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:
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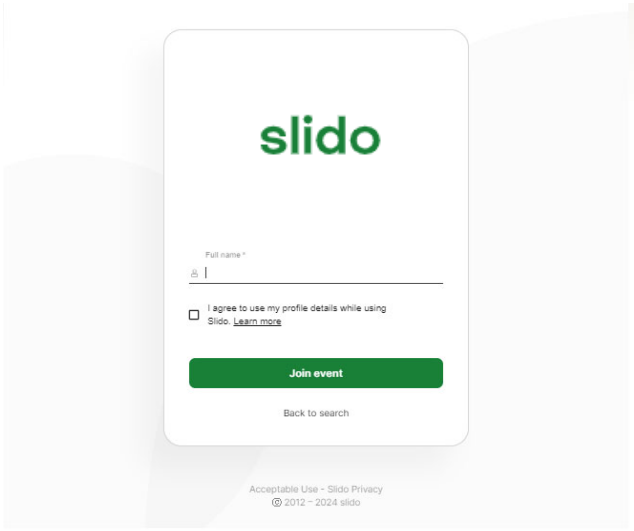
Please submit questions using the slido box below the webcast window or visit slido.com with ***event code #SSPH***



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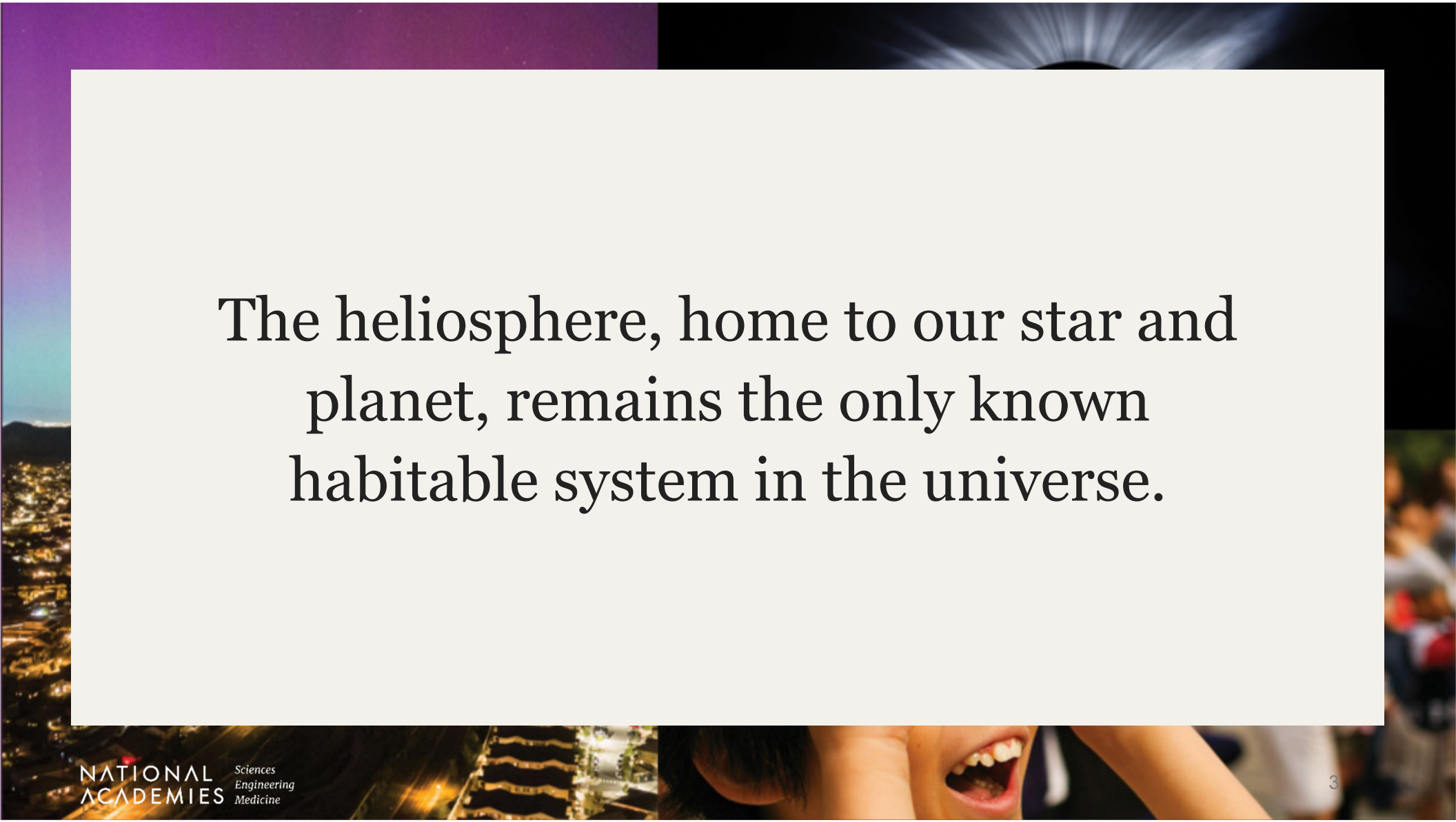

The heliosphere, home to our star and planet, remains the only known habitable system in the universe.

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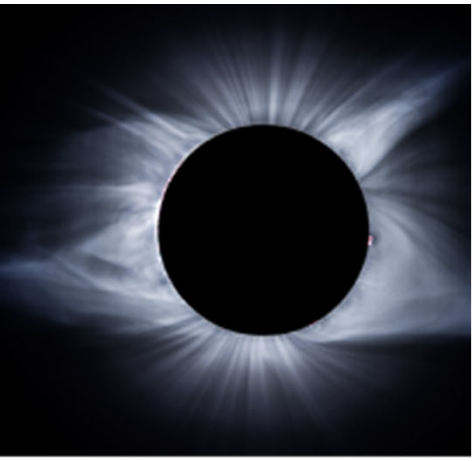
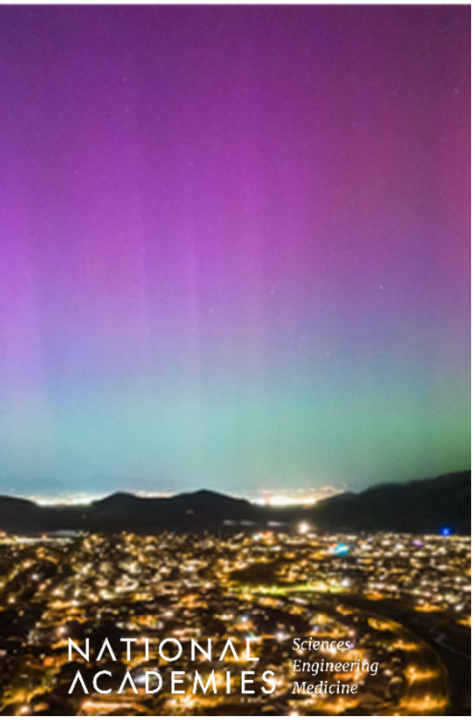
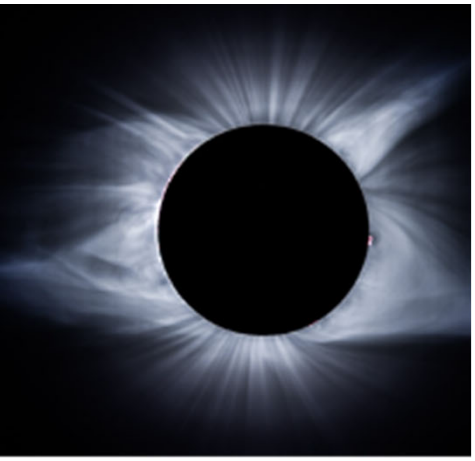


