends that their science targets be ordered as follows so as to systematically advance understanding of the full coupled solar-terrestrial system:**

**R3.1 The first new STP science target is to understand the outer heliosphere and its interaction with the interstellar medium, as illustrated by the reference mission<sup>6</sup> Interstellar Mapping and Acceleration Probe (IMAP; Chapter 4). Implementing IMAP as the first of the STP investigations will ensure coordination with NASA Voyager missions. The mission implementation also requires measurements of the critical solar wind inputs to the terrestrial system.**

**R3.2 The second STP science target is to provide a comprehensive understanding of the variability in space weather driven by lower-atmosphere weather on Earth. This target is illustrated by the reference mission Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC; Chapter 4).**

**R3.3 The third STP science target is to determine how the magnetosphere-ionosphere-thermosphere system is coupled and how it responds to solar and magnetospheric forcing. This target is illustrated by the reference mission Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI; Chapter 4).**

The rationale for all the selections and for their ordering is detailed in Chapter 4.

## **Living With a Star**

Certain landmark scientific problems are of such scope and complexity that they can be addressed only with major missions. In the survey committee’s plan, major heliophysics missions would be implemented within NASA’s LWS program; the survey committee recommends that they continue to be

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<sup>6</sup> In this report, the committee uses the terms “reference mission” and “science target” interchangeably, given that the mission concepts were developed specifically to assess the cost of addressing particular high-priority science investigations. The concepts presented in this report underwent an independent cost and technical analysis by the Aerospace Corporation, and they have been given names for convenience; however, the actual recommendation from the committee is to address the science priorities enumerated in the reference mission concept.

managed and executed by NASA centers. Other integral thematic elements besides the flight program are essential to the LWS science and technology program: the unique LWS research, technology, strategic capabilities, and education programs remain of great value.

**R4.0 Implement a large Living With a Star mission to study the ionosphere-thermosphere-mesosphere system in an integrated fashion.**

**The survey committee recommends that, following the launch of RBSP and SPP, the next LWS science target focus on how Earth’s atmosphere absorbs solar wind energy. The recommended reference mission is Geospace Dynamics Constellation (GDC).**

As detailed in Chapter 4, the GDC reference mission would provide crucial scientific measurements of the extreme variability of conditions in near-Earth space. Within anticipated budgets, the completion of the baseline LWS program, which includes the launch of two major missions—RBSP in 2012 and SPP in 2018—does not allow for the launch of a subsequent major mission in heliophysics until 2024, 6 years after SPP. This establishes what the survey committee regards as the absolute minimum needed cadence for major missions.

**Applications Recommendations: Enabling Effective Space Weather and Climatology Capabilities**

Multiple agencies of the federal government have vital interests related to space weather, and efforts to coordinate these agencies’ activities are seen in the National Space Weather Program (NSWP).<sup>7</sup> Nonetheless, the survey committee concluded that additional approaches are needed to develop the capabilities outlined in the 2010 National Space Policy document and envisioned in the 2010 NSWP plan. Chapter 7 presents the committee’s vision for a renewed national commitment to a comprehensive program in space weather and climatology (SWaC). Enabling an effective SWaC capability will require action across multiple agencies and an integrated program that builds on the strengths of individual agencies.

**A1.0 Recharter the National Space Weather Program**

**The survey committee recommends that, to coordinate the development of this plan, the National Space Weather Program should be rechartered under the auspices of the National Science and Technology Council and should include the active participation of the Office of Science and Technology Policy and the Office of Management and Budget. The plan should build on current agency efforts, leverage the new capabilities and knowledge that will arise from implementation of the programs recommended in this report, and develop additional capabilities, on the ground and in space, that are specifically tailored to space weather monitoring and prediction.**

**A2.0 Work in a multi-agency partnership to achieve continuity of solar and solar wind observations.**

**The survey committee recommends that NASA, NOAA, and the Department of Defense work in partnership to plan for continuity of solar and solar wind observations beyond the lifetimes of ACE, SOHO, STEREO, and SDO. In particular:**

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<sup>7</sup> Committee for Space Weather, Office of the Federal Coordinator for Meteorological Services and Supporting Research, *National Space Weather Program Strategic Plan*, FCM-P30-2010, August 17, 2010, available at <http://www.ofcm.gov/nswp-sp/fcm-p30.htm>.

