Progress Toward Implementation of the 2013 Decadal Survey for Solar and Space Physics

A Midterm Assessment

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Committee on the Review of Progress Toward Implementing the Decadal Survey – Solar and Space Physics: A Science for a Technological Society

Space Studies Board

Division on Engineering and Physical Sciences

A Consensus Study Report of

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Preface

Solar and Space Physics: A Science for a Technological Society[1] was the second National Academies of Sciences, Engineering, and Medicine "decadal survey" in the disciplines often referred to as heliophysics. Building on the research accomplishments realized in the period since publication of the inaugural decadal survey for heliophysics,[2] the report presented a program of basic and applied research for the period 2013-2022 to:

- 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 was directed primarily at NASA and the National Science Foundation (NSF), the report also recommended actions by other federal agencies, especially the parts of the National Oceanic and Atmospheric Administration (NOAA) charged with the day-to-day (operational) forecast of space weather.

In the NASA Authorization Act of 2005, Congress directed NASA to have the performance of each division in the Science Mission Directorate reviewed and assessed by the National Research Council, the operating arm of the National Academies, at 5-year intervals. Responding to this mandate for the heliophysics decadal survey, NASA, in the fall of 2018, asked the Space Studies Board of the National Academies to convene an ad hoc committee to review the alignment of their Heliophysics program with the survey.

The statement of task for the midterm assessment (reprinted in Appendix A) included a request for guidance regarding implementation of the recommended portfolio for the remaining years of the current decadal survey interval, as well as actions that should be undertaken to prepare for the next decadal survey. The midterm assessment committee, the Committee on the Review of Progress Toward Implementing the Decadal Survey—Solar and Space Physics: A Science for a Technological Society (the "committee") was also asked to consider steps to enhance the careers of solar and space physics practitioners, which is directly related to the "health" of the disciplines that comprise solar and space physics. In making its recommendations, it is important to note that the committee, per the study terms of reference, did not revisit the priorities, including those pertaining to the science objectives and associated missions recommended for development by NASA, that were made in the 2013 decadal survey. Biographies of the committee, chaired by Robyn Millan, Dartmouth College, and Tom Woods, University of Colorado, are provided in Appendix B.

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[1] National Research Council, 2013, *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, DC.

[2] National Research Council, 2003, *The Sun to the Earth —and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, DC.

The committee was formed in Fall 2018 and met three times in person over the course of the study.[3] The committee also met on an approximate bi-weekly schedule via teleconference. Input from the solar and space physics community was solicited via professional society newsletters and at town hall sessions held at NSF summer workshops for its CEDAR (Coupling, Energetics, and Dynamics of Atmospheric Regions), GEM (Geospace Environment Modeling), and SHINE (Solar, Heliosphere and Interplanetary Environment) programs. A town hall was also held at a meeting of the Solar Physics Division (SPD) of the American Astronomical Society. Poster presentations about the committee activities were also presented at the GEM workshop, SHINE workshop, SPD meeting, and NOAA's Space Weather Week meeting. Agendas for the committee's in-person meetings are shown in Appendix C.

The organization of this report is as follows: Chapter 1 provides a brief description of the field of heliophysics and the current heliophysics programs at relevant federal agencies. In Chapter 2, several science highlights in each of the three heliophysics subdisciplines are described to provide a flavor for some of the exciting science accomplishments already realized during the first part of the decade (2013-2019). Chapter 3 provides a more detailed assessment of progress towards each of the *research* recommendations made in the 2013 decadal survey, as well as opportunities and challenges for the remainder of the current decade. Similarly, Chapter 4 discusses the recent progress and near future opportunities for the *application* recommendations in the 2013 decadal survey. Consideration of steps to further enhance and develop a strong and diverse workforce in order to maximize progress in heliophysics exploration and research in the coming decades is the subject of Chapter 5. Chapter 6 discusses planning that could be undertaken in preparation for the 2023-2033 decadal survey in solar and space physics. A full list of findings and the section where each is discussed in the report is provided in Appendix D, Appendix E includes a more detailed description of science progress since the 2013 decadal survey, and a full acronym list is found in Appendix F. Note: Information in this report was current as of October 10, 2019, which coincides with the date of the successful launch of NASA's Ionospheric Connection Explorer.

[3] Disruptions, including cancelation of a planned in-person meeting, due to the federal government shutdown from late December 2018 through late January 2019 resulted in delays in the completion of this report.

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APPENDIXES

Summary

Heliophysics is the study of our star, the Sun, its influences on Earth and other bodies throughout the heliosphere, and its interaction with interstellar space. Our solar system contains a rich diversity of environments for studying neutral and plasma processes that occur throughout the universe. Increasingly, our knowledge about planetary environments and fundamental processes is being applied to emerging research areas such as exoplanet habitability. Heliophysics is also the science behind space weather. As our society becomes increasingly dependent on technologies that are influenced by space weather, the importance of understanding, and ultimately forecasting, space weather continues to grow.

The 2013 solar and space physics decadal survey (NRC, 2013), hereafter referred to as "thedecadal survey," outlined a program of basic and applied research for the period 2013-2022. At the highest level, this program was organized around four "key science goals," each considered of equal priority:

1. Determine the origins of the Sun's activity and predict the variations in 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. Determine the interaction of the Sun with the solar system and the interstellar medium.
4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

To address these goals, the survey steering committee developed the "research" and "applications" recommendations that are shown below in Table 1.4 of Chapter 1. An assessment of scientific progress in the period since publication of the decadal survey, an assessment of progress in meeting the recommendations shown in Table 1.4, consideration of steps to enhance career opportunities in solar and space physics, and a look forward to the next decadal survey, are among the key elements of the present study's tasks.

The midterm assessment committee's recommendations are presented in this Summary along with selected findings that are not associated with a recommendation. A full list of findings and the section where each is discussed in the report can be found in Appendix D. Figures S.1 and S.2 show a summary of progress toward decadal survey recommendations (also shown in Chapters 3 and 4 with detailed discussions about each decadal survey recommendation).

A CHANGING LANDSCAPE FOR HELIOPHYSICS

Best-laid plans of mice and men often go awry. *Believe you can and you're halfway there*.
—Adapted from *To a Mouse* by Robert Burns —President Theodore Roosevelt

With all long-term plans, the landscape changes and opportunities evolve in ways that the original planners could not foresee. Some changes accelerate progress, but many tend to complicate, slow down, or challenge implementation of the original plans. This has been the case over the some 6 years since publication of the decadal survey report. *Despite these challenges, the majority of the 2013 decadal* *survey recommendations have been implemented or are in progress towards being implemented over the next few years.*[1]

The list below summarizes the "changing-landscape" topics identified by the committee as being particulary significant; they are discussed further in Chapters 3 and 4 in the context of progress on heliophysics research and applications.

- *Budget.* The Heliophysics Division (HPD) budget did not increase as expected in the 2013 decadal survey (see Figure 3.2). Over the last 5 years, the NASA HPD budget rose by 14 percent, but this is in fact a decrease in purchasing power when corrected for inflation. In contrast, the NASA overall budget rose by 23 percent, and the NASA Science Mission Directorate (SMD) budget rose by 30 percent over this time period. The budget reality impacts NASA's ability to add new missions and fully implement the recommendations of the decadal survey. Similarly, the National Science Foundation (NSF) budget increased by roughly 14 percent but most of that increase occurred only recently.
- *Leadership.* Another challenge, particularly for NASA, has been frequent changes in leadership. The current HPD director, Nicola Fox, started in September 2018. Prior to this change, there were six different directors or acting directors since 2011.
- *Changes for space weather at the national level.*
  - The release of the National Space Weather Action Plan and Strategy defines the responsibilities of 10 government agencies to advance space weather capabilities and provides new opportunities for effective collaboration between agencies. However, these additional responsibilities come with a cost and require additional resources. These developments show the ever more important need for involvement of NOAA in the decadal survey process. Coordination with other agencies, such as the Department of Defense (DoD), is also critically important. This is discussed further in Chapter 4 and Chapter 6.
  - More recently, NASA's Exploration goals promise to take us back to the Moon and beyond. Space weather impacts on humans and technology in space are increasingly important and heliophysics research plays a critical role. New programs like Artemis and Lunar Gateway will also provide new opportunities for scientific discovery.
- *Opportunities for crossdisciplinary research.* The explosion of scientific interest in exoplanets and planetary habitability and the continual discovery of new exoplanets provides opportunities for the solar and space physics community to contribute to these emerging areas of science. In particular, the detailed understanding of processes important for magnetospheres, atmospheres, astrospheres, stellar dynamos, and the sophisticated models developed to study our own solar system can be adapted to new stellar and planetary systems.
- *Emerging small-satellite revolution.* Rapid technology development to support CubeSats and small-sats has accelerated the number of small satellite (SmallSat) science missions for NASA and NSF. Growth in the SmallSat commercial sector is providing new ways of designing and building satellites, as well as new opportunities for rideshares, hosted payloads, and commercial data buys. An opportunity exists to leverage these developments for space science.

[1] The decadal survey report included recommendations for three major (notional) missions to be implemented by NASA. There is now a Science and Technology Definition Team (STDT) report for the Geospace Dynamics Constellation (GDC) mission, but the definition studies for the DYNAMIC (Dynamical Netural Atmosphere-Ionosphere Coupling) and MEDICI (Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation) missions have not yet started due to budget constraints.

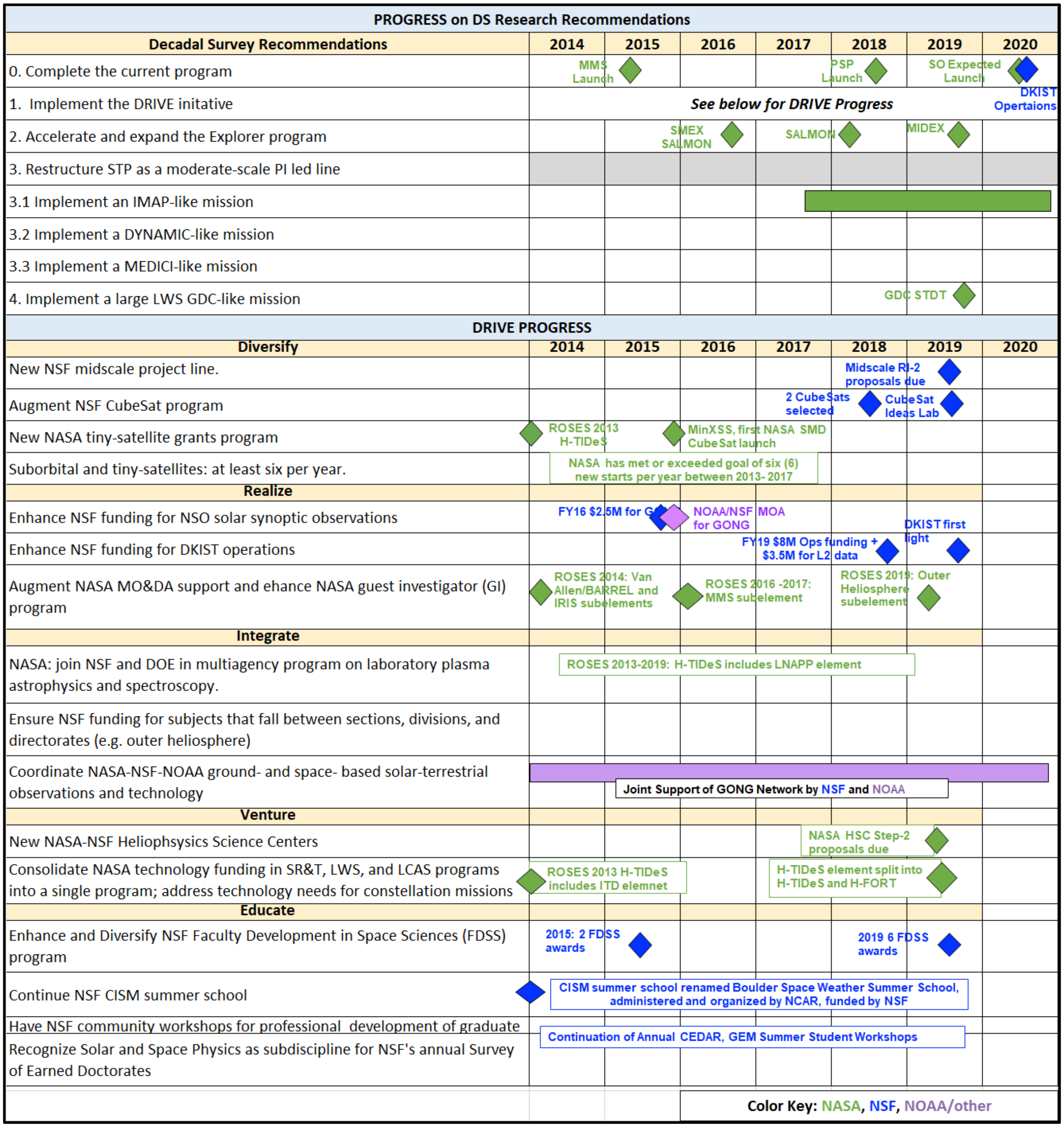

FIGURE S.1. Highlights of progress and plans for the heliophysics decadal survey *research* recommendations. NOTE: This is the same as Figure 3.1.

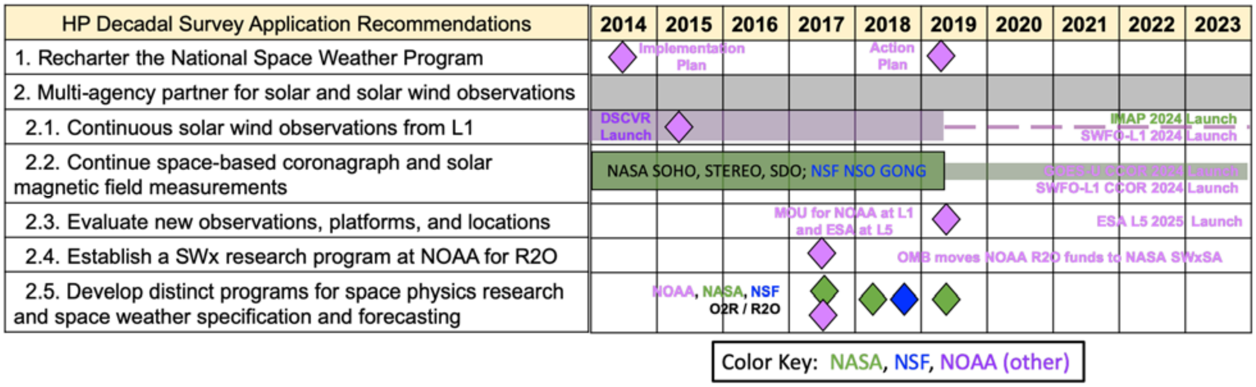

FIGURE S.2. Highlights of progress and plans for the heliophysics decadal survey *applications* recommendations. NOTE: This is the same as Figure 4.1.

- *Increasing role of data science.* Maximizing the scientific return from increasingly large and complex data sets requires better infrastructure, enhanced professional training, and support for open source software. Advanced observational and theoretical tools have become increasingly available since the decadal survey was published, providing new opportunities for realizing the scientific potential of data from NASA missions and NSF large facilities.
- *Citizen science.* The involvement of the broader population in scientific pursuits has led to the discovery of STEVE (Strong Thermal Emission Velocity Enhancement, a previously undescribed optical auroral phenomenon; MacDonald, et al., 2018) and played an important role in the scientific observations of the 2017 Eclipse. It is anticipated that this emerging area of citizen science will lead to further scientific discovery and opportunities for outreach.

HELIOPHYSICS RESEARCH RECOMMENDATIONS

The Heliophysics System Observatory

The decadal survey committee's highest priority was to complete the program of record, the assumed baseline that informed the committee's subequent recommendations. By placing the highest priority on completing the program of record, the committee was emphasizing both the importance of studying the coupled Sun-Earth system as a whole and the significance of the Heliophysics System Observatory (HSO), which comprises all currently operating missions and ground-based facilities. Since the decadal survey was released, NASA has launched the Van Allen Probes, the Magnetospheric Multiscale (MMS) four satellites, the Interface Region Imaging Spectrograph (IRIS) Explorer, and the Parker Solar Probe (PSP). For NSF, the Daniel K. Inouye Solar Telescope (DKIST) plans to be operational in 2020.

> ***Finding:*** Completion of the program of record as recommended in the 2013 decadal survey, combined with new tools and data analysis approaches, has resulted in significant scientific advances as highlighted in Chapter 2 and has added important elements to HSO. (Finding 3.1)

DRIVE

The second-priority research recommendation in the decadal survey, the DRIVE initiative, provided a new way to structure Research and Analysis (R&A) programs in order to maximize the science return of large NASA missions and NSF facilities. DRIVE aims to “diversify” observing platforms, “realize” the scientific potential of existing assets, “integrate” observing platforms into successful investigations, “venture” forward with new technologies, and “educate” the future heliophysics workforce. The decadal survey made 16 recommendations as part of these five DRIVE categories, summarized in Figure S.1.

> ***Finding:*** NASA and NSF have made progress on most of their DRIVE elements, although some of the DRIVE elements were implemented only recently. Funding constraints imposed by the decadal survey requirement to complete the current program are a contributing factor. (Finding 3.20)

The DRIVE initiative has led to increased funding of suborbital and CubeSat missions, a boost to R&A programs, the imminent selection of the first Heliophysics Science Centers (HSCs), new selections in the NSF midscale project line, and NSF continued support for DKIST development with its first light expected in early 2020.. A number of committee findings highlighting this progress can be found in Chapter 3. Below, the committee calls attention to the DRIVE findings that are not associated with a committee recommendation, but which identify places where the agencies have not yet reached the decadal survey goals, or where new developments require attention.

There are now 18 NASA HPD CubeSats funded, 6 of which have been launched so far. Due to this significant increase in the number of CubeSats missions, NASA Headquarters has added additional oversight support at the Wallops Small Satellite Project Office. NSF recently selected several new CubeSat missions, including two 3-satellite constellation missions through the CubeSat Ideas Lab. Wallops has also provided support for NSF CubeSats since initiation of the NSF CubeSat program.

> ***Finding:*** CubeSat missions are intended to be low-cost, higher-risk exploratory missions. The number of CubeSat science missions has increased significantly in this decade. While recognizing the challenge of managing a rapidly increasing number of CubeSat projects, NASA will need to ensure that managerial oversight does not translate into the imposition of additional reviews and reporting requirements to the level of larger missions. (Finding 3.2)

Interest in exoplanet research—from planetary evolution to habitability—is rapidly growing. The knowledge gained by studying our own planet and star can be applied to other systems for which we will never have detailed observations of microphysical processes.

> ***Finding:*** Heliophysics has much to contribute to areas of broad interest within NASA’s SMD, including stellar system and exoplanet research as well as future major exploratory efforts; for example, the Lunar Gateway missions. However, the expertise and knowledge that exists within the heliophysics community is not as widely exploited at SMD as it could be because there are insufficient opportunities to engage across division lines. (Finding 3.15)

To promote the crossdisciplinary research among observers, theorists, modelers, and computer scientists that is needed to address grand-challenge questions in the field of heliophysics, the decadal survey recommended the creation of HSCs. Selection of the first NASA HSC is anticipated to occur soon. The HSCs are expected to enable transformative research.

> ***Finding:*** A regular cadence for HSCs is needed. In order for HSCs to be impactful, the next call for Step-1 proposals should be released within a year of the down selection for Step-2 proposals. Moreover, full NSF participation in the HSCs has not been realized. (Finding 3.16)

As described above, completion of the program of record, the baseline decadal survey recommendation, has resulted in important additions to the HSO. Most of the HSO missions are in their extended mission phase, and there was a period during this decadal interval for which none of the HSO missions were in prime phase.

> ***Finding:*** Many elements of the HSO are aging, and there is a risk of losing key capabilities. In order to realize the vision of the HSO, some longer-term strategic planning is required to prioritize the critical support needed at both the mission level and the program level. Moreover, the HSO can be viewed as a national resource that goes beyond NASA missions. Data from small missions, ground-based facilities, and international assets have become increasingly important. An opportunity exists to elevate the HSO concept to better manage and exploit this critical resource for scientific progress. (Finding 3.14)

Overall, DRIVE has been successful as an organizational framework for the research programs at NASA and NSF. The spirit of DRIVE is to continue to innovate and look for new ways to maximize scientific progress. Thus DRIVE should be viewed as a means for structuring the R&A programs in a way that can respond and adapt to new opportunities.

> **Recommendation 3.1: NASA and NSF should continue to use the DRIVE framework within their Research and Analysis programs. As the program elements that are part of DRIVE continue to evolve, they should remain visible and continue to be tracked in a transparent manner.**
>
> The committee found that a few DRIVE recommendations have not yet been implemented fully.
>
> ***Finding:*** Laboratory research, from plasma physics to spectroscopy, is a critical, foundational component for heliophysics research. The NASA LNAPP program is a positive step towards increasing opportunities for laboratory experiments, but it does not fully address the decadal survey recommendation, specifically the need for increased NASA-Department of Energy collaboration. (Finding 3.11)
>
> ***Finding:*** Some elements of DRIVE for NSF have not been fully implemented. These include ensuring funding for science areas that fall between divisions such as outer heliosphere research, full participation in HSCs, and recognition of solar and space physics as a subdiscipline in the annual survey of earned doctorates. (Finding 3.21)

In addition to evaluating the progress on decadal survey recommendations, the committee identified new DRIVE-related opportunities that have emerged since the decadal survey was published. The committee findings lead to a recommendation for building on recent progress and taking advantage of new opportunities through the rest of the decade.

> **Recommendation 3.2: In consideration of developments and emerging opportunities since the decadal survey was published, and to optimize the science value of the agencies' programs for the remaining years of the current decadal survey interval,**
>
> 1. **NSF should extend support for the routine delivery of DKIST (the Daniel K. Inouye Solar Telescope) higher level data products past 2020 with the goal to routinely process data to Level 2 (physical quantities based on calibrated measurements) at the DKIST Data Center.**
> 2. **NSF and NOAA should extend the operations for the National Solar Observatory's synoptic observations past 2021, and NSF should begin investigating potential agency partners and design concepts for the next generation GONG (Global Oscillation Network Group) instruments.**

3. **NSF should critically evaluate its facilities operations model to ensure that the science return is maximized over the life cycle of each instrument.** Some of the operations and maintenance cost pressures for NSF facilities could be addressed through implementing critical recommendations from the recent National Science Board study on this topic (NSB, 2018).
4. **NASA and NSF should maximize the scientific return from large and complex data sets by supporting (1) training opportunities on modern statistical and computational techniques, (2) science platforms to store, retrieve, and process data using common standards, (3) funding opportunities for interdisciplinary collaboration, and (4) the development of open-source software. These four components should be considered alongside experimental hardware in the planning and budgeting of instrumentation.**
5. **NASA should find ways to increase solar and space physics community participation in strategic missions and enhance the diversity of mission teams.** The Planetary Science Division's Participating Scientist program is a model that could be considered to achieve this goal.
6. **NASA and NSF should strengthen their mutual coordination of ground-based and space-based observations, to include NASA investment in ground-based measurements that support their missions and coordination of NSF ground-based facilities in support of NASA missions, including suborbital campaigns.**
7. **Both NASA and NSF should create inter-divisional funding opportunities that support science areas that bridge established divisional boundaries at the agencies.** Specific examples of science areas include outer heliosphere, Sun-as-a-star, and star-exoplanet couplings. Progress will require collaboration between divisions at each agency to create inter-divisional programs.

Heliophysics Explorers

The third-priority research recommendation made in the decadal survey was to accelerate and expand the Heliophysics Explorers program, enabling both a Medium-Class Explorer (MIDEX) line (denoted as "Mid-size" in the survey report) and more frequent missions of opportunity (MoOs). The recommended cadence was 2-3 years, alternating between Small Explorer (SMEX) and MIDEX.

The Ionospheric Connection Explorer (ICON) and Global-Scale Observations of the Limb and Disk (GOLD) MoO were selected shortly after the decadal survey was published. ICON had a 2-year launch delay due to problems with the launch vehicle, but was recently launched in October 2019. GOLD was successfully launched in January 2018 and is in prime mission phase. Between 2013 and 2015, no Explorer Announcements of Opportunity (AOs) were released. However, between 2016 and 2019, both SMEX and MIDEX AOs have been released, two SMEX missions (TRACERS [Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites] and PUNCH [Polarimeter to Unify the Corona and Heliosphere]) were selected after their Phase A concept studies, the Atmospheric Waves Experiment (AWE) mission of opportunity was selected, and several MoOs are also moving into Phase A in 2019-2020. MIDEX proposals were due at the end of September 2019.

Findings on the Explorer Program

> ***Finding:*** NASA is responding positively to the decadal survey recommendation to strengthen the Explorer program. Although no Explorer AOs were released during the first 3 years following the decadal survey, the 3-year spacing between Heliophysics Explorer AOs for SMEX and MIDEX of 2016 and 2019 is a move to implement the decadal survey recommendation. (Finding 3.22)

Finding: The committee sees the growth of mission cost in a relatively flat budget setting as a significant hazard to the ability to sustain a 3-year cadence in the future. (Finding 3.23)

Finding: NASA management of Explorer[2] missions is in need of optimization to ensure that the program fullfils it goal to: "provide frequent flight opportunities…from space utilizing innovative, streamlined and efficient management approaches…" (Finding 3.24)

Recommendation 3.3: In order to maintain a 3-year (or ideally faster) launch frequency of Explorers, the committee recommends that NASA develop a more efficient management environment and an improved contract/grant structure, both to reduce mission cost and to shorten the interval from the Announcement of Opportunity to launch. In this context, the committee recommends that NASA (1) adopt new procedures to facilitate a more cost-efficient implementation of smaller satellites and instruments using game-changing SmallSat technology, and (2) continue to strive towards reduced launch costs—for example, through ride sharing.

Solar-Terrestrial Probes

The fourth-priority research recommendation of the 2013 decadal survey was to restructure NASA's Solar-Terrestrial Probes (STP) program as a principal-investigator (PI)-led mission line. The decadal survey further recommended that STP missions should be cost-capped at $520 million per mission (in fiscal year 2012 dollars) with a minimum recommended launch cadence of 4 years. This recommendation also included three notional mission concepts: IMAP (Interstellar Mapping and Acceleration Probe), DYNAMIC (Dynamical Neutral Atmosphere-Ionosphere Coupling), and MEDICI (Magnetosphere Energetics, Dynamics and Ionospheric Coupling Investigation). The STP program is an important component of heliophysics research, focusing on studying fundamental processes occurring throughout the heliosphere, including the coupled Sun-Earth system. The committee focused its attention on IMAP and DYNAMIC because the decadal survey assumed that MEDICI would not launch before the end of its decadal period (2013-2023).

Finding: Formulation of the first of three recommended STP missions has begun, but IMAP comes 3 years later than anticipated in the decadal survey, and the next STP mission (DYNAMIC) has not started. As anticipated in the decadal survey, the MEDICI mission is not expected to start until the next decade. (Finding 3.26)

The recently launched GOLD and ICON missions, and the AWE MoO, will answer important targeted science questions that contribute to our understanding of lower atmospheric impacts on the AIM (atmosphere-ionosphere-magnetosphere) system. However, these missions do not adequately observe Earth's poles and thus will not fully address one of the decadal survey top-level Research Recommendation 3.2 "to provide a comprehensive understanding of the variability in space weather driven by lower-atmosphere weather on Earth." To fully achieve the goals set out in the decadal survey, a constellation of satellites covering all latitudes and multiple local times is still required.

Finding: The DYNAMIC science goals remain compelling and of the highest priority for the heliophysics community. The targeted science goals and measurement capabilities of GOLD, AWE, and ICON do not address several key objectives in the top-level decadal survey science challenge posed by DYNAMIC. (Finding 3.27)

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[2] NASA Science Mission Directorate, "Explorers," https://science.nasa.gov/heliophysics/focus-areas/explorers.

Recommendation 3.4: NASA should take the steps necessary to release an Annoucement of Opportunity for a DYNAMIC-like mission as the next Solar-Terrestrial Probes mission.

The Next Living With a Star Mission

The Living With a Star mission line stands apart from the STP missions by focusing on science that improves our understanding of those aspects of the Sun and space environment that affect life and society. The decadal survey recommended a notional mission, Geospace Dynamics Constellation (GDC), to provide global observations of the coupled atmosphere-ionosphere-magnetosphere system. GDC will be the first mission to address important questions on a global scale due to its use of a spacecraft constellation, thereby providing simultaneous multi-point observations. A Science and Technology Definition Team (STDT) was established as a subcommittee of the Heliophysics Advisory Committee (HPAC) in 2018 to refine the science objectives of GDC.

Finding: The GDC STDT, per their charge, was not permitted by NASA Headquarters to select a particular mission architecture to meet GDC science objectives. (Finding 3.28)

Recommendation 3.5: In order to proceed towards meeting the top-level decadal survey Living With a Star mission recommendation, NASA should take the steps necessary to define a specific mission architecture formulation and implementation scheme in order to release an Announcement of Opportunity for Geospace Dynamics Constellation within the next 3 years.

SPACE WEATHER APPLICATION RECOMMENDATIONS

> I believe we're on the threshold of a new era in which space weather can be as influential in our daily lives as ordinary terrestrial weather.
>
> —*NASA HPD 2002-2012 Director Richard Fisher, 2010*

The release of the *National Space Weather Strategy and Action Plan* (NSWAP; OSTP, 2019) in March 2019 has completely changed the landscape for space weather since the decadal survey was published. The NSWAP "identifies strategic objectives and high-level actions necessary to achieve a space-weather-ready Nation," clearly defines the roles for different agencies, and identifies the lead agencies, thereby enabling improved coordination. NASA and NSF play a key role by advancing the science behind space weather. NASA also has a responsibility to protect its spacecraft and astronauts in space. The agencies are actively working together to make progress on NSWAP goals. Nevertheless, the committee identified some opportunities for improved effectiveness of these activities. A critical missing piece in the current strategic planning is a roadmap that coordinates scientific activities and provides metrics for measuring progress. Such a roadmap is needed to outline how all of the agencies' programs work in concert to improve our predictive capabilities. Key missing pieces include a capability gap analysis based on prioritized science goals.

Finding: Currently, the combination of Advanced Composition Explorer (ACE) and Deep Space Climate Observatory (DISCOVR) in situ particle and field measurements at Lagrangian Point L1, the GOES solar extreme ultraviolet (EUV) imager and solar EUV and X-ray irradiance sensors at geostationary Earth orbit (GEO), the ground-based GONG network for solar magnetograms, and the Solar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronagraph (LASCO) at L1 provide the primary set of space weather monitoring assets, with support from Solar Dynamics Observatory (SDO) solar observations at GEO and STEREO solar and in-situ observations in an Earth trailing/leading orbit. NOAA has plans to continue in situ solar wind observations at L1, to establish new coronagraph observations at L1 and at GEO, and to continue their support of solar magnetograms in the GONG network. (Finding 4.3)

Finding: NASA and NOAA are conducting a dialogue with the European Space Agency (ESA) regarding participation in the Lagrange operational mission to the L5 location. NOAA has a formal agreement with ESA for their L5 mission, but no agreements are yet in place for NASA. Additional observations, platforms, and locations are informally discussed as a part of the ongoing agency and community interactions and communications relevant to the NSWAP. Coordination with India and China could further enhance space weather observations at the L1, L4, and L5 locations. (Finding 4.4)

Finding: The agencies can take advantage of commercial, interagency, and inter-divisional collaborations to make progress toward their space weather goals. To assure that this happens effectively, open data policies and standardized data interfaces need to be established. Inputs from the science community are critical for assessing how useful the commercial data are and assuring that the right data are accessible (and not merely higher-level derived products). (Finding 4.7)

Recommendation 4.1: In order to make efficient progress on the high-level goals in National Space Weather Action Plan, NASA should initiate an implementation roadmap for space-weather science and for capability transfer between research and operations (R2O and O2R) in collaboration with the National Science Foundation's Directorate for Geosciences and Directorate for Mathematical and Physical Sciences and their research communities. This document should identify and prioritize the science focus areas and the associated essential observables and data-driven space-environmental models that are critical to "significantly advance understanding and enable improved characterization and prediction of space weather" as part of the overall national space weather enterprise as well as for NASA's internal needs related to the exploration of space.

- The plan should reflect an assessment of key scientific and observational "capability gaps in the current space weather operational baseline."
- This plan should be developed in close consultation with NOAA as a representative of the space-weather user community and other agencies identified in the NSWAP.
- This plan should take advantage of reports that already exist in this area, and its formulation can make use of national advisory committees, the Committee on Space Research's (COSPAR's) space weather roadmap team, and other advisory entities.
- This plan, along with an associated budget, should be available as input to the next decadal survey in solar and space physics to further develop how the research programs at the different agencies can best work together to obtain the required space weather measurements and models.
- The agencies involved should have ongoing activity to guarantee a succession plan for continued acquisition of critical space weather diagnostics.

The previous heliophysics decadal survey was unable to fully integrate NOAA plans for space weather research and applications with the strategic plans for NASA and NSF. The NSWAP (2019) details many new aspects of integrated plans and coordination across many agencies but does not provide extra funding for implementing those plans. As NOAA is the key civil agency for space weather operations, it is imperative that the next decadal survey engage with NOAA in developing its space weather plans.

Recommendation 4.2: NOAA, along with other operational agencies, should develop notional budgets for space weather operations that would include identifying the need for new space weather funding lines required to fulfill the responsibilities added to their existing tasks by the National Space Weather Action Plan. This should be available as input to the next decadal survey.

HELIOPHYSICS CAREER ENHANCEMENTS

Diversity of thought, backgrounds, races, ethnicities, genders, and sexual orientations enables different environments that spark more innovation, stimulates more variety in problem solving for the science challenges, and thus achieves a broader range of creative outcomes. Diversity is an emerging element in some opportunities, such as in NASA HSCs and formerly in NSF's CISM (Center for Integrated Space Weather Modeling), and a few specific early-career research opportunities are supported by NSF and NASA. The committee identified five findings and one recommendation to enhance opportunities over the next 4 years that pertain to all career stages for scientists and engineers in the solar and space physics community. These findings are particularly important for early career scientists, although there is concern that enhanced successs for retention of early-career researchers could inadvertently reduce support for mid-career and senior researchers.

Finding. The effectiveness of grants issued by NSF and NASA for research in solar and space physics could be improved by:

- Shortening the cycle from proposal to funding availability. In some programs, and especially for younger scientists and postdocs, the cycle is too long.
- Adjusting the size of grants. Typical grants, while they have grown in size, are often too small or short-term to tackle the larger challenges. Larger grants may be more effective for some programs. On the other hand, smaller grants or "seed grants," with smaller proposals, quicker reviews, and shorter funding cycles, could invigorate new research directions and could be more supportive of early-career scientists. (Finding 5.1)

The committee notes that low selection rates of proposals overall tend to work in particular against early-career researchers. A portfolio of different magnitudes of grants, but given comparable award percentages per round, could address some of these concerns while maintaining flexibility and frequency in research opportunities.

Finding: The NSF and NASA ongoing education programs involving heliophysics summer schools, Research Experiences for Undergraduates (REU) programs, and student workshops offer opportunities for exposing undergraduates to space physics research, as well as hands-on training. There is great potential for the heliophysics community to significantly expand their involvement of undergraduate students by having more heliophysics-related REU programs. (Finding 5.2)

Finding: The infrastructure of large data archives and advanced numerical research and analysis tools is a critical element of modern-day science. Professional training on these rapidly evolving tools and modeling techniques is important for the health of heliophysics research programs. The development and maintenance of such tools is given insufficient attention in the development of roadmaps and strategic plans. These infrastructure components, and the teaching of their use, could be discussed on an equal footing with experimental hardware in the planning and budgeting of space- and ground-based observatories. (Finding 5.3)

Finding: Involving students in the development of spaceflight hardware for missions is key to the long-term success of developing the workforce for the U.S. space programs. Enhancing the number of partnerships between universities and non-university institutions and further increases in the number and frequency of small satellite missions are example pathways to train more students and early-career scientists and engineers for space missions. (Finding 5.4)

Finding: The participation and inclusion of individuals of different genders, races, cultures, and ages in positions of leadership roles in heliophysics (e.g., mission PIs) and for recognition (e.g., honors, awards) could better reflect today's societal makeup. For example, it has been shown that women and underrepresented minorities in science, technology, engineering, and mathematics (STEM) fields face consistent bias in proposal selections, hiring, salaries, observing time awards, paper citations, and prizes/awards. These all are relevant to scientific success, so these can affect career success at all stages and could limit contributions to the field from the diverse population.. (Finding 5.5)

Recommendation 5.1: NASA, NSF, and NOAA should develop strategic plans for the heliophysics community with goals and metrics to improve the diversity of race, gender, age, and country of origin. The next decadal survey should include a State of the Profession Panel, similar to the Astro2020 decadal survey. The State of the Profession Panel should have in advance the demographics and diversity survey data recommended in this report's Recommendation 6.2.

Some potential solutions for the diversity problem include the following:

- Adjusting the evaluation and selection methods for awarding proposals and observing time, such as dual anonymous reviews as one example;
- Incentivizing or requiring activities that increase diversity and inclusion, such as mentoring and apprenticeships to create a broader pool of possible mission and project PIs and reaching out to minority-serving universities to establish partnerships and recruit students; and
- Encouraging review panels, workshops, conferences, and other meetings to adopt explicit codes of conduct which remind all involved to respect civil, inclusive conduct in these activities.

PREPARING FOR THE NEXT HELIOPHYSICS DECADAL SURVEY

The committee has three recommendations for actions that could identify information pertinent for the next decadal survey. There are nine findings in Chapter 6 supporting these recommendations, but these are not listed in this summary. A stand-alone finding (Finding 6.10) on some emerging topics of interest for the next decadal survey committee to consider is listed here.

The process of preparing for decadal surveys has evolved since the last solar and space physics decadal survey, and lessons learned from the other science divisions could benefit Heliophysics strategic planning. For example, NASA-funded science definition and mission concept studies for the Planetary Science Division (PSD) and Astrophysics Division (APD), enabled them to prepare well in advance of their next decadal surveys. The PSD initially formed Assessment/Analysis Groups (AG) in different disciplines and science areas (e.g., Mars, Outer Planets) in 2004 to involve the community in defining/prioritizing targeted science goals, and formulating implementation plans before its next decadal survey.

The AGs function both as standing, inclusive science forums and as resources whose ongoing activities naturally lead to decadal survey and related "road mapping" and Science Definition Team (SDT) inputs. In another approach involving higher investment, the APD charged its Program Analysis Groups to solicit community input on a small number of compelling and executable strategic mission concepts. Both of these approaches enabled a broader range of institutions to participate in both science definition and mission concept development. NASA continues to support the AGs, whose current activities include preparation for the initiation of the third planetary science decadal survey, which will cover the period 2023-2032.

The NSF Mid-Scale Research Infrastructure (RI) program, which began in 2018, represents an important potential resource for heliophysics research that needs to be examined in the next decadal survey. The Mid-Scale RI program competition is NSF-wide and is thus highly competitive and expected to be over-subscribed. Prioritization of critical heliophysics goals and related Mid-Scale RI projects by the heliospheric community and by the next solar and space physics decadal survey could provide the needed justification for future Mid-Scale RI facilities.

Recommendation 6.1: NASA and NSF should implement and fund advanced planning for the next decadal survey that involves the community in strategic planning of the next decade science challenges, science goals, and related high-priority measurements, and that also considers stretch goals (ambitious objectives that might extend past the next decade). NASA and NSF could request the Space Studies Board's Committee on Solar and Space Physics to evaluate options for implementing this planning for the next decadal survey.

Some specific ideas for this advanced planning include the following:

- NASA-supported opportunities for the heliophysics community to host Assessment Group workshops in order to develop strategic science challenges and goals and to define high-priority measurements for the STP (Solar-Terrestrial Probe) and LWS (Living With a Star) programs in advance of starting the next solar and space physics decadal survey, and
- NSF-supported workshops to strategically plan the next decade science challenges and goals and to identify high-priority measurements for the Mid-Scale RI and other research infrastructure concepts with the heliophysics community.

The demographics and diversity of scientists and engineers in heliophysics may have evolved significantly since the last decadal survey. An important part of understanding and supporting those changes begins with a demographics and diversity survey of students and early-career scientists and engineers, followed by development of action plans to positively encourage continued growth of diversity for the science and engineering communities who support the science programs, missions, and facilities of NASA, NSF, and NOAA.

Recommendation 6.2: NASA Heliophysics Division should conduct a demographics and diversity survey before the next heliophysics decadal survey to understand how the community's demographics have evolved and to assess whether progress has occurred in enhancing diversity in the community (see also this report's Recommendation 5.1). Thereafter, to benefit all of the space science disciplines within NASA's SMD and to inform decadal survey planning across SMD, NASA at the SMD-level should conduct this demographics and diversity survey on a 5-year cadence with clear identification of science areas relevant for each science division. It is important that career survey specialists, such as the American Institute of Physics (AIP), are involved in a new survey.

Recommendation 6.3 outlines topics that could be considered by the agencies when defining the statement of task for the next decadal survey, with an underlying goal to help focus the decadal survey studies and to actively address the evolving strategic needs of the heliophysics community.

Recommendation 6.3: NASA, NSF, and NOAA, the anticipated principal sponsors of the next solar and space physics decadal survey, should work together to develop an integrated statement of task that reflects the research and application needs for each agency and

across the federal government. To address the evolving needs for science-driven strategic plans, the agency sponsors should ensure the following items are included as tasks for the next decadal survey committee:

- **Definition of distinct science goals and implementation strategies for NASA's Solar-Terrestrial Probes and Living With a Star programs,**
- **Evaluation of strategic plans with nominal (baseline) budget and optimal (best-case) budget,**
- **Inclusion of decision rules for guiding implementation of recommendations, and**
- **Identification of enabling technology needed in the coming decade to support longer-term stretch goals.**

The 2015 National Academies report *Space Science Decadal Surveys Lessons Learned and Best Practices* (NASEM, 2015) considered the lessons learned from previous surveys and presented options for possible changes and improvements to the process. Suggestions for improvement or change included the statement of task, advanced preparation, organization, and execution. Based on an examination of this report, and as a result of its own deliberations, the midterm assessment committee offers the following for consideration in advance of the next decadal survey in solar and space physics:

Finding: The next solar and space physics decadal survey committee could consider the following important topics:

- Trade study on SMEX/MIDEX AO cadence versus number of missions selected per AO,
- Expansion of the HSO concept to include NSF's ground-based facilities and many upcoming SmallSat science missions,
- Identifying critical measurements in the current NASA and NSF facilities for future system-science plans and how to continue such observational capabilities,
- Better integrated approach for including the science of space weather within NASA and NSF to improve space weather predictability,
- Engaging NOAA in developing space weather research and applications for the next decadal survey,
- Improving the multi-agency and international coordination of heliophysics research and space weather applications,
- NASA cross-divisional opportunities for exoplanetary-planetary, astrospheric-heliospheric, solar-stellar, and atmosphere-Earth science research and development of a prioritized strategy for implementing such cross-disciplinary research,
- Consolidation of ground-based solar, heliospheric, and space weather science could be better supported within a new division under a single directorate at NSF,
- NSF improving and broadening its structure for heliophysics research (e.g., outer heliosphere and planetary science elements are currently missing),
- NSF improving the cost effectiveness of the operations of their solar ground-based observatories, such as by sharing data analysis tools and data centers,
- Evaluating the mission class requirements for NASA's Explorer program,
- Identifying viable structural solutions to better support the heliophysics research grant programs, with particular emphasis on early-career scientists and soft-money scientists (those who are not professors or government employees), and
- Better inclusion of emerging computer, data, and cloud technology and practices. (Finding 6.10)

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1

Introduction to Heliophysics and the 2013 Decadal Survey

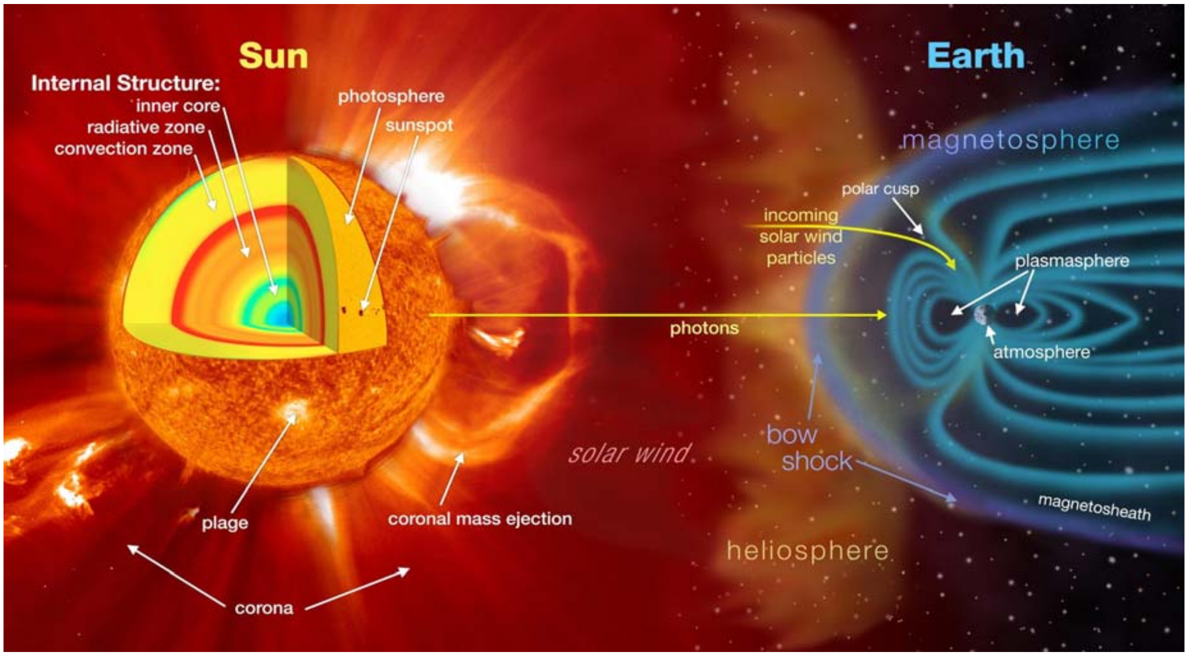
1.1 HELIOPHYSICS SCIENCE INTRODUCTION

Heliophysics is the study of our star, the Sun, its influences on the planets of our solar system, and its interaction with interstellar space (Figure 1.1). The region of space influenced by the Sun, called the heliosphere, extends past Pluto's orbit into the local interstellar medium. Filled with plasma (ionized gas) and neutrals (non-ionized gas) and threaded by the magnetic fields of the Sun and the magnetized planets, the heliosphere and the planetary atmospheres within provide a rich laboratory for studying neutral and plasma processes, dynamics (waves), and interactions that occur throughout the universe. Heliophysics is a discovery science that is deeply connected to questions of life and habitability and thus embodies fundamental questions about the origin and fate of habitable planetary environments. The influence of these processes is increasingly important here on Earth as our society becomes more dependent on technologies that are impacted by space weather. This important aspect of heliophysics research focuses on understanding the science behind the solar and lower-atmosphere influences on Earth's upper atmosphere, the near-Earth space environment, and the space weather effects that can disrupt our satellite, communication, navigation, and power grid technologies. A number of resources are available to learn more about the field of heliophysics (Box 1.1).

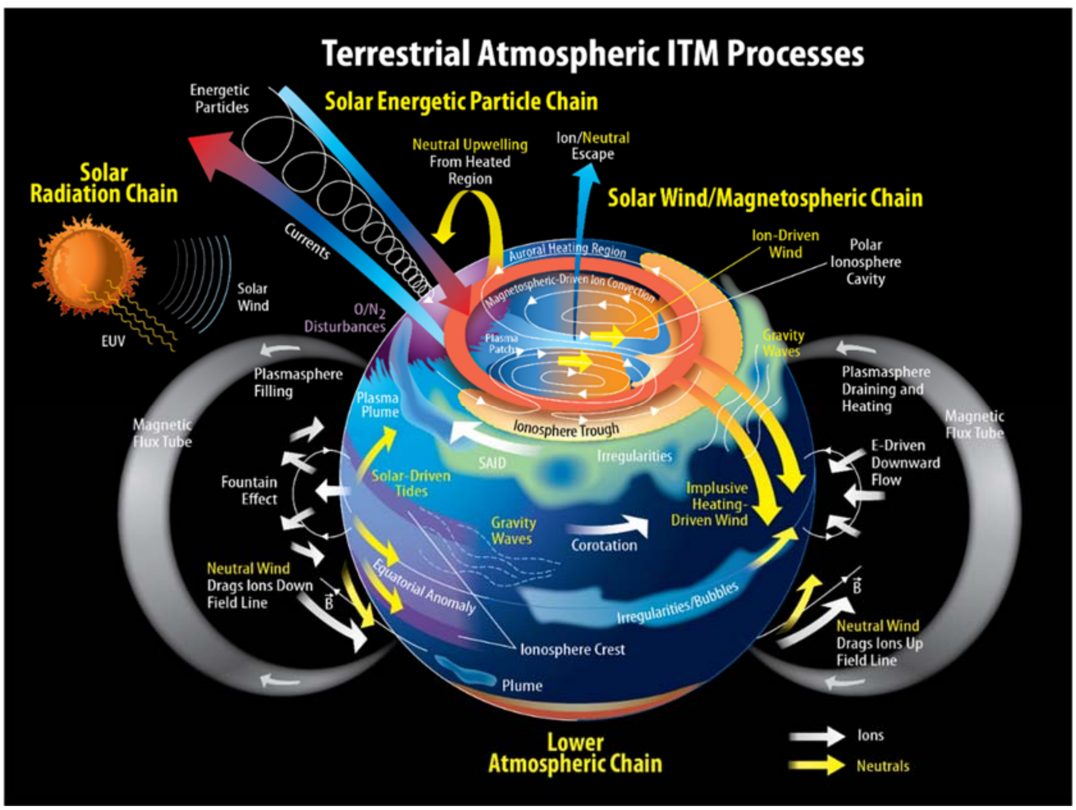
As shown in Figure 1.1a, the Sun consists of several layers: an inner core, the surrounding convection zone, the photosphere that is its visible surface, and its highly ionized atmosphere, which ultimately becomes the solar wind. The solar wind plasma reaches supersonic speeds at a distance of a few solar radii from the Sun. From there, the solar wind carries its energy and momentum through interplanetary space, interacting with the magnetic fields, atmospheres, or surfaces of solar system bodies along the way.

Earth's extended magnetic field in space, known as the magnetosphere, is shaped by the solar wind, which compresses Earth's intrinsic dipole magnetic field on its sunward side and elongates it on the nightside to produce the magnetotail. Earth's upper atmosphere, consisting of the ionosphere, thermosphere, and mesosphere at about 50-500 km above ground, makes up the inner boundary of the magnetosphere. The ionosphere, thermosphere, and mesosphere serve as the critical link between external particle and energy inputs related to the solar wind interaction with the magnetosphere and the lower atmosphere from which waves generated in the troposphere near Earth's surface have propagated upward (Figure 1.1b). At the same time, the thermosphere acts as a natural thermostat for Earth's upper atmosphere by radiating away excess energy received from the Sun into space.

(a)


Sun
Internal Structure:
inner core
radiative zone
convection zone
photosphere
sunspot
plage
coronal mass ejection
corona
photons
solar wind
Earth
magnetosphere
polar cusp
incoming solar wind particles
plasmasphere
atmosphere
bow shock
magnetosheath
heliosphere

(b)


Terrestrial Atmospheric ITM Processes
Solar Energetic Particle Chain
Energetic Particles
Solar Radiation Chain
Neutral Upwelling From Heated Region
Ion/Neutral Escape
Solar Wind/Magnetospheric Chain
Currents
Solar Wind
EUV
O/N2 Disturbances
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Ion-Driven Wind
Polar Ionosphere Cavity
Plasma Patch
Gravity Waves
Plasmasphere Filling
Plasma Plume
Ionosphere Trough
Plasmasphere Draining and Heating
Magnetic Flux Tube
SAID
Irregularities
E-Driven Downward Flow
Fountain Effect
Solar-Driven Tides
Implusive Heating-Driven Wind
Gravity Waves
Corotation
Neutral Wind Drags Ions Down Field Line
Equatorial Anomaly
Irregularities/Bubbles
Neutral Wind Drags Ions Up Field Line
Ionosphere Crest
Plume
Lower Atmospheric Chain
Ions
Neutrals

(c)

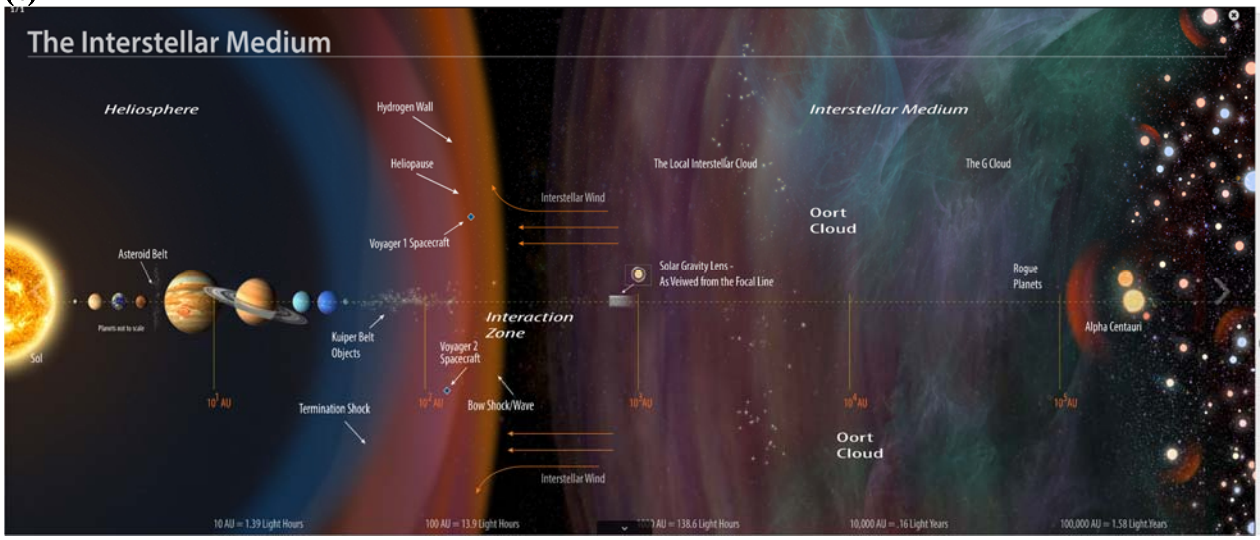


FIGURE 1.1 Heliophysics overview. Heliophysics research includes (a) all aspects of solar physics, the propagation of solar photons, solar wind, and energetic particles throughout the solar system, (b) the dynamic conditions and interactions in planetary magnetospheres, ionospheres, and thermospheres, and (c) the interactions of the heliosphere with the interstellar medium. SOURCE: (a) http://svs.gsfc.nasa.gov/30481, courtesy of NASA Goddard Space Flight Center; (b) https://svs.gsfc.nasa.gov/vis/a010000/a012900/a012960/TerrestrialAtmosITMProcesses.jpg, courtesy of NASA Goddard Space Flight Center; (c) https://www.nasa.gov/sites/default/files/thumbnails/image/newinterstellarmedium_art.jpg, courtesy of NASA.

BOX 1.1 Resources for More Information on Heliophysics Science

A number of resources are available to learn more about the field of heliophysics. The UCAR-NASA-NSF Heliophysics Summer School program has produced a series of textbooks, laboratories, and other materials.[1] The MetEd COMET program has provided a set of education modules about space weather as well as basic space physics concepts.[2] In addition, there are some popular science books about space weather (e.g., *Storms from the Sun* [Carlowicz and Lopez, 2002]). Finally, there are a number of traditional textbooks (e.g, *Introduction to Space Physics* [Kivelson and Russell, 1995]; *Basic Space Plasma Physics* [Baumjohann and Treumann, 1996]; *Understanding Space Weather and the Physics Behind It* (Knipp, 2011]; *Space Physics: An Introduction* [Russell et al., 2016]; and *The Sun from Space* [Lang, 2016]).

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[1] See https://cpaess.ucar.edu/heliophysics/resources.
[2] See https://www.meted.ucar.edu/index.php.

The ionosphere and thermosphere are also sources of magnetospheric material and are a load on the solar wind "driving" of the coupled magnetosphere-ionosphere-thermosphere system. Magnetic storms and auroral activity, including their effects on the radiation belts and ionosphere, are some of the more widely known aspects of the highly variable solar wind-magnetosphere interaction. Chains of heliophysics processes are involved in producing such outcomes, including complex physical couplings of the already complex subsystems that make up our natural environment in space.

At the furthest reaches of the heliosphere, the distant solar wind mingles with interstellar gas and dust before coming to a stop at a boundary called the heliopause (Figure 1.1c). Recently, Voyager 2, a NASA spacecraft launched in 1977 that flew by Jupiter and Saturn before becoming the first (and only) spacecraft to fly by Uranus and Neptune, crossed this boundary, more than 18 billion km from Earth. Here galactic cosmic rays are both entering the heliosphere from outside the solar system and being energized by ambient particle populations. These highly energetic cosmic rays have important space weather implications for exploration beyond our home planet.

1.2 FUNDAMENTAL PHYSICAL PROCESSES IN HELIOPHYSICS

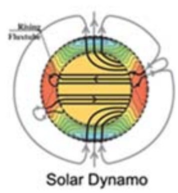
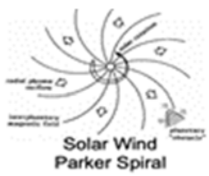
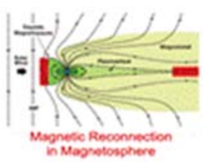
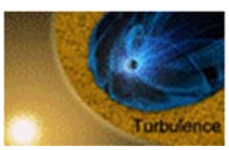
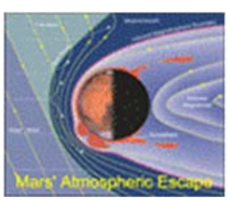
Heliophysics research provides an opportunity to explore fundamental plasma processes that also have important applications in laboratory plasma physics and for other astrophysical systems. Six fundamental, universal processes were discussed in *Solar and Space Physics: A Science for a Technological Society* (NRC, 2013), the second National Academies of Sciences, Engineering, and Medicine decadal survey in solar and space physics, or heliophysics (hereafter 2013 decadal survey)—as listed in Table 1.1: dynamos, magnetic reconnection, solar and planetary winds, collisionless shocks, turbulence, and plasma-neutral interactions. Each of these is briefly described in this section, and a few examples of recent research results are highlighted in Chapter 2 to further elucidate some of these fundamental processes.

