NATIONAL ACADEMIES *Sciences Engineering Medicine*

The Next Decade of Discovery in Solar and Space Physics

Exploring and Safeguarding Humanity's Home in Space

Robyn Millan and Stephen Fuselier
Co-Chairs: Steering Committee

Art Charo and Abigail Sheffer
Study Directors

Download the report and report resources:
nationalacademies.org/ssp-decadal

The heliosphere, home to our star and planet, remains the only known habitable system in the universe.

The Next Decade

Exploring and Safeguarding our Home in Space

- **A two-part vision and mission**
  - Discovery science in the pursuit of knowledge
  - Space weather advancement for a rapidly-evolving technological society
- **A balanced research strategy**
  - Organizes science goals organized around common themes
  - Leverages previous investments and adds targeted new investments to fill critical gaps
  - Enables a healthy community and its evolving workforce
- **Coordination and Cooperation**
  - Cross-disciplinary, -divisional, -directorate, -agency
  - Integrating multipoint, heterogenous data sets, including space, ground, and simulation, to unravel the complex physics of heliosystems
  - International collaboration

Study Scope

A broader Statement of Task than previous decadal surveys

- Provide an overview of the current state of solar and space physics science and applications, including
  - Topics historically part of solar and space physics
  - New and emerging frontiers
  - The space weather pipeline
- Describe the highest priority science goals to be addressed in the period of the survey
- Develop a comprehensive ranked research strategy that provides an ambitious, but realistic, approach to address these science goals
- Assess the state of the profession

Additional guidance and agency requests were also provided.

Steering Committee

Stephen A. Fuselier SwRI Co-Chair	**Robyn M. Millan** Dartmouth Co-Chair	**Fran Bagenal** Univ. of Colorado, Boulder	**Timothy S. Bastian** NRAO
Sarbani Basu Yale University	**Richard Doe** Cornell Technical Services	**Eileen Dukes** Interplanetary Horizons	**Scott L. England** Virginia Tech
Allison N. Jaynes University of Iowa	**Dana W. Longcope** Montana State Univ.	**Viacheslav G. Merkin** Johns Hopkins APL	**Daniel Müller** European Space Agency
Terrance G. Onsager NOAA/Retired	**Tai D. Phan** Univ. of California, Berkeley	**Tuija Pulkkinen** Univ. of Michigan	**Liying Qin** NCAR
Marilia Samara NASA GSFC	**Joshua Semeter** Boston University	**Endawoke Yizengaw** Aerospace Corp.	**Gary Zank** Univ. of Alabama, Huntsville

Note: Tomoko Matsuo through June 2023; Scott England joined the committee in August 2023.

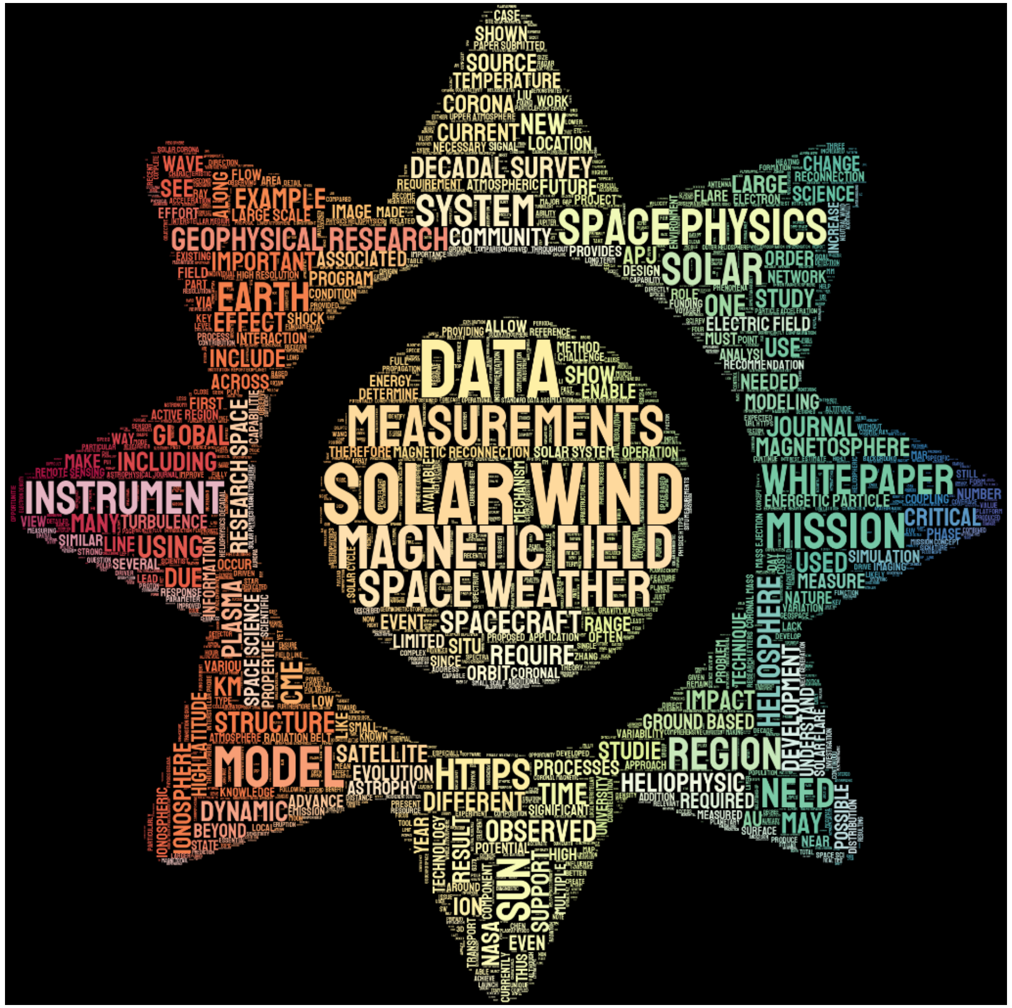
Discipline Panels and Cross-cutting Working Groups

Study Panels				
Panel on the Physics of the Sun and Heliosphere (SHP)	Panel on the Physics of Magnetospheres (MAG)	Panel on the Physics of Ionospheres, Thermospheres, and Mesospheres (ITM)	Panel on Space Weather Science and Applications (SWSA)	Panel on the State of the Profession (SoP)

Working Groups

- Integrating Ground and Space Observatories
- Theory and Modeling
- Data Exploitation
- Access to Space
- Communications Infrastructure and Innovations

Built on Community Input



Source: James Mason, JHU/APL

- 450 community input papers
- 80 community members on steering committee, panels and working groups
- Community-initiated mission concept studies, papers, and presentations
- Agency-supported workshops (e.g., Helio 2050)
- Town halls at conferences and workshops
- Working group panel discussions with community members, government and industry

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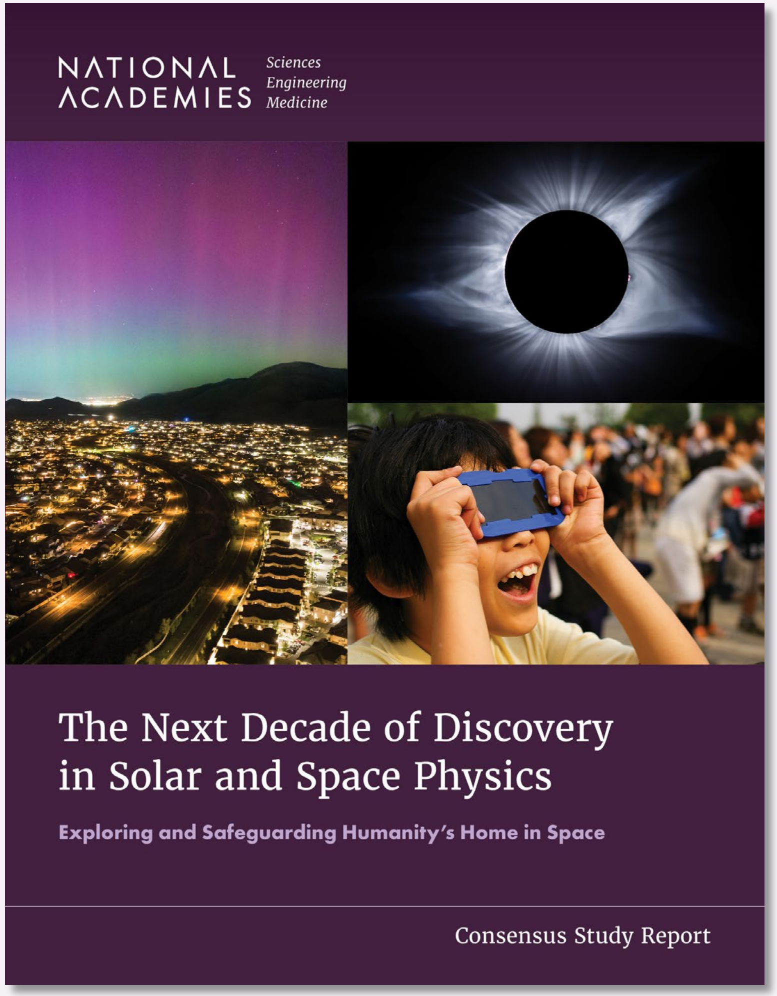
We thank the Space Studies Board, staff, members of the steering committee and study panels, Agency liaisons, and community members who submitted input papers.

Report Snapshot



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Summary

Ch. 1. Solar and Space Physics

Ch. 2. New and Emerging Frontiers in Science

Ch. 3. Solar and Space Physics in the Service of Humanity

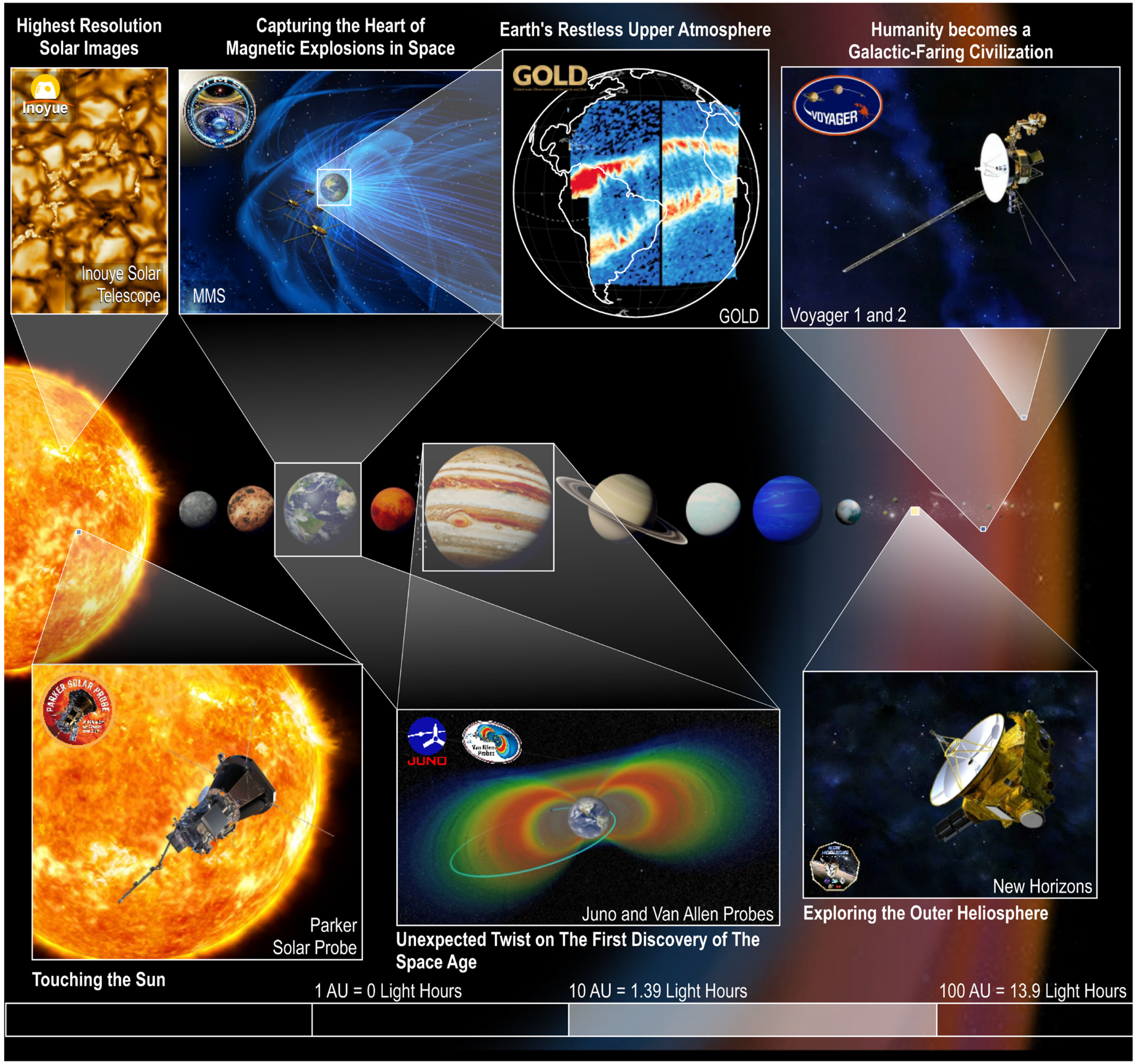
Ch. 4. Towards a Thriving Solar and Space Physics Community