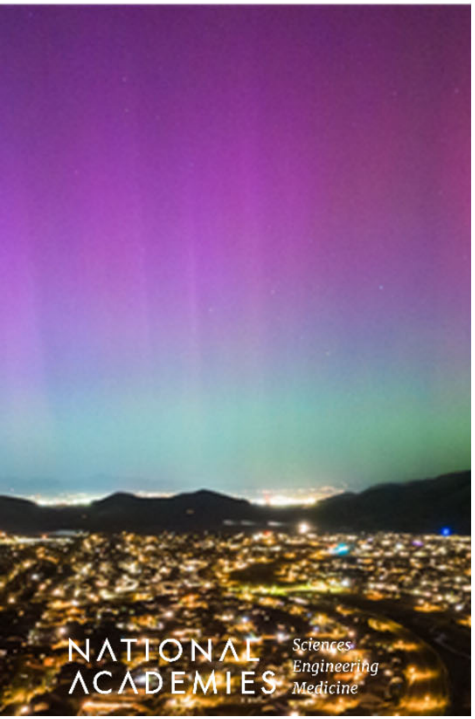


The Next Decade

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

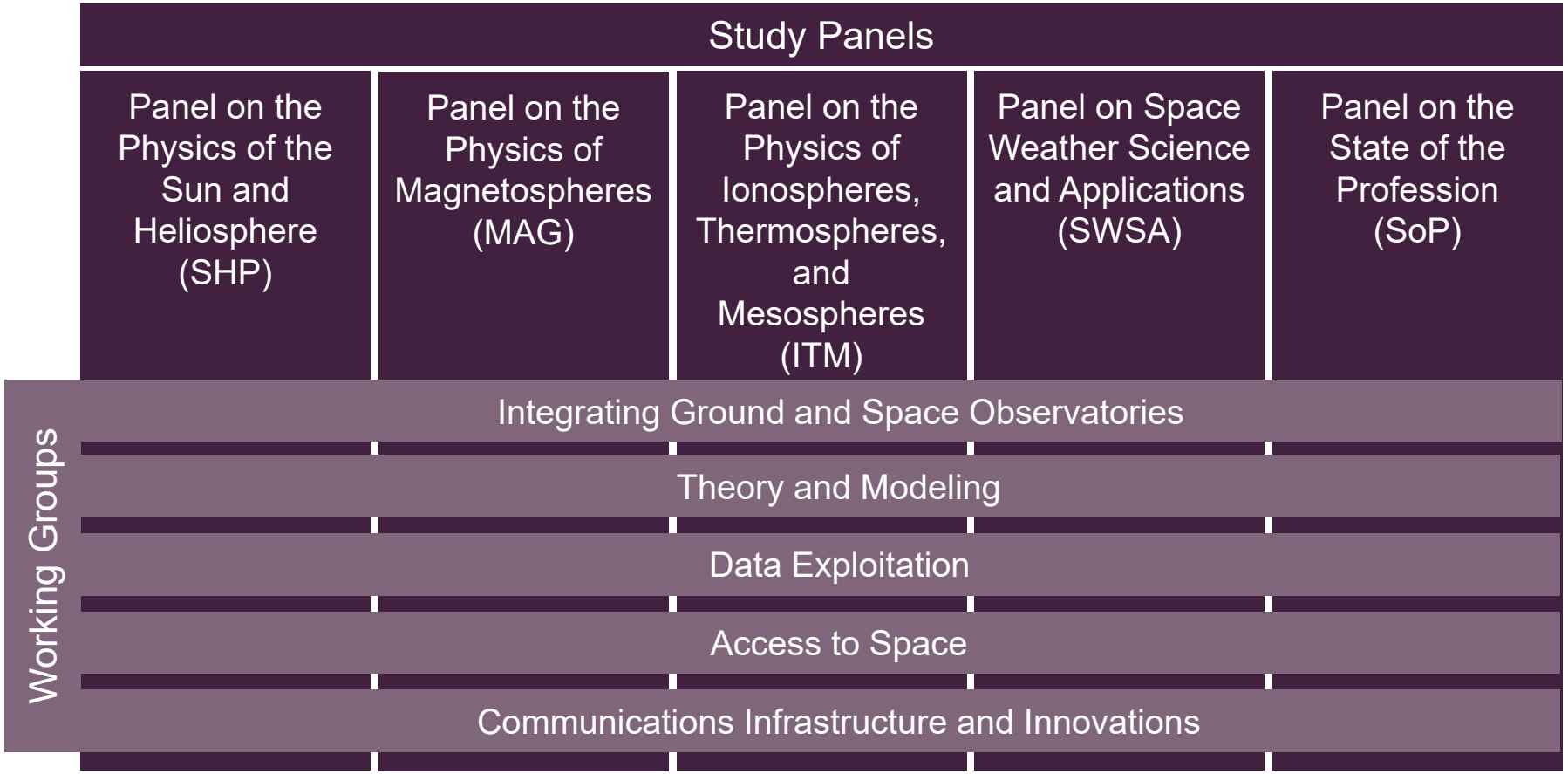
Additional guidance and agency requests were also provided.

Steering Committee

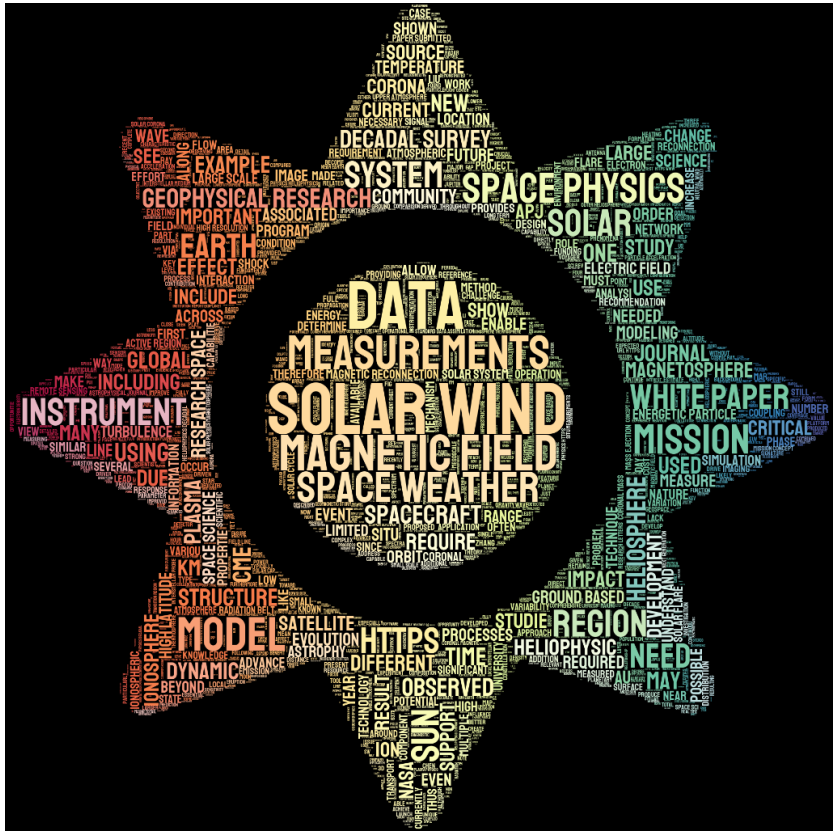
Stephen A. Fuselier SwRI Co-Chair	**Robyn M. Millan** Dartmouth Co-Chair	**Fran Bagenal** Univ. of Colorado, Boulder	**Timothy S. Bastian** NRAO
Sarbani Basu Yale University	**Richard Doe** Cornell Technical Services	**Eileen Dukes** Interplanetary Horizons	**Scott L. England** Virginia Tech
Allison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