Dynamos

The level of solar activity is primarily due to the Sun's response to its internal dynamo cycles. The dynamo produces complex patterns of magnetic fields, including sunspots, that both structure the Sun's corona and solar wind, and lead to flaring and the eruptive activity called coronal mass ejections (CMEs)—giant transient expulsions of plasma and magnetic field that drive energetic particle-producing interplanetary shock waves. Dynamos are also active in other stars, producing star spots and stellar activity that influences the space environments of exoplanets. The first observation of a CME from another star was recently made with the Chandra X-ray Observatory (Argiroffi et al., 2019).

Uncovering how internal solar couplings drive dynamo cycles and how that dynamo leads to the phenomena at the solar surface are among the most challenging problems in heliophysics. The dynamo occurs deep within the Sun, hidden from direct observation. The tool of helioseismology provides access to some of the deep large-scale flows involved, but even this powerful diagnostic cannot probe the relatively small scale of convective motions, and helioseismology has not yet been able to measure the slow circulation known as the "meridional flow" at depth considered essential in transporting magnetic field across latitude. The solar dynamo problem requires an intrinsically multidisciplinary approach: development of a comprehensive, first-principles numerical model of the solar dynamo that (1) requires sustained investment in state-of-the-art computational means, (2) will benefit from the development of multi-perspective long-term helioseismology, and (3) needs multiyear observations of a substantial sample of Sun-like stars to test and validate the forecast capability of any dynamo model within years rather than the decades needed if only the Sun were used.

TABLE 1.1 Six Universal Processes as listed in 2013 Solar and Space Physics (Heliophysics) Decadal Survey

Universal Process		Description
	**Dynamos**	Process that creates and transports magnetic field. Important for 11-year solar activity cycle, generation of electric field in Earth's polar regions, and magnetic activity in stars and galaxies.
	**Solar and Planetary Winds**	Process of heating and ejecting particles from an atmosphere. Important for the solar wind, Earth's ionosphere wind into the magnetosphere, and stellar wind.
	**Magnetic Reconnection**	Process of magnetic field of opposite direction annihilating each other to explosively convert magnetic energy into heat, radiation, and energetic particles. Important for solar flares, coronal mass ejections, driver for substorms in Earth's magnetosphere, stellar flares, and astrophysical jets.
	**Collisionless Shocks**	Shock waves are formed in the transition from supersonic to subsonic flow, which then heats the plasma and accelerate particles. Important for planetary bow shocks, interplanetary shock waves, supernova shocks, and galaxy collisions.
	**Turbulence**	Process of plasma interaction that heats the plasma and accelerates particles. Important for heating the solar corona, driving plasma transport in Earth's magnetosphere, and facilitating accretion disk formation around stars and planets.
	**Plasma-Neutral Interactions**	Process of ionized plasma (charged) and neutral particles (uncharged) interacting to increase ionization and direct outflows. Important for heating in the solar chromosphere, enhanced ionization in Earth's ionosphere/thermosphere, interaction of solar wind with the interstellar medium, planetary atmospheric escape, and structuring in astrophysical molecular clouds.

SOURCE: Figures (top to bottom) from https://figshare.com/articles/Schematic_of_the_Solar_Dynamo/102094, courtesy of Paul Higgins; https://pwg.gsfc.nasa.gov/istp/outreach/images/Gusts/windsprl.jpg, courtesy of NASA Goddard Space Flight Center; https://mms.gsfc.nasa.gov/images/science_page/science_1_lg.png, courtesy of NASA Goddard Space Flight Center; https://www.bu.edu/blazars/BLLac.html, courtesy of Wolfgang Steffen, UNAM; https://svs.gsfc.nasa.gov/vis/a010000/a012900/a012901/MMS_Poster_Turbulence_v8_Cropped.jpeg, courtesy of NASA Goddard Space Flight Center/Mary Pat Hrybyk-Keith; see R. J. Lillis, D.A. Brain, S.W. Bougher, F. Leblanc, J.G. Luhmann, B.M. Jakosky, R. Modolo, et al., Characterizing Atmospheric Escape from Mars Today and Through Time, with MAVEN, *Space Science Reviews* 195:357-422, courtesy of S. Bartlett and D. Brain.

Earth's ionosphere exhibits several neutral wind dynamo processes that at high latitudes generate large-scale electric fields which affect the magnetosphere. Electric fields generated at low latitudes through the wave-driven E-region dynamo are the primary mechanism by which meteorological weather at the surface, such as El Niño, is imprinted upon the space weather of the ionosphere and thermosphere, leading to very large variations in plasma densities generated by solar radiation. The same dynamo-driven waves are fundamental to all planetary atmospheres, especially so for planets with strong magnetic fields like Jupiter, thus heliophysics research results are important for comparative planetary studies (Bagenal, 2013). For example, these waves are very prominent on Mars as observed by the Mars Reconnaissance Orbiter (MRO) and Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft. Significant challenges to understanding neutral wind dynamo effects exist—for one, single satellites inherently lack the local time resolution to resolve the ionospheric imprints of day-to-day weather variability. The neutral wind dynamo problem requires a suite of complementary electric field, plasma, and neutral wind measurements from multi-point spatial and local time perspectives, which only constellations can provide, to constrain models and to close the loop on the weather-space weather connection.

Solar and Planetary Winds

Ion and electron "winds" or outflows occur from both stars, including our Sun, as well as from planets with significant atmospheres. These winds can be driven by radiative heating at the base of the atmosphere, which can even cause neutral gas to participate. Other means of energy transfer involving often multi-stage, complicated processes are also possible. The solar wind was originally conceived as an exosphere-like expansion of the heated, mainly ionized hydrogen corona into the heliosphere. However, even the earliest observations of solar wind in the 1960s indicated that much of its behavior is fluid-like, and that magnetohydrodynamic (MHD) and plasma waves are involved in both its initial creation as well as its heliospheric evolution. In addition, the Sun's structured coronal source regions produce streams of different speeds, densities, and compositions that interact as they move outward from the rotating Sun. Transient variations in the solar magnetic field significantly affect the solar wind in the ecliptic plane over a wide range of temporal and spatial scales. During times of high solar activity, the solar wind can be dominated by transient outflows, including the massive outbursts—CMEs. Thus, there is a variety of solar wind behaviors whose physical underpinnings continue to challenge researchers, even as new observations and physics-based modeling allow us to better understand the underlying processes. Meanwhile, inferring stellar wind properties of other stars from much more limited observational information is still in its infancy.

By contrast, the light gases escaping from a planet's atmosphere, also known as planetary winds, are much more quiescent outflows but are potentially key to understanding to what extent, and how, the Sun transfers energy to planetary atmospheres via nonradiative processes. While planetary upper atmospheric gases, especially lighter species, can escape via atmospheric expansion due to thermal pressure gradients, observations (especially at Earth) show that other processes also energize heavier ions in the upper atmosphere at high latitudes, leading to heavy ion outflows. These ion winds can affect the magnetosphere by providing a source of heavy ions that influence its response to both external driving by the solar wind interaction and its internal dynamics. For example, on Earth, waves caused by auroral precipitation or solar wind energizes oxygen ions in the high latitudes. Oxygen ions are driven upward by diverging magnetic fields, where they can escape and populate the outer magnetosphere. These ions then become a major component of the geomagnetic storm ring current. In planetary settings where a magnetosphere is weak or absent, similar energized ion outflows occur. In all cases, they contribute to the loss of atmospheric gasses over time, with possible profound effects on geological time scales. Required for these winds are processes that can accelerate the charged particles to be faster than the escape velocity, which is about 10 km/s for Earth and about 600 km/s for the Sun. Both experimental and theoretical research continues to provide new insights into these diverse ion wind-generating settings.

Magnetic Reconnection

The generation and evolution of the magnetic field of the Sun is driven by its dynamo, but magnetic reconnection is the process that causes explosive events. During magnetic reconnection, magnetic fields embedded in a plasma change their topology and, in the process, release enormous amounts of energy. Reconnection is the fundamental process responsible for solar flares and CMEs, for the dynamic coupling of the solar wind to the near-Earth space environment, and the ultimate driver for space weather. It is also thought to be responsible for many explosive phenomena in astrophysical plasma environments, such as acceleration of astrophysical jets, pulsars, and possibly gamma-ray bursts and cosmic ray acceleration (e.g., Lazarian et al., 2014; Zweibel and Yamada, 2009). On Earth, understanding magnetic reconnection is critical for realizing successful magnetic confinement schemes for energy-producing fusion devices. However, the scale of laboratory plasmas is too small to make detailed measurements of magnetic reconnection. Only in space can we probe the region where magnetic reconnection occurs. The near-Earth environment is the only practical place in the solar system where we can study the microphysics of this universal process.

Another area of broad interest, particle acceleration, is ubiquitous throughout the universe. Close to home, on the Sun and in Earth's and other planetary radiation belts, we can learn how particles get accelerated to ultra-relativistic energies. In fact, some 50 percent of the energy released during a solar flare magnetic reconnection event goes into the acceleration of particles. In ground-level-events (GLEs), giga-electron-volt protons generated near the Sun in connection with some fast CMEs produce secondary radiation signatures in distributed neutron monitor networks over wide swaths of Earth's surface. Both shocks in the plasmas and reconnection are possible contributors. Understanding these processes may shed light on particle acceleration in other corners of the universe such as in black holes and pulsars.

Collisionless Shocks

Shocks are formed when the relative speed of an object in a medium is faster than the sound speed of the medium. For example, in a neutral fluid, any disturbance, like that produced by a flying plane, causes a compression of air—a sound wave—to propagate in the medium. When the speed of the plane reaches the sound speed and becomes supersonic, it overtakes the compression wave front resulting in rapid change of state—a shock, which can be heard as a sonic boom. The upstream and downstream properties of the fluid through the shock are different, and the state of the downstream fluid is not constant but continuously changes to reach the new equilibrium state. In neutral fluids, the thickness of the shock is determined by the distance between collisions of the fluid particles.

There are fundamental differences between shocks in neutral fluids and in magnetized plasmas such as the solar wind or interstellar medium. The planetary bow shock that forms in front of magnetized planets is an example of a collisionless shock, where the thickness of the shock is much less than the distance between collisions of the plasma particles. Instead of collisions, the particles at collisionless shocks communicate by electromagnetic fields. These interactions are fundamentally responsible for the deceleration, compression, and heating of the magnetized plasma downstream of the shock.

Interplanetary shock waves arise due to CMEs moving faster than the surrounding medium (i.e., the solar wind) by more than the sound speed. Various wave-particle interactions in the shocked region of the CME accelerate the particles. Due to their common occurrence in the universe, collisionless shocks can be considered as universal particle accelerators. For example, they occur in the interstellar medium when a star reaches the end of its life cycle and explodes as a supernova as well as in the accretion process at the edge of galaxy clusters. These shocks are responsible for the generation of extremely energetic particles, galactic cosmic rays (GCRs), which can reach Earth more easily during the solar minimum when the Sun's magnetic field offers less protection. Recent heliophysics missions (e.g., NASA's THEMIS and MMS or the European Space Agency's Cluster) have made it possible to probe the bow shock with in situ, multi-point measurements. Such measurements help us better understand the shock structure and physics responsible for particle acceleration processes during varying solar wind conditions and space weather events. Understanding shock-driven acceleration processes from a basic physics perspective is essential for the better prediction of the energetic particle environment and for keeping technological societies safe at Earth, and eventually perhaps the Moon, Mars, and beyond.

Turbulence and Instabilities

Another fundamental process in heliophysics is related to plasma turbulence, instabilities, and associated cross-field transport. These are also critical topics for building more stable laboratory plasma experiments and fusion devices. For example, one advance for steady-state operation of a tokamak fusion device is suppression of the plasma instabilities near the plasma boundary by introducing small-scale magnetic ripples that disrupt the formation of larger scale instabilities (Nazikian et al., 2018). Further investigations of natural plasma turbulence in the solar wind and in Earth's magnetosphere could provide important input to these laboratory problems. Furthermore, the key roles of turbulence in Jupiter's vast magnetosphere, as learned from NASA's Juno mission (Clark et al., 2018), are applicable for comparison to solar atmosphere turbulence.

The stability of an environment determines if small perturbations are damped out or grow to large amplitudes. Plasma instabilities can grow due to sources of free-energy in the system. Turbulence is ubiquitous in the ionosphere where it is largely driven by atmospheric waves that are themselves a universal process in planetary atmospheres. In the heliosphere, free-energy sources are ubiquitous including, for example, magnetic shear, velocity shear, and gravity acting on a density gradient. Velocity shear–driven Kelvin-Helmholtz instability (KHI) has been observed at the magnetopause/ionopause of most planets in the solar system and can lead to the formation of flow vortices and the onset of turbulence. Secondary instabilities and processes (e.g., magnetic reconnection) can occur within these vortices, which can lead to plasma transport. Small-scale turbulence and wave-particle interactions are important for plasma heating and producing anomalous resistivity, which can lead to violation of frozen-in conditions in collisionless reconnection. In the ionosphere, electrons heated by electrojet turbulence lower the electric potential across the polar-cap and thus impact magnetosphere-ionosphere coupling, such as increasing the peak pressure in the inner magnetosphere. Thus local, small-scale processes can have global implications that affect the entire magnetosphere.

Plasma-Neutral Interactions

Plasma-neutral interactions can be thought of as a unique physics domain present throughout the sun's heliosphere, where neutral particles and charged particles collisionally interact in a manner that influences the behavior and structure of both neutral and plasma states. These interactions produce phenomena and variability unique to this environment. In our solar system, plasma-neutral interactions exist within the ionosphere-thermosphere-mesosphere (ITM) regions of planetary atmospheres and also at the boundary of the solar system with the local interstellar medium, and within the solar chromosphere and prominences, where transitions between strongly neutral and strongly ionized plasma in magnetic environments are common. There is also important plasma-neutral interactions at a larger scale with the moons embedded in Jupiter's vast magnetosphere. An even broader net is cast in astrophysics, where plasma-neutral interactions play a key role in defining protostellar discs, galactic molecular clouds, exoplanet atmospheres, stellar atmospheres, and dusty plasmas of comets (Ballester et al., 2018).

Plasma-neutral interactions in planetary systems occur in the transition region where outer space interacts with the gaseous envelope of the planet, forming an energy terminus in the chain of stellar-planetary interactions. This energy terminus forms the basis of "space weather" in Earth's geospace system with plasma-neutral interactions playing a critical role in spawning ITM variability that continues to limit predictability and plague our space assets. That one of the most complex examples of plasma-neutral interactions — Earth's ITM — is readily accessible to all modern research tools for investigation offers an extraordinary opportunity not only to advance understanding of Earth, but to expand knowledge of the nature of plasma-neutral interactions everywhere.

For objects with dense gases at their visible surface (the Sun, stars, the giant planets of our solar system, and exoplanets), investigation of variability in their weakly or partially ionized environments (i.e., regions within which plasma-neutral interactions are operative) includes direct ion-neutral momentum coupling, photochemistry between both neutrals and ions, and plasma transport. A further complex source of variability occurs for worlds where surface topology modulates upwardly directed–wave energy and transfers that energy by coupling from neutrals to plasmas. Earth, Venus, Mars, and Titan are specific examples of this additional complexity. Further complexities occur in the presence of a strong intrinsic geomagnetic field that communicates distant and disparate fields and waves from the plasma to the neutral gas through plasma-neutral interactions; Earth, Saturn, and Jupiter are examples of planets whose upper atmospheres are magnetically influenced in this way, as are stellar atmospheres.

These six fundamental, universal processes are examples of the many complex processes important in understanding heliophysics. Rarely is a single process the only key process; instead, the different processes are in play all the time, and features of a specific process can be revealed more clearly during specific events or with specialized instrumentation or observational configurations (e.g., multiple views of the same observation). The complexity of interacting processes requires a system-level approach for many of the research topics in heliophysics. A few of these research topics are further discussed in Chapter 2.

1.3 CURRENT HELIOPHYSICS MISSIONS AND MAJOR PROGRAMS

Heliophysics research is broadly supported by NASA's Heliophysics Science Division, NSF's Geospace Section of its Division of Atmospheric and Geospace Sciences (AGS), and NSF's Division of Astronomical Sciences (AST). Space weather, which is often considered an applied part of heliophysics, is supported by those science divisions as well as space weather operations that are led by the NOAA Space Weather Prediction Center (SWPC) and Air Force Weather Agency (AFWA). Furthermore, the National Space Weather Program (NSWP) has facilitated collaborations between 10 federal agencies, industry, and the academic community to provide improvements in the capabilities of space weather services (Bonadonna et al., 2017). The current NASA and NOAA missions and NSF major facilities and programs are summarized here to provide context on the resources needed for heliophysics research and space weather operations.

There are currently 19 NASA research missions, encompassing 26 spacecraft, that are operating as of October 2019 (see Figure 1.2 and Table 1.2), and there are 5 missions being prepared for launch in the next 5 years. Strategic missions are funded through the Solar-Terrestrial Probes (STP) Program, which focuses on fundamental physical processes, and the Living With a Star (LWS) program, which focuses on those aspects of heliophysics science that may affect life and society. Smaller missions are developed as part of the Explorers program, which includes medium-class explorers (MIDEX), small explorers (SMEX), and missions of opportunity (MoOs). NASA Heliophysics Division also has dozens of CubeSats, rockets, and balloon experiments that are not included in the Table 1.2 list.

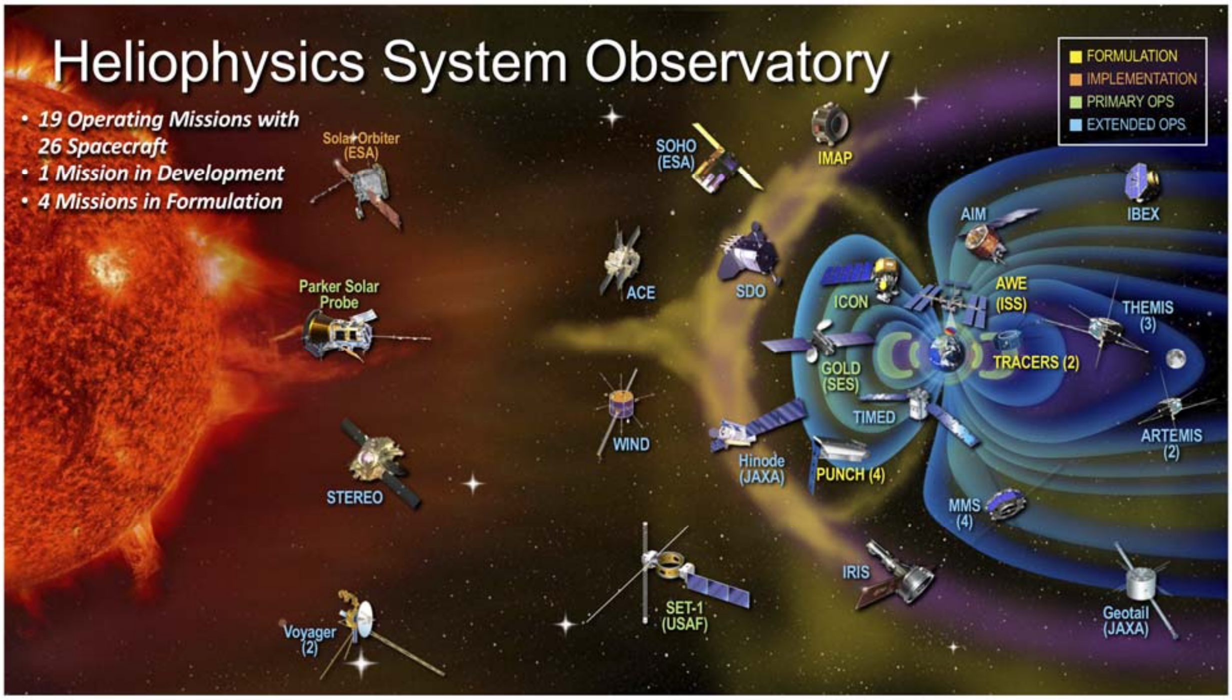


FIGURE 1.2 NASA Heliophysics System Observatory (HSO). The HSO includes 19 missions in operations as of November 2019. Five more missions to be launched before 2024 are LWS-ESA Solar Orbiter, STP IMAP, SMEX PUNCH, SMEX TRACERS, and SALMON AWE. SOURCE: https://svs.gsfc.nasa.gov/vis/a030000/a030800/a030822/HELIO_FLEET_20190220_print.jpg, courtesy of NASA Goddard Space Flight Center.

In addition to missions, NASA has research programs for data analysis, theory, and computational studies. The majority of these are program elements of the annual ROSES (Research Opportunities in Earth and Space Science) call. Examples include Heliophysics Guest Investigator (HGI), Heliophysics Supporting Research (HSR), Heliophysics Theory, Modeling and Simulations, LWS Science, and Heliophysics Technology and Instrument Development for Science (H-TIDeS) program elements. These programs play a vital part in addressing NASA's Heliophysics science goals and maximizing the science return from the Heliophysics missions.

There are currently 19 NSF facilities and programs operating as listed in Table 1.3. Many of these facilities and laboratories have been in operation for decades. The more recent observatory developments include the Atacama Large Millimeter Array (ALMA), Low-latitude Ionospheric Sensor Network (LISN), Expanded Owens Valley Solar Array (EOVSA), and Daniel K. Inouye Solar Telescope (DKIST). NSF facility investments have been shifting toward distributed facility concepts, often involving cost-effective opportunistic networks (e.g., Global Positioning System [GPS], SuperMAG, and Active Magnetosphere and Planetary Electrodynamics Response Experiment [AMPERE]), as illustrated in Figure 1.3. NSF supports scientific research through its open grant program and focused-topic grants through Geospace Environment Modeling (GEM), Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR), and Solar Heliospheric and Interplanetary Environment (SHINE). NSF also supports annual GEM/CEDAR/SHINE workshops that enable community organization and collaboration and have a significant educational impact. For example, in 2018, 73 graduate students attended GEM, 68 of whom received full support from NSF to attend the meeting.[3]

[3] Data taken from GEMStone, Volume 29, No. 1, http://spc.igpp.ucla.edu/gem/GEMstone/GEMstone_Vol29_No1.pdf.

TABLE 1.2 List of NASA Heliophysics Mission Currently Operating in 2019

MISSION	OVERVIEW	Launch Date	End of Prime Mission (duration)	Class of Mission	AIMI	SWMI	SHP
Voyager 1 & 2	Planetary Probes that are beyond the boundary of the heliosphere	8/20/77	1986 (encounter with Uranus)	Planetary Flagship		X	X
Geotail	Measuring global energy flow and transformation in the magnetotail	7/24/92	1994 (2 years)	STP		X	
Wind	A comprehensive solar wind laboratory in space	11/1/94	1996 (2 years)	STP		X	
SOHO	Solar and Heliospheric Observatory (ESA / NASA mission at L1)	12/2/95	1997 (2 years)	Flagship		X	X
ACE	Advanced Composition Explorer, provides Sp Wx products	8/25/97	2002 (5 years)	Explorer		X	
THEMIS (3 S/C) ARTEMIS (2 S/C)	Time History of Events and macroscale Interactions during Substorms (THEMIS with 5 S/C) and then 2 spacecraft repurposed in 2011 for Acceleration, Reconnection, Turbulence & Electodynamics of Moon's Interaction with the Sun (ARTEMIS)	2/17/07	2009 (2 years)	MIDEX		X	
TIMED	Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) mission	12/7/01	2003 (1.5 years)	STP	X		X
Hinode (Solar-B)	Japanese for "Sunrise", Joint JAXA/NASA mission to study the Sun	9/22/06	2009 (3 years)	STP			X
STEREO	Solar Terrestrial Relations Observatory (original 2 S/C, 1 in operation now)	10/26/06	2008 (2 years)	STP		X	X
AIM	Aeronomy of Ice in the Mesosphere	4/25/07	2009 (2 years)	SMEX	X		
IBEX	Interstellar Boundary Explorer	10/19/08	2010 (2 years)	SMEX		X	X
SDO	Solar Dynamics Observatory, in GEO to study the Sun	2/11/10	2015 (5 years)	LWS			X
IRIS	Interface Region Imaging Spectrograph to study the Sun	6/27/13	2015 (2 years)	SMEX			X
MMS (4 S/C)	Magnetospheric Multiscale, formation flying 4 S/C	3/15/15	2017 (2 years)	STP		X	
GOLD	Global-scale Observations of the Limb and Disk, in GEO	1/25/18	2020 (2 years)	MOO	X		
Parker Solar Probe	Previously Solar Probe Plus, a mission with closest approach to the Sun	8/12/18	2025 (7 years)	LWS		X	X
SET-1	First in series for Space Environment Testbed (SET) to characterize the harmful space environment, in MEO	6/25/19	2020 (1 year)	LWS		X	
ICON	Ionospheric Connection Explorer (ICON) is in LEO with low inclination to study the equatorial ionosphere	10/10/19	2021 (2 years)	Explorer	X		

Of the 19 NASA missions, four are in prime mission (green highlight) and 15 missions are extended. Note that there was a period in 2017-2018 when there were no prime missions for NASA Heliophysics Division.

Although the NSWP is spread across 10 federal agencies, the midterm assessment committee focus is on the agencies that conduct space weather research and whose roles in the NSWP were examined by the decadal survey committee: NASA, NSF, and NOAA. The key NOAA space weather observations include their Geostationary Operational Environmental Satellites (GOES) series in GEO, the Space Environment Monitor (SEM) on NOAA POES polar satellites, and the Deep Space Climate Observatory (DSCOVR) at the Lagrange point 1 (L1) location. NOAA also supports space weather observations from the NSF GONG ground network for solar magnetic fields and the NASA ACE satellite for L1 solar wind data. NOAA has a future Space Weather Follow-On (SWFO) mission planned for L1 with a launch in Fall 2024 with NASA's IMAP mission. NOAA is also considering space weather operations at L5 (east view of Sun) with potential partners of ESA and NASA. In addition, NOAA's COSMIC-2 (Constellation Observing System for Meteorology, Ionosphere, and Climate) with its six-satellite constellation for radio occultation measurements provides space weather products about the total electron content (TEC) in Earth's ionosphere.

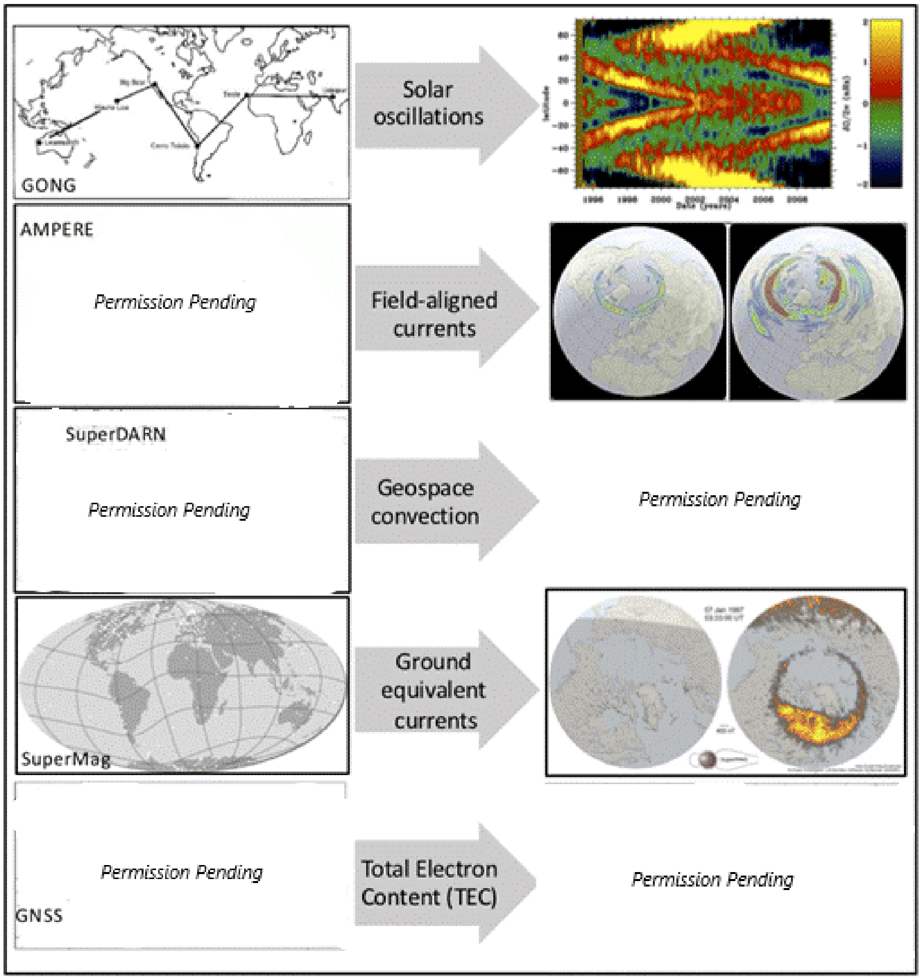


FIGURE 1.3 Recent investments by the National Science Foundation in distributed facility concepts responds to the need for global information to complement the detailed regional measurements provided by traditional monolithic facilities (e.g., DKIST, Advanced Modular Incoherent Scatter Radar [AMISR]). New enabling data products include solar oscillations via interferometry (Global Oscillation Network Group, GONG), magnetic field–aligned currents derived from the Iridium satellite constellation (AMPERE), ionospheric convective circulation from High Frequency (HF) radar networks (SuperDARN), geomagnetically induced currents derived from magnetometer networks (SuprMAG), and ionospheric total electron content (TEC) from opportunistic signals used by Global Navigation Satellite Systems (GNSS). SOURCE: *GONG:* GONG/NSO/AURA/NSF. *AMPERE:* Iridium Satellite (left); NSF, JHU/APL, Iridium, Boeing (right). *SuperDARN:* Erickson et al. 2013, JGR, Space Physics. *SuperMag:* JHU/APL; *GNSS:* Pankratius et al., eds, Encyclopedia of GIS. Springer, Cham, 2016.

TABLE 1.3 Active Major National Science Foundation Facilities and Programs in 2019

FACILITY	OVERVIEW	Year Started	AIMI	SWMI	SHP
NCAR - High Altitude Observatory (HAO)	NCAR is a major NSF facility operated by UCAR. Its HAO division focusses on heliophysics research involving ground-based observatories, portable solar-eclipse instrumentation, and modeling. They operate K-COR and CoMP instruments at MLSO site, two FPI polar sites, and the CSAC data center.	1940	X	X	X
National Solar Observatory (NSO)	The major NSF facility operated by AURA for solar physics and operation of solar observatories that include DKIST, SOLIS, and GONG network. The DKIST 4 m solar telescope will start operations in 2020. NSO has data centers for DKIST and NISP (SOLIS, GONG).	1950			X
Arecibo Observatory (AO)	World's 2nd largest single-dish telescope (305 m) for ionosphere sounding. Located in Arecibo, Puerto Rico.	1961	X	X	
Jicamarca Radio Observatory (JRO)	JRO is the premier facility for studying the equatorial ionosphere and upper atmosphere with one of the largest Incoherent Scatter Radar (ISR) in the world. Located east of Lima, Peru.	1962	X	X	
Millstone Hill Observatory (MHO)	Primary instrument of the MIT Haystack Observatory, focused on radio astronomy. Primarily used as a near-space surveillance system using ISR techniques.	1963	X	X	
Wilcox Solar Observatory (WSO)	A small solar telescope for observing synoptic solar magnetic fields. Stanford Univ. operates WSO. NSF support for WSO began in 2018.	1975			X
The Karl G. Jansky Very Large Array (JVLA) [previously VLA]	A set of 27 radio antennas in New Mexico for astrophysics observations, including the Sun.	1980			X
San Fernando Observatory (SFO)	A solar visible-light telescope for synoptic solar studies. CSUN operates SFO.	1986			X
Super Dual Auroral Radar Network (SuperDARN)	SuperDARN is an international scientific radar network of 35 high frequency radars in the Northern and Southern Hemispheres. They maps high-latitude plasma convection in the ionosphere.	1990	X	X	
Community Coordinated Modeling Center (CCMC) at NASA/GSFC	CCMC is a multi-agency partnership to enable, support and perform the research and development for next-generation space science and space weather models. https://ccmc.gsfc.nasa.gov/	2002	X	X	X
African Meridian B-Field Education and Research (AMBER)	A network of magnetometers in Africa to study the equatorial ionosphere. It began as joint project by NSF and NASA for the IHY campaign. NSF grant awarded to Univ. of Michigan.	2003	X	X	
Advanced Modular Incoherent Scatter Radar (AMISR)	AMISR is a modular, mobile radar facility to study upper atmosphere and ionosphere and to observe SpWx events. First deployed in Poker Flat, Alaska (PFISR) and another in Resolute Bay (RISR-N).	2006	X	X	
SuperMAG	SuperMAG is worldwide collaboration that operates more than 300 ground-based magnetometers. SuperMAG provides easy access to validated ground magnetic field perturbations in the same coordinate system, identical time resolution and with a common baseline removal approach. NSF grant awarded to JHU/APL .	2009	X	X	
Goode Solar Telescope (GST)	A 1.6 m solar telescope at the BBSO and is operated by NJIT. It is the largest aperture solar telescope currently in operation in USA.	2009			X
Radio Array of Portable Interferometric Detectors (RAPID)	Major Research Instumentation (MRI) RAPID provides ionospheric studies through high resolution interferometric imaging of ionospheric structures in equatorial and/or auroral regions, via coherent and enhanced scatter of signals from existing transmitters, both commercial (TV and radio) and scientific (incoherent scatter radar installations). Instruments also can make solar images at high time and frequency resolution. They allow highly detailed, spatially resolved study of solar and heliosphericradio bursts. Collaboration MIT, U of Cambridge, and JPL. Developed at Haystack Observatory.	2010	X	X	X
Active Magnetosphere and Planetary Electrodynamics Response Experiment-II (AMPERE-II)	AMPERE-II will provide key observations and derived products of the global Birkeland currents at timescales within geomagnetic storms and substorms together with analysis tools to facilitate research on magnetosphere and ionosphere coupling and dynamics.	2010	X	X	
Atacama Large Millimeter/submillimeter Array (ALMA)	A set of 66 millimeter/submillimeter antennas in Chile for astrophysics observations, including the Sun.	2013			X
Low-latitude Ionospheric Sensor Network (LISN)	A network in South America with 50 GPS stations, 5 magnetometers, and 5 ionosondes with research focus on equatorial spread-F (ESF) in the ionosphere.	2016	X	X	
Expanded Owens Valley Solar Array (EOVSA)	A set of 15 microwave/radio antennas in California for solar research. NJIT operates EOVSA.	2017			X

NOTE: Facility names in green are in NSF's Geospace Section of its Division of Atmospheric and Geospace Sciences (AGS). Facility names in red are in NSF's Division of Astronomical Sciences (AST). This list is sorted by start date. The 2013 decadal survey science discipline panels are defined in Table 1.2.

1.4 HIGHLIGHTS OF THE 2013 SOLAR AND SPACE PHYSICS (HELIOPHYSICS) DECADAL SURVEY RECOMMENDATIONS

The 2013 decadal survey (NRC , 2013) recommended a comprehensive program of research organized around four key science goals:

> *Key Science Goal 1. Determine the origins of the Sun's activity and predict the variations in the space environment.*
>
> *Key Science Goal 2. Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.*
>
> *Key Science Goal 3. Determine the interaction of the Sun with the solar system and the interstellar medium.*
>
> *Key Science Goal 4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.* (p. 3)

Flowing from these goals were science challenges and objectives (NRC, 2013, Chapter 2). To fulfill the objectives of the decadal survey, the survey committee made 20 top-level next-decade recommendations for NASA, NSF, and NOAA heliophysics and space weather programs. These are shown in Table 1.4; they are the focus for this midterm assessment.

The decadal survey committee included a top-level steering committee and three science discipline panels (also referred to as study panels): Atmosphere-Ionosphere- Magnetosphere Interactions (AIMI), Solar Wind- Magnetosphere Interactions (SWMI), and Solar and Heliospheric Physics (SHP). It also included five working groups that examined crosscutting areas: Theory, Modeling, and Data Exploitation; Explorers, Suborbital, and Other Platforms; Innovations: Technology, Instruments, and Data Systems; Research to Operations/Operations to Research; and Education and Workforce.

The science discipline panels specified a number of science objectives that steered the decadal survey top-level goals and recommendations. These disciplinary panels also defined 12 top-level science challenges organized by the three disciplines. This midterm assessment committee view of the relationship of these 12 challenges to the key science goals is presented below in Chapter 2 and its Table 2.1.

1.5 MIDTERM ASSESSMENT COMMITTEE CHARGE AND REPORT OUTLINE

The midterm assessment committee was convened by the Space Studies Board of the National Academies of Sciences, Engineering, and Medicine in December 2018 to address seven tasks—listed in Table 1.5, which also lists findings from this committee that are mapped to subsequent chapters in this report. It should also be noted that in addition to the present midterm assessment, there are other recent reviews of NASA and NSF solar and space physics programs (Box 1.2).

TABLE 1.4 The 20 Top-Level Recommendations from the 2013 Solar and Space Physics (Heliophysics) Decadal Survey

Top-Level Recommendations for **Research**				
Research Priority	Recommendation	NASA	NSF	Other (NOAA/AF/ NSWP)
0.0	Complete the current program	X	X	
1.0	Implement the DRIVE initiative	X	X	X
1.1	Diversify observing platforms with microsatellites and mid-scale ground-based assets	X	X	X
1.2	Realize scientific potential by sufficiently funding operations and data analysis	X	X	X
1.3	Integrate observing platforms and strengthen ties between agency disciplines	X	X	X
1.4	Venture forward with science centers and instrument and technology development	X	X	X
1.5	Educate, empower, and inspire the next generation of space researchers	X	X	X
2.0	Accelerate and expand the Heliophysics Explorer program	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		
Top-Level Recommendations for **Applications**				
Applications Priority	Recommendation	NASA	NSF	Other (NOAA/AF/ NSWP)
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 LQ (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 research and space weather application and forecasting	X	X	X

NOTE: Acronyms defined in Appendix F.

BOX 1.2 Recent Reviews of NASA and NSF Portfolios

In addition to this midterm assessment committee review, there have been recent internal reviews of NASA's Heliophysics Portfolio (Office of Inspector General Report No. IG-19-018, 2019), NSF's Geospace Section Portfolio (Lotko et al., 2016), NSF's Astrophysics Section Portfolio (Eisenstein et al., 2012), and NSF's AST Response to the 2012 AST Portfolio review (Ulvestad, 2012). These reviews have been considered by this committee, and comparisons to those review results are primarily in this report's Chapters 3 and 4.

TABLE 1.5 Tasks for the Solar and Space Physics (Heliophysics) Decadal Survey Midterm Assessment Committee

Task Number	Task Description	Report Chapters
1	Describe the most significant scientific discoveries, technical advances, and relevant programmatic changes in solar and space physics over the years since the publication of the decadal survey	2
2	Assess the degree to which the Agencies' programs address the strategies, goals, and priorities outlined in the 2013 decadal survey and other relevant NRC and Academies reports, considering the national policy framework	3, 4
3	Assess the progress toward realizing these strategies, goals, and priorities	3, 4
4	Recommend any actions that could be taken to optimize the science value of the Agencies' programs including how to take into account emergent discoveries and potential partnerships since the decadal in the context of current and forecasted resources available to them	3, 4
5	Provide guidance about implementation of the recommended portfolio for the remaining years of the current decadal survey given actual funding levels, progress on decadal missions, and science and technology advances, but do not revisit or redefine the scientific priorities or recommended mission science targets	3, 4
6	Recommend any actions that should be undertaken to prepare for the next decadal survey—for example: enabling community-based discussions of (a) science goals, (b) potential mission science targets and related implementations, and (c) the state of programmatic balance; as well as identifying the information the survey is likely to need regarding the vitality of the field	6
7	Recommend actions that would enhance all stages of careers for scientists and engineers in the solar and space physics community	5

This report is organized into six chapters plus a Summary. Chapter 1 (this chapter) provides a brief description of the field of heliophysics and current heliophysics programs at relevant federal agencies. In Chapter 2, a few science highlights in each of the three heliophysics subdisciplines are described to provide a flavor for some of the exciting science accomplishments already realized during the first part of the decade (2013-2019). Chapter 3 provides a more detailed assessment of progress towards each of the *research* recommendations made in the 2013 decadal survey, as well as identifying challenges and opportunities for the remainder of the current decade. Similarly, Chapter 4 discusses the recent progress and near future opportunities for the *application* recommendations in the 2013 decadal survey. Consideration of ways to further enhance and develop a strong and diverse workforce in order to maximize progress in the coming decades is discussed in Chapter 5. Chapter 6 discusses planning that could be undertaken during the remainder of the decade in preparation for the next decadal survey, which is expected to start in 2022.

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2

Science Discoveries and Technical Advances

2.1 BRIEF INTRODUCTION OF SCIENTIFIC PROGRESS

The first half of the period covered by the 2013 solar and space physics decadal survey (NRC, 2013) has witnessed a series of major scientific advances in solar and space physics, spurred by a vibrant community with the robust support of the relevant federal agencies. Many of these advances are sparked by new instrumentation and the new perspectives that result from advances in theory, modeling, and computation.

Among the new instrumentation launched over the past 6 years are the Parker Solar Probe (PSP), which has set the record for closest approach to the Sun; the Interface Region Imaging Spectrograph Small Explorer (IRIS SMEX), which resolves the solar atmosphere with unprecedented resolution; the Magnetospheric Multiscale Mission (MMS), which has probed the fine-scale processes in Earth's magnetosphere; and Global-Scale Observations of the Limb and Disk Mission of Opportunity (GOLD MoO), NASA's first scientific payload hosted on a commercial spacecraft. The twin Van Allen Probes were launched in August 2012, just before the decadal survey was published, and recently completed their mission to unlock the secrets of particle acceleration in Earth's Van Allen radiation belts. Most recently, the Space Environment Testbeds (SET-1) mission and Ionospheric Connection Explorer (ICON) were launched this year, growing NASA's solar and space physics fleet.

Missions in their extended phase continue to provide new perspectives and the continuous measurements necessary for studying and monitoring the Sun-Earth system. Notably, the two Voyager spacecraft have now both reached interstellar space (Box 2.1). Missions working in tandem also stimulate advances in understanding. For example, combining data from spacecraft near Mercury, Venus, and Earth, along with remote observations of distant comets, enables scientists to track how solar disturbances change as they propagate through the solar system.

New ground-based observatories and operational assets have also been deployed. The National Science Foundation (NSF) has completed the Jansky Very Large Array (JVLA) and is projected to complete the Daniel K. Inouye Solar Telescope (DKIST) observatory in 2020. Moreover, the National Oceanic and Atmospheric Adminisration (NOAA) has launched the Deep Space Climate Observatory (DSCOVR) and the Geostationary Operational Environmental Satellite (GOES-16 (R) and GOES-17 (S)) missions. All of these resources contribute to a system-spanning observational network—the Heliospheric System Observatory (HSO). The HSO is the fundamental workhorse within which an evolving fleet of individual observatories from different agencies and international partners contribute to understanding the workings of the local cosmos as a system-of-systems and thereby uncover, and ultimately mitigate, its impacts on society.

Ongoing investigations combining observations, models, and theory have provided new views of the workings of the solar atmosphere—from small-scale heating to vast eruptions; how couplings in the solar corona, the magnetosphere, and high in Earth's atmosphere are guided by waves; the details of the radiation belts; how magnetic reconnection converts magnetic energy into particle acceleration; and how heating processes and cooling aerosols affect the chemistry in the upper reaches of Earth's atmosphere. The multitude of perspectives and measurements are increasingly combined in system-wide numerical models, while machine learning is used with rapidly increasing frequency and skill to sift through the growing volumes of data. Learning about solar and space physics is also helped by the Sun itself: the unusually weak recent solar cycle gives us a better view of background processes that were until now generally masked by strong solar variability. In turn, these background processes help researchers differentiate anthropogenic from solar-induced effects.

Solar and space physics has reached a level of sophistication where more comprehensive physics-based numerical modeling, which relies much less on simplifying approximations, is possible. Such numerical sophistication enables both the interpretation of observations and the exploration of new scientific questions. This advance is especially apparent in areas where there are complex couplings[1] between regions, such as the various layers of the solar atmosphere, and also between the solar wind and Earth's magnetic cocoon and upper atmosphere. The importance of advancing all branches of heliophysics to further understand the entire Sun-Earth chain (and much more broadly to understand the diversity of star-planet chains) was stressed in the decadal survey, and that insight is paying off.

Over the past several decades, a number of computational models have been developed. However, the ability of the community at large to take advantage of these had been limited by both access and user capability. The Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center (GSFC) was developed over 19 years ago in part to address this need, by working with model developers to transition selected modeling resources to available tools for research. The 6-year period since publication of the 2013 decadal survey has seen a dramatic rise in the use of these models, due in part to an active program of information dissemination and user training through programs such as NASA's Living With a Star (LWS) and the NSF workshops for Solar Heliospheric and Interplanetary Environment (SHINE), Geospace Environment Modeling (GEM), and Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR). NASA has also led the continuation of several summer schools focused on the fundamentals of heliophysics and on its space weather aspects (including model-based forecasting). In addition, model user support through those programs and through the broader heliophysics research opportunities in NASA's Research Opportunities in Space and Earth Science (ROSES) has resulted in cross-community partnerships of both intellectual and practical value.

The period since publication of the decadal survey has also seen the emergence of new areas of scientific exploration. With the recent explosion of interest in exoplanets and astrobiology, space physicists are applying the knowledge gained about "universal processes" from studying our local cosmos to these other systems (Box 2.2). Other exciting developments have their origin in comparisons of different environments, including (1) the exploration of space-weather conditions in other planetary systems using models based on our local cosmos, (2) the comparison of the planetary environments of Earth and Mars to better constrain atmospheric losses induced by space weather, and (3) the ion-neutral couplings that occur in settings as different as the solar chromosphere, Earth's ionosphere, and the interaction of the solar wind with the partially ionized interstellar medium.

The importance of space weather continues to grow as illustrated by the recent development of the National Space Weather Strategy and Action Plan. The challenges of forecasting space weather are rooted in the complexity of the Sun-Earth system, but significant progress has been made in organizing a national effort to improve our predictive capabilities (Box 2.3). Finally, a chapter reviewing significant events since the decadal survey would not be complete without mention of the "Great American Eclipse" of 2017 (Box 2.4).

The 2013 decadal survey identified four key science goals and the science challenges that flow from these goals from the three primary branches of heliophysics—atmosphere-ionosphere-magnetosphere interactions (AIMI), solar wind-magnetosphere interactions (SWMI), and solar and heliospheric physics (SHP) (see Table E.1). The sections below provide a brief overview of science highlights from the first half of the decadal period in each of these subdisciplines. Appendix E provides a more in-depth look at selected scientific discoveries and their relationship to the 12 science challenges outlined in the decadal survey. Substantial scientific and technical progress has been made in each of the science challenge areas, but for brevity, only a few examples of progress are presented in this chapter and

[1] These couplings may involve different combinations of matter, energy and charge transfer, chemical or composition alterations, and mechanical and electromagnetic forces.

in Appendix E. Additionally, this chapter discusses in Section 2.5 some recent advances in research tools important for heliophysics science.

2.2 SOLAR AND HELIOSPHERIC PHYSICS

Over the first half of the decade covered by the decadal survey, scientists have made great advances in understanding the dynamic solar magnetic field and how it shapes the whole of the space environment, ranging from the Sun to far beyond the planets. Some highlights are given here in brief, with more detail on selected findings mapped back to the decadal survey challenges in Appendix E.

- Close to the Sun, the Parker Solar Probe has set the record for closest approach to the Sun; its ongoing mission is to sample solar coronal particles and the solar electromagnetic field to understand coronal heating, solar wind acceleration, and the formation and transport of solar energetic particles.
- Far from the Sun, measurements by the Voyager spacecraft (that exited the heliosphere in 2012 and 2018, respectively), combined with Interstellar Boundary Explorer (IBEX) and Cassini data, transformed our knowledge of the outer boundary of the heliosphere, placing outer-heliospheric science solidly among the other fast-developing branches of heliophysics.
- Fine-scale High Resolution Coronal Imager (Hi-C) rocket imagery combined with global-scale Solar Dynamics Observatory (SDO) images of the solar corona revealed the small-scale signatures of the reconfiguration of the magnetic field and of Alfvén waves running through that magnetic field. Combined SDO, IRIS, and Hinode observations have furthered our understanding of the mechanisms that extract energy from the magnetic field either in the form of heat or through explosive eruptions, and also of the mechanisms that transport energy between different wave types and physical domains.
- Technical advances in computational methods and infrastructure provide critically needed insights into both the source of the solar magnetism and the formation of, and explosive instabilities in, the globally connected solar atmosphere as discovered with SDO observations. These newly developed computer models can be applied to new data, but also to archival data to efficiently learn from decades-long historical archives.
- Machine learning and big data techniques are helping us move toward improved multi-day predictions of space weather, while increasingly realistic computer models in regular use at the CCMC are now able to work across multiple physical regimes as they simulate quantities that can be directly compared to real-world observations.
- Detailed observations of space-weather throughout the solar system helped planetary scientists and stellar astrophysicists understand the range of possibilities for stellar wind conditions, and thus how these conditions influence exoplanets.

These exciting new results from both space-based missions and ground-based instruments demonstrate the importance of diverse and complementary observing capabilities, both remote and in situ, in order to understand fundamental physical processes. They also emphasize the importance of accessible, standardized archives and the need to develop community-usable numerical tools for modeling and analysis, sometimes using artificial intelligence, including data-driven full-system models that include the space-weather forecasting systems.

Selected findings are discussed in detail in Appendix E for the four SHP science challenges that include understanding the solar dynamo, the solar dynamic atmosphere, solar eruptions (e.g., magnetic reconnection), and interactions with the local interstellar medium. As one example here, the key drivers for solar activity are magnetic field emergence, transport, and energy release on the Sun. The solar dynamo (Section 1.2) is the underlying fundamental process inside the Sun. Measurements and models of these subsurface movements are critical to understand the dynamo and to forecast the 11-year solar cycle. Results from two methods are combined to infer plasma flows in the solar interior. One method is called helioseismology whereby the properties of sound waves are measured as they run through much of the solar interior in order to deduce the conditions of the gas that they traverse. Another method is to track magnetic elements as they move across the solar surface based on high-resolution magnetographs and (for sunspots) direct imaging. In a recent result from using helioseismology, Zhao et al. (2013) detected an equatorward flow in the Sun's interior between 0.83 and 0.91 solar radii, sandwiched between poleward flows below and above. This flow (illustrated in Figure 2.1) may be a key ingredient of the dynamo as it can transport magnetic field lines both in the deep interior and near the surface. However, the rise of bundles of magnetic field to the solar surface was found to be much slower than expected from some models (Birch et al., 2016), meaning more theoretical work is needed to better understand how flux tubes rise through the surrounding gas.

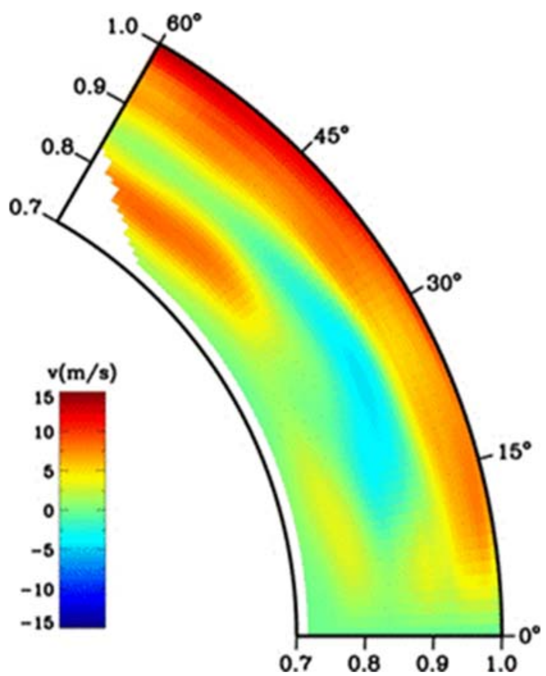


FIGURE 2.1 The figure shows different veloicities of plamsa flows in a cross section of a quarter of the solar disk. Warm colors show flows toward the solar poles, while cool colors show flows toward the solar equator. SOURCE: R. Chen and J. Zhao, A comprehensive method to measure solar meridional circulation and the center-to-limb effect using time-distance helioseismology, 2017, *The Astrophysical Journal* 849(2):144, doi: 10.3847/1538-4357/aa8eec. © American Astronomical Society. Reproduced with permission.

2.3 SOLAR WIND-MAGNETOSPHERE INTERACTIONS

Solar extreme ultraviolet radiation and the solar wind, including transients related to stream structure and CMEs, impinge on Earth's protective magnetic shield, producing a variety of conditions in Earth's space environment. Since the publication of the decadal survey, significant progress has been made in understanding how these conditions come about, involving both the externally driven and the internally shaped processes by which the solar radiation and solar wind couple to a planetary magnetosphere, and how these processes transport mass and energy into and within the magnetosphere. Selected discoveries for the SWMI challenges are discussed in some detail in Appendix E. Some of the SWMI highlights include the following:

- MMS has observed how electrons are accelerated and heated even as they slip across the magnetic field in the process of magnetic reconnection.
- Waves excited by the solar wind flowing along Earth's magnetosphere in the interface layer called the magnetopause have been discovered to play a substantive role in controlling how efficiently the magnetic fields of the solar wind and of Earth reconnect. Where such waves are strongest depends both on the solar wind conditions and plasma and field conditions close to the magnetopause.
- The Van Allen Probes mission has changed our understanding of the structure of Earth's Van Allen belts and of the processes that accelerate charged particles to ultra-high speeds. At times we observe three or more radiation belts. The inner edge of the outer belt for ultra-high energy electrons is unexpectedly sharp, and the inner belt is nearly void of high-energy electrons most of the time.
- The unusually weak recent solar cycle is providing important insights into how the inner-heliospheric conditions affect the propagation of coronal mass ejections, thereby changing the magnetic field and the dynamic pressure of heliospheric storm fronts as they reach Earth. The weak cycle has also given new insights into how the ionosphere responds to levels of lower-energy ionizing radiation.
- With spacecraft near Mercury, Venus, and Earth, Jupiter, and Saturn, the evolution of solar eruptions traveling through the heliosphere could be observed and compared with simulation results. The analysis of many tails of comets over their observable trajectories is helping us understand solar-wind variability, specifically its turbulence, and how that evolves from near the Sun outward.
- Space-weather conditions at Mars were studied with particular emphasis on the solar wind coupled to that planet's atmosphere with its weak, local magnetism.

Selected discoveries discussed in detail in Appendix E for the four SWMI science challenges include understanding magnetic reconnection in the magnetosphere; energetic particle processes; coupling between the magnetosphere, ionosphere, and thermosphere; and different magnetospheric systems (e.g., other planets). As one example, our understanding of the physics of magnetic reconnection has undergone a revolutionary change since publication of the DS. Specifically, the role of electrons in the process of magnetic reconnection was revealed using new measurements from the Magnetospheric Multiscale mission (MMS).

MMS uses four identically instrumented spacecraft, flying in the tightest-ever pyramid formation for a satellite constellation, to measure the electromagnetic field with unprecedented accuracy, sampling 100 times faster than previous missions. MMS observed that the reconnection process is highly localized at the magnetopause, the boundary between the solar wind and Earth's magnetosphere. Moreover, the reconnection process can strongly energize electrons (Figure 2.2). Reconnection briefly decouples electrons from the magnetic field and then accelerates them in the electric field aligned with the magnetic field as a consequence of the strong gradients in the reconfiguring field (Burch et al., 2016; Burch and Phan, 2017; Chen et al., 2016; Graham et al., 2016, 2017; Torbert et al., 2018*)*. The extraordinary time resolution of the electron instruments on MMS captured this acceleration while the unprecedented accuracy of the electric field measurements captured the reconnection electric fields responsible for the acceleration. However, because the electron diffusion regions cover only a small volume, they are insufficient to explain the overall observed energization. The details of the cross-scale coupling facilitated by reconnection remains a challenge.

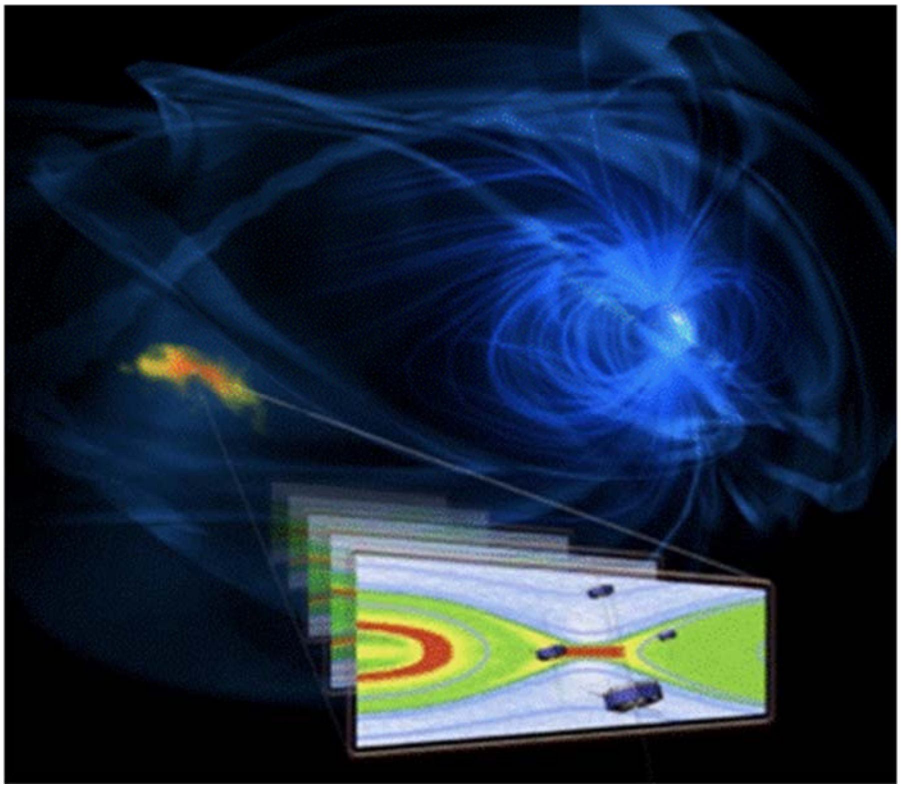


FIGURE 2.2 The MMS mission unlocked the secrets of magnetic reconnection by making unprecedented measurements inside the tiny (< 1km) electron diffusion region where magnetic energy is converted to particle energy. SOURCE: Southwest Research Institute.

