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

Decadal Surveys in a Nutshell

- **Community-driven studies produced by the National Academies of Sciences, Engineering, and Medicine**
  - Articulate a community consensus about the most compelling science questions for the decade ahead in each of the disciplines
  - Early career webinar: https://www.nationalacademies.org/our-work/decadal-survey-for-solar-and-space-physics-early-career-webinars
- **Why do decadal surveys matter?**
  - Mandated by Congress for each NASA Science Division
  - For every proposal we write, it’s either powerful or required to relate your research to the priorities outlined in the decadal survey
  - Specific programs are often created in response to DS recommendations.
  - A lot of the data available to you were produced by missions or facilities that were either directly recommended or selected in response to DS priorities.
- **What’s next?**
  - Advocate for the Decadal vision and science
  - Midterm assessment in ~5 years

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

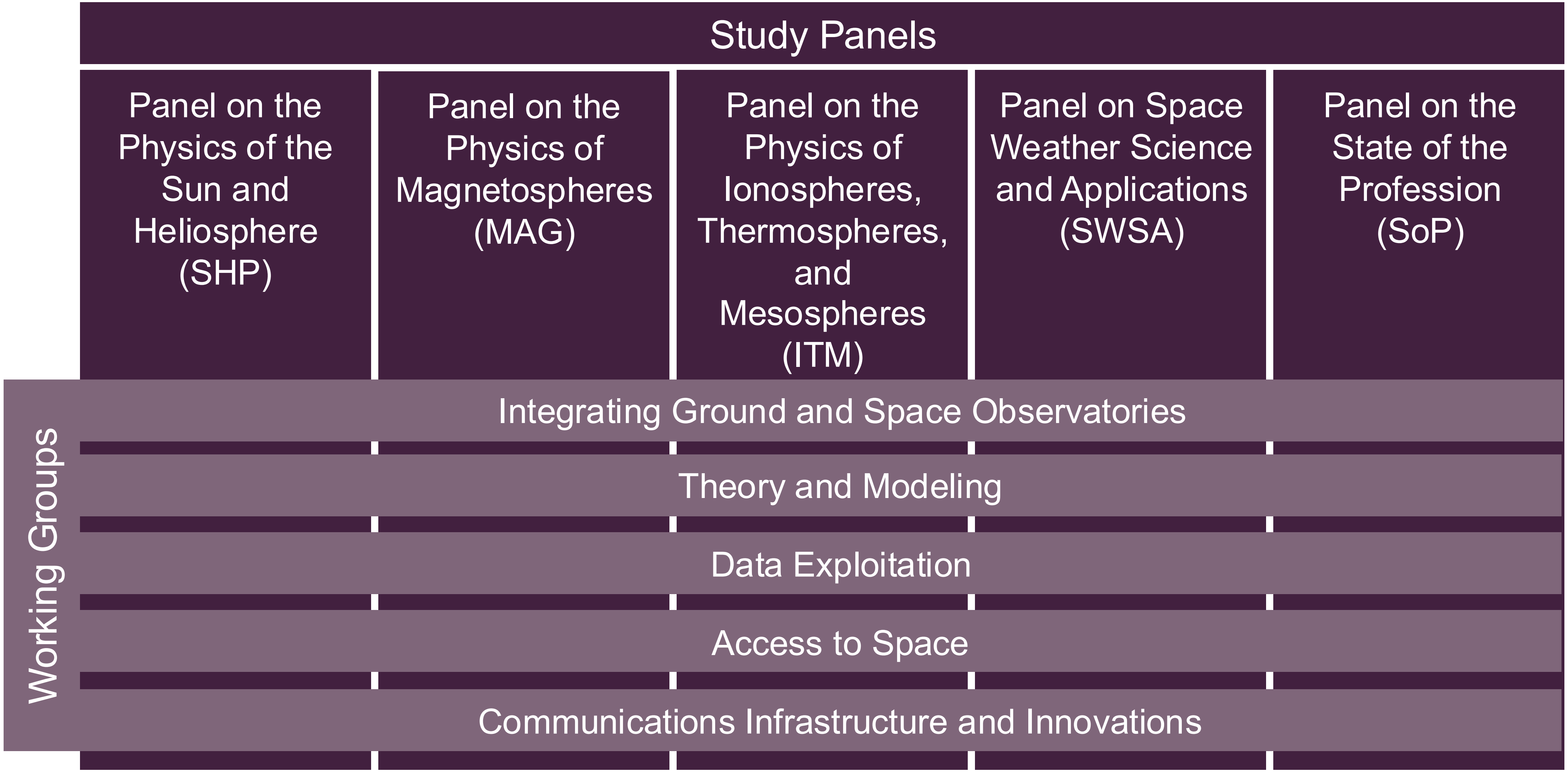
Additional guidance and agency requests were also provided.

Steering Committee

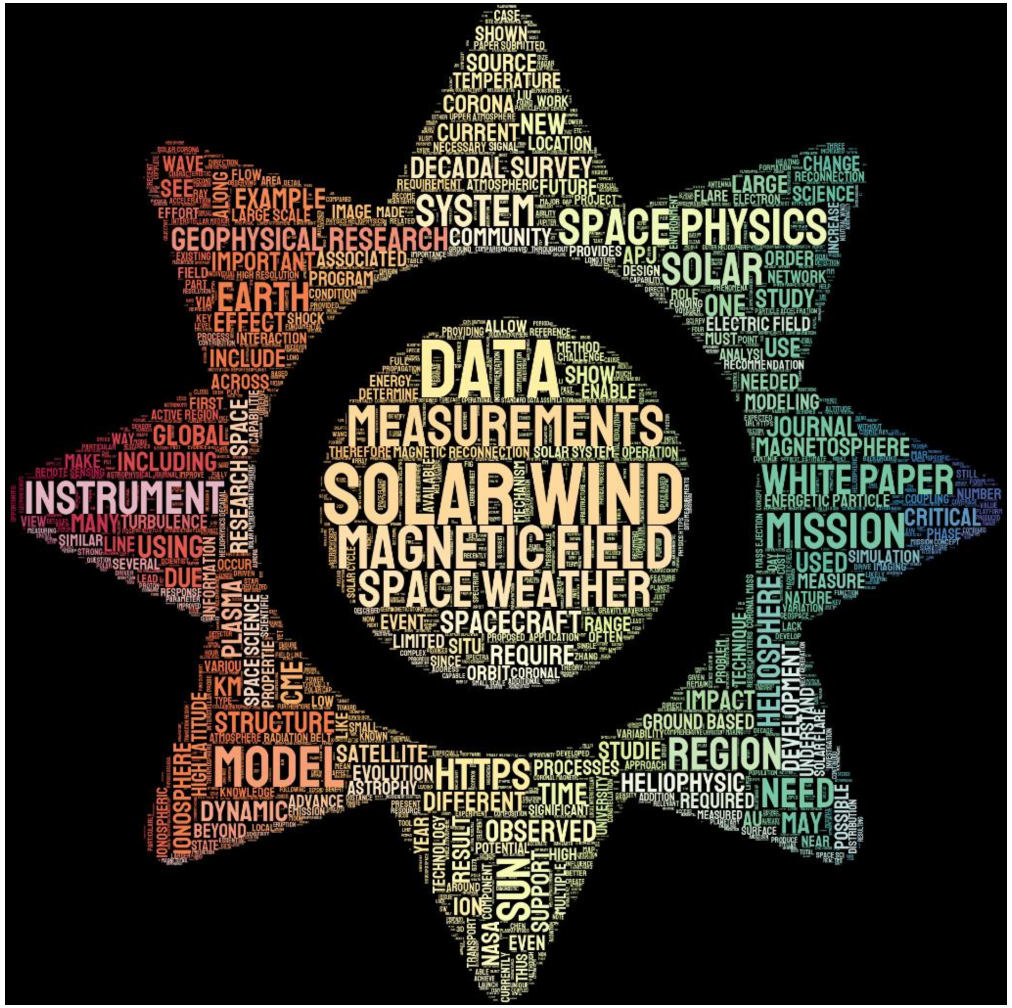
Stephen A. Fuselier SwRI Co-Chair	**Robyn M. Millan** Dartmouth Co-Chair	**Fran Bagenal** Univ. of Colorado, Boulder	**Timothy S. Bastian** NRAO
Sarbani Basu Yale University	**Richard Doe** Cornell Technical Services	**Eileen Dukes** Interplanetary Horizons	**Scott L. England** Virginia Tech
Allison 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