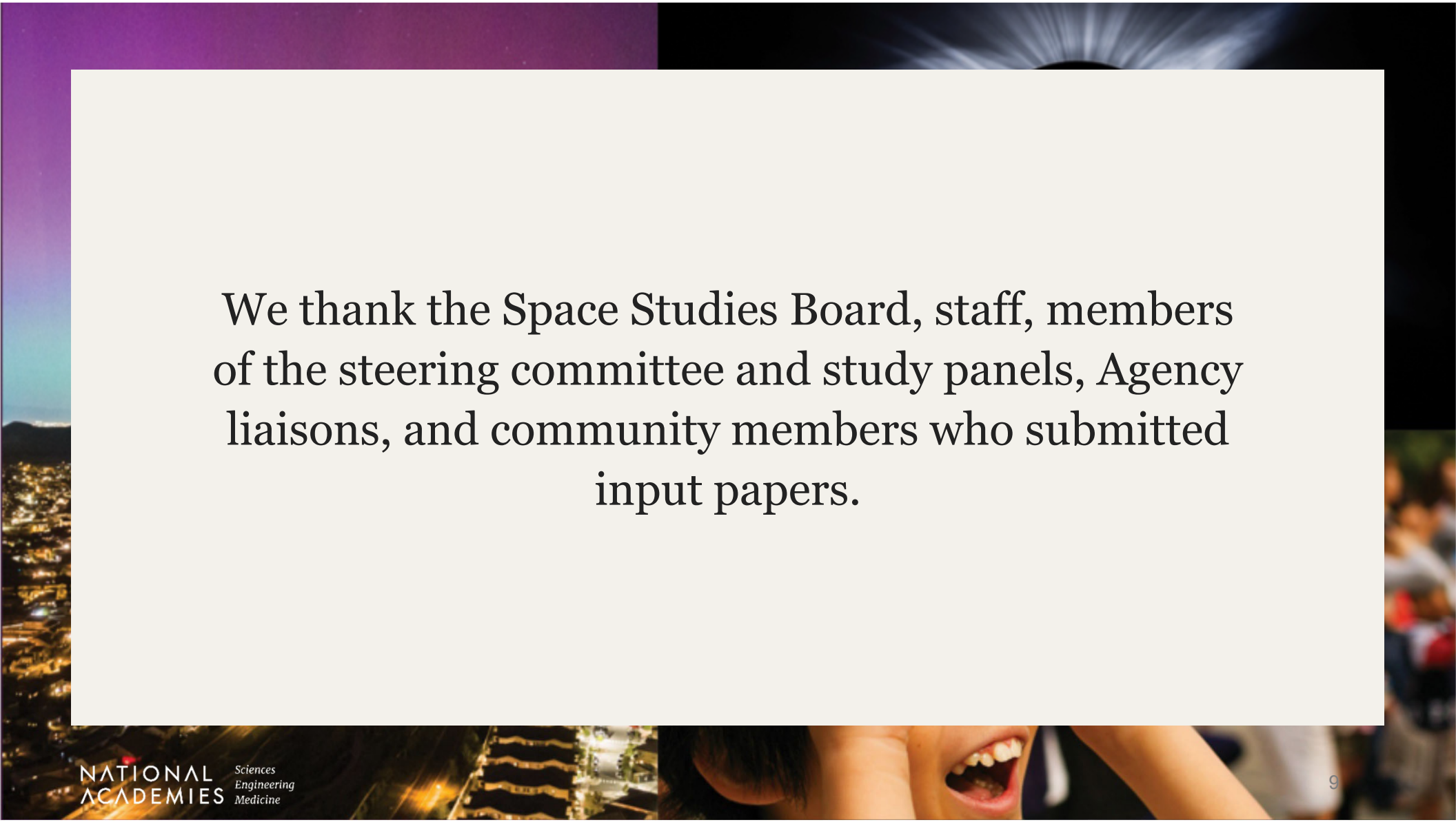


Built on Community Input



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



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

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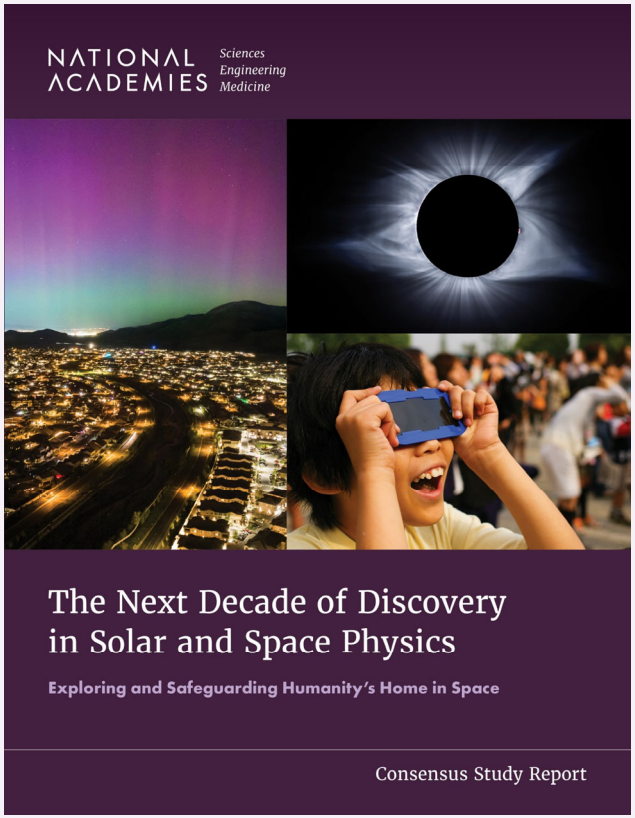
Report Snapshot



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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

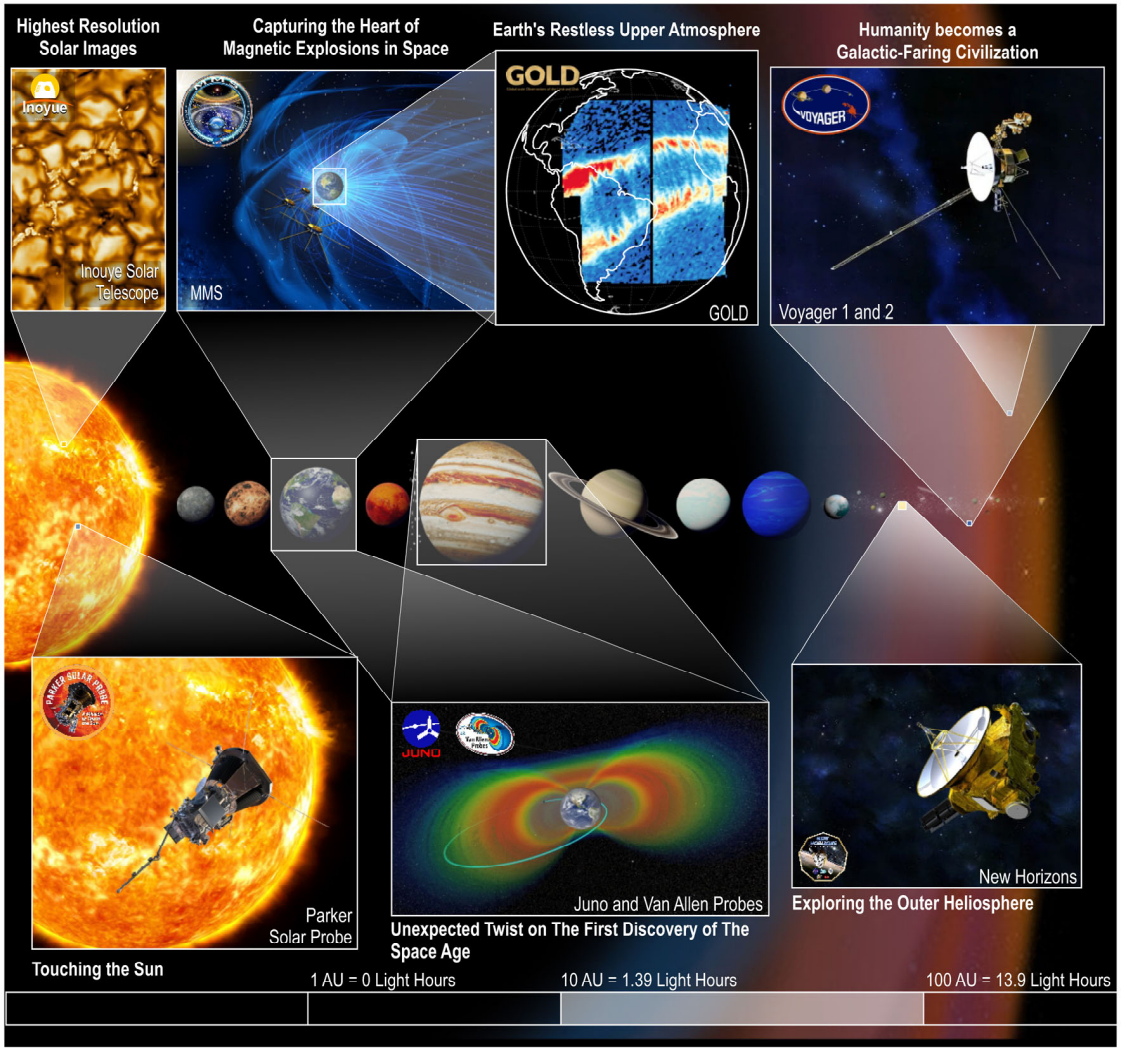
Ch. 4. Towards a Thriving Solar and Space Physics Community

Ch. 5. Comprehensive Research Strategy

Ch. 6. Summary of Research Strategy and Budget Implications

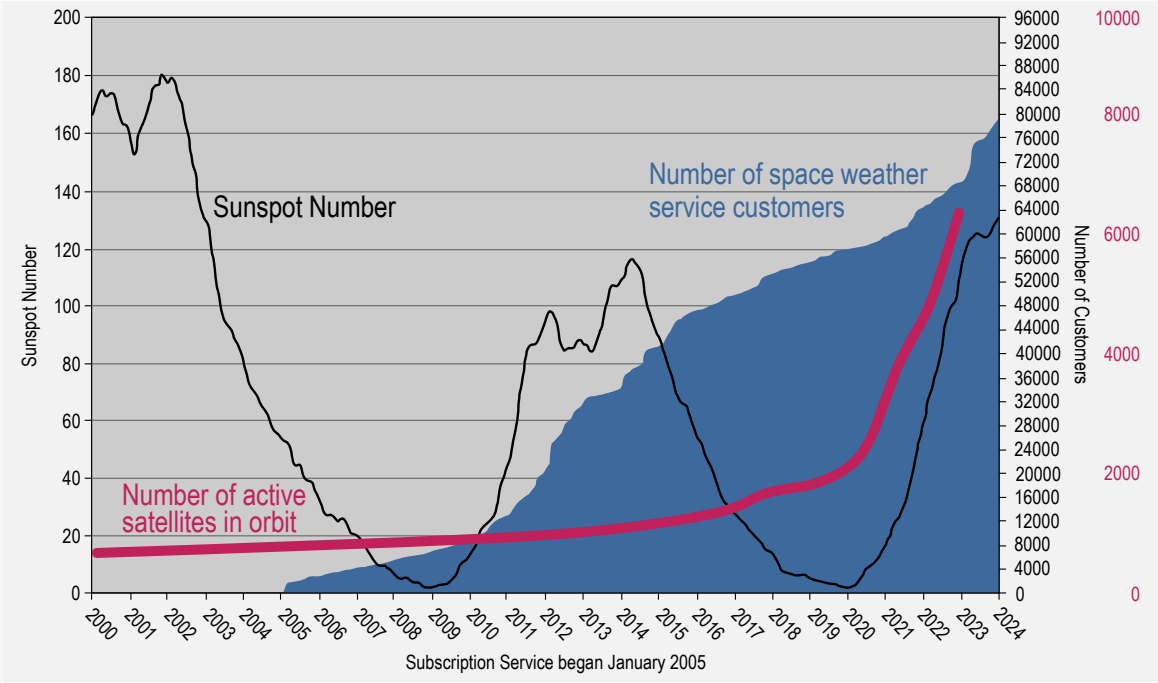
Appendices

- 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

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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.

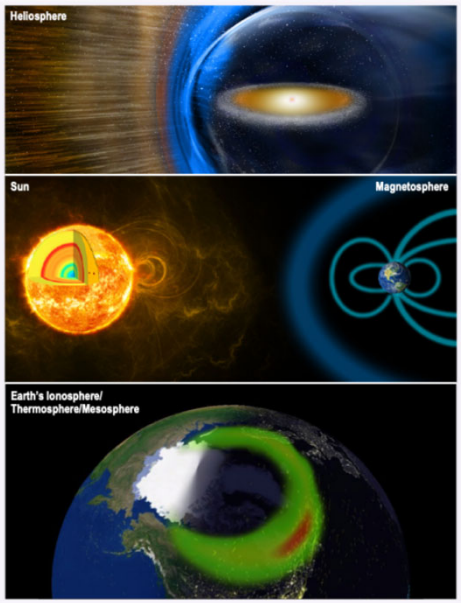
We develop models and theories that explain the physics and interconnections of the heliosphere and to understand conditions for life elsewhere in the universe.

and to serve humanity

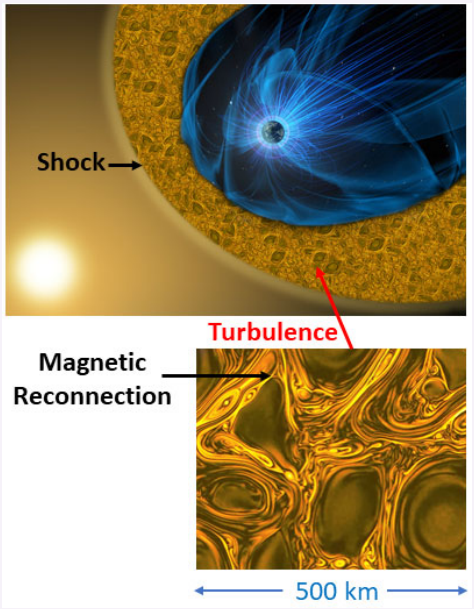
We analyze the space environment to project its future changes.
We develop tools and products to issue space weather warnings and forecasts and to safeguard activities at and beyond Earth.