2.4 ATMOSPHERE-IONOSPHERE-MAGNETOSPHERE INTERACTIONS

The AIMI region starts roughly just above Earth's stratosphere (50 km) and extends up to several thousand kilometers above ground. The AIMI region is impacted by the Sun, interactions with the magnetosphere, and also by processes occurring in the atmosphere below. Discovering the processes that govern the conditions at this interface between Earth and space is fundamental to understanding planetary atmospheres and exospheres, as well as for operational needs, including the protection of astronauts and spacecraft, the protection of humans on the ground, and for radio and navigation signal situational awareness. Distributed observational capabilities increasingly enforce the realization that the geospace system, from below the ionosphere to the outer reaches of the magnetosphere, is a single connected system. Among the many advances in understanding the AIMI are the following:

- The weak recent solar cycle simplified the separation of solar influences from effects from the lower atmosphere, enabling improved understanding of the coupling processes between the AIMI region and the atmosphere below. Models are bridging the knowledge gap on the coupling between larger-scale instabilities and smaller-scale turbulence that is important in regulating the dynamics of geospace.
- The energy of precipitating particles and heat from solar radiation enhance the concentration of nitric oxide (NO) in the thermosphere, which in turn has brighter infrared emissions to cool the thermosphere back down efficiently.
- Joint analyses and comparisons of plasma-neutral interactions in the solar chromosphere and in the terrestrial ionosphere stimulated by the NASA LWS Research and Analysis program

has provided deeper insights into the similarities and differences between these environments and is leading to sharing of insights between two communities previously working largely in isolation.

- Atmospheric waves generated by tides, terrain, and atmospheric instabilities have been observed and modeled as they travel upward, strengthening in the process. Waves are also generated in the dynamics of the polar vortex at stratospheric altitudes. All these wave phenomena can modify high-atmospheric properties, including ionospheric properties, far from the latitudes where they originally formed, which, in turn, couple to space weather phenomena further out.
- Drivers of long-term trends in upper atmospheric properties are better clarified using ever more sophisticated global circulation models (GCMs) to reveal the dynamics effects from solar variability, the cooling influence of anthropogenic methane and carbon dioxide, and even the top-down coupling of atmospheric changes resulting from the long-term change of the terrestrial magnetic field, of which the shift of the magnetic poles is one consequence.

Selected discoveries are discussed in detail in Appendix E for the four AIMI science challenges, including understanding how the ionosphere-thermosphere system responds to magnetosphere forcing, plasma-neutral coupling processes, lower-atmosphere forcing effects in the ionosphere-thermosphere, and the causes for long-term changes in the AIM system. The discovery of a new, different auroral phenomenon is noted here as one example of the new AIMI findings. Bright visible auroras are produced by energetic particles flowing along magnetic field lines into the upper atmosphere. Auroras have long been exploited as diagnostic of less accessible magnetospheric processes, but there are still surprises. Recently a new, very different, auroral phenomenon has been discovered by a large ad hoc network of citizen auroral watchers. This faint feature, known as STEVE (Strong Thermal Emission Velocity Enhancement) and shown in Figure 2.3, appears to be caused by a high-speed plasma jet flowing perpendicular to Earth's magnetic field, exciting optical emissions through pathways not yet identified. The discovery of STEVE (MacDonald et al., 2018; Gallardo-Lacourt et al., 2018) highlights the discovery potential of geospace facilities that may be realized in creative and cost-effective ways.

Permission Pending

FIGURE 2.3 Example of STEVE (Strong Thermal Emission Velocity Enhancement), a newly discovered optical phenomenon, overlooked by the auroral research community. Its discovery by amateur photographers highlights the potential of citizen scientists to contribute to heliophysics research. SOURCE: Robert Downie Photography, "Steve over Ness Lake," https://www.robertdowniephotography.com/Astrophotography/i-hWf5WQ4/A.

2.5 ADVANCES IN RESEARCH TOOLS FOR HELIOPHYSICS SCIENCE

The past 5 years have seen significant advances in computational, data science, and observational tools. Some highlights include the following:

- Ultra-high-resolution magneto-hydrodynamic (MHD) simulations of Earth's magnetosphere have been pushed to the limits of the physics that MHD can capture, revealing highly structured features in dipolarization fronts.
- A new generation of whole-Earth atmosphere models now span from Earth's surface to the upper thermosphere and ionosphere and can capture the atmospheric driving of space weather effects.
- The heliophysics community is embracing advances in data science, with broad applications ranging from forecasting of solar flares to scintillation in the ionosphere.
- Machine learning and other new data analysis tools are becoming increasingly important as missions and simulations produce increasingly large amounts of data.
- The rapid development of the small satellite industry, including the plans for large commercial satellite constellations, provides new opportunities for heliophysics science.
- Increased rideshares, opportunities for hosted payloads, and new manufacturing methods offer new and low-cost access to space.

2.5.1 Computational Tools

Simulations have been a critical tool in heliophysics for a while, but new models have unprecedented spatial resolution (global MHD), include detailed physics (hybrid and particle-in-cell (PIC) simulations), and/or make use of vast observational data (empirical models, and data assimilation), to name just a few advancements. Computer power has increased to the level that three-dimensional (3D) simulations of different heliophysical regions can have higher spatial and temporal resolution than the corresponding observations. For example, simulation of the response of the chromosphere, transition region, and corona can have higher spatial and temporal resolution than is presently observable with IRIS. The new generation of whole-Earth atmosphere models such as WACCM-X (Liu et al., 2018) now span the altitude range from Earth's surface to the upper thermosphere with an interactive ionosphere and electric wind dynamo to connect tropospheric weather with space weather at resolutions capable of resolving mesoscale processes. While the simulations are more detailed than what can be currently observed, that does not mean the simulations are correctly emulating the observed physical processes. Each improvement of the simulations, whether that be by increased spatial or temporal resolution of more sophisticated physical models, must be validated by real observations. Nevertheless, these tools are providing important context for observations, and they are necessary for the system-level science approach that is critical for advancing heliophysics research.

The benefits of model development and CCMC support to make them accessible can be seen in the many applications for both observational and theoretical studies. For example, the WSA-ENLIL-cone heliospheric model and MAS/CORHEL (Corona-Heliosphere) are widely applied to space weather event interpretation (e.g., Jian et al., 2011; Moestl et al., 2015; Colaninno et al., 2013; Rouillard et al., 2016; Gibson et al., 2016), and to further modeling (e.g., interplanetary shocks used for solar energetic particle (SEP) event modeling) (Lario et al., 2017; Schwadron et al., 2017; Luhmann et al., 2017). The Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme (BATS-R-US), Lyon-Fedder-Mobarry (LFM) and Open Geospace General Circulation Model (OpenGGCM) magnetosphere models have been used to investigate topological and phenomenological characteristics and responses to both nominal external conditions and solar events (e.g., Haiducek et al., 2017; Samsonov et al., 2016; Ilie et al., 2015). The Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) and Global Ionosphere Thermosphere Model (GITM) have been applied to interpretations of measurements of airglow and total electron content, toward understanding ion-neutral coupling across species and altitudes, vertical momentum transport (Zhu et al., 2017), and to studying the effects of waves and instabilities (e.g., Maute and Richmond, 2017; Greer et al., 2018; Li et al., 2018; Lin et al., 2018). Processes previously excluded, such as polar outflow, are now also being incorporated into models (Welling et al., 2016*)*. These models are only a handful of the many models used in heliophysics research, and this discussion is intended to just provide examples of science usages of a few models. Applications of the broad range of models that have been made available so far have scarcely touched the breadth and scope of investigations that can be pursued as a result of this greater accessibility.

2.5.2 The Increasing Role of Data Science in Heliophysics

The solar and space physics community is also increasingly employing data science in their research, in particular to analyze the large and complex data sets that our facilities now produce. Data science tools encompass three main areas: modern statistical techniques, modern computational techniques, and knowledge of a specific scientific domain—in this case, solar and space physics.

These techniques have recently been used to forecast and characterize solar flares (e.g., Bobra and Couvidat., 2015; Nishizuka et al., 2018; Panos et al., 2018) and Solar Energetic Particle (SEP) events (e.g., Winter et al., 2015), to study electron densities in the Van Allen belts (e.g., Zhelavskaya et al., 2016), scintillation in the ionosphere (e.g., McGranaghan et al., 2018) and particles and waves in the inner magnetosphere (e.g., Bortnik et al., 2016) and solar wind (e.g., Camporeale et al., 2017).

One especially useful class of techniques, called machine learning and data mining, unearth patterns and behaviors in data sets that are difficult to discover via simple statistical relationships or by eye in a way that is scalable and reproducible (Ivezic et al., 2014; LeCun et al., 2015). Machine learning algorithms may be easiest to understand via an example. Identifying features on the solar surface, such as prominences, flare ribbons, and sunspots in terabyte and petabyte scale data sets are important for solar physics and space weather applications, but it is not feasible to manually identify these features in millions of images. Further, manually identified features prove difficult to reproduce. Learning algorithms can identify features in a way that is reproducible, scalable, and fast.

2.5.3 The Small Satellite Revolution

In addition to advances in theoretical and analysis tools, there has been rapid development in the capabilities of small satellites (<180 kg) as an observational tool. Tiny satellites of less than 10 kg, often called CubeSats because of their commonly used 10 cm × 10 cm × 10 cm unit (1 U) form factor, have been in development for more than 20 years, but their scientific potential has been broadly recognized only recently. Although the decadal survey recognized the growing potential of CubeSats, the extent to which small satellites would be embraced in the commercial sector was not fully anticipated. Commercial satellite constellations of hundreds of small (approximately 100 kg) satellites are now being deployed to create an internet in space. Additionally, commercial satellite constellations of dozens of nano (approximately 10 kg) satellites are now being deployed to regularly image Earth from space and monitor Earth's weather, Earth's climate, and space weather using radio occultation measurements. These efforts in turn are leading to a growing industry of commercial off-the-shelf parts, launch opportunities, and new ways of manufacturing small satellites.

The rapid growth of low-cost access to space is one of the key components for this small satellite revolution. Rideshares on large-lift launch vehicles are now common place, and rideshare costs continue to drop as the space industry is positioning itself for more customers. Small-lift launch vehicles, such as the Rocket Lab Electron, are also competing for their share of launches of small satellites. Opportunities for hosted payloads, such as the flight of the NASA GOLD instrument on a commercial communication satellite in GEO, are also growing, but less so than rideshares and small-lift launch vehicles.

These advances present a real opportunity for all areas of science, including heliophysics. Moreover, the large constellation class missions that have been discussed for decades may soon be within reach. The COSPAR roadmap *Small Satellites for Space Science* was recently published (Millan et al., 2019) and outlines some pathways by which the science community can leverage these developments and form international partnerships to pursue ambitious goals using small satellites.

BOX 2.1 The Voyager Spacecraft Journey Beyond the Heliosphere

In 2012, as the decadal survey was under way, Voyager 1 crossed the heliopause, becoming the first human-made object to leave the heliosphere. The heliopause is the edge of the bubble, called the heliosphere, produced by the expanding solar wind and solar magnetic field. This boundary has long been considered to be where the Sun's influence ends and the local interstellar medium dominates. The crossing of the heliopause was hotly debated, even within the Voyager team. One surprise was that the heliopause was located at about 121 AU from the Sun, closer by about 30 AU than originally thought. Thus, the heliosphere is smaller than originally presumed, at least in the direction of the Sun's motion within the galaxy. The first 5 years of the current decadal interval saw many important discoveries regarding the local interstellar medium, the heliopause, and the Sun's influence therein. In particular, the Sun's influence on the local interstellar medium does not appear to end at the heliopause. Instead, the magnetic field in the local interstellar medium drapes and piles up against the heliopause. Shock waves produced in the solar wind near the Sun propagate outward and cross the heliopause. In the local interstellar medium, these shocks produce disturbances that were observed by Voyager 1 many astronomical units beyond the heliopause. Finally, the neutral solar wind is unimpeded by the heliopause and propagates into interstellar space where it interacts with the interstellar medium and is likely the primary source of the "Ribbon" seen by NASA's Interstellar Boundary Explorer (IBEX). The new and exciting results from the edge of the heliosphere reached an apex with Voyager 2's crossing of the heliopause at the end of 2018. Now, NASA has two human-made objects that have reached the space between the stars. The Voyager 2 heliopause crossing was even closer to the Sun, by about 2 AU, and is dramatic confirmation of the crossing years earlier by Voyager 1. Over the remaining 5 years of the decadal survey, observations from Voyager 2 in the local interstellar medium are likely to produce many new and interesting discoveries about our place in the galaxy.

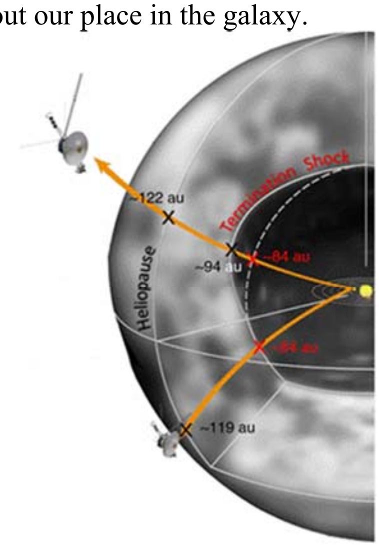


FIGURE 2.5 The Voyager spacecraft crossed the boundary of the heliosphere in 2012 and 2018. Voyager 1 reached interstellar space about 121 AU from the Sun while Voyager 2 crossed out of the heliosphere at about 119 AU. Adapted from Krimigis et al., *Nature Astronomy*, 2019.

BOX 2.2 Universal Processes, System Science, and Applications for (Exo-)Planets

The state and evolution of the solar system are set by a multitude of processes that create a rich diversity of local conditions. However, that very diversity is increasingly used to deepen scientific understanding as the study of common processes in different settings enables the testing and validation of ideas, often resulting in new insights. For example, magnetic reconnection can be studied in settings as diverse as the magnetosphere, inner heliosphere, heliospheric boundary, solar atmosphere, and Martian remanent magnetism; ionosphere-magnetosphere couplings can be studied in detail for Earth, but also more generally for planets as different as Venus and Jupiter; and atmospheric losses are now being studied on Earth, Mars, and other solar system bodies.

A new and much bigger challenge is emerging: the solar system is but one of thousands of known planetary systems, and the processes that we know from our "home in space"—the "local cosmos"—occur in each of these exoplanetary systems, modified by the local conditions. Thus, on the one hand, a vastly larger diversity of conditions becomes available to test our understanding, while on the other hand, exoplanetary scientists look to the solar system for guidance.

The principle of "universal processes" was recognized in the 2013 decadal survey. The report emphasizes that

> Underlying the extraordinarily complex and dynamic space environment are identifiable fundamental processes that can sometimes be explored as independent problems. These fundamental processes can also play a role in other astrophysical settings. In that sense, the Sun, the heliosphere, and Earth's magnetosphere and ionosphere serve as cosmic laboratories for studying universal plasma phenomena, with applications to laboratory plasma physics, fusion research, and plasma astrophysics. Discoveries from these fields, of course, also contribute to the scientific progress in solar and space physics.

Examples of universal processes are dynamos, solar and planetary winds, magnetic reconnection, collisionless shocks, turbulence, and plasma-neutral interactions (Section 1.2).

The decadal survey did not, however, anticipate the rapid growth in the need by scientists to reach beyond the traditional funding pathways. A new challenge is therefore to improve coordination of research in the disciplines of astronomy and astrophysics, heliophysics, planetary sciences, and Earth sciences. The development of a coordinated approach, funding of multidisciplinary science, and support for multi-instrument observations is needed at the organizational level, as well as the development of instrument and data infrastructures that efficiently advances the decadal survey defined goals and science challenges.

BOX 2.3 Investigating the Space Environment and Forecasting Space Weather

Chapter 7 of the 2013 decadal survey "provides the survey committee's vision for a space weather and space climate program for the nation that could provide the new, integrated capabilities needed to serve the needs of a society ever more reliant on space." The report notes that

> Owing to the complexity of this variable, coupled system, scientists have not yet achieved a sufficiently reliable predictive capability for when and in what direction major disturbances will be emitted by the Sun; or for how disturbances from the Sun, coupled with inputs from Earth, affect the space environment near Earth; or for what the radiation environment through which astronauts might fly will be; or for exactly how changes on the Sun may affect Earth's climate, atmosphere, and ionosphere. Despite these challenges, prediction of the space environment is, in principle, a decipherable problem. New ground- and space-based measurements are adding considerable knowledge to enhance understanding of the space environment and its governing

processes. In parallel, increasingly sophisticated comprehensive physical models are being developed that run on ever more powerful computers. Given an adequate investment of effort in fundamental scientific research and modeling, the research community should be able to leverage advances in computing capability to develop the predictive models required to specify the extended space environment in order to protect society and advance growing aspirations for the use of space.

From this flowed its recommendations (A2) to ensure continuing key observations, explore new observation systems, and develop new information systems.

Starting its work in the final phases of the decadal survey, a COSPAR/ILWS committee identified the scientific challenges and the needs for observations, models, and research infrastructure in its 2015 report entitled *Understanding Space Weather to Shield Society: A Global Road Map for 2015-2025 Commissioned by COSPAR and ILWS*. Among its primary findings are the need to investigate magnetic configurations and their potential instabilities in both the solar atmosphere and geospace; only advances in that area can lead to reliable, actionable space weather forecasts out to beyond the half day to one day required by, among others, the electric power providers, GNSS users in—for example, drilling and mining, airlines operating high-latitude flights, delicate spacecraft operations on orbit or during launch, and crewed spaceflight activities in low-Earth orbit, on the Moon, or beyond.

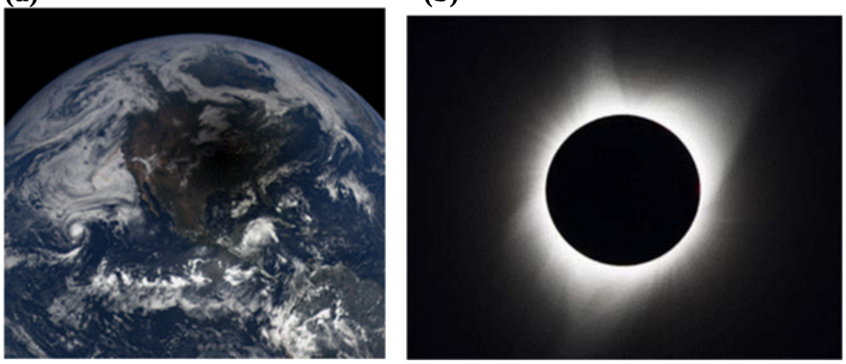
The COSPAR/ILWS roadmap (Schrijver et al., 2015) provides a global assessment of the challenges to the science of space weather, involving scientists, forecasters, and users of space weather information. Decadal survey recommendation A2.3 would benefit from the integration of this COSPAR/ILWS roadmap, and it is important to note that international coordination is essential to the development of scientific understanding, in contrast to the national needs of research-to-operations and operational space weather that would follow from the scientific investigations. Decadal survey recommendation A2.4 could be achieved, for example, through an update of the COSPAR/ILWS roadmap if such an update included the comparison of the roadmap's findings with agency operations and plans.

BOX 2.4 Reaching the Public and "The Great American Eclipse"

For the first time in 26 years, a total solar eclipse occurred over the continental United States (CONUS) on August 21, 2017 (Figure 2.4.1a). While total eclipses are known for their spectacular visual displays, they also play significant roles in the study of the ionosphere and radio science (Figure 2.4.1b). Eclipses create predictable yet unusual solar inputs to the upper atmosphere by temporarily blocking ultraviolet (UV) radiation, causing reductions in photoionization and increases in recombination (Huba and Drob, 2017). For the August 2017 eclipse, totality was observed from the Oregon coast at approximately 9:15 local standard time (LST) (17:20 UT) to the South Carolina coast at approximately 13:27 LST (18:47 UT). This eclipse offered the chance for ionospheric modelers to test and further develop their models, to measure the effects with greater observational sensitivity and spatial/temporal resolution than ever before, and to involve a large group of citizen scientists.

This was the first eclipse-ionospheric study (Frissell et al., 2018) to make use of measurements from a citizen-operated, global-scale high-frequency (HF) propagation network and develop tools for comparison to a physics-based model ionosphere. Citizen-science is of growing importance in many areas of science, including solar and space physics. For this historic event, in situ data directly measured by low Earth orbiting satellites during the eclipse period was also available and is being studied. In particular, the U.S. Defense Meteorological Satellite Platform (DMSP) satellite constellation and the NASA Thermosphere, Ionosphere, and Mesosphere Energetics and Dynamics (TIMED) satellite, and the European Space Agency (ESA) Swarm satellites flew through the Moon's shadow and sampled ionospheric and thermospheric parameters during the eclipse. This event also benefited from the vast increase in fidelity and coverage of ground-based monitoring tools, especially Global Navigation Satellite Systems (GNSS) monitoring of total electron content (TEC).

(a) **(b)**



Permission Pending

(c)

FIGURE 2.4 Images from the 2017 total solar eclipse from (a) the Earth Polychromatic Imaging Camera (EPIC) instrument on the Deep Space Climate Observatory (DSCOVR) satellite and (b) . Eclipse studies for the 2017 event have benefited from the vast increase in fidelity and coverage of ground-based monitoring tools, especially Global Navigation Satellite Systems (GNSS) monitoring of total electron content (TEC). Shown in (c) is the differential TEC measured at a single time (18:00 UT) by the global network of GNSS receivers; the red line shows local noon. The white dot displays the location of the peak of the solar eclipse, and the black line indicates the path of the eclipse. The dark blue area shows the depleted TEC during and following the total solar eclipse, observed to peak a few minutes after the peak of the eclipse. Evidence of TEC changes in the form of large and medium-scale TIDs were observed over the United States during and after eclipse shadow made initial contact with the U.S. west coast. SOURCE: (a) https://epic.gsfc.nasa.gov/epic-galleries/2017/total_solar_eclipse/full/epic_1b_20170821181450.png, courtesy of NASA/DSCOVR EPIC team. (b) https://www.nasa.gov/image-feature/2017-total-solar-eclipse, courtesy of NASA/Aubrey Gemignani. (c) Zhang et al., 2017.

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3

Progress, Opportunities, and Challenges for Decadal Survey Research Goals and Recommendations

3.1 AN OVERVIEW OF PROGRESS TOWARDS THE DECADAL RESEARCH RECOMMENDATIONS

The 2013 heliophysics decadal survey included five top-level research recommendations and two top-level space weather application recommendations, some of which were divided into sub-parts (shown in Table 1.4 in Chapter 1). The present chapter reviews the research recommendations; Chapter 4 reviews the application recommendations.

Figure 3.1 summarizes progress made towards the research recommendations. A detailed description of progress, along with programmatic and other changes that have occurred since publication of the decadal survey (items 2 and 3 in the committee's statement of task), is provided in the sections below. The committee's research-related recommendations for the remainder of the survey decadal interval are also included in this chapter (committee tasks 4 and 5).

A key challenge affecting NASA's implementation of the decadal survey recommendations is that the Heliophysics Division (HPD) budget has not increased to the level expected by the 2013 decadal survey (Figure 3.2). In 2014, NASA published its plan to implement the decadal survey, *Our Dynamic Space Environment: Heliophysics Science and Technology Roadmap for 2014-2033* (Heliophysics Roadmap Team, 2014). The Roadmap's implementation plan accounted for budget expectations that were significantly lower than that assumed by the survey; the difference in projections amounted to an unplanned deficit of $100 million per year by 2024. Further, the decadal survey's even higher "enabling budget," which approached $750 million by the end of 2019, has not been realized. Instead there has been a modest increase to a little below $700 million in government fiscal year (GFY) 2019 (see also OIG 2019 report[1]).

Over the last 5 years, the NASA HPD budget rose 14 percent, which is slightly less than the inflation rate. In contrast, the NASA overall budget rose by 23 percent over this time period, and the NASA Science Mission Directorate (SMD) budget rose by 30 percent. Additionally, according to the OIG Report, although Parker Solar Probe and the Global-scale Observations of the Limb and Disk (GOLD) missions were launched on schedule and within cost, ICON (Ionospheric Connection Explorer), Solar Orbiter, and SET (Space Environment Testbeds) have incurred a collective $41 million growth in cost as the consequence of launch-related delays.[2]

These budgetary factors have contributed to a delay in implementation of the next STP (Solar-Terrestrial Probes) mission recommended in the decadal survey (STP-5/IMAP, Interstellar Mapping and Acceleration Probe) and an inability to start the other recommended STP missions (DYNAMIC, Dynamical Neutral Atmosphere-Ionosphere Coupling; MEDICI, Magnetosphere Energetics, Dynamics and Ionospheric Coupling Investigation) and the recommended Living With a Star (LWS) mission (GDC, Geospace Dynamics Constellation). It should be noted, however, that IMAP (STP-5) and GDC are

[1] Office of the Inspector General (OIG) report on NASA's Heliophysics Portfolio, Report No. IG-19-018, May 2019. This audit assessed to what extent NASA (1) had an effective strategy for maintaining its heliophysics science capabilities, (2) was controlling costs for its current and planned missions, (3) had implemented appropriate recommendations and action plans, and (4) was effectively coordinating heliophysics activities across federal agencies and the private sector.

[2] ICON launched on October 10, 2019. Its delays were due to a problem with the Pegasus launch vehicle. The OIG report notes that launch vehicle risks were not included in the cost analysis, thus leading to unexpected additional costs. However, not including launch vehicle risks in the cost analysis is consistent with agency practice.

substantially delayed compared with the Heliophysics roadmap, even though the actual NASA HPD budget exceeds the roadmap forecast.

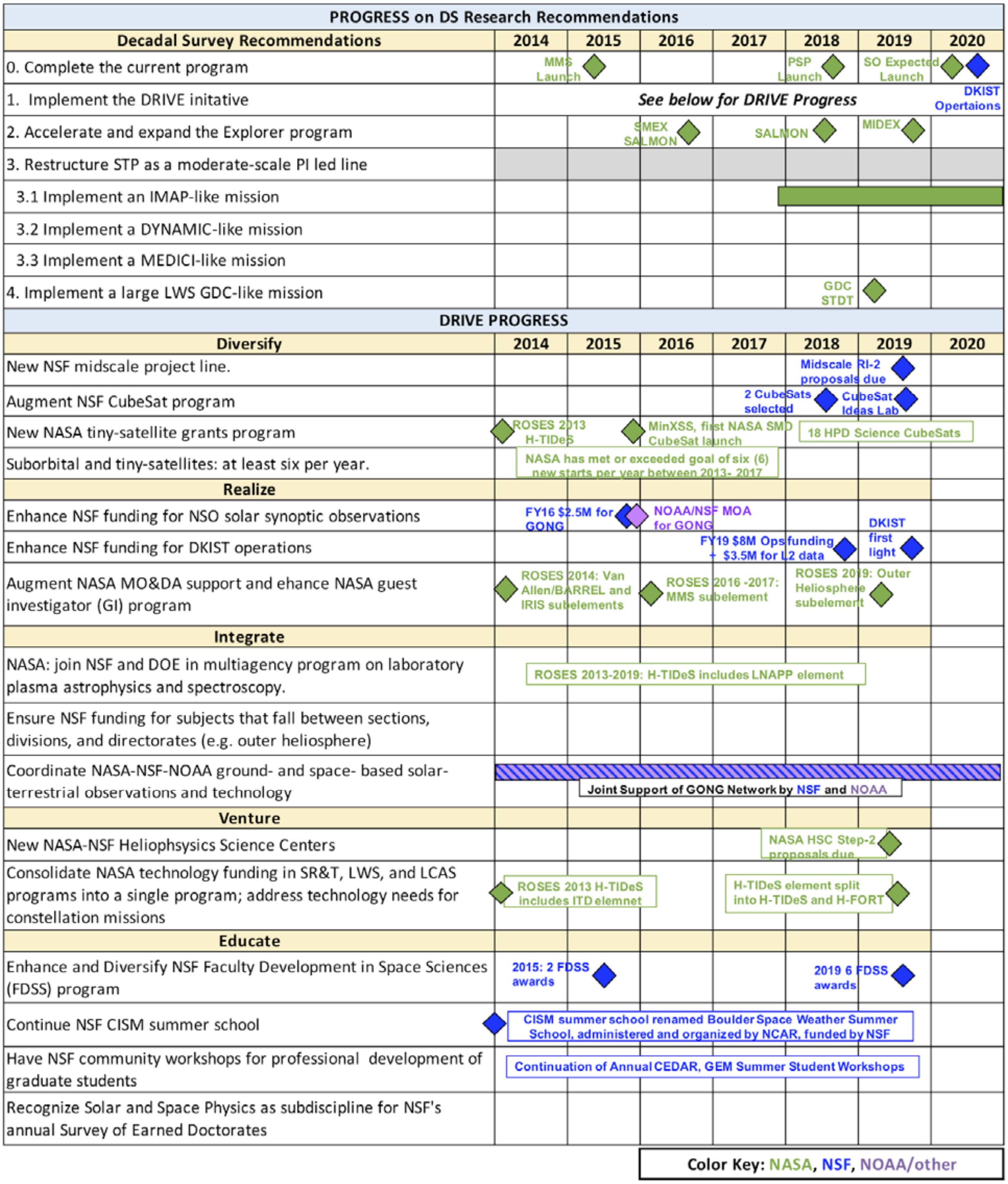

FIGURE 3.1 Highlights of progress and plans for the 2013 decadal survey research recommendations.

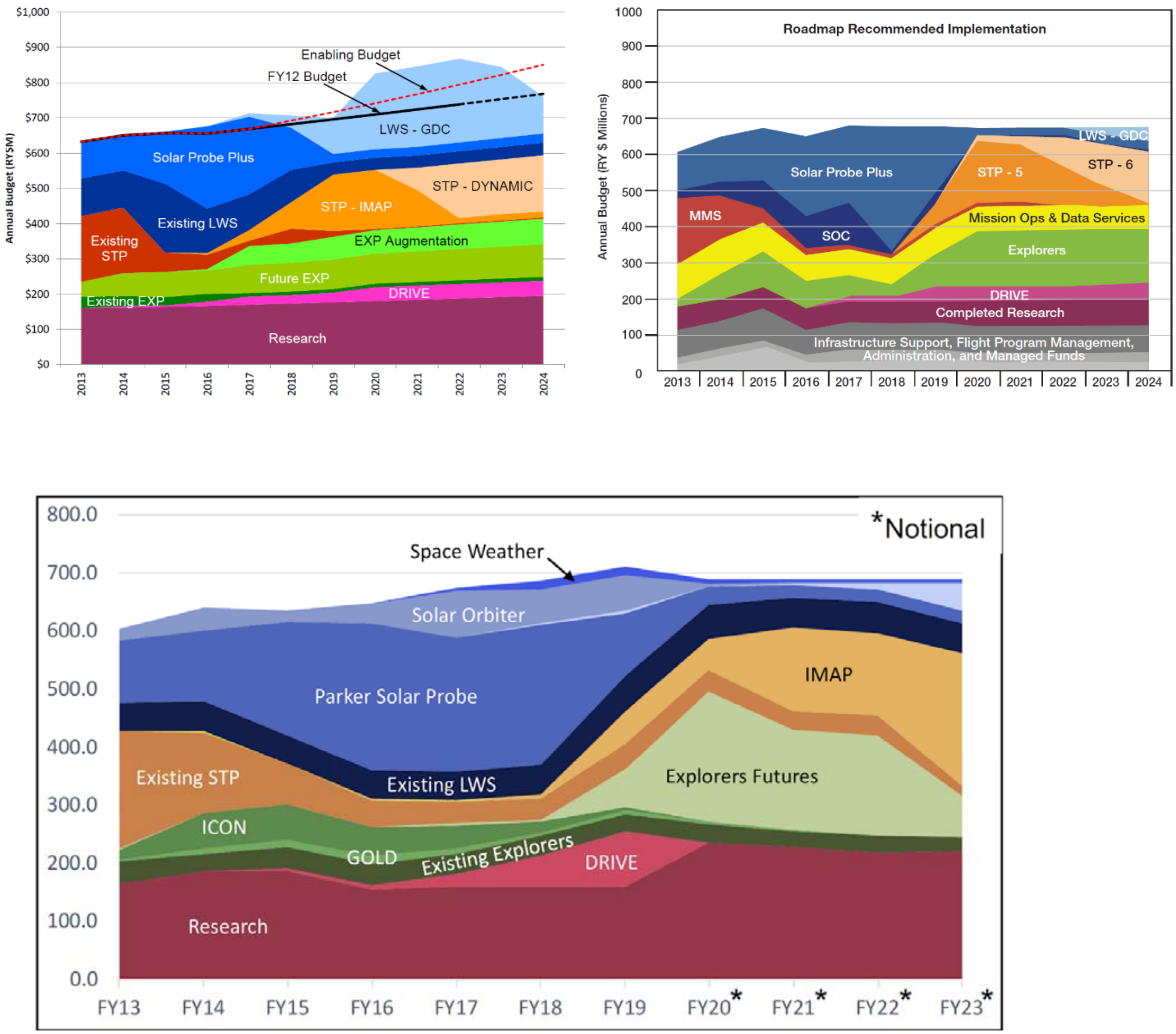

FIGURE 3.2 Budget plans for NASA Heliophysics Division (HPD), as presented in the 2013 decadal survey (NRC, 2013, Figure 6.1; top, left), 2014 Heliophysics roadmap (top, right), and as presented by HPD Director Fox in April 2019 (bottom). NOTE: Infrastructure and management (e.g., for the sounding rocket program) is broken out for the roadmap budget, while it is included in “Research” for the decadal survey and current NASA budgets. The STP-5 and STP-6 in the roadmap budget (top right) is for the IMAP and DYNAMIC missions. The HPD Director April 2019 budget (bottom) does not include funding for GDC or DYNAMIC.

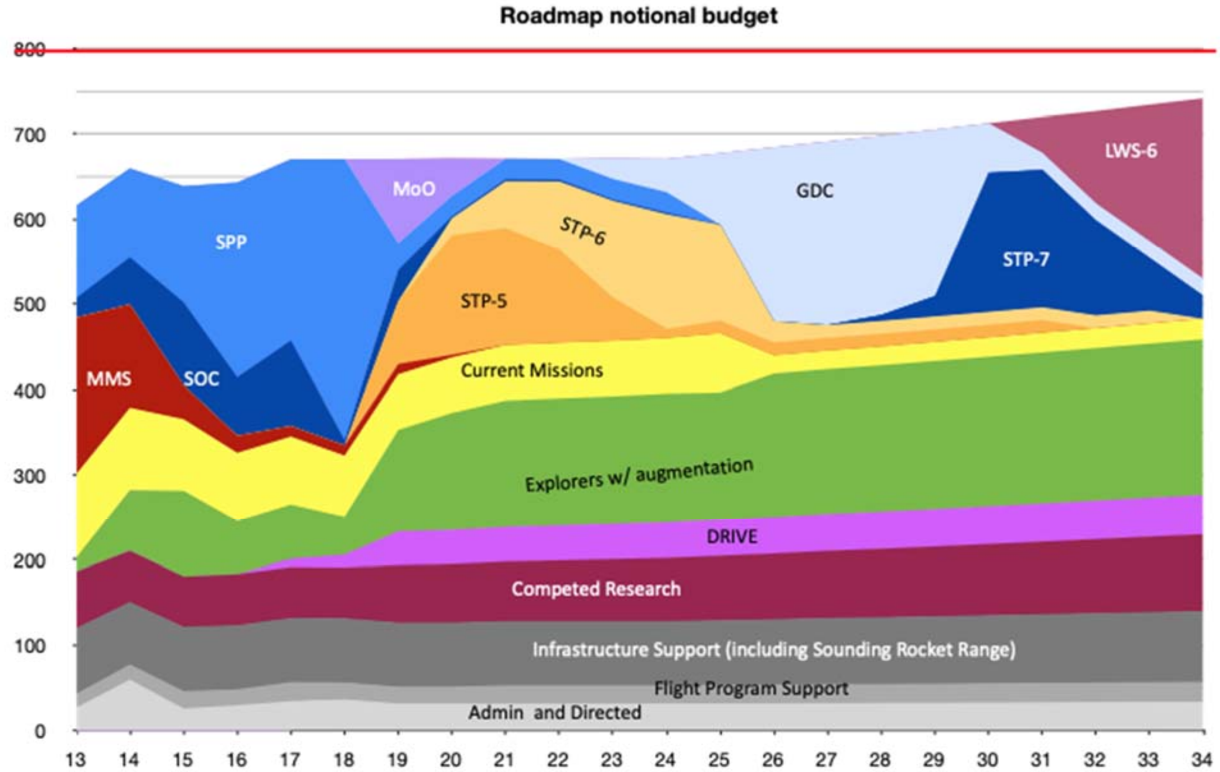

FIGURE 3.3 Full 20-year Heliophysics Division roadmap budget. NOTE: STP-5 = IMAP, STP-6 = DYNAMIC, STP-7 = MEDICI. SOURCE: Courtesy of NASA.

As of October 2019, the IMAP mission is in its formulation phase; the GDC mission has had only a community-supported concept study; and there are no current plans to start the DYNAMIC or MEDICI missions. *Given that neither the 2013 decadal survey nor the roadmap had activity planned for the MEDICI mission in the current decadal interval (Figure 3.3), with respect to future strategic missions, DYNAMIC and GDC missions are the primary focus of study for this midterm assessment (see Sections 3.5 and 3.6, respectively).* In addition to mission postponements, implementation of some DRIVE elements (e.g., Heliophysics Science Centers) has also been delayed, which Section 3.3 of this midterm assessment describes in detail.

The comparison of the roadmap notional budget and currently expected budget provided by NASA HQ requires some additional discussion. The "Research" branch in the NASA budget is separated into its component parts in the roadmap. This allows us to appreciate the impact of the DRIVE program on the competed (grants) research program; DRIVE represents about a 50 percent increase to competed research when fully funded. The amount of research support available to the community is only about 30 percent of the total research funds indicated in the NASA HQ plot, with the remainder of research funds taken up by infrastructure and management support. The budget presented to this committee by NASA (Figure 3.2, bottom) subsumes the DRIVE elements into this same research line after fiscal year (FY) 2019.

In addition to budgetary challenges, execution of the survey's recommended activities has occurred against a backdrop of frequent changes in HPD leadership. The current HPD Director, Dr. Nicola Fox, assumed her position in September 2018. Prior to her arrival, there had been six different directors or acting directors since 2011.

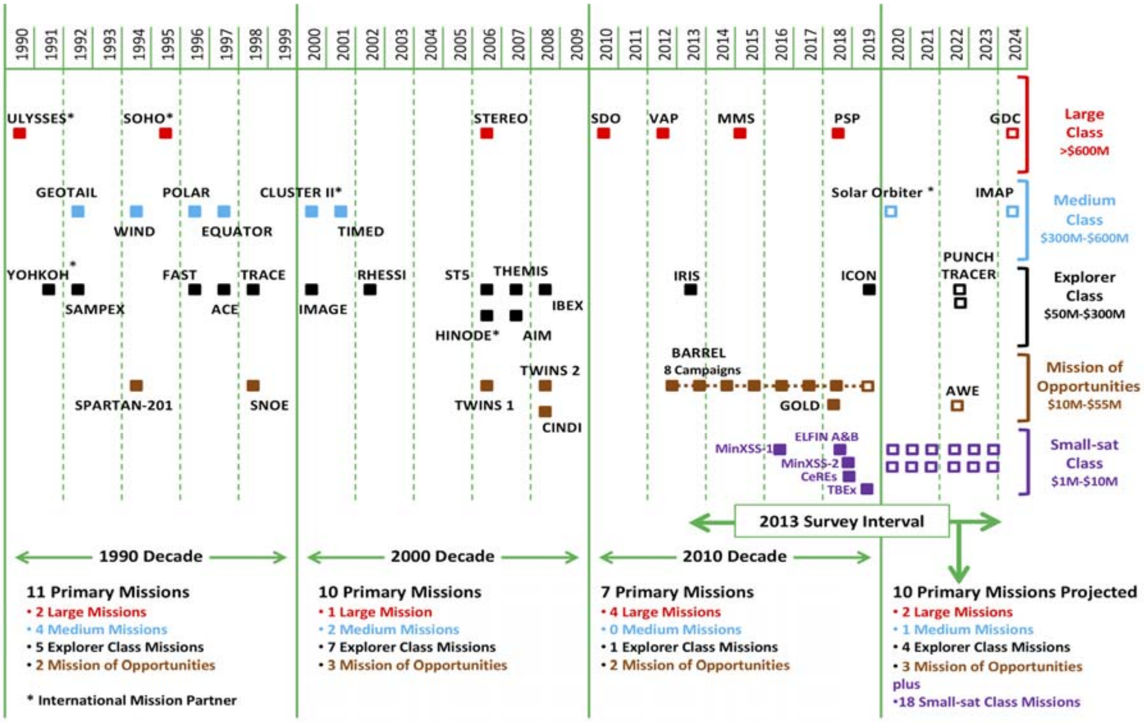

FIGURE 3.4. NASA Heliophysics Mission History from 1990 to Plans to 2023. Filled symbols are missions that have already been launched. Open symbols are planned launch dates. This figure is an updated version of the decadal survey Figure 6.2.

Despite management and budgetary challenges, NASA successfully launched three large-class missions—RBSP/Van Allen Probes, MMS, and PSP—(Figure 3.4). Only two Explorer missions (IRIS, ICON) have been launched in the current decade, a notable difference compared to activity in previous decades, illustrating the motivation for the decadal survey recommendation related to Explorers (see Section 3.4). No medium-class missions have been launched in this decade; however, Solar Orbiter is currently on track to launch in early 2020, and IMAP was recently selected as a principal investigator (PI)-led STP mission. Two new Explorer missions and one new mission of opportunity (MoO) have been selected in 2019. However, Explorers have not seen a reduction in development cost or time despite recent trends in small satellite manufacturing in the commercial sector.

NASA's CubeSat program has shown impressive growth with 18 missions currently in development or recently launched. In addition to missions, NASA has embraced the DRIVE initiative, creating new programs; for example, H-TIDeS ITD (Heliophysics Technology and Instrument Development for Science: Instrument and Technology Development), LNAPP (Laboratory Nuclear, Atomic, and Plasma Physics), and the much anticipated Heliophysics Science Centers (HSC), as well as expanding existing programs; for example, GI. NASA also continues to support the Heliophysics Summer School, which was established in 2006 to help train young scientists and has recently created a new program for early career investigators (ECIP).

The National Science Foundation (NSF) funding profile from 2012-2018 is shown in Figure 3.5. The AGS (Division of Atmospheric and Geospace Sciences) section has seen a 14 percent increase since 2012, with the majority of that increase since 2015. The 2016 NSF Geospace Portfolio review pointed out that 38 percent of the budget goes into operations and maintenance of facilities. The review made recommended closures or reduction in support for several Geospace Science (GS) facilities in order to enable new programs and facilities. In response, the Sondrestrom Incoherent Scatter Radar ceased operations in March 2018.

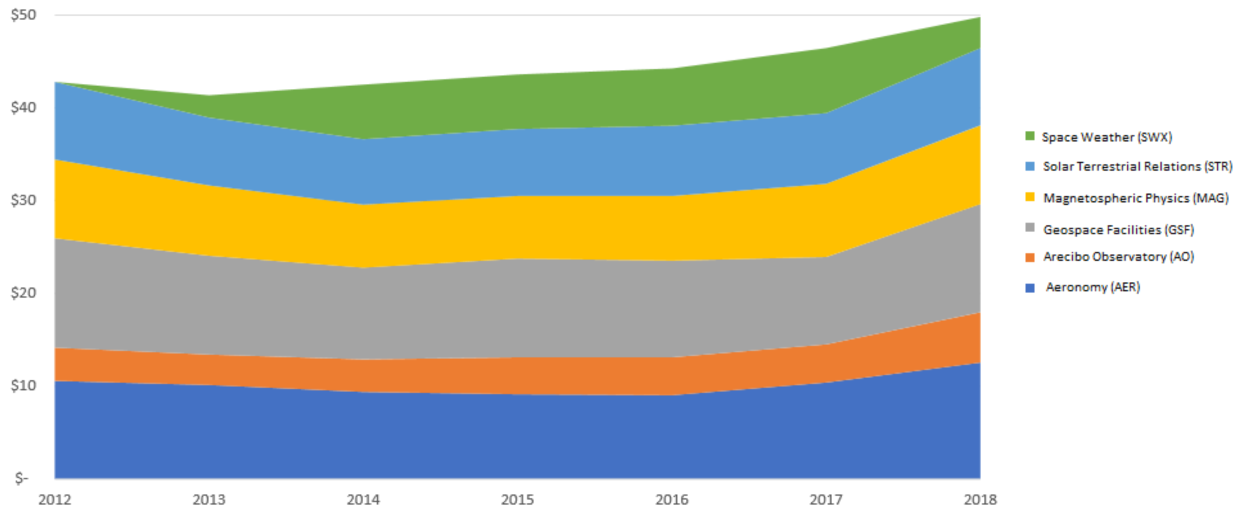

FIGURE 3.5 National Science Foundation Division of Atmospheric and Geospace Sciences (AGS) funding profile (in millions of dollars). NOTE: AER = Aeronomy; AO = Arecibo Observatory; GSF = Geospace Facilities; MAG = Magnetospheric Physics; STR = Solar-Terrestrial Relations; SWX = Space Weather. SOURCE: Presentation by Geospace Section Head M. Wiltberger, NSF, to the committee, February 25-26, 2019.

In 2016, NSF unveiled a set of 10 "Big Ideas," which are described as "bold, long-term research and process ideas that identify areas for future investment at the frontiers of science and engineering."[3] For 2019, NSF plans to invest $30 million for each Big Idea; some of which—for example, "Mid-scale Research Infrastructure"—provide new opportunities for GS awards, albeit only through success in a highly competitive program.

At NSF, construction of the Daniel K. Inouye Solar Telescope (DKIST) is nearing completion and is expected to see first light in late 2019 (see 3.3.2). A Memorandum of Understanding (MOU) was recently signed between NSF and NOAA to support continued operations of Global Oscillation Network Group (GONG) for synoptic observations, at least in the short term. Although the NSF CubeSat program has been highly successful and is largely responsible for the current success and growth of CubeSats more generally, the CubeSat solicitation was not offered between 2015 and 2018 as the program was reinvented as the foundation-wide CubeSat Ideas Lab program. Two Missions (VISORS, SWARM-EX) were selected for development in 2019 as a result of the first Ideas Lab workshop. NSF recently revived its Faculty Development in Space Sciences (FDSS) program, selecting six universities to hire new faculty in 2019-2020. A NSF midscale facilities program was recently created, competed across all NSF divisions. NSF has also continued support of the CISM summer school, now renamed the Boulder Space Weather Summer School.

A detailed assessment of progress towards all of the decadal survey recommendations is provided in the sections below. In Section 3.2, the baseline priority decadal survey recommendation is discussed. Progress towards each element DRIVE is discussed in Section 3.3, and NASA Explorers, STP, and LWS missions are discussed respectively in Sections 3.4-3.6.

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[3] See "NSF's 10 Big Ideas," available online at: https://www.nsf.gov/news/special_reports/big_ideas/index.jsp.

3.2 BASELINE PRIORITY FOR NASA AND NSF: COMPLETE THE CURRENT PROGRAM

The baseline recommendation made in the decadal survey was the following:

***Decadal Survey Recommendation R0.0*:**

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.

This recommendation recognizes the importance of studying the coupled Sun-Earth system as a whole, and thus the necessity of a coordinated Heliophysics System Observatory (HSO) which includes NASA's existing flight missions, missions under development, and NSF's ground-based facilities. To ensure a robust HSO, the baseline and highest priority recommendation made to NASA by the survey committee was to complete the missions that were then under development including the Radiation Belt Storm Probes (RBSP) and related Balloon Array for Radiation belt Relativistic Electron Losses (BARREL), the Magnetospheric Multiscale mission (MMS), and the Interface Region Imaging Spectrograph (IRIS) Explorer. For NSF, the decadal survey recommended continued development of the Advanced Technology Solar Telescope (ATST), which has since been renamed the Daniel K. Inouye Solar Telescope.

RBSP was launched in August 2012 shortly before completion of the decadal survey, and was subsequently renamed the Van Allen Probes, in honor of James Van Allen who is credited with discovering Earth's radiation belts. Van Allen Probes is part of the LWS mission line. It has been highly successful: with over 600 related publications since launch and a mission H-index[4] of 48, the mission has changed our view of the structure of Earth's radiation belts and led to unexpected discoveries. Some of these science highlights are described in Chapter 2 and Appendix E. The BARREL mission of opportunity carried out six balloon campaigns in support of the Van Allen Probes, with a total of 57 balloons launched from Antarctica and Sweden, revealing new information about electron loss to Earth's atmosphere. After nearly 7 years of operation, including 5 years of extended mission operations, the twin Van Allen Probes recently completed their end-of-mission deorbit maneuvers in late 2019.

The MMS was launched during the current decadal survey period in March 2015. The 4-spacecraft mission is the latest in the Solar Terrestrial Probe (STP) line. The prime mission duration was 2 years after the start of science operations in September 2015. The prime mission was highly successful, meeting all of its Level 1 requirements and, to date, producing over 470 publications and achieving a mission H-index of 45. A science highlight from the mission is described in Chapter 2. With the highest time resolution electron measurements and most accurate electric and magnetic field measurements in the reconnection electron diffusion regions at the magnetopause and in the magnetotail, MMS has revolutionized our understanding of reconnection physics.

The Interface Region Imaging Spectrograph, IRIS, is a NASA Small Explorer (SMEX) mission launched in June 2013 and designed to investigate the physics of the Sun's chromosphere, transition region, and corona. IRIS is the highest resolution observatory to provide spectra and images with seamless coverage from the photosphere into the corona. The unique combination of spectra and images at 0.33 arcsec resolution in the far ultraviolet (including C II and Si IV lines) and 0.4 arcsec resolution in the near ultraviolet (including the Mg II h & k lines), at a cadence as high as 2s, allows the tracing of mass and energy through the critical interface between the solar surface and the corona. An integral part of the IRIS science investigation is the development and public release of advanced numerical models to allow detailed statistical comparisons between IRIS observations and synthetic variables from the

[4] For more on the H-index, see: https://bitesizebio.com/13614/does-your-h-index-measure-up/ and references therein.

simulations. During more than 6 years of operation, IRIS has enabled crucial research on each of the four Key Science Goals of the solar and space physics decadal survey, as well as many of the Research Focus Areas of the Heliophysics roadmap. The application of machine learning techniques, combined with the extensive database of IRIS observations, has also revolutionized our diagnostic capabilities of the solar chromosphere, a key region in the solar atmosphere that will be the focus of NSF's new 4m DKIST telescope. IRIS has produced over 315 publications and achieved a mission H-index of 35.

The missions above were in advanced stages of development at the time of the decadal survey. Thus, per the survey's task statement, these missions were not included in prioritization exercises. However, the decadal survey committee did review two missions that were in earlier planning stages.[5] Solar Orbiter is a European Space Agency (ESA)-NASA partnership that was targeted for 2017 launch with the objective of investigating connections between the solar surface, corona, and inner heliosphere from a distance of 62 solar radii. Solar Probe Plus was a mission under development that would fly closer to the Sun than ever before, discovering how the corona is heated and how the solar wind is accelerated. Both of these missions are part of the Living With a Star (LWS) program. Solar Probe Plus was renamed Parker Solar Probe (PSP) after Eugene Parker in May 2017, just over a year before its successful launch on 12 August 2018. The spacecraft will make 24 orbits around the Sun during its prime mission (2018-2025), diving closer and closer to the Sun. PSP has so far completed three perihelion passes (November 5, 2018, April 4, 2019, September 1 2019) and has set the record for closest approach to the Sun and fastest human-made object. An early science result is highlighted in Appendix E. A special issue of the Astrophysical Journal on PSP early results has over 50 submitted papers and is expected out in 2020.

NASA's primary contribution to the ESA-led Solar Orbiter mission is the launch services aboard an Atlas V, with the current plan to launch Solar Orbiter in February 2020. NASA also supports the mission science and instrument hardware for the Heliospheric Imager (SoloHI), Heavy Ion Sensor (HIS), Energetic Particle Detector (EPD), Solar Wind Plasma Analyser (SWPA), and Spectral Imaging of the Coronal Environment (SPICE). The Solar Orbiter will be in an elliptical orbit about the Sun with closest approach near the orbit of Mercury (0.3 AU). The Solar Orbiter will study the dynamics and energetics in the inner heliosphere that complement solar observations by NASA's PSP, SDO, IRIS, and STEREO satellites and NSO's DKIST ground-based observatory. The Solar Orbiter's orbital inclination will be raised to 25° over its 7-year mission (and up to 34° for an extended mission), thus providing new glimpses of the solar pole's magnetic fields that are crucial drivers for the solar dynamo 22-year cycle.

Construction of the ground-based solar telescope DKIST, formerly called ATST, was just underway when the decadal survey was published. With a 4-m aperture, DKIST is by far the largest optical solar telescope in the world and will provide extremely high-resolution measurements of the Sun. Construction is nearing completion, with first light expected Fall 2019. DKIST status and operations are discussed further in Section 3.3.2 below.

> ***Finding 3.1:*** Completion of the program of record as recommended in the decadal survey, combined with new tools and data analysis approaches, has resulted in significant scientific advances (see Chapter 2) and has added important elements to the Heliophysics System Observatory.

3.3 IMPLEMENT THE DRIVE INITIATIVE

Decadal Survey Recommendation R1.0:

[5] Originally, the survey's task statement excluded from consideration Solar Probe Plus. Midway through the survey, NASA requested that the survey committee comment on the scientific rationale for the mission in the context of scientific developments since the publication of the 2003 decadal survey. In addition, the survey committee was asked to provide appropriate programmatic or cost triggers as part of the anticipated decision rules to guide NASA in the event of major technical, cost, or programmatic changes during the development of SPP.

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 initiation of DRIVE was recommended to maximize the science return from NASA heliophysics missions and NSF large solar and space physics ground-based facilities by coordinating existing research programs and making specific, cost-effective augmentations. Specifically, DRIVE aims to “diversify” observing platforms, “realize” the scientific potential of existing assets, “integrate” observing platforms into successful investigations, “venture” forward with new technologies, and “educate” the future heliophysics workforce. Among the specific items highlighted in the decadal survey are increased opportunities for small satellite projects, implementation of an NSF mid-scale facilities line, creation of heliophysics science centers, and increased investment in instrument development.

At NASA, the Research & Analysis (R&A) programs continue to be a major source of support for science research and have taken over much of the research formerly under Mission Operations and Data Analysis (MO&DA) within the mission lines. This is especially true for the large number of heliophysics missions in their extended mission phase. Proposal success rates for non-technological R&A programs at NASA hover around 20-25 percent as of this writing, which is an approximately 5-10 percent increase over rates several years ago. At NSF, operations of solar, space physics, and geospace facilities and data analysis are funded out of the Division of Atmospheric and Geospace Science (AGS) and Division of Astronomical Sciences (AST) under the Directorate for Geosciences and Directorate for Mathematics and Physics Sciences, respectively.

The decadal survey made 16 specific sub-recommendations under the top-level DRIVE recommendation. Progress for DRIVE is summarized in Figure 3.1. NASA research spending exceeded the 2014 Heliophysics roadmap expected spending during the first part of the decade (Table 3.1). While HPD lags behind other NASA SMD divisions in growth, the research grants program is healthy. This is consistent with the decadal survey rules of the road for spending priorities.

Table 3.2 shows the breakdown of DRIVE funding by the NSF Geospace program for 2012-2018. The modest increase in funding for GS is spread relatively evenly across the programs, although the Space Weather (SWx) program has seen a reduction.

A detailed discussion of progress on each DRIVE sub-element is provided in Sections 3.3.1 to 3.3.5, along with a discussion of the relevant programmatic and other changes that have occurred since the decadal survey was published. In Section 3.3.6, recommendations are made to the agencies for implementing DRIVE through the remainder of the decade.

TABLE 3.1 Budget Actuals for NASA Heliophysics Research Programs (in millions of dollars)

NASA HPD Research Program	FY15	FY16	FY17	FY18	FY19	FY20
Guest Investigator	9.3	9.1	10.3	15.6	20.0	21.0
Supporting Research	19.6	16.0	15.5	25.4	26.3	27.1
Grand Challenge	4.3	4.3	4.2	4.6	8.0	9.0
Living With a Star Science	17.4	18.4	18.0	23.8	29.0	30.3
Early Career					1.5	1.5
Data Enhancements	2.0	2.6	2.7	2.7	3.0	3.0
Low Cost Access to Space (LCAS)	6.0	7.1	8.7	11.6	18.8	21.5
SmallSats (including CubeSats)	3.0	1.5	7.9	11.5	23.6	18.5
Instrument Technology Development (ITD)	3.2	6.1	5.2	10.4	11.0	6.9
Laboratory Nuclear, Atomic, and Plasma Physics (LNAPP)	0.2	0.8	0.9	0.8	0.6	0.6
Space Weather Science & Applications			5.0	15.7	20.0	15.9
Total	65.0	65.9	78.4	122.1	161.8	155.3

ROADMAP Expected Budget	59	60	69	74	99.4	107

NOTE: Provided by NASA HPD and the summed expected research budget from the NASA HPD roadmap. Note that the roadmap didn't include any Space Weather Research Funding after FY 2014.

TABLE 3.2 National Science Foundation (NSF) DRIVE Funding (in millions of dollars)

NSF Geospace DRIVE Funding	FY12	FY13	FY14	FY15	FY16	FY17	FY18	Total
Aeronomy (AER)	10.6	10.1	9.4	9.1	9.0	10.4	12.6	71.3
Arecibo Observatory (AO)	3.6	3.3	3.5	4.0	4.1	4.1	5.4	28.0
Geospace Facilities (GSF)	11.8	10.6	9.9	10.6	10.4	9.4	11.7	74.4
Magnetospheric Physics (MAG)	8.5	7.6	6.8	6.8	6.9	7.9	8.5	52.9
Solar Terrestrial Research (STR)	8.4	7.3	7.1	7.2	7.6	7.6	8.3	53.5
Space Weather (SWx)	—	2.4	5.9	5.9	6.2	7.0	3.3	30.7
Grand Total	42.8	41.3	42.5	43.6	44.3	46.5	49.8	310.7

SOURCE: Presented to the committee by the NSF Geospace Section Head.