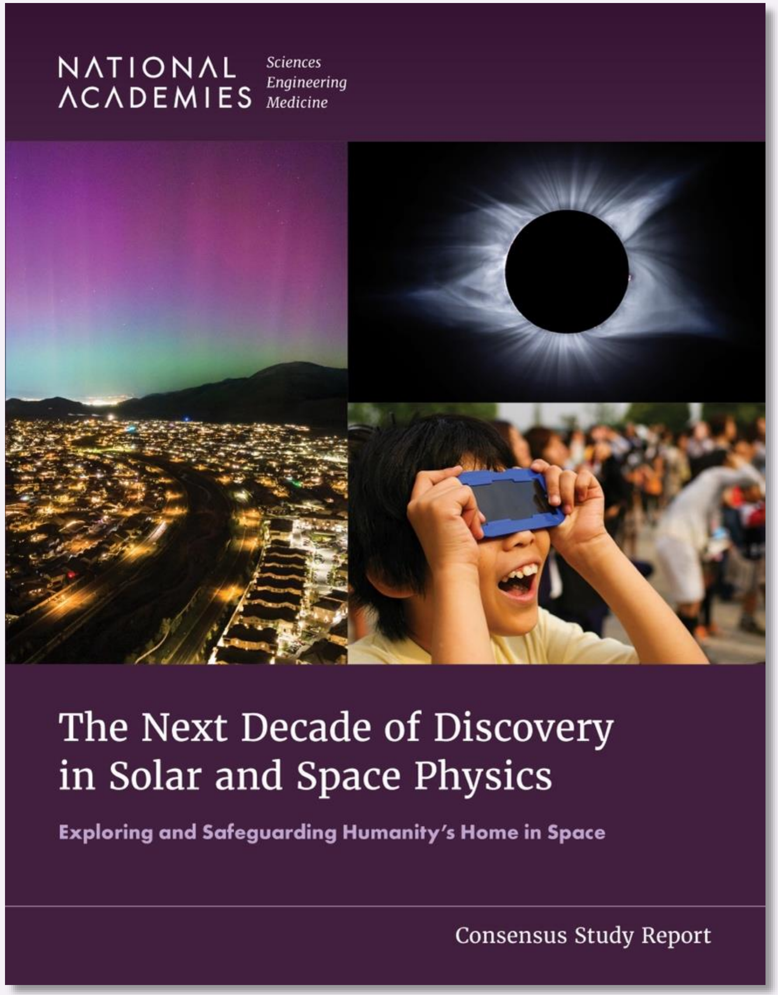
Built on Community Input



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

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

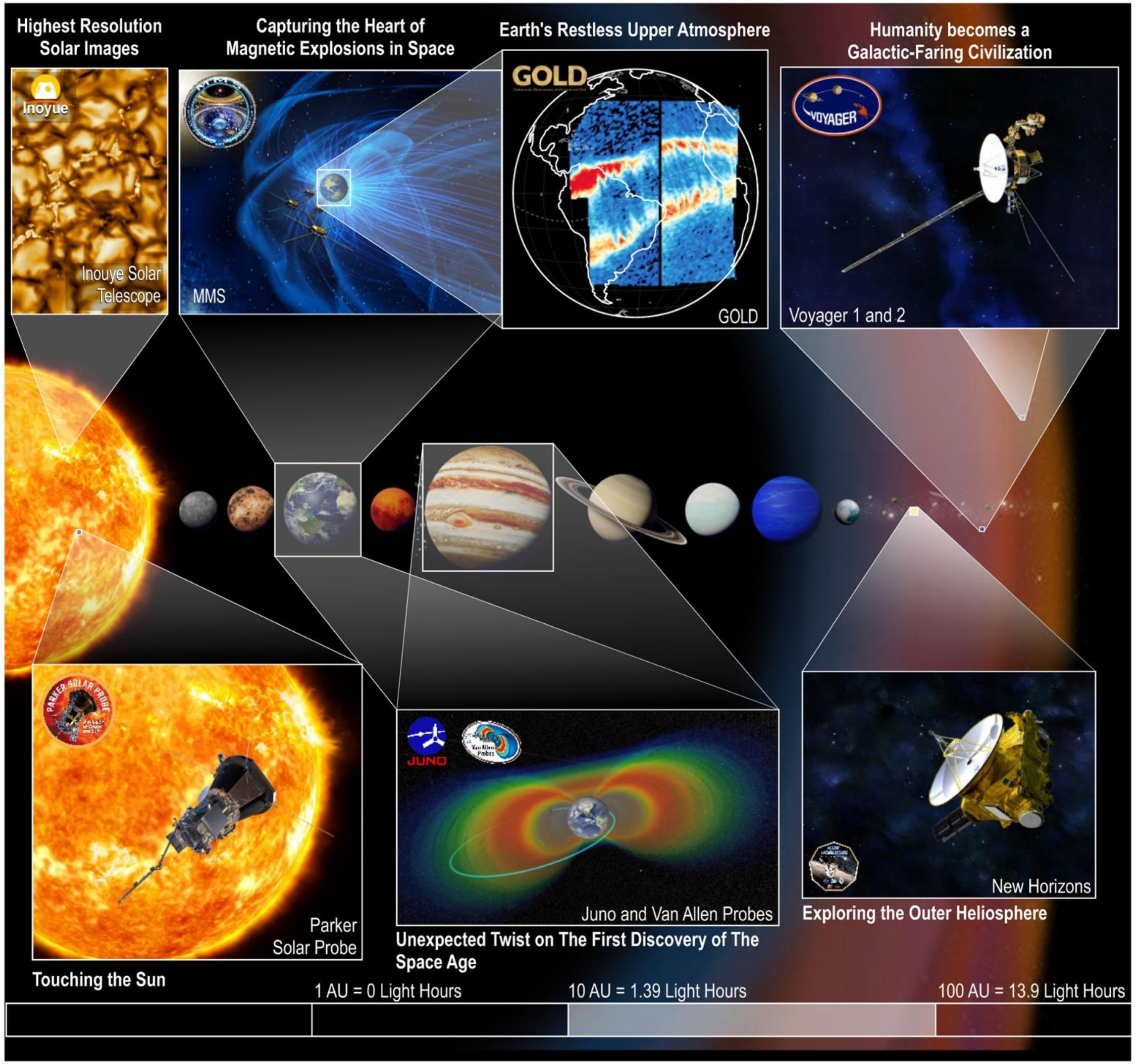
Ch. 4. Towards a Thriving Solar and Space Physics Community

Ch. 5. Comprehensive Research Strategy

Ch. 6. Summary of Research Strategy and Budget Implications

Appendices

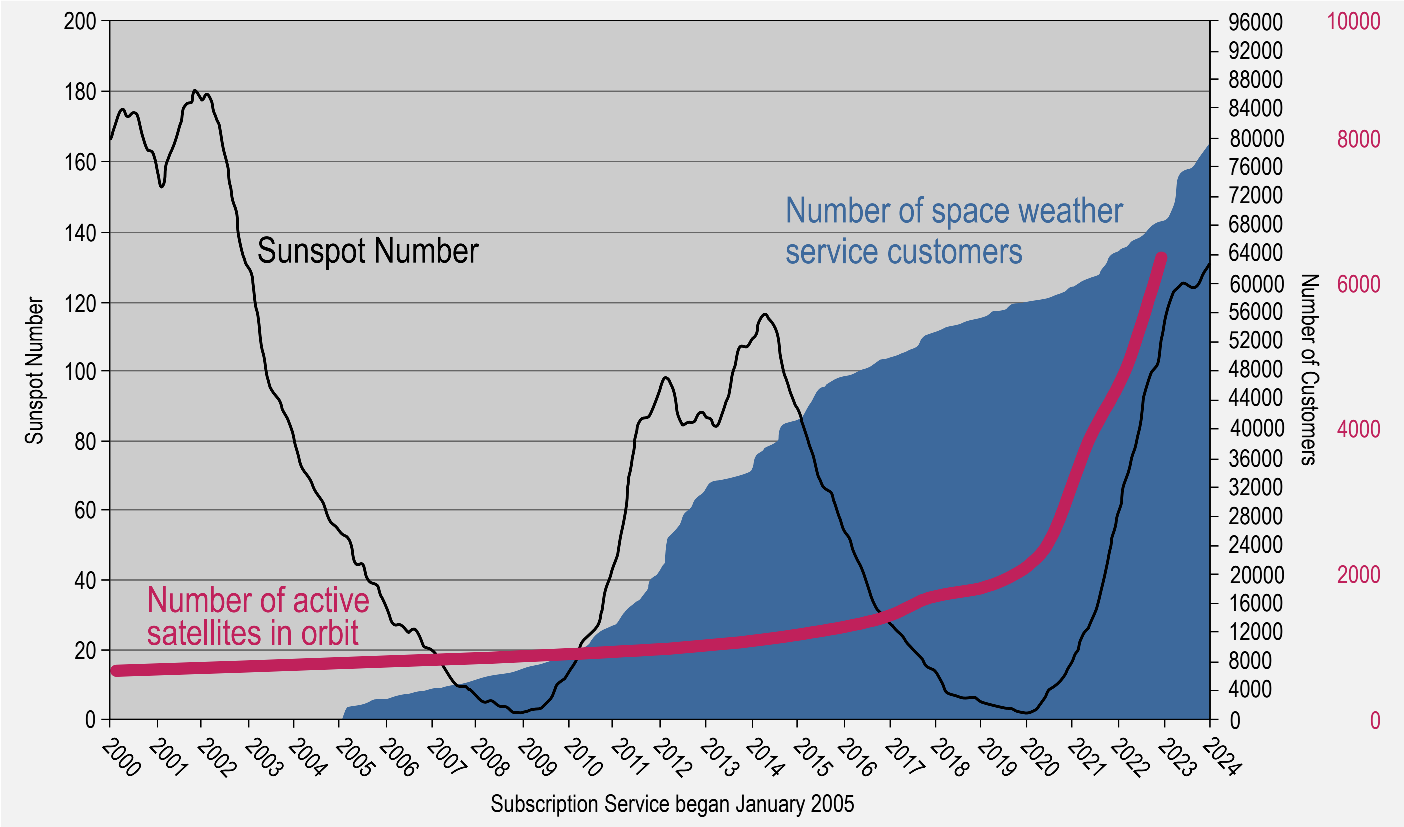
- Statement of Task
- Panel Reports
- Technical, Risk, and Cost Evaluation



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.

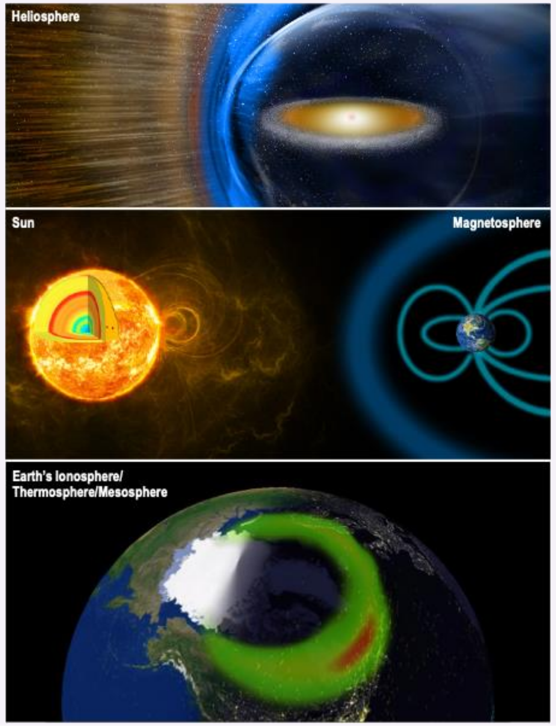
and to serve humanity

We analyze the space environment to project its future changes.

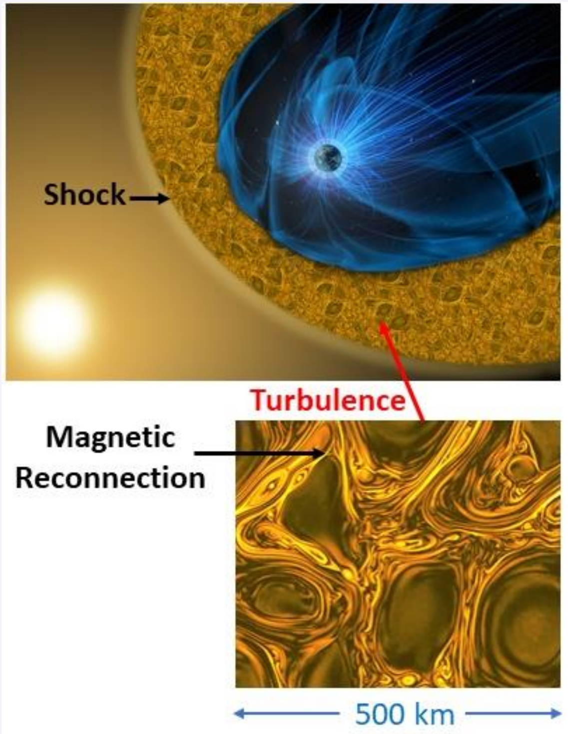
We develop tools and products to issue space weather warnings and forecasts and to safeguard activities at and beyond Earth.

