CubeSats and Heliophysics Decadal Survey Science Priorities

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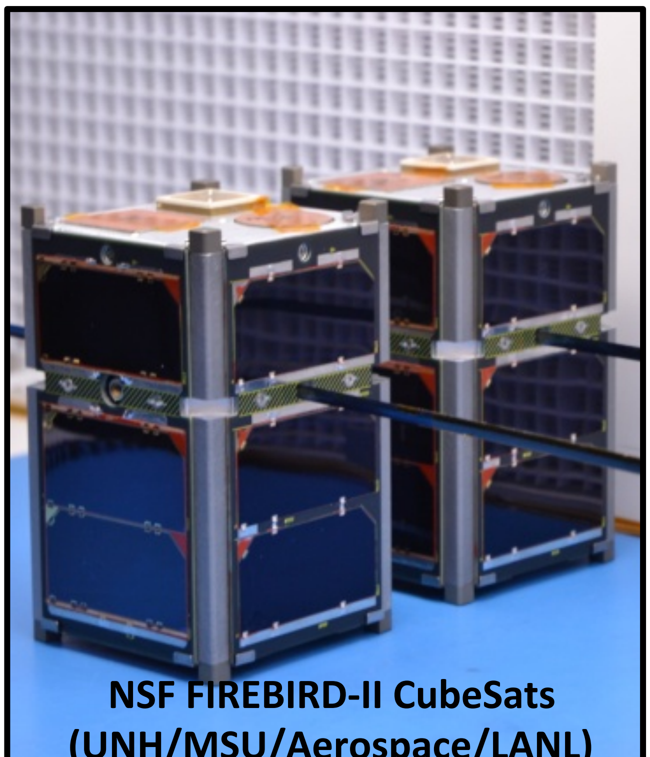
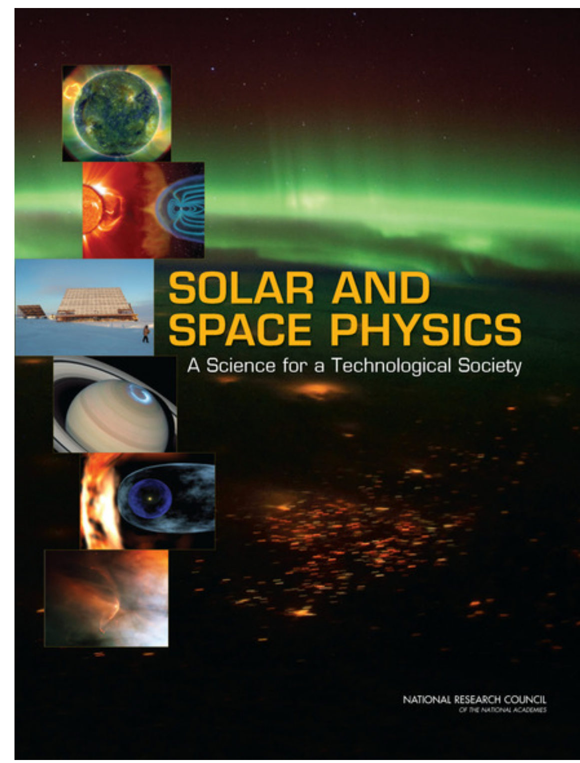
University of New Hampshire

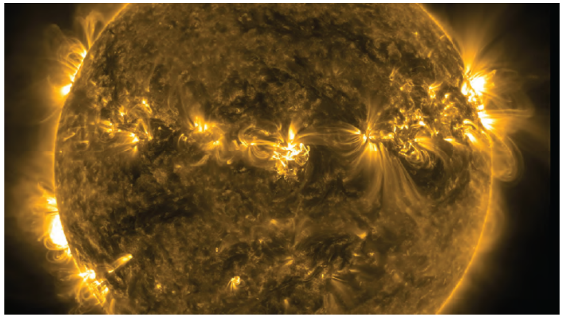


NSF FIREBIRD-II CubeSats
(UNH/MSU/Aerospace/LANL)

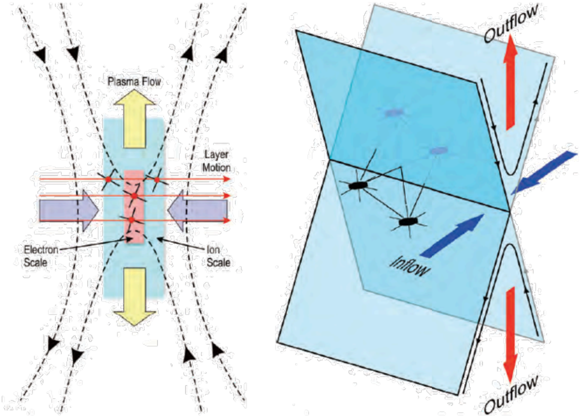
Presentation given at
"Achieving Science Goals with CubeSats"
SSB Symposium
2 September 2015
Beckman Center
Irvine, CA



Overarching Solar and Space Physics Decadal Science Goals

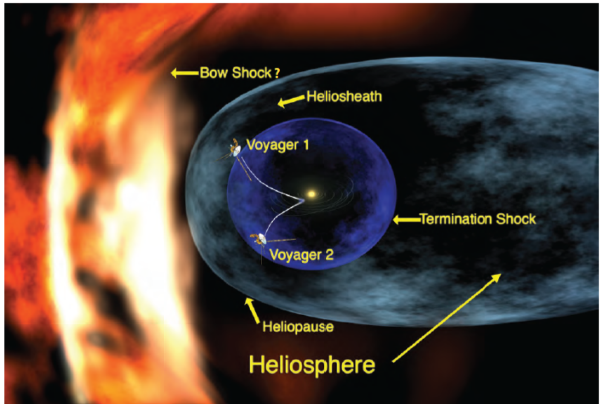


- Determine the origins of the Sun's activity and predict the variations in the space environment.



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

- Determine the interaction of the Sun with the solar system and the interstellar medium.

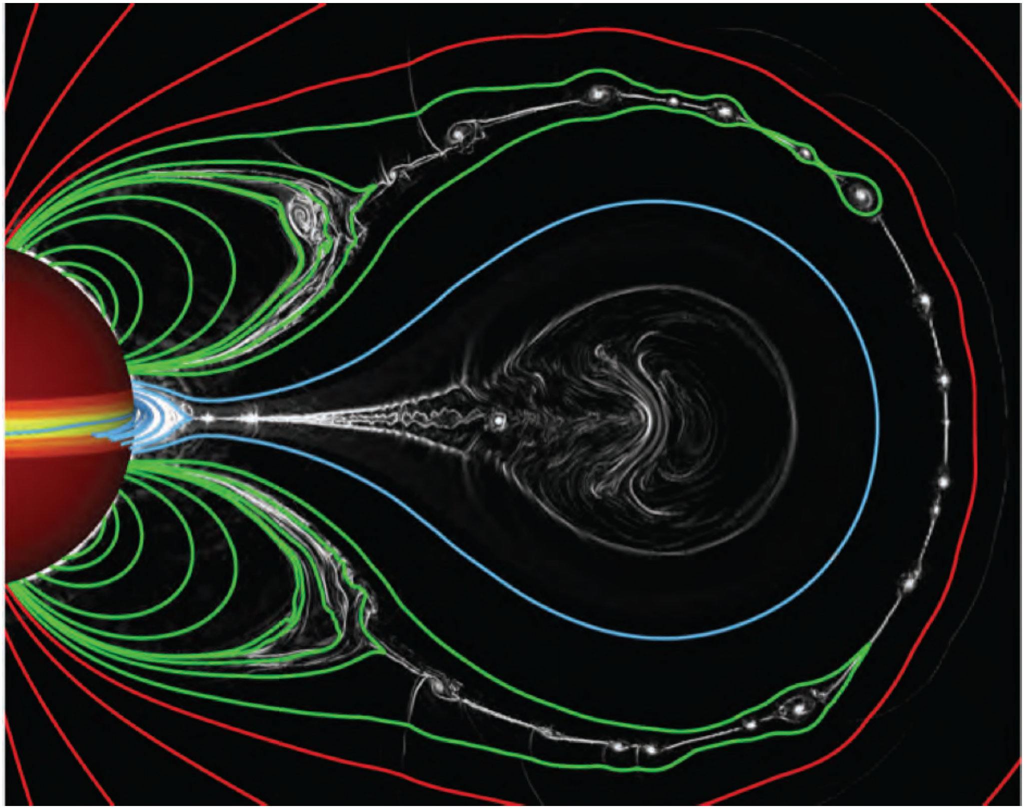


- Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Key Science Challenges (SHP)