3.3.1 DRIVE Diversify

Diversify observing platforms with microsatellites and midscale ground-based assets.

Progress Toward Decadal Survey Recommendations

The decadal survey made several recommendations to develop an increasing diversity of observing platforms, both on the ground and in space. Heliophysics has a long history of successful suborbital experiments that make use of sounding rockets and balloons, and their importance was reaffirmed in the decadal survey.[6] Sounding rockets are the only platform that can make in situ measurements in the mesosphere and lower ionosphere (40-150 km), between the altitudes accessible by balloons and LEO satellites. Balloons can carry heavy payloads high in the atmosphere (typically up to approximately 50 km) and have been instrumental in solar physics and particle precipitation studies. Rockets and balloons have also been used to augment larger NASA missions.[7]

The technology and launch opportunities for CubeSats as science missions have grown at a rapid pace. The NSF Directorate for Geospace Science was first to implement a modest CubeSat research-education program in 2008. For example, one of the highly successful NSF Geospace CubeSats is the Colorado Student Space Weather Experiment (CSSWE) with more than 20 science papers, including one in *Nature* (Li et al., 2017). The decadal survey recognized the potential for space science at low cost using CubeSats.

Decadal Survey Recommendation: **A NASA tiny-satellite grants program should be implemented, augmenting the current Low-Cost Access to Space (LCAS) program, to enable a broadened set of observations, technology development, and student training. Sounding rocket, balloon, and tiny-satellite experiments should be managed and funded at a level to enable a combined new-start rate of at least six per year, requiring the addition of $9 million**

[6] See Appendix C of 2013 Decadal Survey

[7] For example, BARREL recently made supporting measurements of precipitation in support of the Van Allen Probes mission (e.g., Woodger et al., 2015) and the solar EUV underflight calibration rocket flights supported SDO.

per year (plus an increase for inflation) to the current LCAS new-start budget of $4 million per year for all of solar and space physics.

NASA SMD released the first grant solicitation for scientific CubeSats as part of ROSES 2013.[8] The first NASA Heliophysics CubeSat science mission, the Miniature X-ray Solar Spectrometer (MinXSS), was launched in December 2015 to the International Space Station (ISS) and had a highly successful mission until May 2017 when it re-entered Earth's atmosphere. MinXSS was the first CubeSat mission to demonstrate precision 3-axis pointing control of better than 10 arcsec, which enables new scientific observations that require fine pointing control. MinXSS also made new observations of the solar X-ray spectrum to study flare energetics and coronal heating (Woods et al., 2017).

NASA support for scientific CubeSats has steadily grown, and there are now 18 CubeSat science missions funded in the NASA Heliophysics Division. As of August 2019, six (6) NASA funded CubeSats have been launched and another 12 are in development. Of the six NASA CubeSats launched, three have achieved full success, two have achieved partial success, and one is still in commissioning. The small augmentation to ROSES of $10 million for all SMD CubeSats in 2014 has now expanded to include a dedicated SmallSats and Rideshare Opportunities (SRO) line with a $9 million per year budget in the *Heliophysics Flight Opportunities for Research and Technology* (H-FORT) program, initiated in ROSES 2019.[9] The era of science exploration with CubeSats has just begun, and the community is already looking ahead towards constellations of small satellites to provide global coverage with much higher time cadence than what single, larger satellites have traditionally accomplished. NASA HQ (through the H-TIDES program) originally managed NASA Heliophysics CubeSat missions but oversight support has since expanded in 2019 to the NASA GSFC Wallops Small Satellite Project Office.

> ***Finding 3.2:*** CubeSat missions are intended to be low-cost, higher-risk exploratory missions. The number of CubeSat science missions has increased significantly in this decade. While recognizing the challenge of managing a rapidly increasing number of CubeSat projects, NASA will need to ensure that managerial oversight does not translate into the imposition of additional reviews and reporting requirements to the level of larger missions.

Suborbital projects are also supported by the NASA ROSES omnibus solicitation. Figure 3.6 shows the number of suborbital and CubeSat H-TIDeS selections from 2013-2018. The overall selection rate of both suborbital and CubeSat projects has increased, and the inclusion of CubeSats in the solicitation has not had a significant impact on the number suborbital projects selected.

In summary, NASA Heliophysics has implemented a robust and growing CubeSat program. As development takes 3-4 years per mission, the realization of science results and benefits from these new CubeSat science missions is expected during the later half of the heliophysics decade (2019-2023). Additionally, the total number of rocket, balloon, and CubeSat selections has met or exceeded the new start rate of six per year that was recommended in the decadal survey.

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[8] ROSES-2013 separated the "Geospace Science" program, which formerly included Low Cost Access to Space (LCAS), into a number of distinct programs, including Heliophysics Technology and Instrument Development for Science (H-TIDeS). Appendix B.3 for this element states, "This program has three main research thrusts, (1) payloads on balloons, sounding rockets, or as secondary, rocket-class payloads, including CubeSats and International Space Station payloads, on flights of opportunity collectively referred to as Low-Cost Access to Space (LCAS), (2) Instrument and Technology Development (ITD) that may be carried out in the laboratory and/or observatory, and (3) enabling Laboratory Nuclear, Atomic, and Plasma Physics (LNAPP)."

[9] In 2019 NASA created a separate ROSES element, H-FORT, for "Flight Opportunities for Research and Technology" that covered the LCAS (sub-orbital rockets and balloons) and SmallSat and Rideshare Opportunities (SRO). H-TIDeS continues as the program for Laboratory Nuclear, Atomic, and Plasma Physics (LNAPP) and Instrument Technology Development (ITD).

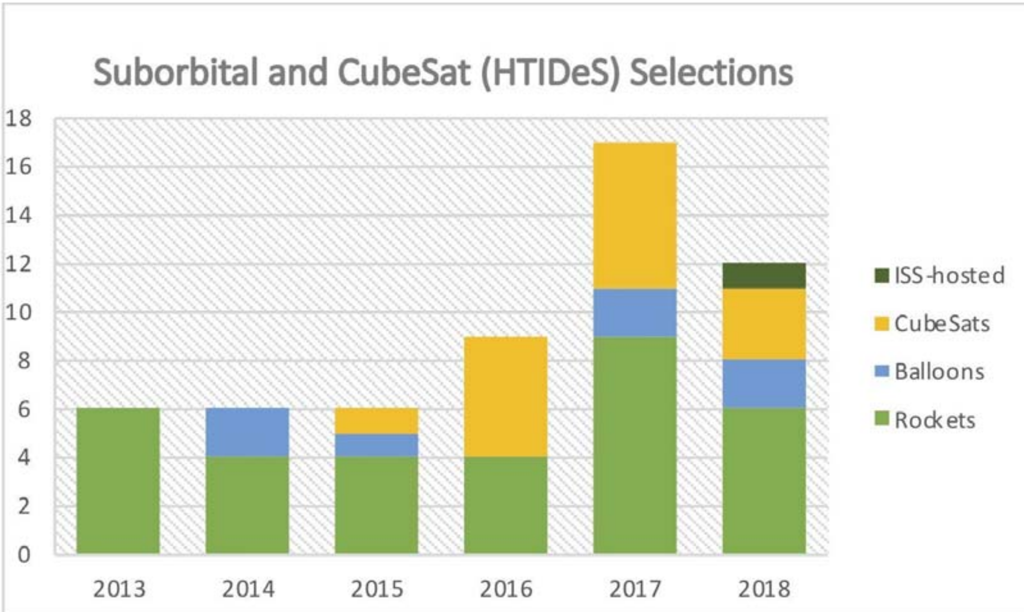

FIGURE 3.6 The number of sounding rocket, balloon, CubeSat, and ISS-hosted instrument proposals selected through the H-TIDeS subelement of NASA ROSES from 2013-2018. Data taken from NASA NSPIRES.

> ***Decadal Survey 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 program in terms of training, research, technology development, and contributions to space weather forecasting.**

For NSF, no CubeSats were selected for funding in 2013 and 2014, while three were selected in 2015. There is also a notable gap between 2015 and 2018, during which the CubeSat solicitation was not released. Two new CubeSat missions were selected for funding at the end of 2018. Following a recommendation that was made in the NSF Portfolio review, a cross-division[10] initiative to spur CubeSat innovation — CubeSat Ideas Lab — was created in 2019. The vision of the Ideas Lab is to "support research and engineering technology development efforts that will lead to new science missions in geospace and atmospheric sciences using self-organizing CubeSat constellations/swarms" (NSF, 2019a). Through this program, NSF initiated a study of constellation concepts and recently selected two 3-satellite constellation projects.

> ***Finding 3.3:*** NSF's CubeSat Program had no new solicitations between 2015 and 2018 and has not received a significant augmentation. However, the new CubeSat Ideas Lab initiative, if continued, will reinstate the program to the level that was recommended in the decadal survey.

In addition to the space-based suborbital and CubeSat platforms discussed above, the decadal survey recognized the importance of ground-based facilities. Facilities such as solar radio arrays, radars, riometers, and magnetometer arrays provide a more global view of the geospace system, and allow for long-term monitoring. All of these instruments also provide important context for single-point spacecraft

[10] The Ideas Lab is organized by the Division of Atmospheric and Geospace Sciences (AGS) in the Directorate for Geosciences (GEO), the Division of Computer and Network Systems (CNS) in the Directorate for Computer and Information Science and Engineering (CISE), and the Division of Electrical, Communications and Cyber Systems (ECCS) and the Division of Engineering Education and Centers (EEC) in the Directorate for Engineering (ENG).

measurements. While recognizing the importance of these facilities, the decadal survey also pointed out that there is a critical funding gap between relatively small to moderate ground-based projects and the very large facilities funded by the agency (such as DKIST). Two key midscale initiatives — the Frequency Agile Solar Radiotelescope (FASR) and the COronal Solar Magnetism Observatory (COSMO) — were identified as priority mid-scale ground-based infrastructure. At the time, no opportunities existed for funding projects of this size.[11]

> ***Decadal Survey 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.**

In response to broad community interest, the NSF has created a budget line for mid-scale research infrastructure[12] as one of its 10 "Big Ideas." Two new solicitations were announced in 2018: the Mid-scale Infrastructure 1 (Mid-scale RI-1) program solicited projects in the $6 million to $20 million range (proposal deadline May 20, 2019), and the Mid-scale RI-2 program targeted projects in the $20 million to $70 million range (proposal deadline August 2, 2019). The Mid-scale RI-1 program also supports design and development programs in amounts down to $600,000. In addition, the threshold for eligibility for the MREFC line was reduced from 10 to 5 percent of an annual directorate budget, or roughly $70 million. These programmatic initiatives by NSF are necessary steps to address the long-standing need of the research community for a more balanced portfolio of research infrastructure in solar and space physics. However, since these opportunities are competed across multiple NSF divisions, the likelihood of more than one proposal in solar and space physics being selected is expected to be low. The AST and AGS divisions need to make the necessary investments to position priority initiatives to compete for midscale project funds successfully. Chapter 6 discusses how the solar and space physics community could improve their chances of being awarded a mid-scale facility.

> ***Finding 3.4:*** NASA and NSF have provided a number of opportunities for the science community to add to the array of diverse observing platforms that enable heliophysics science, including a robust and growing NASA CubeSat program, continuation of a strong suborbital program, and creation of a NSF midscale facilities program.

The Changing Landscape Related to Diverse Observing Platforms

Since the decadal survey was published, there have been significant developments related to small satellites, particularly in the commercial sector. New additions to low Earth orbit (LEO) activity are the planned large satellite constellations, or mega-constellations, promising continuous, global communication and Internet services. Such proposed constellations include SpaceX with 4,000 satellites, Samsung with 4,200 satellites, and OneWeb with 720 satellites (Radtke et al., 2017). This presents potential new opportunities for science, including leveraging the technology development, increased rideshare opportunities, and commercial data buy opportunities.

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[11] At the time of survey publication, the NSF equipment and facilities program supported investments in both small and very large facilities. NSF maintained a major research instrumentation program for instrument development projects (less than $4 million per year) and the Major Research Equipment and Facilities Construction (MREFC) program for large infrastructure projects (greater than 10 percent of an annual directorate budget, of order $140 million).

[12] Creation of the mid-scale line followed the recommendations of the National Science Board. See *Bridging the Gap: Building a Sustained Approach to Mid-Scale Research Infrastructure and Cyberinfrastructure*, NSB-2018-40, October 1, 2018, https://www.nsf.gov/nsb/publications/2018/NSB-2018-40-Midscale-Research-Infrastructure-Report-to-Congress-Oct2018.pdf.

A number of studies have been carried out to assess the scientific potential of small satellites. The 2015 National Academies of Scienes, Engineering, and Medicine report, *Achieving Science with CubeSats*, recognized that CubeSats have already had a scientific impact, and they have significant potential in specific areas of heliophysics research.[13] An Explorer mission of opportunity, SunRISE, was recently selected for an extended Phase A concept study utilizing a small constellation of CubeSats to study solar radio bursts. Thus, CubeSats are already being proposed for larger missions. The recent COSPAR roadmap study for small satellites in space sciences outlined the science potential and opportunities for leveraging developments in the commercial sector (Millan et al., 2019).

On the issue of CubeSats, the 2016 NSF Geospace portfolio review (Lotko et al., 2016) recommended an increased emphasis on scientific mission concepts and instrument development, and less emphasis on engineering of CubeSat buses and communication systems. This recommendation was intended to encourage NSF as a whole to develop a proper home for the CubeSat program, which embodies both science and technology, with potential applications beyond the Geospace Section. In response, Geospace leadership at NSF has taken an innovative approach to advancing the CubeSat program by teaming with the Engineering Directorate (ENG) and the Directorate for Computer and Information Science and Engineering (CISE) to create the CubeSat Ideas Lab (described above).

3.3.2 DRIVE Realize

Realize scientific potential by sufficiently funding operations and data analysis.

Progress Toward Decadal Survey Recommendations

The 2013 decadal survey DRIVE/Realize recommendations had elements directed both to NSF and to NASA. Recommendations addressed to each agency are discussed separately below, followed by consideration of the role of data science in meeting DRIVE/Realize recommendations.

DRIVE/Realize for NSF

NSF's role in DRIVE includes support of essential ground-based facilities for obtaining synoptic data sets, such as the GONG solar magnetic maps regularly used for global coronal and solar wind analyses, modeling, and forecasting. These facilities continue to struggle to survive in spite of their widespread use. In addition, with the construction of DKIST, a major, new need for infrastructure support to maintain and utilize this state-of-the-art research tool must also be managed.

> ***Decadal Survey 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.**

With respect to synoptic observations, FY 2016 support for the National Solar Observatory (NSO) included a one-time $2.50 million investment in GONG to increase its robustness for future space weather predictions. NSO is in the process of upgrading the GONG facility with this funding, with completion expected in FY 2020. As part of the NSF plan to ramp up DKIST operations support, NSO's synoptic program was cut from about $4 million per year to $2 million per year. This is partially mitigated by a NSF and NOAA interagency agreement in 2016 whereby NOAA is providing

[13] For Heliophysics, the report noted that CubeSats can provide measurements from high risk orbits, augment large facilities with targeted supporting measurements, and have the potential to enable constellation missions.

approximately $800,000 per year in funding support for GONG operations.[14] However, concerns remain that the GONG and other synoptic observations by NSO are at high risk of ceasing operations in 2021 when the NOAA-NSO agreement ends. NSO proposals to the Air Force and NSF to enhance the synoptic instrumentation for research and space weather operations were declined in 2019. To maintain and grow the synoptic program beyond the NOAA-NSO agreement, NSO would need additional funding sources prior to 2021. As one example, such support could be acquired through the NSF Mid-Scale RI program.

> ***Finding 3.5:*** A plan exists to support NSO's synoptic observations in the short term. The long-term plan past 2021 for supporting these synoptic observations is unclear. To address this would require immediate attention.

The Daniel K. Inouye Solar Telescope (DKIST, formerly ATST) is a ground-based, advanced-technology solar telescope operating at optical and infrared wavelengths. As an NSF AST facility operated by the National Solar Observatory, DKIST will be the flagship ground-based solar facility for the foreseeable future. Located on the summit of Haleakala on Maui, Hawaii, this $344 million construction project is nearing completion,[15] and operations of DKIST should commence in summer of 2020.

Planning for operations of DKIST continues in parallel to the construction effort. Operations staffing is ramping up, and the DKIST Science Support Center on Maui has been completed. The DKIST Data Center, located in Boulder, Colorado, will process, store and distribute approximately 3 PB/year of fully calibrated data to the user community (i.e., Level 1 data). The data center completed its design phase in 2019 and is now entering the implementation phase. The community, led by the DKIST Science Working Group, is preparing the critical science plan, which captures high-priority observations to be conducted with DKIST during the initial operations phase.

The DKIST steady state operating cost is estimated to be $21.6 million per year, 13 percent higher than that estimated for the current AURA-NSO Cooperative Agreement (CA) for FY 2015-2024. However, by re-profiling the budget, NSO expects to remain within the 10-year CA budget. Under this plan, DKIST Data Center will provide Level 1 data, but the production of derived data products (Level 2 data) for detailed scientific research—e.g., magnetic field, temperature, and velocity in the solar atmosphere—are not included in current science operations planning.

NSF has recently provided supplemental funds to NSO for 2 years ($7 million total[16]) to define Level 2 data products and to develop processing algorithms under a plan that involves NSO scientists, postdocs, and graduate students from the community. The prospects for providing Level 2 data products to the community as part of steady state operations are not clear. The committee has concerns that there is no funding identified to routinely process or to improve Level 2 products past 2020. Continuation of the DKIST Level 2 development is important and is motivated by the 2013 decadal survey statement: "Realizing the full scientific potential of solar and space physics assets … requires investment in their continuing operation and in effective exploitation of data."

[14] Information from the FY 2019 NSF Budget Request to Congress. See https://www.nsf.gov/about/budget/fy2019/pdf/40t_fy2019.pdf.

[15] All major site construction is complete. All large mechanical structures, including the Telescope Mount and the Coudé rotator, have been integrated and tested. The DKIST 4-meter primary mirror and the secondary mirror have been installed and aligned to specifications. The telescope has achieved first light pointing at stars and planets. Integration of instrument systems, including the polarization calibration unit, is now progressing (Rimmele, 2019). The integration, test, and commissioning phase of the project will continue into 2020 with the installation of optics to complete the optical path to the Coudé instrument laboratory and implementation of adaptive optics and four first-light instruments. The first high-resolution solar images from DKIST's Visible Broadband Imager are scheduled to be obtained in fall of 2019 (V.M. Pillet, personal communication, 2019).

[16] See https://www.nsf.gov/about/budget/fy2020/pdf/27_fy2020.pdf.

Finding 3.6: The scientific success of DKIST will depend on Level 2 and higher data processing. The committee is concerned that provision of robust Level 2 data products to the user community is not part of steady-state operations planning and no resources have been allocated by NSF for Level 2 data products and their development past 2020.

DKIST, like other NSF facilities in the AST division, will include a proprietary period during which data will not be publicly available. Additionally, there does not appear to be a plan for development of analysis tools to facilitate broad use of the data. In contrast, NASA's SDO (Solar Dynamics Observatory) mission, which was recommended in the 2001 decadal survey of astronomy and astrophysics at the same time that DKIST was recommended, made data available to the international community in near-real time. From the first, there was a library of SDO software tools that could be applied to aid in the production of scientific results. Further, NASA funds were available to carry out the SDO data analysis. DKIST will be a giant step forward in understanding how magnetic fields are generated and dispersed over the solar surface, how flares occur, how prominences are formed, and how coronal mass ejections are driven. In order to realize this scientific potential, DKIST data will be combined with data from NASA, ESA, and JAXA missions. The mission science teams will expend a great deal of effort to supply collaborative observations that are freely available, while the DKIST observations are proprietary.

Finding 3.7: DKIST is the flagship observatory of NSF solar astronomy. DKIST funding past 2020 supports primarily DKIST operations and its data center, but with limited support for research. Substantial research funding, of more than $5 million per year, from NSF needs to be available in anticipation of the number of science proposals that will be submitted. Coordinated efforts that use DKIST along with NASA, ESA, and JAXA mission data will lead to scientific breakthroughs, requiring adequate support.

At NSF, the construction of large facilities is typically funded by programs outside of the divisions (e.g., AGS or AST); however, maintenance and operating costs must be covered by the division budget. Every new facility comes with a large operations and maintenance cost within a fixed divisional budget. This has led to closure of the Sondrestrom facility and funding challenges for the Arecibo Observatory. As another example, DKIST construction funds came from the NSF facilities budget, while its operations budget and grants program will be in the AST budget—a budget that will not be incremented because of the new major facility. This results in the paradox that the world's most scientifically powerful ground-based solar telescope will reduce the funding available to support that very telescope's scientific potential.

A recent National Science Board (NSB) study[17] was conducted on operations and maintenance costs for NSF facilities. This study found that, because operations and maintenance costs have not been a major budgetary problem for NSF as a whole, impacts at the divisional level might not be apparent. Moreover, choices made at the divisional level out of budgetary necessity, such as maintenance deferral, descoping of science, and underutilization, may not be in alignment with NSF's strategic priorities. The report recommended that (1) the NSB and the NSF director should continue to enhance agency-level ownership of the facility portfolio through processes that elevate strategic and budgetary decision-making, (2) NSF and NSB should reexamine what share of NSF's budget should be devoted to research infrastructure, and (3) NSB and NSF should develop model funding and governance schemes for the next generation of partnerships at the agency, interagency, and international levels. Such recommendations could be achieved, for example, by having separate maintenance and operational budgets for any facilities developed with the support of NSF funding at the agency level rather than at the division level.

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[17] NSB, *Study of Operations and Maintenance Costs for NSF Facilities*, NSB-2018-17, https://www.nsf.gov/nsb/publications/2018/NSB-2018-17-Operations-and-Maintenance-Report-to-Congress.pdf.

Finding 3.8: The operations and maintenance model for NSF's large facilities has had significant impacts on the AGS and AST budgets.

DRIVE/Realize for NASA

In order to realize the scientific potential of the Heliophysics System Observatory (HSO), the decadal survey recommendations to NASA included increased mission operations and data analysis (MO&DA) funding and institution of a mission-specific guest investigator (GI) program.

Decadal Survey Recommendation: **NASA should permanently augment MO&DA support by $10 million per year plus annual increases for inflation, in order to take advantage of new opportunities yielded by the increasingly rich Heliophysics Systems Observatory assets and data.**

In making this recommendation, the decadal survey refers both to MO&DA funding for mission extensions and the importance of a stable general GI program. However, the suggested funding increase appears to refer only to MO&DA for extended missions. Table 3.3 shows the 2014 Heliophysics roadmap extended mission operations budgets for 2013 and 2017 versus the FY 2017 actuals taken from the 2018 OIG report. The GI program budget is not included. Note that NASA HPD had no missions in prime operations phase in 2017. The comparison between 2013 and 2017 may in part reflect how mission costs are bookkept. Nevertheless, the MO&DA funding for some missions was higher than projected in the roadmap budget for FY 2017.

In the years leading up to the last decadal survey, support for the GI program was sporadic. The decadal survey pointed out the importance of a stable GI program and also recommended creation of a mission-specific directed GI element in order to address cuts in both Phase E mission funding and cuts in the general GI program that occurred in the prior decade (e.g., see Box 4.2 in the decadal survey).

Decadal Survey Recommendation: **A directed guest investigator program, set at a percentage (approximately 2 percent) of the total future NASA mission cost, should be established in order to maximize each mission's science return. Further, just as an instrument descoping would require an evaluation of impact on mission science goals, so, too, should the consequences of a reduction in mission-specific guest investigator programs and Phase-E funding merit an equally stringent evaluation.**

Funding for the GI program has increased from $9 million in 2015 to an expected $21 million in 2020 (Table 3.1), compared with a notional approximately $8 million in the 2014 roadmap. In 2013, the ROSES GI element solicited both general proposals and proposals that focused on the Van Allen Probes mission. ROSES-2014 GI was also open to general and mission-specific (Van Allen Probes/BARREL and IRIS) proposals. In ROSES-2016 and 2017, however, the GI program was separated into two different elements, an open GI element and a mission-specific (MMS) element. ROSES-2018 included only an open GI program. The intended ICON/GOLD GI element was delayed; the solicitation states, "This Program element has been delayed to ROSES-2019, at which point the data streams will be stable for both missions." However, ROSES-2019 also did not include this program element, presumably due to the ICON launch delay, though GOLD has been operating for well over a year. The ROSES solicitation in 2019 did include both the open GI program and an outer heliosphere element which supports analysis of IBEX, Voyager, and other relevant heliospheric data, such as from New Horizons and Cassini. However, while a healthy GI program is critical in enhancing the scientific potential of missions, particularly in their extended phase, it does not support the mission team and primary science objectives, and thus should not be viewed as a replacement for adequate Phase E funding.

TABLE 3.3 Comparison of Extended Mission Operating Costs (in millions of dollars), 2013 and 2017

Mission	Roadmap 2013	Roadmap 2017	2017 Actuals*
ARTEMIS/THEMISa	$4.4	$4.5	$5.4
ACE	3.0	3.0	3.0
AIM	3.0	3.0	3.0
Cluster	0.4	0.0	not included
GEOTAIL	0.5	0.2	0.4
Hinode	8.0	7.0	7.0
IBEX	4.0	3.4	3.4
IRIS	prime	1.0	7.7
MMS	pre-launch	12.0	19.9
RHESSI	2.0	1.9	1.9
SDO	prime	10.5	12.1
SOHO	2.1	2.1	2.3
STEREO	9.0	10.0	6.5
TIMED	3.0	3.0	2.6
TWINS	1.0	0.6	0.6
Van Allen	prime	6.0	13.3
Voyager	5.3	5.5	5.6
WIND	2.1	2.0	2.2
Total	**47.8**	**75.7**	**96.9**

*From OIG Report, Table 2

NOTE: From the NASA 2014 Heliophysics roadmap with actual 2017 costs taken from the 2018 Office of the Inspector General report. Missions in prime phase or pre-launch were not included in the totals as indicated. These costs are not adjusted for inflation, so a flat budget between 2013 and 2017 is actually a decrease due to inflation.

The Changing Landscape Related to Realizing Scientific Potential

Broad community involvement in NASA Heliophysics missions is critical for realizing their maximum scientific potential. The GI program, while extremely valuable, has traditionally enabled such participation primarily after launch. The recent implementation of the decadal survey recommendation to make Solar-Terrestrial Probes missions PI-led (Section 3.5), could have the unintended side effect of reducing this kind of community involvement in strategic missions. It is critical to maintain and enhance community involvement during the earlier phases of mission development. This will (1) expand the diversity of perspectives and ideas for accomplishing the mission science goals, (2) engage the community earlier so they are familiar with the mission and can be more productive immediately after launch, and (3) enhance the diversity of mission teams.

The GI program as it is traditionally implemented is not the best way to address this issue because GIs are not viewed as part of the mission team. Better mechanisms may exist that provide an opportunity for scientists to be engaged as members of the mission team earlier in the process without having to compete against proposals that use data from already-operating missions. A recent IMAP mission paper (McComas et al., 2018) outlines a plan for community engagement, welcoming participation from outside scientists. However, this participation is unfunded, potentially excluding members of the community. Funding will be provided during Phase-E (after launch) through a mission GI program, and the mission plans both a student collaboration and future leaders component to involve early career scientists. Nevertheless, HPD can learn from past experiences and other divisions to insure broad and diverse participation.

The model used by NASA's Planetary Science Division, their Participating Scientist (PS) Program,[18] provides a useful example that HPD could learn from and consider for future missions. The PS Program provides a mechanism by which scientists can participate in team meetings and contribute ideas early in the mission. A similar model has been used successfully for previous Heliophysics missions. For example, the MMS and TIMED missions had interdisciplinary scientists (IDS). However, the IDS model has not been routinely implemented for all HPD strategic missions. It should be emphasized that, to be successful, such a program must be implemented with care; in the new PI-led model for STP missions, the PI is responsible for meeting Level 1 requirements. Thus, such a program must be implemented in a way that is value-added and does not impose additional requirements on the PI and team.

> ***Finding 3.9:*** A model similar to the PS Program used in the Planetary Science Division would contribute to realizing the scientific potential of Heliophysics missions by ensuring broad and diverse community participation.

DRIVE/Realize and the Role of Data Science in Solar and Space Physics

Another development mentioned in the decadal survey, but which has become even more pressing in recent years, is the size of data sets and our ability to efficiently store, retrieve, and analyze the data in a reproducible way. DKIST is expected to produce 25 terabytes of data a day for some 40 years, amounting to hundreds of petabytes throughout its lifetime (Berukoff et al., 2015). Existing NASA satellites already produce large amounts of data. For example, the SDO produces 1.5 terabytes of data a day (Pesnell et al., 2012) and has accumulated a few petabytes of data to date. Moreover, simulations also have higher spatial and temporal evolution than ever before. The advent of these incredibly large and complex data sets, along with sophisticated data-processing techniques and relatively inexpensive computing power, created what NSF calls "the data revolution" (NSF, 2019c).

Science Platforms: Developing a Modern Data Infrastructure and Workflow Using Common Standards

In order to efficiently explore and analyze large and complex data sets, the solar and space physics community will need to develop a modern data infrastructure and workflow to store, retrieve, and process large data sets (e.g., Bauer et al., 2019). This will require a change in scientific workflow; instead of moving data to a local machine to analyze, users move their software to an external computing environment and perform their analysis there, minimizing data transfer. Several institutes have developed science platforms to analyze large data sets in astronomy, such as the National Optical Astronomy Observatory Data Lab (Fitzpatrick et al., 2014) and the Large Synoptic Survey Science Platform (Dubois-Felsmann et al., 2019).

Scientific Software: Incentivizing and Supporting the Development and Adoption of General Purpose Open-Source Software Tools

Open-source software packages such as scikit-learn (Pedregosa et al., 2011), which include machine learning and data mining algorithms, have enabled nearly all of the machine learning and data mining studies within solar and space physics over the last 5 years (Burrell et al., 2018). Many of these studies also used open-source libraries for efficient data analysis, such as cloud computing and parallel processing. In addition to these general computing applications, the number of open-source software

[18] The benefits of the Participating Scientist program are described in Grebowsky et al., (2015): "Science Enhancements by the MAVEN Participating Scientists".

packages specific to the solar and space physics community has grown considerably over the last 5 years,[19] such as space weather open-source applications in the CCMC.

However, these packages developed by members of the community remain largely unfunded. At present, funding to support digital infrastructure is often donation based—for example, the Linux Foundation's Core Infrastructure Initiative, NumFOCUS, Mozilla's Open Source Support (MOSS) program, the Free Software Foundation, the Sloan Foundation, the Ford Foundation, and the Moore Foundation. For example, SunPy received $265.00 from NumFOCUS in 2017.[20] This increased to $3,120 in 2018 (NumFOCUS, 2018). According to statistics from OpenHub, a service that tracks open-source software, the cost of producing the SunPy code base using paid software developers (with an annual salary of $75,000) would take about 7 years and cost approximately $500,000.[21]

In 2018, the National Academies published the report *Open Source Software Policy Options for NASA Earth and Space Sciences* and recommended increased support from NASA SMD for open source software development.[22] Some funding opportunities are beginning to appear. The NASA ROSES-2019 HDEE (Heliophysics Data Environment Enhancements) program solicits proposals entirely for the development of open-source software and encourages the community to adhere to a set of standards and workflows to maximize interoperability and reduce duplicate efforts. NSF is also responding with its Cyberinfrastructure for the Geosciences program. Continued support is essential, as is recognition within the reviewing community that software and associated computing hardware cost are significant and critical for much of solar and space physics research. Accepting these costs in proposals, and questioning proposals that claim to be able to carry out research without these resources, can quickly change the working environment in the heliophysics community.

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[19] About 50 such open source software packages (e.g., Annex et al., 2018) exist today—such as SunPy (SunPy Community et al., 2015), SpacePy (Morley et al, 2014), and PlasmaPy (Plasma Py Community et al., 2018). The foundation of the open source scientific programming stack—a collection of five packages for array manipulation (NumPy; Van Der Walt et al., 2011), time series analysis (Pandas; McKinney et al., 2010), plotting (matplotlib; Hunter et al., 2007), numerical methods (SciPy; Jones et al., 2001) and development environments (Pérez et al., 2007)—contributed significantly to the rapid development of general-purpose tools for the solar and space physics community.

[20] The 2017 annual report from NumFOCUS, a 501(c)(3) public charity which serves as a fiscal sponsor for many open-source scientific software packages.

[21] Figures cited on "The Black Duck Open Hub" at: https://www.openhub.net/p/sunpy/estimated_cost/.

[22] Among the key recommendations of *Open Source Software Policy Options for NASA Earth and Space Sciences* (NASEM, 2018) were the following (p. 4):

- NASA Science Mission Directorate should explicitly recognize the scientific value of open source software and incentivize its development and support, with the goal that open source science software becomes routine scientific practice.
- NASA Science Mission Directorate should initiate and sponsor programs to educate and train researchers in open source best practices. Topics could include, but are not limited to, export controls, licensing and intellectual property, workflows, and software development. These resources could be made available to the community via in-person trainings as well as webpages, screencasts, and webinars.
- Any open source software policy that NASA Science Mission Directorate develops should not impose an undue burden on researchers; therefore, any policy should be as simple as possible, and any mandates should be fully funded.
- NASA Science Mission Directorate should support the infrastructure, governance, and maintenance of a healthy open source community, taking advantage of existing community resources to the greatest extent possible.
- NASA Science Mission Directorate should support open source community-developed libraries that advance NASA science.
- NASA Science Mission Directorate should foster career credit for scientific software development by encouraging publications, citations, and other recognition of software created as part of NASA-funded research.

Education and Training: Participating in Workshops, Conferences, and Courses to Learn Modern Statistical and Computational Techniques

Gleaning meaningful scientific results from large and complex data sets requires a new kind of scientist — a data scientist — well-versed in both their physical domain and also in modern statistical and computational techniques (VanderPlas, 2014; Faris et al., 2011). Yet, much of the solar and space physics community is still unfamiliar with data science. Additional opportunities to educate and train the community with such modern data science techniques are needed. Agencies can help by sponsoring workshops and university training programs. An example of an existing program is the Large Synoptic Survey Telescope (LSST) Data Science Fellowship Program (DSFP), which teaches data skills not easily addressed by current astrophysics programs.

Interdisciplinary Collaboration: Establishing Opportunities for Solar and Space Physicists to Collaborate with Data Scientists, Statisticians, and Computer Scientists

To effectively implement modern statistical and computational techniques, the solar and space physics community will need support for engaging in interdisciplinary collaboration with data scientists, statisticians, and computer scientists specializing in machine learning and data mining. For example, funding agencies could encourage and sponsor the development of interdisciplinary data science centers — such as the three Moore-Sloan Data Science Environments (the Berkeley Institute of Data Science, the University of Washington eScience Institute, and the NYU Center for Data Science) — and interdisciplinary grant programs, such as those that compete under the NSF Harnessing the Data Revolution (HDR) Big Idea.

> ***Finding 3.10:*** A modern data infrastructure, support for the development of software tools, education about data science methods, and interdisciplinary collaboration are needed to realize the scientific potential of the large and complex data sets being produced today.

3.3.3 DRIVE Integrate

Integrate observing platforms and strengthen ties between agency disciplines.

Progress Toward Decadal Survey Recommendations

> ***Decadal Survey Recommendation:*** **NASA should join with NSF and DOE in a multiagency program on laboratory plasma astrophysics and spectroscopy, with an expected NASA contribution ramping from $2 million per year (plus increases for inflation), in order to obtain unique insights into fundamental physical processes.**

In ROSES-2013, NASA created the LNAPP (Laboratory Nuclear, Atomic, and Plasma Physics) program within H-TIDeS. This program is currently funded at $0.6 million per year (Table 3.1) with an average of two new selections per year (Figure 3.7 below). The LNAPP program is separate from the existing joint NSF-Department of Energy (DOE) program, so this does not completely address the decadal survey recommendation, and the level of investment does not meet the decadal survey target. In particular, LNAPP supports laboratory experiments, but there is currently no program at NASA supporting development of computer codes or tools that support laboratory plasma science.

Connections between the heliophysics community and the plasma physics community are growing. There are several plasma laboratories that focus on experiments motivated by questions that have arisen in space physics. DOE is supporting laboratories and personnel that work with the outside community to develop new experimental investigations. These facilities are eager to support new users, thus there is a real opportunity for the heliophysics community. NASA can facilitate progress by making efforts to better coordinate with DOE and by enabling the community to take advantage of these opportunities. Currently, Plasma 2020,[23] a decadal assessment of plasma science, is being conducted by the National Academies; NASA may find new opportunities arising from this assessment.

Finding 3.11: Laboratory research, from plasma physics to spectroscopy, is a critical, foundational component for heliophysics research. The NASA LNAPP program is a positive step toward increasing opportunities for laboratory experiments, but it does not fully address the decadal survey recommendation, specifically the need for increased NASA-DOE collaboration.

Decadal Survey 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, research on the outer heliosphere should be included explicitly in the scope of research supported by the Atmospheric and Geospace Sciences Division at NSF.**

Significant progress has not been made towards this recommendation. For example, Sun-as-a-star and planetary magnetospheric research falls between the AGS and AST divisions. Another example is the science of the outer heliosphere. Recent observations of the outer heliosphere by NASA satellites raise fundamental science questions pertaining to the structure of shocks, where and how magnetic reconnection takes place, and how particles are accelerated, all of which are subjects integral to the Sun-Earth-heliosphere system science program. However, there is still no clear home for outer heliosphere research at NSF.

Finding 3.12: The placement of solar and space physics in multiple divisions and directorates arises from the cross-cutting relevance of the science. However, there are very few cross-divisional funding opportunities at the agencies. This makes it difficult for proposers to obtain funding for basic research on subjects that are not clearly aligned with one division. Proposals that cross divisional lines also pose significant challenges to agencies and review panels.

Decadal Survey Recommendation: **NASA, NSF, and other agencies should coordinate ground- and space-based solar- terrestrial observational and technology programs and expand efforts to take advantage of the synergy gained by multiscale observations.**

The 2019 ROSES solicitation Appendix B.4 for the Open Guest Investigators program was recently amended to allow for ground-based instrumentation associated with the THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission to be used as a primary data source for investigations.[24] Note, however, that these particular ground-based instruments were originally funded by NASA as part of THEMIS mission development. Currently, NASA only funds the use of other (e.g., NSF-funded) ground-based observations if they are used as supporting data. The importance of coordinated observations is only growing. For example, the combination of ground-based radio and optical data with Parker Solar Probe measurements will be a powerful tool for studying the Sun. Such coordination requires support.

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[23] Information about Plasma 2020 is available on at NASEM, “Decadal Assessment of Plasma Science,” https://sites.nationalacademies.org/BPA/BPA_188502.

[24] “April 1, 2019. B.4 Heliophysics Guest Investigator—Open Program has been updated to indicate that All Sky Imagers (ASI) and Ground Magnetometers (GMAG) associated with the THEMIS mission are considered to be part of the Heliophysics System Observatory (HSO). Investigations using these data as their primary data source are permitted.” (From ROSES 2019 solicitation, as amended.)

Finding 3.13: Diverse observing platforms continue to produce important scientific results and augment the capabilities of larger facilities. The opportunities for maximizing the use of diverse platforms and combining their measurements have not been fully exploited; further opportunities exist to leverage international collaboration and combine measurements from space-based and ground-based platforms.

The Changing Landscape Related to Integrating Platforms and Strengthening Ties

Heliophysics System Observatory

The decadal survey makes regular reference to the richness of the HSO and its role in major discoveries and progress on the key science goals laid out in the decadal survey. However, as shown in Table 1.2, the HSO is largely populated by missions in their (sometimes much) extended phase of operation. Losing spacecraft will result in the loss of critical measurements necessary to understand the global and system-level picture of the heliosphere. There are several regions within the heliosphere where critical measurements may be lost at any time. Examples include the following:

- SDO is the only satellite providing high-resolution and high-cadence solar magnetograms. These data yield critical information on the solar magnetic field that cannot be obtained in sufficient detail from the ground and enable off-Sun-Earth axis observations that allow reconstruction of three-dimensional (3D) features and vector information.
- With the TIMED satellite nearing the end of its life,[25] critical information about Earth's natural thermostat, the nitric oxide 5.3 μm cooling of the thermosphere, will be lost. TIMED also currently provides temperature and constituent measurements at the poles and in the mesosphere that connect Earth's space environment with Earth's lower and middle atmosphere.
- With the Van Allen mission at its end, only the Japanese mission Arase (also in extended mission phase) is able to provide measurements across the heart of the radiation belts.
- Since the last decadal, it has become clear that the Voyager spacecraft may be nearing the end of their productive lifetimes. At the same time, both have uncovered new phenomena in the outer heliosphere that cannot be understood with the measurements of their limited payload.

One exception is the specific attention given to the ongoing necessity of L1 solar wind observations and coronagraphs to monitor Earth space weather conditions and to enable space weather–related science. The continuation of those measurements is discussed more in Chapter 4. However, it should be noted that the capabilities of instruments developed primarily for operational use may differ from those developed to satisfy research needs; therefore, there may be some scientific objectives that are not met with the operational measurements.

In addition to its elements aging, the vision of the HSO—to have strategically placed missions that enable the systems-science approach required to understand the Sun and its effects on planets in our solar system—can only be achieved if the HSO is driven by some strategic planning. Currently, all NASA-selected missions must be stand-alone; a mission's contributions to the HSO are not considered during the procurement process. Moreover, to fully realize the HSO vision will require integration of ground-based facilities and missions of all sizes into the HSO concept since, more often than not, multiple data sources are used for scientific studies. The decadal survey recognized the HSO as a fully integrated systems-science observatory, but it is not clear that the agencies currently recognize this. The continuation of and enhancements for the HSO are discussed in more detail in Chapter 6.

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[25] The Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) mission was launched on December 7, 2001. Its nominal design life was 2 years.

Finding 3.14: Many elements of the HSO are aging, and there is a risk of losing key capabilities. In order to realize the vision of the HSO, some longer-term strategic planning is required to prioritize the critical support needed at both the mission level and the program level. Moreover, the HSO can be viewed as a national resource that goes beyond NASA missions. Data from small missions, ground-based facilities, and international assets have become increasingly important. An opportunity exists to elevate the HSO concept to better manage and exploit this critical resource for scientific progress.

Crossdisciplinary Science

Some of the most important advances in heliophysics lie in its connections to other disciplinary areas. There are obvious connections with the Earth sciences; for example, the coupling of the ionosphere, thermosphere, and mesosphere above 50 km to the lower atmosphere is studied instensely by the Earth science community. Climate change is another area where heliophysics research overlaps with Earth science; for example, anthropogenic increases of CO_2 are being observed in the thermosphere. Comparative planetology is a growing field within the planetary science community, particularly for Earth-Mars comparisons largely inspired by the MAVEN Mars mission, which also significantly involves the heliophysics community. Applying knowledge from heliophysics research also helps to interpret stellar activity in other systems, while observing other Sun-like stars can teach us about the potential extremes of solar activity. Similarly, heliophysics research contributes to exoplanet science through the applications of concepts and models used for solar system planet-solar wind interactions and space weather influences on atmospheres and surfaces. Understanding planetary evolution and habitability relies in large part on our knowledge of the current solar system environment and solar outputs, as well these conditions in the past and future. Finally, Voyager and IBEX results have transformed our understanding of the interstellar boundaries of astrophysical objects, while observations of other astrospheres provide alternate realizations of heliosphere-like systems with different internal and external properties.

In all of these examples, research that incorporates broader perspectives that go beyond disciplinary boundaries has the potential to open new horizons and raise new questions. Real breakthroughs are often made in cross-disciplinary areas—breakthroughs that benefit heliophysics research as a whole.

Funding structures and review panels currently are not set up for efficient support of the inherently multidisciplinary approach needed to address these science challenges. A few Living With a Star–focused science topics have featured this type of research, but opportunities are limited and there is no obvious home for such proposals at the NSF. The NExSS (Nexus for Exoplanet System Science) Program at NASA attempts to be inclusive in creating virtual institutes from already-selected proposals across all four divisions within SMD to accomplish astrobiology goals in particular. However, heliophysics participation is relatively small, perhaps because this opportunity is not widely known or advertised within heliophysics. The historical lack of support may also be limiting participation in these areas. The rapid development of transiting exoplanet studies warrants particular attention within the context of the decadal survey DRIVE program and based on all four of the survey's key science goals.

Finding 3.15: Heliophysics has much to contribute to areas of broad interest within NASA's Science Mission Directorate (SMD), including stellar system and exoplanet research as well as future major exploratory efforts; for example, the Lunar Gateway missions. However, the expertise and knowledge that exists within the heliophysics community is not as widely exploited at SMD as it could be because there are insufficient opportunities to engage across division lines.

3.3.4 DRIVE Venture

Venture forward with science centers and instrument and technology development.

Progress Toward Decadal Survey Recommendations

The decadal survey also made recommendations to push the boundaries in the areas of both theory and technology developments, arguing that transformational progress often comes from collaborations between theorists, modelers, computer scientists, and observers.

> ***Decadal Survey Recommendation:* NASA and NSF together should create heliophysics science centers 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 announcement of opportunity (AO) for the heliophysics science centers was released in 2019. The selection of the centers will proceed via a two-phase process. Phase 1 proposals proceeded through a standard Step-1 and Step-2 proposal process, with Step 1 due on March 1, 2019 and the Step-2 (full) proposals for phase 1 due on June 20, 2019. The response from the community was significant, with 44 Step-1 proposals ruled to be compliant with the AO. The number of completed Step-2 proposals is unclear, but the community response indicates great enthusiasm for the implementation of this recommendation. It is expected that approximately 6 Phase 1 proposals will be selected and funded at approximately $650,000 per year for 2 years. At the end of this 2 years, the Phase 1 teams will submit Phase 2 proposals for the full implementation on their center concepts.

The 2013 decadal survey recommendation to establish science centers is on its way to being implemented by NASA. While slower to start than anticipated, the ongoing proposal process is nonetheless a very positive step toward ensuring more adequate support for realizing the results of missions, suborbital and ground-based heliophysics observations, and for the basic research that seeds the next heliophysics endeavors. NSF is not currently providing funding for science centers, but it has supported science and technology centers competed across all areas of science and engineering since 1987. The Center for Integrated Space Weather Modeling (CISM) was funded through this program from 2002-2013, for example. More recently, NSF has created an Artificial Intelligence Institutes program. NSF is currently contributing to the HSCs by "providing input on best practices for conducting science center operations."[26] However, it is unclear how the different centers and institutes relate to one another. Some coordination between agencies is needed to ensure that the HSCs are effective.

> ***Finding 3.16:*** A regular cadence for HSCs is needed. In order for HSCs to be impactful, the next call for Step-1 proposals should be released within a year of the down selection for Step-2 proposals. Moreover, full NSF participation in the HSCs has not been realized.

> ***Decadal Survey Recommendation:* NASA should consolidate the technology funding now in the SR&T, LWS, and LCAS programs into a single heliophysics instrument and technology development program and increase current annual funding levels, ramping to $4 million per year (plus increases for inflation) in order to facilitate urgently needed innovations required for implementation of future heliophysics mission. Further, issues pertaining to implementation of constellation missions (e.g., communications, operations, propulsion, and launch mechanisms) should be explicitly addressed.**

[26] From Geospace Section Head presentation to committee in February 2019.

As mentioned above, ROSES 2013 included support for instrument development through its H-TIDeS program. Figure 3.7 shows the number of ITD and LNAPP proposals selected for 2013-2018. An example of the success of the ITD program was the development of terahertz (THz) measurement capability for measuring winds. A new sensor technology, called the TeraHertz Limb Sounder (TLS), was developed with NASA funding to make these critical wind measurements under a wide range of observational conditions (e.g., day and night, with and without aurora) from a low Earth orbit.[27]

As of 2019, flight projects, including small satellite technology demonstrations, have been moved into the new ROSES H-FORT element (Figure 3.8). H-TIDeS retains the Instrument Technology Development (ITD) line at $4 million per year (in ROSES 2019). This matches the decadal survey goal of consolidating NASA technology funding and exceeds the funding level recommended in the decadal survey (see Table 3.1).

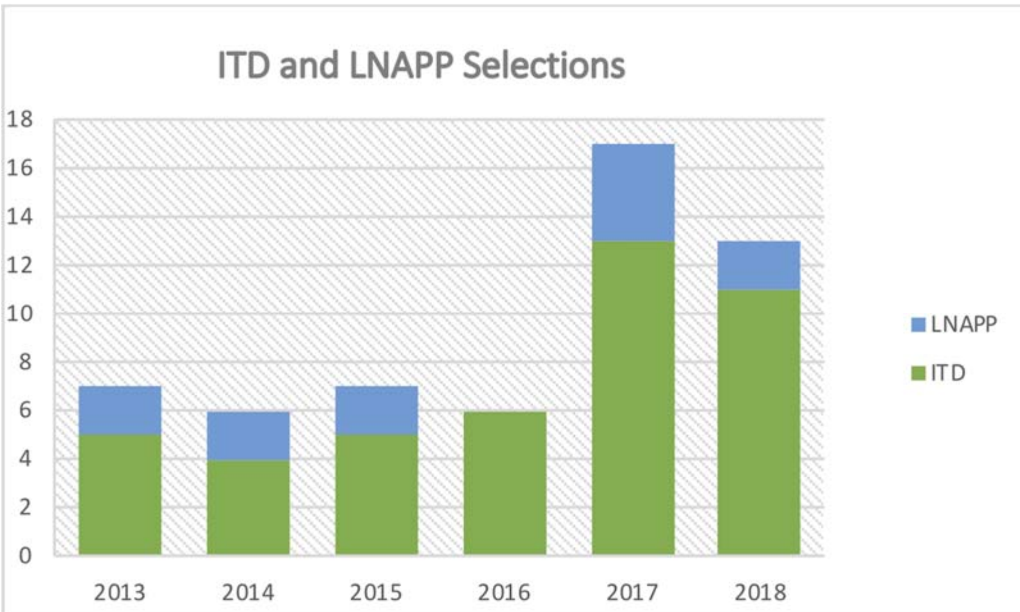

FIGURE 3.7 Number of ITD (Instrument and Technology Development) and LNAPP (Laboratory Nuclear, Atomic, and Plasma Physics) proposals selected from 2013-2018. SOURCE: Data taken from NASA NSPIRES.

[27] From NASA Science Mission Directorate Technology Highlights 2016 report.

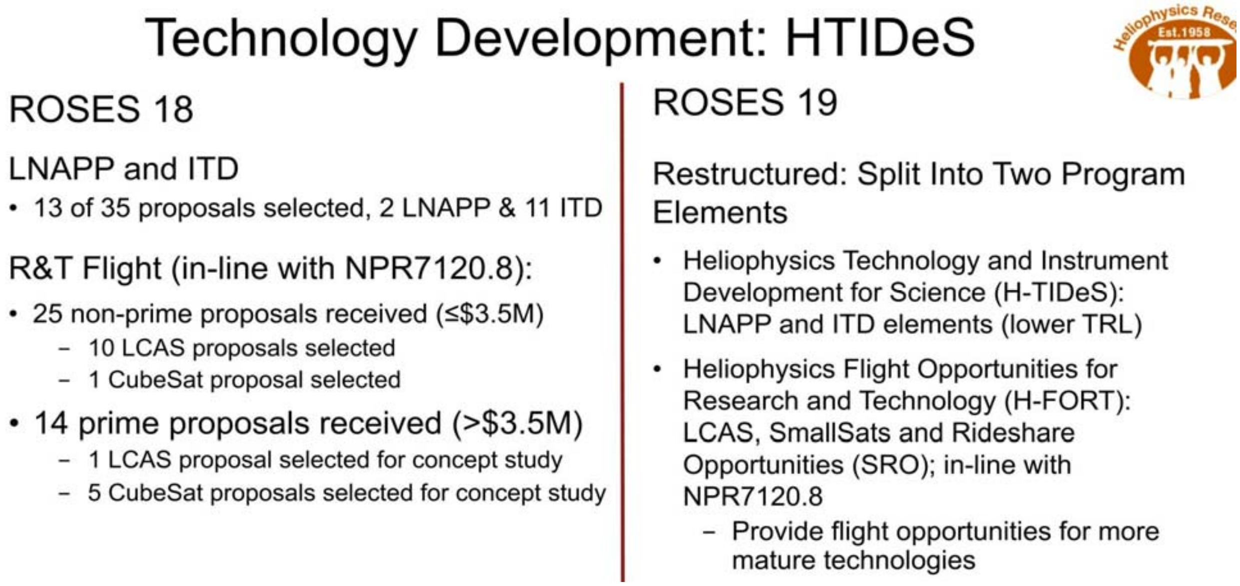

FIGURE 3.8 Technology Development: HTIDeS. SOURCE: Nicola Fox, NASA HPD Director, presentation to the committee on February 25, 2019.

The Changing Landscape Related to Venturing Forward

The growth of the commercial small spacecraft industry and increased launch opportunities are enabling growth in small innovative instrumentation projects. NASA needs to be prepared for a dramatic increase in the number of H-TIDeSand H-FORT proposals over the next few years.

Since publication of the decadal survey, NASA has announced ambitious plans to return to the Moon and to establish a Lunar Gateway. Extending a long-term presence beyond Earth's protective magnetic shield raises many issues in space weather, both for predictions and for the mitigation of its adverse effects on technological systems and human health (Chapter 4). NASA's lunar plans also provide potential new opportunities for heliophysics science as NASA extends human flight outside of low-earth orbit for extended periods of time. The new NASA Heliophysics Space Weather Science and Applications (SWxSA) program, as discussed in Chapter 4, could explore space weather partnerships with Artemis flight opportunities and in collaboration with the NASA Human Exploration and Operations Mission Directorate (HEOMD).

3.3.5 DRIVE Educate

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

Progress Toward Decadal Survey Recommendations

> ***Decadal Survey Recommendation:*** **The NSF Faculty Development in the Space Sciences (FDSS) program should be continued and be considered open to applications from 4-year as well as Ph.D.-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 to support its faculty.**

Following a gap in opportunities for NSF FDSS, NSF recently revived the program by selecting six universities (Arizona State University, Georgia State University, University of Hawaii, Montana State University, New Mexico State University, West Virginia University) to hire new faculty in 2019-2020 and to support curriculum development in solar and space physics. As noted in the NSF Geospace Portfolio Review, the FDSS program has been successful. Of the eight faculty members supported by the program through 2014, all but one led to a tenured faculty member. The 2019 selections for the NSF FDSS program meet the goal of this DRIVE recommendation, although a regular cadence is needed to ensure that this program has a positive impact on solar and space physics.

> ***Decadal Survey Recommendation:*** **A suitable replacement for the NSF Center for Integrated Space Weather Modeling summer school should be competitively selected, and NSF should enable opportunities for focused community workshops that directly address professional development skills for graduate students.**

Over the past decade, the NASA Heliophysics Summer School has instructed well over 300 of the most promising students across the variety of research subfields within heliophysics. Each year of the school, a particular theme is selected, enabling the school to continually evolve with its scientific disciplines while always covering the fundamentals of the physics of the local cosmos. In parallel to teaching, the Heliophysics Summer School project has resulted in a series of five books (four published in printed form (Schrijver et al., 2009, 2010a, 2010b, 2016) and a fifth available online at the school's website[28]) reviewing the diverse environments and connected processes in the Sun-planet system. These address past, present, and future of the solar system, compare terrestrial and other planets, and look beyond the local cosmos to other planetary systems and their stars. These five books are complemented by recorded lectures and by problem sets and laboratory experiments (largely developed with help from the NASA CCMC), all hosted on the Internet. A condensed textbook based on the extensive heliophysics texts is currently being developed. The continuation of this summer school is a valuable asset in the training of the next generation of heliophysics researchers.

NSF funded the CISM Space Weather Summer School from 2002-2013. Post-CISM, a separate NSF-funded program, called the Boulder Space Weather Summer School (SWSS), administered by the High Altitude Observatory (HAO), has been put in place to continue the CISM summer school. This is a 2-week program that targets beginning graduate students and advanced undergraduates who are considering a career in solar, space, atmospheric, or related sciences. It is also open to space weather practitioners in government and industry who are interested in enriching their understanding of the solar-terrestrial system and the causes and impacts of space weather events. Admission is open to both U.S. and international students, although the SWSS cannot provide support for international travel. Enrollment is limited to about 30 students each year. The program is funded through 2020 with expected renewal in subsequent years.

In addition, there are student workshops that NSF hosts at the annual CEDAR, GEM, and SHINE workshops. These training opportunities about new data systems and emerging software tools occur both at those workshops, as well as at the Solar Physics Division (SPD) and American Geophysical Union (AGU) meetings.

> ***Finding 3.17:*** NSF and NASA have responded positively to this graduate student training recommendation. The CISM summer school, now the Boulder Space Weather Summer School, has been funded by the NSF. In addition, NASA has continued to fund the Heliophysics Summer School. The former has a focus on beginning students and modeling of space weather, while the latter is more targeted to basic research science for advanced graduate students and post-doctoral researchers. These activities provide an outstanding resource to a community in which heliophysics graduate students in a given department are often few in number and specialized courses in the discipline are not feasible.

[28] See https://cpaess.ucar.edu/sites/default/files/heliophysics/documents/HSS5.pdf.

NASA also recently established the Early Career Investigator Program (ECIP) at a level of $1.5 million per year in FY 2019 and FY 2020 (expected). The program supports early career professionals within 10 years of receiving their Ph.D. In response to its first offering, the program received broad interest with 101 Step-1 proposals submitted, 50 step-2 proposals reviewed, and 11 proposals selected for funding.[29] While the program addresses the challenges faced by early career professionals in heliophysics to establish secure funding, it is obviously heavily oversubscribed.

> ***Decadal Survey Recommendation:* To further enhance the visibility of the field, NSF should recognize solar and space physics as a specifically named subdiscipline of physics and astronomy by adding it to the list of dissertation research areas in NSF's annual Survey of Earned Doctorates.**

No progress has been made on this recommendation. The 2016 NSF Portfolio Review reinforced the decadal survey recommendation,[30] pointing out that students who apply for NSF Graduate Research Fellowships in geospace science may be at a disadvantage due to the absence of solar and space physics as a category.