**A2.1 Solar wind measurements from L1 should be continued, because they are essential for space weather operations and research. The DSCOVR and IMAP STP missions are recommended for the near term, but plans should be made to ensure that measurements from L1 continue uninterrupted into the future.**

**A2.2 Space-based coronagraph and solar magnetic field measurements should likewise be continued.**

Further, the survey committee concluded that a national, multifaceted program of both observations and modeling is needed to transition research into operations more effectively by fully leveraging expertise from different agencies, universities, and industry and by avoiding duplication of effort. This effort should include determining the operationally optimal set of observations and modeling tools and how best to effect that transition. With these objectives in mind:

**A2.3 The space weather community should evaluate new observations, platforms, and locations that have the potential to provide improved space weather services. In addition, the utility of employing newly emerging information dissemination system for space weather alerts should be assessed.**

**A2.4 NOAA should establish a space weather research program to effectively transition research to operations.**

**A2.5 Distinct funding lines for basic space physics research and for space weather specification and forecasting need to be developed and maintained.**

Implementation of a program to advance space weather and climatology will require funding well above what the survey committee assumes will be available to support its research-related recommendations to NASA (see Table S.1). The committee emphasizes that implementation of an initiative in space weather and climatology should proceed only if it does not impinge on the development and timely execution of the recommended research program.

## **RECOMMENDED PROGRAM, DECISION RULES, AND AUGMENTATION PRIORITIES FOR NASA**

### **Recommended Program**

The committee's recommended program for NASA Heliophysics Division is shown in Figure S.1. As detailed in Chapter 6, the plan restores the medium-class Explorers and, together with small-class Explorer missions and Missions of Opportunity, achieves the recommended minimum mission cadence. The plan also begins the DRIVE initiative as early in the decade as budgets allow, with full implementation achieved by mid-decade. However, funding constraints affect the restoration and recommended rebalance of heliophysics program elements such that full realization of the survey committee's strategy is not possible until after 2017 (Figure S.1).

### **Decision Rules to Ensure Balanced Progress is Maintained**

The recommended program for NASA cost-effectively addresses key science objectives. However, the survey committee recognizes that the already tightly constrained program could face further budgetary challenges. For example, with launch planned in 2018, the Solar Probe Plus project has not yet

entered the implementation phase when expenditures are highest.<sup>8</sup> Significant cost growth in this very important, but technically challenging, mission beyond the current cap has the potential to disrupt the overall NASA heliophysics program.

To guide the allocation of reduced resources, the committee recommends the following decision rules intended to provide flexibility and efficiency if funding is less than anticipated, or should some other disruptive event occur. These rules, discussed in greater depth in Chapter 6, maintain progress toward the top-priority, system-wide science challenges identified in this survey. The decision rules should be applied in the order shown to minimize disruption of higher-priority program elements:

*Decision Rule 1.* Missions in the STP and LWS lines should be reduced in scope or delayed to accomplish higher priorities (Chapter 6 gives explicit triggers for review of Solar Probe Plus).

*Decision Rule 2.* If further reductions are needed, the recommended increase in the cadence of Explorer missions should be scaled back, with the current cadence maintained as the minimum.

*Decision Rule 3.* If still further reductions are needed, the DRIVE augmentation profile should be delayed, with the current level of support for elements in the NASA research line maintained as the minimum.

### **Augmentations to Increase Program Value**

The committee notes that the resources assumed in crafting this decadal survey's recommended programs are barely sufficient to make adequate progress in solar and space physics; with reduced resources, progress will be inadequate. It is also evident that with increased resources, the pace at which the nation pursues its program could be accelerated with a concomitant increase in the achievement of scientific discovery and societal value. The committee recommends the following augmentation priorities to aid in implementing a program under a more favorable budgetary environment:

*Augmentation Priority 1.* Given additional budget authority early in the decade, the implementation of the DRIVE initiative should be accelerated.

*Augmentation Priority 2.* With sufficient funds throughout the decade, the Explorer line should be further augmented to increase the cadence and funding available for missions, including Missions of Opportunity.

*Augmentation Priority 3.* Given further budget augmentation, the schedule of STP missions should advance to allow the third STP science target (MEDICI) to begin in this decade.

*Augmentation Priority 4.* The next LWS mission (GDC) should be implemented with an accelerated, more cost-effective funding profile.

### **EXPECTED BENEFITS OF THE RECOMMENDED PROGRAM**

Implementation of the survey committee's recommended programs will ensure that the United States maintains its leadership in solar and space physics and, the committee believes, lead to significant—even transformative—advances in scientific understanding and observational capabilities (Table S.3). In turn, these advances will support critical national needs for information that can be used to

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<sup>8</sup> On January 31, 2012, Solar Probe Plus passed its agency-level confirmation review and entered what NASA refers to as mission definition or Phase B of its project life cycle.

anticipate, recognize, and mitigate space weather effects that threaten to human life and the technological systems society depends on.