Science Themes *to discover*

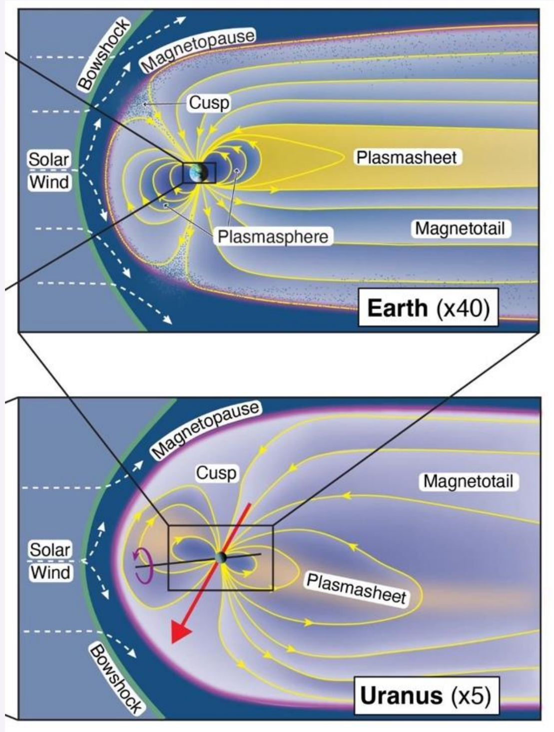
Sun-Earth-Space:
Our Interconnected Home



A Laboratory in Space:
Building Blocks of Understanding



New Environments:
Exploring our Cosmic Neighborhood and Beyond



GUIDING Q'S

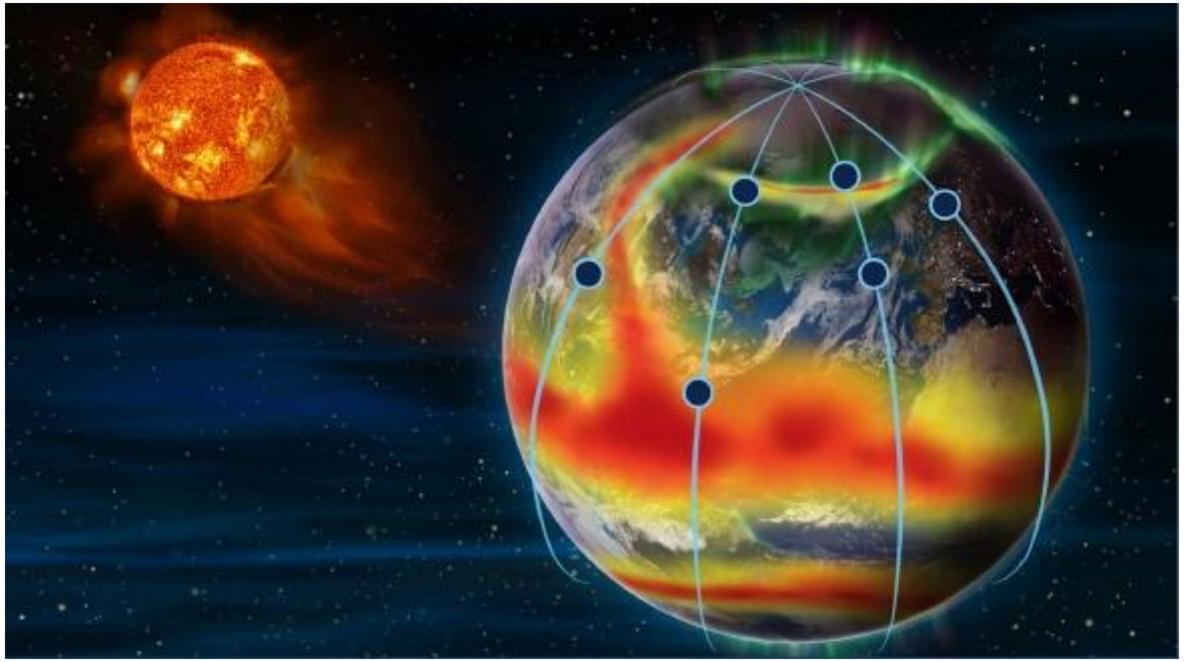
How does our Heliosphere function as a nested system?

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.

GUIDING Q'S

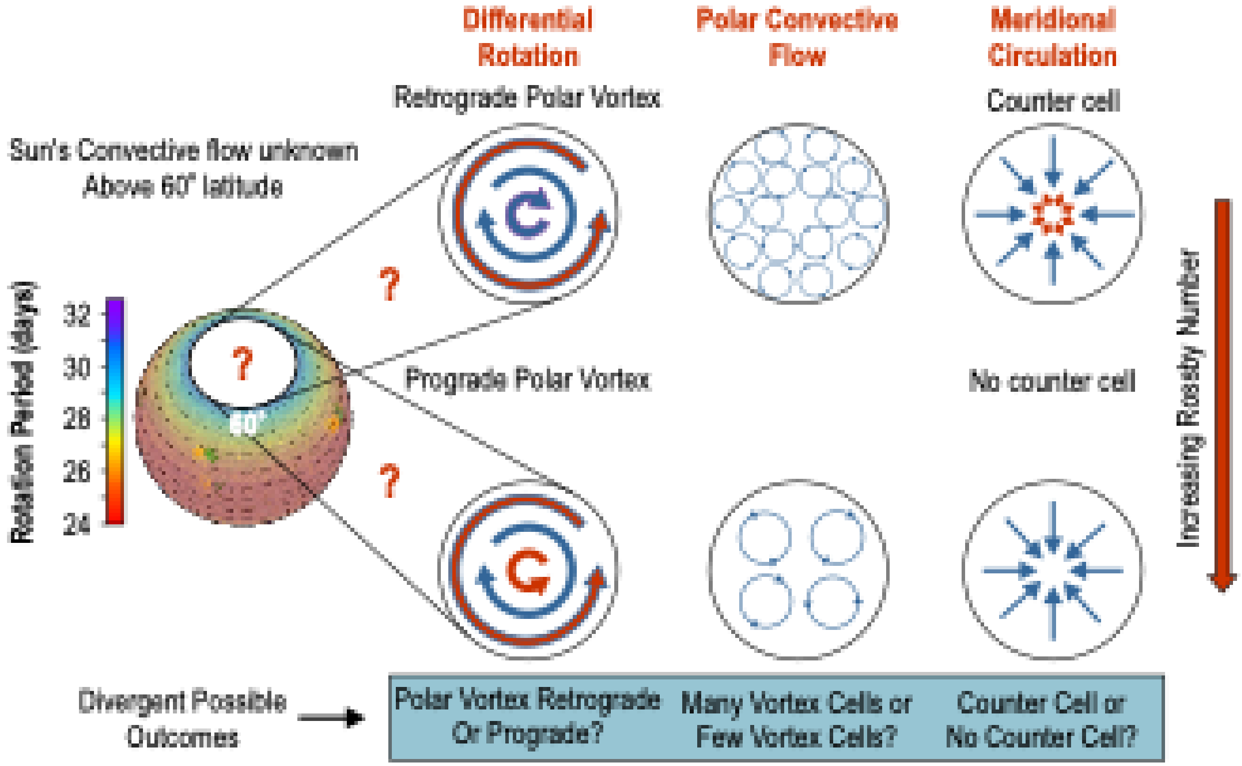
How is the Sun's global magnetic field created and maintained, and what causes its cyclical variations?

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

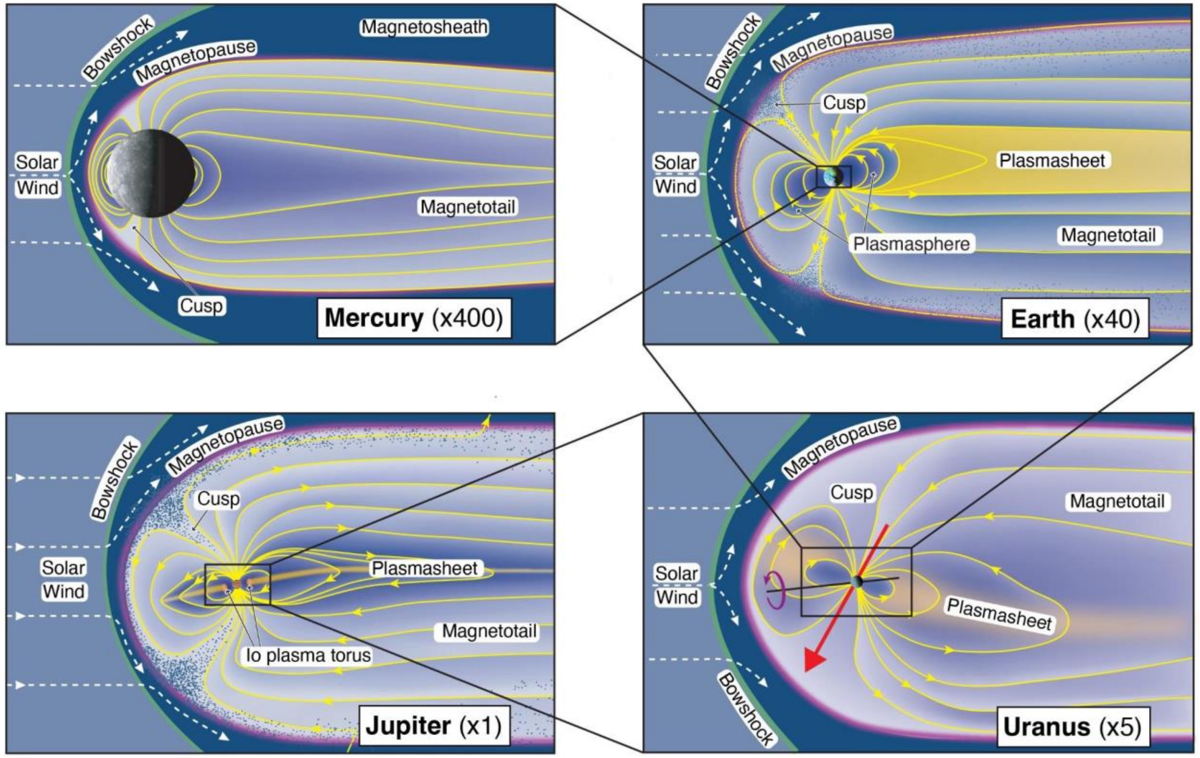
What can we learn from comparative studies of planetary systems?

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

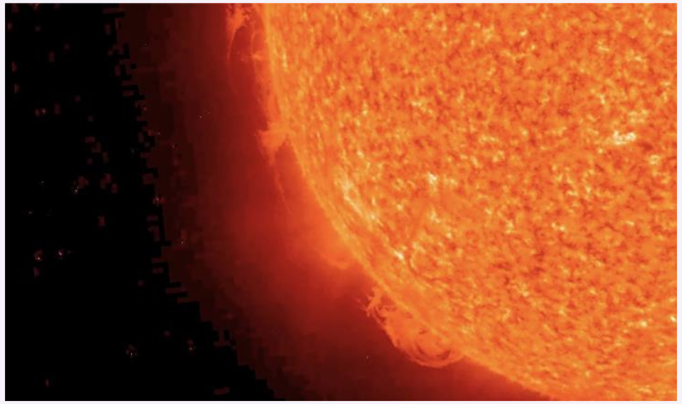


- Huge differences in magnetosphere scales are evidence for different external and internal drivers.
- Differences and similarities provide guidance for understanding exoplanet magnetospheres.