The Changing Landscape Related to Education

As described in Section 3.3.2, significant developments in data analysis methods and tools have occurred both within and beyond the science community. Moreover, many of these software developments are "open source"—facilitating further collaborative development. The NASEM report on open source software (OSS) states, "the fact that coding is becoming as essential as calculus to scientists could motivate secondary schools and colleges to include software development best practices in their curricula for all science, technology, engineering, and mathematics (STEM)-bound students. OSS provides a way to educate and train new talent."

> ***Finding 3.18:*** Advances in the capability of OSS and the related heliophysics tool sets are not often covered in undergraduate and graduate education. Training the next generation in software best practices enables robust and maintainable code.

Since the publication of the 2013 decadal survey, citizen science (public participation in scientific research) has become more prominent in solar and space physics. An example of the scientific benefits of citizen science, the discovery of STEVE, was discussed in Chapter 2. Another example is the Aurorasaurus project,[31] a citizen science website where participants report sightings and details of the aurora. The data have been used to improve models for auroral forecasts. Citizen science allows the research community to leverage a large volunteer workforce that can provide a unique set of measurements—for example, those distributed around the globe in the case of Aurorasaurus. In addition, citizen science provides an important outreach tool. It has the ability to engage many thousands of volunteers in scientific research and the potential to inspire new generations of heliophysics researchers.

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[29] Data taken from NASA NSPIRES.

[30] Recommendation 4.10 in the report: The GS should work with the NSF office that maintains "Survey of Earned Doctorates" to implement immediately the category "Solar and Space Physics" (or another name to be determined) into the survey.

[31] http://www.aurorasaurus.org/.

3.2.6 DRIVE Recommendations for the Next Four Years

The 2013 decadal survey made specific actionable recommendations under the DRIVE initiative, and these have been largely addressed by NASA and NSF. The DRIVE elements have led to increased funding of suborbital and CubeSat missions, a boost to R&A programs, and the imminent selection of the first DRIVE science centers. The spirit of DRIVE is to continue to innovate and look for new ways to maximize scientific progress. Thus DRIVE should be viewed as a means for organizing the R&A programs in a way that can respond and adapt to new opportunities.

Finding 3.19: DRIVE is an organizational framework that encourages innovation and balance across NASA and NSF R&A programs, thus maximizing the science return of agency investments. In the future, DRIVE may include new elements or augmentations that go beyond the limited number of recommendations made in the decadal survey. It is essential to continue tracking and making visible the elements of DRIVE.

Recommendation 3.1: NASA and NSF should continue to use the DRIVE framework within their Research and Analysis programs. As the program elements that are part of DRIVE continue to evolve, they should remain visible and continue to be tracked in a transparent manner.

Finding 3.20: NASA and NSF have made progress on most of their DRIVE elements, although some of the DRIVE elements were implemented only recently. Funding constraints imposed by the decadal survey requirement to complete the current program are a contributing factor.

Finding 3.21: Some elements of DRIVE for NSF have not been fully implemented. These include ensuring funding for science areas that fall between divisions such as outer heliosphere research, full participation in HSCs, and recognition of solar and space physics as a subdiscipline in the annual survey of earned doctorates.

In addition to evaluating the progress on decadal survey recommendations, the committee identified new opportunities that have emerged since the decadal survey was published. The findings outlined in the sections above lead to a recommendation for building on recent progress and taking advantage of new opportunities through the rest of the decade.

Recommendation 3.2: In consideration of developments and emerging opportunities since the 2013 solar and space physics decadal survey was published, and to optimize the science value of the agencies' programs for the remaining years of the current decadal survey interval,

1. **NSF should extend support for the routine delivery of DKIST higher-level data products past 2020 with the goal to routinely process data to Level 2 (physical quantities based on calibrated measurements) at the DKIST Data Center.**
2. **NSF and NOAA should extend the operations for NSO's synoptic observations past 2021, and NSF should begin investigating potential agency partners and design concepts for the next generation of GONG instruments.**
3. **NSF should critically evaluate its facilities operations model to ensure that the science return is maximized over the life cycle of each instrument.** Some of the operations and maintenance cost pressures for NSF facilities could be addressed through implementing critical recommendations from the recent National Science Board study on this topic (NSB, 2018b).
4. **NASA and NSF should maximize the scientific return from large and complex data sets by supporting (1) training opportunities on modern statistical and**

computational techniques; (2) science platforms to store, retrieve, and process data using common standards;, (3) funding opportunities for interdisciplinary collaboration; and (4) supporting the development of open-source software. These four components should be considered alongside experimental hardware in the planning and budgeting of instrumentation.

5. **NASA should find ways to increase solar and space physics community participation in strategic missions and enhance the diversity of mission teams.** The Planetary Science Division's Participating Scientist program is a model that could be considered to achieve this goal.
6. **NASA and NSF should strengthen their mutual coordination of ground-based and space-based observations, to include NASA investment in ground-based measurements that support their missions, and coordination of NSF ground-based facilities in support of NASA missions, including suborbital campaigns.**
7. **Both NASA and NSF should create inter-divisional funding opportunities that support science areas that bridge established divisional boundaries at the agencies.** Specific examples of science areas include outer heliosphere, Sun-as-a-star, and star-exoplanet couplings. Progress will require collaboration between divisions at each agency to create inter-divisional programs.

3.4 ACCELERATE AND EXPAND THE HELIOPHYSICS EXPLORER PROGRAM

Progress Toward Decadal Survey Recommendations

The third recommendation of the decadal survey was to accelerate and expand the highly successful Heliophysics Explorer program, enabling a MIDEX line and frequent Missions of Opportunity (MoO).

> ***Decadal Survey Research Recommendation R2.0:*** **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.**

In April 2013, shortly after the decadal survey was released, NASA selected the Ionospheric Connection Explorer (ICON) mission, along with the GOLD (Global-scale Observations of the Limb and Disk (GOLD) mission of opportunity, for development. GOLD was launched in January 2018 into a geostationary orbit onboard a commercial telecommunications satellite. GOLD makes images of the thermosphere and ionosphere, providing atmospheric composition and temperature and the density and structure of the ionosphere. The first data from GOLD have been released and reveal, for example, dramatic plasma instabilities in the ionosphere during and after sunset that appear far more common than anticipated (Eastes et al., 2019). The ICON spacecraft was delivered on schedule in late 2017; however, its launch was delayed repeatedly due to issues with the Pegasus launch vehicle.[32] ICON finally launched on October 10, 2019; all systems are currently operating nominally, and an initial return of science data is expected November 2019. ICON will provide coordinated observations of the neutral atmosphere and ionosphere at low latitude, aimed at understanding the interaction between the gas and plasma. Given their complementary views from geostationary and low earth orbits, overlap between the GOLD and ICON observations are expected to enable significant discoveries that would not have been possible with either mission alone.

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[32] See IG-19-018 pgs. 17-18 and Table 5.

Between 2013 and 2015, no Explorer AOs were released in heliophysics. In 2016, the Heliophysics SMEX AO was released which included a Stand-alone missions of opportunity (SALMON) element. Five SMEX missions and three MoOs were selected for Phase A concept studies. In 2019, the AWE MoO was selected for implementation and is expected to launch to the International Space Station (ISS) in 2022. AWE is focused on studying atmospheric waves in the mesopause region, where such waves often become large in amplitude and non-linear effects increase dramatically. The SunRISE mission to study solar radio bursts was also provided with additional funding for an extended Phase A study. In June 2019, two SMEX missions were selected to continue into Phase B. PUNCH will focus on the Sun's outer atmosphere, the corona, and how it generates the solar wind. TRACERS will study magnetic reconnection in the cusp region of Earth's magnetosphere. In July 2019, a MIDEX AO was released, with proposals due in September 2019; thus a cadence of 3 years was achieved between the SMEX and MIDEX AOs.

The 2018 SALMON opportunity solicited several different types of MoO. Two technology demonstrations and two science missions were selected for Phase A study as potential rideshares for the IMAP mission.[33] It is anticipated that one from each category will be selected to launch with IMAP. Rideshare opportunities at NASA are discussed in more detail below. In September 2019, three stand-alone science MoOs were also selected for Phase A study.[34]

The Changing Landscape Related to Explorers

Small missions, from CubeSats up to mid-sized Explorers (MIDEX), are critical elements of the toolset needed to advance the science of heliophysics. These relatively small to mid-sized missions, if effectively implemented along with the large strategic missions, should enable us (1) to fill gaps in observables, particularly in the current environment of infrequent large missions and aging on-orbit resources, (2) to efficiently implement the use of innovative technologies, and (3) to motivate and involve a larger and younger segment of the research and engineering communities. Increasing proposal costs and mission budgets, the burden of undesirably high standards for risk mitigation, and the growing AO-to-launch intervals all need to be addressed to optimize the role that small-sats up to MIDEX can play in advancing solar and space physics.

Launch costs continue to be a major component of the Explorer budget. NASA has recently committed to including an ESPA[35] ring on every SMD launch. This has the potential to benefit the Explorers program, in particular by reducing launch costs and providing launch opportunities to orbits that are not easily accessible otherwise. For example, NASA has taken an innovative approach in its planning for the IMAP mission by offering five ESPA-ring slots for small satellites to share the ride to the Lagrange L1 point. For one of the slots, NOAA has partnered with NASA to launch its Space Weather Follow-On (SWFO) mission to L1.[36] As discussed above, in 2018, NASA released a call for both a

[33] The two science rideshare missions are the Spatial/Spectral Imaging of Heliospheric Lyman Alpha (SIHLA) mission to study the heliosphere boundary with the interstellar medium and the Global Lyman-alpha Imagers of the Dynamic Exosphere (GLIDE) to study Earth's exosphere, consisting mostly of hydrogen. The two tech-demo rideshare missions selected are the Science-Enabling Technologies for Heliophysics (SETH) mission to demonstrate higher data rates from deep space with optical communication and the Solar Cruiser mission to demonstrate solar sail technology. A downselect to one science mission and one tech-demo mission is expected after Phase A studies are completed in 2020, and both will be launched in October 2024 as rideshare missions with IMAP.

[34] Extreme Ultraviolet High-Throughput Spectroscopic Telescope (EUVST) Epsilon Mission, Aeronomy at Earth: Tools for Heliophysics Exploration and Research (AETHER), and Electrojet Zeeman Imaging Explorer (EZIE).

[35] ESPA stands for EELV Secondary Payload Adapter. It was originally developed by the Air Force to facilitate launch of secondary payloads on large launch vehicles.

[36] For more on SWFO, see, Elsayed Talaat, "Accelerating Progress Toward NOAA's Next Generation Architecture," 2019 Goddard Memorial Symposium, March 21, 2019, https://astronautical.org/dev/wp-content/uploads/2019/04/RHG_Thu_0800_Talaat.pdf.

science and a technology demonstration MoO to fly as rideshares with the IMAP mission. While rideshares can contribute to reduced cost and increased flight opportunities, the potential impact of delays imposed on the major mission by the minor mission has to be managed.

The Explorers Office website[37] states, "The mission of the Explorers Program is to provide frequent flight opportunities for world-class scientific investigations from space utilizing innovative, streamlined and efficient management approaches within the heliophysics and astrophysics science areas." However, the most recent SMEX selection took 3 years from AO to selection (this timeframe included AO, review, Phase A, review, and selection). Reducing the number of requirements for the Phase A Concept Study Report (CSR) might help shorten the Phase A duration. If future SMEX missions continue to have a long review and down-select time and high cost, there will be adverse impacts on the rate of scientific progress and innovation. There is also a potential negative impact on workforce development and retention. This topic is further discussed in Chapter 5.

The commercial sector is developing new ways to manufacture small satellites using technologies and processes learned from aircraft manufacturing. One example, among several, is OneWeb, which has partnered with Airbus to produce 900 satellites with a mass of 150 kg each — similar to a SMEX — at a rate of three per day and for less than $1 million per satellite (Iannotta, 2019). There is an opportunity for the science community and agencies to learn from and leverage these developments in order to reduce the costs of small missions, to enable more frequent access to space, and to support constellations of small-satellites.

In December 2017, NASA Associate Administrator Thomas Zurbuchen released the document "Class D Tailoring/Streamlining Decision Memorandum,"[38] announcing a new streamlined process for implementing Class-D missions with costs below $150 million (not including launch cost), which includes the Explorers SMEX and MoOs.[39] The impact of this memo on the recent MoO and SMEX proposals and the development of the selected missions requires tracking and evaluation. This topic is further discussed in Chapter 6.

Findings on the Explorer Program

> ***Finding 3.22:*** NASA is responding positively to the decadal survey recommendation to strengthen the Explorer program. Although no Explorer AOs were released during the first 3 years following the decadal survey, the 3-year spacing between Heliophysics Explorer AOs for SMEX and MIDEX of 2016 and 2019 is a move to implement the decadal survey recommendation.
>
> ***Finding 3.23:*** The committee sees the growth of mission cost in a relatively flat budget setting as a significant hazard to the ability to sustain a 3-year cadence in the future.
>
> ***Finding 3.24:*** NASA management of Explorer missions is in need of optimization to ensure that the program fullfils it goal to "provide frequent flight opportunities … from space utilizing innovative, streamlined and efficient management approaches."[40]
>
> **Recommendation 3.3: The committee encourages NASA to continue to work toward the goals set out by the decadal survey for Explorer missions. In order to maintain a 3-year (or ideally faster) launch frequency of Explorers, the committee recommends that NASA**

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[37] See https://explorers.gsfc.nasa.gov.

[38] See https://essp.nasa.gov/essp/files/2018/05/SMD-Class-D-Policy.pdf.

[39] Information about risk classification for NASA missions is further described in a 2014 slide presentation by Chief Safety and Mission Assurance engineer, Dr. Jesse Leitner, which can be found at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150001352.pdf.

[40] From http://explorer.gsfc.nasa.gov.

develop a more efficient management environment and an improved contract/grant structure, both to reduce mission cost and to shorten the interval from AO to launch. In this context, NASA should (1) adopt new procedures to facilitate a more cost-efficient implementation of smaller satellites and instruments using disruptive small-sat technology and (2) continue to strive towards reduced launch costs—for example, through ride sharing.

Finding 3.25: In order to maintain the decadal survey-recommended 3-year (or ideally faster) launch frequency of Explorers, NASA will need to develop a more efficient management environment and an improved contract/grant structure, both to reduce mission cost and to shorten the interval from AO to launch

3.5 RESTRUCTURE STP AS A MODERATE-SCALE, PI-LED LINE

Implement IMAP, DYNAMIC, MEDICI-Like Missions

Decadal Survey Recommendation R3.0: 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.

Decadal Survey Recommended STP Science Targets: 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 Interstellar Mapping and Acceleration Probe (IMAP). 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).**
>
> **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).**

NASA has transitioned the Solar Terrestrial Probes (STP) program to be a moderate-scale, competed, principal-investigator (PI)-led mission line. Figure 3.9 shows the decadal survey–recommended budget and 4-year cadence for the next STP missions. The first of these, called IMAP (Interstellar Mapping and Acceleration Probe), was prioritized to take advantage of the overlap with the historic Voyager missions and would study the outer heliosphere and its interaction with the interstellar medium. The launch date for IMAP anticipated in the decadal survey was 2021 and had already been shifted to 2022 by the time NASA issued its survey implementation plan in the 2014 Roadmap. The second STP science target would study the variability in space weather driven by lower-atmosphere weather on Earth. This notional mission was called DYNAMIC (Dynamical Neutral Atmosphere-Ionosphere Coupling) with a decadal survey anticipated launch date of 2025. The 2014 Roadmap estimated DYNAMIC to start in 2020 and launch in 2025. The third and final STP science target recommended for this decade focused on how the magnetosphere-ionosphere-thermosphere system is coupled and how it responds to solar and magnetospheric forcing. This science target was illustrated by the reference mission called MEDICI (Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation) with a decadal survey anticipated launch date of 2029. The decadal survey already anticipated that MEDICI would not start before the next decadal interval; thus, this midterm assessment focuses on IMAP and DYNAMIC.

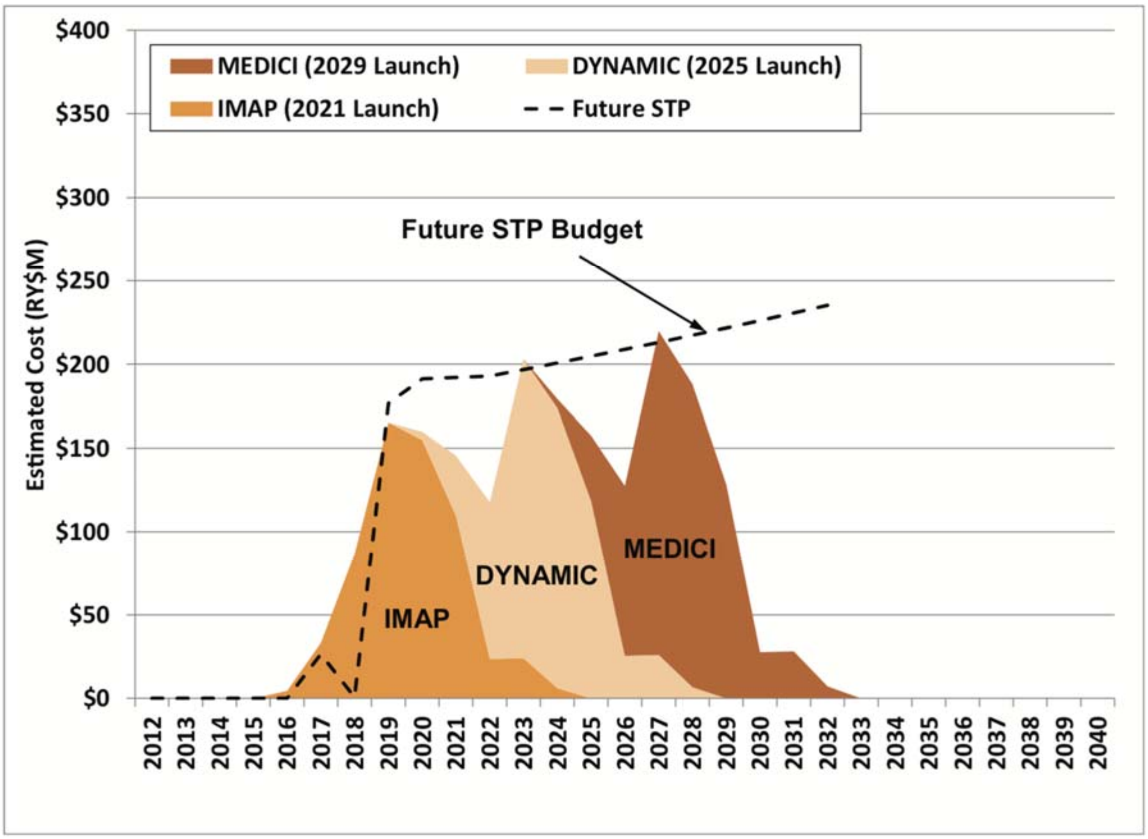

FIGURE 3.9 Figure 6.5 from the 2013 decadal survey showing the recommended timeline for implementing three notional Solar Terrestrial Probe (STP) missions. The dashed line represents the recommended funding level for the STP program, including a 2 percent inflation slope. The selection of the IMAP mission development in 2018 represents a 2-year delay for the restructured STP program from the decadal survey timeline. SOURCE: National Research Council, 2013, *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, DC.

In 2017, an announcement of opportunity was released for a mission addressing IMAP science goals. The AO outlined a PI-led mission cost capped at $492 million (in GFY 2017 dollars). In response to this AO, two proposals were submitted, and one of these was selected in 2018. The selected IMAP mission with 10 instruments is planned for a launch to Lagrange L1 in October 2024. The IMAP mission will study the solar wind and energetic particles from the Sun that modulate the boundary of the heliosphere and the harmful cosmic radiation that penetrates deep into the heliosphere to Earth.

> ***Finding 3.26:*** Formulation of the first of three recommended STP missions has begun, but IMAP comes 3 years later than anticipated in the decadal survey, and the next STP mission (DYNAMIC) has not started. As anticipated in the decadal survey, the MEDICI mission is not expected to start until the next decade.

In June 2019, a community workshop was held at the CEDAR meeting to discuss the science goals for the notional DYNAMIC constellation mission in light of the selection of two missions of opportunity (single instruments; GOLD and AWE) and one explorer (ICON) since the decadal survey was published. DYNAMIC's main science goals are (1) to resolve lower atmosphere influences on the AIM system by measuring the height evolution of the wave spectrum in the thermosphere that produces spatio-temporal variability within the system and (2) to provide the much needed day and nighttime wind measurements throughout the whole thermosphere to study ion-neutral interactions and dynamo processes.

The AWE instrument, to be installed on the ISS in late 2022, will remotely sense airglow emission from the lower boundary of the AIM system to extract part of the gravity wave spectrum impinging on this boundary from lower atmosphere sources. The GOLD instrument, launched in January 2018, offers a unique geosynchronous vantage point, viewing one-third of the globe with a resolution sufficient to resolve large- and small-scale thermosphere structures in temperature and composition. As such, both missions address parts of AIMI science goals 1 (GOLD) and 3 (GOLD and AWE) specified in the decadal survey. The ICON mission will advance our understanding of day-to-day ionospheric variability and monthly mean global-scale neutral atmospheric wave-ionospheric interactions at low-to-midlatitudes and partly contributes to AIMI science goal 2.

The newly selected GOLD and AWE MoOs and ICON explorer mission will answer important targeted science questions that contribute to our understanding of lower atmospheric impacts on the AIM system. However, these missions do not adequately observe Earth's poles and thus will not fully address one of the decadal survey top-level Research Recommendation 3.2 "to provide a comprehensive understanding of the variability in space weather driven by lower-atmosphere weather on Earth." As discussed in Chapter 2, progress made since the decadal survey highlights an increasing community need for a DYNAMIC-like whole atmosphere mission, particularly to resolve day-to-day wave and mean state variability, and to obtain the highly coveted day and nighttime wind measurements throughout the whole thermosphere that drive many processes in the AIM system. GOLD, AWE, and ICON can only partially address science questions that would be answered by DYNAMIC. These missions do not provide needed coverage in high latitudes, and their instruments lack the nighttime capability to measure winds in a portion of the thermosphere where the transition into diffusive equilibrium occurs, waves dissipate, and ion-neutral and dynamo interactions take place. The daily local time resolution needed to resolve day-to-day wave variability cannot be provided by single satellites or instruments. Single platforms are unable to resolve the tidal and planetary wave fields from the lower atmosphere due to aliasing caused by incomplete sampling. A constellation of satellites covering all latitudes and multiple local times is required to remove aliasing issues and address the influence of planetary-scale wave sources on the AIM system and dynamo processes. Day and night-time wind measurements throughout the thermosphere are needed to study ion-neutral interactions and dynamo processes in the AIM system.

> ***Finding 3.27:*** The DYNAMIC science goals remain compelling and of the highest priority for the heliophysics community. The targeted science goals and measurement capabilities of GOLD, AWE, and ICON do not address several key objectives in the top-level decadal survey science challenge posed by DYNAMIC.

> **Recommendation 3.4: NASA should take the steps necessary to release an announcement of opportunity for a DYNAMIC-like mission as the next Solar Terrestrial Probe mission.**

3.6 IMPLEMENT A LARGE LWS GDC-LIKE MISSION

Decadal Survey Research Recommendation R4.0: 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).

The Geospace Dynamics Constellation (GDC) was outlined as a notional LWS mission concept in the decadal survey. The mission would consist of six identical satellites in low Earth orbit, providing simultaneous, global observations of the coupled atmosphere-ionosphere-magnetosphere system. GDC will address crucial scientific questions pertaining to the dynamic processes active in Earth's upper atmosphere; their local, regional, and global structure; their response to magnetospheric drivers; and their role in modifying magnetospheric activity. It will be the first mission to address these questions on a global scale due to its use of a constellation of spacecraft that permit simultaneous multi-point observations. This investigation is central to understanding the basic physics and chemistry of the upper atmosphere and its interaction with Earth's magnetosphere, but also will produce insights into space weather processes. GDC science continues to be of high priority to the heliophysics community, specifically in the field of atmosphere-ionosphere-magnetosphere interactions. If successful, GDC would revolutionize scientific understanding of the dynamics within the ionosphere/thermosphere system.

The decadal survey's recommended scientific investigation and design reference mission for GDC was refined and updated in 2019 by a community-based Science and Technology Definition Team (STDT)[41] established as a subcommittee of the Heliophysics Advisory Committee (HPAC), an advisory committee established under the Federal Advisory Committee Act. The STDT assessed the science rationale for the mission and the provision of science and mission parameters, including the optimal number of spacecraft required to address the science, and any other scientific aspects needed. At the end of its work, the STDT submitted a final report on October 2, 2019, to HPAC that contains a description of its mission concept study, design reference missions, and the scientific trade-off between the studied potential mission implementations.[42]

The STDT has defined various mission implementation scenarios that are feasible, effective, and allow for the evolution of the system to be tracked across a range of temporal and spatial scales. The mission concept fully addresses the requirements specified by NASA in the STDT charter while also ensuring alignment with the recommendations of the 2013 decadal survey.[43]

The GDC STDT was an important first step in reviewing and refining the science goals for the reference mission outlined in the decadal survey. However, in contrast to previous STDTs for similar missions, a number of topics related to mission formulation and implementation were excluded from consideration.[44] The report examines four possible mission architectures and assesses the science closure

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[41] The STDT's membership consisted of 17 experts from the Heliophysics community that covered relevant scientific and technical expertise. The committee met in person 3 times, with additional teleconferences, and solicited community input through a NASA Request for Information (RFI); 56 responses were transferred to the STDT by NASA.

[42] The GDC STDT report is available at: https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/GDC%20STDT%20Report%20FINAL.pdf

[43] The GDC mission will unravel complex mysteries in the combined and interacting ionized and neutral gases of the IT (ionosphere-thermosphere) system by using an array of satellites. GDC is anticipated to be capable of measuring, for the first time, both the large-scale and localized dynamics of the interaction between the upper atmosphere and the near-Earth space plasma environment. The GDC mission will address two overarching science goals with specifically actionable objectives: 1) understand how the high latitude ionosphere-thermosphere system responds to variable solar wind/magnetosphere forcing; 2) understand how internal processes in the global ionosphere-thermosphere system redistribute mass, momentum, and energy.

[44] These are listed in the STDT report as follows:

1. Particular instrument types, instrument builds, non-spacecraft capabilities (e.g. models, ground-based observatories). While some measurement requirements have generally been met by particular instruments,

that would be achieved with each of these. No recommendation on the preferred architecture was made, although the report suggests that CubeSats may offer some advantages. In order to fully realize the mission goals for a GDC-like mission, it will be necessary to determine the best implementation of a satellite constellation.

> ***Finding 3.28:*** The GDC STDT, per their charge, was not permitted by NASA HQ to select a particular mission architecture to meet GDC science objectives.
>
> **Recommendation 3.5: In order to proceed towards meeting the top-level decadal survey Living With a Star mission recommendation, NASA should take the steps necessary to define a specific mission architecture formulation and implementation scheme in order to release an announcement of opportunity for the Geospace Dynamics Constellation within the next 3 years.**

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the STDT shall not recommend those particular instruments to the exclusion of other instruments (or combinations thereof) that could meet the requirement of measuring particular physical parameters.

2. The method, structure, content, or target of any mission formulation activity. This includes the direction, competition (e.g. AO, RFP), or invited contribution (e.g. from international partners) of mission components (e.g., spacecraft, instruments, inter-mission collaboration).
3. Any procurement activity in support of the mission formulation activity. In instances where a need or opportunity outside of the mission concept is recognized, the STDT shall identify for NASA to address.
4. Mission development costs or mission budget targets, either projected or recommended. All needed budgetary constraints will be provided by NASA.
5. Any provider-specific bus or bus type.
6. Any specific launch vehicle or launch strategy. In instances where a design reference mission requires the launch or deploying of multiple spacecraft, NASA will provide launch constraints.
7. Any potential NASA collaborations with specific US or non-US organizations.
8. Any space weather operational goals or requirements.

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4

Progress, Opportunities, and Challenges for Decadal Survey Applications Goals and Recommendations

4.1 INTRODUCTION

The 2013 decadal survey devoted an entire chapter to the topic of space weather and space climatology, an important application of heliophysics science. The decadal survey noted the necessity, from both economic and societal perspectives, of having reliable knowledge of geospace environmental conditions from the Sun to Earth over a range of timescales, including for forecasting space weather conditions up to several days ahead. Despite the well-documented vulnerability of essential societal, economic and security services, space environment monitoring remains resource challenged.

The decadal survey stated that the committee “envisions a national commitment to a new program in solar and space physics that would provide long-term observations of the space weather environment and support the development and application of geospace models to protect critical societal infrastructure, including communication, navigation, and terrestrial weather spacecraft, through accurate forecasting of the space environment” (NRC, 2013, p. 141). In support of this vision, the decadal survey committee described new (notional) agency-specific activities that would be needed to develop the required capabilities.

Figure 4.1 shows the survey’s space weather-related decadal survey recommendations and summarizes progress to date in addressing these recommendations. Subsequent sections of this chapter discuss the progress in more detail. However, an important note is that the survey committee assumed the availability of *new* resources at each agency to implement its notional space weather and climatology program.

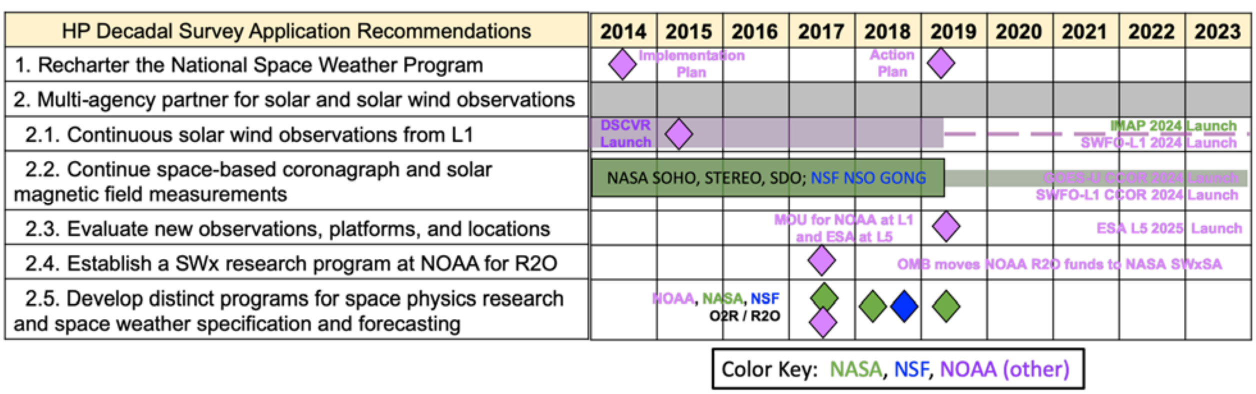

FIGURE 4.1 Highlights of progress and plans for the heliophysics decadal survey applications Recommendations. The National Solar Observatory’s GONG network of solar magnetograms is supported by the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA). NOTE: R2O, research to operations; SWx, space weather.

4.2 RECHARTER THE NATIONAL SPACE WEATHER PROGRAM

The Applications Recommendation 1 from the decadal survey reads as follows:

A1.0 Recharter the National Space Weather Program

As part of a plan to develop and coordinate a comprehensive program in space weather and climatology the survey committee recommends that the National Space Weather Program be rechartered under the auspices of the National Science and Technology Council. With the active participation of the Office of Science and Technology Policy and the Office of Management and Budget, the program 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.

Two years after publication of decadal survey, the 2015 National Space Weather Strategy (NSWS) (OSTP, 2015a) and the National Space Weather Action Plan (NSWAP) (OSTP, 2015b) were both released. The NSWAP outlines an interagency initiative to organize and enhance the nation's space weather monitoring, research, and forecasting infrastructure. In 2019, a new and more streamlined version of the NSWAP merged the 2015 NSWAP and the 2015 NSWS into a single National Space Weather Strategy and Action Plan (NSWSAP) (OSTP, 2019). The 2019 NSWSAP identifies 14 agencies involved with assessing, implementing, and executing its goals and plans. The primary and secondary agencies responsible for each objective are clearly listed in the report. Unfortunately, no new funding was identified with the release of the NSWSAP, so there are serious challenges in implementing the plans in the 2019 report to their fullest extent.

The NSWSAP is a major national initiative in which NASA Heliophysics Division, two NSF Directorates—Geoscience (GEO/AGS) and Mathematics and Physical Sciences (MPS/AST) —and NOAA SWPC (Space Weather Prediction Center) and NESDIS (National Environmental Satellite, Data, and Information Service) play dominant roles. These entities must interface in a collaborative and highly effective manner to fulfill their NSWSAP roles and complete their agreed upon contributions. Whereas some of these directives are already part of their present and/or planned activities and programs, others require new actions.

As a whole, the NSWSAP has precipitated rethinking of agencies' strategies for this area of both fundamental and applied research, which was not foreseen at the time of the decadal survey. Space weather-related assets and research within NASA's Heliophysics Division are now generally viewed in light of the much larger picture of human uses of space and the space weather impacts on terrestrial technology and infrastructure. NASA has responded by expanding its role in space weather (SWx) science by establishing the Space Weather Science and Application (SWxSA) program within its Heliophysics Division. The SWxSA program is distinguished from the other heliophysics research elements in that it is specifically focused on (1) advancing understanding of space weather, (2) applying this progress to more accurate characterization and predictions, and (3) developing transition tools, models, data, and knowledge from research to application. The SWxSA program plans to secure community expertise through the Heliophysics Advisory Committee (HPAC). One of the listed goals of SWxSA is to collaborate with other agencies and partner with user communities.

NASA's SWxSA has developed strategic documents to address the following space weather goals: (1) the NASA SWxSA R2O Strategy, which focuses exclusively on research-to-operations (R2O), and (2) the Heliophysics Space Weather Science and Application Strategy (Spann, 2019). Both of these documents provide general direction for the agency, but neither addresses the "identification of capability gaps," nor do they address when, how, or by whom the described tasks are to be executed. These details are left for what they describe as the implementation plan, which is presumed to be in development.

NASA's plans for participation in the National Space Weather Action Plan, together with related progress, were reviewed in detail in the 2019 Office of the Inspector General (OIG) Report on NASA's Heliophysics Portfolio. NASA has assigned all NSWAP activities to its Heliophysics Division, although many of them directly impact the Human Exploration Division as well as technology considerations across all space exploration, technology, and support disciplines. Heliophysics funding toward fulfilling its NSWAP task list (reproduced from the Appendix of the OIG report) is limited by its current budget.

Additional funds have been made available at NSF to support an O2R/R2O (Operations-to-Research/Research-to-Operations) pilot program. NOAA has also allocated funds for a new SWO2R (Space Weather O2R) program administered by Heliophysics Division (HPD). The SWO2R program objective is "broadly defined as the joint pursuit of improvements of operational capabilities and advancements in related fundamental research." Toward this end, HPD hosted a NOAA detailee at NASA HQ to kick-start and manage the program. While it is early to comment on the extent to which these research programs address the NSWAP agenda, the OIG report specifically points out NASA's "difficulty implementing several NSWAP tasks," which were attributed to "task complexity and shortage of NASA and partner agency officials' subject matter expertise," "unrealistic deadlines," and "competing priorities at other agencies." The OIG report concludes, "Further delays in implementing NSWAP tasks could hinder the ability to predict, protect against, and mitigate adverse space weather incidents." In addition, the new directive to return humans to the Moon by 2024 adds further impetus to tasks related to space radiation impacts, including forecasting. This midterm committee agrees with the assessment of the OIG report.

The NSWAP laid out the basic issues and challenges relating to the development of reliable, actionable space weather forecasts for a wide user base. One of the complications is to transition deep scientific understanding of the complex web of Sun-Earth connections into tools and procedures that provide SWx forecasts. NASA and NSF are stimulating the advancement of our scientific understanding in a multitude of areas important to space weather applications. NOAA, NASA, and NSF have a good understanding of the transition protocol as demonstrated in the SWxSA strategy documents and Space Weather Benchmark Reports (see e.g., https://www.sworm.gov/publications/2018/Space-Weather-Phase-1-Benchmarks-Report.pdf). Successful forecasting depends on a deep understanding of the multitude of connections and couplings between phenomena and domains. A clear plan to gain this deep understanding—as was described in the 2013 decadal survey—is missing. This will limit the success of the NSWAP.

An analysis of these issues was performed under the auspices of the Committee on Space Research (COSPAR), published in its 2015 space weather roadmap (Schrijver et al., 2015). This comprehensive, international, interdisciplinary analysis identified multiple key science area "gaps" that particularly need filling to increase forecast lead times and reliability. Among these gaps are better descriptions of instabilities in the geomagnetic and solar magnetic fields, the processes of energization of particles in geospace, the structure and variability of the heliosphere and the solar atmosphere, and the exchanges of energy and momentum between the various drivers and coupled domains of space weather. The resulting roadmap identifies the highest-priority observables, models, and research focus areas based on current knowledge and infrastructure capabilities. This document is a resource that could be used, together with the NSWAP report, as the basis for defining Strategic Knowledge Gap (SKG) targets and exercises (e.g., such as those done for Lunar Radiation within NASA's HEOMD (Human Exploration and Operations Mission Directorate) (Shearer et al., 2016) Such SKG targets could then be addressed within the existing NASA SWxSA and NSF Space Weather Benchmarking activities.

> ***Finding 4.1:*** The NASA Space Weather Science and Application (SWxSA) strategic documents are an excellent start to address the NSWAP goals and responsibilities identified for NASA Heliophysics Division. However, these documents do not "identify new research-based capabilities and outline expectations for gap-filling products." The committee emphasizes the importance of a science gap analysis in order to develop implementation plans, interagency coordination, and budgets. NASA and NSF, in coordination with their research communities, and in consultation with NOAA, are best positioned to develop a scientific gap analysis to address the scientific and observational challenges that currently hamper the formulation of reliable space weather forecasts for time scales from several hours to a few days.

The analysis of critical gaps in our scientific understanding, modeling abilities, and essential observables is crucial as the foundation for the development of implementation plans that, in turn, form the basis for the required budget. The agencies can opt to initiate a new gap analysis, but several such efforts have been, in whole or in part, executed recently. The following reports that can be taken as input documents for such a gap analysis. First, there is the 2015 COSPAR roadmap ("Understanding space weather to shield society" (Schrijver et al., 2015)). That report founded its gap analysis on the highest-priority needs and highest-value forecasts identified by the space-weather user communities, as assembled by the NOAA Space Weather Prediction Center (SWPC). As such, the roadmap presents a study in line with the NSWAP and SWxSA initiatives. Another gap analysis is presented in the 2016 NSF Geospace Portfolio Review (Lotko et al., 2016). That report lists "critical capabilities needed to make progress in achieving [decadal survey] goals" and is therefore more focused on the fundamentals of heliophysics than on its applied science aspects. A third document is the report of NASA's Lunar Human Exploration team (Shearer et al., 2016), which identifies strategic knowledge gaps relating to human exploration of the Moon and beyond and is therefore strongly focused on NASA's needs to specify and forecast Solar Energetic Particles (SEP). Each of these documents presents a gap analysis from a different perspective, thus their integration should form a comprehensive foundation for the gap analysis that we identify as needed for the space-weather applications component of NSWAP. NASA could consult its SMD Heliophysics Advisory Committee (HPAC), the Committee on Solar and Space Physics (CSSP) of the National Academies of Sciences, Engineering, and Medicine, or other advisory entities on the most effective and expedient ways to develop this analysis. Alternatives to working with the existing gap analyses include executing a new national NASA/NSF-led gap analysis, or partnering with COSPAR as it plans to update its SWx roadmap that assesses science gaps from an international, global perspective. The committee encourages NASA to opt for coordinating with COSPAR.

> ***Finding 4.2:*** Stable funding lines were not identified for the work defined in the NSWAP. The development of a scientific gap analysis, and an associated prioritization of required observables, models, data systems, and R2O/O2R projects are needed in order to develop a well-founded budget for the NSWAP-related tasks of NASA, NSF, NOAA, and other agencies.

4.3 PROGRESS ON A MULTI-AGENCY PARTNERSHIP TO ACHIEVE CONTINUITY OF SOLAR AND SOLAR WIND OBSERVATIONS

The decadal survey included a series of recommendations concerning operational space weather measurements and products. For example, the decadal survey stressed the need to maintain the continuity of critical measurements for space weather applications and the agency partnerships that would be required to achieve this. Additionally, the decadal survey made recommendations concerning the evaluation of new observations, platforms and locations, as well as NOAA's role in establishing a clear path to transition research to operations. Finally, the decadal survey noted that distinct funding lines for space weather research, and for space weather specification and forecasting, are needed. This new growth opportunity could further enhance the heliophysics workforce (a topic in this report's Chapter 5).

> **Decadal Survey Recommendation A2.0 states:**
>
> **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:**
>
> **A2.1 Solar wind measurements from L1 should be continued, because they are essential for space weather operations and research. The DSCOVR L1 monitor and IMAP STP mission 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.

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 systems 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 should be developed and maintained.

4.3.1 Progress on Decadal Survey Applications Recommendation A2.1: Continuous Solar Wind Observations from L1

Forecasting of space weather relies on observational input of conditions on the Sun, in the inner heliosphere, and near Earth. The decadal survey recognized in particular the importance of having uninterrupted measurements of solar wind observations from Sun-Earth Lagrange point 1 (L1). In situ magnetic field and particle measurements in the near-upstream region of the solar wind provide the properties of incoming disturbances some 15 minutes to 1 hour before these disturbances reach Earth. These observations are essential to short-term space weather forecasts, for situational awareness in geospace, and as inputs for comprehensive models of the space environment. The NASA Advanced Composition Explorer (ACE) spacecraft has provided solar wind measurements at L1 since 1997, and its mission has been extended well past its design life to support space weather operations. Concerns about ACE's advancing age precipitated earlier coordinated agency discussions and actions leading to the refurbishment of plasma and field instrumentation available from the unlaunched Triana spacecraft.[1] Following the decadal survey, these updated instruments were launched on the DSCOVR spacecraft in 2015 as a partnership of NASA, NOAA, and the U.S. Air Force to provide solar wind measurements at L1. ACE continues to operate and was recently reclassified by NASA as an operational asset considered separate from extended scientifically focused missions. DSCOVR is approaching its planned mission life of 5 years while IMAP, with in situ solar wind measurements, is in Phase A with launch to L1 planned for October 2024. Considering the 2019 anomalies for DSCOVR and the advancing age of the ACE spacecraft, there is concern for a gap in L1 solar measurements until the IMAP spacecraft comes online in late 2024 to continue solar wind measurements at L1. In addition to the space weather-related in situ instruments on IMAP, the ESPA ring on the IMAP launch will carry NOAA's first SWFO-L1 (Space Weather Follow-On) space weather monitor,[2] which is potentially the first of a new operational line of L1 assets.

4.3.2 Progress on Decadal Survey Applications Recommendation A2.2: Continuous Space-Based Coronagraph and Solar Magnetic Field Measurements

The decadal survey identified continuous space-based photospheric (solar surface) magnetic field measurements and coronagraphic observations as key space weather data. For early forecasting, the photospheric magnetic field provides the first signs of potentially active (e.g., flaring or eruptive) conditions and is also the basis for still-developing space weather forecast models. Currently, the HMI magnetograph on the Solar Dynamics Observatory (SDO) is making space-based measurements of the

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[1] See https://directory.eoportal.org/web/eoportal/satellite-missions/d/dscovr.
[2] See https://www.nesdis.noaa.gov/OPPA/swfo-L1.php.

photospheric magnetic field. SDO was launched in 2010 with a mission design lifetime of 5 years; it is currently operating successfully in its extended mission phase. Several planned missions will carry next-generation magnetographs to continue and expand perspectives on the state of the Sun's surface magnetic field.

A mission concept to observe the Sun far from the Sun-Earth line at the L5 vantage point (trailing Earth by some 60 degrees in its orbit around the Sun) is currently being discussed with the European Space Agency (ESA) as a potential partner. Among its other space weather instrumentation, this mission would carry a magnetograph to provide advanced warning of developing active regions before they rotate onto the visible disk of the Sun. A new mission with an additional capable magnetograph, ESA's Solar Orbiter, is already due to launch into a heliocentric orbit in February 2020. This mission will orbit the Sun between the orbit of Mercury and 1 AU at increasingly high latitudes, providing important new insights on the solar surface polar and farside fields. Measurements from the Polarimetric and Helioseismic Imager (PHI) instrument aboard the Solar Orbiter will be available, but only in campaign-mode. Thus, these measurements will have long delays in data availability and are thus not suitable for real-time space weather monitoring.

The ground-based GONG chain of magnetographs is in the meantime an important, and widely used, complementary observatory to SDO/HMI. Moreover, GONG magnetographs could provide an alternative source of data should anything happen to disrupt the continuous data stream from SDO. NSO is currently working on upgraded instrumentation for GONG, and an interagency agreement is in place between NSO and NOAA to continue funding of GONG through 2021, with a likely extension to support NOAA's space weather operations in the near future (as described in this report's Chapter 3.) Currently, an L1 or GEO magnetograph replacement for SDO HMI is not included the near-term plan.

Coronagraphic observations provide essential information on the initial speed and direction of coronal mass ejections (CMEs) when they first occur at the Sun. Coronagraph images, often used in conjunction with EUV images like those available from SDO-AIA (Atmospheric Imaging Assembly), are used to predict if and when the related interplanetary shocks and plasma and field disturbances will impact L1 and then Earth's magnetosphere, causing a magnetic storm. Ground-based coronagraph observations, such as those from MLSO (Mauna Loa Solar Observatory), can provide some of the information on CMEs and other solar activity, but these ground-based facilities depend on the local time at the observatory location and are also extremely sensitive to Earth weather conditions. In the absence of a suitable global network, continued space-based observations were identified as essential in the decadal survey. Currently, space-based coronagraph observations come from the LASCO (Large Angle and Spectrometric Coronagraph) instrument on the SOHO (Solar and Heliospheric Observatory) spacecraft, the COR1 and COR2 imagers on the STEREO (Solar Terrestrial Relations Observatory) spacecraft,[3] and WISPR (Wide-Field Imager for Solar Probe) on the Parker Solar Probe. Additionally, there will soon be coronagraph observations from METIS[4] on ESA's Solar Orbiter. SOHO was launched in 1995, and is currently maintained only for its coronagraph observations for space weather operations. NOAA's near-future plans for coronagraph observations include flying the Naval Research Laboratory (NRL) Compact Coronagraph (CCOR) on both the SWFO mission to L1 mentioned above that will launch with IMAP in 2024 and also on the geosynchronous GOES-U spacecraft (to become GOES-18 after its launch in 2024). Having two near-Earth space-based coronagraphs simultaneously would be unprecedented. The selection of the PUNCH[5] project as a NASA SMEX to be launched around 2022 will provide additional coronagraph observations, but as a research mission rather than a dedicated space weather monitoring facility.[6]

Finding 4.3: Currently, the combination of ACE and DISCOVR in situ particle and field

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[3] STEREO-A, which also includes an EUV imager, is still operational, but not STEREO-B.
[4] Multi Element Telescope for Imaging and Spectroscopy.
[5] Polarimeter to Unify the Corona and Heliosphere.
[6] See National Space Weather Strategy and Action Plan 2019.

measurements at L1, the GOES solar EUV imager and solar EUV and X-ray irradiance sensors at GEO, the ground-based GONG network for solar magnetograms, and the SOHO LASCO coronagraph at L1 provide the primary set of space weather monitoring assets, with support from SDO solar observations at GEO and STEREO solar and in-situ observations in an Earth trailing/leading orbit. NOAA has plans to continue in situ solar wind observations at L1, to establish new coronagraph observations at L1 and at GEO, and to continue their support of solar magnetograms in the GONG network.

4.3.3 Progress on Decadal Survey Applications Recommendation A2.3: Evaluate New Observations, Platforms, and Locations

As mentioned above, the agencies involved in NSWAP, primarily NASA and NOAA, have seriously engaged in the study and implementation of a space weather monitoring observatory at the L5 location. An aggressive plan on the part of ESA to carry out the Lagrange operational mission,[7] with desired participation from the United States, is under way. ESA's goal for the Lagrange mission is to be online at L5 before the next solar maximum in approximately 2025. ESA and NOAA have together developed an operational plan where NOAA provides space weather observations at L1, while ESA provides space weather observations near L5. NASA's participation is still under discussion. In the meantime, other future mission discussions include a complementary observatory at L4, which is on the other side of Earth at an equivalent to the L5 location (with L4 leading Earth and L5 trailing). As discussed in subsections 4.2.1 and 4.2.2 above, NOAA has a new SWFO line to have space weather operational missions at L1, with its first launch in 2024. International collaboration for space weather looks promising: India plans a 2022 launch for a space weather mission to L1, and both China and India are developing L5/L4 space weather missions. Further possibilities for future consideration involve a "L1-L5 drifter" and a "string of pearls"[8]—mission concept that envision gradual population of the entire Earth orbit, with solar and space weather monitors surrounding the Sun.

> ***Finding 4.4:*** NASA and NOAA are conducting a dialogue with ESA regarding participation in the Lagrange operational mission to the L5 location. NOAA has a formal agreement with ESA for their L5 mission, but no agreements are yet in place for NASA. Additional observations, platforms, and locations are informally discussed as a part of the ongoing agency and community interactions and communications relevant to the NSWAP. Coordination with India and China could further enhance space weather observations at the L1, L4, and L5 locations.

4.3.4 Progress on Applications Recommendations A2.4: Establish a SWx Research Program at NOAA for R2O and A2.5: Develop Distinct Programs for Space Physics Research and Space Weather Specifications and Forecasting

The decadal survey provided a concise general vision for the growth of space weather activities. Most of their guidance was directed at NASA, with only limited treatment regarding the roles of NSF and NOAA, and passing mention of the Department of Defense (DoD) and the Department of Energy. Since 2013, space weather has been elevated to a bonafide issue of national security, with multiple documents providing specific recommendations and benchmarks on how the agencies should proceed. The explosive increase in public and political interest in space weather represents a significant divergence from the decadal survey. Heliophysics activities must consider this new status and implement new guidance moving forward.

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[7] See https://www.esa.int/Our_Activities/Space_Safety/Lagrange_mission2.
[8] See, for example, Vourlidas et al. (2018): https://www.hou.usra.edu/meetings/deepspace2018/pdf/3055.pdf.

The support for O2R (operations-to-research) and R2O (research-to-observations) efforts is evolving, starting first with an O2R/R2O research opportunity in 2017 co-funded by NASA and NOAA. In 2018, NSF also solicited an O2R research opportunity, and the Office of Management and Budget (OMB) consolidated the NOAA-NASA funding for O2R/R2O solely into the NASA Heliophysics budget. OMB is also expanding this research within NASA's new Space Weather Science and Applications (SWxSA) program with $20 million planned for FY 2020. Space weather is a rapidly evolving area, and many aspects regarding future plans and funding will likely have progressed by the time this Midterm report is published.

> ***Finding 4.5:*** The decadal survey did not address the specific contributions of the primary agencies (NASA, NSF, NOAA, DoD) to the National Space Weather Program. In particular, the role of research targeting the magnetosphere, ionosphere, and thermosphere was not represented in the decadal survey at a level commensurate with current NSWAP priorities. The NOAA/NASA/NSF support for O2R/R2O efforts is evolving with the majority of this research being planned in FY 2020 under the NASA Heliophysics Division's new SWxSA program.

Since the decadal survey was published, the landscape has changed with respect to the numbers and designs of space-based platforms and related infrastructure. First, there is more widespread use of small satellites, including CubeSats, for research, education, commercial, and other purposes. Second, there is a general movement toward options for shared launch opportunities. This midterm assessment also notes that HSO assets are aging just as the HSO, as a programmatic framework, is being increasingly used.

In 2018, the previously mentioned Space Weather Benchmark report (also called the White House's Space Weather Phase 1 Benchmarks report[9]) was released, addressing one of the NSWAP's deliverables. This report provided initial benchmarks for five phenomena associated with space weather events: induced geo-electric fields, ionizing radiation, ionospheric disturbances, solar radio bursts, and upper atmospheric expansion. These benchmarks are designed to capture an event's ability to affect the nation as well as provide clear and consistent descriptions of space weather events based on current scientific understanding and the historical record. More recently, the Next Step Benchmarks study, an NSF and NASA funded task, was formed to re-evaluate the Phase 1 Benchmarks with respect to their application to extreme space weather events. The final output of the Next Step Benchmarks task will be a public document that provides recommendations for improving benchmarks specifically for extreme space weather events.[10]

To address the benchmark studies and to properly support the National Space Weather program needs, the required space weather data and associated observational platforms on the ground and in space, should be identified. Different types of partnerships will be necessary to support these observations, which should include not only shared launches but also rideshare opportunities and data-sharing agreements. An important example relevant to NSWAP is the recent partnership between NOAA and NASA to use the IMAP launch ESPA ring for the next NOAA L1 monitor. In other cases, uniquely useful measurements are extractable from routine data streams obtained by non-NOAA or NASA satellites and satellite networks. Certain "swarm" measurements (e.g., total electron content (TEC) from Global Navigation Satellite Systems (GNSS), ionospheric and magnetospheric currents from the Iridium satellites) have been transformative for our ability to observe temporal and spatial trends. Moreover, such collaborations need not be restricted to hardware and measurements alone. For example, coordination between various modeling programs would improve space weather forecasting. The Community Coordinated Modeling Center (CCMC), jointly supported by several of the NSWAP agency members,

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[9] See https://www.sworm.gov/publications/2018/Space-Weather-Phase-1-Benchmarks-Report.pdf.

[10] A town hall was held in September 2019 to incorporate community feedback as the final report is being prepared. http://www.cvent.com/events/town-hall-on-next-step-space-weather-benchmarks/event-summary-6ca0f9319ed04cd2937278474f7b47ff.aspx.

has already carried out validations of some of the most widely used heliophysics models. Although the validation practices and standards of CCMC may differ from those at NOAA SWPC, some normalization would enable R2O progress.

The involvement of different agencies with different standards and agendas is both a challenge and an advantage for realizing the NSWAP vision. Both NASA Heliophysics and NSF Geosciences currently have program directors dedicated to space weather activities who could host regular NSWAP coordination exchanges. The anecdotal successes summarized above serve to emphasize the far greater efficacy that could be achieved through formal close collaboration.

> ***Finding 4.6:*** The minimum observation requirements and baseline research infrastructure need to be defined by drawing on space weather O2R/R2O activities at NSF and NASA. Ongoing space weather benchmark activities are a step in this direction.

Critical to the advancement of science is access to data through open data policies and standardized data interfaces. Science moves forward through continued testing and re-evaluation of ideas. Without easy access to data this progression is stymied. A prime example of the advantages of open data was the establishment of GNSS databases in the early 1990s. These databases utilized a standard RINEX (receiver independent exchange) format for their data products. The GNSS database was established for geodetic purposes to monitor the movement of Earth's plates.

Over time, GNSS has become a prime data source for monitoring the changes in the total electron content (TEC) of the ionosphere and for measuring the total precipitable water vapor. Another example is AMPERE (Iridium), which provides magnetic field measurements. Both GNSS and AMPERE depend on open data sources, including data about spacecraft design and from the spacecraft instruments. New plans for buying commercial data products from the suite of newly launched CubeSats, which provide radio occultation (RO) data, are of concern. These data products can provide electron density and water vapor measurements. However, if the science community does not have access to the original data, there will be little chance of data verification or of future data analysis advancements. These issues require close monitoring and definition.

> ***Finding 4.7:*** The agencies can take advantage of commercial, interagency, and inter-divisional collaborations to make progress toward their space weather goals. To assure that this happens effectively, open data policies and standardized data interfaces need to be established. Inputs from the science community are critical for assessing how useful the commercial data are and assuring that the right data are accessible (and not merely higher-level derived products).

4.4 APPLICATIONS RECOMMENDATIONS

In view of the progress and changes in the situational landscape discussed in this chapter, and in the context of the latest NSWAP, the committee reached the following recommendations.

> **Recommendation 4.1: In order to make efficient progress on the high-level goals in the National Space Weather Action Plan, NASA should initiate an implementation roadmap for space-weather science and for capability transfer between research and operations (research-to-operations and operations-to-research) in collaboration with the National Science Foundation's Geosciences (GEO) and Mathematical and Physical Sciences (MPS) directorates and their research communities. This document should identify and prioritize the science focus areas and the associated essential observables and data-driven space-environmental models that are critical to "significantly advance understanding and enable improved characterization and prediction of space weather" as part of the overall national space weather enterprise as well as for NASA's internal needs related to the exploration of**

space.

- The plan should reflect an assessment of key scientific and observational "capability gaps in the current space weather operational baseline."
- This plan should be developed in close consultation with NOAA as a representative of the space-weather user community and other agencies identified in the NSWAP.
- This plan should take advantage of reports that already exist in this area, and its formulation can make use of national advisory committees, COSPAR's space weather roadmap team, and other advisory entities.
- This plan, along with an associated budget, should be available as input to the next decadal survey in solar and space physics to further develop how the research programs at the different agencies can best work together to obtain the required space weather measurements and models.
- The agencies involved should have ongoing activity to guarantee a succession plan for continued acquisition of critical space weather diagnostics.

Recommendation 4.2: NOAA, along with other operational agencies, should develop notional budgets for space weather operations that would include identifying the need for new space weather funding lines required to fulfill the responsibilities added to their existing tasks by the National Space Weather Action Plan. This should be available as input to the next decadal survey.

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5

Heliophysics Career Enhancements

This chapter discusses findings, recommended actions, and opportunities over the next 4 years to enhance all stages of careers for scientists and engineers in the solar and space physics community (midterm committee task 7). Career enhancement needs are organized into three categories: (1) the need to enhance funding opportunities for heliophysics scientists, (2) the need to enhance professional training and apprenticeships for instrument development, mission development, project management, software development, and theory, and (3) the need to improve diversity, equity, and inclusion in the heliophysics community. For this discussion, we have defined early-career scientists to be those with less than 10 years' experience since their PhD. While some of the discussion in this chapter pertains to all stages of career development, this committee emphasizes the higher vulnerability for early-career scientists who are at greater risk of leaving the heliophysics community due to low funding and/or limited opportunities for heliophysics research.