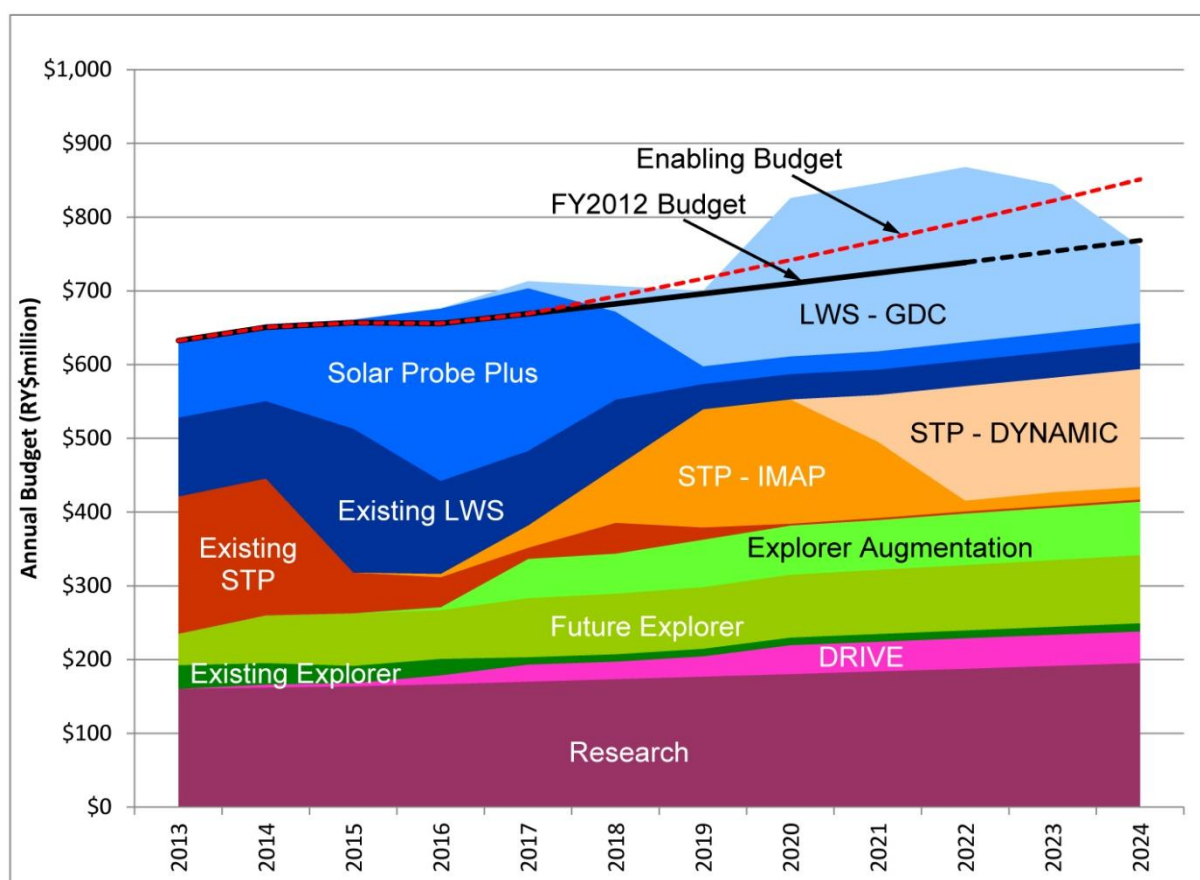


FIGURE S.1 Heliophysics budget and program plan by year and category from 2013 to 2024. The solid black line indicates the funding level from 2013 to 2022 provided to the committee by NASA as the baseline for budget planning, and the dashed black line extrapolates the budget forward to 2024. After 2017 the amount increases with a nominal 2 percent inflationary factor. Through 2016 the program content is tightly constrained by budgetary limits and fully committed for executing existing program elements. The red dashed “Enabling Budget” line includes a modest increase from the baseline budget starting in 2017, allowing implementation of the survey-recommended program at a more efficient cadence that better meets scientific and societal needs and improves optimization of the mix of small and large missions. From 2017 to 2024 the Enabling Budget grows at 1.5 percent above inflation. (Note that the 2024 Enabling Budget is equivalent to growth at a rate just 0.50 percent above inflation from 2009.) GDC, the next large mission of the LWS program after SPP, rises above the baseline curve in order to achieve a more efficient spending profile, as well as to achieve deployment in time for the next solar maximum in 2024. NOTE: LWS refers to missions in the Living With a Star line and STP refers to missions in the Solar-Terrestrial Probes line.