Science Themes *to discover*

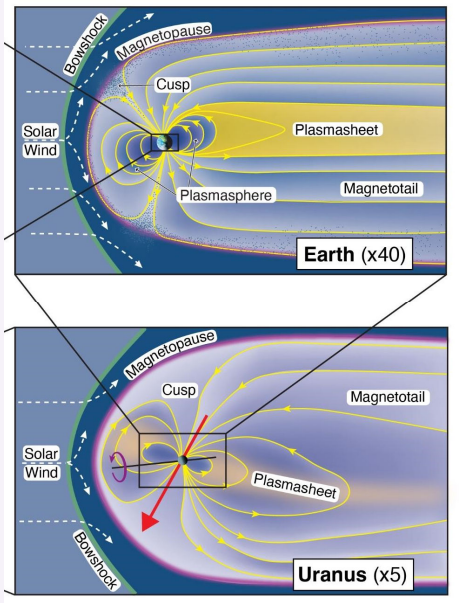
Sun-Earth-Space:
Our Interconnected Home



A Laboratory in Space:
Building Blocks of Understanding



New Environments:
Exploring our Cosmic Neighborhood and Beyond



GUIDING Q'S

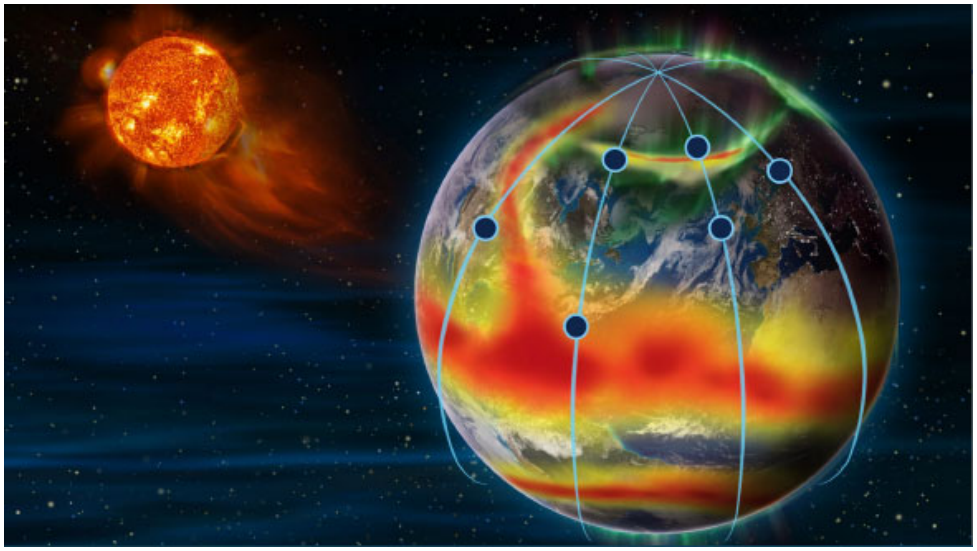
How does our Heliosphere function as a nested system?

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

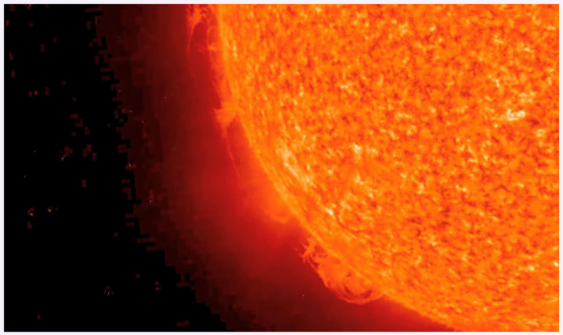


- The upper atmospheric system is driven from above by solar radiation and strongly influenced from below.
- Observations that follow the global dynamics in detail are needed to understand how these drivers and their relative roles change in time.

Space Weather
Science-Space Weather Linkage

Space Weather Themes *to serve humanity*

System of Systems:
Drivers of Space Weather

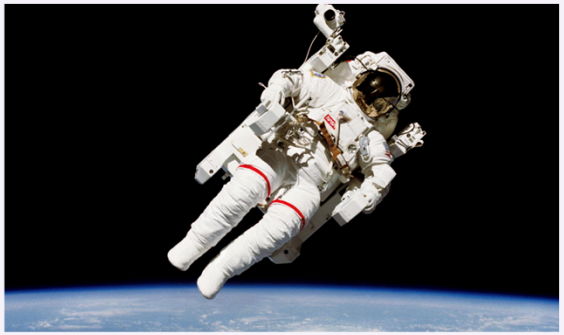


- Solar Eruptions
- Atmospheric Driving

Space Weather Responses
of the Physical System

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

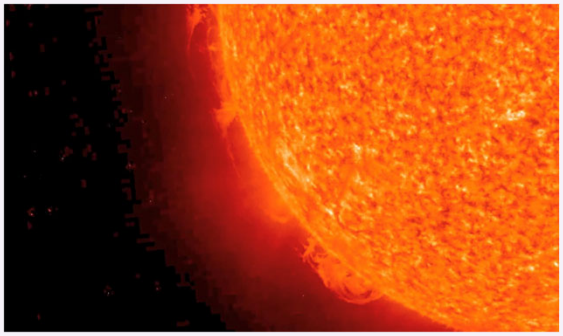
Space Weather Impacts
On Infrastructure and Human Health



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

Space Weather Themes – Research Focus Areas - Outcomes

System of Systems:
Drivers of Space Weather



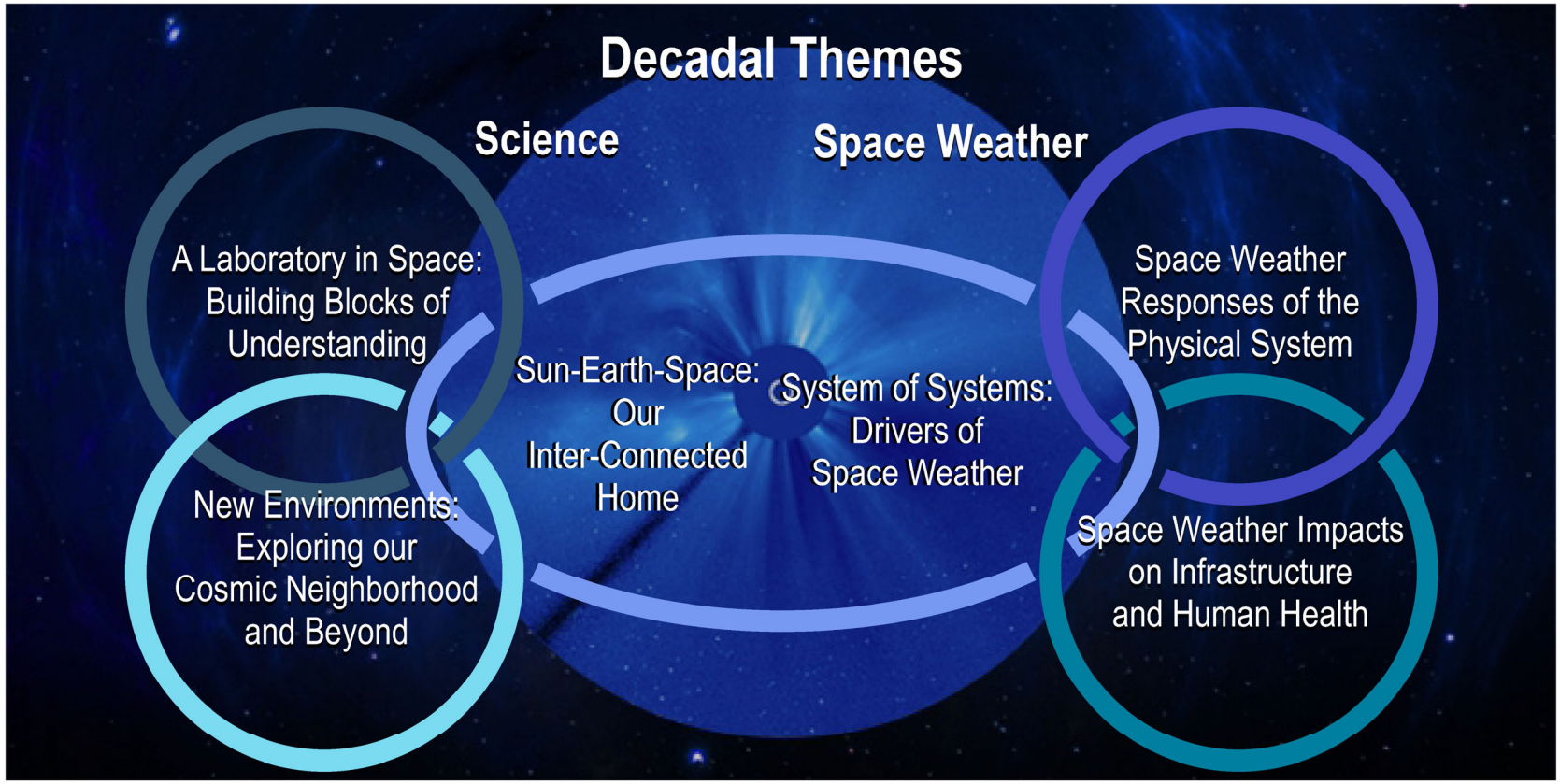
- Solar Eruptions
- Atmospheric Driving

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

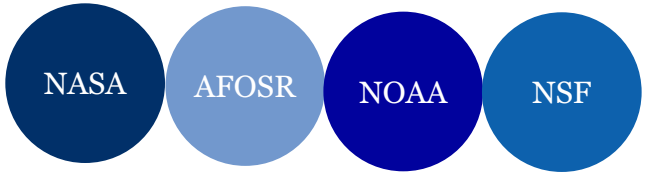
Science and Space Weather Themes are Integrally Linked