The increasing importance of space weather applications presents a new growth opportunity for the heliophysics community (discussed more in this report's Chapter 4). The National Space Weather Action Plan (2015, 2019) calls for more research to improve the accuracy of space weather forecasts through Research-to-Operations (R2O) and Operations-to-Research (O2R) efforts at NASA, NSF, and NOAA. To address those needs and also to support NASA's new plans for sending astronauts to the Moon in 2024, NASA Heliophysics Division has created a new Space Weather Science and Applications (SWxSA) research program. There is much promise that these new opportunities can enhance the heliophysics community, but it is too early to tell how impactful these opportunities will be on heliophysics careers.

5.1 ENHANCING FUNDING OPPORTUNITIES FOR HELIOPHYSICS SCIENTISTS

The complexity of solar and space physics research is growing: projects tend to increasingly involve large data volumes, require interdisciplinary expertise, and use complementary observational and computational approaches. This complexity involves more researchers in larger projects that then require more time for significant progress. The funding awarded for the typical research grant, while increasing, is insufficient for proposing teams to effectively take on larger and more interdisciplinary problems. The NASA HSCs were designed to address this issue. Smaller, linked projects, which would support larger teams on a single grant, may also be a worthwhile approach to consider in order to expand opportunities for complex projects. Another idea could be the implementation of some renewable grants based on previous work, or longer-term grants (4-5 years). These approaches could provide greater stability for scientists and graduate students (whose time in graduate school usually exceeds the 3-yr span of the typical grant).

A significant concern is the timescale for evaluation and funding of proposals in some NASA programs. While many programs have been effective in getting proposals reviewed, decisions made, and funds disbursed within 6-8 months after the proposal due date, there are some cases of serious delays. For example, the 2017 Living With a Star (LWS) proposal due date for Step-1 was moved from June 7, 2017 to Dec 5, 2017 because the result from the previous LWS competition was drastically delayed; the due date for a new competition could not occur before the results of the last one were announced. Such long delays and shifting deadlines have a significant impact on postdocs (who often operate on a 1-2 year time-scale) and any individuals who rely on soft money.

Moreover, most NASA programs only allow for one opportunity per year, with applications at specified times that may not line up with the timeline of postdocs and early-career scientists. For example, for a program that has its Step-1 due date in March, a graduate student who is hoping to graduate in May (or during the summer) would likely not be able to apply. This graduate student's next opportunity to apply would be near the end of the first year of their postdoc, with the outcome known 8 months later, in the second half of the second year of their postdoc. The NSF flexibility on proposal submission without a firm due date for some of their research opportunities has helped significantly. A survey of postdocs and early-career scientists to determine the extent of this problem should be considered, perhaps as part of the demographics survey recommended in this report's Chapter 6.

Moldwin et al. (2013) indicate that the number of long-term scientist positions is not keeping pace with the number of PhDs produced. Anecdotally, one hears of young people leaving the field, more so than in the previous decade. This is not necessarily a negative outcome and may indicate that our students have increasing opportunities in other sectors. However, a more deliberate monitoring of the situation is in order. Heliophysics scientists are currently facing some daunting challenges: the prospect of many years of low-selection rates for proposals, low-level funding per research grant, a slow cycle between proposal and availability of funding, in most cases only one opportunity per year to apply to a program, and few opportunities for applying for a permanent research position (e.g., academic faculty position or a government position). The result is that many very promising young researchers may opt to leave the field to find more lucrative employment in other sectors, and that even older researchers may opt to leave the field or retire early. Retention of graduates into academic jobs has been low for years, so it is important that students are advised about non-academic career opportunities, such as through AGU, AAS, and APS. It is also critical that talent is retained in the heliophysics research community. While the community wants to ensure that sufficient talent is retained to continue to advance the science, it is a mistake to automatically regard scientists leaving academic research for positions that better serve them and their desires as a bad thing. Society as a whole benefits from the application of quantitative analysis to a wide range of productive activity.

On the other hand, student support from NASA seems to be holding steady. The decadal survey expressed a, "strong desire to see NASA Earth and Space Science Fellowship (NESSF) support for solar and space physics maintained at levels as high as those the Graduate Students Researchers Program (GSRP) historically provided." Graduate student fellowship awards in heliophysics have increased since 2013 (to 23 percent in 2018's NESSF and 21 percent in 2019 with the newly instated Future Investigators in NASA Earth and Space Science in Technology (FINESST) program), and total funding by NASA has increased slightly over the past few years. A key to enhancing diversity in the heliophysics community is attracting more students at the undergraduate level and even earlier through science outreach and citizen science projects. At the undergraduate level, the number of NSF/REU programs in solar and space physics is small—there were only 4 in 2019 as discussed more in the next subsection.

Finding 5.1: The effectiveness of grants issued by NSF and NASA for research in solar and space physics could be improved by:

- Shortening the cycle from proposal to funding availability. In some programs, and especially for younger scientists and postdocs, the cycle is too long.
- Adjusting the size of grants. Typical grants, while they have grown in size, are often too small or short-term to tackle the larger challenges. Larger grants may be more effective for some programs. On the other hand, smaller grants or "seed grants", with smaller proposals, quicker reviews, and shorter funding cycles could invigorate new research directions and could be more supportive of early-career scientists.

The committee notes that low selection rates of proposals affect all stages of scientist careers and more so for entry-level researchers. A portfolio of different magnitudes of grants, but given comparable award percentages per round, could address some of these concerns while maintaining flexibility and frequency in research opportunities. . There is the concern that enhanced success for retention of early-career researchers could inadvertently reduce support for mid-career and senior researchers.

5.2 ENHANCING PROFESSIONAL TRAINING FOR HELIOPHYSICS RESEARCH

NSF and NASA have supported heliophysics summer schools for the past 18 years, and these have been a cornerstone for professional training for graduate students and post-docs. The Center for Integrated Space Weather Modeling (CISM) Space Weather Summer School has been in operation since 2001 at Boston College and then at NCAR-HAO since 2016. The NASA Living With a Star (LWS) Heliophysics Summer School at the University Corporation for Atmospheric Research (UCAR) in Boulder has been active since 2006. The NSF Research Experience for Undergraduates (REU) program supports about 800 summer programs for undergraduate students each year. The goal of the NSF REU program is to have undergraduate students participate in research and consider a STEM-related career path; however, only four of the 793 REU programs in 2019 were related to heliophysics. Some other training opportunities include student workshops at the annual CEDAR (Couplings, Energetics, and Dynamics of Atmospheric Regions), GEM (Geospace Environment Modeling), SHINE (Solar, Heliosphere, and Interplanetary Environment), and SPD (Solar Physics Division) conferences, which are mostly hosted by NSF. The education of the heliophysics workforce is an important element for NSF research programs, and is also critically important for NASA, NOAA, and other agencies involved in heliophysics research and space weather applications. Most of heliophysics is taught through university physics, astronomy, and atmospheric science departments. Growing the number of heliophysics-related faculty in those departments, and even creating new academic departments specializing in heliophysics, is important for enhancing heliophysics education. Aspects of heliophysics education are also discussed for the DRIVE "Education" element in Section 3.3.5.

> ***Finding 5.2:*** The NSF and NASA on-going education programs involving heliophysics summer schools, REU programs, and student workshops offer opportunities for exposing graduate and undergraduates to space physics research, as well as hands-on training. There is great potential for attracting more talent to the heliophysics community by significantly expanding involvement of undergraduate students through more heliophysics-related REU programs and by growing the number of heliophysics-related professors.

We also suggest some enhancements in professional training to address some gaps as related to the evolving nature of research tools and the need to attract and train the next generation of instrument scientists and engineers. We present two findings related to those enhancements, and we encourage NSF, NASA, and the next decadal survey committee to consider these and other ways to enhance the opportunities for more professional training.

The volume of data delivered by our observatories on the ground and in space continues to grow rapidly, often expanding by factors of 1,000 and more from one generation of instrumentation to the next. The rapidly growing data archives with data spanning years or decades now readily enable ensemble studies, along with the traditional detailed case studies, often through a combination of data from multiple instruments. The development of advanced 'numerical laboratories' is an ever more critical component of how we learn about the local cosmos. This is in part because of the need for high-fidelity first-principle modeling, and in part because the desired physical quantity is often separated from the observables by processes that require cutting-edge forward modeling (such as helioseismic inversions to learn about the Sun, or full heliosphere modeling to understand what energetic neutral atoms tell us about the outer bounds of the heliosphere). Increasingly, machine learning is utilized to extract essential features and trends from large data volumes. Furthermore, other tools such as data visualization and cloud computing are rapidly evolving for scientific analysis with large data sets. The challenge of "big data" also often means the analysis tool is brought to the data rather than the other way around. Training for the use and analysis of big-data and associated tools for research could be additional topics for future summer schools and student workshops. By educating and training the solar and space physics community, funding agencies will help create a culture that encourages scientists at all career levels to learn new techniques and maximize their scientific return. Report Chapters 3 and 6 also discuss additional aspects of big-data and associated analysis techniques and models. Of special note, this discussion overlaps significantly with the DRIVE "Education" element discussed in Section 3.3.5, and the following Finding 5.3 is collaborative with Recommendation 3.2 in Section 3.3.6.

> ***Finding 5.3:*** The infrastructure of large data archives and advanced numerical research and analysis tools is a critical element of modern-day science. Professional training about these rapidly evolving tools and modeling techniques is important for the health of the heliophysics research programs. The development and maintenance of such tools is given insufficient attention in the development of roadmaps and strategic plans. These infrastructure components, and the teaching of their use, could be discussed on an equal footing with experimental hardware in the planning and budgeting of space- and ground-based observatories.

Involving students with rockets, balloons, and CubeSat experiments has proven to be a positive way to train students as the next-generation workforce for future space missions. Much of this training is done at universities, though there are also several intern opportunities, mostly as summer programs, at NASA centers and in commercial space industry. There is a desire to involve more students in development of space hardware in order to maintain and grow the heliophysics workforce. One approach is to have more partnering between universities and non-University institutions. Some examples of current successful partnerships include SwRI San Antonio and University of Texas San Antonio, SwRI Boulder and CU Boulder, LMSAL and Stanford in Palo Alto, NASA GSFC and University of Maryland, and JPL and 13 universities (see https://surp.jpl.nasa.gov/). This committee has identified several barriers to involving more students, which NASA and the next decadal survey committee could address. One barrier for early-career scientists is learning about the management and quality assurance requirements in developing Class D or higher missions for NASA or NOAA. Enhancing training about NASA's mission standards and requirements (e.g., NPR 8705.4, and NPR 7120.5), and more intern and apprenticeship opportunities for students and postdocs in mission development could help address this barrier. Increases in quality assurance and management requirements, and proposal development costs, even for small explorer (SMEX) missions, limit the number of academic institutions that can participate, thus limiting opportunities for graduate students and postdoc to receive hands-on training. Another barrier is related to the low number and frequency of low-cost missions (SMEX, CubeSats). The recent increase in CubeSat science missions, currently at 18 in NASA Heliophysics Division (HPD) and at 16 in NSF Geoscience, is significantly helping to address this barrier.

> ***Finding 5.4:*** Involving students in the development of spaceflight hardware for missions is key to the long-term success of developing the workforce for the U.S. space programs. Enhancing the number of partnerships between universities and non-University institutions and further increases in the number and frequency of small satellite missions are example pathways to train more students and early-career scientists and engineers for space missions.

5.3 IMPROVING DIVERSITY IN THE HELIOPHYSICS COMMUNITY

Diversity of thought, backgrounds, races, ethnicities, genders, and sexual orientations creates and environment that sparks more innovation, stimulates more variety in problem solving approaches to science challenges, and thus achieves a broader range of creative outcomes. Giving heliophysics scientists an opportunity to succeed and creating a diverse, equitable, inclusive, and safe work environment should be a priority for NASA Heliophysics, NSF, and NOAA. Such an environment will enable the full range of talent to emerge in order to develop the next generation of research and analysis tools. There are a few specific early-career research opportunities provided by NSF and NASA, and broadening activities of workforce development, diversity and inclusion, and science outreach are emerging elements in some opportunities, such as in NASA's Heliophysics Science Centers[1] and the former NSF's Center for Integrated Space Weather Modeling (CISM) program.[2]

This committee did not have the resources, nor the expertise, to attempt to evaluate the current state of diversity in the heliophysics community; instead we offer considerations for enhancing diversity and recommend that a new demographics survey of the community be done before the next decadal survey as discussed in Chapter 6. Anecdotally, the heliophysics community does not likely reflect the diversity of the American population, as is the case for most other science communities. The benefits of diversity to the community are already evident in its large group of international collaborators. For example, the 2018 Science and Engineering indicators from the National Science Board (NSB) show that astonomy in general is the most international field, with more than half of its publications (54 percent) internationally co-authored in 2016 (NSB, 2018). It is clear that the solar and space physics community depends on a continuous, high-quality stream of scientific and engineering talent, and a lack of diversity represents a loss of talent (National Academies Press, 2011). Although the present NASA leadership has recognized the problem and has tried to take some action, the proposed solutions so far are somewhat ad hoc, and it is not clear if there is a long-term strategy or metrics that can be used to measure progress. The development of a strategic plan for inclusion and diversity at either the NASA HPD or SMD level would be beneficial. Such a strategy should be based on current research and should include a plan for measuring progress. Some solutions for this problem, as discussed next, include (1) changing the selection methods for awarding mission PIs, proposals, and observing time, (2) increasing efforts in mentoring, and (3) incentivizing activities that increase diversity and inclusion.

Female and minority mission PIs in NASA Heliophysics are severely underrepresented. One concern is that no women or minorities proposed as PI for the SMEX 2016 Announcement of Opportunity (AO). A more positive trend is that there are about a half dozen female mission PIs for CubeSats, rockets, and balloon experiments, and one of the four recent selections for SALMON Interstellar Mapping and Acceleration Probe (IMAP) rideshare missions has a female PI. Is this trend for more female mission PIs a sign of more women in the younger sector of the heliophysics community? Or might the selection criteria for NASA PI-led missions have an unintended effect to bias by race and gender? If so, encouraging or mandating apprentice opportunities with well-integrated mentoring and training plans for underrepresented groups as a part of the mission proposals could provide a good way to ensure a larger pool of trained PI candidates for future mission AOs. Of more general concern, the selection criteria may be biased by race and gender in many areas: selecting proposals (National Academies Press, 2011; Lerback et al., 2017), hiring faculty and staff (Moss-Racusin et al., 2012), awarding observing time (Reid, 2014), selecting which papers to cite and co-authors to include (West et al., 2013; Larivière et al., 2013), determining salaries (Porter and Ivie, 2019) , and awarding prizes (Lincoln et al., 2012). For example, only 2 out of 32 (6 percent) of Hale prizes, the highest honor bestowed by the Solar Physics Division of the American Astronomical Society, went to women. The prize started in 1978 and the first woman to win the prize was in 2010. To address this, funding agencies should examine and potentially adjust their selection methods for awarding mission PIs, proposals, and observing time. One successful solution for increasing the diversity of proposal awardees and recipients of observing time is the use of dual-anonymous (double-blind) peer reviews (e.g., Urry, 2015). Another

[1] See "Heliophysics Phase I Drive Science Centers," on the NSPIRES website at: https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=648385/solicitationId=%7B1FE15C46-31FA-783D-4ED2-F77BC1A233C9%7D/viewSolicitationDocument=1/B.13%20DRIVE%20Science%20Centers%20Amend%2069.pdf.

[2] See http://www.bu.edu/cism/Publications/StrategicPlan.pdf.

example is including the list of authors on a proposal but not specifying who is PI and who are Co-Is. Another solution is to give under-represented groups visibility in prestigious settings—such as prizes, committees, lectures, and panels—without over-burdening the same few people over and over again.

Positive mentoring has had an extraordinarily positive impact on increasing diversity and retaining talent. The solar and space physics decadal survey (NRC, 2013) recommended programs that specifically target enhancing diversity, such as the NSF Opportunities for Enhancing Diversity in the Geosciences program. This program focuses on REUs and financial aid. NSF has several other programs to enhance diversity, including Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science (INCLUDES), NSF's ADVANCE (Organizational Change for Gender Equity in STEM Academic Professions), NSF's Louis Stokes Alliances for Minority Participation Program (LSAMP), NSF's Alliances for Graduate Education and the Professoriate (AGEP), and now-defunct programs like CISM. The committee recommends strengthening these programs and emulating their core principles in other programs.

The recently started NASA IMAP mission provides a positive example of desirable, proactive inclusion in its Student Collaboration and Future Heliophysics Leaders programs (McComas et al., 2018). This PI-led Solar-Terrestrial Probes (STP) mission is integrating, as part of its overall mission plan, opportunities for 'real-world, hands-on' participation for earlier career team members from diverse backgrounds. In a similar vein, the NSF's review of its Science and Technology centers found that CISM, the Center for Integrated Space Weather Modeling, had the most successful diversity program of the eleven STC's reviewed (Chubin et al., 2010). These illustrate several ways that heliophysics major research and technology projects have made meaningful strides toward addressing the demographic challenges of STEM fields while maintaining their emphasis on achieving their scientific and technical goals. Using these examples as models for designing/defining future programs is one relatively straightforward way to make progress.

Incentivizing activities that increase inclusion and diversity remains important, as does making sure that these incentives are properly rewarded. The new mentoring and diversity components required in NASA's HSC 2019 proposals have good potential for increasing the diversity within the Centers, as well as providing additional training opportunities. Best practices learned from the HSCs over the next couple of years could guide future proposal opportunities to further incentivize more diversity in the heliophysics community. Diversity is also discussed in this report's Chapter 3 as part of the DRIVE Realize element and as part of Recommendation 3.2.

It is unclear how NASA measures diversity and inclusion. Some solicitations have begun to include positive language about assembling a diverse team. It would be helpful for future solicitations to specify the types of diversity sought, what the proposal evaluation criteria concerning diversity are, and how diversity is evaluated over the course of a project.

The committee recommends that the next solar and space physics decadal survey include a State of the Professional Panel, similar to the Astro2020 decadal survey. As discussed more in this report's Chapter 6, the solar and space physics community should partner with the American Institute of Physics (AIP) Statistical Research Center to collect and report demographic and climate data specific to solar and space physics (a similar undertaking was recommended by Rudolph et al. (2018) for the Astronomy community). It is also important to note that solar and space physicists can identify with more than one under-represented group. The committee also suggests computing statistics about intersectionality instead of, for example, computing statistics for underrepresented minorities and women separately (Bowleg, 2012). The heliophysics community can also learn about diversity from other similar science discipline surveys, such as the Planetary Workforce Survey (2011) (Rathbun 2017).

> ***Finding 5.5:*** Increasing the participation and inclusion of individuals of different genders, races, cultures, and ages in positions of leadership roles in heliophysics (e.g., mission PIs) and for recognition (e.g., honors, awards) would better reflect today's societal makeup. It has been shown that women and underrepresented minorities in STEM fields face consistent bias in proposal selections, hiring, salaries, observing time awards, paper citations, and prizes / awards. It is

critical to better track the demographics of the heliophysics community in order to assess the effectiveness of programs that seek to increase the diversity of its membership.

Recommendation 5.1: NASA, NSF, and NOAA should develop strategic plans for the heliophysics community with goals and metrics to improve the diversity of race, gender, age, and country of origin. The next decadal survey should include a State of the Profession Panel, similar to the Astro2020 decadal survey. The State of the Profession Panel should have in advance the demographics / diversity survey data recommended in this report's Recommendation 6.2.

Some potential solutions for the diversity problem include:

- Adjusting the evaluation and selection methods for awarding proposals and observing time, such as dual anonymous reviews;
- Incentivizing or requiring activities that increase diversity and inclusion, such as mentoring and apprenticeships to create a broader pool of possible mission and project PIs and reaching out to minority-serving universities to establish partnerships and recruit students;
- Encouraging review panels, workshops, conferences, and other meetings to adopt explicit codes of conduct which remind all involved to respect civil, inclusive conduct in these activities.

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6

Preparing for the Next Heliophysics Decadal Survey

Item six in the midterm assessment committee's charge is to, "Recommend any actions that should be undertaken to prepare for the next decadal survey—for example: enabling community-based discussions of (a) science goals, (b) potential mission science targets and related implementations, and (c) the state of programmatic balance; as well as identifying the information the survey is likely to need regarding the vitality of the field." In responding to this charge, the committee drew on discussions at several Town Halls, internal deliberations, and the findings and recommendations in the 2015 National Academies report, *The Space Science Decadal Surveys Lessons Learned and Best Practices*.[1] The committee was also attentive to recent changes in agency responsibilities for the science behind space weather, as well as emerging science and technology topics. Included in this chapter are three recommendations calling for action to: 1) support advanced planning for the next decadal survey, 2) have a demographics / diversity survey prior to the next decadal survey, and 3) ensure the next decadal survey statement of task addresses the evolving needs for science-driven strategic plans. The committee also makes nine findings in conjunction with these recommendations and an additional Finding — 6.10 — that lists several emerging topics of interest for the next committee to consider for its decadal survey study.

6.1 PREPARATIONS BEFORE NEXT DECADAL SURVEY

The preparation for decadal surveys has evolved since the last heliophysics decadal survey, and lessons learned from the other science divisions decadal surveys could benefit heliophysics strategic planning. First, there have been funded NASA opportunities to define mission concepts for the Planetary Science Division (PSD) and Astrophysics Division (APD) that enable them to prepare well in advance for their next decadal surveys. For example, the PSD initially formed Assessment / Analysis Groups (AG) in 2004 in different disciplines and science areas, including groupings such as Mars and Outer Planets, to involve the community in defining and prioritizing targeted science goals and formulating strategic plans before the next planetary decadal survey. These AGs function both as standing, inclusive science forums and as resources whose ongoing activities naturally lead to decadal survey and related 'road mapping' and Science Definition Team (SDT) inputs.

In another approach —one requiring significant agency investment— the APD charged its Program Analysis Groups to solicit community input on a small number of compelling and executable strategic mission concepts. The latter resulted in four large strategic missions—HabEX (the Habitable Exoplanet Observatory), LUVOIR (the Large Ultraviolet/Optical/Infrared Surveyor), OST (Origins Space Telescope), and Lynx—being endorsed for further study by Science and Technology Definition Teams (STDT). These STDTs were drawn from a large cross section of the community.

An attractive characteristic of these approaches is that they enable a broader range of institutions to participate in both science definition and mission concept development. The AG approach, in particular, involves relatively low direct cost because it takes advantage of all levels of participation, from those who choose to provide science input—based on their research funded by existing missions and other sponsored programs—to NASA Centers and other enterprises with internal sources of support for such purposes. The playing field can also be leveled to some degree by providing programs to fund

[1] National Academies of Sciences, Engineering, and Medicine. 2015. *The Space Science Decadal Surveys: Lessons Learned and Best Practices*. Washington, DC: The National Academies Press. https://doi.org/10.17226/21788.

mission concept studies, such as those recently fielded by NASA's PSD and APD. Such funded efforts are especially important to kick-start PI-led missions, which are increasing within the NASA Heliophysics Division now that STP missions along with Explorers are executed in PI-mode.

Funded mission concept studies also enable non-NASA-Center participation in strategic mission studies. Such practices allow NASA to draw from a larger pool of expertise and ideas, and to develop and consider strategic mission concepts in a more complete and updated context, in advance of the decadal survey process. For example, rapid progress toward an AG-like heliophysics vehicle could be attached to the widely-attended SHINE, GEM, CEDAR, and AAS/SPD (American Astronomical Society/Solar Physics Division) workshops that provide a regular opportunity and open forum where sponsoring agency personnel interact in a relatively informal setting. These are already well-established venues where researchers and (active and potential) mission/project architects and planners meet in an atmosphere that both fosters science debate/definition/prioritization and creates additional paths to mission/project ideas, involvement, and leadership. The matter of funded mission concept studies could be explored through heliophysics agencies' internal inquiries regarding the benefits and costs of these types of programs relative to present practices.

Finally, we note that the solicitation of "white papers" from the community has always been a key feature of decadal surveys. For example, prior to its first meetings, Astro2020, the latest decadal survey for Astronomy and Astrophysics, issued calls for white papers in two categories: "Science" and "Activities, Projects, and State-of-the-Profession Considerations (APC)."[2] These white papers are informing the work of the steering committee and the 12 Astro2020 science and program panels.

> ***Finding 6.1:*** Community analysis group workshops and funded mission concept development for defining critical science goals and related mission concepts as employed by NASA's Planetary Science Division and Astrophysics Division in preparation for their decadal surveys have been productive for broader and deeper definitions of strategic mission concepts based on key science objectives and any emerging technology important for future missions. This midterm assessment committee emphasizes that the science objectives and related measurement requirements are more important to define than specific missions / facilities.

The NSF Mid-Scale Research Infrastructure (RI) program, which began in 2018, represents an important potential resource for heliophysics research that needs to be examined in the next decadal survey. There are two classes of Mid-Scale RI projects: those costing between $6 million and $20 million, and projects costing between $20 million and $70 million. Such projects can play a very important role in meeting the NSF research goals. However, the Mid-Scale RI program competition is NSF-wide across all science areas and is thus highly competitive and over-subscribed (Box 6.1). As in the case involving mission concepts and definition, prioritization of heliophysics Mid-Scale RI projects by the heliospheric community and by the next heliophysics decadal survey could provide critical science goals and needed justification for reference Mid-Scale RI projects for the future NSF-wide Mid-Scale RI opportunities. The ideas for new Mid-Scale RI projects could have broad appeal to other disciplines and connect to other NSF divisions. This need could also be filled within the community engagement framework suggested above.

[2] Science and APC white papers are described on the Astro2020 community input link: http://sites.nationalacademies.org/DEPS/Astro2020/DEPS_192906.

BOX 6.1

A large number of ideas (approximately 250, requesting $2.5 billion) were proposed for the spring 2019 NSF Mid-Scale Research Infrastructure-1 (RI-1) solicitation for projects in the $6-20 million range. Forty-two were invited for the full proposal submission and only 3-10 are expected to be selected. Similarly, there was a large number of ideas proposed (approximately 50 requesting $2.0 billion) for the summer 2019 NSF Mid-Scale Research Infrastructure-2 (RI-2) solicitation for projects in the $20-70 million range. Fourteen were invited for the full proposal submission and only 4-6 are expected to be selected.

Finding 6.2: The NSF Mid-Scale Research Infrastructure (RI) opportunity is highly competitive; since proposals are competed across all NSF divisions, the selection rate is expected to be low. The NSF AGS (Atmospheric and Geospace Sciences) and AST (Astronomical Sciences) divisions could improve their chance of selection within the NSF-wide Mid-Scale RI program if they strategically planned and prioritized a few key RI concepts that have broad community support.

Recommendation 6.1: NASA and NSF should implement and fund advanced planning for the next decadal survey that involves the community in strategic planning of the next decade science challenges, science goals, and related high-priority measurements, and that also considers stretch goals (ambitious objectives that might extend past the next decade). NASA and NSF could request the Space Studies Board's Committee on Solar and Space Physics (SSB-CSSP) to evaluate options for implementing this planning for the next decadal survey.

Some specific ideas for this advanced planning include:

- NASA-supported opportunities for the heliophysics community to host Assessment Group workshops in order to develop strategic science challenges and goals and to define high-priority measurements for the STP (Solar-Terrestrial Probe) and LWS (Living with a Star) programs in advance of starting the next heliophysics decadal survey, and
- NSF-supported workshops to strategically plan the next decade science challenges and goals and to identify high-priority measurements for the Mid-Scale Research Infrastructure and other research infrastructure concepts with the heliophysics community.

While, anecdotally, more women and minority scientists are studying heliophysics, and more nations every year are becoming involved in heliophysics research and practical space weather applications, the impact on the heliophysics workforce in general, and its diversity in particular, is not well understood. An important part of understanding and supporting those changes begins with a demographics/diversity survey of students and early-career scientists and engineers, followed by development of action plans to positively encourage continued growth of diversity for the science and engineering communities who support the science programs, missions, and facilities of NASA, NSF, and NOAA. To ensure that such efforts are successful, career survey specialists should be involved, such as the American Institute of Physics (AIP) who conducted the early career survey for the American Astronomical Society (AAS).

Finding 6.3: The demographics and diversity of scientists and engineers in heliophysics may have evolved significantly since the 2013 heliophysics decadal survey. A new demographics / diversity survey would clarify those changes over the past few years, and results from such a survey could enlighten planning for improving diversity in the heliophysics community.

Some members of the previous decadal survey have commented that the demographics survey for the last decadal survey came too late in the process, and thus the information was not fully analyzed and incorporated into the last decadal survey report. Furthermore, as many space scientists work in multiple disciplines and across different NASA science divisions, a demographics survey of all space science communities would benefit all of the future decadal survey activities.

Finding 6.4. The demographics survey for the last decadal survey was completed late in the study, limiting its utility. It is important that an updated demographics survey be available in advance of the initiation of the next decadal survey.

Recommendation 6.2: NASA Heliophysics Division should conduct a demographics / diversity survey before the next heliophysics decadal survey to understand how the community's demographics have evolved and to assess whether progress has occurred in enhancing diversity in the community (see also this report's Recommendation 5.1). Thereafter, to benefit all of the space science disciplines within NASA's Science Mission Directorate (SMD) and to inform decadal survey planning across SMD, NASA at the SMD-level should conduct this demographics / diversity survey on a 5-year cadence with clear identification of science areas relevant for each science division. It is important that career survey specialists, such as the American Institute of Physics (AIP), are involved in a new survey.

6.2 CONSIDERATIONS FOR NEXT DECADAL SURVEY PROCESS

With an underlying goal to give additional focus to the decadal survey and to actively address the evolving strategic needs of the heliophysics community, the midterm assessment committee identified several topics that agency sponsors could include in the next survey's task statement for the next decadal survey.

Distinguish Between NASA's STP and LWS Programs

NASA's Solar Terrestrial Probe (STP) program has traditionally supported missions to explore fundamental physical processes important for heliophysics, while their Living With a Star (LWS) program missions have focused on the variability of the Sun and in Earth's environment and those aspects of heliophysics science that can have societal impacts. Both STP and LWS programs have supported the studies of interactions between the different heliophysics components. The 2013 heliophysics decadal survey made recommendations that future STP missions should all be PI-led (and lower-cost) strategic missions while the larger (and more-expensive) strategic missions should be in the LWS program.

Separation of strategic missions into the STP and LWS programs by their cost, instead of by their science focus, is not an effective long-term scenario to maintain two distinct programs, nor for planning a regular cadence for strategic missions that comparably advance the different heliophysics sub-disciplines. Lessons learned from implementing the PI-led IMAP (Interstellar Mapping and Acceleration Probe) mission under STP and from implementing the Parker Solar Probe and planning the GDC-like (Geospace Dynamics Constellation) mission under LWS will provide valuable guidance in defining future NASA strategic missions. Furthermore, elucidation of the overarching and unique science goals for the distinct STP and LWS programs are important as guidance for the next decadal survey studies.

Finding 6.5: The next decadal survey committee may want to consider how to best distinguish the NASA Heliophysics LWS and STP strategic mission lines, both in terms of critical science goals and implementation strategies. Without distinct goals for these two programs, there is a risk to limit effective planning for larger strategic missions.

Realistic Agency Budget Plans

Soon after the 2013 heliophysics decadal survey was released, the NASA Heliophysics Division budget plan had significant decreases resulting in a flat budget instead of a rising budget with an assumed inflation rate. Consequently, the planning for the NASA Heliophysics Roadmap in 2014 was challenged by how to implement the recommendations in the 2013 decadal survey, and thus there was a slow start for NASA implementing any of the 2013 decadal survey recommendations.

> ***Finding 6.6.*** To mitigate the risk of decadal survey recommendations being regarded as difficult or not possible to implement in the next decade period, each agency needs to ensure that the budget 10-year plan is as accurate, up-to-date, and complete as possible throughout the course of the survey's work. It can benefit strategic planning if future budget scenarios included a nominal (baseline) budget and optimal (best-case) budget. The two-budget approach can allow for defining clear decision rules for reprioritizing under each scenario.

Keep Decision Rules for Large Programs/Missions

Cost growth of large programs/missions beyond the phase C/D cost cap threatens to disrupt the progress of the overall heliophysics program and should not be accepted without careful consideration. The 2013 decadal survey (its Chapter 6) recommended specific trigger points that NASA should implement to maintain the program balance through the decade. The decadal survey went on to emphasize that these trigger points should initiate a review by NASA, in which the expected outcome would be actions by NASA to preserve the large program in question and also maintain balanced progress through the decade. These decision rules put programs on notice that they are to remain within their budgets and, at the same time, do not overly constrain NASA's ability to execute the most cost effective and scientifically rewarding overall program possible within the budget constraints.

> ***Finding 6.7.*** The next decadal survey could benefit by having decision rules for large programs/missions as was done in the 2013 heliophysics decadal survey.

Developing New Technology for Long Term Stretch Goals

Discussion of stretch goals (longer term vision than a decade) could well identify science questions and related future observations that could fall outside the next decadal period. In areas where technology is the limiting factor in making progress, the next decadal survey committee could identify technology developments important for the next decade. One example of that scenario in the previous heliophysics decadal survey is the need to develop solar sail propulsion technology to support an Interstellar Probe mission to the outer limits of the heliosphere and for a Solar Polar Imager mission to fly over the solar poles (e.g., 2013 decadal survey sections 10.5.2.8 and B.4.2.1). NASA Marshall Space Flight Center (MSFC) has developed solar sails with industry partners during the last few years, and they were recently selected for a technology demonstration of their solar sails for the 2018 IMAP rideshare opportunity. Furthermore, JHU APL (the Johns Hopkins University Applied Physics Laboratory) has recently crafted a mission concept for the Interstellar Probe. The other selection for Phase A study for this IMAP technology demonstration rideshare is a NASA GSFC small satellite with optical communication to significantly increase deep space data rates.

The solar sail and optical communication are just two examples of enabling technology that could be considered for future missions in the next decade. Another example (mentioned in both the inaugural and most recent decadal survey) would be the practical implementation of a large constellation concept for magnetospheric studies. Similarly, a sequence of satellites to address long-term science goals, such as understanding the 11-year solar activity cycle, may be important for some stretch goals that cannot be implemented with the historical planning of stand-alone, single-satellite missions.

> ***Finding 6.8:*** For next decadal survey discussions about stretch-goal science objectives and related missions, it will be important to identify what technologies are required for those stretch-goal missions and to consider actions that could develop such technology in the next decade.

NOAA Engagement in Next Decadal Survey

For a variety of reasons, the previous heliophysics decadal survey was unable to provide actionable plans to integrate NOAA plans for space weather research and applications with the strategic plans for NASA and NSF.[3] The National Space Weather Action Plan (NSWAP) has been recently updated in 2019 and details many aspects of integrated plans and coordination across many agencies. As discussed in the NSWAP, NOAA is the key civil agency for space weather operations. Thus it is imperative that the next decadal survey engage with NOAA in developing its space weather plans.

> ***Finding 6.9:*** It is critically important for future planning of space weather applications to have NOAA better integrated into the space weather related strategic plans for the next decade.

> **Recommendation 6.3: NASA, NSF, and NOAA, the anticipated principal sponsors of the next solar and space physics decadal survey, should work together to develop an integrated statement of task that reflects the research and application needs for each agency and across the federal government. To address the evolving needs for science-driven strategic plans, the agency sponsors should ensure the following items are included as tasks for the next decadal survey committee:**
>
> - **Definition of distinct science goals and implementation strategies for NASA's STP and LWS programs,**
> - **Evaluation of strategic plans with nominal (baseline) budget and optimal (best-case) budget,**
> - **Inclusion of decision rules for guiding implementation of recommendations, and**
> - **Identification of enabling technology needed in the coming decade to support longer term stretch goals.**

6.3 EMERGING TOPICS OF INTEREST FOR THE NEXT DECADAL SURVEY

There are many aspects of identifying and prioritizing science goals and related observations and modeling efforts for developing a decadal survey with the scientific community. One aspect is learning from the previous decadal surveys and identifying any missing or new topics of interest for the next decadal survey. From this Midterm Assessment, several key topics arose in the committee discussions that have not been discussed much in the previous chapters. These topics of interest for future strategic studies are briefly discussed in this section and then summarized in Finding 6.10 below.

In response to the decadal survey, NASA brought the Explorer program back to the level where it was a decade ago. NASA issued an AO (announcement of opportunity) for Small Explorer (SMEX) missions in 2016 and an AO for MIDEX missions in 2019. Thus, NASA has achieved the decadal survey-requested 2-3 year cadence for the Explorer program opportunities. For the 2016 SMEX AO, NASA selected five missions for phase A study and down-selected in July 2019 to two missions for flight

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[3] It should be noted that NOAA did not participate formally in the development of the task statement for the survey. In contrast to the inaugural 2003 decadal survey in solar and space physics, the budget process in place at the initiation of the most recent decadal did not permit NOAA to be a financial sponsors.

development. The NASA Heliophysics Division director stated that selecting multiple missions under the same Explorer AO was in response to comments from the community, who conveyed that preparing and reviewing mission proposals is an expensive and time-consuming process. By the time of the next decadal survey, the effectiveness and consequences, both good and bad, of selecting multiple missions from fewer AOs may be evident. *The next decadal survey committee could consider a trade study on the effectiveness and consequences of selecting more missions per AO versus higher cadence for the SMEX/MIDEX AOs.*

The Heliosphere System Observatory (HSO) is an ensemble of operating strategic and Explorer-class missions for the NASA Heliophysics Division, and the combination of these missions has proven valuable for system-level and cross-disciplinary advances in understanding heliophysics. The concept for the HSO can easily be expanded to encompass the NSF ground-based facilities that support heliophysics research. The small-sat missions (with mass less than 100 kg) were used more for technology demonstration than for science when the previous decadal survey study was executed. The recent rapid growth of technology that supports CubeSats has now enabled a new generation of small-sat missions doing science research, such as the Miniature X-ray Solar Spectrometer (MinXSS) CubeSat that flew successfully in 2016-2017 as the first science CubeSat for the NASA Heliophysics Division. With 18 NASA Heliophysics CubeSat missions, with 6 already launched and another 12 being launched in the next few years, the HSO can further be expanded to include this small-sat class of missions. Furthermore, the reliability of the CubeSat technology has progressed to the point that CubeSat missions could be considered for extended missions as part of the Senior Review process. *The concept of the HSO could be expanded beyond NASA's strategic and Explorer-class missions to include NSF's ground-based facilities and the upcoming fleet of heliophysics small-sat science missions to further enhance the scientific exploration involving multiple disciplines and for advancing the understanding of fundamental processes throughout the heliosphere.*

HSO is currently a constellation of 18 spacecraft that make a wide range of measurements throughout the heliosphere. The HSO has only three missions now in their prime mission phase: Parker Solar Probe, GOLD (Global-scale Observations of the Limb and Disk), and SET-1 (Space Environment Testbeds). The rest are in extended mission, and several are well beyond their originally intended lifetime. This aging fleet with mostly extended-mission satellites continues to make system-science advances. For example, measurements of the solar wind at 1 AU from the 22-year old ACE (Advanced Composition Explorer) spacecraft enable long-term studies of the 11-year activity cycle, and continued measurements from the 42-year old Voyager spacecraft reveal new results about the structures of the local interstellar medium beyond the heliosphere.

While individual missions in the HSO have stand-alone science objectives, the community increasingly relies on the HSO for system-level science. Therefore, one of the elements of the decadal survey plan could be how to maintain and augment the HSO for such system-level science endeavors. In particular, there could be modifications to the overall strategic plan should one or more elements of the HSO no longer be available. Additionally, NASA research proposal evaluations could consider how the research proposed can enhance the HSO at a system-level and support cross-disciplinary research. *HSO is a critical asset for addressing key solar and space physics science objectives, one that must be sustained and further developed. Coordination between NSF and NASA is needed to ensure that ground- and space-based assets are integrated into a balanced heliospheric systems observatory.*

The previous heliophysics decadal survey recognized the importance of space weather research for the nation. Since that decadal survey, NASA's role in space weather has continued to be essential, as evidenced in the 2015 National Space Weather Action Plan (NSWAP) and ongoing activities of the Space Weather Operations, Research, and Mitigation (SWORM) Working Group. In decadal survey recommendation A2.5, the decadal survey called for distinct funding lines for basic space physics research and for space weather applications, additionally recommending that forecasting that should be developed and maintained, including at NASA. Funding lines for space weather science are currently being formulated within NASA and NSF. For example, NASA is starting up their Space Weather Science and Applications (SWxSA) program. As pointed out by the Office of Inspector General (OIG) audit of NASA's Heliophysics Portfolio (OIG, 2019)), NASA Heliophysics Division has 19 of its assigned

NSWAP tasks still to complete due in part to space weather physics / modeling complexity, unrealistic deadlines in the NSWAP, and lack of other agency partners' action. This topic is also discussed in this report's Chapter 4. *Further evaluation of enhancing the science of space weather within NASA and NSF is expected to improve the integrated approach for space weather research and applications as specified in the National Space Weather Action Plan (NSTC, 2015; 2019).*

As related to one of the DRIVE Integrate recommendations, there has been some progress during this decade to improve multi-agency coordination for space and ground-based observations. Considering the new plans from NSWAP about expanding space weather research, NASA, NSF, and the next decadal survey committee could consider ways to maximize scientific returns through improved coordination of space weather research with satellite and ground-based facility observations of multiple agencies and also with international collaborations. For example, and as discussed in this report's Chapter 3, NASA could invest in ground-based measurements that support their missions, and NSF ground-based facilities could better support NASA suborbital campaigns and international missions, such as Solar Orbiter. One concept from this Midterm Assessment committee is that the NASA Heliospheric System Observatory (HSO) could be more fully exploited if it was extended to include coordination with NSF observatories. *The next decadal survey committee could identify enhanced approaches and new opportunities to improve the multi-agency and international coordination of heliophysics research and space weather applications*.

The heliophysics focus on "Living With a Star," taken literally, should embrace the rapidly expanding knowledge (and need for heliophysics knowledge) within the areas of exoplanetary and planetary research. Planetary science research seeks to understand the role space weather and solar activity over time have played in planetary evolution and habitability, as in the case of the investigations related to Mars climate change (e.g., Jakosky et al., 2018), Venus climate change (Kumar et al., 1984), and the role of an intrinsic planetary magnetic field. Exoplanet research also relies on heliophysics for interpreting what is remotely sensed, ranging from distinctions between starspots and planets (e.g., Rackham et al., 2018), to planetary transits showing indications of stellar wind erosion of atmospheres (e.g., Spake et al., 2018; Bourrier et al., 2018), to hydrogen walls suggesting the presence of astrospheres and stellar winds (e.g., Wood et al., 2014), and to speculating on causes and consequences of observed superflares (e.g., Howard et al., 2018; Nostu et al., 2019). In the meantime, the topic of our own Star's long-term history, which is critical to understanding our own habitable zone planets, has made little progress since the post-Apollo era of Lunar sample analysis other than through limited studies of Sun-like stars. Cross-fertilization is essential to the progress of what has become one of the major strategic themes of NASA science; exoplanets research is likely to dominate its visibility to the public in the imminent era of the James Webb Space Telescope (JWST) and the search for evidence of extra-Earth and extra-solar system life. The NExSS (Nexus for Exoplanet System Science) Program, functioning as a virtual institute within NASA's Science Mission Directorate (SMD), incorporates some of these valuable interdisciplinary interactions but only as an organization of research projects previously selected and funded within the separate division core programs. *A NASA/SMD cross-divisional R&A program in which heliophysics could play a central role, where work now only touched upon in the context of NExSS, could become a targeted and long-standing competed element managed by the NASA Heliophysics Division.*

NSF solar, heliospheric, and space weather (SHSW) science is currently distributed between two directorates (Mathematical and Physical Sciences (MPS) and Geosciences (GEO)) and in two divisions (AST and AGS). This is not optimum. Not only does it hamper strategic planning, requiring responsiveness to two decadal surveys, it complicates coordination between NSF and other agencies such as NASA. Moreover, important elements of the scientific portfolio—e.g., the outer heliosphere—fall between the cracks. The idea of consolidating SHSW science into a single NSF division under one directorate was explored some years ago. Reconsideration of plans to consolidate all elements relevant to solar, heliospheric and space weather physics under a single division within NSF is timely and necessary given the changing landscape in which new NSF assets like DKIST (Daniel K. Inouye Solar Telescope) and EOVSA (Expanded Owens Valley Solar Array) are coming online, additional SHSW assets are under consideration for development, the National Space Weather Strategy and Action Plan is a significant national priority, and continuing integration and optimization of the HSO is a key community objective.

Ground-based solar, heliospheric, and space weather science could be better supported within a new, consolidated division under a single directorate at NSF.

NSF funding for Management, Operations & Data Analysis (MO&DA) continues to be a challenge for new and currently operating NSF ground-based research facilities. Creative solutions may exist involving inter- and intra-agency collaborations, technological innovations, and partnerships with the commercial sector. For example, multi-purpose facilities can have cost benefits through sharing of logistics, power systems, telemetry, data handling, and data centers by multiple programs (e.g., heliophysics and Earth sciences). For such an approach, data and meta-data standards and guidelines are important to establish. *NSF with the involvement of the heliophysics community could explore these and other creative solutions for improving the operations of their ground-based observatories before the next decadal survey.*

The quality assurance expectations for NASA small missions with costs less than $150M have recently been redefined for the new tailored Class D option (Lightfoot, 2014; Zurbuchen, 2017). This transition to tailored Class D appears to be evolving slowly within NASA centers and thus may be an on-going topic to be evaluated for the next heliophysics decadal survey. Recent history shows that the IRIS (Interface Region Imaging Spectrograph) SMEX ($150M cost cap) was developed as a Class D mission, and the Ionospheric Connection (ICON) Explorer ($200M cost cap) as a Class C mission, and the near future SMEX ($150M cost cap) and MIDEX ($250 million cost cap) missions are planned to be developed as Class D and Class C missions, respectively. Considering the cost of inflation over a decade and limited cost-cap values for NASA Explorer missions, the midterm assessment committee envisions the possibility for reduction of Explorer mission class requirements to enable high-impact exploratory missions at lower cost and with reasonably acceptable risks. Instead of cost as the driver for determining mission classification, Hartman and Bordi (2016), for example, propose a four-part classification scheme based on the measurement difficulty, flexibility of requirements, design lifetime, and budget “rigidity” (the ability to make additional funding available at various stages of development). Heliophysics SALMON (Stand Alone Missions of Opportunities Notice), SMEX, and MIDEX missions could benefit greatly from such a classification scheme. These missions often use existing measurement capabilities, have very flexible requirements (for example, no launch date constraints), are typically designed for a relatively short prime mission of 2 years or less, and often carry ample cost reserves well beyond the needs for missions with no technology development. Re-defining the classification based on these four criteria would reduce the classification of all types of missions and eliminate the issue of cost inflation going forward into the next decade. *The next decadal survey may want to distinguish and clarify for the future Explorer and SALMON missions a consistent implementation plan for Tailored Class D, Class D, and Class C projects. The next survey may also want to consider the arguments that cost should not be the driver for mission classification.*

As discussed more in this report’s Chapter 5, there is a growing concern that research topics have evolved to be more complex and more cross-disciplinary but that the typical research grant funding level has had only modest growth. Anecdotally, there appear to be more scientists, especially early-career scientists, who are leaving heliophysics research due to funding concerns for low-selection rates, low-level funding, and because of the long delays between proposal submission and availability of funding. Established in response to a recommendation from the inaugural decadal survey in heliophysics, the NSF FDSS program was intended to establish a greater university base for the community, however, its outcomes have yet to be formally assessed. In response, *NASA, NSF, and the next decadal survey committee could identify viable, different structural solutions to better support the heliophysics research grant programs, with particular emphasis on early-career scientists and soft-money scientists (i.e., those who are not professors or government employees). In addition, an assessment of the outcomes of the FDSS program could be conducted.*

As also discussed in this report’s Chapter 3, the next decadal survey needs to consider how emergent technology and new data analysis techniques could help transform heliophysics in the next decade. A partial list of emergent analysis tools and techniques include data mining, statistics, machine learning, data visualization, high performance computing (e.g., parallel computing), cloud computing, and collecting, curating, and cleaning high-volume, high-variety, and high-velocity data (Geiger et al., 2018). *It is important that funding agencies encourage and sponsor the solar and space physics community to develop a modern data infrastructure and workflow.*

These emerging topics for the next decadal survey are summarized in Finding 6.10. They are not in priority order nor an exhaustive list of topics for the next decadal survey.

Finding 6.10: The next heliophysics decadal survey committee could consider the following important topics:

- Trade study on SMEX/MIDEX AO cadence versus number of missions selected per AO,
- Expansion of the HSO concept to include NSF's ground-based facilities and many upcoming small-sat science missions,
- Identifying critical measurements in the current NASA and NSF facilities for future system-science plans and how to continue such observational capabilities,
- Better integrated approach for including the science of space weather within NASA and NSF to improve space weather predictability,
- Engaging NOAA in developing space weather research and applications for the next decadal survey
- Improving the multi-agency and international coordination of heliophysics research and space weather applications,
- NASA cross-divisional opportunities for exoplanetary-planetary, astrospheric-heliospheric, solar-stellar, and atmosphere-Earth science research and development of a prioritized strategy for implementing such cross-disciplinary research,
- Consolidation of ground-based solar, heliospheric, and space weather science could be better supported within a new division under a single directorate at NSF.
- NSF improving and broadening its structure for heliophysics research (e.g., outer heliosphere and planetary science elements are currently missing),
- NSF improving the cost effectiveness of the operations of their many ground-based observatories, such as by sharing data analysis tools and data centers,
- Evaluating the mission class requirements for NASA's Explorer program,
- Identifying viable structural solutions to better support the heliophysics research grant programs, with particular emphasis on early-career scientists and soft-money scientists (those who are not professors or government employees), and
- Better inclusion of emerging computer, data, and cloud technology and practices.

Heliophysics is a relatively new science area that has grown significantly during the space era and will continue to evolve as more space technology is deployed, as humans explore beyond the protection of Earth's environment, and as we strive to better understand the habitability of exoplanets. This current decadal interval has seen significant progress for heliophysics studies, and there is much anticipation for further progress as we fully realize the decadal survey goals for heliophysics research and space weather applications.

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Appendixes

A

Statement of Task

The National Academies of Sciences, Engineering, and Medicine shall convene an ad hoc committee to review the responses from NASA's Heliophysics program and the National Science Foundation to the 2013 decadal survey, "Solar and Space Physics: A Science for a Technological Society." The committee's review will include the following tasks:

1. Describe the most significant scientific discoveries, technical advances, and relevant programmatic changes in solar and space physics over the years since the publication of the decadal survey;
2. Assess the degree to which the Agencies' programs address the strategies, goals, and priorities outlined in the 2013 decadal survey and other relevant NRC and Academies reports, considering the national policy framework;
3. Assess the progress toward realizing these strategies, goals, and priorities;
4. Recommend any actions that could be taken to optimize the science value of the Agencies' programs including how to take into account emergent discoveries and potential partnerships since the decadal in the context of current and forecasted resources available to them;
5. Provide guidance about implementation of the recommended portfolio for the remaining years of the current decadal survey given actual funding levels, progress on decadal missions, and science and technology advances, but do not revisit or redefine the scientific priorities or recommended mission science targets;
6. Recommend any actions that should be undertaken to prepare for the next decadal survey—for example: enabling community-based discussions of (a) science goals, (b) potential mission science targets and related implementations, and (c) the state of programmatic balance; as well as identifying the information the survey is likely to need regarding the vitality of the field; and
7. Recommend actions that would enhance all stages of careers for scientists and engineers in the solar and space physics community.

B

Biographies of Committee Members and Staff

ROBYN MILLAN, *Co-Chair*, is a professor of physics and astronomy at Dartmouth College; she previously held research appointments at Dartmouth and at the University of California, Berkeley. Dr. Millan's research includes the use of high-altitude scientific balloon experiments and CubeSats to study Earth's radiation belts. She was principal investigator (PI) for the Balloon Array for Radiation-belt Relativistic Electron Losses (BARREL), and is currently the PI for REAL (Relativistic Electron Atmospheric Loss), a CubeSat that will make high time resolution measurements of electron pitch angle and energy distributions in low Earth orbit in order to characterize the mechanisms responsible for scattering radiation belt electrons. Dr. Millan received her Ph.D. in physics at the University of California, Berkeley, in 2002. She has served as secretary for the Space Physics and Aeronomy section of the American Geophysical Union (AGU; 2013-2016). Since 2017, she has served as co-chair for the COSPAR Scientific Roadmap on Small Satellites for Space Science. Dr. Millan is a recipient of NASA's Exceptional Public Achievement Medal (2017) and Dartmouth's John M. Manley Huntington Award for Newly Promoted Faculty (2017). She has participated in a number of studies of the National Academies of Sciences, Engineering, and Medicine, including "Achieving Science Goals with Cubesats" (2015-2016), the 2013 Decadal Survey in Solar and Space Physics (Panel on Solar-Wind Magnetosphere Interactions and the Platforms Working group), and "The Role and Scope of Mission-Enabling Activities in NASA's Space and Earth Science" (2008-2009). In addition, she has served on the Academy's Committee on Solar and Space Physics (2013-2016).

THOMAS N. WOODS, *Co-Chair*, is associate director of Technical Divisions at the University of Colorado in the Laboratory for Atmospheric and Space Physics (LASP). Dr. Woods joined LASP to work on the UARS SOLSTICE program under the direction of Dr. Gary Rottman. He originally served as the SORCE project scientist, and became the SORCE PI when Gary Rottman retired (2005). He continues in the role of SORCE XPS instrument scientist. In addition, he is the PI of the TIMED SEE and SDO EVE satellite instrument programs and the MinXSS CubeSat mission at LASP. His research is focused primarily on the solar ultraviolet irradiance and its long-term effects on Earth's atmosphere. He obtained his B.S. in physics from Southwestern at Memphis (now Rhodes College) and his Ph.D. in physics from Johns Hopkins University. Dr. Woods is a fellow of the AGU and presented the 2016 AGU Eugene Parker Lecture. He has served on the Academies' Committee on Achieving Science Goals with CubeSats and the Panel on Solar and Heliospheric Physics.

TIMOTHY S. BASTIAN is head of the observatory science operations at the National Radio Astronomy Observatory, where he has been an astronomer since 1990. He is also an adjunct faculty member in the Astronomy Department at the University of Virginia. Dr. Bastian's research interests include solar and stellar radiophysics; planetary/exoplanetary radio emission; radio propagation phenomena as probes of the solar wind; radio interferometry; and the physics of flares and coronal mass ejections. He is currently the principal investigator on the ALMA Development Study to implement solar observing modes with ALMA. He serves as chair of the AAS Publications Board, and is a member of the NASA Living With a Star Steering Committee. Dr. Bastian previously served as scientific editor of the *Astrophysical Journal*. He earned his Ph.D. in astrophysics from the University of Colorado. He has previously served on the Academies' Panel on Solar and Heliospheric Physics, and the Committee on Solar and Space Physics.

MONICA BOBRA is a research scientist at Stanford University in the W. W. Hansen Experimental Physics Laboratory, where she studies the Sun and space weather as a member of the NASA Solar Dynamics Observatory science team. She previously worked at the Harvard-Smithsonian Center for Astrophysics, where she studied solar flares as a member of two NASA Heliophysics missions called TRACE and Hinode. Her research focuses on analyzing large data sets, on the scale of terabytes to petabytes, that describe the Sun and space weather and is the author of a book on the subject. She also serves as vice chair of the advisory board for the SunPy Project, a Python-based ecosystem of open-source software for data analysis in solar physics, and the heliophysics editor for the *Journal of Open Source Software* (JOSS). She also is a frequent contributor to popular science magazines such as *Sky & Telescope* and *Scientific American*, covering topics related to the Sun and Sun-like stars. She received her M.S. in physics from the University of New Hampshire.

ANTHEA J. COSTER is assistant director and principal research scientist at the Massachusetts Institute of Technology in the Haystack Observatory. Her research interests include physics of the ionosphere, magnetosphere, and thermosphere; space weather and geomagnetic storm time effects; coupling between the lower and upper atmosphere; GPS positioning and measurement accuracy; radio wave propagation effects; and meteor detection and analysis. She is a co-PI on the NSF supported Millstone Hill Geospace facility award and a PI/co-PI on numerous projects involving the use of GPS to probe the atmosphere, including investigations of the plasmaspheric boundary layer, stratospheric warming, and the ionosphere over the Antarctic. Dr. Coster and her co-workers developed the first real-time ionospheric monitoring system based on GPS in 1991. She has been involved with measuring atmospheric disturbances over short baselines (GPS networks smaller than 100 km) for the U.S. Federal Aviation Administration, and has coordinated meteor research using the ALTAIR dual-frequency radar for NASA. She received her Ph.D. in space physics and astronomy from Rice University. Dr. Coster previously served on the National Academies' U.S. National Committee for the International Union of Radio Science, and The Role of High-Power, High Frequency-Band Transmitters in Advancing Ionospheric/Thermospheric Research: A Workshop.

EDWARD E. DELUCA is a senior astrophysicist at the Smithsonian Astrophysical Observatory. His research interests are in the theory of magnetic field generation in the Sun and stars, along with coronal heating via magnetic reconnection and MHD turbulence, and the nature and origin of coronal fine structure. Prior to being appointed as the senior astrophysicist of the High Energy Astrophysics Division, he served as a Supervisory astrophysicist at the Smithsonian Astrophysical Observatory and an astronomer at the University of Hawaii. Dr. Deluca has served on numerous committees including the Hinode Science Working Group, the LWS Targeted Research and Technology Steering Committee, the Solar-C International Sub-Working Group Co-Chair for NGXT, the NASA Advisory Council for Heliophysics Sub-Committee, and chair of the American Astronomical Society Solar Physics Division. Dr. Deluca received his Ph.D. in Astrophysics from the University of Colorado.

SCOTT L. ENGLAND is an associate professor at Virginia Polytechnic Institute and State University (Virginia Tech) in the Aerospace and Ocean Engineering Department. His research involves studying coupling of energy and momentum between different regions of the atmosphere via atmospheric waves. He spent 12 years at the Space Sciences Laboratory at the University of California, Berkeley, where his studies focused on the interaction between atmospheric waves and charged particles in the near-Earth space environment. At Virginia Tech his research focuses on using remote sensing instruments to study the upper atmosphere and near-Earth space environment. He is the project scientist for the upcoming NASA ICON spacecraft, a co-investigator on the upcoming NASA GOLD spaceflight mission, and a participating scientist on the NASA MAVEN mission to Mars. He was the recipient of a 2016 NASA RHG Exceptional Achievement for Science award for achieving exciting science results and making fundamental discoveries about the Mars environment from the MAVEN spacecraft. He received his Ph.D. for radio and plasma physics at the University of Leicester, UK.