Ch. 5. Comprehensive Research Strategy

Ch. 6. Summary of Research Strategy and Budget Implications

Appendices

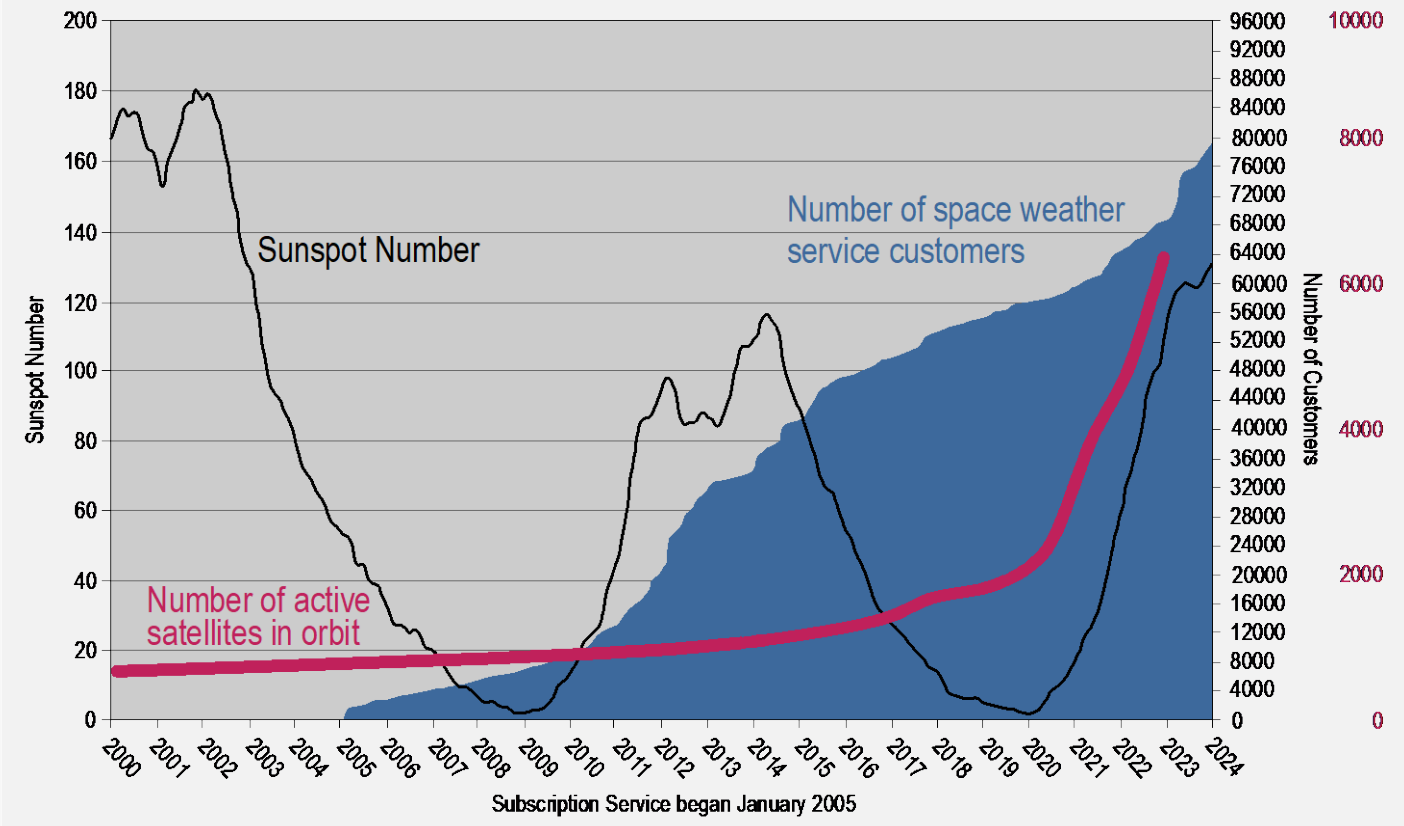
- Statement of Task
- Panel Reports
- Technical, Risk, and Cost Evaluation



Building on a Decade of Achievements

- Past decade firsts: from the Sun to the outer fringes of the solar system.
  - Touching the Sun
  - Magnetic explosions in space
  - Earth's restless upper atmosphere
  - Planetary radiation belts
  - Exiting our heliosphere
- Past decade developments
  - A fleet of small to medium-sized Heliophysics missions ready to launch
  - Recent commissioning of the world's largest solar telescope
  - Small satellite technologies, access to space, computational power and AI

Space Weather Comes of Age



- PROSWIFT act codifies the importance of space weather
  - A framework for the modern era
  - Assigns specific roles to the agencies
  - Links science, national policy, and responsible parties
- Modeling encompasses the entire near-Earth space system
  - Major steps forward for research to operations
- Growing Customer Base
  - “Whether they know it or not, all companies will be space companies”

Vision and Mission
Science Themes

Capturing the Dual Nature of the Field

Vision To discover the secrets of the local cosmos.

To expand and safeguard humanity's home in space.

Mission

Explore our habitable cosmos to discover

We explore the space around us to gain a view of the only known habitable system in the universe.

We develop models and theories that explain the physics and interconnections of the heliosphere and to understand conditions for life elsewhere in the universe.

and to serve humanity

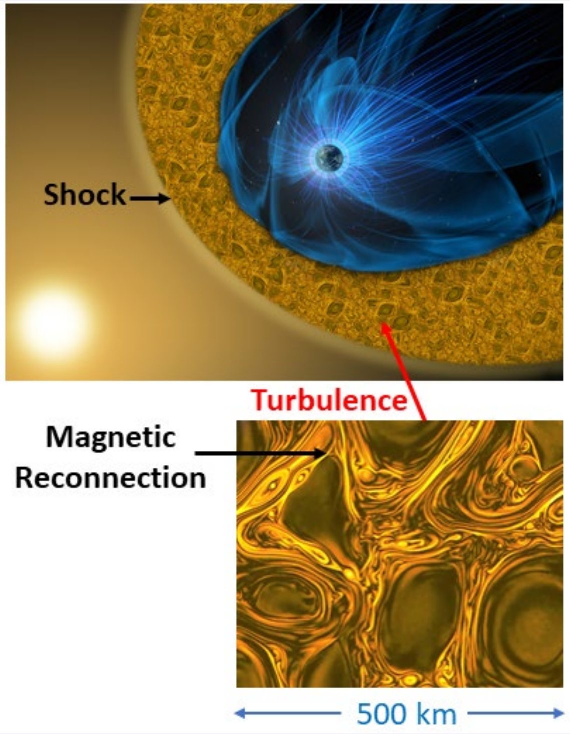
We analyze the space environment to project its future changes.

We develop tools and products to issue space weather warnings and forecasts and to safeguard activities at and beyond Earth.

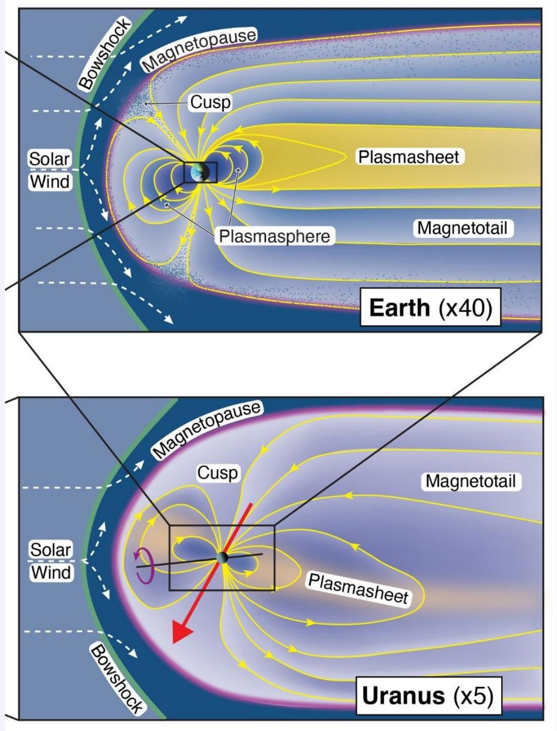
Science Themes *to discover*

Sun-Earth-Space:
Our Interconnected Home

A Laboratory in Space:
Building Blocks of Understanding



New Environments:
Exploring our Cosmic Neighborhood and Beyond



GUIDING Q'S

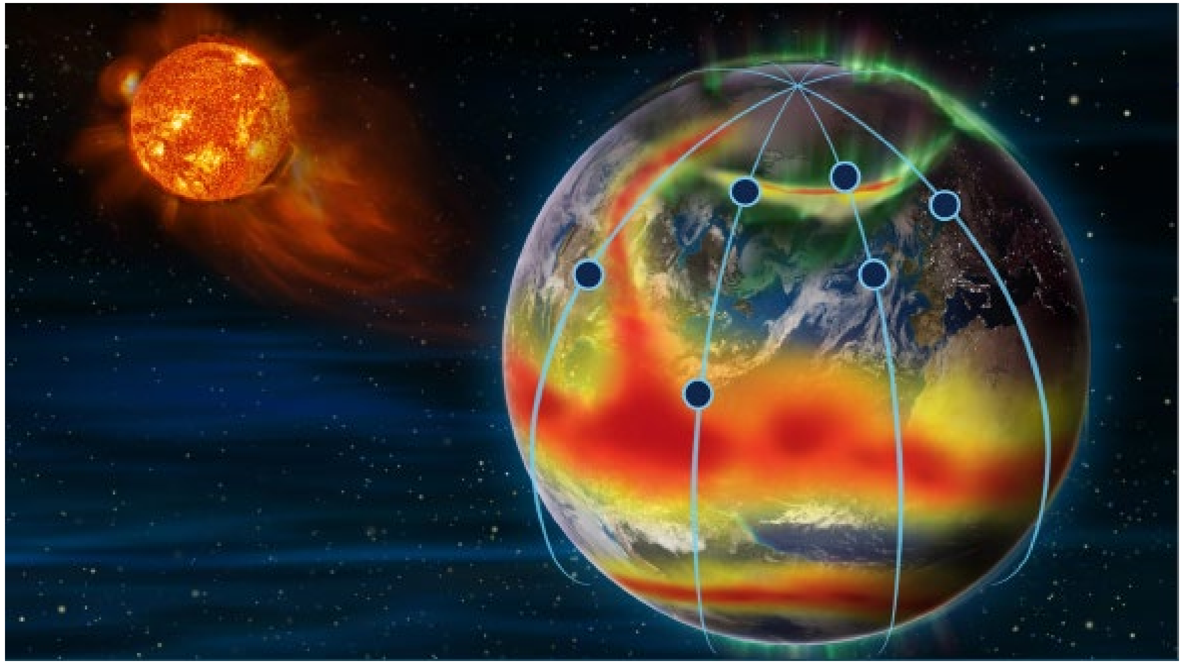
How does our Heliosphere function as a nested system?

RESEARCH FOCUS AREAS

- Energy and momentum flow across and within the Heliosystem parts
- Dominant physical processes within system interactions
- Interactions across large-scale regions and long time scales

Theme: Sun-Earth-Space

Example Focus Area: Energy and Momentum Flow

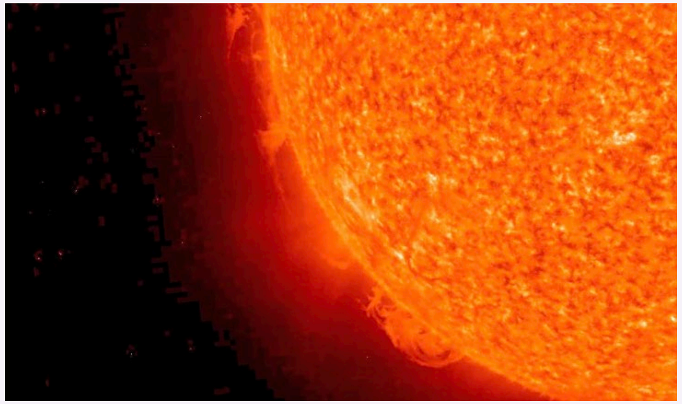


- The upper atmospheric system is driven from above by solar radiation and strongly influenced from below.
- Observations that follow the global dynamics in detail are needed to understand how these drivers and their relative roles change in time.

Space Weather
Science-Space Weather Linkage

Space Weather Themes *to serve humanity*

System of Systems:
Drivers of Space Weather

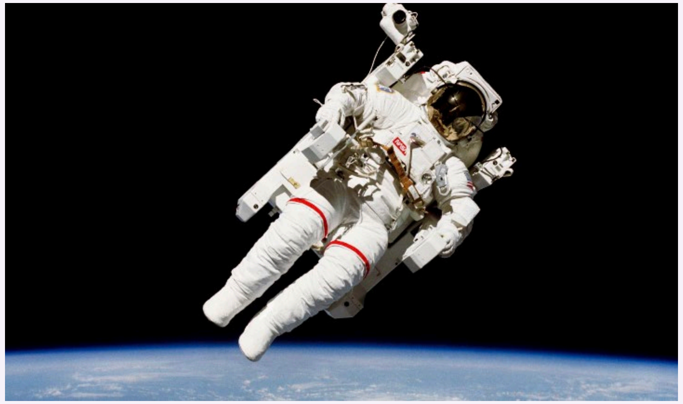


- Solar Eruptions
- Atmospheric Driving

Space Weather Responses
of the Physical System

- Low Earth Orbit (LEO) Neutral Density
- Ionospheric State
- Magnetospheric State

Space Weather Impacts
On Infrastructure
and Human Health



- Radiation Environments
- Spacecraft Effects
- HF Signal Propagation
- LEO Trajectories
- Geoelectric Field

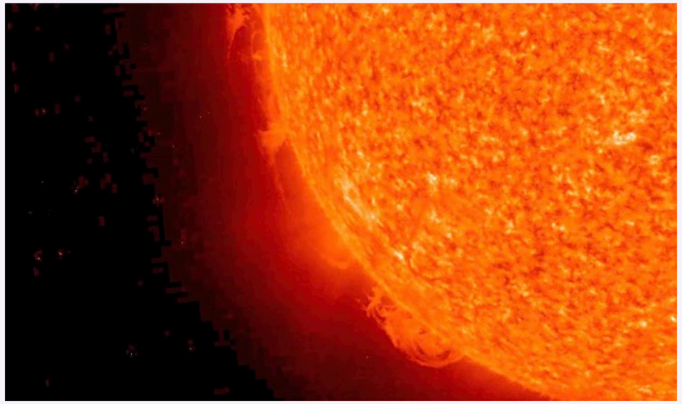
Space Weather Research Themes: Follow the Sun-Earth Connection Process

- Starts with Solar and Atmospheric <u>Driving</u>

- Follows their effects/ <u>responses</u> on the physical system
- Arrives at their <u>impacts</u> on infrastructure and human health

Space Weather Drivers Theme – Research Focus Areas - Outcomes

System of Systems:
Drivers of Space Weather



- Solar Eruptions
- Atmospheric Driving

Outcomes

- >12-hour forecast for solar flares and >6 hours for SEPs
- 12-hour forecast for coronal mass ejections and their magnetic fields
- Quantify the contributions of gravity waves for ionospheric irregularities