<u>Challenges Related to the Sun and Heliosphere (SHP)</u>:

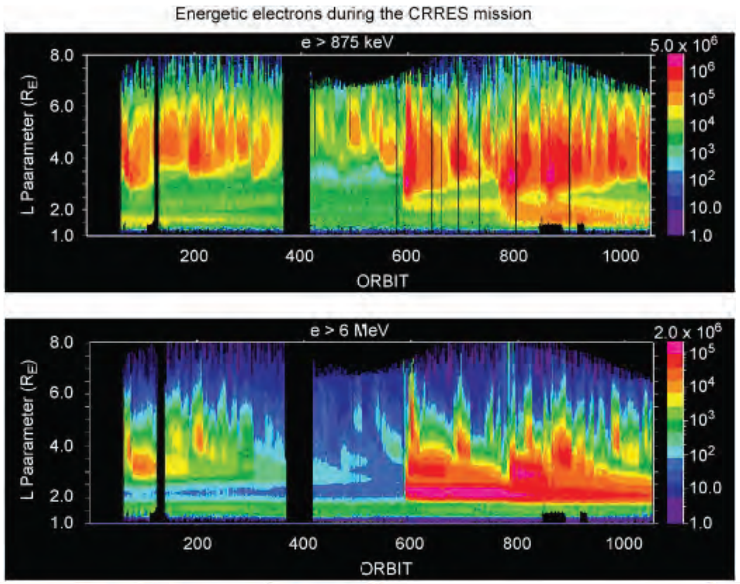
- SHP-1. Understand how the Sun generates the quasi-cyclical magnetic field that extends throughout the heliosphere.
- SHP-2. Determine how the Sun's magnetism creates its hot, dynamic atmosphere.
- SHP-3. Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate through the heliosphere.
- SHP-4. Discover how the Sun interacts with the local interstellar medium.

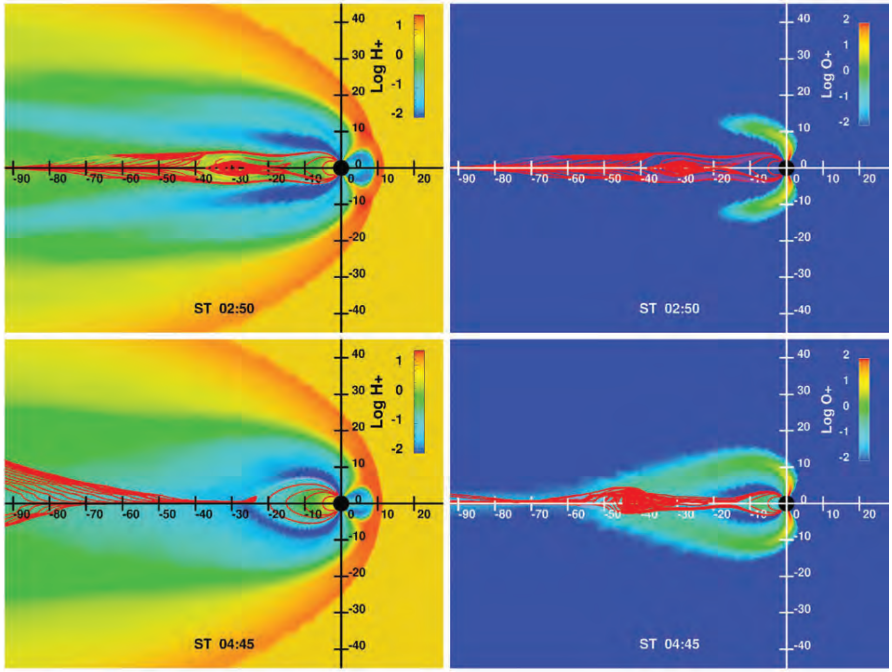


Key Science Challenges (SWMI)

Challenges Related to Solar Wind-Magnetosphere Interactions (SWMI):

- SWMI-1. Establish how magnetic reconnection is triggered and how it evolves to drive mass, momentum, and energy transport.
- SWMI-2. Identify the mechanisms that control the production, loss, and energization of energetic particles in the magnetosphere.
- SWMI-3. Determine how coupling and feedback between the magnetosphere, ionosphere, and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind.
- SWMI-4. Critically advance the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres by comparing models against observations from different magnetospheric systems.

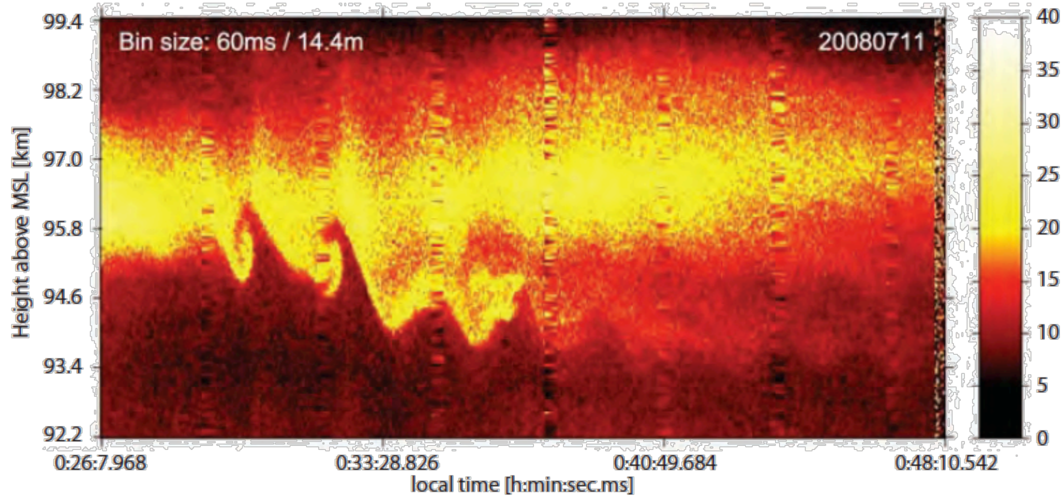


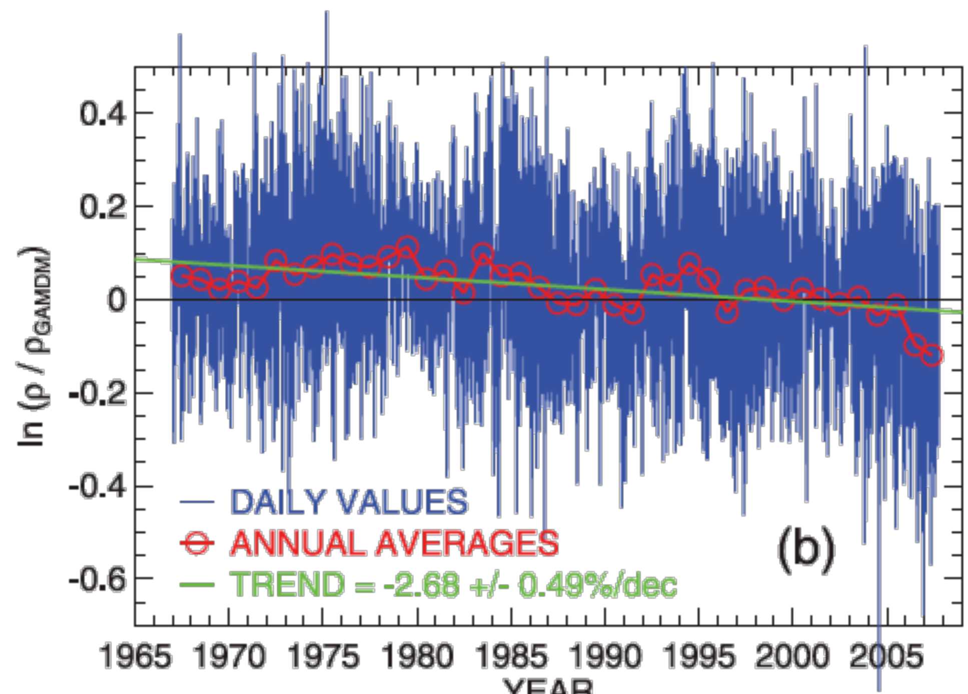


Key Science Challenges (AIMI)