STEPHEN A. FUSELIER is executive director of the Space Science Directorate at Southwest Research Institute. Previously he served as a researcher and senior manager at Lockheed Martin Advanced Technology Center. He has been involved with the development of the IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) spacecraft since its inception. Dr. Fuselier served as co-investigator on two instruments on-board IMAGE: Far Ultraviolet (FUV) imagers and the Low Energy Neutral Atom (LENA) imager. He also led the U.S. investigation on the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) on the joint European Space Agency/NASA ROSETTA mission. He is a co-investigator and lead of an instrument on the Interstellar Boundary Explorer (IBEX) and the Magnetospheric Multiscale missions. Dr. Fuselier is the author or co-author of more than 350 scientific publications, a fellow of the AGU, and the 1995 recipient of the AGU James B. Macelwane Award. He is the 2016 recipient of the EGU Hanes Alfven Award. He received his Ph.D. in space plasma physics from the University of Iowa. He has previously served on the National Academies Standing Committee on Solar and Space Physics, the Committee on Heliophysics Performance Assessment, and the Committee on Distributed Arrays of Small Instruments for Research and Monitoring in Solar-Terrestrial Physics: A Workshop.

RAMON E. LOPEZ is a professor of physics at the University of Texas, Arlington. His research focuses on solar wind-magnetospheric coupling, magnetospheric storms and substorms, and space weather prediction. Dr. Lopez is also working in the areas of teacher education, national science education standards, and physics education research. Dr. Lopez is a fellow of the APS and the AAAS. He received his Ph.D. in space physics from Rice University. He has previously served on the National Academies' Committee on NASA Science Mission Extensions, the Committee on Solar and Space Physics, the Committee on a Decadal Strategy for Solar and Space Physics (Heliophysics), and the Committee on Strategic Guidance for NSF's Support of the Atmospheric Sciences.

JANET G. LUHMANN is a senior fellow at the University of California, Berkeley, at the Space Sciences Laboratory. Her current research includes the use of spacecraft observations and models to investigate the connections between the Sun and heliospheric conditions, and the solar wind interactions with the planets. Dr.Luhmann is the current PI for the IMPACT Investigation on NASA's STEREO mission, and a Deputy PI for the MAVEN mission. She received her Ph.D. from the University of Maryland, College Park. Dr. Luhmann has served on the National Academies' Committee on PI-led Missions in the Space Sciences: Lessons Learned, Committee on Solar and Space Physics, Panel on Solar Wind-Magnetospheric Interactions, Space Studies Board, and the Committee on Solar-Terrestrial Research.

KATARIINA (HEIDI) NYKYRI is the associate dean of Research and Graduate Programs at the College of Arts and Sciences and professor of physics at the Embry-Riddle Aeronautical University. Her major research interests involve understanding the physical mechanisms that transport and heat plasma in solar wind-magnetosphere system. Dr. Nykyri was awarded the NSF career award in 2009 and ERAU researcher of the year award in 2010 and 2018. She is a co-director of the ERAU's LASMIR laboratory. Between 2012 and 2018, she served as a steering committee member of NSF's GEM program as a research area coordinator for the Solar Wind Magnetosphere Interactions research area. Since Fall 2017 Dr. Nykyri is the associate director for Embry-Riddle's Centre of Space and Atmospheric Research and director for the Space Weather Division. She received her Ph.D. in physics from the University of Alaska System: Fairbanks.

JENS OBERHEIDE is a professor of physics and astronomy at Clemson University in the Department of Physics and Astronomy. Previously, he was a research professor in atmospheric physics at the University of Wuppertal, Germany. Dr. Oberheide is a specialist in satellite data analysis and conducts empirical modeling of global-scale wave dynamics in earth's upper atmosphere. His research interests include the dynamics of Earth's mesosphere-thermosphere-ionosphere system; the forcing and vertical propagation of tides, planetary waves, and gravity waves, including their effects on chemistry and electrodynamics; geospace environment coupling to the atmosphere below and to solar activity; and utilization of satellite and ground-based remote sensing data to resolve variability and vertical coupling processes in the atmosphere. Dr. Oberheide is a recipient of the NASA Group Achievement Award to the TIMED team. He is an associate editor for the *Journal of Geophysical Research-Atmospheres*. He received his Ph.D. in physics from the University of Wuppertal. He served on the NASA Senior Review panel of the 2009-2012 Mission Operations and Data Analysis Program for the Heliophysics Operating Missions. Dr. Oberheide served on the Steering Committee of SCOSTEP's Climate and Weather of the Sun-Earth System program and led one of its working groups, investigating the geospace response to variable waves from the lower atmosphere. He served on the National Academies' Panel on Atmosphere-Ionosphere-Magnetosphere Interactions.

MERAV OPHER is an associate professor at Boston University in the Department of Astronomy. Her research interests are in how plasma and magnetic effects reveal themselves in astrophysical and space physics environments. In particular, in how stars interact with the surrounding media, how the solar system interacts with the local interstellar medium, and the interaction of extra-solar planets with their host stars. Her other interests are in how magnetic disturbances are driven and propagate from the Sun to Earth. She uses state-of the art 3D computational models to investigate these phenomena. Dr. Opher was awarded the prestigious NSF CAREER award and the Presidential Early Career Award for Scientists and Engineers (PECASE) for studies of shocks in interplanetary space. She also received the Mason Emerging Researcher/Scholar/Creator Award. She is actively involved in several leadership roles in the Space Physics and Astronomy community. Dr. Opher had her postdoctoral training at the Plasma Group of the Physics Dept of UCLA and was a Caltech Scholar at the Jet Propulsion Laboratory and at the University of Michigan. Before coming to Boston University, she was an associate professor at George Mason University. She obtained her Ph.D. for physics and astronomy in University in Sao Paulo. She has served on the National Academies Panel on Solar and Heliospheric Physics and the Committee on Solar and Space Physics.

CAROLUS J. SCHRIJVER is a senior fellow and director, retired at Lockheed-Martin Advanced Technology Center. He joined Lockheed after postdoctoral appointments at the University of Colorado and the European Space Agency, and a fellowship of the Royal Netherlands Academy of Sciences. His research focused on the magnetic activity of the Sun, the coupling of the Sun's magnetic field into the heliosphere and its solar wind, the manifestations of magnetic activity of other Sun-like stars, and the impact of solar variability on society. In addition to scientific research, he has been actively involved in developing and operating space instrumentation: he was the science lead and later the principal investigator for the Transition Region and Coronal Explorer (TRACE) and for the Atmospheric Imaging Assembly (AIA) of the Solar Dynamics Observatory (SDO), and is co-investigator on the Helioseismic and Magnetic Imager (HMI) on SDO and on the Interface Region Imaging Spectrograph (IRIS) SMEX project. As a Lockheed Martin senior fellow, he was involved in defining and developing instrumentation for future heliophysics missions. He has served in NASA advisory functions, including the NASA Sun-Earth Connection strategic planning (RoadMap) teams, the panel on Theory and Modeling of the NASA LWS initiative, the LWS Science Architecture Team, the LWS Mission Operations Working Group, the Solar-Heliospheric MOWG, the LWS TR&T Steering Group, the NASA Heliophysics Subcommittee, and the Science Definition Teams of the Solar Orbiter and Solar Sentinels. He received his Ph.D. at the University of Utrecht, the Netherlands, for astrophysics. He has served on the National Academies' Committee on the Effects of Solar Variability on Earth's Climate: A Workshop, the Space Studies Board, and the Task Group on Ground-based Solar Research.

JOSHUA SEMETER is a professor at Boston University (BU) in the Department of Electrical and Computer Engineering, and associate director of the BU Center for Space Physics. He was previously a senior research engineer at SRI International, and a staff scientist at the Max Planck Institute for Extraterrestrial Physics. Dr. Semeter's research concerns physical interactions between the outer atmosphere and space environment that underlie space weather. His laboratory uses optical and radio remote sensing techniques, and physics-based assimilation of observations from ground and space. Dr. Semeter was an associate editor of the Journal of Geophysical Research. He has received the Boston University Faculty Teaching Award in Engineering, and was a recipient of the NSF Faculty Early Career Development (CAREER) award. Dr. Semeter has a Ph.D. in electrical engineering from Boston University. He has served on the National Academies Standing Committee on Solar and Space Physics (CSSP) and the Panel on Atmosphere-Ionosphere-Magnetosphere Interactions.

JEFFREY P. THAYER is the Negler professor of Aerospace Engineering Sciences and the director of the Colorado Center for Astrodynamics Research at the University of Colorado, Boulder. He has recently become the university PI of the newly established Space Weather Technology, Research, and Education Center (SWx TREC) within the College of Engineering and Applied Sciences. His research spans the spectrum, from studies of the Sun's chromosphere to Earth's surface, bridging both science and engineering to understand the fundamental processes that govern our solar-terrestrial system. He specializes in geophysical fluid dynamics, gas and plasma interactions, thermodynamics and electrodynamics, and radar and lidar remote sensing of the near-space environment. His research has impacted topics in atmospheric electricity, satellite drag, solar-terrestrial coupling, solar chromosphere plasma-neutral interactions, geospace plasma physics, stratosphere polar vortex dynamics, cloud physics, and water bathymetry. Dr. Thayer is a recipient of several awards including the Negler Professorship, CU Boulder Faculty Assembly Award for Excellence in Research (emphasis on space environment), NASA Group Achievement Award, and SRI Presidential Achievement Award. He has served on many NASA and NSF committees and panels, such as, the NASA Geospace Mission and Operations Working Group, the NASA Sun-Earth Connections Roadmap Team, and the NSF CEDAR Science Steering Committee. He received his Ph.D. for atmospheric and space structure fro the University of Michigan. He has served on the National Academies' Panel on Atmosphere-Ionosphere-Magnetosphere Interactions.

ALAN M. TITLE is a senior fellow at the Lockheed Martin Advanced Technology Center (ATC) in Palo Alto, CA. His primary scientific research interest is the generation, distribution, and effects of the solar magnetic field throughout the Sun's interior and outer atmosphere. At present, he has 201 articles in refereed journals. He was the PI for NASA's solar mission called the Interface Region Imaging Spectrograph (IRIS). Dr. Title was the PI responsible for the Atmospheric Imaging Assembly on NASA's Solar Dynamics Observatory (SDO) launched in 2010, and is a co-investigator for another instrument on SDO, the Helioseismic Magnetic Imager. He was also the PI for NASA's solar telescope on the Transition Region and Coronal Explorer (TRACE) mission, launched in 1998, and the Focal Plane Package on the JAXA/ISAS Hinode mission launched in 2006. Additionally, Dr. Title serves as a co-investigator responsible for the Michelson-Doppler Imager (MDI) science instrument on the NASA-European Space Agency Solar and Heliospheric Observatory (SOHO), launched in 1995. All of these instruments were built under his direction at the ATC. As an engineer, Dr. Title designs, develops, builds, and flies new instruments that will gather the data necessary to inform his solar research interests. He led the development of tunable bandpass filters for space-based solar observations, a version of which is currently operating on the JAXA/ISAS Hinode spacecraft. He also invented a tunable variation of the Michelson Interferometer that has been employed on the SOHO spacecraft, the SDO, the Global Oscillations Network Group of the National Solar Observatory as well as other ground-based systems. Outside of his research, Dr. Title has supported activities at the Tech Museum, Chabot Observatory, Boston Museum of Science, the National Air and Space Museum, and the Hayden Planetarium. In addition, his educational outreach funding has supported a yearly summer program for Stanford undergraduates, and the Stanford Hass Center activities that develop science programs for K-12 classrooms. And for two decades, promising students from the Palo Alto High School District have come to work in his laboratory. Dr.Title is a member of the National Academy of Sciences and the National Academy of Engineering. Among his honors and awards are the 2011 John Adam Fleming Medal, awarded not more than once annually to an individual "for original research and technical leadership in geomagnetism, atmospheric electricity, aeronomy, space physics, and related sciences." He received his Ph.D. in physics from the California Institute of Technology. He is has served on the National Academies' Aeronautics and Space Engineering Board, the Committee on Achieving Science Goals with CubeSats, the NASA Technology Roadmap: Instruments and Computing Panel, the Committee on PI-led Missions in the Space Sciences: Lessons Learned, and the Panel on the Sun and Heliospheric Physics.

Staff

ARTHUR CHARO, *Study Director,* has been a senior program officer with the Space Studies Board (SSB) since 1995. For most of this time, he has worked with the Board's Committee on Earth Science and Applications from Space and the Committee on Solar and Space Physics. He has directed studies resulting in some 38 reports, notably inaugural NRC "decadal surveys" in solar and space physics (*2002*) and Earth science and applications from space (*2007*). He also served as the study director for the second NRC decadal survey in solar and space physics (*2012*) and the second Earth science decadal (*2018*). Dr. Charo received his Ph.D. in experimental atomic and molecular physics in 1981 from Duke University and was a post-doctoral fellow in Chemical Physics at Harvard University from 1982-1985. He then pursued his interests in national security and arms control as a Fellow, from 1985-1988, at Harvard University's Center for Science and International Affairs. From 1988-1995, he worked as a senior analyst and study director in the International Security and Space Program in the Congressional Office of Technology Assessment. In addition to contributing to SSB reports, he is the author of research papers in the field of molecular spectroscopy; reports on arms control and space policy; and the monograph, *Continental Air Defense: A Neglected Dimension of Strategic Defense* (University Press of America, 1990). Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and a Harvard-Sloan Foundation Fellowship (1987-1988). He was a 1988-1989 American Association for the Advancement of Science (AAAS) Congressional Science Fellow, sponsored by the American Institute of Physics.

MIA BROWN joined the Space Studies Board as a Research Associate in 2016. She comes to SSB with experience in both the civil and military space sectors and has primarily focused on policies surrounding US space programs in the international sector. Some of these organizations include NASA's Office of International and Interagency Relations, Arianespace, the United Nations Office for Disarmament Affairs (Austria), and the U.S. Department of State. From 2014 to 2015, Mia was the Managing Editor of the International Affairs Review. She received her M.A. in International Space Policy from the Space Policy Institute at the Elliott School of International Affairs. Prior to entering the Space Policy Institute, Mia received her M.A. in Historical Studies from the University of Maryland-Baltimore County (UMBC), where she concentrated in the history of science, technology, and medicine and defended a thesis on the development of the 1967 Outer Space Treaty.

GAYBRIELLE HOLBERT is a Program Assistant with the Space Studies Board. Prior to joining the Academies, she was a Communication Specialist for a non-profit organization that helped inner-city youth by providing after-school programs and resources to engage their needs. Prior to that, she was the social media consultant for the Development Corporation of Columbia Heights and a Production Assistant for a Startup Multimedia Production Company. She holds a BA in Mass Media Communications from the University of the District of Columbia.

SARAH E. MORAN, a fall 2019 Lloyd V. Berkner Space Policy Intern at the Space Studies Board, completed her undergraduate studies in Astrophysics and Science & Public Policy at Barnard College of

Columbia University in 2015. She is a Ph.D. student in Earth and Planetary Sciences at the Johns Hopkins University, where she is studying exoplanets — planets around other stars. She is the recipient of a NASA Earth and Space Science Fellowship in Astrophysics to investigate the chemical, radiative, and dynamical effects of clouds and hazes on exoplanet atmospheres through laboratory experiments and computational models. At the SSB, she has contributed to reports ranging from solar physics to planetary science.

COLLEEN HARTMAN is the Director of the Aeronautics and Space Engineering Board (ASEB) and the Space Studies Board (SSB) of the U.S. National Academies of Sciences, Engineering, and Medicine. Dr. Hartman has served in various senior positions, including Acting Associate Administrator, Deputy Director of Technology and Director of Solar System Exploration at NASA's Science Mission Directorate and Deputy Assistant Administrator at the National Oceanic and Atmospheric Administration. Dr. Hartman was instrumental in developing innovative approaches to powering space probes destined for the farthest reaches of the solar system, including in-space propulsion and nuclear power and propulsion. She also gained administration and congressional approval for an entirely new class of competitively selected missions called "New Frontiers," to explore the planets, asteroids and comets in the solar system. Dr. Hartman has built and launched balloon and spacecraft payloads, worked on robotic vision, and served as Program Manager for dozens of space missions, including the Cosmic Background Explorer (COBE). Data from the COBE spacecraft gained two NASA-sponsored scientists the 2006 Nobel Prize in Physics. Dr. Hartman earned a bachelor's degree in zoology from Pomona College in Claremont, Calif., a master's in public administration from the University of Southern California, and a doctorate in physics from the Catholic University of America. She started her career as a Presidential Management Intern under Ronald Reagan. Her numerous awards include the Claire Booth Luce Fellowship in Science and Engineering, the NASA Outstanding Performance Award, and multiple Presidential Rank Awards, one of the highest awards bestowed by the President of the United States to senior executives.

C

Committee Meeting Agendas

MEETING 1
National Academies Keck Center
Washington, DC

February 25, 2019

OPEN SESSION

9:10 a.m.	Welcome and Guest Introductions	
9:15	Discussions with Nicky Fox, Director of NASA's Heliophysics Division	
10:45	Break	
11:00	Discussions with NASA's Heliophysics Advisory Committee	Mike Liemohn, HPAC chair Janet Kozyra, HPAC Exec Secretary, NASA HQ
11:30	Review of the Heliophysics Science and Technology Roadmap for 2014-2033	Ed DeLuca, Midterm Committee HPD Roadmap Chair, and Harvard SAO
12:00 p.m.	Working Lunch	
1:00	Discussions with NSF • Mike Wiltberger, Section Head-Geospace, NSF GEO/AGS ~ 50 min • Dave Boboltz, Prog. Director, NSO & DKIST, NSF MPS/AST • Valentin Pillet, Director, National Solar Observatory (NSO)	
2:50	Break	
3:00	The National Space Weather Action Plan	Terry Onsager, NOAA SWPC
3:45-4:00	Reflections on the Survey	Dan Baker, Director of LASP-University of Colorado and Decadal Survey Chair
4:45-5:00	Break to Closed Session	
6:30	(Open) Working Dinner, Karma Modern Indian Restaurant, Washington, DC	
8:30	*Adjourn for the day*	

February 26, 2019

OPEN SESSION

9:00 a.m.	Discussions with Elsayed Talaat, Director, Office of Projects, Planning, and Analysis, NOAA/NESDIS
10:00	Briefing on the 2015 NSF Geospace Portfolio Review Tim Bastian, Committee and NRAO; Portfolio Review Chair
10:45	Break
11:00	Update on the LWS LPAG — Anthea Coster, Committee and LPAG Co-Chair Mark Linton, LPAG Co-Chair
1:30	Open Discussions
12:00 p.m.	Working Lunch/Discussions with Thomas Zurbuchen, Director, NASA SMD and Decadal Survey Vice-Chair
1:30	Break to Closed Session
5:30	*Adjourn for the day*

February 27, 2019

Closed Session in Its Entirety

MEETING 2

Laboratory for Atmospheric and Space Physics
Boulder, Colorado

April 3, 2019

OPEN SESSION

12:00 p.m. Lunch

12:30 Discussions with Nicky Fox, Director of NASA's Heliophysics Division
- Responses to committee queries
- Thoughts on Committee Tasks 4-7

1:30 Discussions with Mike Wiltberger, Section Head-Geospace, NSF GEO/AGS
- Responses to committee queries
- Thoughts on Committee Tasks 4-7

2:30	Discussions with Elsayed Talaat, Director, Office of Projects, Planning, and Analysis, NOAA/NESDIS ● Responses to committee queries ● Thoughts on Committee Tasks 4-7	
3:30	Break	
3:45	COSPAR Roadmap	Karel Schrijver, Committee (via zoom)
4:30-5:30	Closed Session	
6:30	Working Dinner, Boulder Cork, Boulder, CO	
8:30	*Adjourn for the day*	

April 4, 2019

OPEN SESSION

10:00 a.m.	Discussions with Fran Bagenal regarding Committee Task 7, CU Boulder
11:00	Break to closed session, public meeting adjourns

April 5, 2019

Closed session all day

MEETING 3

J. Erik Jonsson Center, Woods Hole, MA

July 23, 2019

CLOSED SESSION

8:30 a.m.	Closed Session, Committee Members and Staff Only
10:00	Closed Session Adjourns and Break

OPEN SESSION

10:00	Break	
10:15	Discussions (Via ZOOM)	Nicky Fox, Director, NASA HPD Peg Luce, Deputy Director, NASA HPD
11:15	Discussions (Via Zoom)	

Mike Wiltberger, Head, Geospace Section (GS), NSF GEO/AGS
Dave Boboltz, Program Director, NSO/DKIST (inv.)
Ralph Gaume, Head, Division of Astronomical Sciences (AST), NSF/MPS (inv.)

CLOSED SESSION

12:15 p.m. Closed Session, Committee Members and Staff Only

6:00 Closed Session Adjourns and Working Dinner

OPEN SESSION

6:30 Working Dinner on site (lobster boil, vegetarian options on request)

8:30 *Adjourn for the Day*

July 24, 2019

CLOSED SESSION

8:30 a.m. Closed Session, Committee Members and Staff Only

OPEN SESSION

12:00 p.m. Discussions (Via ZOOM) David Boboltz
Ralph Gaume

CLOSED SESSION

12:30 p.m. Closed Session, Committee Members and Staff Only

5:30 Meeting Adjourns

July 26, 2019

CLOSED SESSION

8:30 a.m. Closed Session, Committee Members and Staff Only

12:00 p.m. Meeting Adjourns

D

Report Findings

Section	Finding
3.2	F3.1: Completion of the program of record as recommended in the decadal survey, combined with new tools and data analysis approaches, has resulted in significant scientific advances (see Chapter 2) and has added important elements to the Heliophysics System Observatory.
3.3.1	F3.2: CubeSat missions are intended to be low-cost, higher-risk exploratory missions. The number of CubeSat science missions has increased significantly in this decade. While recognizing the challenge of managing a rapidly increasing number of CubeSat projects, NASA will need to ensure that managerial oversight does not translate into the imposition of additional reviews and reporting requirements to the level of larger missions.
3.3.1	F3.3: NSF's CubeSat Program had no new solicitations between 2015-2018 and has not received a significant augmentation. However, the new CubeSat Ideas Lab initiative, if continued, will reinstate the program to the level that was recommended in the decadal survey.
3.3.1	F3.4: NASA and NSF have provided a number of opportunities for the science community to add to the array of diverse observing platforms that enable Heliophysics science, including a robust and growing NASA CubeSat program, continuation of a strong suborbital program, and creation of a NSF Midscale facilities program.
3.3.2	F3.5: A plan exists to support NSO's synoptic observations in the short term. The long-term plan past 2021 for supporting these synoptic observations is unclear. To address this would require immediate attention.
3.3.2	F3.6: The scientific success of DKIST will depend on Level 2 and higher data processing. The Committee is concerned that provision of robust Level 2 data products to the user community is not part of steady state operations planning and no resources have been allocated by NSF for Level 2 data products and their development past 2020.
3.3.2	F3.7: DKIST is the flagship observatory of NSF solar astronomy. DKIST funding past 2020 supports primarily DKIST operations and its data center, but with limited support for research. Substantial research funding, of more than $5M per year, from NSF needs to be available in anticipation of the number of science proposals that will be submitted. Coordinated efforts that use DKIST along with NASA, ESA, and JAXA mission data will lead to scientific breakthroughs, requiring adequate support.
3.3.2	F3.8: The Operations and Maintenance model for NSF's large facilities has had significant impacts on the AGS and AST budgets.
3.3.2	F3.9: A model similar to the Participating Scientist program used in the Planetary Division would contribute to realizing the scientific potential of Heliophysics missions by ensuring broad and diverse community participation.
3.3.2	F3.10: A modern data infrastructure, support for the development of software tools, education about data science methods, and interdisciplinary collaboration are needed to realize the scientific potential of the large and complex data sets being produced today.
3.3.3	F3.11: Laboratory research, from plasma physics to spectroscopy, is a critical, foundational component for heliophysics research. The NASA LNAPP program is a positive step towards increasing opportunities for laboratory experiments, but it does not fully address the decadal survey

Section	Finding
	recommendation, specifically the need for increased NASA-DOE collaboration.
3.3.3	F3.12: The placement of solar and space physics in multiple divisions and directorates arises from the cross-cutting relevance of the science. However, there are very few cross-divisional funding opportunities at the agencies. This makes it difficult for proposers to obtain funding for basic research on subjects that are not clearly aligned with one division. Proposals that cross divisional lines also pose significant challenges to agencies and review panels.
3.3.3	F3.13: Diverse observing platforms continue to produce important scientific results and augment the capabilities of larger facilities. The opportunities for maximizing the use of diverse platforms and combining their measurements have not been fully exploited; further opportunities exist to leverage international collaboration and combine measurements from space-based and ground-based platforms.
3.3.3	F3.14: Many elements of the HSO are aging and there is a risk of losing key capabilities. In order to realize the vision of the HSO, some longer-term strategic planning is required to prioritize the critical support needed at both the mission level and the program level. Moreover, the HSO can be viewed as a National resource that goes beyond NASA missions. Data from small missions, ground-based facilities, and international assets have become increasingly important. An opportunity exists to elevate the HSO concept to better manage and exploit this critical resource for scientific progress.
3.3.3	F3.15: Heliophysics has much to contribute to areas of broad interest within NASA's Science Mission Directorate (SMD), including stellar system and exoplanet research as well as future major exploratory efforts; for example, the Lunar Gateway missions. However, the expertise and knowledge that exists within the Heliophysics community is not as widely exploited at SMD as it could be because there are insufficient opportunities to engage across division lines.
3.3.4	F3.16: A regular cadence for HSCs is needed. In order for HSCs to be impactful, the next call for Step-1 proposals should be released within a year of the down selection for Step-2 proposals. Moreover, NSF participation in the HSCs has not been realized.
3.3.5	F3.17: NSF and NASA have responded positively to this graduate student training recommendation. The CISM summer school, now the Boulder Space Weather Summer School, has been funded by the NSF. In addition, NASA has continued to fund the Heliophysics Summer School. The former has a focus on beginning students and modeling of space weather, while the latter is more targeted to basic research science for advanced graduate students and post-doctoral researchers. These activities provide an outstanding resource to a community in which heliophysics graduate students in a given department are often few in number and specialized courses in the discipline are not feasible.
3.3.5	F3.18: Advances in the capability of Open Source Software (OSS) and the related heliophysics tool sets are not often covered in undergraduate and graduate education. Training the next generation in software best practices enables robust and maintainable code.
3.3.6	F3.19: DRIVE is an organizational framework that encourages innovation and balance across NASA and NSF R&A programs, thus maximizing the science return of Agency investments. In the future, DRIVE may include new elements or augmentations that go beyond the limited number of recommendations made in the decadal survey. It is essential to continue tracking and making visible the elements of DRIVE.
3.3.6	F3.20: NASA and NSF have made progress on most of their DRIVE elements, although some of the DRIVE elements were implemented only recently. Funding constraints imposed by the decadal survey requirement to complete the current program are a contributing factor.
3.3.6	F3.21: Some elements of DRIVE for NSF have not been fully implemented. These include ensuring funding for science areas that fall between divisions such as outer heliosphere research, full participation in Heliophysics Science Centers, and recognition of solar and space physics as a subdiscipline in the annual survey of earned doctorates.
3.4	F3.22: NASA is responding positively to the decadal survey recommendation to strengthen the Explorer program. Although no Explorer AOs were released during the first 3 years following the decadal survey, the 3-year spacing between Heliophysics Explorer AOs for SMEX and MIDEX of

Section	Finding
	2016 and 2019 is a move to implement the decadal survey recommendation.
3.4	F3.23: The committee sees the growth of mission cost in a relatively flat budget setting as a significant hazard to the ability to sustain a 3-year cadence in the future.
3.4	F3.24: NASA management of the Explorer missions is in need of optimization to ensure that the program fullfils its goal to: "... provide frequent flight opportunities …. from space utilizing innovative, streamlined and efficient management approaches…"
3.4	F3.25: In order to maintain the decadal survey-recommended 3-year (or ideally faster) launch frequency of Explorers, NASA will need to develop a more efficient management environment and an improved contract/grant structure, both to reduce mission cost and to shorten the interval from AO to launch
3.5	F3.26: Formulation of the first of three recommended STP missions has begun, but IMAP comes 3 years later than anticipated in the decadal survey, and the next STP mission (DYNAMIC) has not started. As anticipated in the decadal survey, the MEDICI mission is not expected to start until the next decade.
3.5	F3.27: The DYNAMIC science goals remain compelling and of the highest priority for the heliophysics community. The targeted science goals and measurement capabilities of GOLD, AWE, and ICON do not address several key objectives in the top-level decadal survey science challenge posed by DYNAMIC.
3.6	F3.28: The GDC STDT, per their charge, was not permitted by NASA HQ to select a particular mission architecture to meet GDC science objectives.
4.1	F4.1: The NASA Space Weather Science and Application (SWxSA) strategic documents are an excellent start to address the NSWAP goals and responsibilities identified for NASA Heliophysics Division. However, these documents do not "identify new research-based capabilities and outline expectations for gap-filling products". The Committee emphasizes the importance of a science gap analysis in order to develop implementation plans, interagency coordination, and budgets. NASA and NSF, in coordination with their research communities, and in consultation with NOAA, are best positioned to develop a scientific gap analysis to address the scientific and observational challenges that currently hamper the formulation of reliable space weather forecasts for time scales from several hours to a few days.
4.1	F4.2: Stable funding lines were not identified for the work defined in the NSWAP. The development of a scientific gap analysis, and an associated prioritization of required observables, models, data systems, and R2O/O2R projects are needed in order to develop a well-founded budget for the NSWAP-related tasks of NASA, NSF, NOAA, and other agencies.
4.2.2	F4.3: Currently, the combination of ACE and DISCOVR in-situ particle and field measurements at L1, the GOES solar EUV imager and solar EUV and X-ray irradiance sensors at GEO, the ground-based GONG network for solar magnetograms, and the SOHO LASCO coronagraph at L1 provide the primary set of space weather monitoring assets, with support from SDO solar observations at GEO and STEREO solar and in-situ observations in an Earth trailing/leading orbit. NOAA has plans to continue in-situ solar wind observations at L1, to establish new coronagraph observations at L1 and at GEO, and to continue their support of solar magnetograms in the GONG network.
4.2.3	F4.4: NASA and NOAA are conducting a dialogue with ESA regarding participation in the Lagrange operational mission to the L5 location. NOAA has a formal agreement with ESA for their L5 mission, but no agreements are yet in place for NASA. Additional observations, platforms, and locations are informally discussed as a part of the ongoing agency and community interactions and communications relevant to the NSWAP. Coordination with India and China could further enhance space weather observations at the L1, L4, and L5 locations.
4.2.4	F4.5: The decadal survey did not address the specific contributions of the primary agencies (NASA, NSF, NOAA, DoD) to the National Space Weather Program. In particular, the role of research targeting the magnetosphere, ionosphere, and thermosphere was not represented in the decadal survey

Section	Finding
	at a level commensurate with current NSWAP priorities. The NOAA/NASA/NSF support for O2R/R2O efforts is evolving with the majority of this research being planned in FY 2020 under the NASA Heliophysics Division's new program called Space Weather Science and Applications (SWxSA).
4.2.4	F4.6 The minimum observation requirements and baseline research infrastructure need to be defined by drawing on space weather O2R/R2O activities at NSF and NASA. Ongoing space weather benchmark activities are a step in this direction.
4.2.4	F4.7: The agencies can take advantage of commercial, interagency, and inter-divisional collaborations to make progress toward their space weather goals. To assure that this happens effectively, open data policies and standardized data interfaces need to be established. Inputs from the science community are critical for assessing how useful the commercial data are and assuring that the right data are accessible (and not merely higher level derived products).
5.1	F5.1: The effectiveness of grants issued by NSF and NASA for research in solar and space physics would be improved by: — Shortening the cycle from proposal to funding availability. In some programs, and especially for younger scientists and postdocs, the cycle is too long. — Adjusting the size of grants. Typical grants, while they have grown in size, are often too small or short-term to tackle the larger challenges. Larger grants may be more effective for some programs. On the other hand, smaller grants or "seed grants", with smaller proposals, quicker reviews, and shorter funding cycles could invigorate new research directions and could be more supportive of early-career scientists.
5.2	F5.2: The NSF and NASA on-going education programs involving heliophysics summer schools, REU programs, and student workshops offer opportunities for exposing undergraduates to space physics research, as well as hands-on training. There is great potential for the heliophysics community to significantly expand their involvement of undergraduate students by having more heliophysics-related REU programs.
5.2	F5.3: The infrastructure of large data archives and advanced numerical research and analysis tools is a critical element of modern-day science. Professional training about these rapidly evolving tools and modeling techniques is important for the health of the heliophysics research programs. The development and maintenance of such tools is given insufficient attention in the development of roadmaps and strategic plans. These infrastructure components, and the teaching of their use, could be discussed on an equal footing with experimental hardware in the planning and budgeting of space- and ground-based observatories.
5.2	F5.4: Involving students in the development of spaceflight hardware for missions is key to the long-term success of developing the workforce for the U.S. space programs. Enhancing the number of partnerships between universities and non-University institutions and further increases in the number and frequency of small satellite missions are example pathways to train more students and early-career scientists and engineers for space missions.
5.3	F5.5: Increasing the participation and inclusion of individuals of different genders, races, cultures, and ages in positions of leadership roles in heliophysics (e.g., mission PIs) and for recognition (e.g., honors, awards) would better reflect today's societal makeup. It has been shown that women and underrepresented minorities in STEM fields face consistent bias in proposal selections, hiring, salaries, observing time awards, paper citations, and prizes / awards. It is critical to better track the demographics of the heliophysics community in order to assess the effectiveness of programs that seek to increase the diversity of its membership.
6.1	F6.1: Community analysis group workshops and funded mission concept development for defining critical science goals and related mission concepts as employed by NASA's Planetary Science Division and Astrophysics Division in preparation for their decadal surveys have been productive for broader and deeper definitions of strategic mission concepts based on key science objectives and any

Section	Finding
	emerging technology important for future missions. This midterm assessment committee emphasizes that the science objectives and related measurement requirements are more important to define than specific missions / facilities.
6.1	F6.2: The NSF Mid-Scale Research Infrastructure (RI) opportunity is highly competitive; since proposals are competed across all NSF divisions, the selection rate is expected to be low. The NSF AGS (Atmospheric and Geospace Sciences) and AST (Astronomical Sciences) divisions could improve their chance of selection within the NSF-wide Mid-Scale RI program if they strategically planned and prioritized a few key RI concepts that have broad community support.
6.1	F6.3: The demographics and diversity of scientists and engineers in heliophysics may have evolved significantly since the 2013 heliophysics decadal survey. A new demographics / diversity survey would clarify those changes over the past few years, and results from such a survey could enlighten planning for improving diversity in the heliophysics community.
6.1	F6.4: The demographics survey for the last decadal survey was completed late in the study, limiting its utility. It is important that an updated demographics survey be available in advance of the initiation of the next decadal survey.
6.2	F6.5: The next decadal survey committee may want to consider how to best distinguish the NASA Heliophysics LWS and STP strategic mission lines, both in terms of critical science goals and implementation strategies. Without distinct goals for these two programs, there is a risk to limit effective planning for larger strategic missions.
6.2	F6.6: To mitigate the risk of decadal survey recommendations being regarded as difficult or not possible to implement in the next decade period, each agency needs to ensure that the budget 10-year plan is as accurate, up-to-date, and complete as possible throughout the course of the survey's work. It can benefit strategic planning if future budget scenarios included a nominal (baseline) budget and optimal (best-case) budget. The two-budget approach can allow for defining clear decision rules for reprioritizing under each scenario.
6.2	F6.7: The next decadal survey could benefit by having decision rules for large programs/missions as was done in the 2013 heliophysics decadal survey.
6.2	F6.8: For next decadal survey discussions about stretch-goal science objectives and related missions, it will be important to identify what technologies are required for those stretch-goal missions and to consider actions that could develop such technology in the next decade.
6.2	F6.9: It is critically important for future planning of space weather applications to have NOAA better integrated into the space weather related strategic plans for the next decade.
6.3	F6.10: The next heliophysics decadal survey committee should consider the following important topics….see list in Chapter 6.

E

Progress for Science Challenges in 2013 Heliophysics Decadal Survey

Chapter 2 provides a brief overview on a selection of science highlights and advances in research tools from the first half of the decade period covered by the 2013 decadal survey, and this Appendix provides more details about these science highlights and how they relate to the 12 Science Challenges provided in the 2013 decadal survey. The decadal survey identified four Key Science Goals and, subsequently, the Science Challenges that flow from these goals from the three primary branches of heliophysics— Atmosphere-Ionosphere-Magnetosphere Interactions (AIMI), Solar Wind-Magnetosphere Interactions (SWMI), and Solar and Heliospheric Physics (SHP). These are illustrated in Table E.1. Substantial scientific and technical progress has been made in each of the Science Challenge areas, but for brevity, only some of the recent progress results are presented here as organized by the three heliophysics branches.

E.1 SOLAR AND HELIOSPHERIC PHYSICS

As mentioned in Chapter 2, scientists have made great advances over the past six years in understanding the dynamic solar magnetic field and how it shapes the whole of the space environment, ranging from the Sun to far beyond the planets. This appendix provides more details on selected findings for the highlights noted in Chapter 2:

- Close to the Sun, the Parker Solar Probe has set the record for closest approach to the Sun; its ongoing mission is to sample solar coronal particles and the solar electromagnetic field to understand coronal heating, solar wind acceleration, and the formation and transport of solar energetic particles.
- Far from the Sun, measurements by the Voyager spacecraft (that exited the heliosphere in 2012 and 2018, respectively), combined with Interstellar Boundary Explorer (IBEX) and Cassini data, transformed our knowledge of the outer boundary of the heliosphere, placing outer-heliospheric science solidly among the other fast-developing branches of heliophysics.
- Fine-scale High Resolution Coronal Imager (Hi-C) rocket imagery combined with global-scale Solar Dynamics Observatory (SDO) images of the solar corona revealed the small-scale signatures of the reconfiguration of the magnetic field and of Alfvén waves running through that magnetic field. Combined SDO, IRIS, and Hinode observations have furthered our understanding of the mechanisms that extract energy from the magnetic field either in the form of heat or through explosive eruptions, and also of the mechanisms that transport energy between different wave types and physical domains.
- Technical advances in computational methods and infrastructure provide critically needed insights into both the source of the solar magnetism and the formation of, and explosive instabilities in, the globally connected solar atmosphere as discovered with SDO observations. These newly-developed computer models can be applied to new data, but also retrospectively to archival data so that we can efficiently learn from decades-long historical archives.

TABLE E.1 The 12 Science Challenges in the 2013 Heliophysics Decadal Survey are Mapped to the Four Key Science Goals in the Decadal Survey

Key Science Goal 1. Determine the origins of the Sun's activity and predict the variations in the space environment.

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

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

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

Science Challenges in 2013 Heliophysics Decadal Survey	↑ Key Goal 1	↑ Key Goal 2	↑ Key Goal 3	↑ Key Goal 4
AIMI = Atmosphere-Ionosphere-Magnetosphere Interactions				
AIMI-1 Understand how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over global, regional and local scales.		X		X
AIMI-2 Understand the plasma-neutral coupling processes that give rise to local, regional, and globalscale structures and dynamics in the AIM system.		X		X
AIMI-3 Understand how forcing from the lower atmosphere via tidal, planetary, and gravity waves, influences the ionosphere and thermosphere.		X		X
AIMI-4 Determine and identify the causes for long-term (multi-decadal) changes in the AIM system.	X	X		X
SH = Solar and Heliospheric physics	1	2	3	4
SH-1 Understand how the Sun generates the quasi-cyclical magnetic field that extends throughout the heliosphere.	X		X	X
SH-2 Determine how the Sun's magnetism creates its hot, dynamic atmosphere.	X			X
SH-3 Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate through the heliosphere.	X			X
SH-4 Discover how the Sun interacts with the local interstellar medium.	X		X	X
SWMI = Solar-Wind Magnetosphere Interactions	1	2	3	4
SWMI-1 Establish how magnetic reconnection is triggered and how it evolves to drive mass, momentum, and energy transport.		X		X
SWMI-2 Identify the mechanisms that control the production, loss, and energization of energetic particles in the magnetosphere.	X		X	X
SWMI-3 Determine how coupling and feedback between the magnetosphere, ionosphere, and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind.		X		X
SWMI-4 Critically advance the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres by comparing models against observations from different magnetospheric systems.		X		X

- Machine learning and big data techniques are helping us move towards improved multi-day predictions of space weather, while increasingly realistic computer models in regular use at the GSFC Community Coordinated Modeling Center (CCMC) are now able to work across multiple physical regimes as they simulate quantities that can be directly compared to real-world observations.
- Detailed observations of space-weather throughout the solar system helped planetary scientists and stellar astrophysicists understand the range of possibilities for stellar wind conditions, and thus how these conditions influence exoplanets.

These exciting new results from both space-based missions and ground-based instruments demonstrate the importance of diverse and complementary observing capabilities, both remote and in situ, in order to understand fundamental physical processes. They also emphasize the importance of accessible, standardized archives and the need to develop community-usable numerical tools for modeling and analysis, sometimes using artificial intelligence, including data-driven full-system models that include the space-weather forecasting systems.

Decadal Survey Challenge SHP-1: Determine How the Sun Generates the Quasi-Cyclical Variable Magnetic Field that Extends Throughout the Heliosphere

Inside the Sun, hot, ionized gas ('plasma') moves in a complex hierarchy from small-scale to global-scale flows to create and evolve magnetic fields in a process called the solar dynamo (Section 1.2). Where this field breaches the surface it can form sunspots embedded in active regions, becoming part of the solar variability that drives space weather. Measurements of these subsurface movements are critical to understand the dynamo and to forecast the 11-year solar cycle. Results from two methods are combined to infer plasma flows in the solar interior. One is to apply helioseismology: measure the properties of sound waves running through much of the solar interior to deduce the conditions of the gas that they traverse. Another is tracking of magnetic elements as they move across the surface based on high-resolution magnetographs and (for sunspots) direct imaging. Some sound waves travel the Sun's interior extensively. From this interior wave propagation, we can gain insight into the magnetic conditions on the farside of the Sun's surface invisible from Earth by observing the multitude of waves on the Earth-facing side of the Sun. This enables predictions of the magnetism of the Sun's far side about a week before it spins around to become the Earth-facing side (e.g., Arge et al., 2013, Kim et al., 2019). These more complete magnetic maps form the foundation for models of the solar wind sources as needed for space weather forecasts.

Using helioseismology, Zhao et al. (2013) detected an equatorward flow in the Sun's interior between 0.83 and 0.91 solar radii, sandwiched between poleward flows below and above. This flow (illustrated in Figure E.1) may be a key ingredient of the dynamo as it can transport magnetic field lines both in the deep interior and near the surface. However, the rise of bundles of magnetic field to the solar surface was found to be much slower than expected from some models (Birch et al. 2016), meaning more theoretical work is needed to better understand how flux tubes rise through the surrounding gas.

In order to better understand the dynamo, these findings are combined with computer models that incorporate flow-field interactions as much as computing resources allow. Valuable progress has also been made through novel applications of earlier generations of ideas. One promising example is the coupling of geometrically-simplified axially-symmetric dynamo models for the subsurface layers with surface flux transport models. Observed properties of the magnetic field emerging onto, and then moving across, the solar surface are used in machine learning methods to statistically describe the magnetic field that couples the interior and surface. Such modeling reproduces many of the properties of cycle-to-cycle variations and shows promise in forecasting at least one sunspot cycle ahead (e.g., Lemerle and Charbonneau, 2017). This modeling work suggests much, perhaps most, of the cycle-to-cycle variations result from convective flows that nudge emerging sunspot regions away from their average orientation, thereby pushing the solar dynamo into an irregular mode (Karak and Miesch, 2017). Another source of cycle variability has been found in changes in the meridional circulation, that serves as a large-scale ‘conveyor belt’ that transports the field (Upton and Hathaway, 2014). These findings emphasize the importance of continuous and continued observing of field and waves at the solar surface.

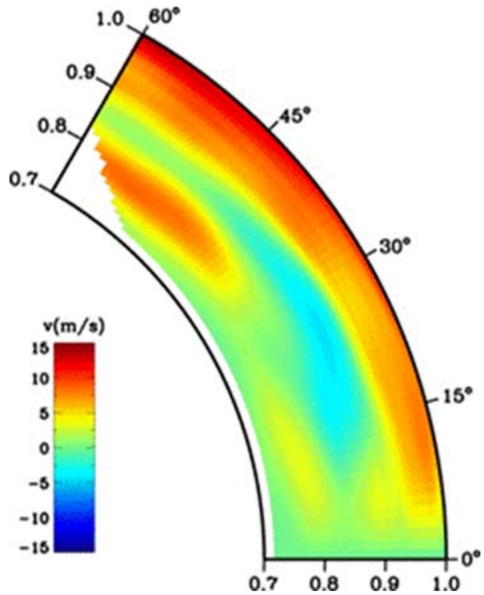

FIGURE E.1 The figure shows different velocities of plasma flows in a cross section of a quarter of the solar disk. Warm colors show flows toward the solar poles, while cool colors show flows toward the solar equator. SOURCE: R. Chen and J. Zhao, A comprehensive method to measure solar meridional circulation and the center-to-limb effect using time-distance helioseismology, 2017, *The Astrophysical Journal* 849(2):144, doi: 10.3847/1538-4357/aa8eec. © American Astronomical Society. Reproduced with permission.

Decadal Survey Challenge SHP-2: Determine How the Sun’s Magnetic Field Creates Its Dynamic Atmosphere

The last 6 years saw numerous advances in what we know of the coupling between the hot solar corona and the heliosphere, driven by both observations and numerical models that span the smallest observable scales on the Sun to the entire heliosphere. Scientists applied a systems approach, by driving numerical models with observational data, to study the corona and heliosphere as a whole.

Magnetic Alfvén waves are thought to play a role in heating the solar corona and in driving the solar wind. These waves are initially excited in the solar interior from where they travel outward along magnetic field lines. Different types of waves travel along distinct paths from the solar interior through the solar atmospheric regimes (Zhao et al., 2016, Morton et al., 2019). New computational results also show how Alfvén waves can transport energy into the solar chromosphere and corona, there to be converted into heat. Properties of Alfvén waves, which are difficult to detect because they are faint and have small amplitudes compared to instrumental resolution, were quantified by combining state-of-the-art spectroscopy and advanced modeling (Okamoto et al., 2015; Goossens et al., 2014; van Ballegooijen et al., 2014; Lionello et al., 2014; van der Holst et al., 2014; Kerr et al., 2016; Arber et al., 2016; Cranmer and Woolsey, 2015; Soler et al., 2015). This new generation of models integrates small-scale processes, such as ion-neutral interactions and shocks, with the global-scale nature of the highly interconnected system on the Sun (e.g., Tadesse et al., 2011). Such models are critical for understanding the observations from high resolution, high cadence spectrographic observations from IRIS (Interface Region Imaging Spectrograph) and future observations from DKIST.

High-cadence observations of the entire Earth-facing side of the Sun by SDO and multi-point observations of the sides and farside of the Sun by the Solar TErrestrial RElations Observatory (STEREO) spacecraft revealed that the corona is a highly interconnected system (Tadesse et al., 2011): changes in one location, such as by an active region emerging onto the solar surface, can trigger the magnetic field to restructure itself elsewhere (Zhang and Low, 2001, 2002; Longcope et al., 2005), sometimes explosively in flares and coronal mass ejections (Fu and Welsch, 2016, Balasubramaniam et al., 2011; Schrijver and Title, 2011), or on large scales by creating and closing coronal holes (Karachik et al., 2010).

There has also been significant progress in computer simulations that reach from the solar interior to the corona (e.g., Amari et al., 2014; Fisher et al., 2015; Rempel et al., 2017; Wyper et al., 2017; Cheung et al., 2019). For example, the physical domain in the model developed by Cheung et al. (2019) encapsulates the solar convection zone, photosphere, chromosphere, transition region, and corona, beginning 7,500 km below the solar surface and extending up to 42,000 km above it. These comprehensive models help scientists understand the heating of the solar atmosphere as well as the mechanisms that trigger flares and Coronal Mass Ejections.

Decadal Survey Challenge SHP-3: Determine How Magnetic Energy Is Stored and Explosively Released

The explosive release of magnetic energy creates a variety of phenomena that include flares, coronal mass ejections (CMEs), shocks and energetic particles, and magnetospheric (sub-storms) and aurorae at Earth. New observations and models of fast magnetic reconnection, leading to a sudden change in the topology of the magnetic field, show that this universal and fundamental process occurs on scales both large and small all over the heliosphere, and is similarly expected to occur in other planetary systems.

Magnetic reconnection in the solar atmosphere has long been elusive owing to the high speed and small spatial scale on which it occurs, but newer generations of instruments are now revealing (1) reconnection-driven heating (based on Hi-C sounding rocket images; Cirtain et al., 2013), (2) outflows (seen in images taken by the Solar Dynamics Observatory (SDO) and the Ramaty High Energy Solar Spectroscopic Imager (RHESSI); Su et al., 2013), (3) shocks (using the Jansky Very Large Array (JVLA); Chen et al., 2015), (4) electron beams from the energy release sites (JVLA; Chen et al., 2013), and (5) extended sources of microwave flare emissions (EOVSA; Gary et al., 2018). An example of one of the largest flares in this solar cycle is given in Figure E.2.

Indirect observations of magnetic energy release also grew considerably along with the advent of big data. In the last 5 years, modern solar and space physics instruments took more data than ever before (e.g., SDO, which takes 1.5 terabytes of data a day) and with higher data rates than ever before (e.g., the Magnetospheric Multiscale Mission (MMS), which takes data as fast as every millisecond). In order to effectively analyze such massive data volumes, scientists introduced machine learning to efficiently and affordably identify features and even to forecast events (LeCun et al., 2015), including solar flares (e.g., Bobra and Couvidat, 2015; Nishizuka et al., 2018; Panos et al., 2018), Solar Energetic Particle (SEP) events (e.g., Winter et al., 2015), and particle density enhancements in Earth's magnetosphere (e.g., Zhelavskaya et al., 2016; Bortnik et al., 2016).

Decadal Survey Challenge SHP-4: Discover How the Sun Interacts with the Local Galactic Medium and Protects Earth

Over the past 6 years there have been several surprises about the boundary between the immense magnetic bubble containing our solar system and the surrounding interstellar medium. These discoveries are also important for astrophysics in general because our local heliosphere is the only astrosphere that we can study up close to learn about fundamental processes which are also likely to occur elsewhere.

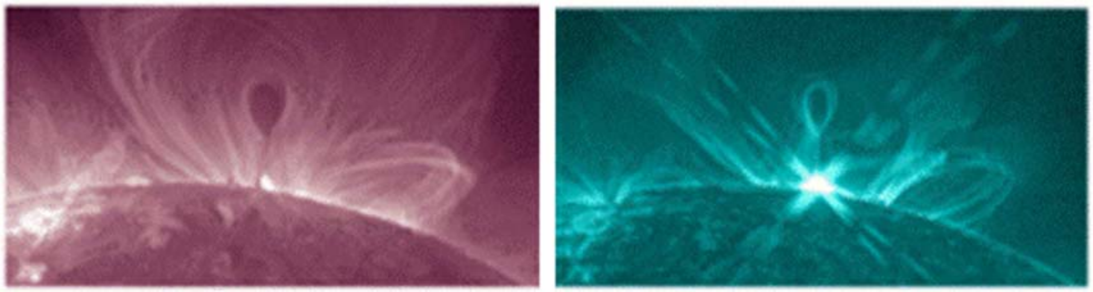

FIGURE E.2 SDO images of plasma in two different wavelengths of the X8.2 flare of September 10, 2017, one of the largest of the current solar cycle, beautifully illustrating an erupting flux rope and reconnecting current sheet. The flare also triggered a secondary blast of particles into interplanetary space. The intense radiation had significant effects on both the terrestrial and Martian space environments. SOURCE: A.M. Veronig, T. Podladchikova, K. Dissauer, M. Temmer, D.B. Seaton, D. Long, J. Guo, B. Vršnak, L. Harra, and B. Kliem, Genesis and impulsive evolution of the 2017 September 10 coronal mass ejection, *The Astrophysical Journal* 868(2):107, 2018, https://doi.org/10.3847/1538-4357/aaeac5.

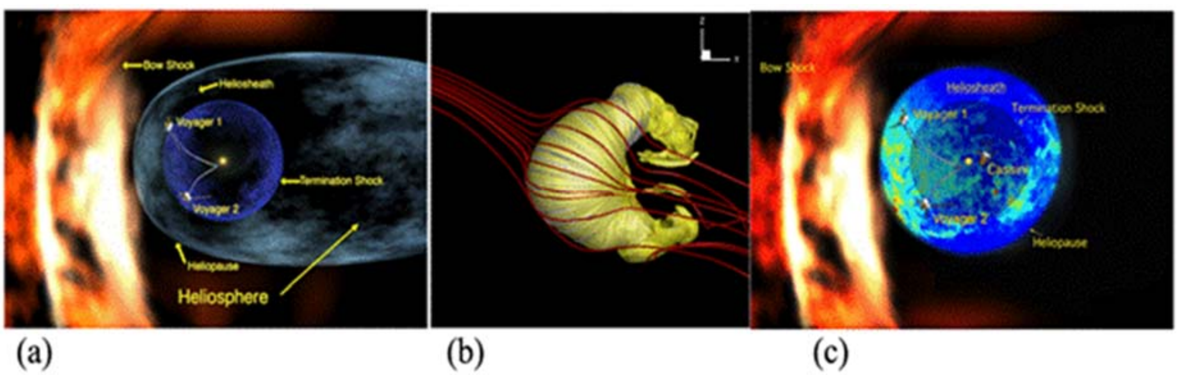

FIGURE E.3 The heliosphere shape remains a mystery. There are currently three competing shapes for the heliosphere: (a) comet-like shape, (b) croissant-like and c) spherical. SOURCE: (a) NASA/Goddard/Walt Feimer. (b) M. Opher, J.F. Drake, B. Zieger, and T.I. Gombosi, Magnetized jets driven by the Sun: The structure of the heliosphere revisited, *Astrophysical Journal Letters* 800(2):L28, 2015, https://doi.org/10.1088/2041-8205/800/2/L28, © American Astronomical Society, reproduced with permission. (c) NASA/JPL/JHU APL.

Voyagers 1 and 2 are currently exploring the local interstellar medium (LISM) outside the heliosphere, from its particle makeup to its turbulence (Burlaga et al., 2015). It turns out that the LISM is far from quiet and pristine (Gurnett et al., 2015) and is strongly influenced by the heliosphere. The galactic cosmic rays there are not isotropic which might be due to the draped interstellar magnetic field (Rankin et al., 2019). Shocks measured in the LISM have different properties than those in the outer heliosphere indicating that the interactions of charged and neutral particles are important. Voyager measurements have for the first time revealed how effectively the heliosphere shields us from galactic cosmic rays—for example, 75 percent in the Voyager 1 direction (Cummings et al., 2016) (See Figure E.4).

Voyager 1 observations indicate that the heliopause (the surface between the solar wind on the inside and the interstellar gas on the outside), is not a perfect boundary (Parker, 1961), but is instead porous, possibly the result of reconnection, in which turbulence may be important (Swisdak et al., 2013 Grygorczuk et al., 2014 Florinski, 2015 Schwadron & McComas, 2013). Comparison of data from the two Voyagers indicates that the conditions at the heliosphere's flanks are substantially different, which is now being further investigated with models.

Anomalous cosmic rays (ACRs) are particles accelerated somewhere inside the boundary of the heliosphere. Until the Voyager observations, they were thought to be accelerated where the solar wind goes through a slow-down shock well ahead of the heliopause, but new data suggest that this acceleration may occur much closer to that interface.

The very shape of the heliosphere remains a mystery (Figure E.3). Older work by Baranov and Malama (1993) suggested a comet-like shape. More recent computer models that include magnetic fields (Opher et al., 2015; Drake et al., 2015) suggest, in contrast, that the tension force of the field could help shape the solar wind between the termination shock and heliopause into two jet-like structures. However, particle measurements with the Cassini spacecraft have led others to argue that the heliosphere is, instead, tailless (Dialynas et al., 2017).

Scientists also advanced their understanding of how the solar magnetic field affects the innermost heliosphere by using observational data from NASA's IRIS and SDO to drive advanced models (Mikic et al., 2018; Yeates et al., 2018; Jin et al., 2017; Jin et al., 2018). These new models were validated by comparing their results to observations of a Sun-grazing comet deep within the solar corona (Downs et al., 2013), by Parker Solar Probe observations of the innermost heliosphere, and by space weather conditions near Earth.