Space Weather
Science-Space Weather Linkage

Space Weather Themes *to serve humanity*

System of Systems:
Drivers of Space Weather

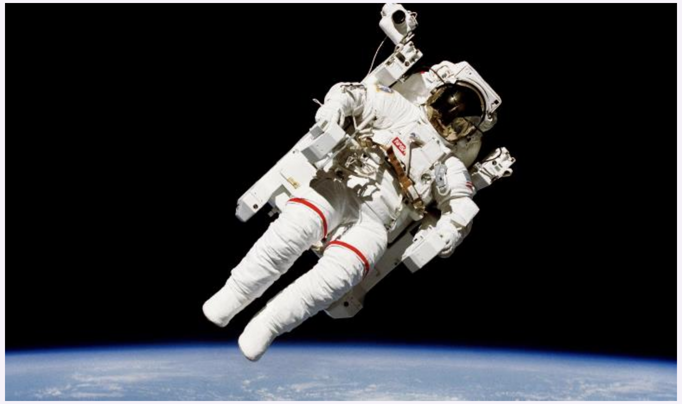


- Solar Eruptions
- Atmospheric Driving

Space Weather Responses
of the Physical System

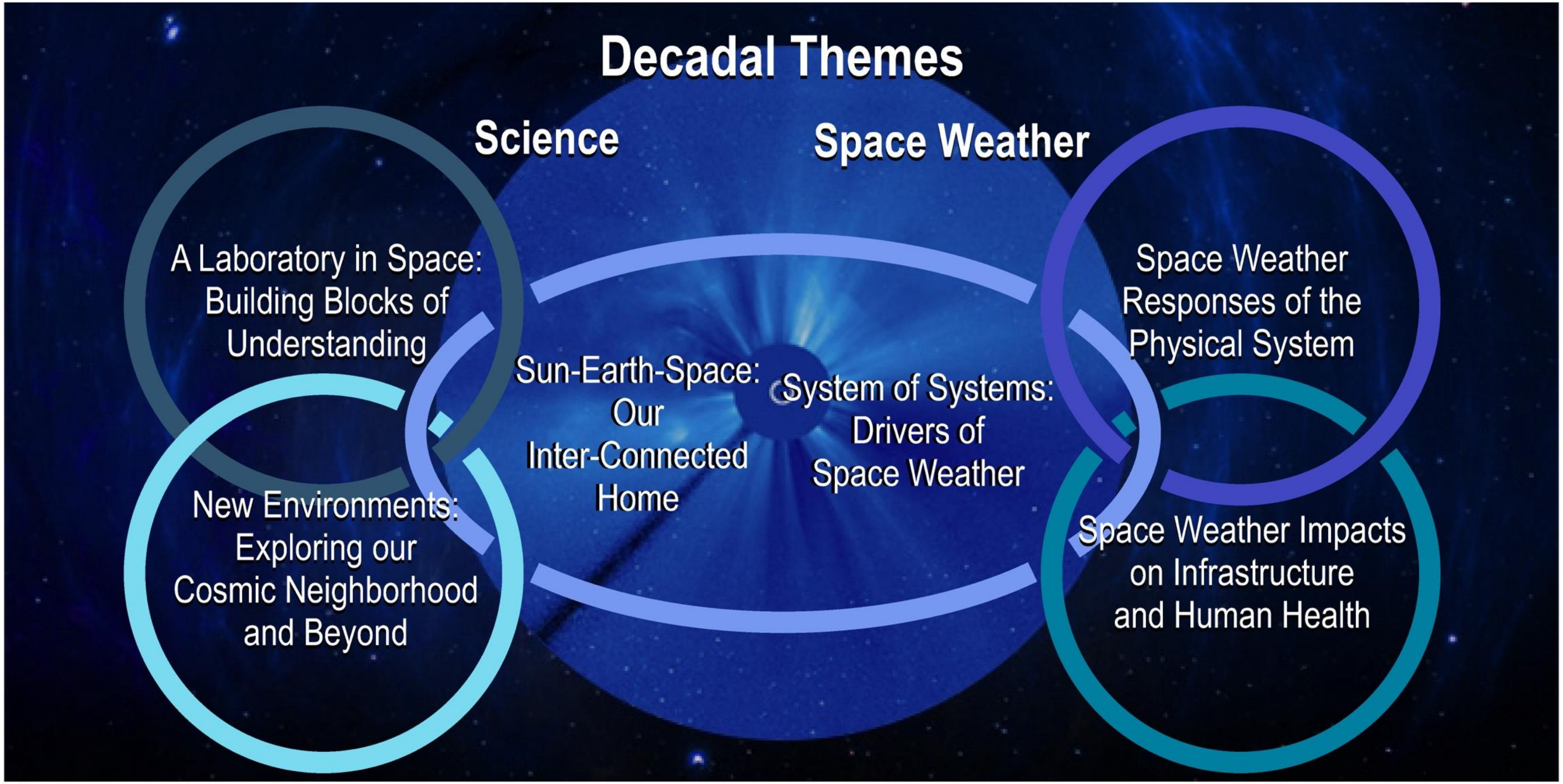
- Low Earth Orbit (LEO) Neutral Density
- Ionospheric State
- Magnetospheric State

Space Weather Impacts
On Infrastructure and Human Health



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

Science and Space Weather Themes are Integrally Linked



A thematic roadmap of discovery and application for the next decade

State of the Profession

State of the Profession

to support, unify, and strengthen the field

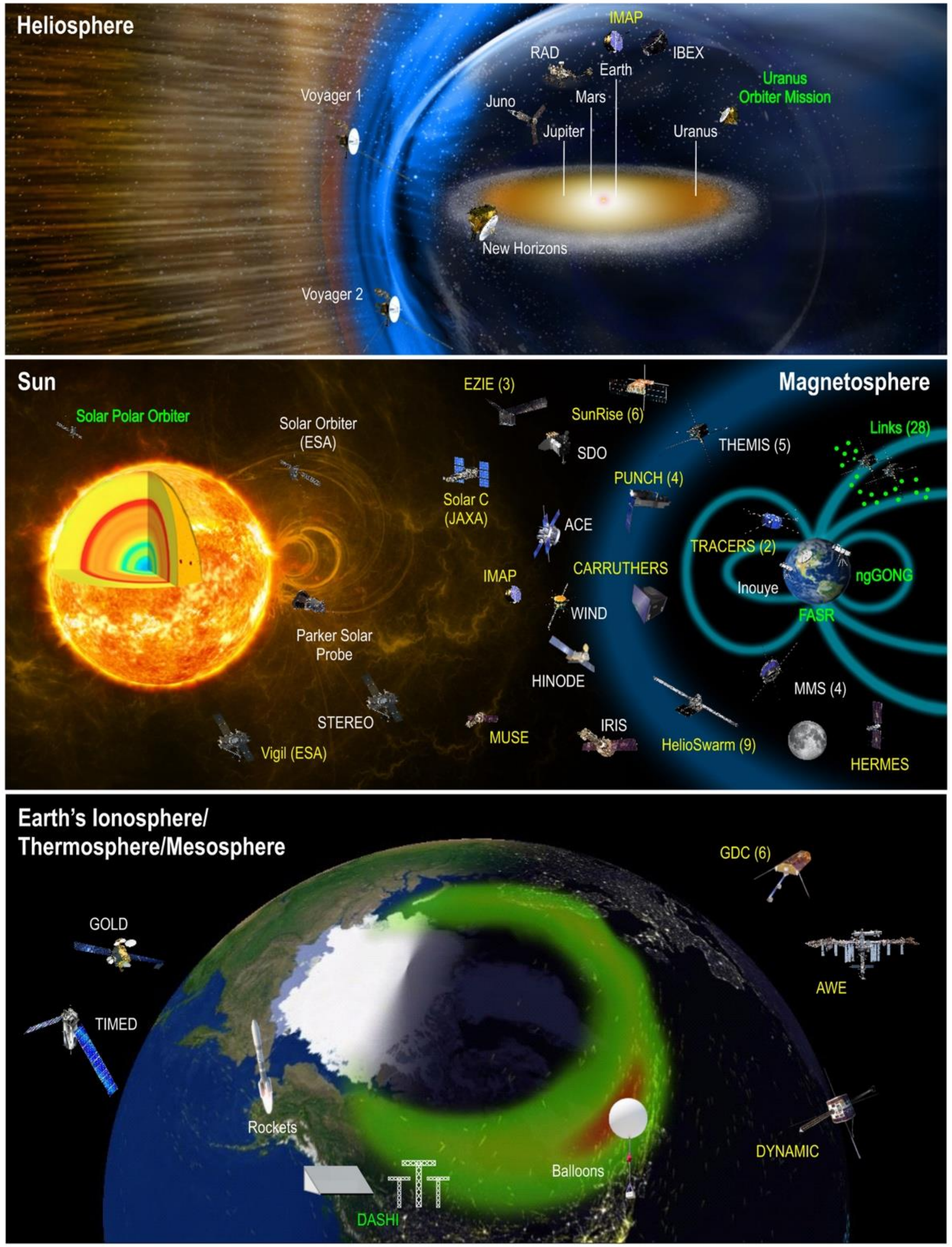
- Building the workforce for tomorrow requires recruiting the best talent through:
  - a sustainable structure for continuous, longitudinal data gathering
  - Common name for the field?
  - expanding education and outreach
  - growing the solar and space physics faculty
  - increasing opportunities for student research
  - Enhancing public communication
  - Enabling citizen science

Comprehensive Research Strategy

Decadal Research Strategy

CRITICAL ELEMENTS

Integrated HelioSystems Laboratory	DRIVE+ - Enhancements in Research and Technology Programs	Preparation for Beyond the Decade
• Ground-based assets • NASA Flagship-Level Community Science Modeling Program • Space-Based Assets	• Workforce of Tomorrow • Collaboration and Coordination • Enhancements in Science support and Research Tools • Technology Development	• Technology development • Cross Divisional and Cross-Directorate Coordination at NASA • Future Opportunities for International Coordination • Communication Infrastructure



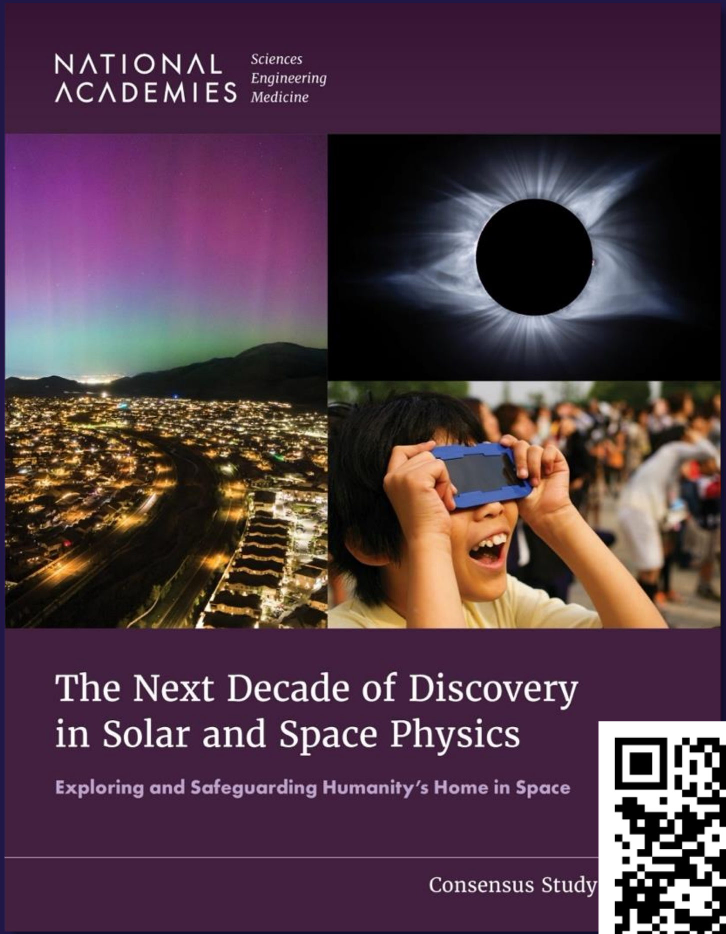
Integrated HelioSystems Laboratory

- 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.