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



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Recs	Multi-agency	NASA	NOAA	NSF

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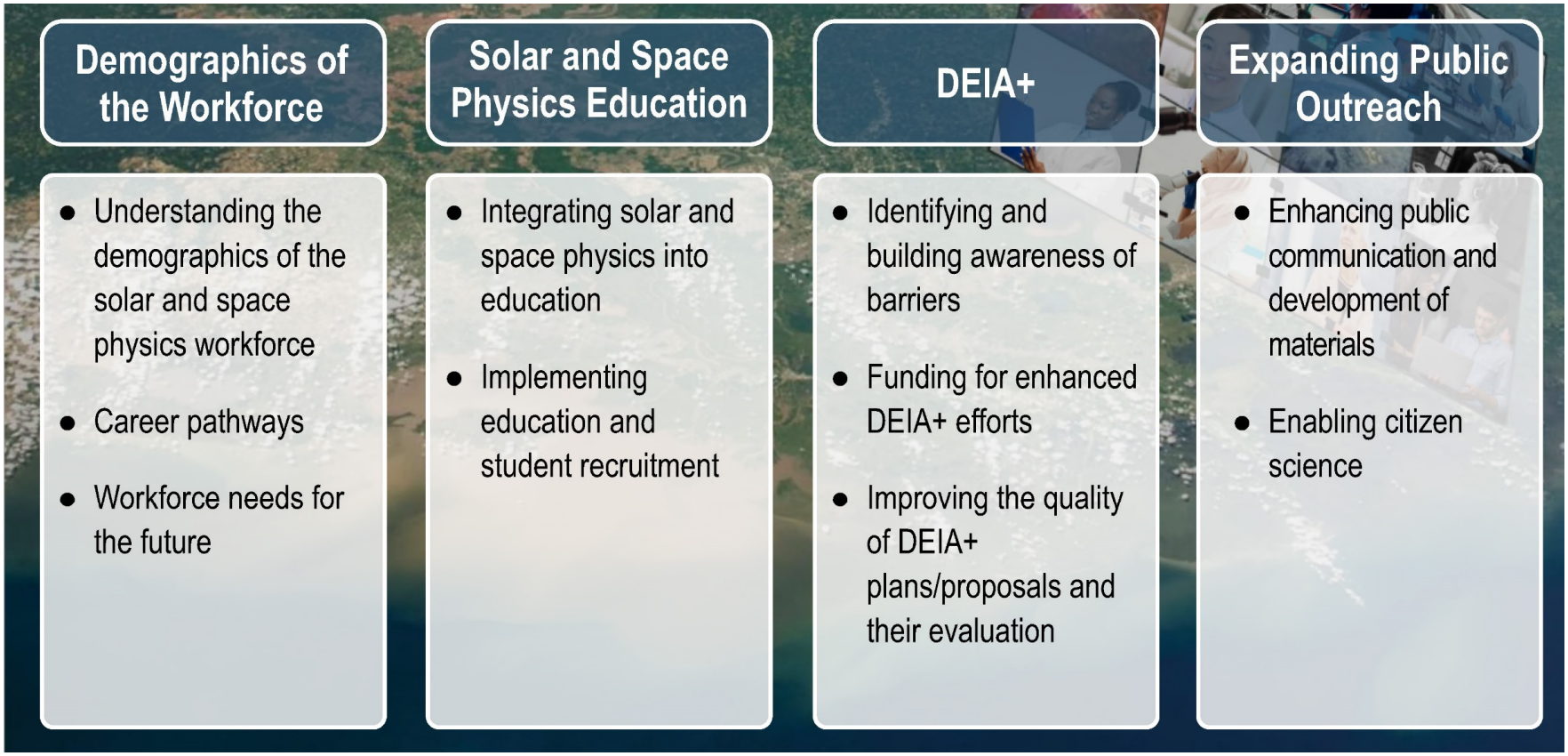
State of the Profession

State of the Profession

Four themes to support, unify, and strengthen the field



State of the Profession Recommendations - Synopsis

- **Building the workforce for tomorrow** requires recruiting the best talent through:
  - A sustainable structure for continuous, longitudinal data gathering.
  - Expanding education and outreach, growing the solar and space physics faculty, increasing opportunities for student research, and enhancing DEIA+ efforts.

Recommendation 4-1: Fund demographic data collection

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

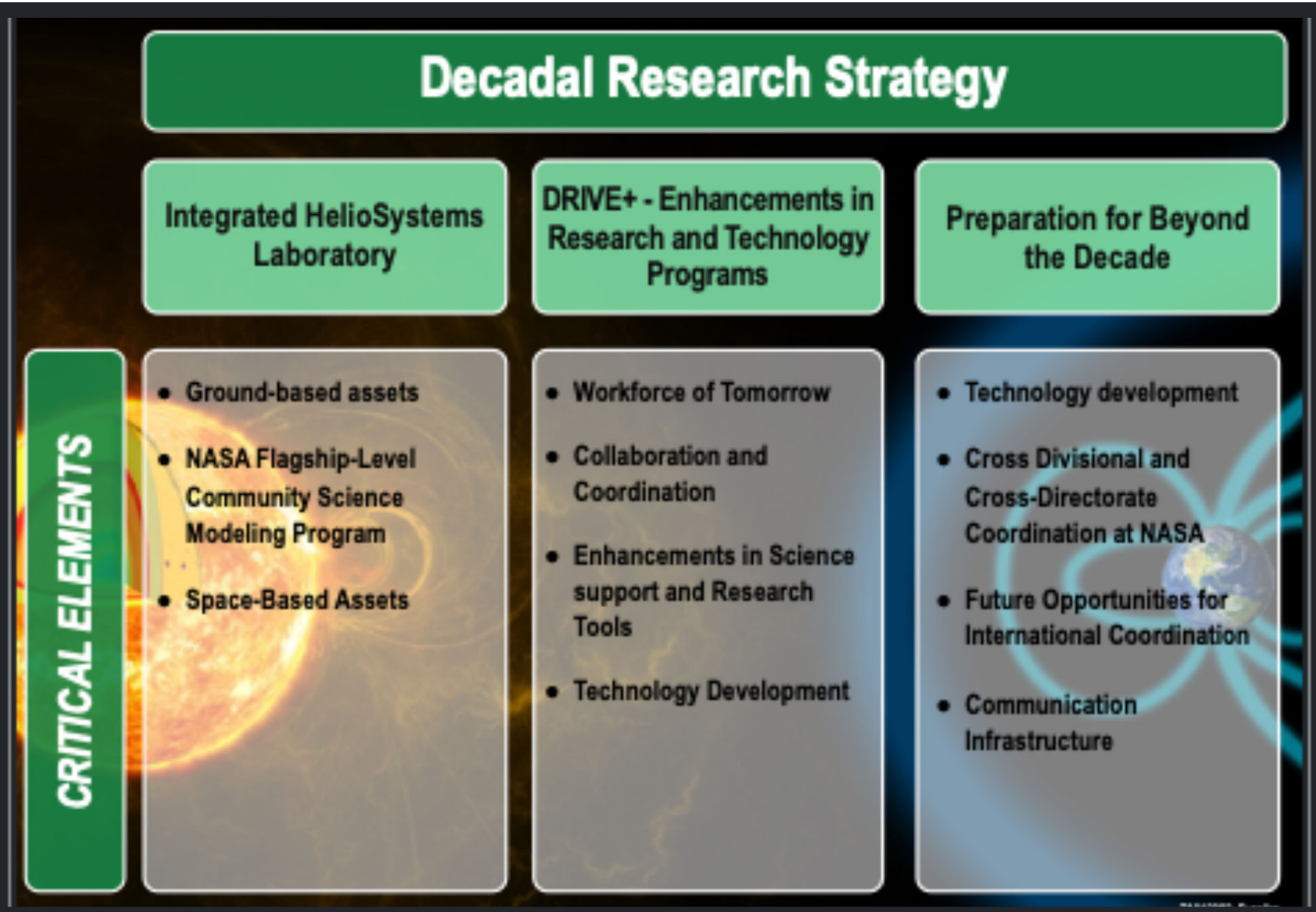
Recommendation 4-3: Faculty Development in geoSpace Sciences (FDSS)