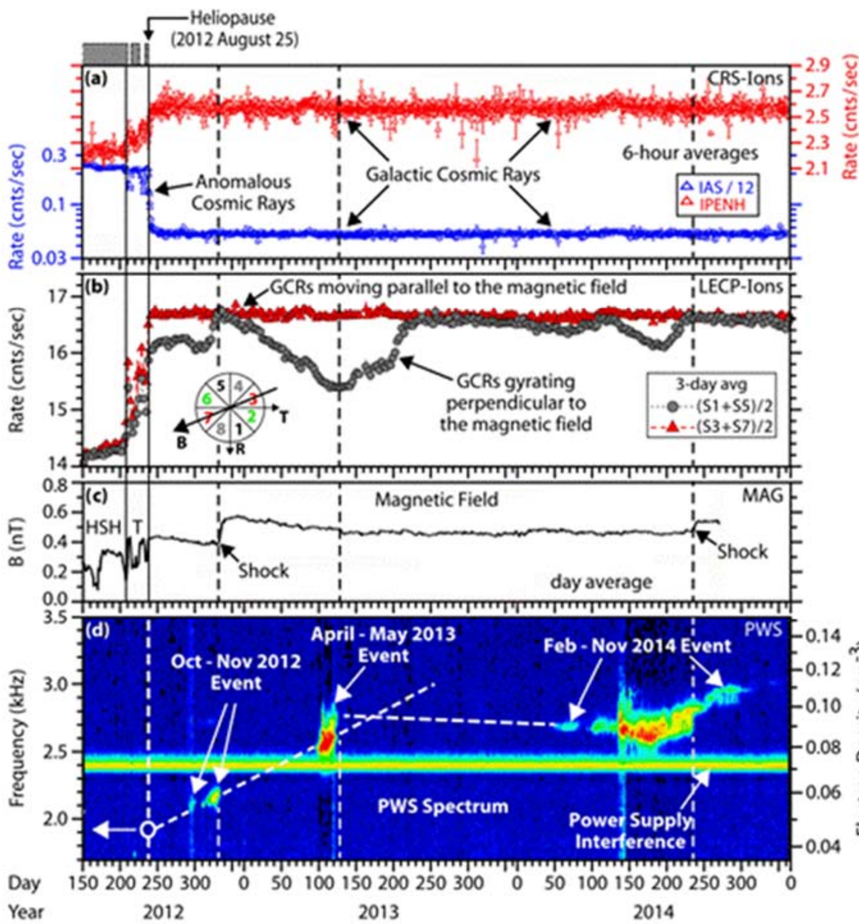

FIGURE E.4 Voyager 1 measurements near and beyond the heliopause. (a) The counting rate from the cosmic ray; (b) The counting rate for GCRs, with energies >211 MeV propagating parallel (red) and perpendicular (gray) to the magnetic field. (c) The magnetic field strength; (d) A spectrogram of the wide B and electric field spectral densities. The frequency is on the left, and the corresponding electron density is on the right. SOURCE: D.A. Gurnett, W.S. Kurth, E.C. Stone, A.C. Cummings, S.M. Krimigis, R.B. Decker, N.F. Ness, and L.F. Burlaga, Precursors to interstellar shocks of solar origin, *The Astrophysical Journal* 809(2):121, 2015, https://doi.org/10.1088/0004-637X/809/2/121. © American Astronomical Society. Reproduced with permission.

Our knowledge of how a rocky planet like Earth responds to the magnetized solar wind provides a laboratory to study conditions at other planets, and even at exoplanets. For example, the in-situ study of the solar wind at Mars by the Mars Atmosphere and Volatile Evolution (MAVEN) mission provides insights into these processes that extend beyond the parameter range seen at Earth: present-day Mars has no active dynamo, so Mars' atmosphere is more directly exposed to the solar wind. Mars-orbiting observatories and Sun and solar-wind observing spacecraft together reveal Mars' atmospheric loss processes and their dependence on the solar extreme ultraviolet (EUV) irradiance (Dong et al., 2017). Measuring, modeling, and understanding these processes at Mars, Earth, and Venus help us understand how atmospheres would have responded billions of years ago, when EUV irradiance and CME activity would have been much stronger, at a phase during which Mars appears to have lost much of its atmosphere and oceans, and when life emerged on Earth.

Finally, in the last 6 years, data and models from solar and space physics helped characterize the space-weather environment of exoplanets around other, relatively Sun-like (G, K, and M-type) stars. Models show how planets in extrasolar systems can experience extreme stellar wind regimes compared to those at present-day Earth (e.g., Garraffo et al., 2017). It is unclear whether some such planets can even retain their atmospheres—especially because their magnetospheres can change rapidly in structure (e.g., Cohen et al., 2014; Cohen et al., 2015; Airapetian et al., 2017; Dong et al., 2017; Wood, 2018). In addition, Sun-like stars can release CMEs with a range of velocities and masses different from the present-day Sun (e.g.,Aarnio et al., 2012; Kay et al., 2016; Moschou et al., 2017; Alvarado-Gómez et al., 2018).

E .2 SOLAR WIND-MAGNETOSPHERE INTERACTIONS

The combination of solar XUV radiation and solar wind conditions, including transients related to stream structure and CMEs, produce a variety of conditions in Earth's space environment. Since the publication of the decadal survey, significant progress has been made in understanding how these conditions come about, involving both the externally-driven and the internally-shaped processes by which the solar radiation and solar wind couple to a planetary magnetosphere, and how these processes transport mass and energy into and within the magnetosphere. Selected discoveries in the SWMI Challenges are discussed in some detail here. The SWMI highlights mentioned in Chapter 2 are the following:

- MMS has observed how electrons are accelerated and heated even as they slip across the magnetic field in the process of magnetic reconnection.
- Waves excited by the solar wind flowing along Earth's magnetosphere in the interface layer called the magnetopause have been discovered to play a substantive role in controlling how efficiently the magnetic fields in the solar wind and of the Earth reconnect. Where such waves are strongest depend both on the solar wind conditions and plasma and field conditions close to the magnetopause.
- The Van Allen Probes mission has changed our understanding of the structure of Earth's Van Allen belts and how processes in these environments, including plasma waves, accelerate charged particles to ultra-high speeds. At times we observe three or more radiation belts. The inner edge of the outer belt for ultra-high energy electrons is unexpectedly sharp, and the inner belt is nearly void of high energy electrons most of the time.
- The unusually weak recent solar cycle is providing important insights into how the inner-heliospheric conditions affect the propagation of coronal mass ejections, thereby changing the magnetic field and the dynamic pressure of heliospheric storm fronts as they reach Earth. The weak cycle has also given new insights into how the ionosphere responds to levels of lower-energy ionizing radiation.

- With spacecraft near Mercury, Venus, and Earth, Jupiter, and Saturn, the evolution of solar eruptions traveling through the heliosphere could be observed and compared with simulation results. The analysis of many tails of comets over their observable trajectories is helping us understand solar-wind variability, specifically its turbulence, and how that evolves from near the Sun outward.
- Space-weather conditions at Mars were studied with particular emphasis on the solar wind coupled to that planet's atmosphere with its weak, local magnetism.

Decadal Survey Challenge SWMI-1: Establish How Magnetic Reconnection Is Triggered and How It Evolves to Drive Mass, Momentum, and Energy Transport

Key Science Goal #2 of the decadal survey is to determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs. Magnetic reconnection plays an important if not dominant role in that coupling. At its basic level, magnetic reconnection converts magnetic energy into particle motion. It is responsible for the transport of plasma and mechanical energy over magnetic boundaries, thus a detailed understanding of this process is crucial for understanding how the solar wind interacts with our magnetosphere during different interplanetary magnetic field (IMF) orientations and solar-wind (and resulting magnetosheath) conditions. The presence of current sheets leads to magnetic reconnection in many heliophysical settings.

A revolution in the understanding of magnetic reconnection came about through the recent Magnetospheric Multiscale mission (MMS). MMS uses the near-Earth environment as a laboratory to study the microphysics of magnetic reconnection using in situ measurements. The near-Earth environment is the only practical place in the solar system where we can study the microphysics of this universal process that occurs throughout the domains of heliophysics. MMS uses four identically instrumented spacecraft, flying in the tightest ever pyramid formation for a satellite constellation, to measure the electromagnetic field with unprecedented accuracy, sampling 100 times faster than previous missions.

MMS provided important new measurements on where and how electrons contribute to reconnection. For example, at the magnetopause, the boundary between the solar wind and Earth's magnetosphere, MMS observed that the reconnection process is highly localized, and can strongly energize electrons (Figure E.5). Reconnection briefly decouples electrons from the magnetic field and then accelerates them in the electric field aligned with the magnetic field as a consequence of the strong gradients in the reconfiguring field, while often also heating the electrons in that process (Burch et al., 2016; Burch and Phan, 2017; Chen et al., 2016; Graham et al., 2016, 2017; Torbert et al., 2018).

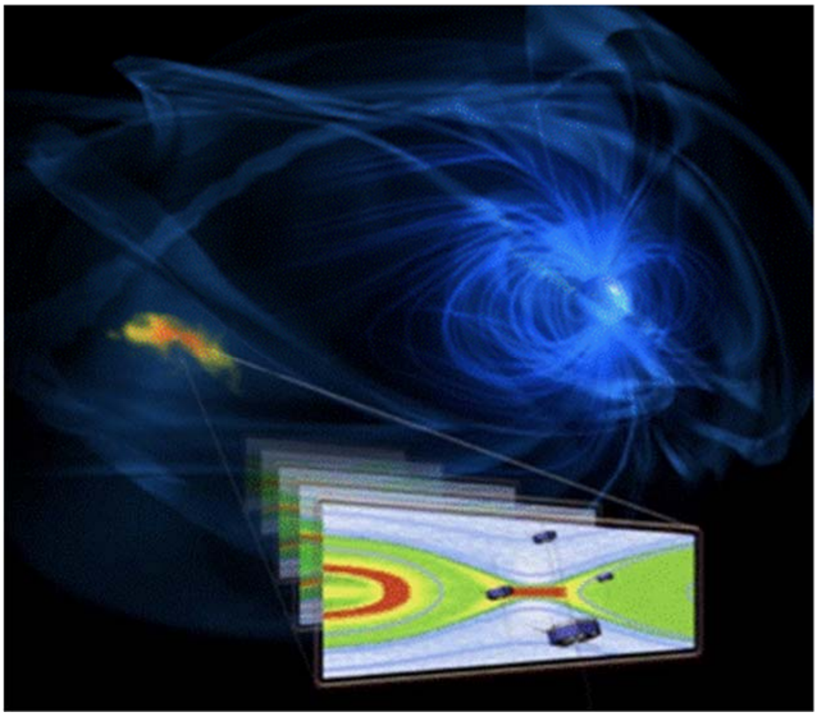

FIGURE E.5 The MMS mission unlocked the secrets of magnetic reconnection by making unprecedented measurements inside the tiny electron diffusion region where magnetic energy is converted to particle energy. SOURCE: Courtesy of Southwest Research Institute.

However, because the electron diffusion regions cover only a small volume, they are insufficient to explain the overall observed energization. The details of the cross-scale coupling facilitated by reconnection remains a challenge. Computer simulations have shown that, for strong non-adiabatic heating to occur in association with shock waves in the outflow of the reconnecting field, the energy in the field must far exceed the energy in the particles, which is unlikely in the magnetosheath (Ma and Otto, 2014). Such conditions can more readily occur in, for example, the magnetosheath transition layer to the magnetopause (known as the plasma depletion layer), or near the magnetopause in waves that are excited by the solar-wind flowing by Earth's magnetic field, just as ocean waves are excited by strong atmospheric winds (via Kelvin-Helmholtz instability, or KHI).

In recent years, advanced computer simulations have clarified better how reconnection is strongly driven at the subsolar magnetopause under southward IMF and also how the reconnection rate on the flanks may be significantly modified in the presence of large-scale nonlinear Kelvin-Helmholtz waves running along the magnetopause (Ma et al., 2014; 2017). NASA's Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission has shown that such waves are very frequent there, in fact for most IMF orientations (Kavosi and Raeder, 2015), although where their occurrence peaks around the magnetopause depends on the magnetic field in the solar wind (Henry et al., 2017). These KH waves appear not only able to facilitate reconnection (Eriksson et al., 2016) and energize electrons, but they also heat the ions (Moore et al., 2016; 2017).

The processes taking place within Earth's bow shock and magnetosheath also affect the process of reconnection near the magnetopause. Recently, the THEMIS spacecraft detected that high speed jets in the solar wind compressed the originally thick magnetopause current-sheet until it was thin enough for reconnection to efficiently occur (Hietala et al., 2018). The effect on reconnection is transient and high speed jets are relatively rare (Plaschke et al., 2018).

Another MMS discovery is that low-latitude reconnection can lead to formation of higher-latitude magnetic bottle structures that contain significant populations of energetic electrons and ions, as well as oxygen ions of ionospheric origin (Nykyri et al., 2019), although the exact energetic particle sources and energization mechanisms need more study. Another surprise was that the MMS spacecraft encountered "electron-only" magnetic reconnection without ion coupling in Earth's turbulent magnetosheath (Phan et al., 2018). MMS observations also revealed how a hot flow anomaly at the bow shock accelerates solar-wind ions to almost 1 MeV (Turner et al., 2018). This provides new insight into how foreshock transients may be important in the generation of cosmic rays at astrophysical shocks throughout the universe.

The ensemble of compact and evolving regions of magnetic reconnection regulates much of the transfer of energy and momentum from the solar wind to the geospace system as a whole. This results in feedback to the reconnection region, altering the conditions of the reconnection itself, although the details of that back-reaction remain under study (Borovsky and Birn, 2014; Lopez, 2016; Zhang et al., 2016).

Decadal Survey Challenge SWMI-2 Identify the Mechanisms that Control the Production, Loss, and Energization of Energetic Particles in the Magnetosphere

In Earth's inner magnetosphere, charged particles are accelerated to speeds approaching the speed of light, forming the highly dynamic region known as the Van Allen radiation belts. The variability of the radiation belts has been a long-standing mystery, and this region is important both as a laboratory for studying particle acceleration and due to its space weather impacts on the nation's space assets.

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FIGURE E.6 (Left) Measurement of inner belt electrons showing "zebra stripes." (Right) Model of quasi-resonant interactions between drifting electrons and Earth's rotational electric field SOURCE: Ukhorskiy et al., *Nature,* 2014.

NASA's twin Van Allen Probes, launched in 2012, have changed our understanding of the very structure of the radiation belts, with their high-resolution instruments and the use of a pair of probes that enables us to tell apart structures in space from evolution in time. Not only did the probes discover a third radiation belt, likely a remnant of a prior geomagnetic storm (Baker, et al., 2013), they also found so-called "Zebra stripes" in the inner electron belt (explained as a consequence of a resonance with Earth's rotation; Ukhorskiy et al., 2014, see Figure E.6). The inner boundary for ultra-relativistic electrons at about 2.8 Earth radii was found to be unexpectedly sharp (Baker et al., 2014), and, contrary to previous belief, there are typically no high energy electrons in the inner radiation belt (e.g., Fennell et al., 2015; Claudepierre, et al., 2019).

Understanding particle acceleration is a key objective of the Van Allen Probes. The mission answered the long standing question of whether local acceleration by high-frequency plasma waves could cause observed rapid enhancements of high energy electrons (Reeves et al., 2013). Acceleration caused by non-linear wave-particle interactions has also been observed for the first time (e.g., Foster et al., 2017).

New processes important for the creation of Earth's radiation belts have also been uncovered, including rapid spikes in the electric field that could be caused by highly nonlinear evolution of strong whistler mode waves. Such structures accelerate very low energy particles up to the keV energy range, thus creating the seed population from which very high energy electrons are created (Mozer et al., 2013; Mozer et al., 2014). This and many other discoveries from the Van Allen Probes has led to next-generation radiation belt models (e.g., Sorathia et al., 2018) and improvements to space weather models (e.g., Yu et al., 2019).

The mission also revealed new insight into production and propagation of plasma waves (e.g., Li et al., 2016b; Agapitov et al., 2016; Malaspina et al., 2017), particle injections (e.g., Turner et al., 2015; Mitchell, et al., 2018), and the plasma populations that coexist with the radiation belts in the inner magnetosphere (e.g., Gkioulidou et al., 2014). The importance of plasmaspheric drainage plumes on ULF waves (e.g., Degeling et al., 2018) and on particle loss to the atmosphere (e.g., Li et al., 2019) has also been explored. Finally, significant progress has been made on understanding radiation belt particle loss using coincident measurements between Van Allen Probes and balloons (e.g., Blum et al., 2015; Li et al., 2014) and CubeSats (e.g, Blake and O'Brien, 2016; Breneman et al., 2017).

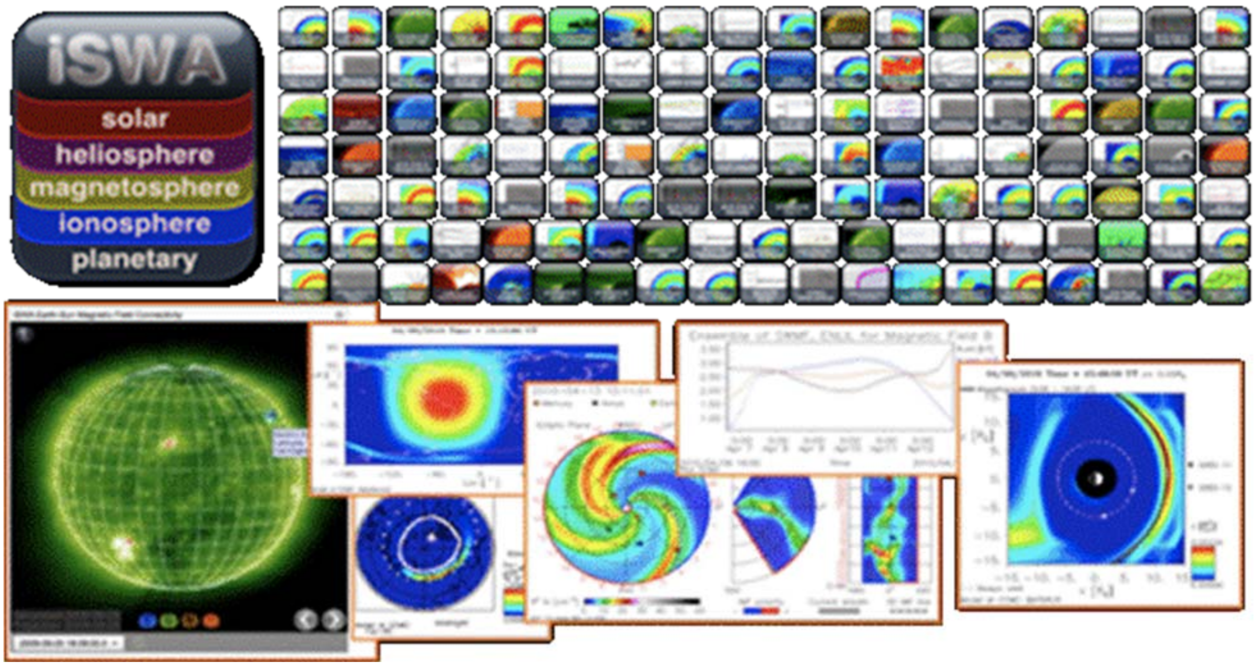

FIGURE E.7 Illustration showing the broad selection of modeling tools and results available through the CCMC and space weather research center at GSFC (see https://ccmc.gsfc.nasa.gov/iswa/). Each tile represents a link to results routinely run numerical and empirical 'community' accessible models made available by developers supported by NASA's Heliophysics and NSF's Space Weather programs. SOURCE: NASA/Goddard/iSWA.

Decadal Survey Challenge SWMI-3: Determine How Coupling and Feedback Between the Magnetosphere, Ionosphere, and Thermosphere Govern the Dynamics of the Coupled System in Its Response to the Variable Solar Wind

The progress on coupled community-accessible computer models has made them sufficiently realistic to be driven by, and in some cases to reproduce, observations (Figure E.7). For example, solar magnetograms are the basis for describing coronal and solar wind properties and activity. Additionally, solar ionizing emissions and solar wind time series determine simulated magnetosphere and ionosphere states, including ground induced currents (GICs) and total electron content (TEC) (e.g., Boteler and Pirjola, 2017).

Of especially broad interest are the extreme ranges of space weather conditions and their consequences for the space environment of Earth in particular, although the results are also relevant for planetary science and astrophysics. While extremes are often thought of as high intensity episodes, the last few solar cycles (23 and 24) have produced historically weak solar outputs and activity compared to earlier cycles of the space age. Conditions normally associated with both solar maximum—such as flares, coronal mass ejections, solar energetic particle events, and geomagnetic storms—and with solar minimum—such as enhanced galactic cosmic ray fluxes—have been modified in response to various combinations of the diminished solar XUV and solar wind fluxes and a weakened solar magnetic field. For example, McComas et al. (2013) describe observations of solar wind mass fluxes and interplanetary field diminished by approximately 30 percent during the cycle 23 maximum, with solar wind dynamic pressures reaching some of the lowest levels in the space age. Other studies of the solar wind properties (e.g., Kilpua et al., 2016; Tindale and Chapman, 2017) examined changes to the inferred sources of the slow solar wind at Earth orbit and the increased ease with which Galactic Cosmic Rays (GCR) reach the inner heliosphere (e.g., Leske et al., 2013). The weak solar cycle also saw less impact from solar eruptions, possibly because CMEs could more readily expand near the Sun, lowering their impact at Earth (Gopalswamy et al., 2014), in part by weakening the magnetic field and in part by lowering the dynamic pressure of the events (Kilpua et al., 2014; Jian et al., 2018). At Earth, Solomon et al. (2013, 2018) found approximately 30 percent reductions in thermospheric density during solar minimum and approximately 15 percent reductions in global mean ionospheric electron content related primarily to the reduced solar EUV fluxes.

Decadal Survey Challenge SWMI-4: Critically Advance the Physical Understanding of Magnetospheres and Their Coupling to Ionospheres and Thermospheres by Comparing Models Against Observations from Different Magnetospheric Systems

Space weather is usually associated with Earth's space environment, but it is in its broader definition solar system-wide (Figure E.8). Solar activity affects each planet and solar system body in ways determined by the properties of that body (including its orbital distance from the Sun). Many investigations of the environments of other solar system bodies rely on information obtained by the Heliophysics System Observatory (HSO), including the Advanced Composition Explorer (ACE), Solar and Heliophysics Observatory (SOHO), SDO, and STEREO, for example, to interpret space weather conditions at Mercury, Venus, and Mars, while at the same time these studies provide information about the radial evolution of events as they propagate through the heliosphere and into the interstellar medium. For example, Winslow et al. (2015) combined near-Earth observations with Mercury MESSENGER observations to establish a clear overall weakening of most leading shocks en route to Earth, consistent with an average deceleration of the ejecta drivers in that heliocentric distance range. Good and Forsyth (2016) combined data over a time span of 7 years from Mercury MESSENGER, Venus Express, STEREO, and ACE when in alignment along the path of solar eruptions to analyze both the differences in space weather at the innermost three terrestrial planets and the heliospheric distributions of events.

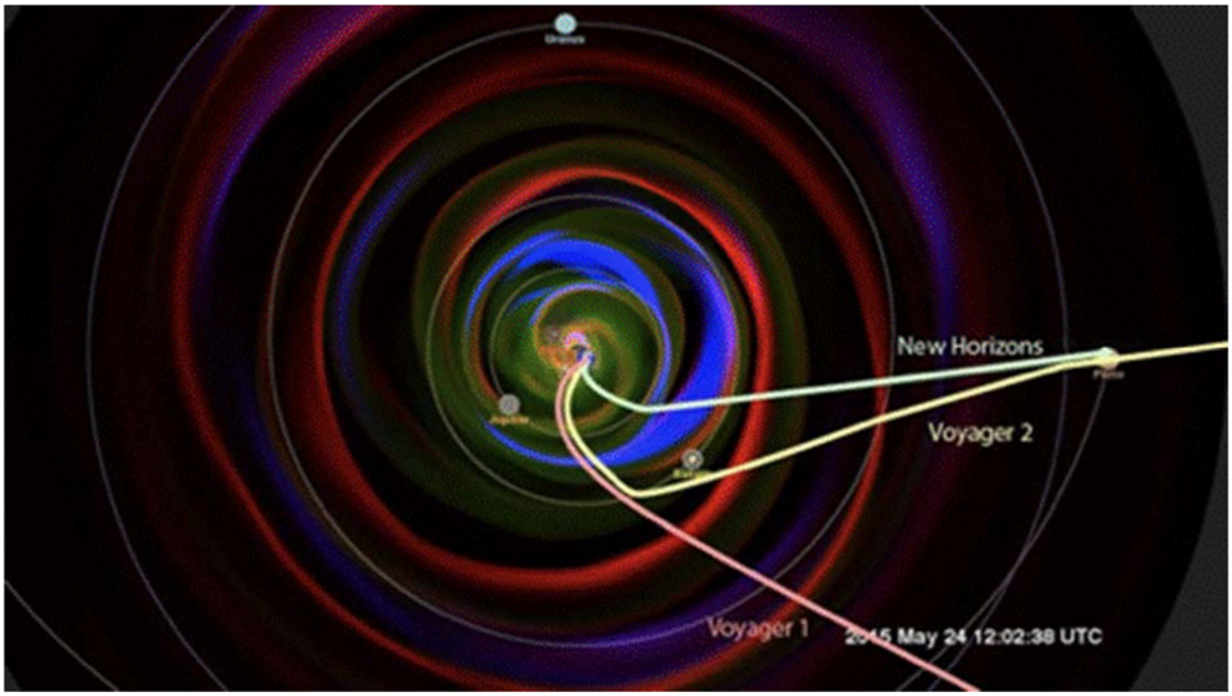

FIGURE E.8 NASA illustration of a customized run of the ENLIL heliospheric simulation by the CCMC and space weather research center at GSFC in support of the New Horizons mission Pluto flyby. This run was used to forecast conditions at Pluto's approximately 30 AU distance, and to illustrate the heliophysics goal of providing heliosphere-wide descriptions of space weather. SOURCE: NASA's Goddard Space Flight Center Scientific Visualization Studio, the Space Weather Research Center (SWRC) and the Community-Coordinated Modeling Center (CCMC), Enlil and Dusan Odstrcil (GMU)

Heliophysics resources have also supported investigations of space weather conditions at Mars, which concern how the solar wind interacts with its atmosphere and have significance for ongoing planning for human missions. The MAVEN mission, which arrived in late 2014, is specifically instrumented to measure the local space environment conditions and their consequences, while the Mars Science Laboratory (MSL) Curiosity rover has carried the Radiation Assessment Detector (RAD) around the surface since its landing in late 2012. RAD observes the Martian equivalent of ground level enhancement (GLE) events and Forbush decreases. Several significant flare and CME-related events, including widespread solar energetic particle stimulated Martian auroras, were interpreted with the aid of the HSO observations (Hassler et al., 2014; Lee et al., 2018). These observations lend themselves to developing and testing models that can be used in forecasting space environment conditions at Mars and indeed throughout the inner heliosphere. In another study involving the observation of an interplanetary coronal mass ejection (ICME) at Mars, Möstl et al. (2015) use STEREO observations to model the direction and expansion of the initial coronal event, concluding its non-radial propagation was significant.

Heliophysics imaging capabilities are also being exploited by cometary observers for both characterizing comets and cometary orbits (Ye et al., 2014) and for studying the phenomenology and nature of observed comet coma structure (Raouafi et al., 2015). The STEREO images are especially well-suited for determining the properties of near-Sun and Sun-impacting comets (Ye et al., 2014) and for relating structural features such as 'high velocity evanescent clumps' to surrounding structure in the solar wind. Also harkening back to the original concept of comets as wind socks in the solar wind, deForest et al. (2015) tracked over 200 tail features in Comet Enke's tail to explore turbulent motions in the solar wind.

This progress requires integrating observations and interpretations of everything from solar activity to atmospheric responses. Moreover, it requires the multipoint, multiperspective information available from the HSO to assemble the 3D picture of the external conditions affecting different planetary locations. In short, it exercises all our scientific options in order to understand occurrences at a remote location due to the local space weather there. The work in this area also requires us to interpret the responses observed at the various Solar system planets in terms of what we know in much more detail from our Earth experiences. Furthermore, this type of research in many ways provides the 'ground-truth' for applications of our understanding to exoplanet-stellar wind interaction studies.

E.3 ATMOSPHERE-IONOSPHERE-MAGNETOSPHERE INTERACTIONS

The AIMI region starts roughly just above Earth's stratosphere (50 km) and extends up to several thousand kilometers above ground. The AIMI region is impacted by the Sun, interactions with the magnetosphere, and also by processes occurring in the atmosphere below. Discovering the processes that govern the conditions at this interface between Earth and space is fundamental to understanding planetary atmospheres and exospheres, as well as for operational needs including the protection of astronauts and spacecraft, of humans on the ground, and for radio and navigation signal situational awareness. Distributed observational capabilities increasingly enforce the realization that the geospace system, from below the ionosphere to the outer reaches of the magnetosphere, is a single connected system. Selected discoveries in the AIMI Challenges are discussed in some detail here, and as mentioned in Chapter 2, some of the many advances in understanding the AIMI are the following highlights:

- The weak recent solar cycle simplified the separation of solar influences from effects from the lower atmosphere, enabling improved understanding of the coupling processes between the AIMI region and the atmosphere below. Models are bridging the knowledge gap on the coupling between larger-scale instabilities and smaller-scale turbulence that is important in regulating the dynamics of geospace.
- The energy of precipitating particles and heat from solar radiation enhance the concentration of NO in the thermosphere, which in turn has brighter IR emissions to cool the thermosphere back down efficiently.
- Joint analyses and comparisons of plasma-neutral interactions in the solar chromosphere and in the terrestrial ionosphere stimulated by the NASA/LWS R&A program has provided deeper insights into the similarities and differences between these environments, and is leading to sharing of insights between two communities previously working largely in isolation.
- Atmospheric waves generated by tides, terrain, and atmospheric instabilities have been observed and modeled as they travel upward, strengthening in the process. Waves are also generated in the dynamics of the polar vortex at stratospheric altitudes. All these wave phenomena can modify high-atmospheric properties, including ionospheric properties, far from the latitudes where they originally formed, which, in turn, couple to space weather phenomena further out.
- Drivers of long-term trends in upper atmospheric properties are better clarified using ever more sophisticated global circulation models (GCMs) to reveal the dynamics effects from solar variability, the cooling influence of anthropogenic methane and carbon dioxide, and even the top-down coupling of atmospheric changes resulting from the long-term change of the terrestrial magnetic field, of which the shift of the magnetic poles is one consequence.

Decadal Survey Challenge AIMI-1: Understand How the Ionosphere-Thermosphere System Responds to, and Regulates, Magnetospheric Forcing over Global, Regional, and Local Scales

The combination of electromagnetic fields, impact ionization (auroras), and heating leads to complex three-dimensional flows within the ionosphere-magnetospheric system. New distributed observations and computer modeling of plasma transport have called into question the traditional paradigm of treating the ionosphere and magnetosphere as distinct regions. Instead, this new work suggests that the entire geospace system should be treated as an extension of Earth's atmosphere to understand how the atmosphere-magnetosphere system regulates the entry, storage, and dissipation of solar wind power.

Recent research has revealed an important manifestation of this paradigm shift: observations (Varney et al., 2016a) and models (Lund et al., 2018) have suggested that outflow of ionospheric ions along magnetic field lines affect a particular pathway of energy release in the magnetosphere. So called "sawtooth oscillations" are quasi-periodic injections of energetic particles observed near geosynchronous orbit, similar to periodic substorms but more global in nature. The outflow of heavy ions is thought to regulate the rate of reconnection, thereby producing the sawtooth-shaped events (Varney et al. 2016b).

Electromagnetic fields, plasma gradients, and rapid plasma flow arise ubiquitously in the geospace system through instabilities, and in turn produce small-scale turbulent local conditions. But how the larger-scale instabilities and the small-scale turbulence affect one another in detail represents a critical gap in our understanding. The technical advances of tools to quantitatively couple these processes has led to a new understanding of how the formation of turbulent cells in the lower ionosphere affects electric currents that couple the outer atmosphere to the magnetosphere (Dimant and Oppenheim, 2011; Liu, 2016a).

The electromagnetic power generated by a geomagnetic storm is dissipated as heat in Earth's outer atmosphere, in much the same way a battery heats a resistor. This heating causes the atmosphere to expand, which has deleterious effects on satellite orbits through increased satellite drag and increased outgassing (Wiltberger, 2015). However, there is a stabilizing backreaction: researchers have found that in addition to heat, intense storms also increase the amount of nitric oxide (NO), which acts as an efficient cooling agent (Weimer et al., 2015) The larger the geomagnetic storm, the greater the NO cooling (Knipp et al., 2017). In fact, the cooling may win out under extreme conditions, producing the counterintuitive effect of atmospheric contraction. This result has substantial implications on our understanding of how geomagnetic storms affect the tenuous atmosphere within which satellites orbit.

Bright visible auroras are produced by energetic particles flowing along magnetic field lines into the upper atmosphere. Auroras have long been exploited as diagnostic of less accessible magnetospheric processes, but there are still surprises. Recently a new, very different, auroral phenomenon has been discovered—by a large ad hoc network of citizen auroral watchers. This faint feature, known as STEVE (for 'Strong Thermal Emission Velocity Enhancement') and shown in Figure E.9, appears to be caused by a high speed plasma jet flowing perpendicular to Earth's magnetic field, exciting optical emissions through pathways not yet identified. The discovery of STEVE (MacDonald et al., 2018; Gallardo-Lacourt et al., 2018) highlights the discovery potential of geospace facilities that may be realized in creative and cost-effective ways.

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FIGURE E.9 Example of STEVE (Strong Thermal Emission Velocity Enhancement), a newly discovered optical phenomenon, overlooked by the auroral research community. Its discovery by amateur photographers highlights the potential of citizen scientists to contribute to heliophysics research. SOURCE: Robert Downie Photography, "Steve over Ness Lake," https://www.robertdowniephotography.com/Astrophotography/i-hWf5WQ4/A.

Decadal Survey Challenge AIMI-2: Understand the Plasma-Neutral Coupling Processes that Give Rise to Local, Regional, and Global-Scale Structures and Dynamics in the AIM System

Ground-based NSF incoherent scatter radar observations have shown dramatic enhancements of the E-region electron temperature in the subauroral and auroral electrojet regions during geomagnetic storms. These temperature enhancements are associated with electrojet turbulence introduced by instabilities from large velocity differences between the electrons following the magnetic field and the ions scattered off the field by collisions. Although long considered a local phenomenon, the extent of enhanced electric fields across the high latitudes during geomagnetic storms suggests that this phenomenon can influence the large-scale, high-latitude ionospheric current system. This is supported by modeling efforts. NCAR-TIEGCM simulations revealed that the phenomenon led to increased electron heating, reduced electron losses, and more than 30 percent enhanced conductivity (Liu et al., 2016). LFM-RCM global simulations show a lowering of the cross-polar-cap potential, improvements in current descriptions in the auroral electrojet, and increased peak pressure in the inner magnetosphere (Wiltberger et al., 2017). These advanced studies reveal how local and detailed small-scale processes can have global consequences.

A NASA LWS focused science team effort in plasma-neutral interactions brought together solar chromospheric and terrestrial ionospheric researchers. The effort culminated in an extensive paper (Leake et al., 2014) describing the similarities and differences in coupling processes of ionized plasma to neutral gas in the weakly ionized, stratified, electromagnetically-permeated regions of the Sun's chromosphere and Earth's ionosphere/thermosphere. Related phenomena in the two environments were compared and described in a unified way, significantly improving on previously used contrasting paradigms. This study typifies the collaborative and elucidating approach to understanding our heliophysics system.

A discovery using ground-based resonance lidars of metallic neutral layers in the thermosphere reaching altitudes of 200 km has changed the view of how minor species transport and plasma-neutral chemistry interact in the thermosphere (Figure E.10). Theory suggests that thermospheric neutral-iron layers are formed through direct recombination of iron ions with electrons during the dark polar night at thermospheric altitudes above 120 km, and furthermore, that geomagnetic activity may play a role. However, it is known that there is no permanent stationary presence of iron ions at such high altitudes because meteor ablation and sputtering are insufficient sources to counter gravitational sedimentation of these heavy ions. Instead, Chu and Yu (2017) conceived the dynamic lifecycle of meteoric metals via deposition, transport, chemistry, and wave dynamics for thermospheric iron layers with gravity waves.

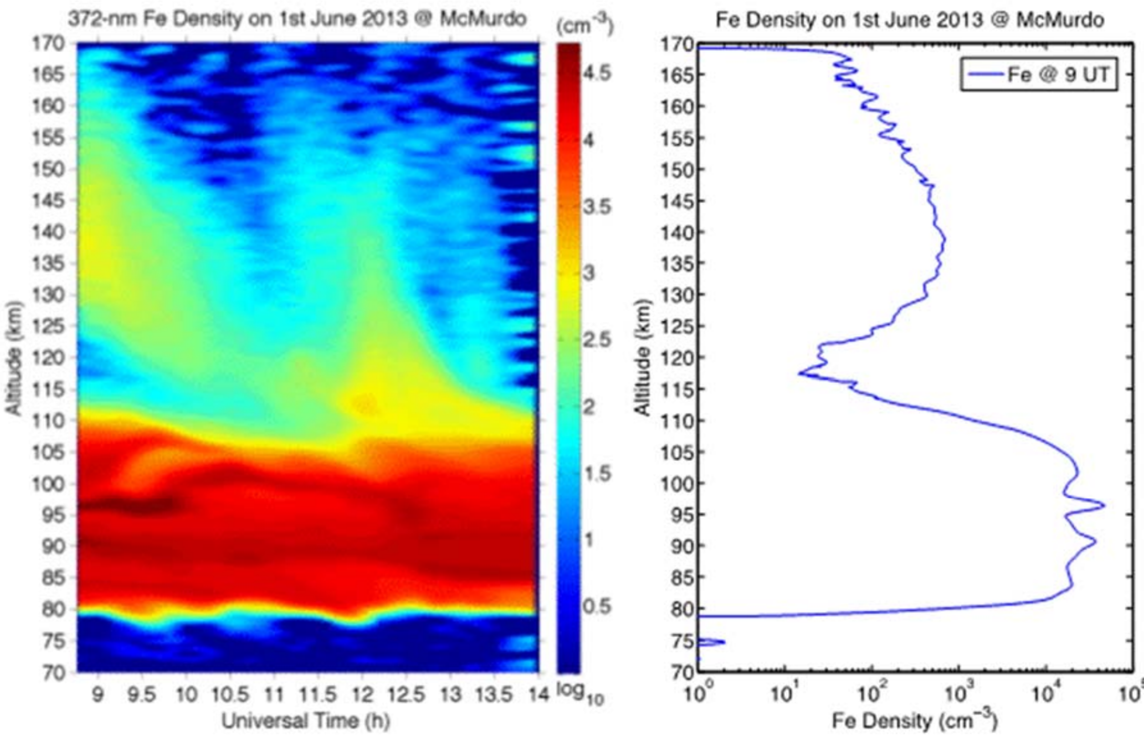

FIGURE E.10 Tenuous layers of Fe, Na and K atoms exist well into the thermosphere. They can be probed with resonance fluorescence lidars to determine the temperature and wind velocity of the neutral atmosphere. Shown here are observations made with a modest lidar at McMurdo, Antarctica, showing neutral Fe layers reaching as high as 170 km. SOURCE: X. Chu, Z. Yu, W. Fong, C. Chen, J. Zhao, I.F. Barry, J.A. Smith, X. Lu, W. Huang, and C.S. Gardner, From Antarctica lidar discoveries to oasis exploration, *EDP Web of Conferences* 119: 12001, 2016.

Decadal Survey Challenge AIMI-3: Understand How Forcing from the Lower Atmosphere via Tidal, Planetary, and Gravity Waves Influences the Ionosphere and Thermosphere

The vertical transport of energy and momentum by atmospheric waves is a fundamental process in planetary atmospheres and—on Earth—links tropospheric weather with the space weather of the ionosphere and thermosphere. The modulation of input of energy into the troposphere and stratosphere due to Earth's rotation excites a range of planetary-scale thermal tides, while surface topography, unstable flows, and cloud dynamics excite waves all the way down to scales of only a few km, introducing a range of periods from several weeks to a few minutes. The vertically propagating waves grow exponentially with height into the more rarefied atmosphere where they change neutral density, temperature and winds. These wave-induced wind variations then collisionally couple into the ionosphere, involving instabilities and seeding of plasma bubbles. Over the past 5 years, understanding vertical wave coupling has advanced significantly, capitalizing on advances in numerical modeling and multi-instrument observations in a systems approach. Many of these observations have come from NASA's Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED), Aeronomy of Ice in the Mesosphere (AIM) and Communication/Navigation Outage Forecast System-Coupled Ion Neutral Dynamic Investigation (C/NOFS-CINDI) missions. This has yielded numerous exciting scientific discoveries, four of which are highlighted here:

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FIGURE E.11 Observations of concentric-ring patterns produced as atmospheric waves radiate away from a storm over Texas, tracked from the stratosphere near 30 km altitude up to the ionosphere, around 300 km altitude. Left: stratospheric observation from the Atmospheric Infrared Sounder on NASA's Aqua satellite. Right: the impact on the ionosphere, identified using a distributed network of ground-based GPS receivers. SOURCE: Adapted from Azeem et al., *Geophysical Research Letters,* 2015.

Small-scale gravity waves have been tracked all the way from their thunderstorm sources to the F-region of the ionosphere at 100-300 km altitude (Figure E.11), exhibiting effects even above that, through a combination of ground- and space-based assets, e.g., from Aqua, AIM, Visible Infrared Imaging Radiometer Suite (VIIRS), Global Navigation Satellite Systems (GNSS), and Arecibo (Yue et al., 2014; Azeem et al., 2015; Hysell et al., 2018). Computer simulations, meanwhile, elucidated how these waves perturb winds, temperatures and ion densities (Vadas et al., 2014; 2018). It has now been realized that gravity waves generated by tropical monsoons can propagate to the polar regions and affect the frequency of polar mesospheric clouds, an important indicator of climate change in the upper atmosphere (Thurairajah et al., 2017). On larger scales, combined TIMED, satellite drag, and numerical model studies have unequivocally revealed that the ionosphere/thermosphere responds strongly to the global El Niño weather phenomenon and to the stratospheric quasi-biennial oscillation (Liu, 2016b; Li et al., 2016a; Warner and Oberheide, 2014).

Polar vortex dynamics in the stratosphere cause massive holes in the ionosphere over North America lasting 2 to 4 weeks (Frissell et al., 2016), most likely through a coupling by waves that have been tracked through the mesosphere (Harvey et al., 2018). Dramatic stratospheric warmings—a break-up of the polar vortex in the stratosphere—carved a hole in the nighttime ionosphere over North America (Goncharenko et al., 2018), and are linked to changes throughout the entire atmosphere (Pedatella et al., 2018). The formation of the massive hole is more consistent with winds near 300 km altitude, instead of near 100 km as suggested by previous studies, which provides new insights how the polar vortex can impact space weather.

Thermosphere-ionosphere general circulation modeling driven by NASA TIMED and Modern-Era Retrospective analysis for Research and Applications (MERRA)-2 data at its lower boundary predict that the tidal spectrum modulated by planetary waves causes the thermosphere at orbital altitudes to oscillate by tens of meters per second with planetary wave periods from 2 to 16 days. These oscillations subsequently modify F-region electron densities by 50 percent, with significant implications for satellite drag and radio propagation (Forbes et al., 2018; Gan et al., 2017). First estimates of the tidal weather in the E region based on NASA TIMED data (Oberheide et al., 2015; Dhadly et al., 2018) revealed that the day-to-day variability is larger than previously thought and can approach 100 percent of the monthly average values.

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FIGURE E.12 Comparison of short-term tidal variability due to tropospheric convection at 100 km for TIMED/SABER (black) and WACCM+DART data assimilation (red). The thin light red lines are the individual WACCM+DART ensemble members. The green line is the wave imprint in the thermospheric density observed by the GRACE-A satellite and the blue line is the ionospheric response in the equatorial ionization anomaly diagnosed from COSMIC satellite constellation observations. SOURCE: Pedatella et al., JGR Space Physics, 2016.

Significant progress in multi-platform data assimilation for the mesosphere and lower thermosphere has been made (Pedatella et al., 2014, 2016a; Siskind et al., 2015). Coupled with ionospheric models (McDonald et al., 2018), the new models perform much better in nowcasting the state of the neutral and ionized atmosphere, an important milestone towards space weather predictability. Using the new data assimilation research testbed (DART), measurements from ground level up to 110 km have been used in the Whole Atmosphere Community Climate Model (WACCM) (Pedatella et al., 2014; 2016a), and new versions of this model including the ionosphere (WACCM-X, v2; Liu et al., 2018) capture the near-space imprint of multi-scale wave dynamics from the lower atmosphere from first-principles—a major milestone (Figure E.12).

Decadal Survey Challenge AIMI-4: Determine and Identify Causes for Long-Term (Multi-Decadal) Changes in the AIMI System

The decadal survey recognized the continued long-term cooling of the thermosphere as *"a remarkable planetary change attributable, at least in part, to human society's modification of the atmosphere."* The decadal survey identified the increasing lifetime of orbital debris caused by a less dense atmosphere as an important practical consequence. It recommended to protect long-term observations and to conduct research on understanding how the long-term changes are embodied in or transmitted through the AIMI system.

Solar Cycle 24 had an extremely low level of solar activity compared to the three preceding ones, which resulted in uncommon impacts on conditions of the upper atmosphere and altered atmospheric coupling from above (magnetosphere-ionosphere coupling, e.g., (Xu et al., 2015; Liu et al., 2015) and below (troposphere/stratosphere coupling into the mesosphere and above). Interestingly, the reduced solar activity has simplified identifying signatures of couplings from below, advancing our understanding of them (Jones et al., 2014; Goncharenko et al., 2018; Pedatella et al., 2018) and providing a major push for further modeling development (Liu et al., 2016; Pedatella et al., 2016a).

In contrast, studies of effects on the AIMI region by CME-induced geomagnetic storms declined because of the low frequency and relative weakness of the driving events. This led to an increased interest in, and thereby understanding of, the effects of high speed solar-wind streams. These streams push into the slower solar wind ahead creating fronts that, while less intense than CME fronts, can deposit more energy into Earth's magnetosphere because the streams are sustained longer.

Based on Sounding of the Atmosphere using Broadband Emission Radiometry (SABER)/TIMED observations of infrared emissions from carbon dioxide and nitric oxide, Mlynczak et al. (2015, 2016) developed a thermosphere climate index to represent properties of the thermosphere. This index also represents the global infrared power radiated from Earth's thermosphere since 1947, which proved surprisingly constant over the past 70 years. From that, it is inferred that the geoeffective energy input from the Sun in the form of ultraviolet photons and particle precipitation is also relatively constant over a solar cycle.

The capabilities of numerical models for simulating thermospheric density variations on timescales from decades to days have much improved over the past 5 years (Bruinsma et al., 2018), which is important, for example, for characterizing the lifetime of orbital debris. The new generation of whole atmosphere models shows an anthropogenic thermospheric cooling of 2.8 Kelvin per decade and a 3.9 percent per decade decrease in mass density for solar minimum conditions (Solomon et al., 2018). Exospheric hydrogen densities are important for assessing atmospheric evolution through planetary escape and ring current decay during geomagnetic storms. Nossal et al. (2016) found that the hydrogen response to methane is relatively independent of solar activity but that the impact of carbon dioxide is highly dependent on it. Greenhouse gas emissions will thus not only lead to a long-term trend in the exospheric hydrogen but also to an increased solar cycle variability of this important species.

Using WACCM-X simulations, Cnossen et al. (2016) predicted that long-term changes in Earth's magnetic field directly impact the ionosphere and thermosphere via changes in ion-neutral interactions and also the atmosphere below through a top-down coupling, with polar surface temperature changes of up to about 1.3 Kelvin between 1900 and 2000. Because Earth's magnetic field has been changing rapidly since 2000 (Chulliat et al., 2015), this finding is important for global climate modeling.

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Acronyms

AAS	American Astronomical Society
ACE	Advanced Composition Explorer
ACRs	Anomalous cosmic rays
ADVANCE	Organizational Change for Gender Equity in STEM Academic Professions
AER	Aeronomy (NSF program)
AETHER	Aeronomy at Earth: Tools for Heliophysics Exploration and Research
AFWA	Air Force Weather Agency
AG	Analysis/Assessment Group
AGEP	Alliances for Graduate Education and the Professoriate
AGS	Atmospheric and Geospace Sciences Division (NSF)
AIA	Atmospheric Imaging Assembly
AIM	Aeronomy of Ice in the Mesosphere
AIM	Atmosphere-ionosphere-magnetosphere
AIMI	Atmosphere-Ionosphere-Magnetosphere Interactions
AIP	American Institute of Physics
ALMA	Atacama Large Millimeter/submillimeter Array
AMISR	Advanced Modular Incoherent Scatter Radar
AMPERE	Active Magnetosphere and Planetary Electrodynamics Response Experiment
AO	announcement of opportunity
APD	Astrophysics Division (NASA)
AST	Division of Astronomical Sciences (NSF)
ATST	Advanced Technology Solar Telescope
AWE	Atmospheric Waves Experiment
BARREL	Balloon Array for Radiation-belt Relativistic Electron Losses
BATS-R-US	Block-adaptive-tree-solarwind-Roe-Upwind Scheme
CCMC	Community Coordinated Modeling Center
CCOR	Compact Coronagraph
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
CeREs	Compact Radiation Belt Explorer
CINDI	Coupled Ion-Neutral Dynamics Investigations
CISE	Computer and Information Science & Engineering Directorate (NSF)
CISM	Center for Integrated Space Weather Modeling
CME	Coronal mass ejection
CNS	Division of Computer and Network Systems (NSF)
CO-I	Co-Investigator
CONUS	continental United States
COSMO	COronal Solar Magnetism Observatory
COSPAR	Committee on Space Research
CSSP	Committee on Solar and Space Physics
CU	University of Colorado

DKIST	Daniel K. Inouye Solar Telescope
DMSP	Defense Meteorological Satellite Platform
DOD	Department of Defense
DOE	Department of Energy
DRIVE	Diversify, Realize, Integrate, Venture, Educate
DSCOVR	Deep Space Climate Observatory
DSFP	Data Science Fellowship Program
DYNAMIC	Dynamical Neutral Atmosphere-Ionosphere Coupling (mission)
ECCS	Division of Electrical, Communications, and Cyber Systems (NSF)
ECIP	Early Career Investigator Program
EEC	Division of Engineering Education and Centers (NSF)
EELV	Evolved Expendable Launch Vehicles
ELFIN	Electron Losses and Fields Investigation (mission)
ENG	Directorate for Engineering (NSF)
EOT-PACI	Education, Outreach and Training Partnerships for Advanced Computational Infrastructure
EOVSA	Expanded Owens Valley Solar Array
EPD	Energetic Particle Detector
ESA	European Space Agency
ESPA	EELV Secondary Payload Adaptor
EUV	Extreme ultraviolet
EUVST	Extreme Ultraviolet High-Throughput Spectroscopic Telescope
EZIE	Electrojet Zeeman Imaging Explorer
FACA	Federal Advisory Committee Act
FASR	Frequency Agile Solar Radiotelescope
FAST	Fast Auroral Snapshot Explorer
FDSS	Faculty Development in Space Science
FINESST	Future Investigators in NASA Earth and Space Science and Technology
FY	fiscal year
GCM	general circulation model
GCR	Galactic cosmic ray
GDC	Geospace Dynamics Constellation
GEM	Geospace Environment Modeling (workshop)
GEO	Directorate for Geosciences (NSF)
GEO	Geostationary Earth orbit
GFY	Government fiscal year
GICs	ground induced currents
GI	Guest investigator
GITM	Global Ionosphere Thermosphere Model
GLE	Ground level event
GLIDE	Global Lyman-alpha Imagers of the Dynamic Exosphere
GNSS	Global Navigation Satellite Systems
GOES	Geostationary Operational Environmental Satellite
GOLD	Global Observations of the Limb and Disk
GONG	Global Oscillation Network Group
GPS	Global positioning system
GSFC	Goddard Space Flight Center

GS	Geospace Section (NSF)
GSRP	Graduate Student Researchers Program
HabEX	Habitable Exoplanet Observatory
HAO	High Altitude Observatory
HDEE	Heliophysics Data Environment Enhancements
HEOMD	Human Exploration and Operations Mission Directorate (NASA)
HF	high frequency
H-FORT	Heliophysics Flight Opportunities for Research and Technology
HGI	Heliophysics Guest Investigator
Hi-C	High Resolution Coronal Imager
HIS	Heavy Ion Sensor
HMI	Helioseismic and Magnetic Imager
HPAC	Heliophysics Advisory Committee
HPD	Heliophysics Division (NASA)
HP	Heliophysics
HSC	Heliophysics Science Centers
HSO	Heliophysics System Observatory
HSR	Heliophysics Supporting Research
H-TIDeS	Heliophysics Technology and Instrument Development for Science
IBEX	Interstellar Boundary Explorer
ICME	interplanetary coronal mass ejection
ICON	Ionospheric Connection Explorer
IDS	Interdisciplinary Scientists
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMAP	Interstellar Mapping and Acceleration Probe
IMF	interplanetary magnetic field
INCLUDES	Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science
IRIS	Interface Region Imaging Spectrograph
ISS	International Space Station
ITD	Instrument and Technology Development
IT	ionosphere-thermosphere
ITM	Ionosphere-Thermosphere-Mesosphere
JAXA	Japan Aerospace Exploration Agency
JHU APL	Johns Hopkins University Applied Physics Laboratory
JPL	Jet Propulsion Laboratory
JVLA	Jansky Very Large Array
JWST	James Webb Space Telescope
LASCO	Large Angle and Spectrometric Coronagraph
LCAS	Low Cost Access to Space
LEO	Low Earth orbit
LFM	Lyon-Fedder-Mobarry
Lidar	light detection and ranging
LISM	local interstellar medium
LISN	Low-latitude Ionospheric Sensor Network
LMSAL	Lockheed Martin Solar and Astrophysics Laboratory
LNAPP	Laboratory Nuclear, Atomic, and Plasma Physics

LSAMP	Louis Stokes Alliances for Minority Participation Program
LST	local standard time
LUVOIR	Large Ultraviolet/Optical/Infrared Surveyor
LWS	Living With a Star
MAG	Magnetospheric Physics (NSF program)
MAS/CORHEL	Magnetohydrodynamic Algorithm outside a Sphere/Corona-Heliosphere
MAVEN	Mars Atmosphere and Volatile Evolution (mission)
MEDICI	Magnetosphere Energetics, Dynamics and Ionospheric Coupling Investigation
MERRA	Modern-Era Retrospective analysis for Research and Applications
METIS	Multi Element Telescope for Imaging and Spectroscopy
MHD	Magnetohydrodynamics
MIDEX	Medium-Class Explorer
MinXSS	Miniature X-Ray Solar Spectrometer
MLSO	Mauna Loa Solar Observatory
MMS	Magnetospheric Multiscale Mission
MO&DA	Management, Operations, & Data Analysis
MOA	Memorandum of Agreement
MoO	Mission of Opportunity
MOU	Memorandum of Understanding
MPS	Directorate for Mathematical and Physical Sciences (NSF)
MREFC	Major Research Equipment and Facilities Construction
MRO	Mars Reconnaissance Orbiter (mission)
MSFC	Marshall Space Flight Center
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Science, Engineering, and Medicine
NCAR	National Center for Atmospheric Research
NESDiS	National Environmental Satellite, Data, and Information Service
NESSF	NASA Earth and Space Science Fellowship
NExSS	Nexus for Exoplanet System Science
NOAA	National Oceanic and Atmospheric Administration
NO	nitric oxide
NRC	National Research Council
NRL	Naval Research Laboratory
NSB	National Science Board
NSF	National Science Foundation
NSO	National Solar Observatory
NSWAP	National Space Weather Action Plan
NSWP	National Space Weather Program
NWSW	National Space Weather Strategic Plan
O2R	Operations-to-Research
OIG	Office of the Inspector General
OMB	Office of Management and Budget
OpenGGCM	Open Geospace General Circulation Model
OSS	Open Source Software
OST	Origins Space Telescope
PHI	Polarimetric and Helioseismic Imager

PIC	Particle-in-cell
PI	Principal Investigator
POES	Polar-orbiting Operational Environmental Satellite
PSD	Planetary Science Division (NASA)
PS	Participating Scientist
PSP	Parker Solar Probe
PUNCH	Polarimeter to Unify the Corona and Heliosphere
R&A	Research and Analysis
R2O	Research-to-Operations
RAD	Radiation Assessment Detector
RCM	Rice Convection Model
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
RINEX	Receiver independent exchange
RI	Research Infrastructure
ROSES	Research Opportunities in Space and Earth Science
SALMON	Stand Alone Missions of Opportunities Notice
SAMPEX	Solar, Anomalous, and Magnetospheric Particle Explorer
SDO	Solar Dynamics Observatory
SDT	Science Definition Team
SEM	Space Environment Monitor
SEP	Solar Energetic Particles
SETH	Science-Enabling Technologies for Heliophysics
SET	Space Environment Testbeds
SFG	Sum Frequency Generation Spectrometer
SHINE	Solar, Heliosphere, and Interplanetary Environment
SHP	Solar and heliospheric physics
SHSW	Solar, Heliospheric, and Space Weather
SIHLA	Spatial/Spectral Imaging of Heliospheric Lyman Alpha
SKG	Strategic Knowledge Gap
SMD	Science Mission Directorate (NASA)
SMEX	Small Explorer
SNOE	Student Nitric Oxide Explorer
SOC	Solar Orbiter Collaboration
SOHO	Solar and Heliophysics Observatory
SoloHI	Solar Orbiter Heliospheric Imager
SO	Solar Orbiter
SOT	Solar Optical Telescope
SPD	Solar Physics Division
SPICE	Spectral Imaging of the Coronal Environment
SPP	Solar Probe Plus
SR&T	supporting research and technology
SRO	SmallSats and Rideshare Opportunities
SSB	Space Studies Board
ST5	Space Technology 5 (mission)
STDT	Science and Technology Definition Team
STEREO	Solar Terrestrial Relations Observatory
STEVE	Strong Thermal Emission Velocity Enhancement
STP	Solar-Terrestrial Probes (NASA program)
STR	Solar-Terrestrial Research (NSF program)

SunRISE	Sun Radio Interferometer Space Experiment
SWARM-EX	Space Weather Atmospheric Reconfigurable Multiscale Experiment
SWFO	Space Weather Follow-On
SWMI	solar wind-magnetosphere interactions
SWO2R	Space Weather Operations-to-Research
SWORM	Space Weather Operations, Research, and Mitigation
SWPA	Solar Wind Plasma Analyzer
SWPC	Space Weather Prediction Center
SwRI	Southwest Research Institute
SWSS	Space Weather Summer School
SWxSA	Space Weather Science and Application
SWx	Space Weather
TBEX	Tandem Beacon Experiment
TEC	total electron content
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIE-GCM	Thermosphere-Ionosphere-Electrodynamics General Circulation Model
TIMED	Thermosphere Ionosphere Mesosphere Energetics and Dynamics
TLS	Terahertz Limb Sounder
TMC	Technical, management, cost
TRACERS	Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites
TRACE	Transition Region and Coronal Explorer
TRL	technology readiness level
TWINS	Two Wide-Angle Imaging Neutral-Atom Spectrometers
UCAR	University Corporation for Atmospheric Research
ULF	ultra low frequency
USAF	United States Air Force
VAP	Van Allen Probes
VIIRS	Visible Infrared Imaging Radiometer Suite
VISORS	VIrtual Super-resolution Optics with Reconfigurable Swarms
WACCM(-x)	Whole Atmosphere Community Climate Model
WISPR	Wide-Field Imager for Solar Probe
WSA-ENLIL	Wang-Sheeley-Arge-Enlil