Space Weather Responses Theme – Research Focus Areas - Outcomes

Space Weather Responses
of the Physical System

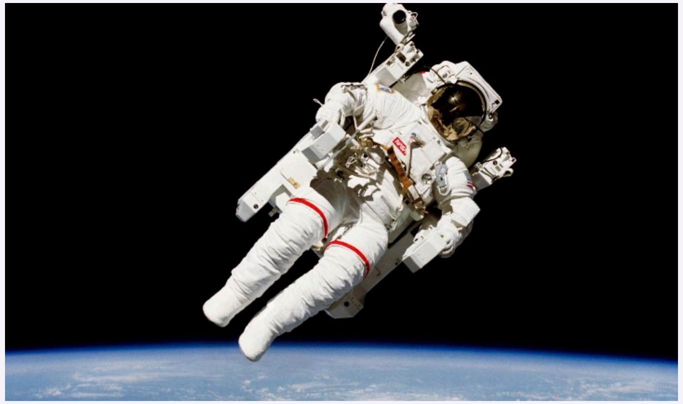
- Low Earth Orbit (LEO) Neutral Density
- Ionospheric State
- Magnetospheric State

Outcomes

- 24-48 hour forecast of thermospheric density during geomagnetic storm conditions
- Nowcast for comprehensive characterization of magnetospheric and ionospheric conditions

Space Weather Responses Theme – Research Focus Areas - Outcomes

Space Weather Impacts
On Infrastructure
and Human Health



- Radiation Environments
- Spacecraft Effects
- HF Signal Propagation
- LEO Trajectories
- Geoelectric Field

Outcomes

- Characterize and monitor space weather environment in cis-lunar space and on the lunar surface in support of the Artemis program
- Accurate and reliable aviation radiation nowcast and forecast during large SEP events
- Reliability forecast for on-orbit surface charging (3-day lead time), internal charging (28-day lead time), single event effects (6-hour lead time), total dose (1-day lead time)
- 30-minute to 1-hour forcase of radio wave signal impacts in the ionosphere
- Integrated modeling framework for predicting LEO satellite and debris trajectories during geomagnetic storms
- 1-Hour reliable forecasting of geoelectric field with increased spatial resolution (200 km)

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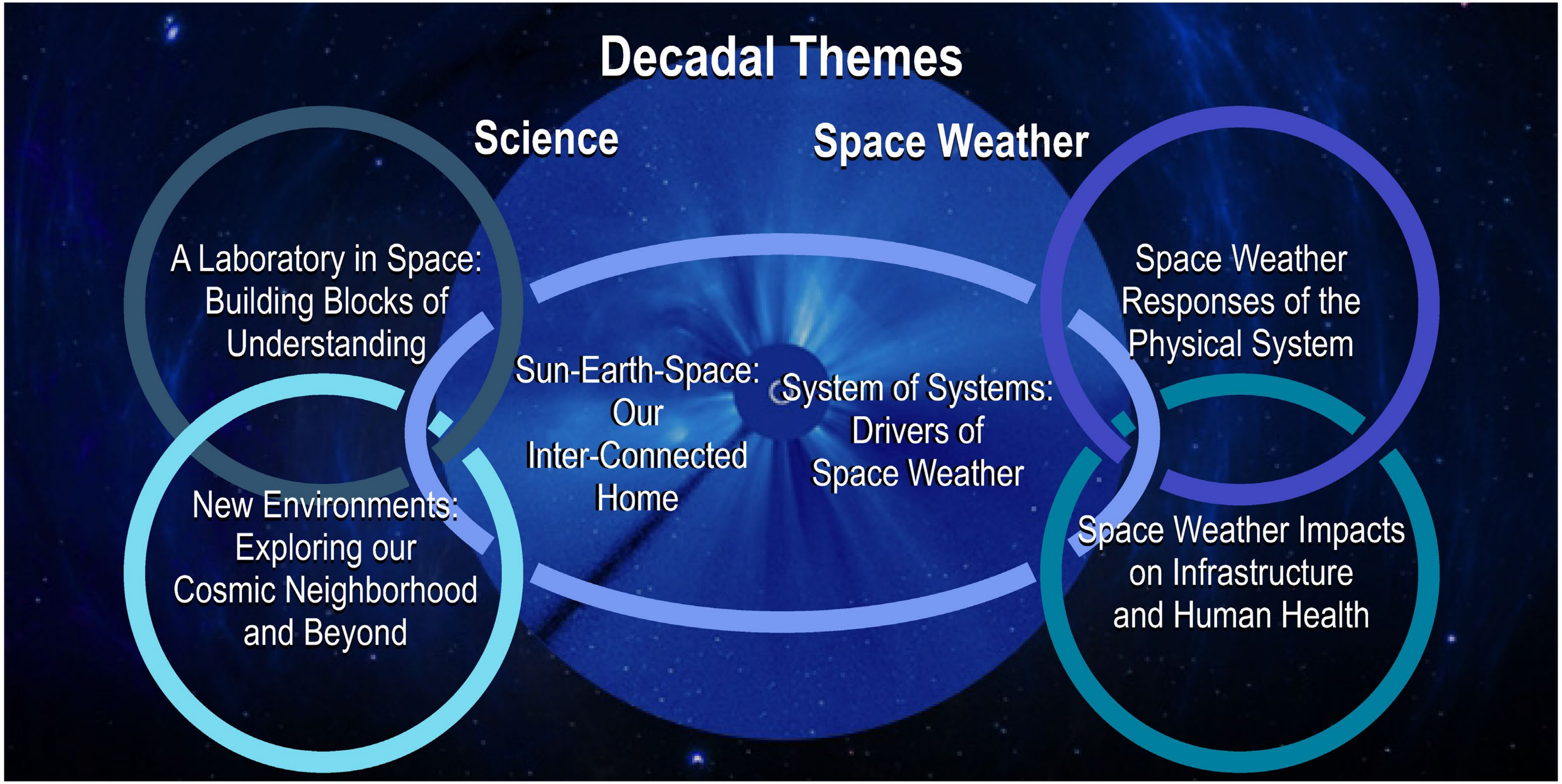
Science and Space Weather Themes are Integrally Linked



A thematic roadmap of discovery and application for the next decade

Space Weather Strategy for the Next Decade

1. **Implement** research-to-operations-to-research framework as specified in PROSWIFT Act
2. **Document** research priorities, performance metrics, and validation methods based on user needs
3. **Target** applied research programs to prioritized space weather goals
4. **Develop** Sun-Earth system models using all available data
5. **Exploit** new data opportunities
6. **Coordinate** international activities

NASA AFOSR NOAA NSF

7	3	2	1	1
Recs	Multi-agency	NASA	NOAA	NSF

NSF Space Weather Strategic Plan

- The PROSWIFT Act requires NSF to (1) Make available to the public key data streams from the platforms and facilities ... for research and to support space weather model development; (2) develop experimental models for scientific purposes; (3) support the transition of the experimental models to operations

Conclusion: Implementation will require collaboration across multiple NSF divisions. New research infrastructure, such as ngGONG, FASR, and DASHI, would bring significant new contributions to observing space weather drivers and impacts, as strategic assets of the R2O2R framework.

Recommendation 3-1: The NSF should develop an agency-wide strategic space weather plan. The plan, as directed by the PROSWIFT Act, should include the incorporation of data streams for space weather purposes from both currently available ground-based facilities and networks, as well as those that would become available after implementation of the decadal survey’s recommendations for ground-based observations. It should also support experimental model development and transition to operations. The development and implementation of the strategic plan is likely to require augmentations to the current level of effort and budget.

Space Weather Requires Multiagency Coordination: Motivation

- The past decade was pivotal in how the federal government regards space weather.
- The 2020 Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT Act; P.L. 116-181) outlined the roles and responsibilities of key federal agencies, mandates that the agencies coordinate their activities
- The PROSWIFT Act did not authorize funds for implementation of the multiagency framework, and many of activities will require additional funding.

Conclusion: The NOAA-NASA R2O2R framework agreement, together with the quad-agency MoA between NOAA, NASA, NSF, and DoD, will facilitate the transition of new developments in space weather research to operational services and address the existing communication gaps between the user and research communities, as specified in the PROSWIFT Act.

Conclusion: The PROSWIFT Act tasks the Space Weather Advisory Group (SWAG) to conduct a user survey, to be reevaluated not less than every 3 years, to “assess the adequacy of current federal government goals for lead time, accuracy, coverage, timeliness, data rate, and data quality for space weather observations and forecasting.” As these surveys are currently in the planning stage, the results needed for prioritization of activities are not yet available, and the research community lacks a clear set of targets to work toward.

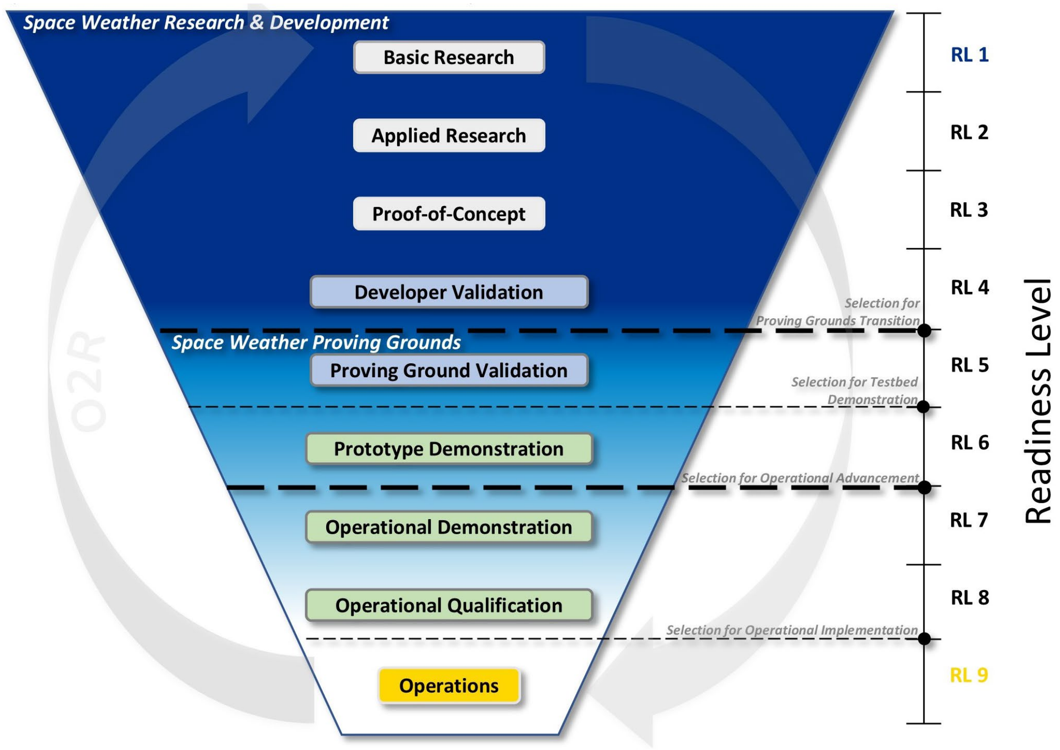
Coordinated Space Weather Research Programs

- Cross-agency collaboration in the field of space weather has advanced significantly; December 2023 memorandum of agreement between agencies is a positive step, but needs to be followed by action.
- It's critical that space weather research priorities be informed by user-driven needs and outcomes.

Recommendation 3-2: NOAA and DoD-AFOSR space weather user surveys to set priority research goals

Recommendation 3-3: NASA and NSF space weather research programs targeted to the prioritized goals

Recommendation 3-4: NOAA space weather research program and partnership with DoD-AFOSR to develop predictive space weather models



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Space Weather User Surveys

- NOAA and DoD to recommend priorities for near-term and long-term service targets based on
  - an established process to communicate with industry & government to understand space weather needs
  - documentation of performance metrics and validation information for operational models and products
  - identification of potential mitigating actions that could be taken with improved space weather information

Recommendation 3-2: NOAA and DoD should build upon the periodically repeated Space Weather Advisory Group surveys of space weather product users to document the highest-priority customer needs and the best performance metrics and validation methods for available space weather applications. The results should be used to identify high-priority space weather research goals. In addition, processes should be developed to ensure communication of these priorities across NOAA, DoD, NASA, and the NSF to be used when setting research priorities in the agencies' space weather–related programs.

Conclusion: This decadal survey outlines research focus areas that are not further prioritized owing to lack of accurate understanding of current and future user needs. However, the committee recognizes the growing space traffic management problems at LEO caused by increased number of spacecraft and debris as a critically important issue.

NSF and NASA Space Weather Research Programs

- Targeted research programs are valuable for advancing space weather capabilities.
- However, each agency operates based on its own priorities, and the current funding structure doesn't prioritize targeted research according to the highest-priority customer needs in a systematic way

Conclusion: By coordinating the space weather research programs of NASA, NSF, NOAA (see Recommendation 3-4), and DoD, the national research effort will focus on the highest user needs, and it will effectively integrate advances in basic science into the development of targeted applications.

Conclusion: The increased importance of space weather has created growing workforce needs in areas of application development, research to operations transitions, mitigation planning, and execution. Stable, coordinated applied research programs help to create healthy career paths for applications-oriented space weather research to meet the workforce needs.

Recommendation 3-3: NSF and NASA space weather research programs (such as NSF's Advancing National Space Weather Expertise and Research toward Societal Resilience [ANSWERS] and NASA's Heliophysics Space Weather Programs) should be targeted to prioritized space weather goals (see Recommendation 3-2).

NOAA Space Weather Research Program

- Assimilative system models have accelerated progress in operational forecasting in Earth science, and such methods are now entering the Sun–Earth system modeling and space weather enterprise
- Space weather modeling efforts are focused on transition to operations, development of new models to meet user needs, and development of tools that address the quality and improvement of the forecasts

Conclusion: The development of advanced data assimilation capabilities is important for conducting observing system experiments (OSEs) and observing system simulation experiments (OSSEs) that quantitatively determine the value of observations for accurate specifications and forecasts. These new data assimilation capabilities are important not just for improving research and operational services, but also for their ability to inform decisions on future investments in the observing system, which is a capability is currently lacking.

Recommendation 3-4: The National Oceanic and Atmospheric Administration should establish a space weather research program. It should partner with the Department of Defense to develop large-scale predictive space weather models that can meet operational requirements, which may differ from those of scientific research models. Model development should make use of the versatile set of available space weather data.

NOAA Space Weather Observations (Full Text)

Recommendation 3-7: To take advantage of new data opportunities, NOAA should assess the value (e.g., through observing system experiments or observing system simulation experiments) of new data streams (e.g., from NASA's research satellites or proof-of- concept studies) and incorporate those that promise to make substantial quantitative improvements into operational services. These data could also come from other ground- and space-based instruments, from U.S. agencies partnering with NOAA, commercial entities, and international partners.