Challenges Related to Atmosphere-Ionosphere-Magnetosphere Interactions (AIMI):

- AIMI-1. Understand how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over global, regional, and local scales.
- AIMI-2. Understand the plasma-neutral coupling processes that give rise to local, regional, and global-scale structures and dynamics in the AIM system.
- AIMI-3. Understand how forcing from the lower atmosphere via tidal, planetary, and gravity waves influences the ionosphere and thermosphere.
- AIMI-4. Determine and identify the causes for long-term (multi-decadal) changes in the AIM system.





Summary of Solar and Space Physics Decadal Science Challenges

The Sun and Heliosphere

SHP-1	Understand how the Sun generates the quasi-cyclical magnetic field that extends throughout the heliosphere.
SHP-2	Determine how the Sun's magnetism creates its hot, dynamic atmosphere.
SHP-3	Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate through the heliosphere.
SHP-4	Discover how the Sun interacts with the local interstellar medium.

Solar Wind-Magnetosphere Interactions

SWMI-1	Establish how magnetic reconnection is triggered and how it evolves to drive mass, momentum, and energy transport.
SWMI-2	Identify the mechanisms that control the production, loss, and energization of energetic particles in the magnetosphere.
SWMI-3	Determine how coupling and feedback between the magnetosphere, ionosphere, and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind.
SWMI-4	Critically advance the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres by comparing models against observations from different magnetospheric systems.

Atmosphere-Ionosphere-Magnetosphere Interactions

AIMI-1	Understand how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over global, regional, and local scales.
AIMI-2	Understand the plasma-neutral coupling processes that give rise to local, regional, and global-scale structures and dynamics in the AIM system.
AIMI-3	Understand how forcing from the lower atmosphere via tidal, planetary, and gravity waves influences the ionosphere and thermosphere.
AIMI-4	Determine and identify the causes for long-term (multi-decadal) changes in the AIM system.

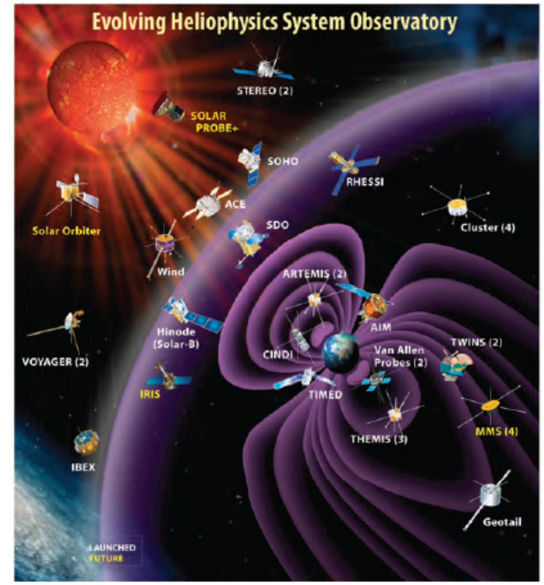
Summary of Top-Level Decadal Survey Research Recommendations

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

Baseline Recommendation #0.0: Complete the Current Program

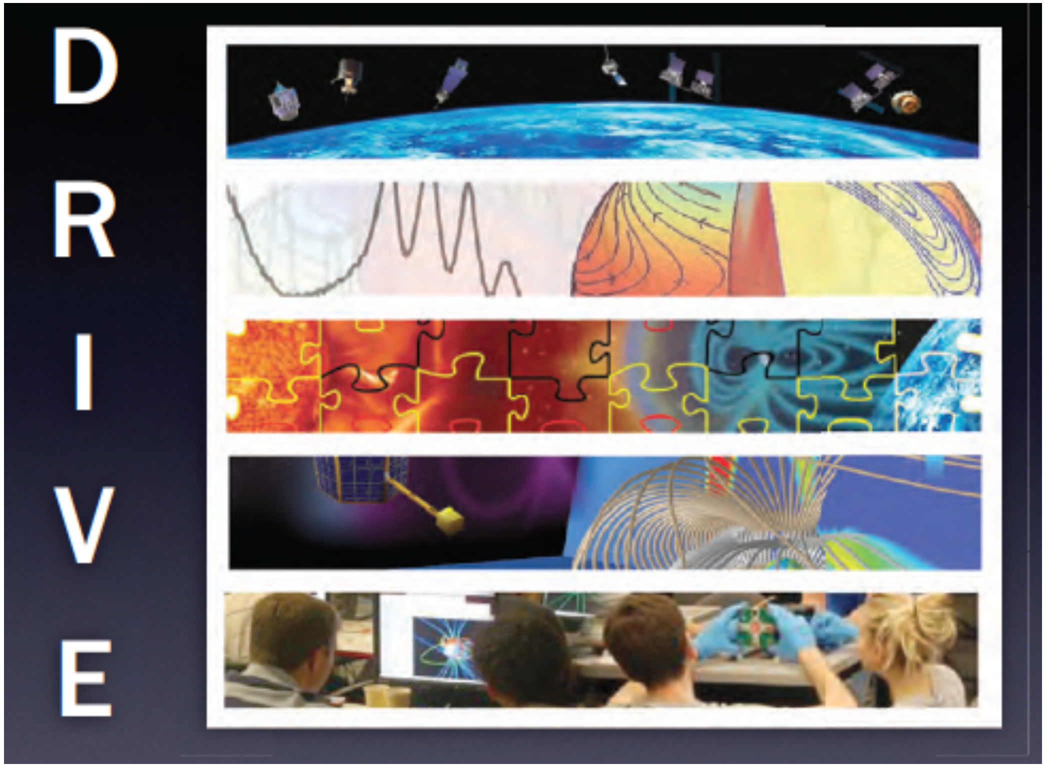
The survey committee's recommended program for NSF and NASA assumes continued support in the near term for the key existing program elements that constitute the Heliophysics Systems Observatory (HSO) and successful implementation of programs in advanced stages of development.