**TABLE S.1 Summary of Top-Level Decadal Survey Research Recommendations**

0.0	Complete the current program	X	X	
1.0	Implement the DRIVE initiative  Small satellites; mid-scale NSF projects; vigorous ATST and synoptic program support; science centers and grant programs; instrument development	X	X	X
2.0	Accelerate and expand the Heliophysics Explorer program  Enable MIDEEX line and Missions of Opportunity	X		
3.0	Restructure STP as a moderate-scale, PI-led line	X		
3.1	Implement an IMAP-Like Mission	X		
3.2	Implement a DYNAMIC-Like Mission	X		
3.3	Implement a MEDICI-Like Mission	X		
4.0	Implement a large LWS GDC-like mission	X		

**TABLE S.2 Summary of Top Level Decadal Survey Applications Recommendations**

1.0	Recharter the National Space Weather Program	X	X	X
2.0	Work in a multi-agency partnership for solar and solar wind observations	X	X	X
2.1	Continuous solar wind observations from L1 (DSCOVR, IMAP)	X		X
2.2	Continue space-based coronagraph and solar magnetic field measurements	X		X
2.3	Evaluate new observations, platforms, and locations	X	X	X
2.4	Establish a SWx research program at NOAA to effectively transition from research to operations			X
2.5	Develop and maintain distinct programs for space physics	X	X	X



TABLE S.3 Fulfilling the Science Goals of the Decadal Survey

Advances in Scientific Understanding and Observational Capabilities		Goals
Advances due to Implementation of the existing program	Twin Radiation Belt Storm Probes will observe Earth's radiation belts from separate locations, finally resolving the importance of temporal and spatial variability in the generation and loss of trapped radiation that threatens spacecraft.	2, 4
	The Magnetospheric Multiscale mission will provide the first high-resolution, three-dimensional measurements of magnetic reconnection in the magnetosphere, by sampling small regions where magnetic field line topologies reform.	2, 4
	Solar Probe Plus will be the first spacecraft to enter the outer atmosphere of the Sun, repeatedly sampling solar coronal particles and fields to understand coronal heating, solar wind acceleration, and formation and transport of energetic solar particles.	1, 4
	Solar Orbiter will provide the first high-latitude images and spectral observations of the Sun's magnetic field, flows, and seismic waves, relating changes seen in the corona to local measurements of the resulting solar wind.	1, 4
	The 4-meter Advanced Technology Solar Telescope will resolve structures as small as 20 km, measuring the dynamics of the magnetic field at the solar surface down to the fundamental density length scale and in the low corona.	1, 4
	The Heliophysics Systems Observatory will gather a broad range of ground- and space-based observations and advance increasingly interdisciplinary and long-term solar and space physics science objectives.	All
New starts on programs and missions to be implemented within the next decade	The DRIVE initiative will greatly strengthen our ability to pursue innovative observational, theoretical, numerical, modeling, and technical advances.	All
	Solar and space physicists will accomplish high-payoff, timely science goals with a revitalized Explorer program, including leveraged Missions of Opportunity.	All
	The Interstellar Mapping and Acceleration Probe, in conjunction with the twin Voyager spacecraft, will resolve the interaction between the heliosphere, our home in space, and the interstellar medium.	2, 3, 4
	A new funding line for mid-size projects at the National Science Foundation will facilitate long-recommended ground-based projects, such as COSMO and FASR, by closing the funding gap between large and small programs.	All
New starts on missions to be launched early in the next decade	The Dynamical Neutral Atmosphere-Ionosphere Coupling mission's two identical orbiting observatories will clarify the complex variability and structure in near-Earth plasma driven by lower atmospheric wave energy.	2, 4
	The Geospace Dynamics Constellation will provide the first simultaneous, multipoint observations of how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over local and global scales.	2, 4

Possible new start this decade given budget augmentation and/or cost reduction in other missions	The Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation will target complex, coupled, and interconnected multi-scale behavior of the magnetosphere-ionosphere system by providing global, high-resolution, continuous three-dimensional images and multi-point in situ measurements of the ring current, plasmasphere, aurora, and ionospheric-thermospheric dynamics.	2, 4
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