State of the Profession

State of the Profession

Four themes to support, unify, and strengthen the field

Demographics of the Workforce	Solar and Space Physics Education	DEIA+	Expanding Public Outreach
• Understanding the demographics of the solar and space physics workforce • Career pathways • Workforce needs for the future	• Integrating solar and space physics into education • Implementing education and student recruitment	• Identifying and building awareness of barriers • Funding for enhanced DEIA+ efforts • Improving the quality of DEIA+ plans/proposals and their evaluation	• Enhancing public communication and development of materials • Enabling citizen science

State of the Profession Recommendations - Synopsis

- A **common name for the field** to improve efforts in data gathering, recruitment, education, and public outreach.
- A sustainable structure for continuous, longitudinal **data gathering** is needed.
- Building the workforce for tomorrow requires recruiting the best talent.

Recommendation 4-1: Fund demographic data collection

Recommendation 4-2: Expanding the reach of space science education

Recommendation 4-3: Faculty Development in geoSpace Sciences (FDSS)

Recommendation 4-4: Increase opportunities for student research

Recommendation 4-5: Enhancing DEIA+ in research

Recommendation 4-6: Increase public outreach and citizen science programs

Comprehensive Research Strategy

Decadal Research Strategy

CRITICAL ELEMENTS

Integrated HelioSystems Laboratory

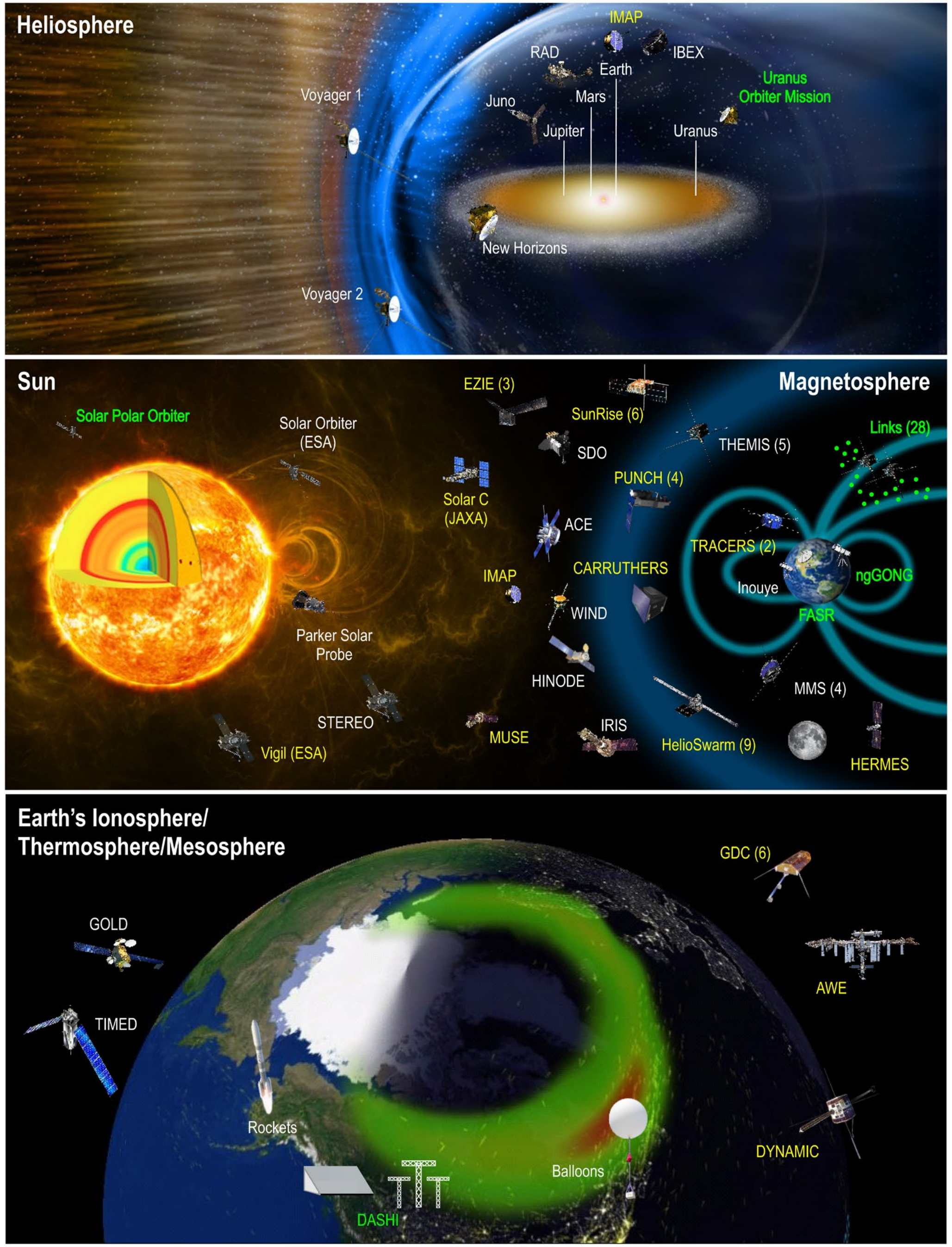
- Ground-based assets
- NASA Flagship-Level Community Science Modeling Program
- Space-Based Assets

DRIVE+ - Enhancements in Research and Technology Programs

- Workforce of Tomorrow
- Collaboration and Coordination
- Enhancements in Science support and Research Tools
- Technology Development

Preparation for Beyond the Decade

- Technology development
- Cross Divisional and Cross-Directorate Coordination at NASA
- Future Opportunities for International Coordination
- Communication Infrastructure



Integrated HelioSystems Laboratory

- Meeting diverse observational and modeling needs is achieved only through an interagency strategic planning activity.
- Space-based missions, ground-based projects, and flagship-level community modeling work together to provide data for scientific and space weather research.

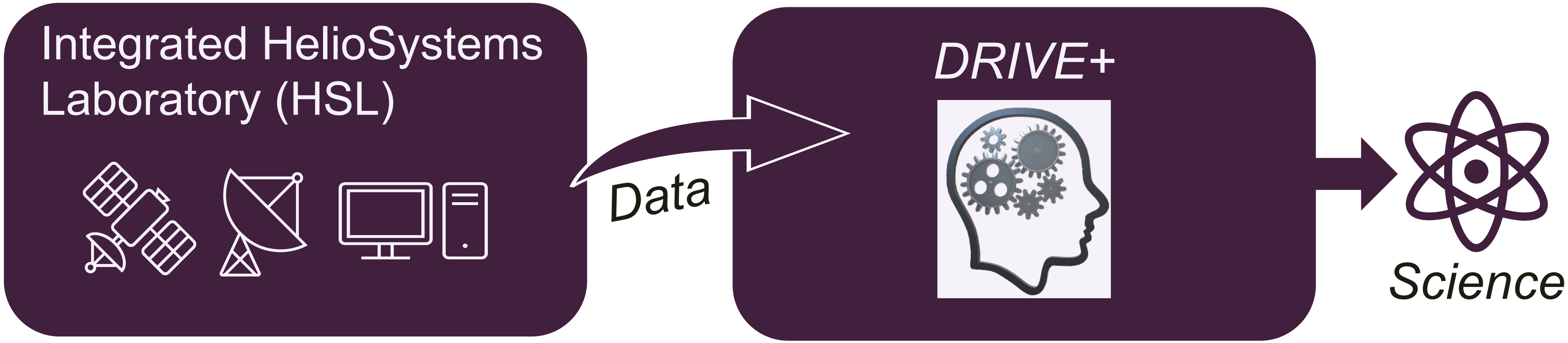
Recommendation 5-1: NASA, NSF, and NOAA should address the goals of the decadal survey by managing all assets as part of an integrated HelioSystems Laboratory.

NOAA-specific Contribution to the HSL (Rec. 5-1)

- To contribute to the HSL, NOAA should make the data from its missions fully accessible and useable for scientific research.

- NOAA's contributions to HSL would include
  - SWFO-L1 (2025), GOES-19 (2024), and Space Weather Next projects SOL-A (2029), SOL-B (2032), and Vigil L5 collaboration (2031) as well as plans for Space Weather Next GEO observations

How the HSL and DRIVE+ Work Together

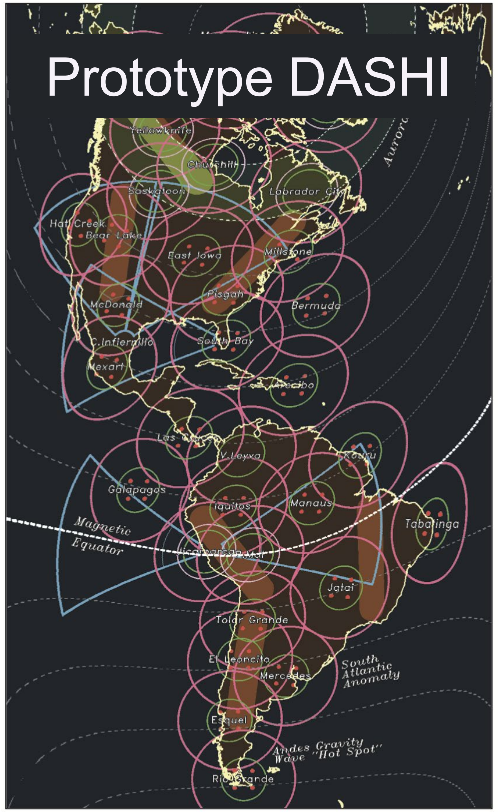


- NASA Strategic Missions
- NSF and NOAA Ground-based Assets
- Multi-agency Space Weather Observations
- Flagship Modeling
- Explorers, CubeSats, and Suborbital Missions

- Workforce
- Collaboration/Cooperation
- Research Tools
- Technology Development

Ground-based Assets of the HSL (NSF)

MREFC: Next Generation Global Oscillations Network Group – The Sun's interior and far side of the Sun through Helioseismology



MSRI-1 ($4-20M): (Prototype) Distributed Array of Scientific Heterogeneous Instruments – Systems science: coupling of Earth's upper atmosphere to space

MSRI-2 ($20-100M): Frequency Agile Solar Radiotelescope – A 3D radio "camera," observes the Sun's atmosphere as a coupled system

Recommendation 5-2: Mid-scale Research Infrastructure (MSRI)

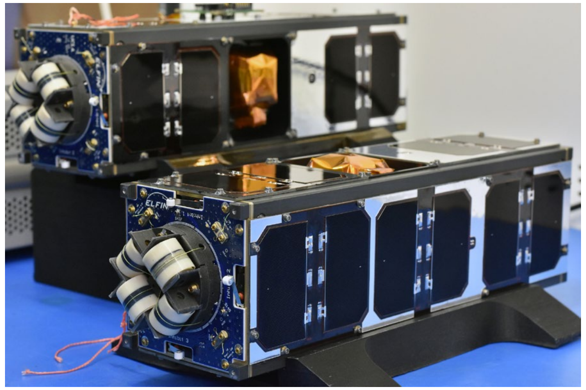
Recommendation 5-3: Major Research Equipment and Facilities Construction (MREFC)

NASA Suborbital Program and NASA/NSF CubeSats

- **Highly successful programs** that are important for science, instrument development, and training
- Suborbital Rockets and Balloons
  - Low-cost access to space for heavy payloads
  - Primary access to the "ignorosphere" at 80-300 km
- CubeSat Programs at NASA and NSF
  - Capabilities have grown significantly in last decade
  - Important elements of the HSL

Recommendation 5.5: To ensure continued success, NASA and NSF should conduct comprehensive, community-based reviews of their CubeSat programs.

TRICE-2 Rocket Launch Source: NASA/Jamie Adkins



ELFIN CubeSats. Source: UCLA

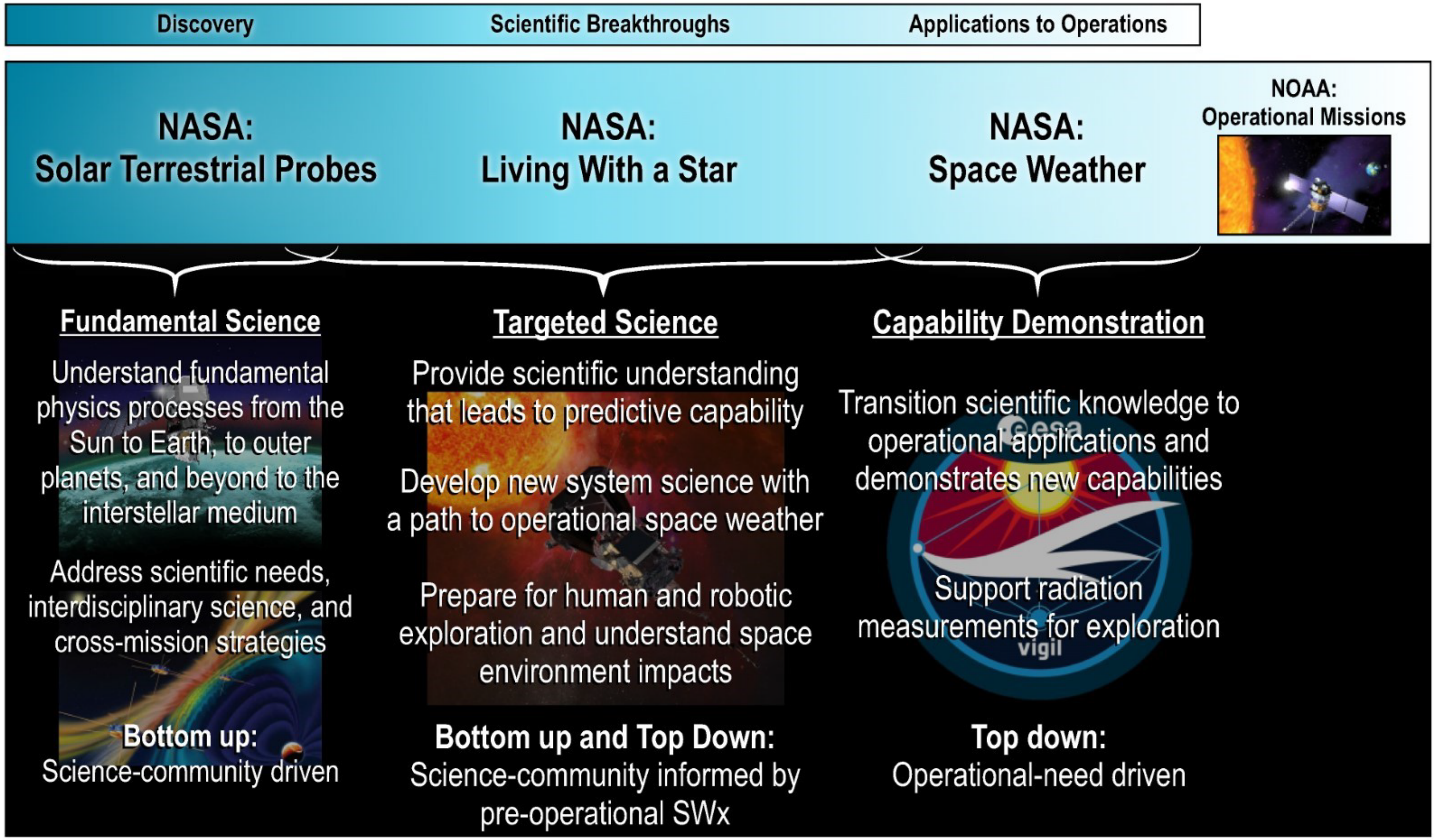
Launch of the Sunrise balloon payload
Source: University Corporation for Atmospheric Research