- Van Allen Probes/Balloon Array for RBSP Relativistic Electron Losses (BARREL) launched in 2012/2013+ and now in extended science phases – NASA LWS radiation belt physics mission
- Interface Region Imaging Spectrograph (IRIS) launched in 2013 – NASA Explorer solar chromospheric dynamics mission
- Magnetospheric Multiscale Mission (MMS) launched in 2015 – NASA STP magnetic reconnection physics mission
- Solar Orbiter to launch in 2017 – NASA/ESA Partnership – coupling of solar surface through inner heliosphere
- Solar Probe Plus to launch in 2018 – NASA LWS solar corona physics mission
- Continuation of Advanced Modular Incoherent Scatter Radar (AMISR) and development of Advanced Technology Solar Telescope (ATST) – NSF ground based facilities studying the upper atmosphere and small-scale solar features, respectively



Recommendation #1.0
Implement the DRIVE Initiative

The survey committee recommends implementation of a new, integrated, multiagency initiative (DRIVE—Diversify, Realize, Integrate, Venture, Educate) that will develop more fully and employ more effectively the many experimental and theoretical assets at NASA, NSF, and other agencies. – Chapters 4 (NASA), 5 (NSF), and 6 (costs)



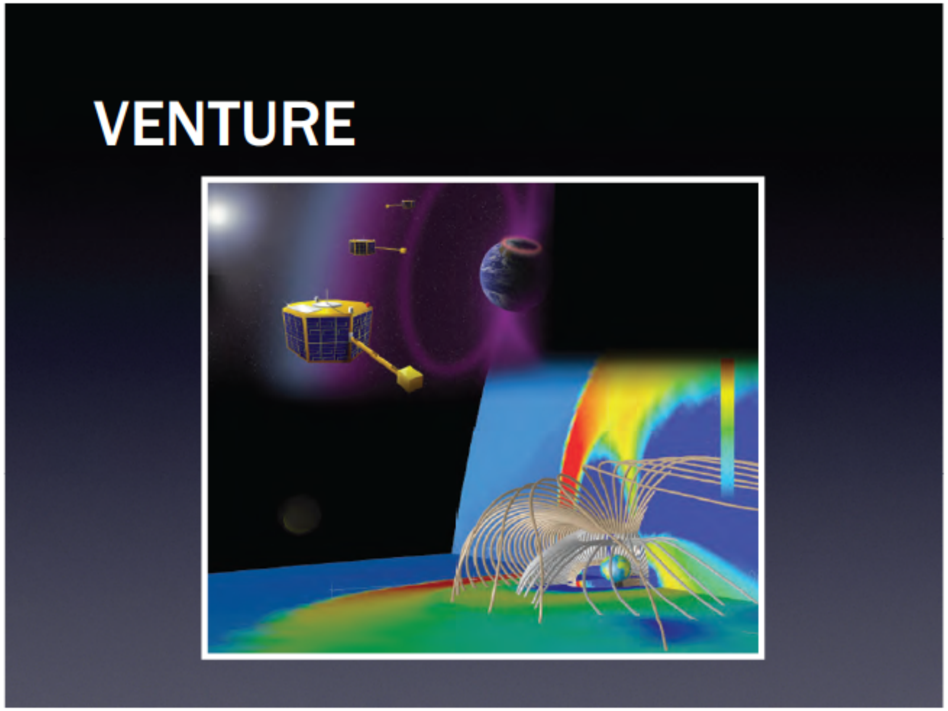
- **D**iversify observing platforms with **microsatellites** and midscale ground-based assets.
- **R**ealize scientific potential by sufficiently funding operations and data analysis.
- **I**ntegrate observing platforms and strengthen ties between agency disciplines.
- **V**enture forward with science centers and **instrument and technology development**.
- **E**ducate, empower, and inspire the next generation of space researchers.

Recommendation #1.0: Small Satellites and "Diversify"

Small Satellite Recommendations:

- **NSF's CubeSat program** should be augmented to enable at least two new starts peryear. Detailed metrics should be maintained, documenting the accomplishments of the program in terms of training, research, technology development, and contributions to space weather forecasting.
- **A NASA tiny-satellite grants program should be implemented**, augmenting the current Low-Cost Access to Space (LCAS) program, to enable a broadened set of observations, technology development, and student training. Sounding rocket, balloon, and tiny-satellite experiments should be managed and funded at a level to enable a combined new-start rate of at least six per year, requiring the addition of $9 million per year (plus an increase for inflation) to the current LCAS new-start budget of $4 million per year for all of solar and space physics.

Recommendation #1.0: Small Satellites and "Venture"

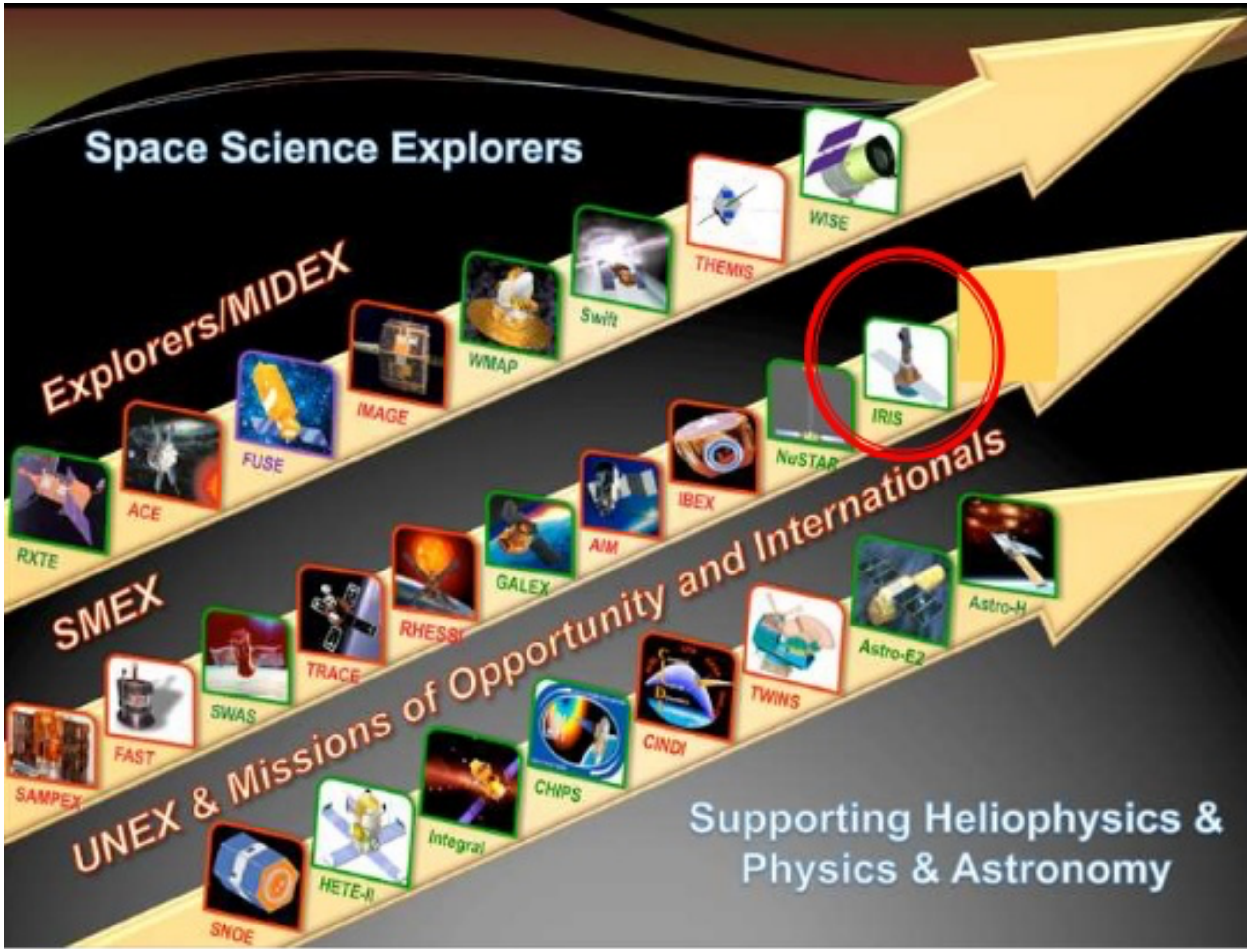


Small Satellite Recommendations:

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

Recommendation #2.0 Accelerate and Expand the Heliophysics Explorer Program

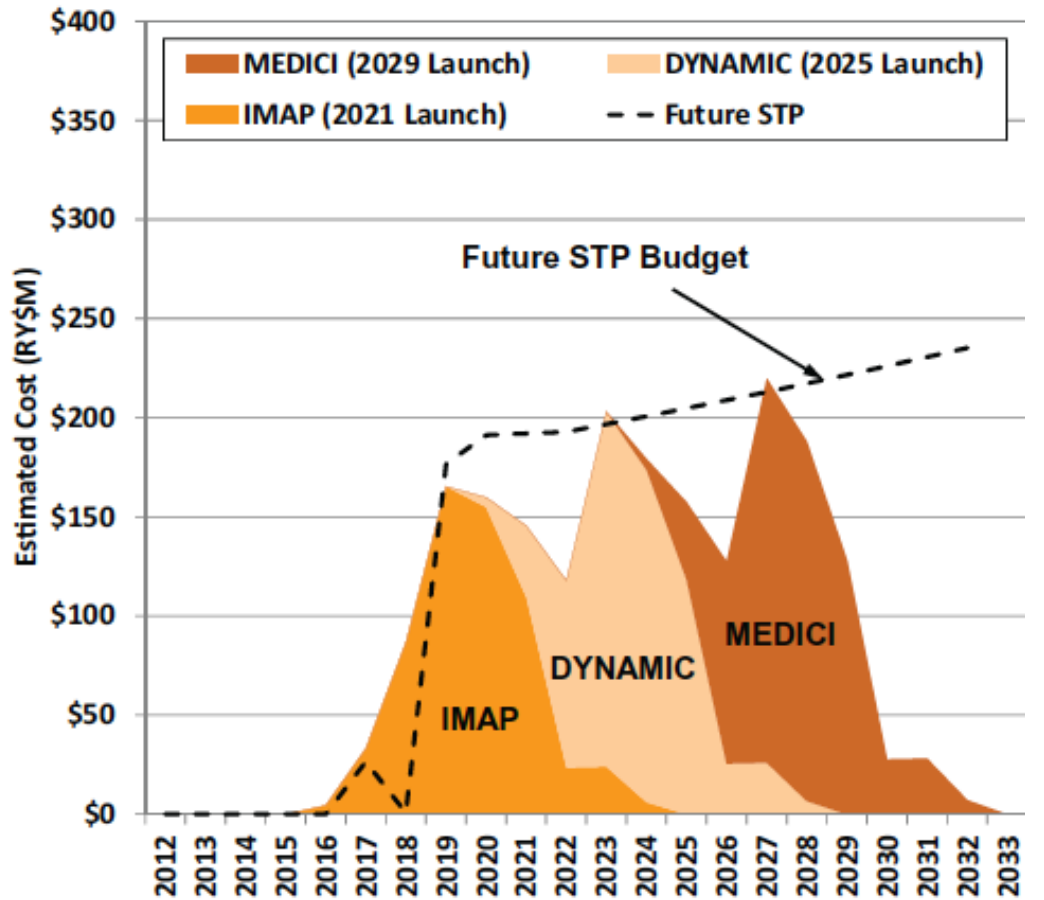
The survey committee recommends that NASA accelerate and expand the Heliophysics Explorer program. Augmenting the current program by $70 million per year, in fiscal year 2012 dollars, will restore the option of Mid-size Explorer (MIDEX) missions and allow them to be offered alternately with Small Explorer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



Recommendation #3.0 Restructure Solar-Terrestrial Probes as a Moderate-Scale, PI-Led Line

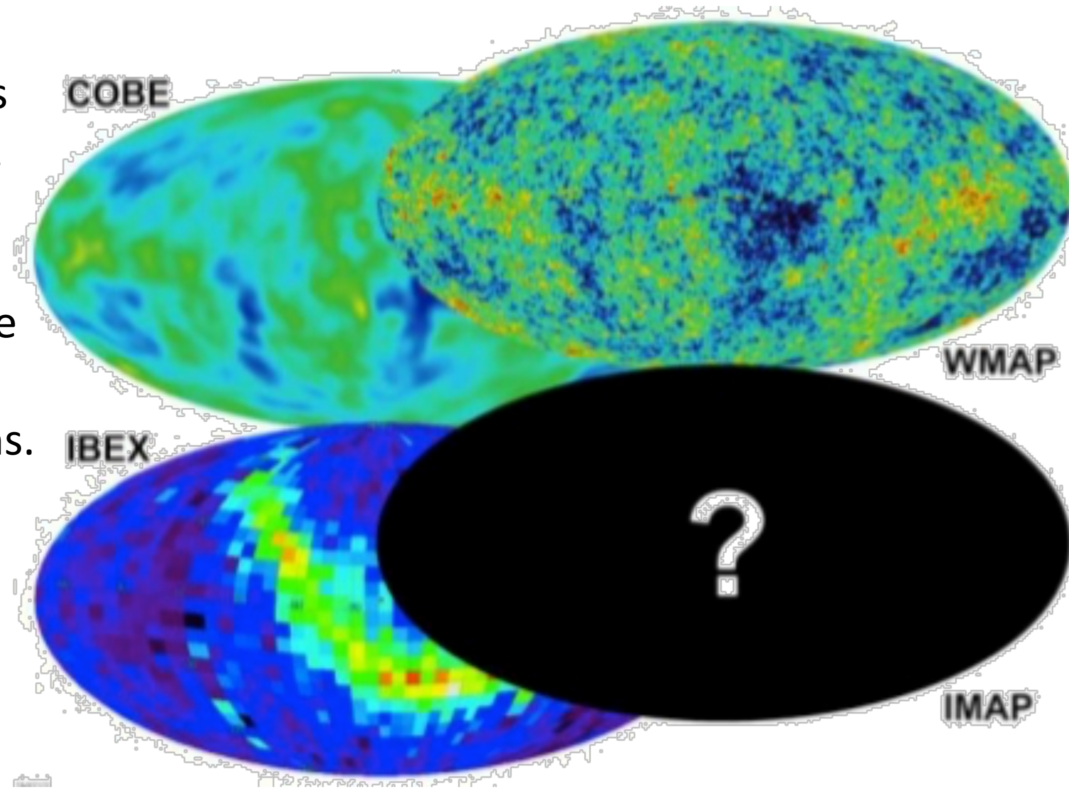
The survey committee recommends that NASA's Solar-Terrestrial Probes program be restructured as a moderate-scale, competed, principal-investigator-led (PI-led) mission line that is cost-capped at $520 million per mission in fiscal year 2012 dollars including full life-cycle costs.

Although the new STP program would involve moderate missions being chosen competitively, the survey committee recommends that their science targets be ordered as shown to right so as to systematically advance understanding of the full coupled solar-terrestrial system, with an approximate 4-year cadence between missions.



Recommendation #3.1: First Science Target - Understand the outer heliosphere and its interaction with the interstellar medium