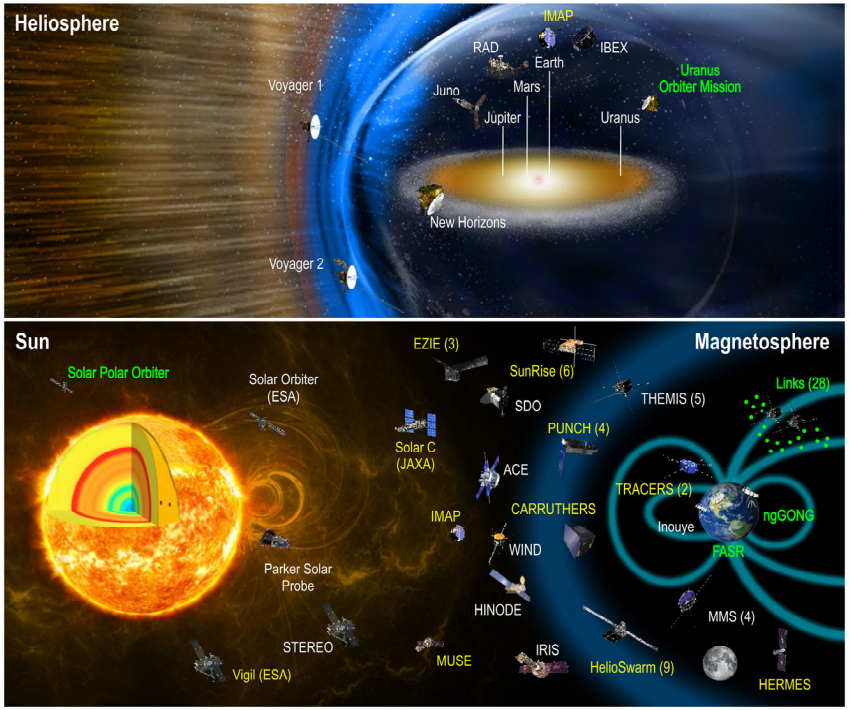
Recommendation 4-4: Increase opportunities for student research

Recommendation 4-5: Enhancing DEIA+ in research

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

Comprehensive Research Strategy


Decadal Research Strategy
Integrated HelioSystems Laboratory
DRIVE+ - Enhancements in Research and Technology Programs
Preparation for Beyond the Decade
CRITICAL ELEMENTS
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.

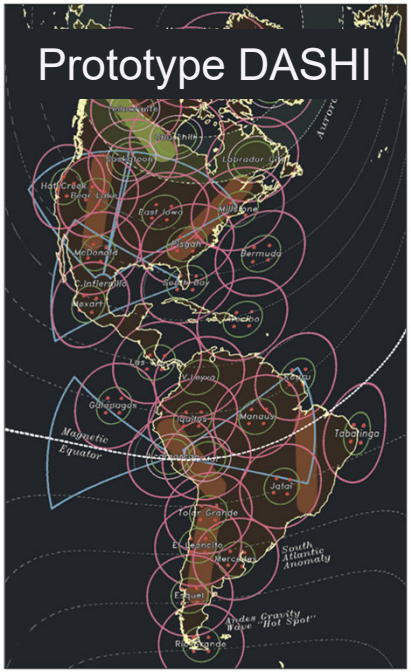
How the HSL and DRIVE+ Work Together

- 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: (Prototype) Distributed Array of Scientific Heterogeneous Instruments – Systems science: coupling of Earth's upper atmosphere to space

MSRI-2: 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)

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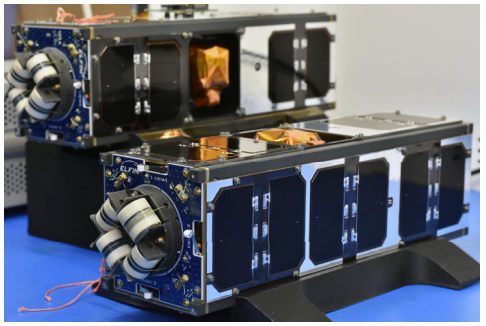
NASA Suborbital Program and NASA/NSF CubeSats

- **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

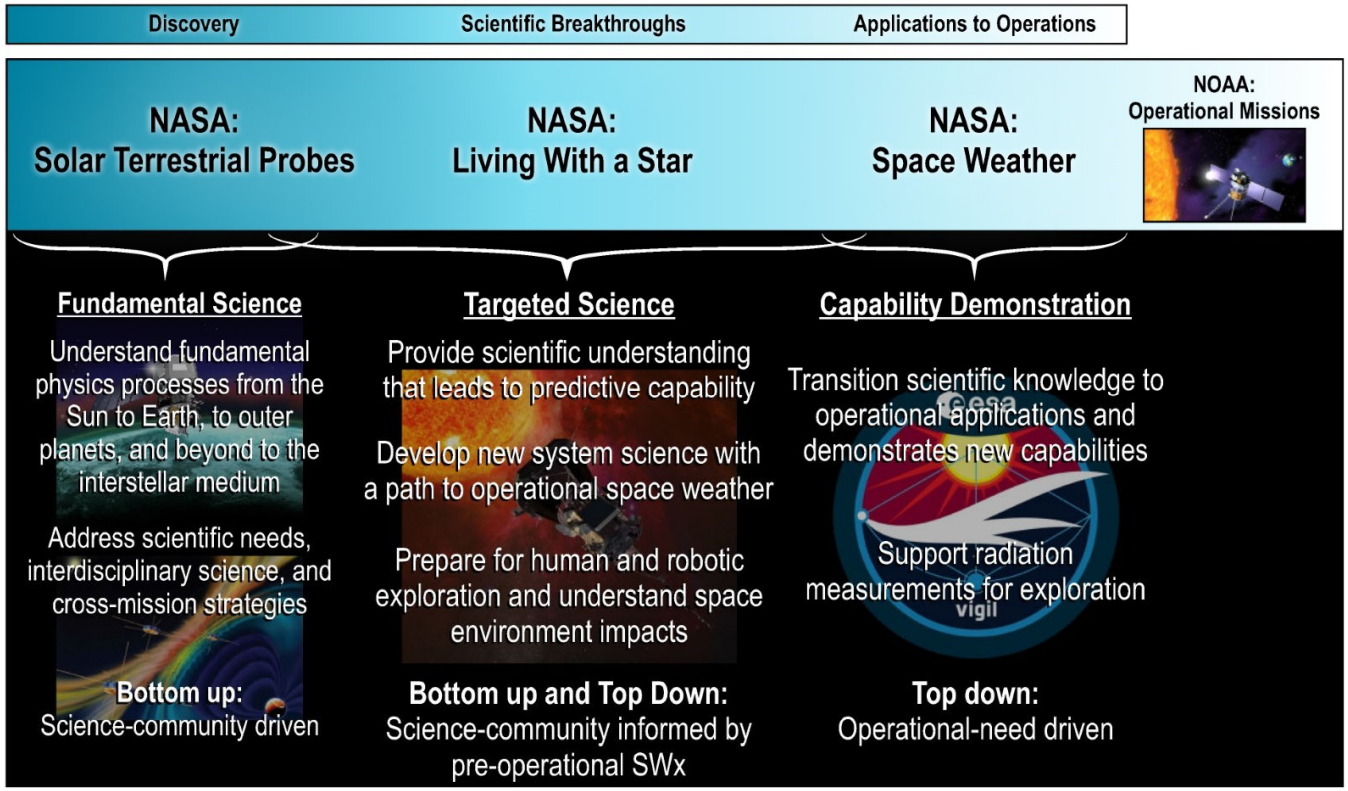
Launch of the Sunrise balloon payload
Source: University Corporation for Atmospheric Research

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



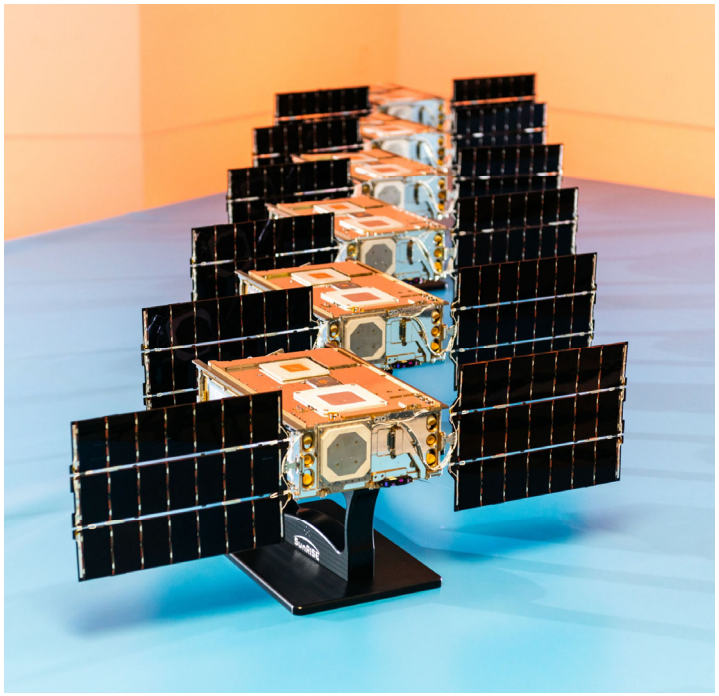
Space Weather Program is an effective bridge between the NASA science missions and NOAA operational missions

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
- …

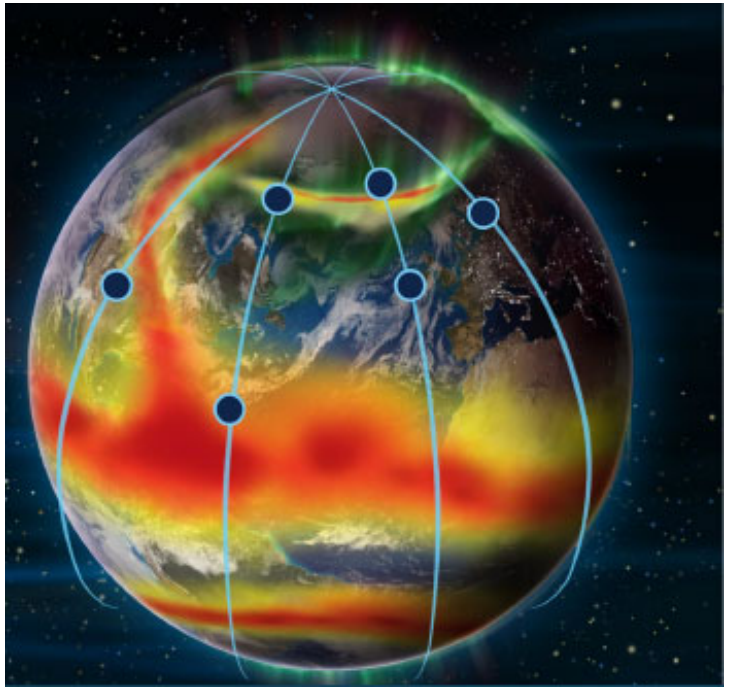


Six CubeSats for the SUNRISE Mission of Opportunity. Credit: Space Dynamics Laboratory/Allison Bills