Enhancing the NASA Space Weather Program

Recommendation 3-5: NASA should grow the space-flight element of its Space Weather Program

- Support stand-alone space weather demonstration missions

Recommendation 3-6: NASA should consider space weather enhancements on all NASA missions and other federal agency missions



Space Weather Program is an effective bridge between the NASA science missions and NOAA operational missions

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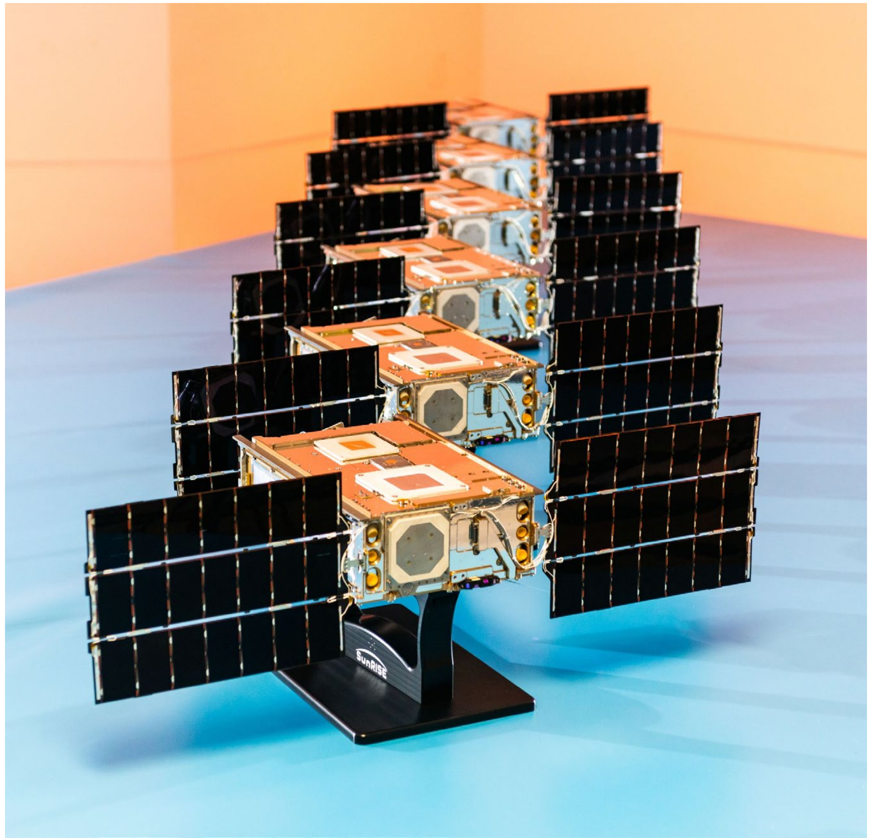
NASA Explorer Program

- Successful increase in the Explorer cadence in the last decade ➔ Currently 7 Explorers in development!
- Broad range of cost caps provide balance in the Heliophysics program
- Recommendation designed to enhance the effectiveness of an already **extremely successful program**

Recommendation 5-7: NASA should maintain a robust and vibrant Explorers Program by:

- Adding a HeLEX-class mission to fill a gap in mission costs
- Maintaining balance in Explorer mission sizes and cadences
- …

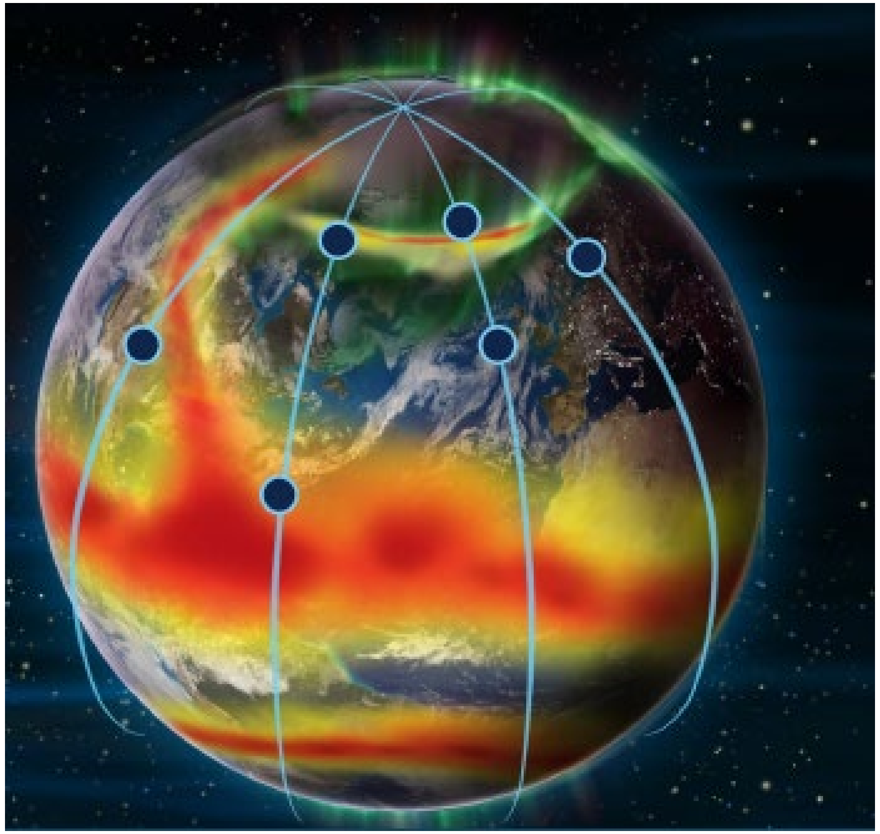


Six CubeSats for the SUNRISE Mission of Opportunity. Credit: Space Dynamics Laboratory/Allison Bills

Integral Parts of the Program of Record:

Geospace Dynamics Constellation (GDC) and Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)

- Highest-priority LWS and STP missions from the 2013 decadal survey
- Four reasons to complete GDC/DYNAMIC in the next decade:
  - Make significant progress on decadal high-priority science
  - Help balance the overall Heliophysics research program
  - Act as a pathfinder for the heterogeneous constellation class missions that are to follow in the next decade
  - Have significant space weather science components as well as near-real-time measurement capabilities



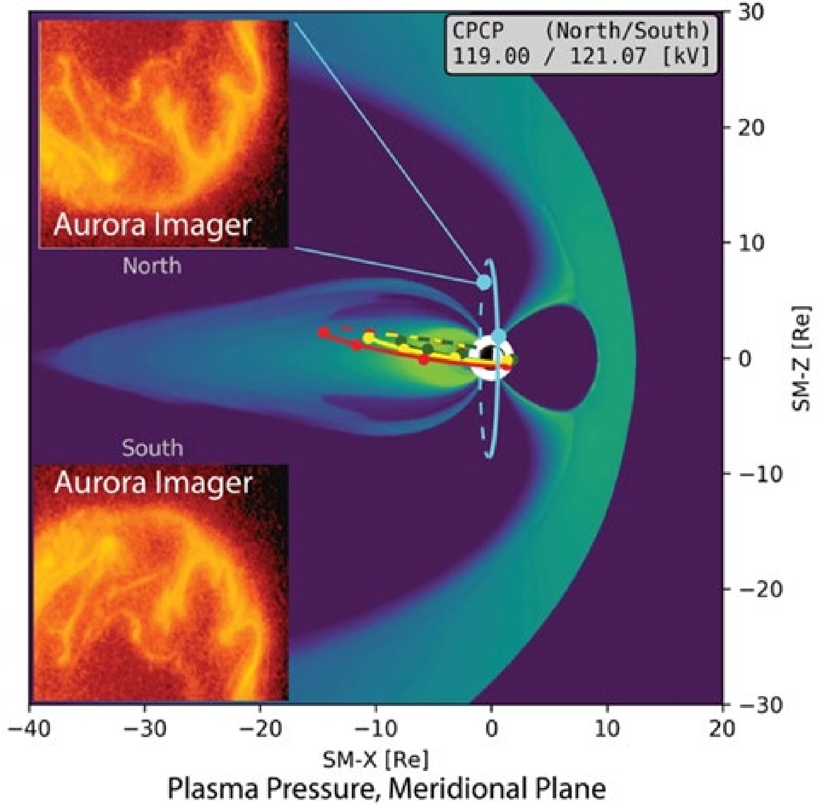
Theme: Sun-Earth-Space
Together, GDC and DYNAMIC provide breakthroughs in our fundamental understanding of Earth's upper atmosphere

Highest-Priority New STP Mission

Notional Mission: Links between Regions and Scales in Geospace

Theme: Sun-Earth-Space

- *Links discovers the connections across regions and scales in the near-Earth space environment.*

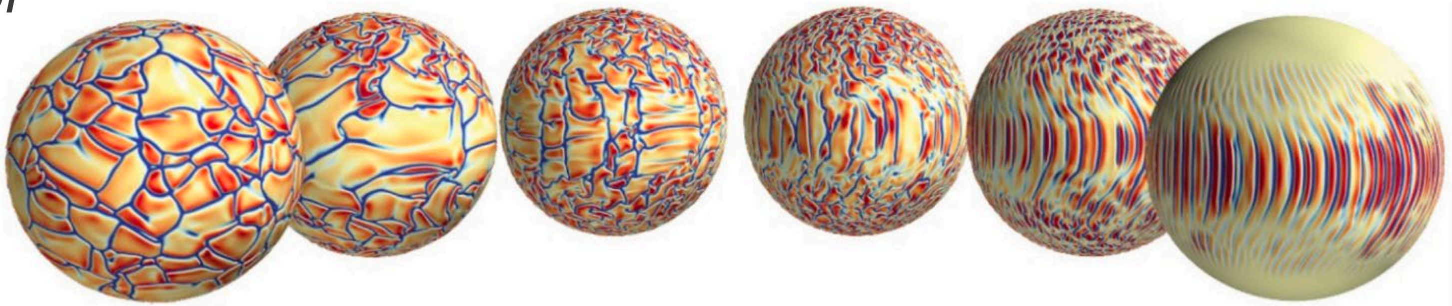


Highest-Priority New LWS Mission

Notional Mission: Solar Polar Orbiter

Theme: A Laboratory in Space

- *SPO makes observations of the Sun's poles, critical to understanding the cyclic behavior of solar activity.*



Enhancements in Research and Technology

Rec. 5-10: Research that combines ground- and space-based observations

Rec. 5-11: Cyberinfrastructure development

Rec. 5-12: Cross-disciplinary research

Rec. 5-13: NSF organizational structure review

Rec. 5-14: Funding for infrastructure missions to validate data

Rec. 5-15: Support for analysis of archival data

Rec. 5-16: Augmentation of Heliophysics research program

Rec. 5-17: Theory and modeling for strategic missions

Rec. 5-18: Review the structure of DRIVE Centers and Space Weather Centers of Excellence

Rec. 5-19: Instrument development

Enhancements to NASA Research Programs

- A significant amount of archival data has not been fully analyzed, leading to an underutilization of prior investments
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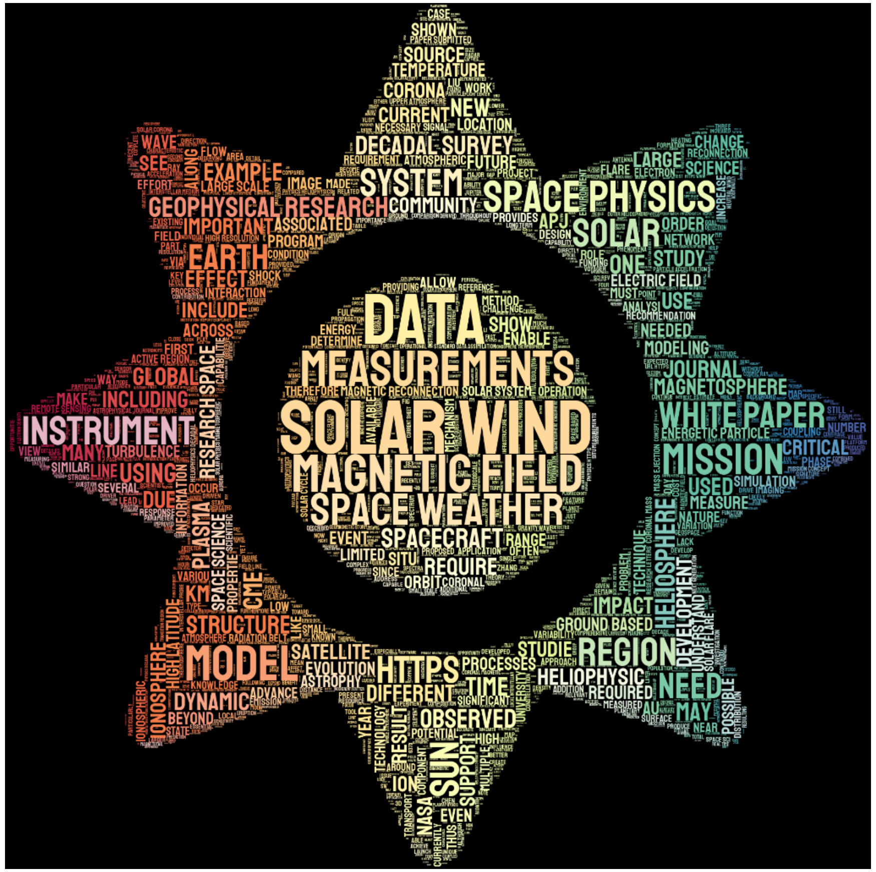
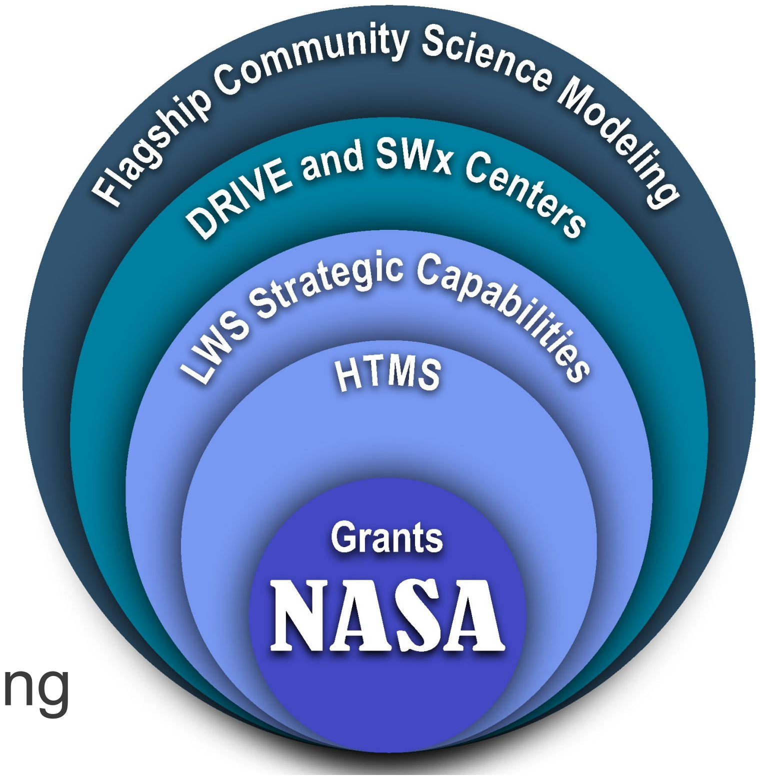