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

Thank You



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Backup Slides

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)

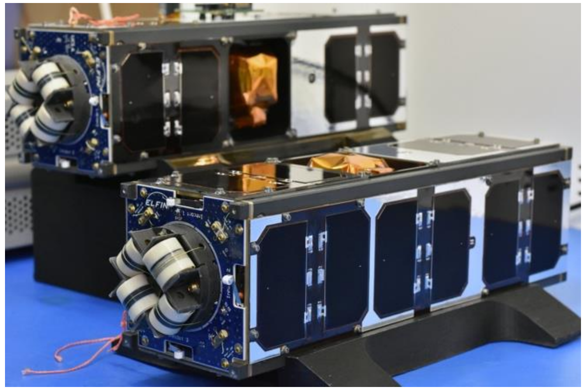
Recommendation 5-3: Major Research Equipment and Facilities Construction (MREFC)

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

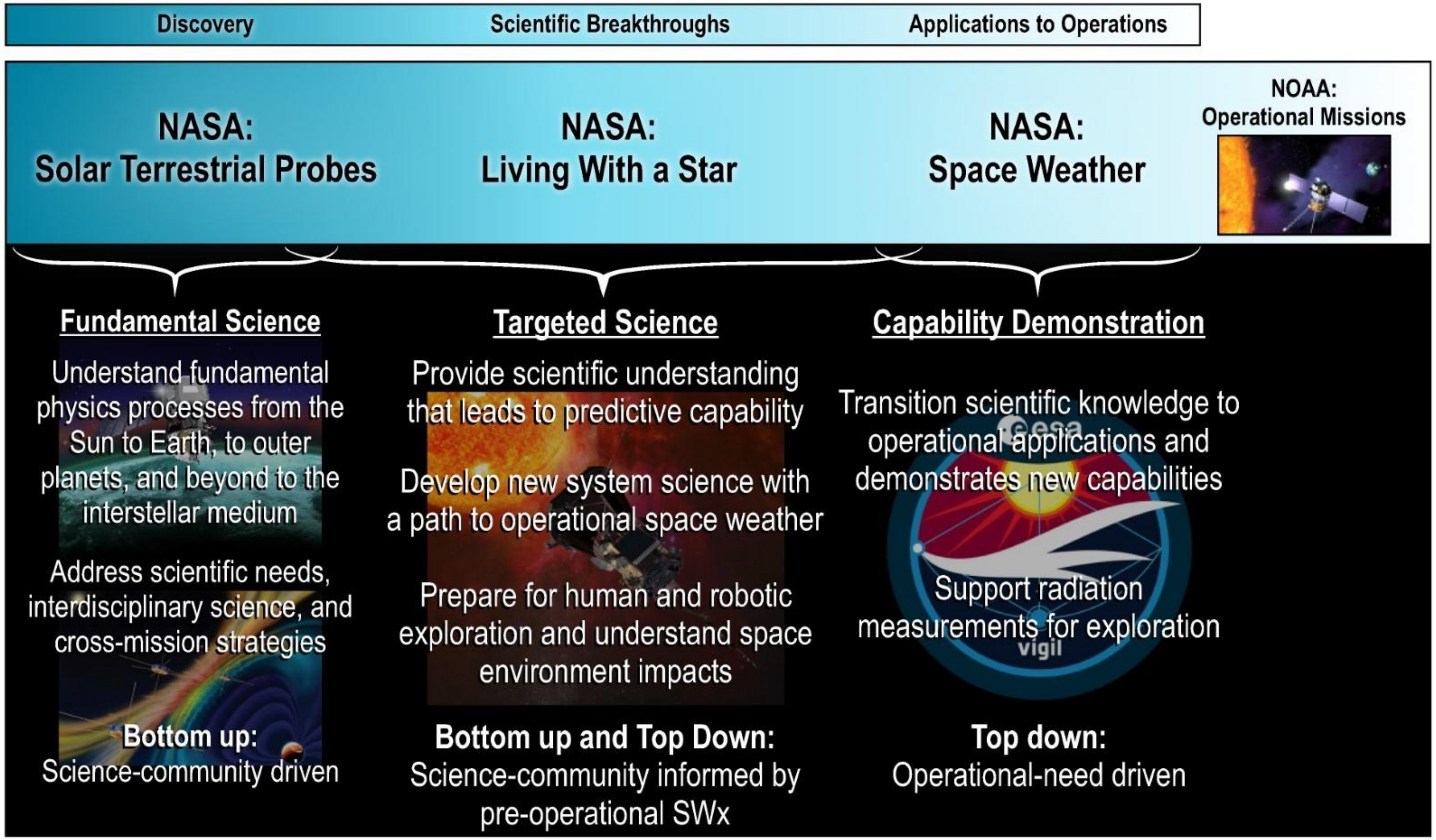
Launch of the Sunrise balloon payload
Source: University Corporation for Atmospheric Research

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



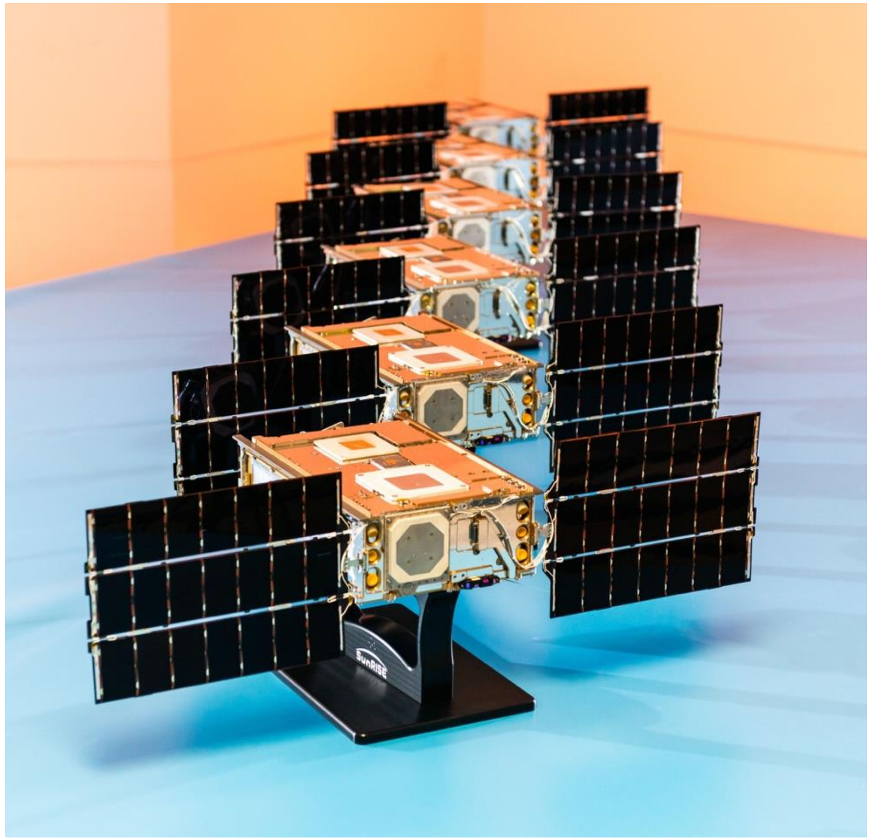
Space Weather Program is an effective bridge between the NASA science missions and NOAA operational missions

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
- …

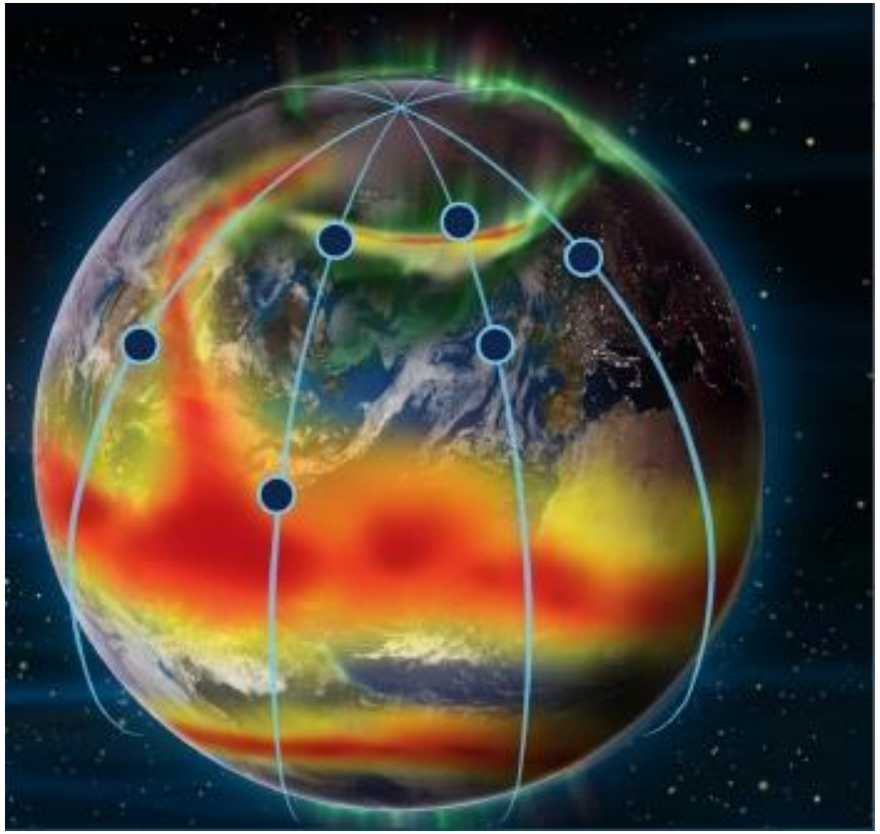


Six CubeSats for the SUNRISE Mission of Opportunity. Credit: Space Dynamics Laboratory/Allison Bills

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

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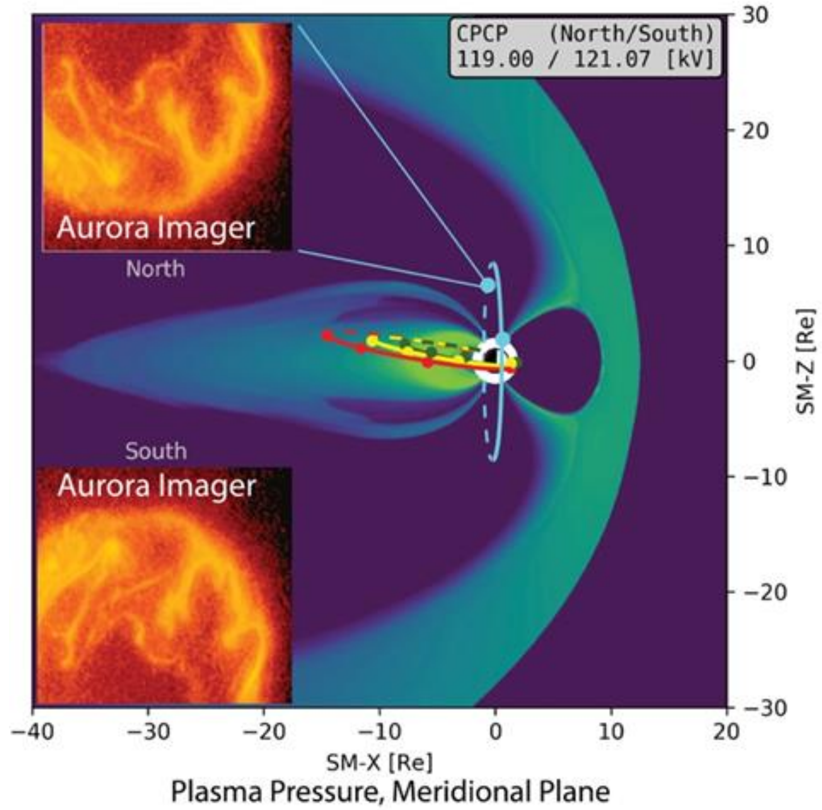
Decadal Talking Points – Chapter 5: GDC/DYNAMIC

- Guidance given to the committee
  - Do not re-prioritize the program of record
  - Reaffirm the priority science for GDC and DYNAMIC
  - The Decadal does this assuming GDC/DYNAMIC are the next LWS and STP missions
    - Provides several reasons why these missions should be done, including the space weather component