Integral Parts of the Program of Record:

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

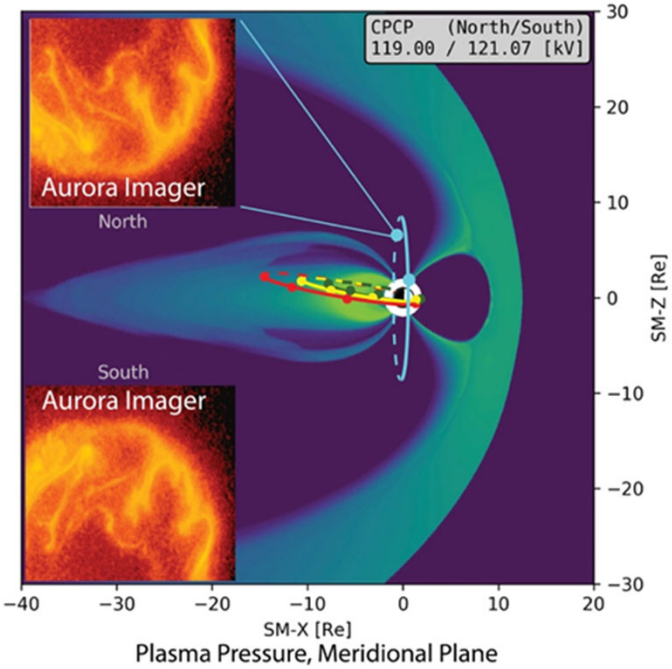
- Highest-priority LWS and STP missions from the 2013 decadal survey
- Four reasons to complete GDC/DYNAMIC in the next decade:
  - Make significant progress on decadal high-priority science
  - Help balance the overall Heliophysics research program
  - Act as a pathfinder for the heterogeneous constellation 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

Highest-Priority New STP Mission

Notional Mission: Links between Regions and Scales in Geospace



Theme: Sun-Earth-Space

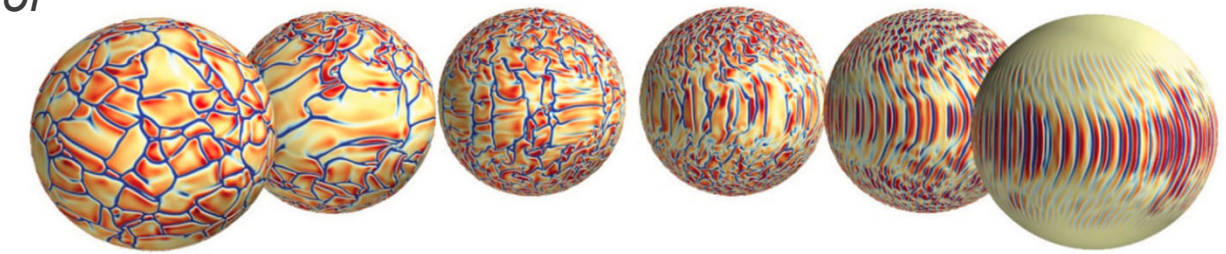
- *Links discovers the connections across regions and scales in the near-Earth space environment.*

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.*

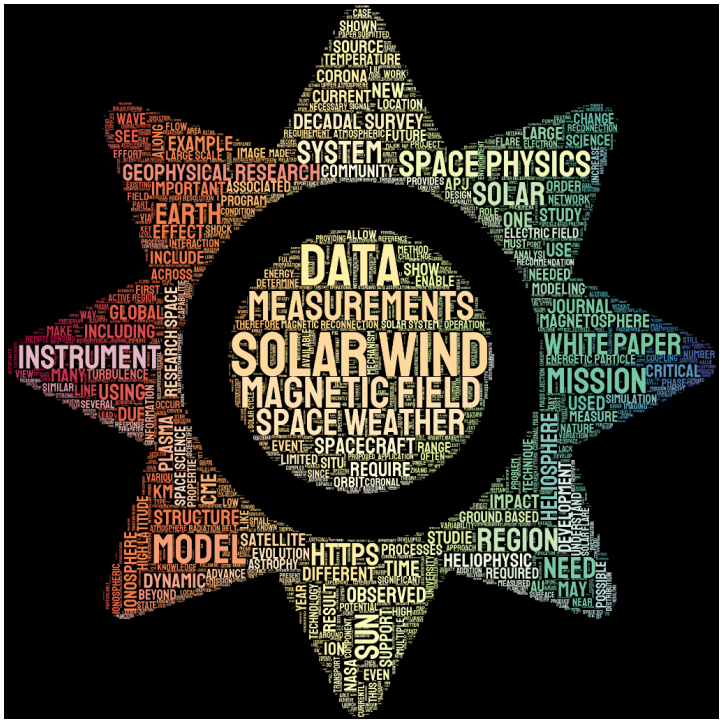


Enhancements in Research and Technology

- Education and Workforce Development
- Combining ground-and space-based data
- Develop modern cyberinfrastructure
- Expanded research programs
- Coordinated Space Weather Research
- Increased opportunities for instrument and technology development

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%

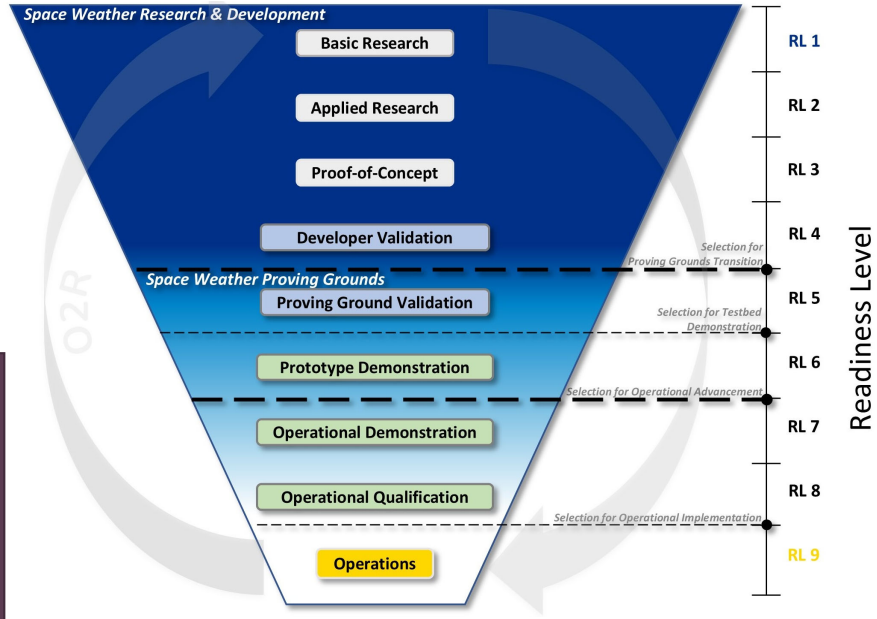


Recommendation 5-15: Support for Analysis of Archival Data

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.



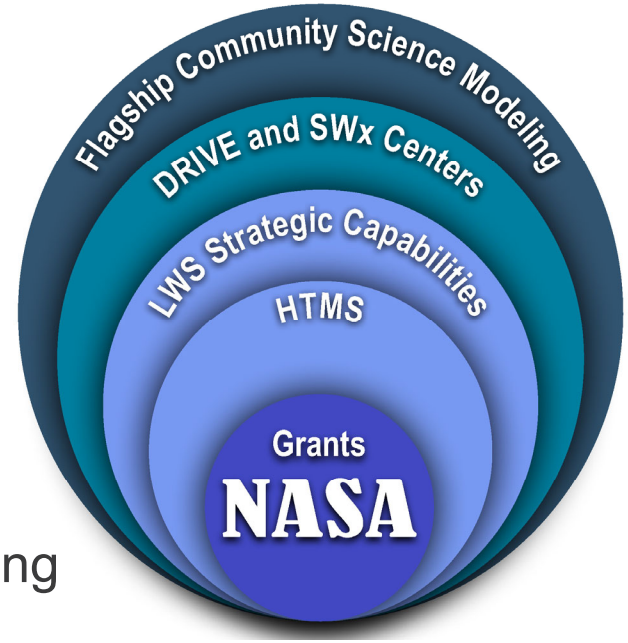
Recommendation 3-2: NOAA and DoD-AFOSR space weather user surveys to set priority research goals