Recommendation 5-15: Support for Analysis of Archival Data

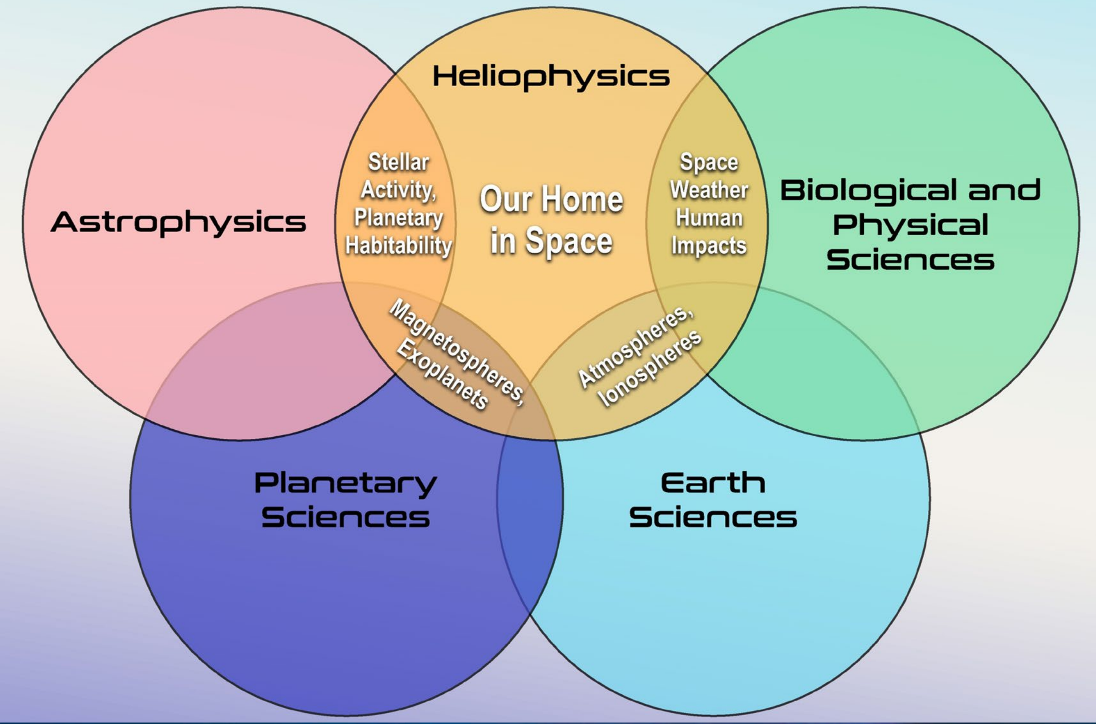
Recommendation 5-16: Augmentation of the Heliophysics Research Program

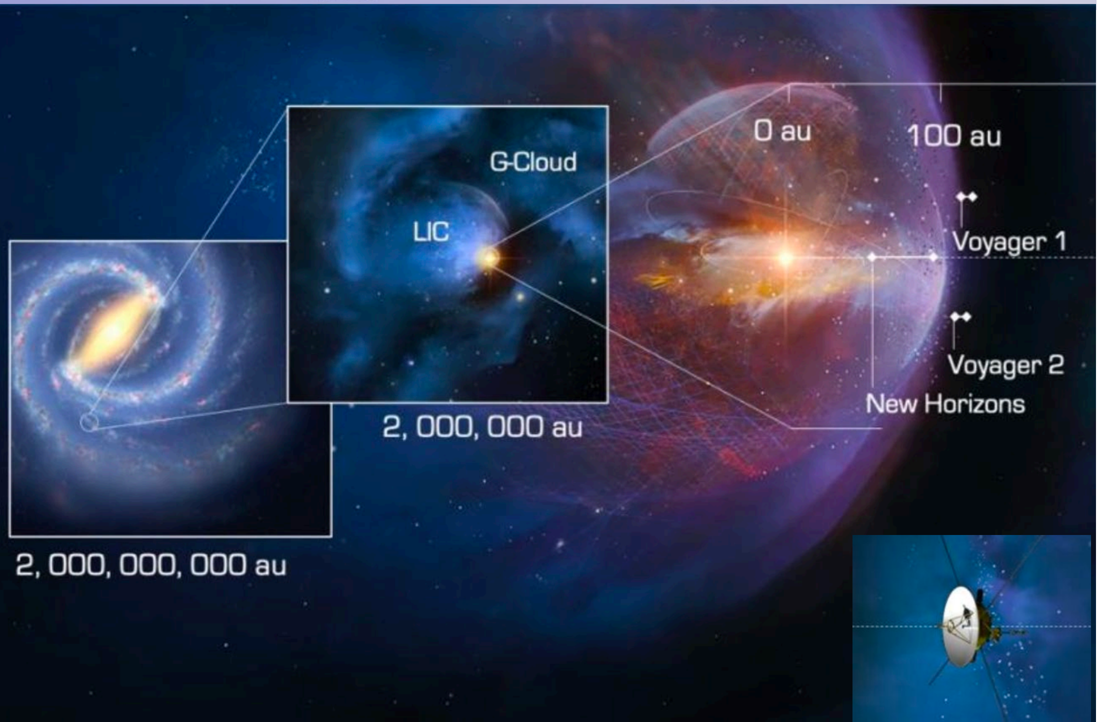
A New NASA Flagship-Level Community Science Modeling Program

- Builds on existing research efforts
- Solves the complex problems of the next decade
  - Systems level science
  - Fundamental processes
- Leverages rapid developments in high power computing



Recommendation 5.4: …NASA should establish a flagship-level heliophysics community science modeling program capable of addressing heliophysics problems that have broad community interest and require complex community models…



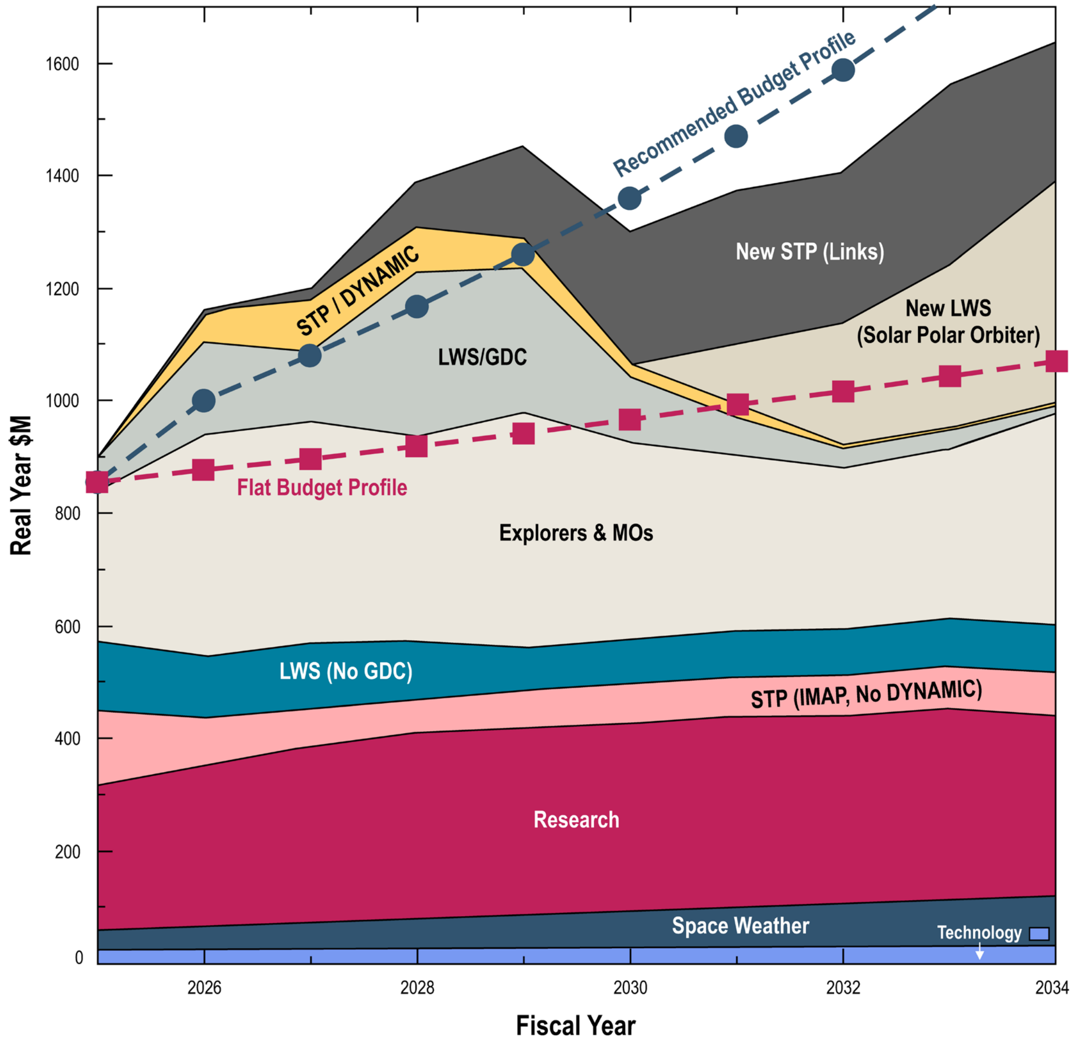


Preparation for the Decade and Beyond

- Continued progress requires a multidecadal effort.
- Investments in the next decade prepare for future endeavors.
  - New technologies and mission architectures
  - Future international collaboration
- A cross-divisional approach to planning is needed for:
  - Habitable Worlds Observatory
  - A mission to interstellar space
  - Uranus Orbiter Probe
  - Space weather (e.g., radiation prevention and prediction) and Moon-to-Mars missions.

Heliophysics Budget Profile to Accomplish the Recommended Ambitious but Realistic Research Strategy

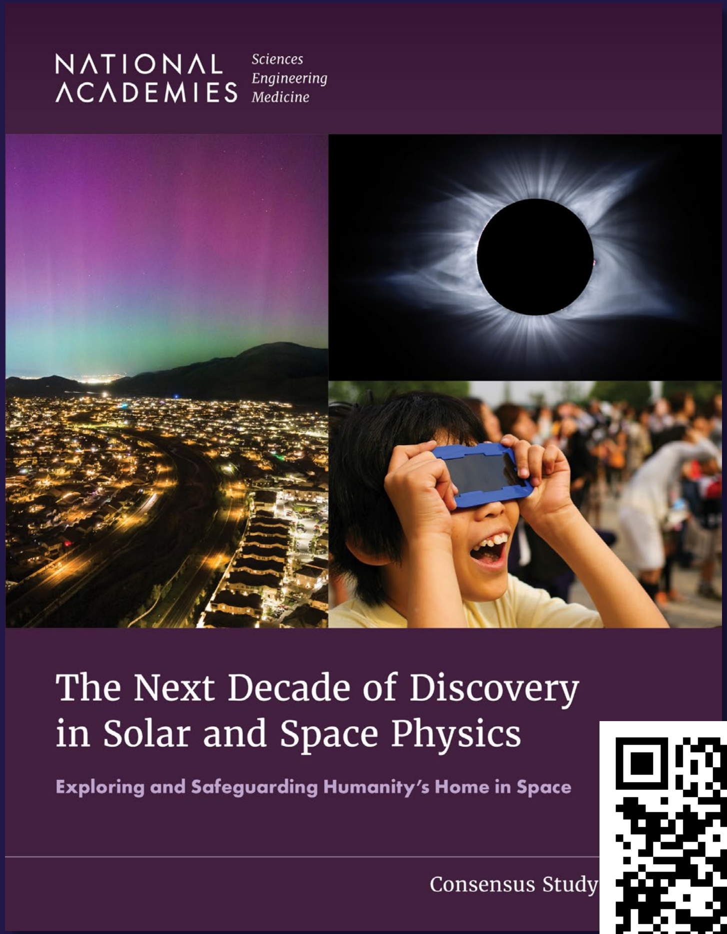
- Budget needs to grow to complete the POR (including GDC and DYNAMIC) and accommodate new missions
- Budget growth in two stages:
  - FY25 to FY26: One-time increase (17%) to restart GDC and start DYNAMIC
  - FY26 onward: Growth at ~8.25% per year
- Budget Profile Accommodates:
  - Augmentation to the Research Program, New Community Modeling
  - Growing Space Weather Program
  - Explorer cadence of 2-3 years, with a HeLEX mission (~2x MIDEX cost cap) start in FY31
  - Simultaneous launch of GDC and DYNAMIC in FY31
  - New STP Mission (Links, 2027) and LWS Mission (SPO, 2029



Key Takeaways

Advancing solar and space physics research will require:

- **Combined investments** from NASA, NSF, NOAA, and the DoD-AFOSR, as well as international partners.
- A **balanced, comprehensive research strategy**.
- **Increased coordination** within the agencies to capitalize on the solar and space physics expertise that has resulted from decades of investment.
- A **thriving community** to support these efforts.