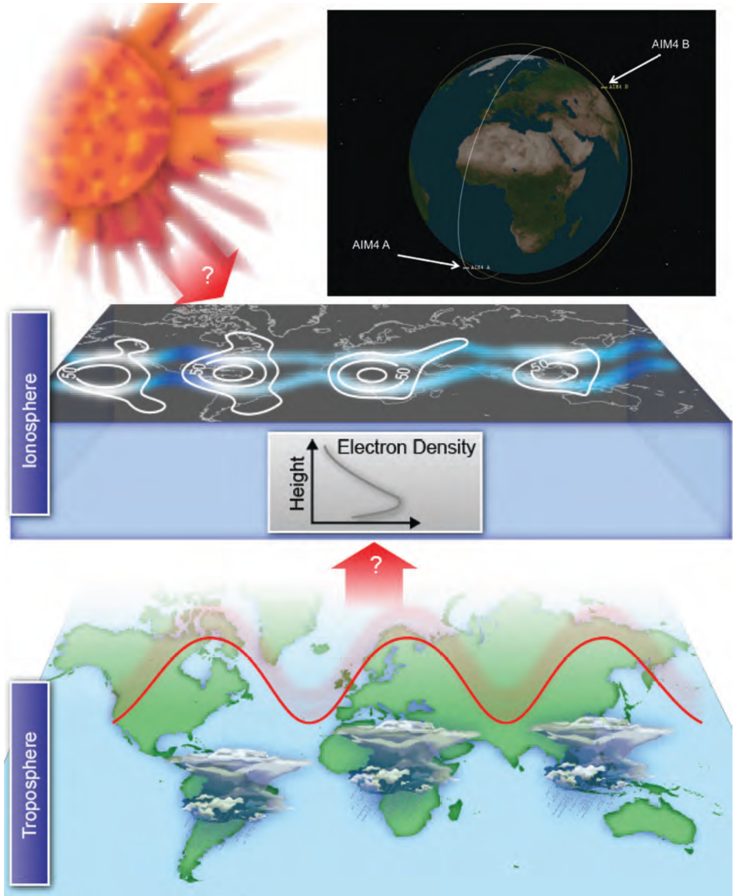
The first new STP science target is to understand the outer heliosphere and its interaction with the interstellar medium, as illustrated by the reference mission **Interstellar Mapping and Acceleration Probe (IMAP).** Implementing IMAP as the first of the STP investigations will ensure coordination with NASA Voyager missions. IMAP would orbit the inner Lagrangian point (L1) with comprehensive, highly sophisticated instruments to make the key ENA and particle observations. The mission implementation also requires measurements of the critical solar wind inputs to the terrestrial system.



Recommendation #3.2:
Second Science Target - Understand the the variability in space weather driven by lower-atmosphere weather on Earth

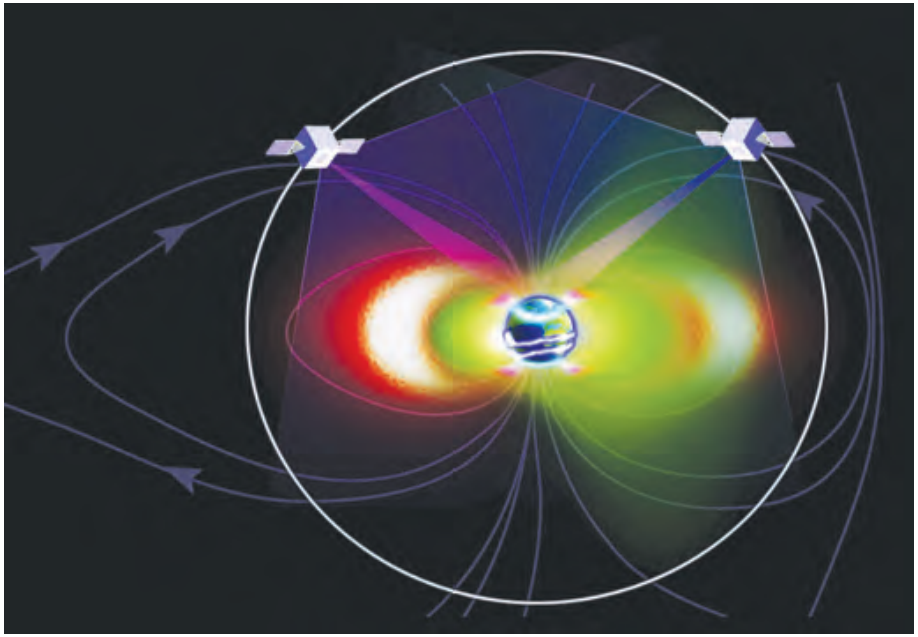
The second STP science target is to provide a comprehensive understanding of the variability in space weather driven by lower-atmosphere weather on Earth. This target is illustrated by the reference mission **Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC).**

DYNAMIC targets the effects of lower atmospheric processes on conditions in space, characterizing how the energy and momentum carried into this region by atmospheric waves and tides interact and compete with solar and magnetospheric drivers. Full spatial and temporal resolution of the wave inputs is accomplished by using two identical, high-inclination, space-based platforms in similar orbits, offset by 6 hours of local time.



Recommendation #3.3: Third Science Target - Determine how the magnetosphere-ionosphere-thermosphere system couples

The third STP science target is to determine how the magnetosphere-ionosphere-thermosphere system is coupled and how it responds to solar and magnetospheric forcing. This target is illustrated by the reference mission **Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)** MEDICI targets complex, coupled, and interconnected multiscale behavior of the magnetosphere-ionosphere-thermosphere system by providing high-resolution, global, continuous three-dimensional images of the ring current (orange), plasmasphere (green), aurora, and ionospheric-thermospheric dynamics and flows, as well as multipoint in situ measurements



Recommendation #4.0: Implement a large Living With a Star mission to study the ionosphere-thermosphere-meso-sphere system in an integrated fashion

The survey committee recommends that, following the launch of RBSP and SPP, the next LWS science target focus on how Earth's atmosphere absorbs solar wind and magnetospheric energy. The recommended reference mission is **Geospace Dynamics Constellation (GDC)** – 2024 launch time frame. The nominal plan for GDC is to have six identical satellites that will be spread individually into equally spaced orbital planes separated by 30° longitude, providing measurements at 12 local times, with a resolution of 2 hours local time,

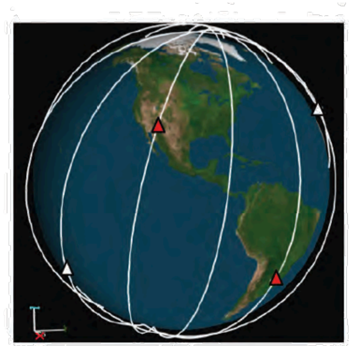


Figure 1 (a) Full global coverage

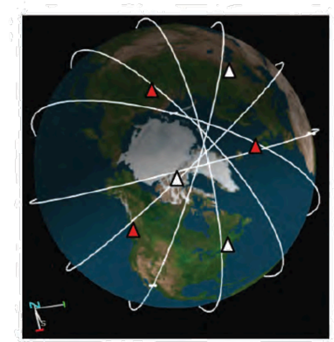


Figure 1 (b) 6-spacecraft high-latitude "armada"