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

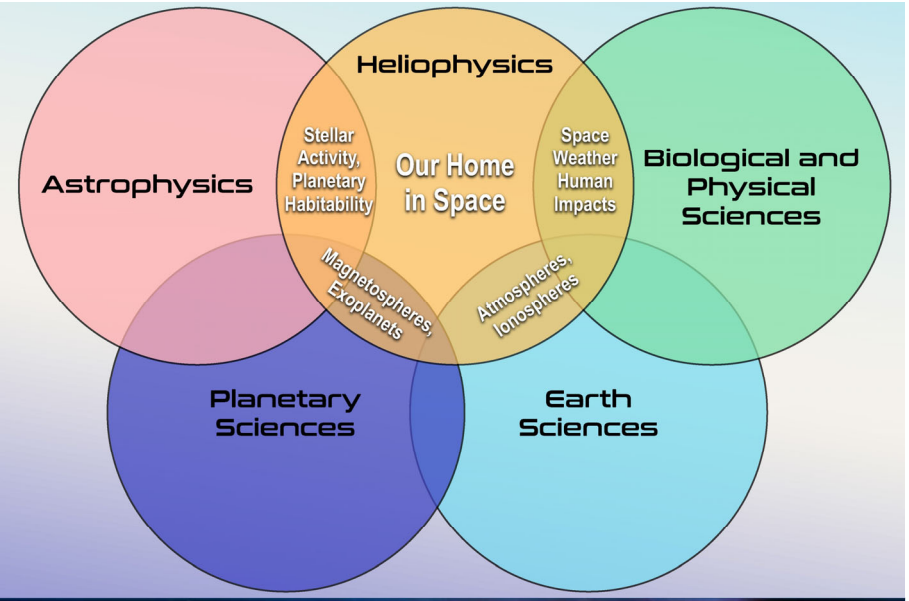
Recommendation 3-4: NOAA space weather research program and partnership with DoD-AFOSR to develop predictive space weather models

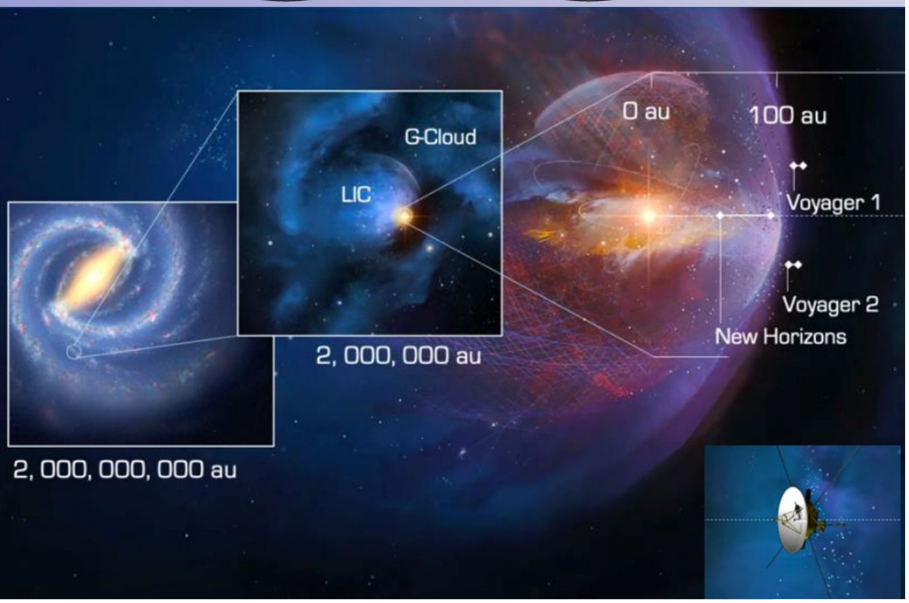
A New NASA Flagship-Level Community Science Modeling Program

- 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.

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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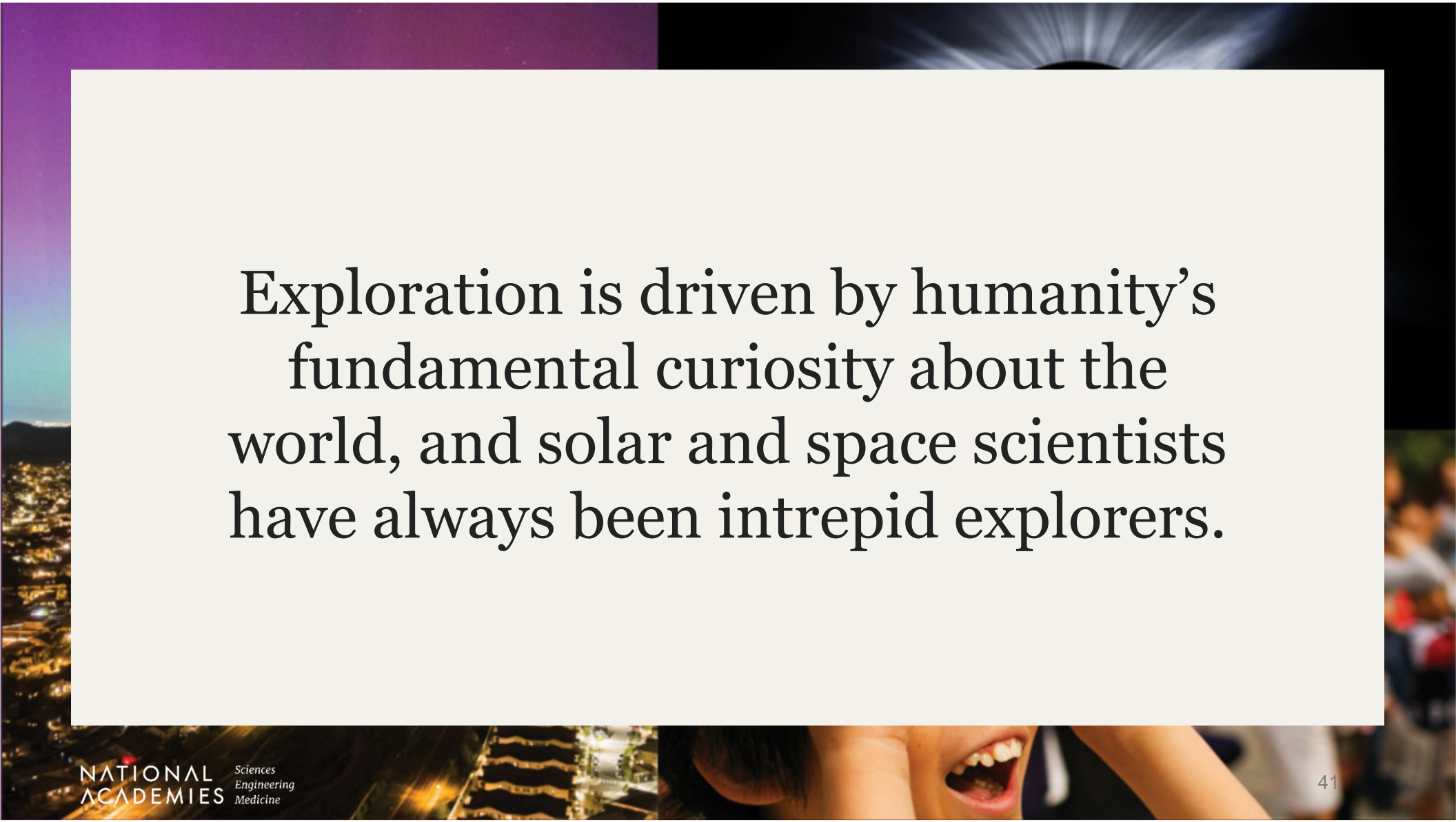
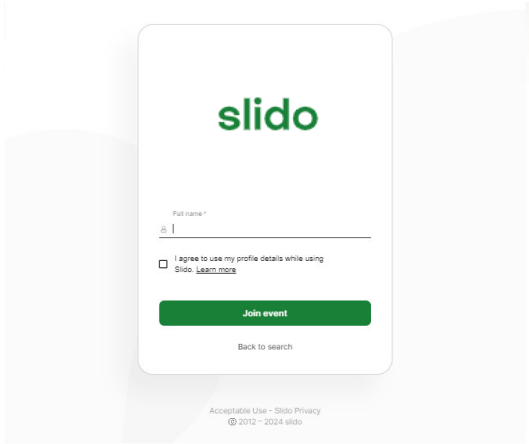


Exploration is driven by humanity's fundamental curiosity about the world, and solar and space scientists have always been intrepid explorers.

Thank You

Please submit questions using the slido box below the webcast window or visit slido.com with ***event code #SSPH***



See us next at:

AGU Town Hall

Wednesday, 12/11 at 6 PM ET

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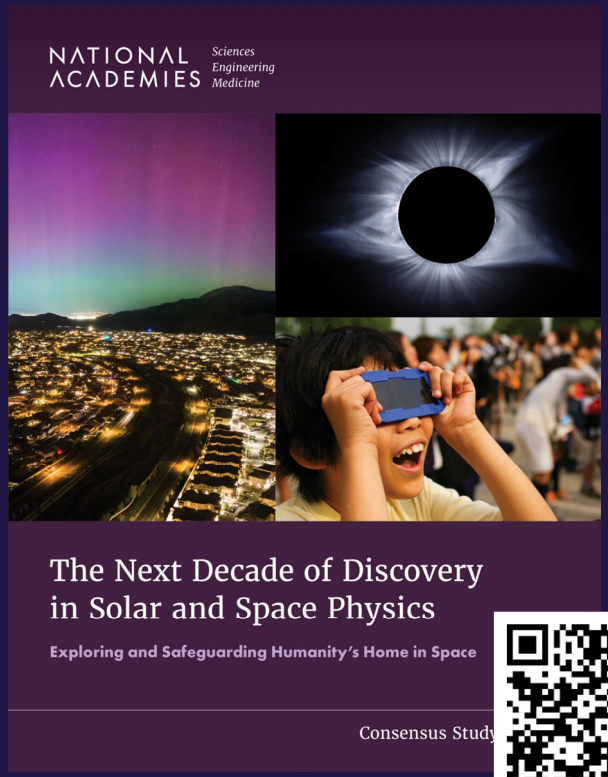

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