Download the report and report resources:

nationalacademies.org/ssp-decadal

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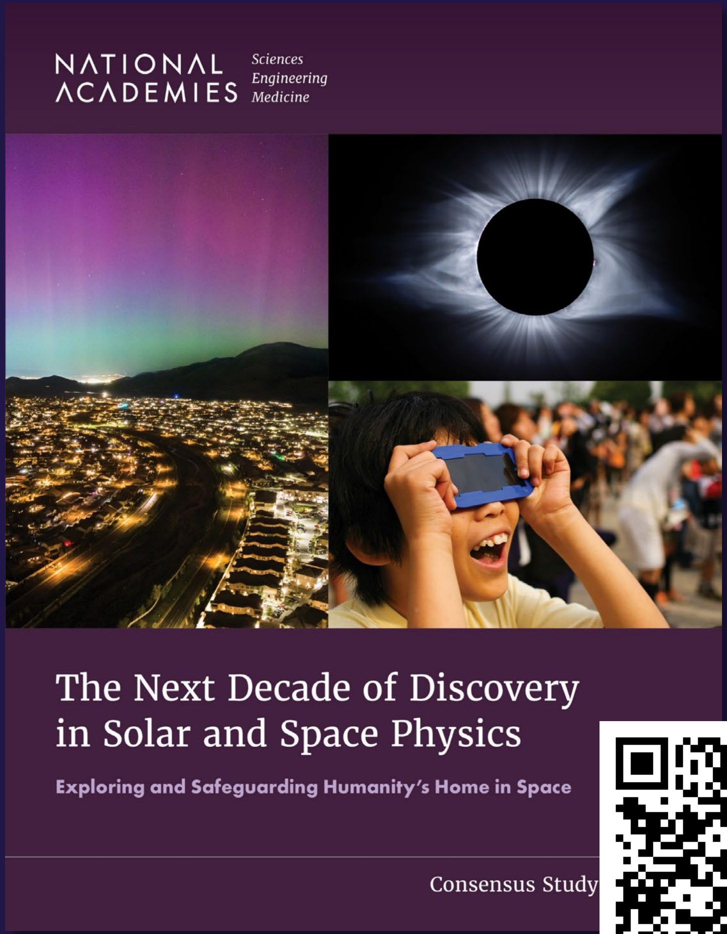
Exploration is driven by humanity's fundamental curiosity about the world, and solar and space scientists have always been intrepid explorers.

Thank You



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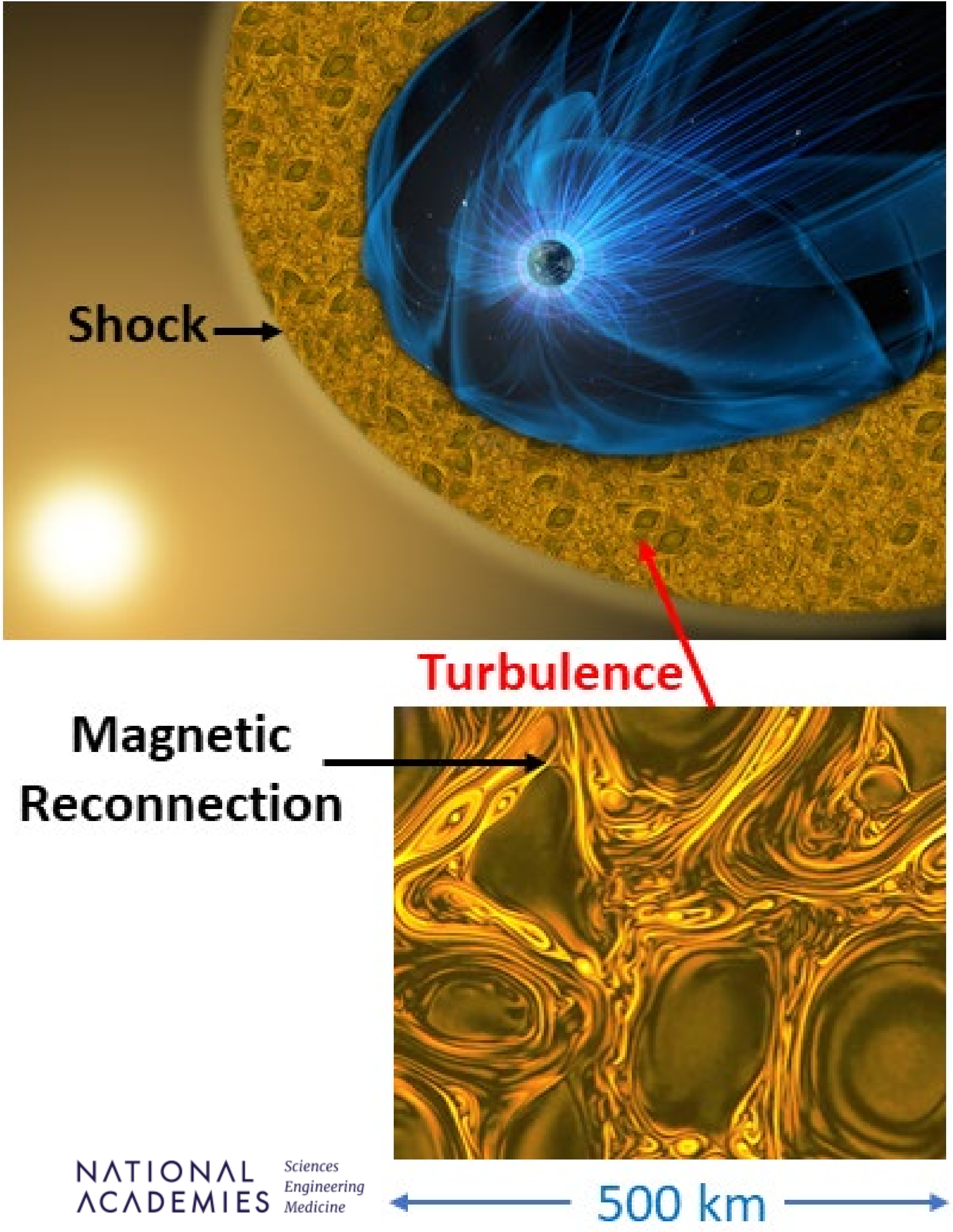
Backup Slides

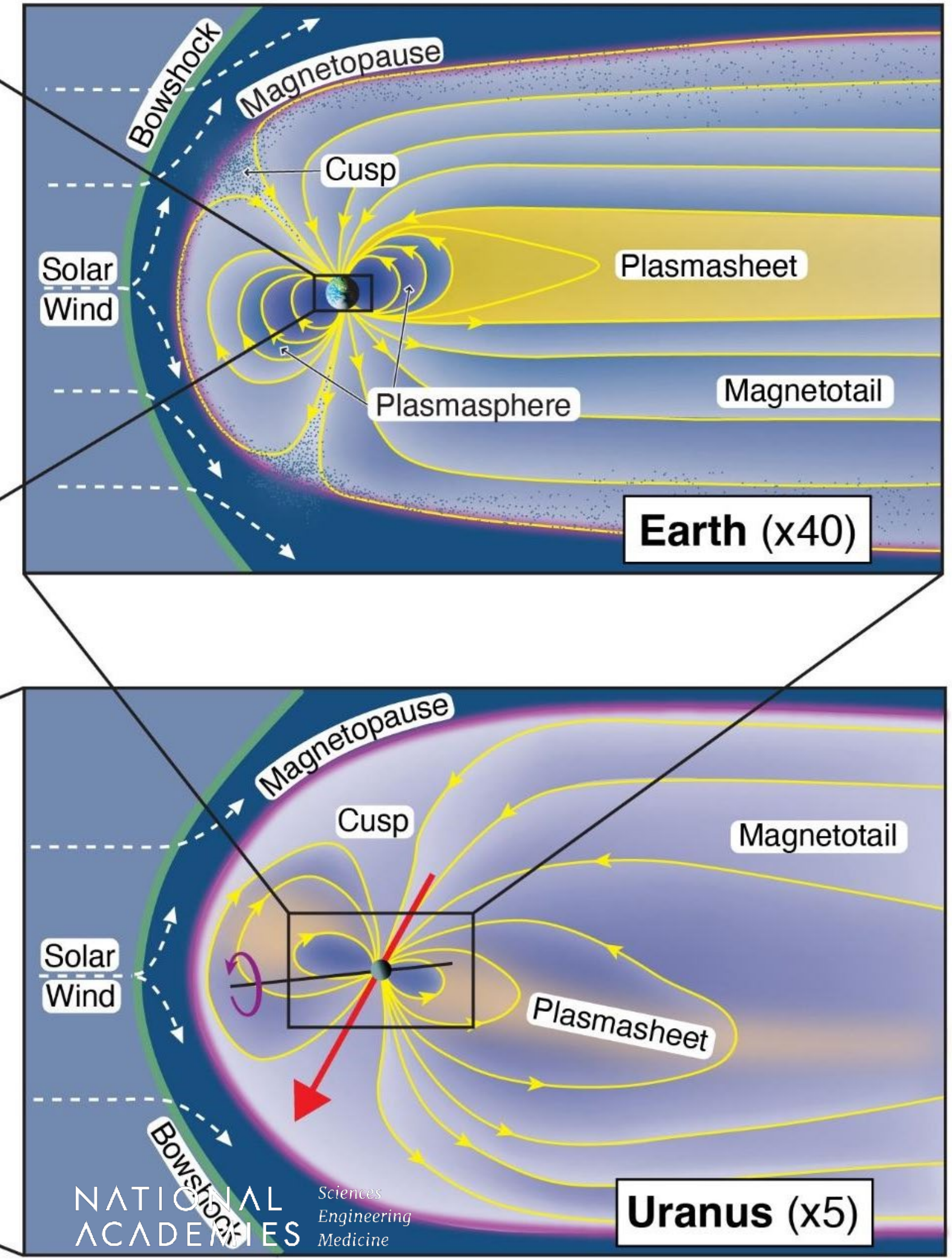
Sun-Earth-Space
Guiding Questions

- How does our Heliosphere function as a nested system?
- How do Heliosystem boundaries manifest themselves?
- How do the Sun-Earth system parts interact with each other?



A Laboratory in Space
Guiding Questions

- How is the Sun's global magnetic field created and maintained, and what causes its cyclical variation?
- How are explosive phenomena created and dissipated across the heliosphere, and what are the fundamental processes that contribute to energy conversion?
- How do the fundamental processes govern the cross-scale coupling and what are the global properties and consequences of the processes?



New Environments
Guiding Questions

- What can we learn from comparative studies of planetary systems?
- Why does the Sun and its environment differ from other similar stars?
- What internal and external characteristics have played a role in creating a space environment conducive to life?

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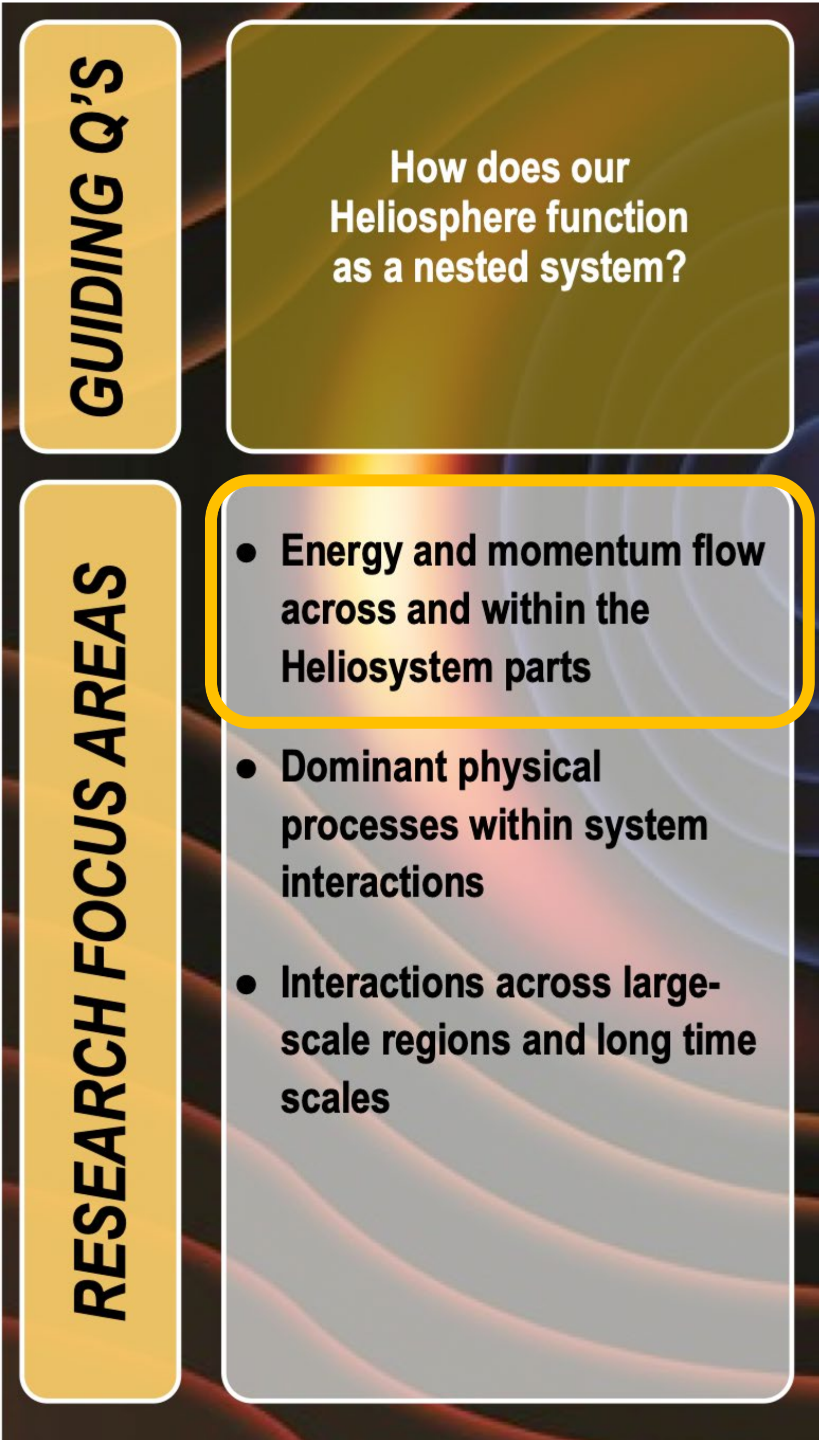
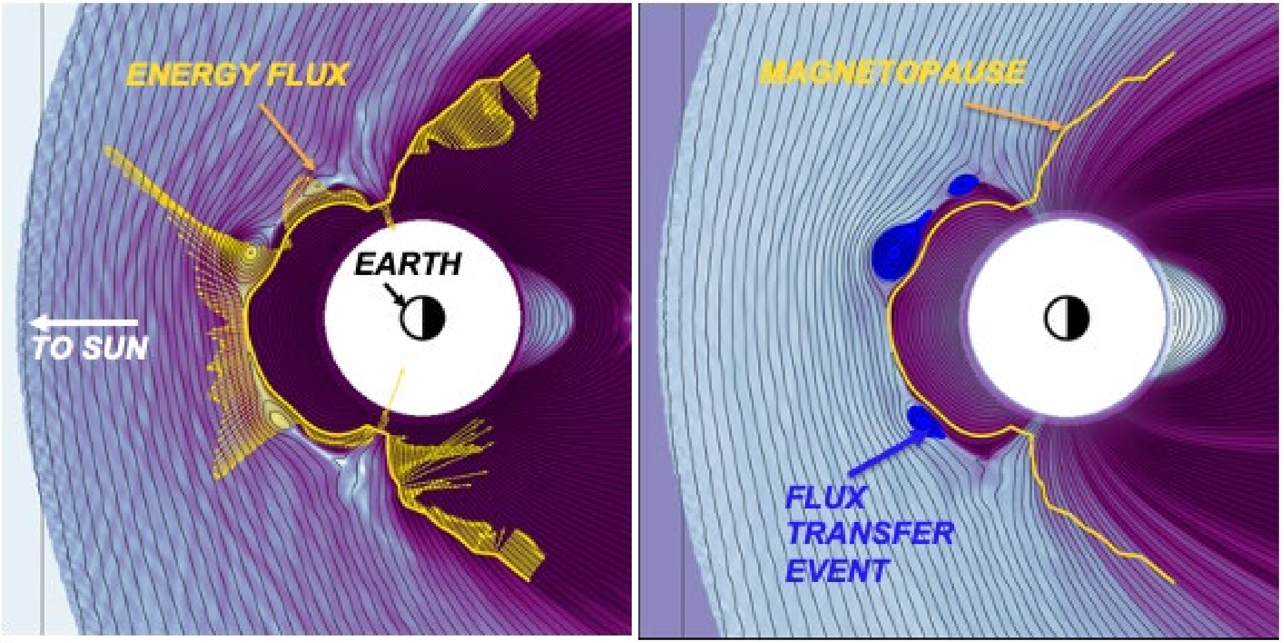