Highest-Priority New STP Mission

Notional Mission: Links between Regions and Scales in Geospace



Theme: Sun-Earth-Space

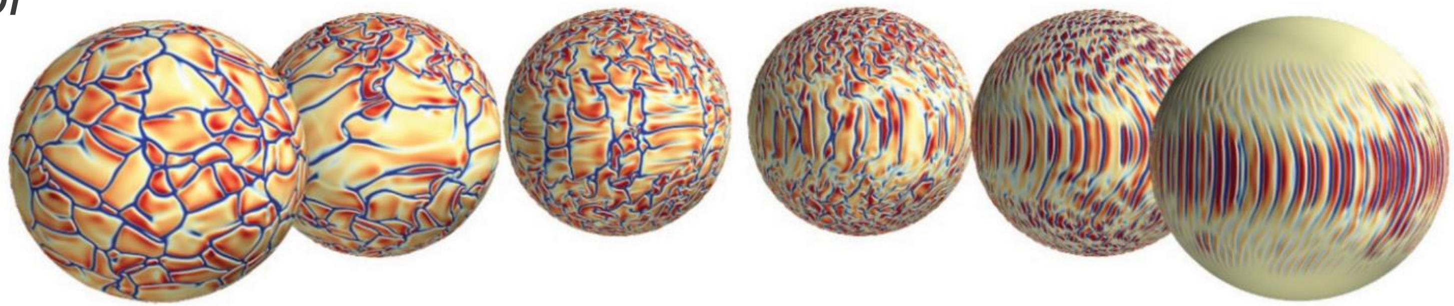
- *Links discovers the connections across regions and scales in the near-Earth space environment.*

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.*



Decadal Talking Points – Chapter 5: New LWS and STP Missions

- Two new missions recommended after GDC and DYNAMIC
- Both missions fill strategic gaps in science and space weather research
- There is no queue
  - 12 missions were costed through the required TRACE process
  - These are listed in an appendix NOT in priority order
  - They are provided in an appendix because they are not a recommendation

Enhancements in Research and Technology

10+6

10 DRIVE+ and 6 Related Recommendations

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

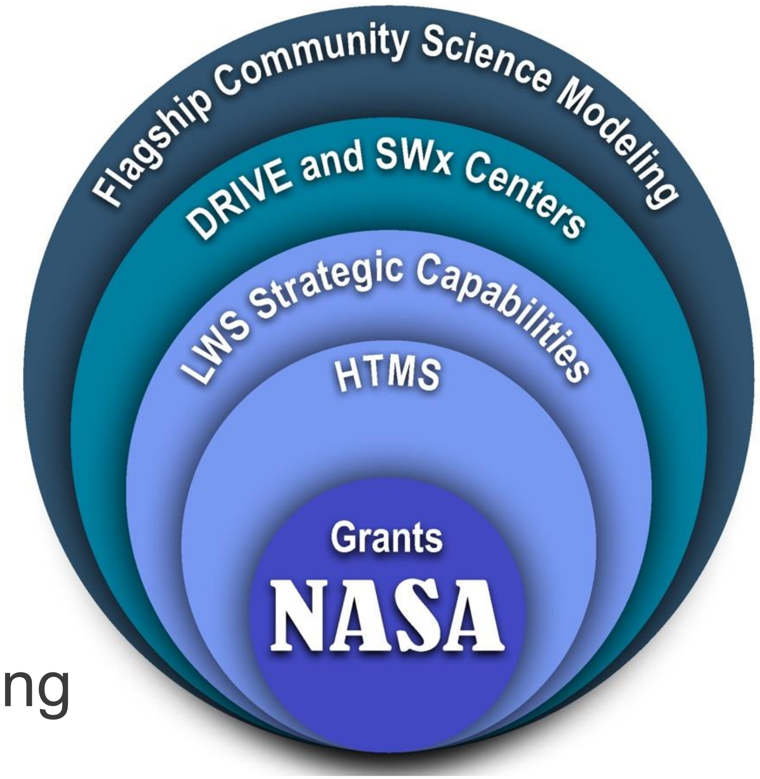
Rec. 5-17: Theory and modeling for strategic missions

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

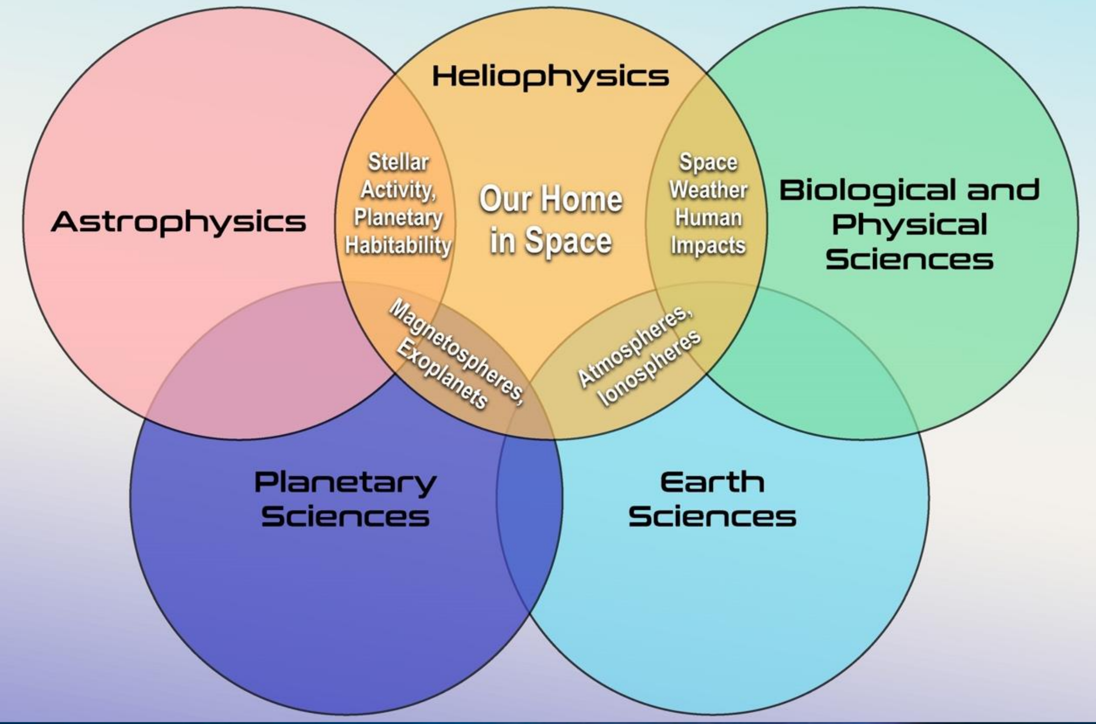
Rec. 5-19: Instrument development

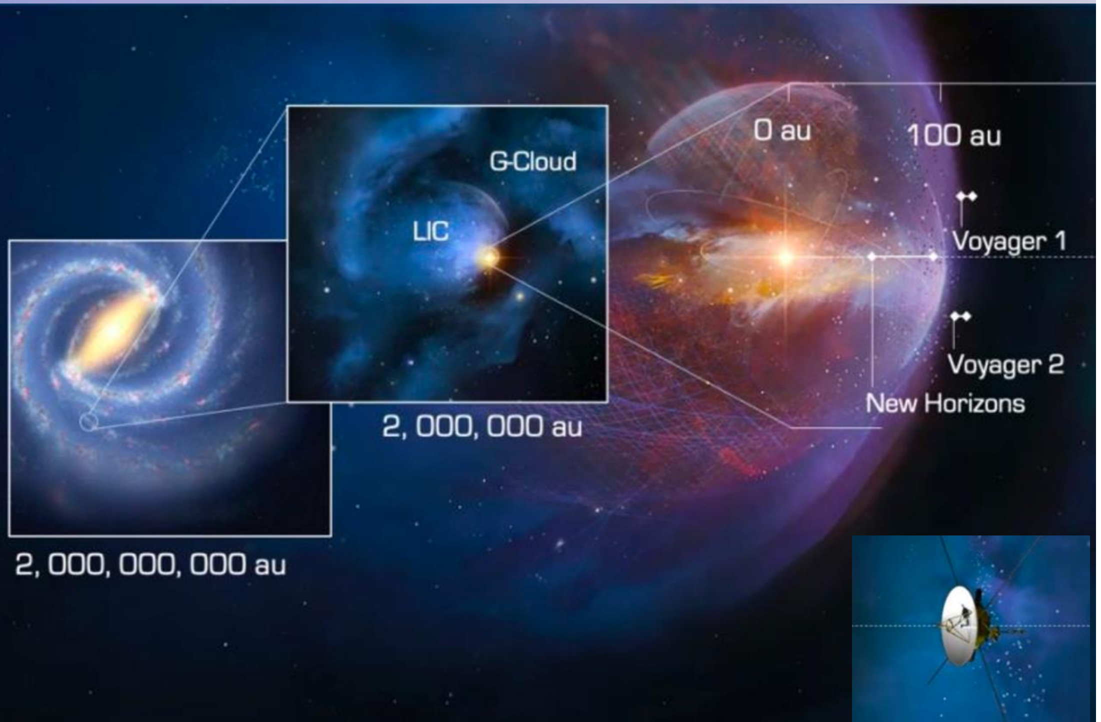
A New NASA Flagship-Level Community Science Modeling Program

- 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…



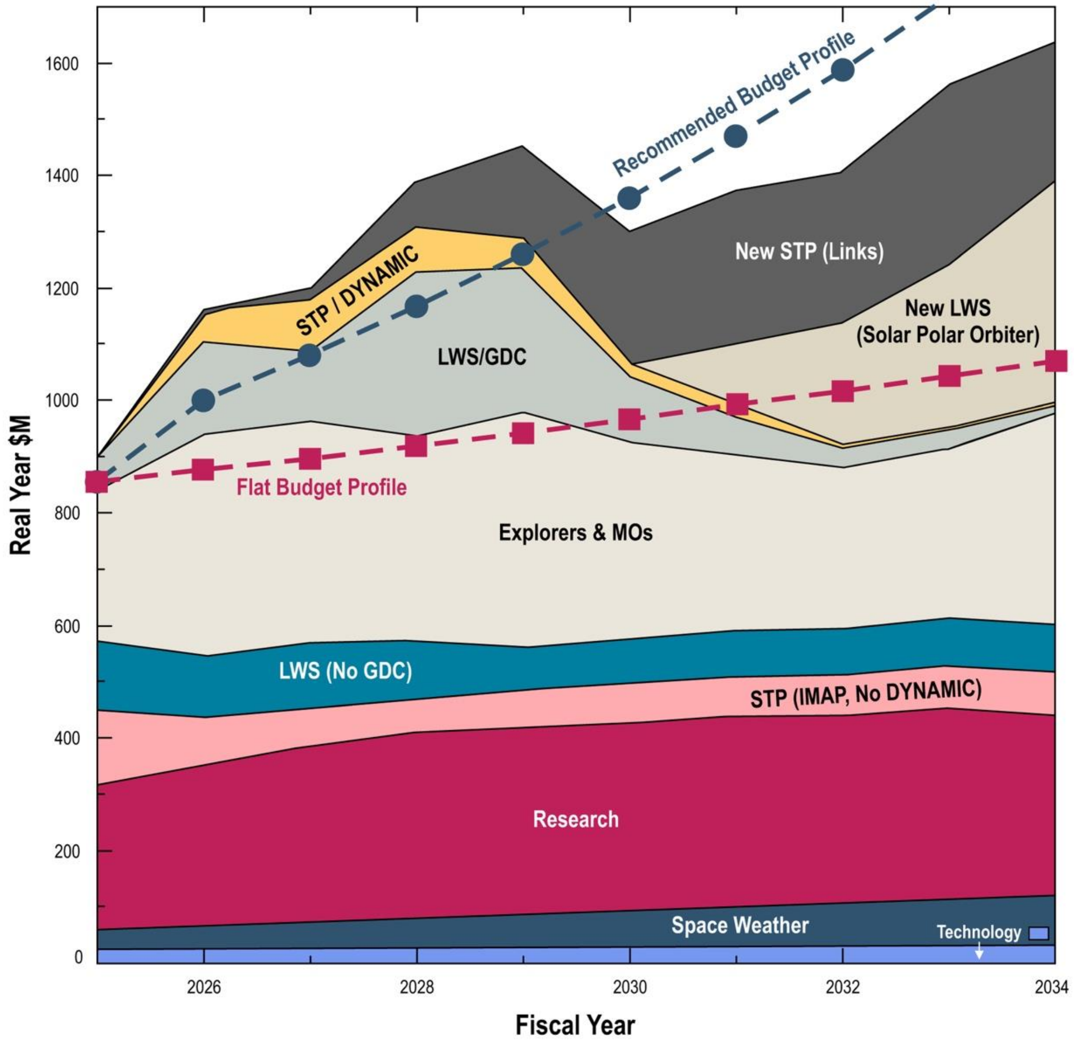


Preparation for the Decade and Beyond

- 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
  - Uranus Orbiter Probe
  - A mission to interstellar space
  - 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