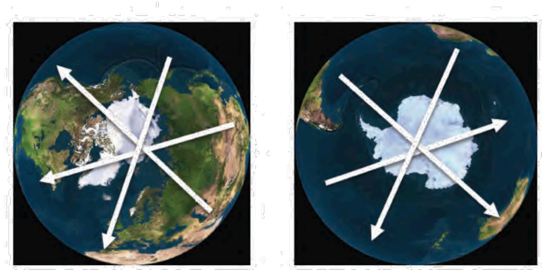


Figure 1 (c) 3 spacecraft simultaneously sampling each pole

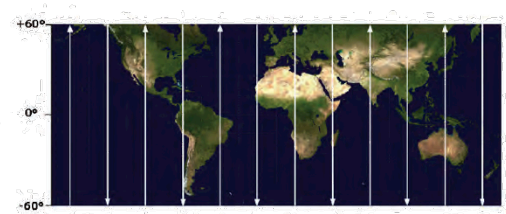
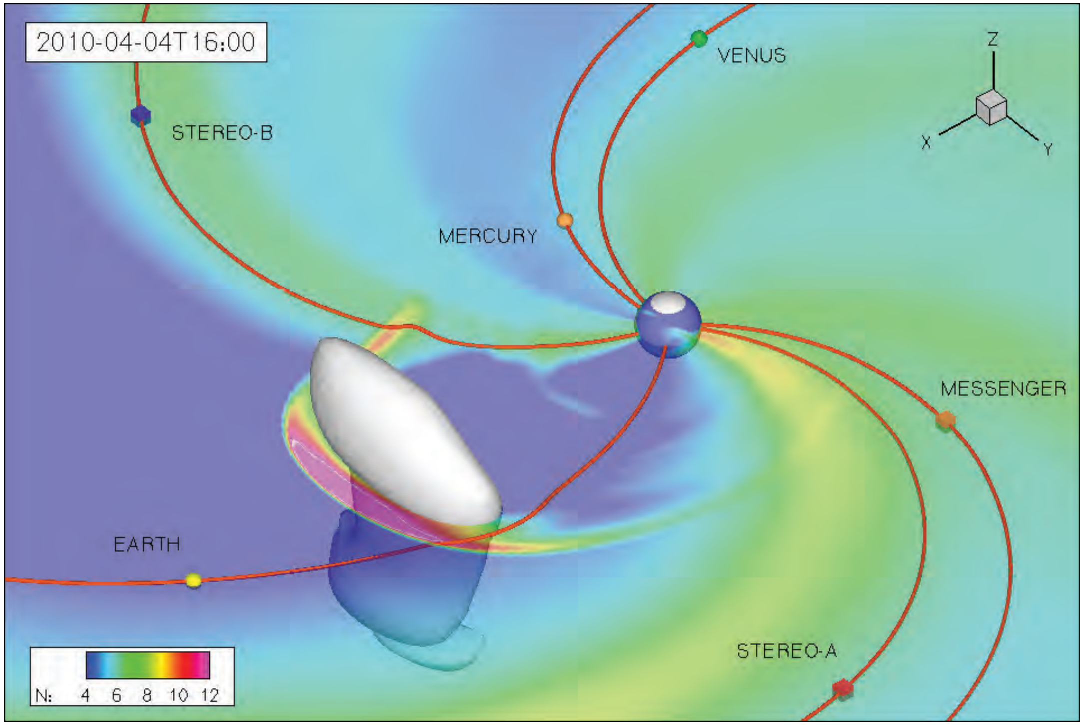


Figure 1(d) 6 s/c cross the equator every 45 min.

Applications #1.0: Recharter the National Space Weather Program

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



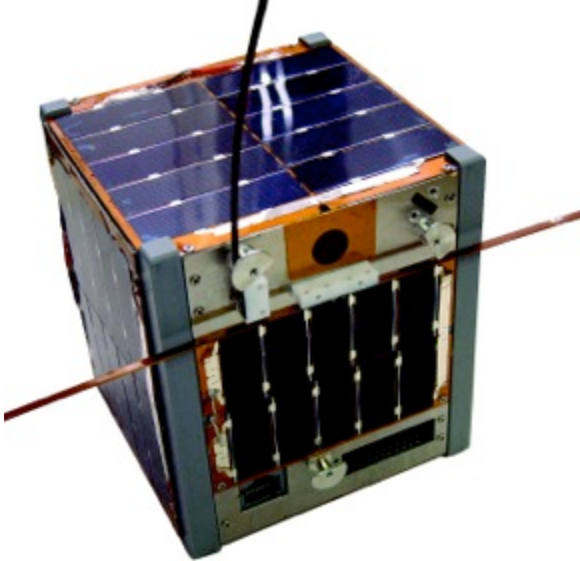
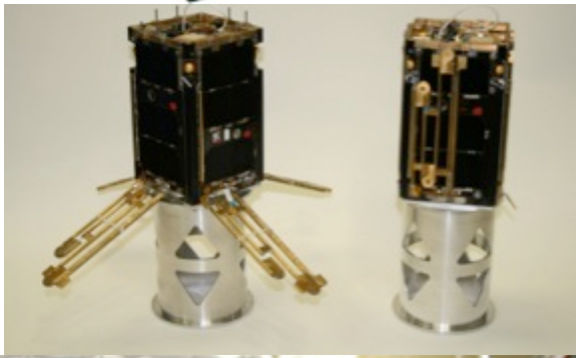
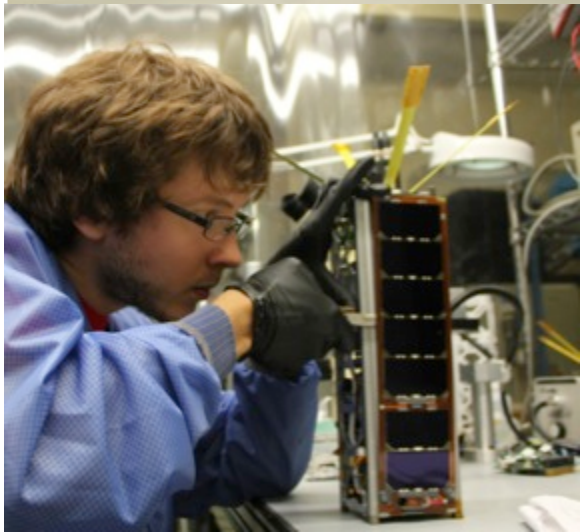
Applications Recommendation #2.0: Work in a multiagency partnership to achieve continuity of solar and solar wind observations

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

- A2.1 Solar wind measurements from L1 should be continued, because they are essential for spaceweather operations and research. The DSCOVR L1 monitor and IMAP STP mission are recommended for the near term, but plans should be made to ensure that measurements from L1 continue uninterrupted into the future.
- A2.2 Space-based coronagraph and solar magnetic field measurements should likewise be continued.
- A2.3 The space weather community should evaluate **new observations, platforms**, and locations that have the potential to provide improved space weather services. In addition, the utility of employing newly emerging information dissemination systems for space weather alerts should be assessed.
- A2.4 NOAA should establish a space weather research program to effectively transition research to operations
- A2.5 Distinct funding lines for basic space physics research and for space weather specification and forecasting should be developed and maintained.

NSF Cubesat Program Since 2008

- Geospace & atmospheric science and education run out of the Geospace Section of GEO/AGS at NSF (Therese Moretto)
- 2 new projects per year
- >80 unique missions proposed
- 12 projects funded
- Grants $900,000 total cost and 3 year duration
- NSF CubeSat program is demonstrating scientific value