Theme: Sun-Earth-Space

Example Focus Area: Energy and Momentum Flow



- Magnetospheric boundary continuously exchanges shocked solar wind and magnetospheric mass and energy.
- Resolving energy transfer processes requires multi-point resolution of mesoscales in combination with imaging.

GUIDING Q'S

How do Heliosystem boundaries manifest themselves?

RESEARCH FOCUS AREAS

- System impacts of magnetic boundary processes
- Role of transition regions in system coupling
- Interactions at plasma-neutral transition regions

Theme: Sun-Earth-Space

Example Focus Area: Plasma-neutral interactions

- STEVE (Strong Thermal Emission Velocity Enhancement) is formed through a yet unknown interaction between the neutral atmosphere and the ionosphere.

GUIDING Q'S

How is the Sun's global magnetic field created and maintained, and what causes its cyclical variations?

RESEARCH FOCUS AREAS

- Flows and fields across all solar latitudes
- Linkage of the interior field to the global heliosphere
- Longitudinal variation of the dynamo and the field

Theme: A Laboratory in Space

Example Focus Area: Flows and fields across all solar latitudes

- The Sun's global velocity structure above 60° latitude is currently unconstrained by direct observations.
- These divergent predictions motivate the need for measurements of the polar regions of the Sun.

GUIDING Q'S

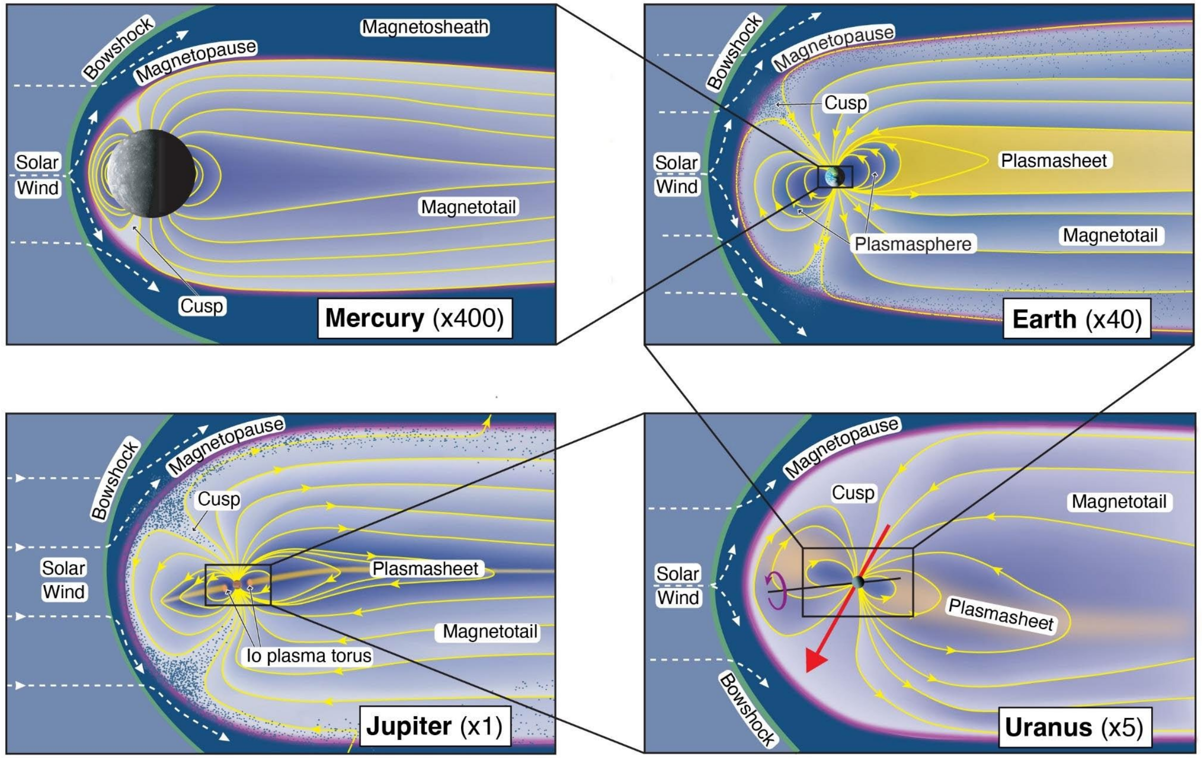
What can we learn from comparative studies of planetary systems?

RESEARCH FOCUS AREAS

- **Mass and energy flow processes driving planetary magnetospheres**
- **Interactions of plasmas with solid body surfaces and atmospheres**
- **Diversity of auroral processes**

Theme: New Environments

Example Focus Area: Mass and Energy Flow Processes Driving Planetary Magnetospheres



- Huge differences in magnetosphere scales are evidence for different external and internal drivers.
- Differences and similarities provide guidance for understanding exoplanet magnetospheres.

Major Research Equipment and Facilities Construction

- ngGONG – a modern and enhanced successor to the NSO's GONG network
- Exploring the Sun's interior through Helioseismology
- A valuable space weather asset – providing magnetograms and far-side images

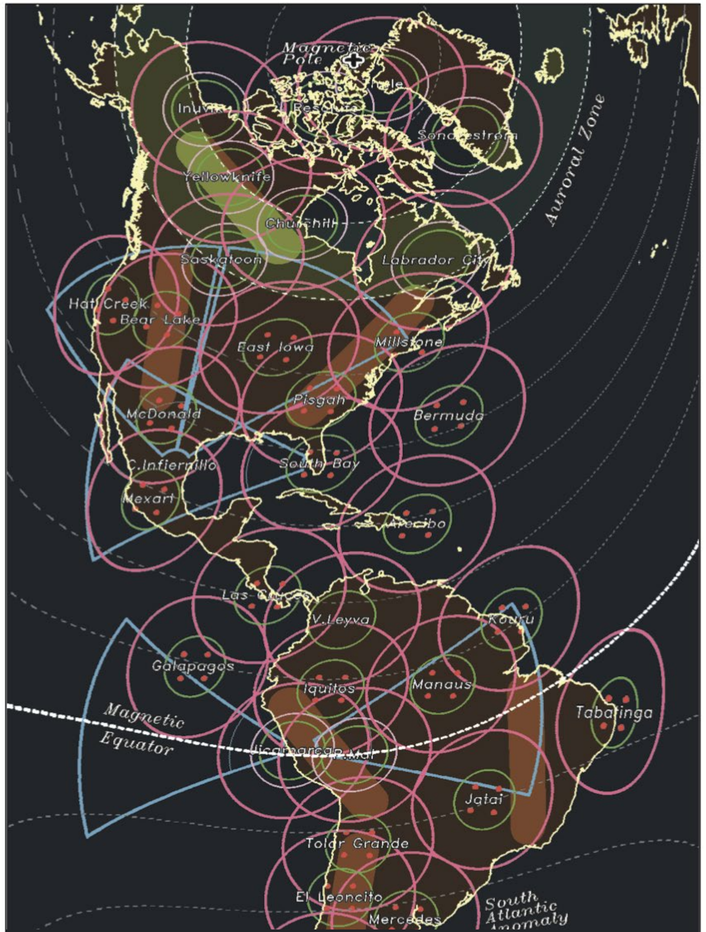
Recommendation 5-3: The highest-priority large Major Research Equipment and Facilities Construction-scale project for the National Science Foundation for the next decade is the Next Generation Global Oscillations Network Group (ngGONG). In light of its importance to space weather, the development, implementation, and operation of ngGONG should be supported through partnerships with the NOAA, the DoD-AFOSR, and international partners.

Mid-scale Research Infrastructure

Recommendation 5-2: The highest priorities for the National Science Foundation's Mid-scale Research Infrastructure (MSRI) programs are to

- Develop the project execution plan for the Frequency Agile Solar Radiotelescope (FASR) and proceed to implementation as a MSRI-2 project; and
- Develop and deploy a prototype Distributed Array of Scientific Heterogeneous Instruments (DASHI) as a MSRI-1 project that includes an observing system simulation experiment and a cost estimate for a full-scale DASHI.

To foster the integration of the HSL, NASA, NSF, and NOAA need to enhance their cooperation on ground-based projects



Concept for DASHI - one of two recommended MSRI projects

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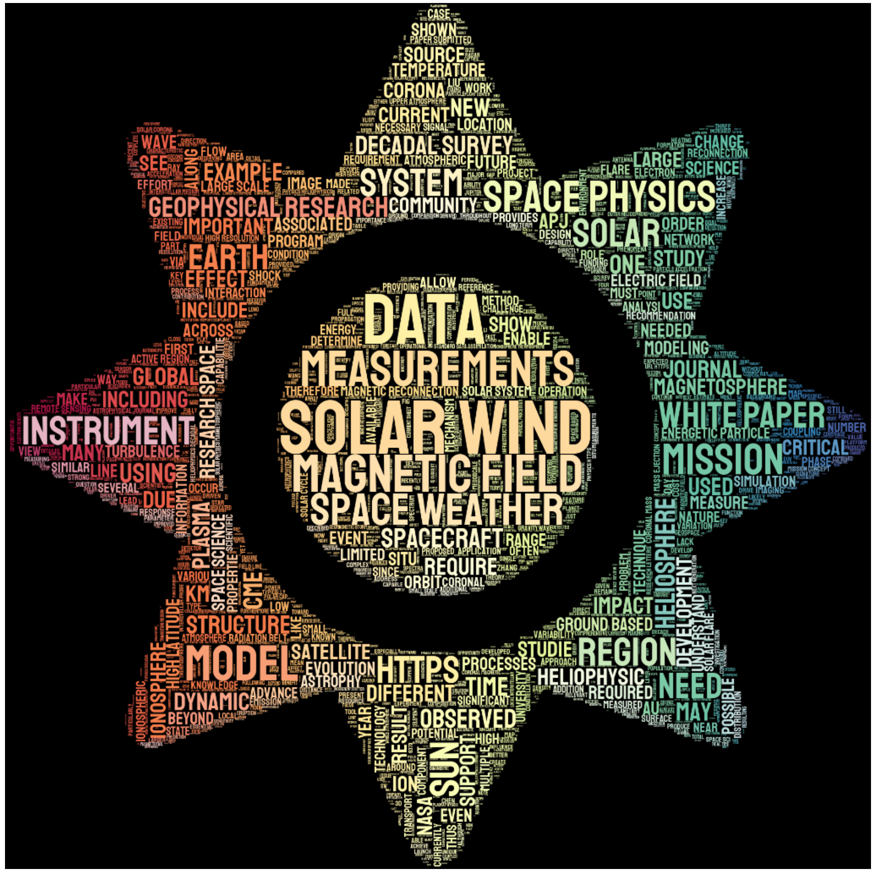

NASA Decision Rules (Full Text)

Recommendation 6-1: If there is insufficient funding to accomplish the entire research strategy, then NASA should implement decision rules in the following order:

- First, delay the start of the Living With a Star (LWS) Solar Polar Orbiter reference mission, and then
- Delay the start of the Solar Terrestrial Probes (STP) Links reference mission;
- Delay the Space Weather budget augmentation for space weather demonstration missions;
- Delay the announcement of opportunity for the next Explorer/Mission of Opportunity (but revert to the 3-year cadence after budget conditions become favorable again);
- Delay implementation of the community science modeling program;
- Delay the augmentation of the Heliophysics Research Program;
- Delay the development, implementation, or launch of the Dynamical Neutral Atmosphere–Ionosphere Coupling (DYNAMIC) STP mission; then
- Delay the development, implementation, or launch of the Geospace Dynamics Constellation (GDC) LWS mission.