NASA Decision Rules (Full Text)

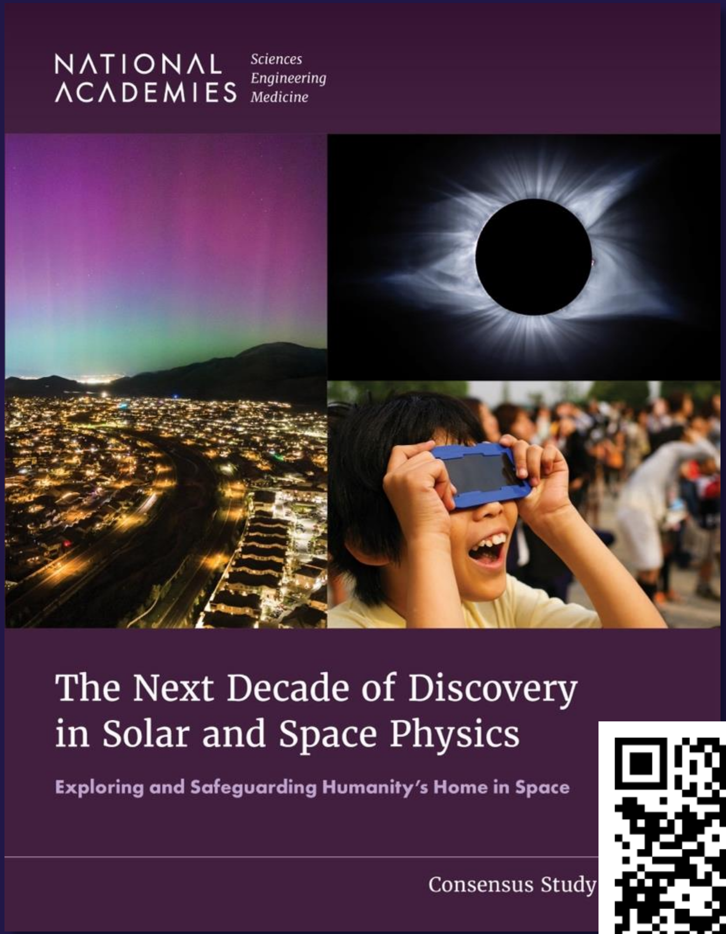
Recommendation 6-1: If there is insufficient funding to accomplish the entire research strategy, then NASA should implement decision rules in the following order:

- 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.

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.



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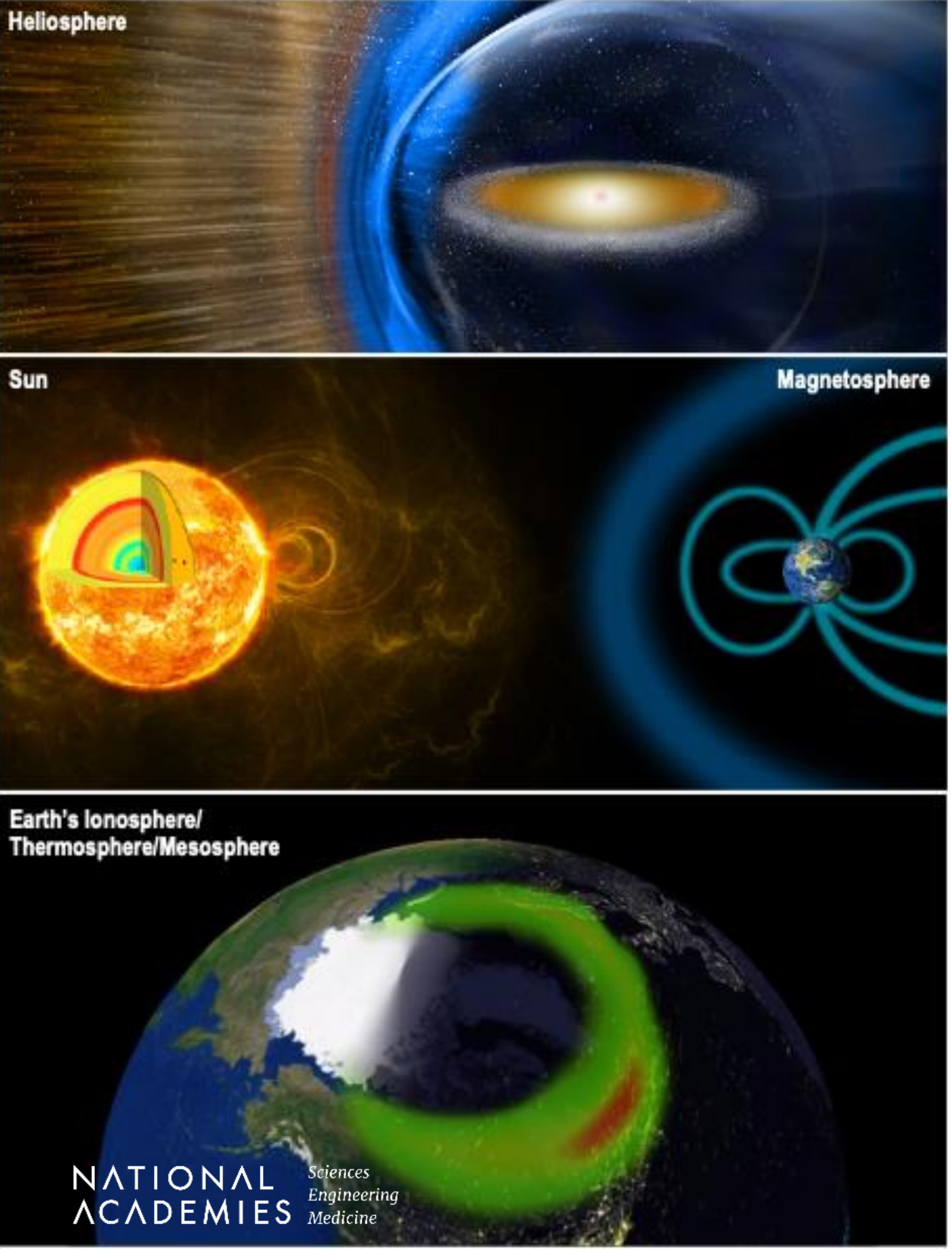
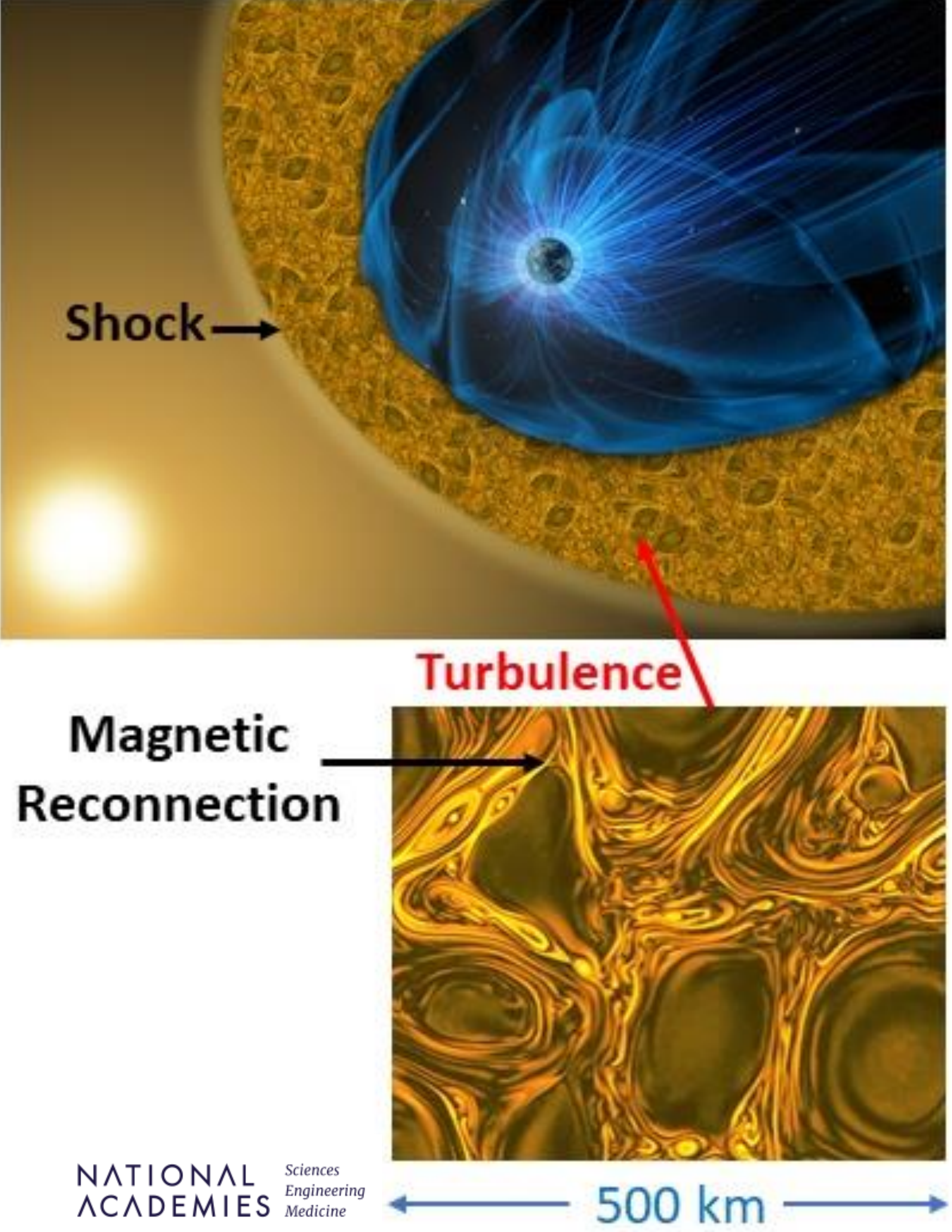
Exploration is driven by humanity's fundamental curiosity about the world, and solar and space scientists have always been intrepid explorers.

Backup 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?

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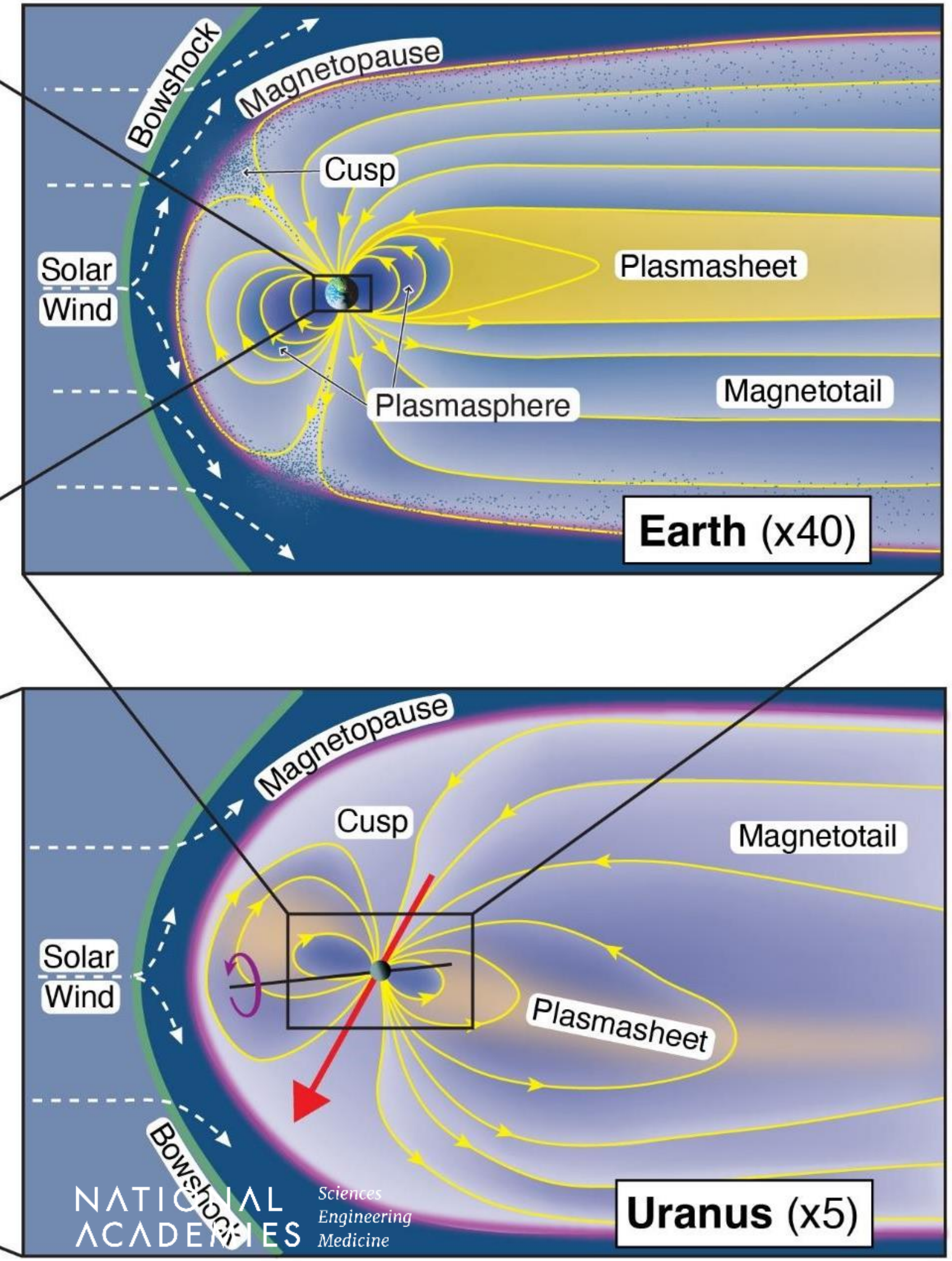

New Environments
Guiding Questions

- 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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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

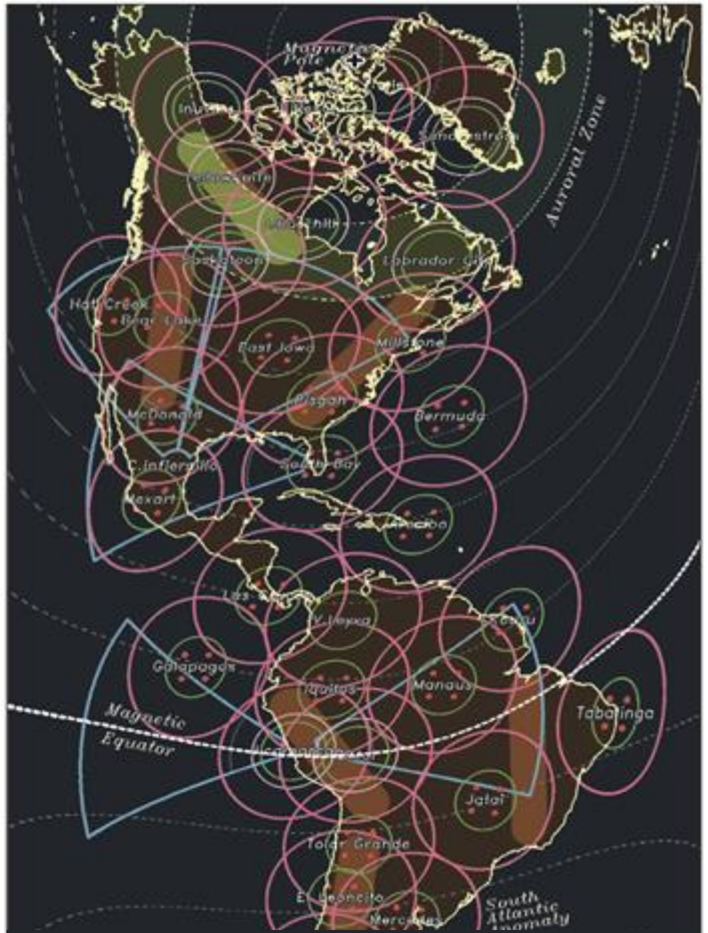
Recommendation 5-3: The highest-priority large Major Research Equipment and Facilities Construction-scale project for the National Science Foundation for the next decade is the Next Generation Global Oscillations Network Group (ngGONG). In light of its importance to space weather, the development, implementation, 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.

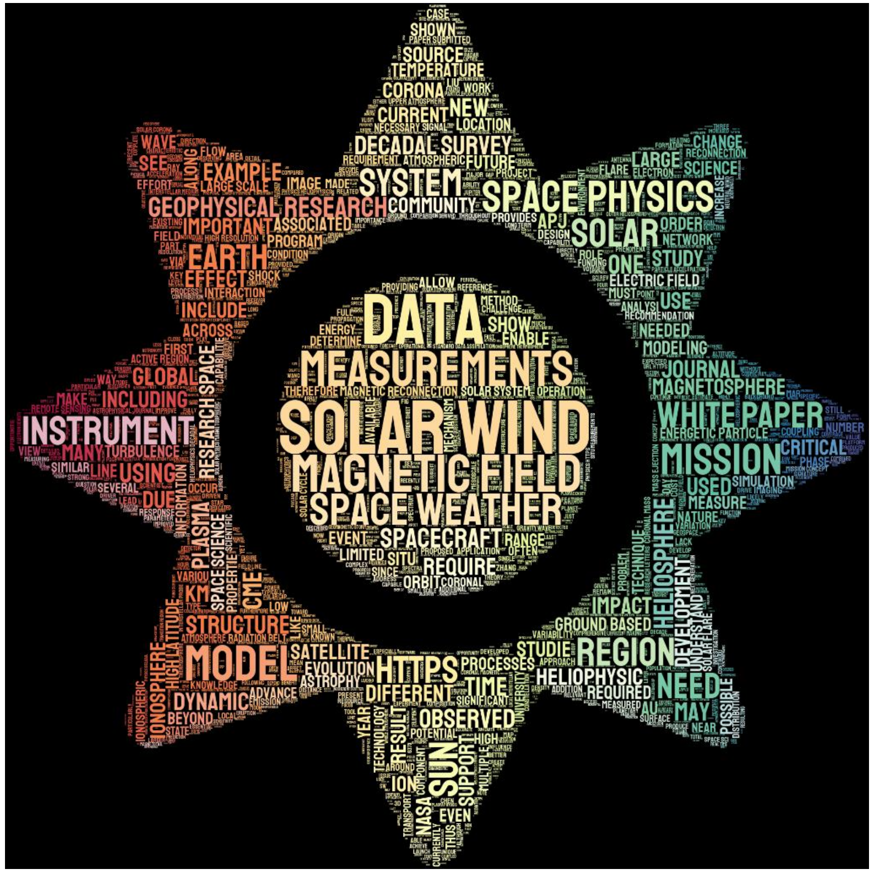
To foster the integration of the HSL, NASA, NSF, and NOAA need to enhance their cooperation on ground-based projects



Concept for DASHI - one of two recommended MSRI projects

Enhancements to NASA Research Programs

- A significant amount of archival data has not been fully analyzed, leading to an underutilization of prior investments
- The cost of doing research has increased due to e.g., inflation, increases in graduate student stipends, and increased costs associated with open science requirements
- Proposal pressure has increased leading to selection rates below the healthy rate of 25%

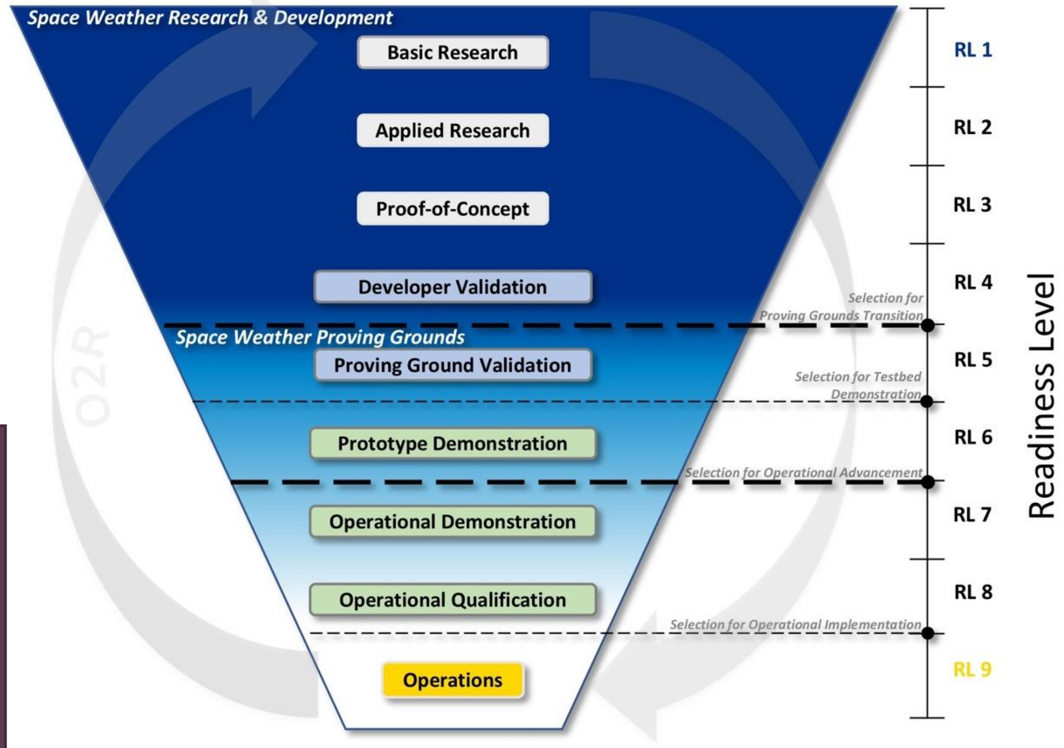


Recommendation 5-15: Support for Analysis of Archival Data

Recommendation 5-16: Augmentation of the Heliophysics Research Program

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