SRI INTERNATIONAL · U MICHIGAN · NSF · ELANA-3 · NPP · NASA · DELTA II · VAFB

RAX 2

Scientia

Ex Cubus

DICE

ASTRA
USU/SDL
Clemson
Embry Riddle

CADRE

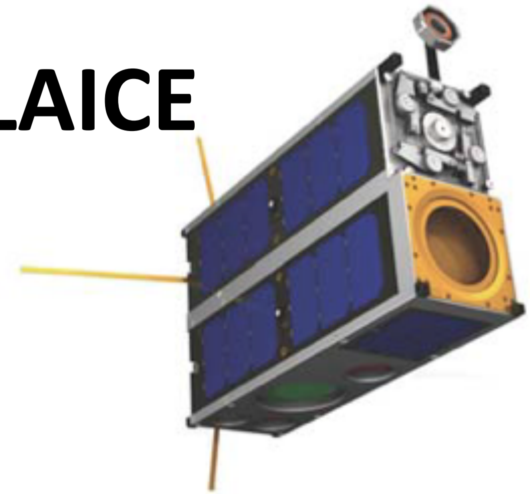
ExoCube

CSSWE
Colorado Student Space
Weather Experiment

CubeSat for Ions Neutrals Electrons and MAgnetic fields

trio cinema 3

LAICE



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FIREBIRD

THE AEROSPACE CORPORATION

MONTANA STATE UNIVERSITY

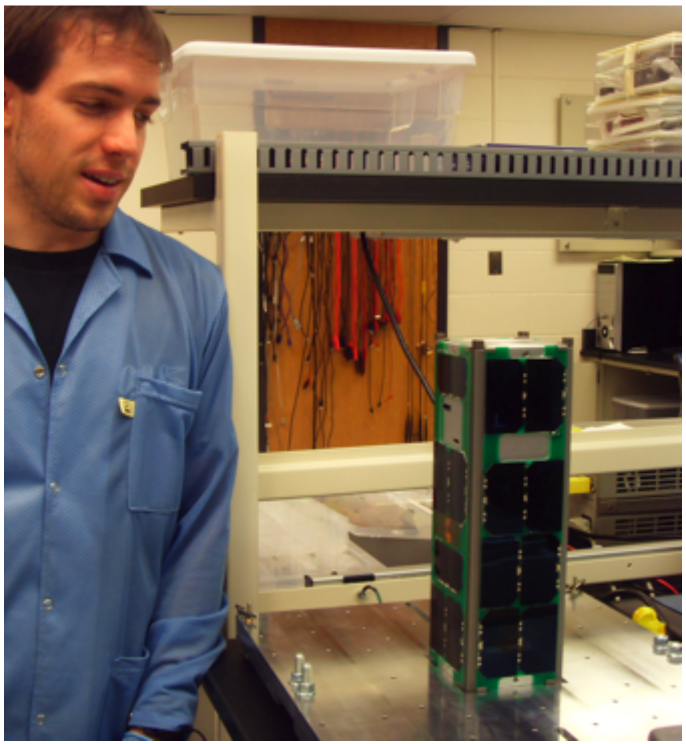
BOSTON UNIVERSITY

Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics

OPAL

CSSWE
Colorado Student Space Weather Experiment

- **U. Colorado, Boulder**
- **Solar Proton Events & Radiation belt dynamics**
  - **3U cubesat**
  - **Energetic electrons (0.5-3MeV) and protons (10-40MeV)**
- **Launched Sep 2012**
  - **Complete mission success**
  - **More than 2 years operation**



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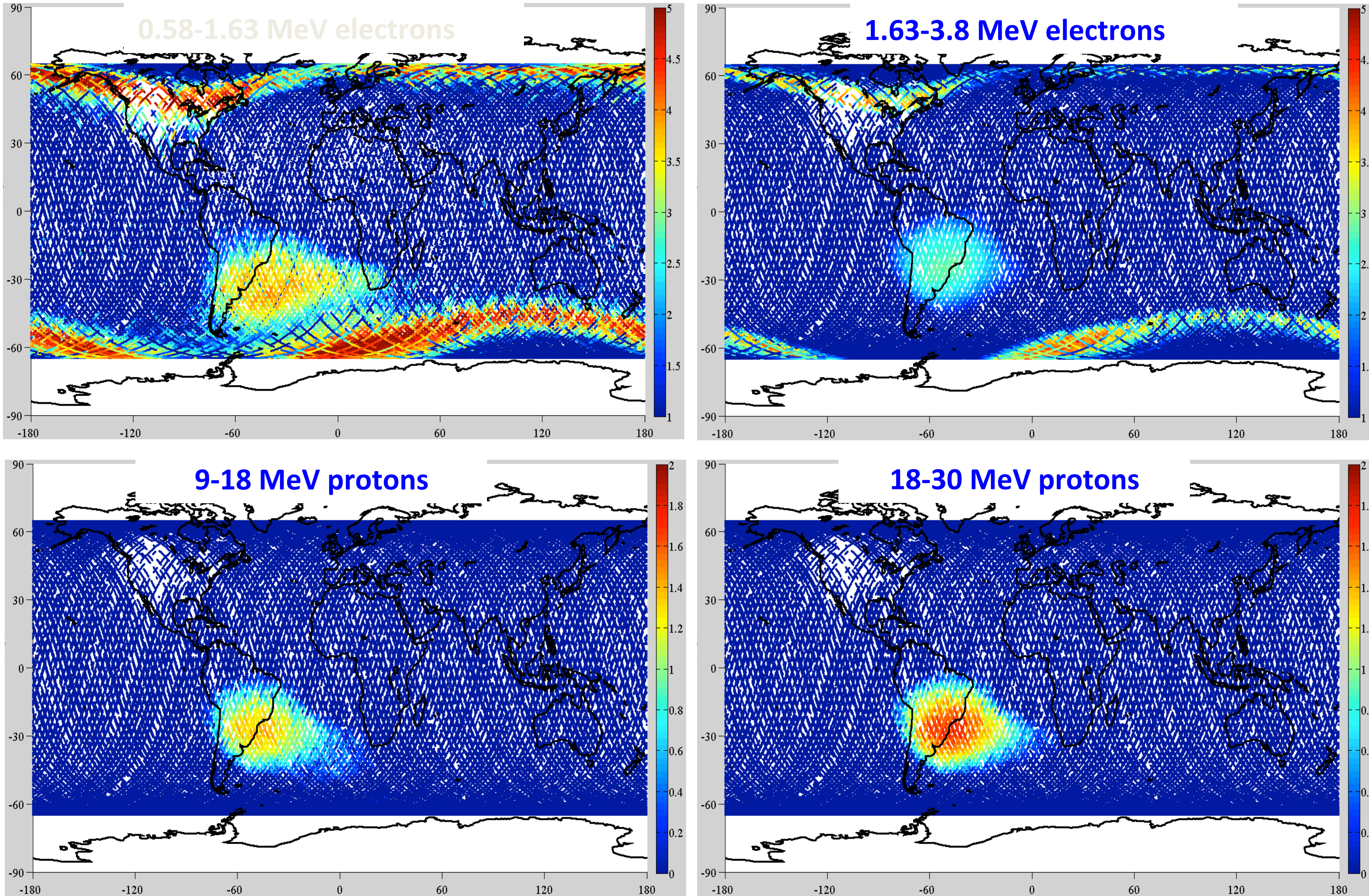
0.58-1.63 MeV electrons
1.63-3.8 MeV electrons
9-18 MeV protons
18-30 MeV protons
90
60
30
0
-30
-60
-90
-180
-120
-60
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0

Science Summary of NSF FIREBIRD-I and -II Missions

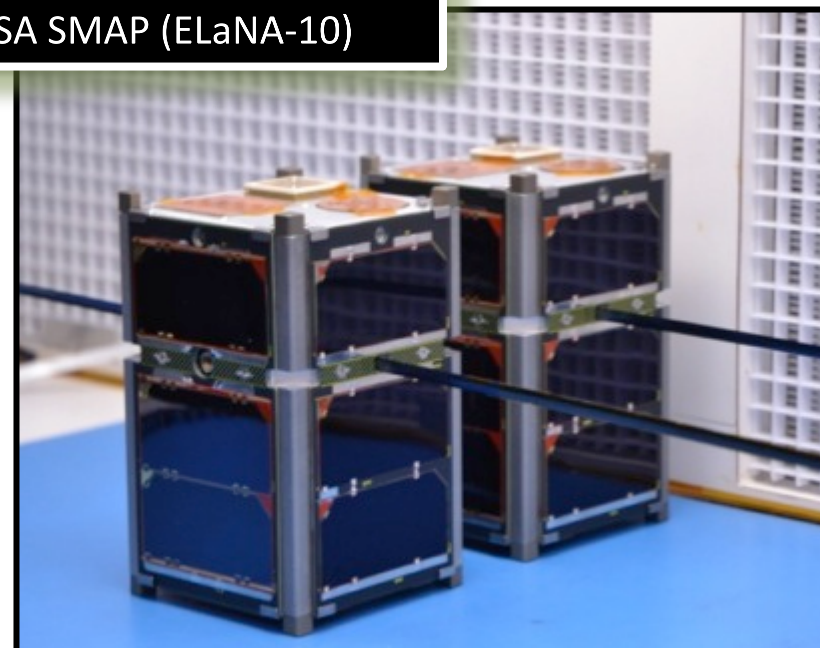
PIs: Harlan Spence (UNH) and David Klumpar (MSU)

FB-I LAUNCHED: Dec 6, 2013
VAFB Atlas-5 NROL-39

FB-II Launched late 2015
VAFB Delta-II 7320 NASA SMAP (ELaNA-10)

FIREBIRD- I: Flight Units 1 and 2

Provided excellent science results;
FU1: 12/13 - 1/14, FU2: 4/14 – 9/14



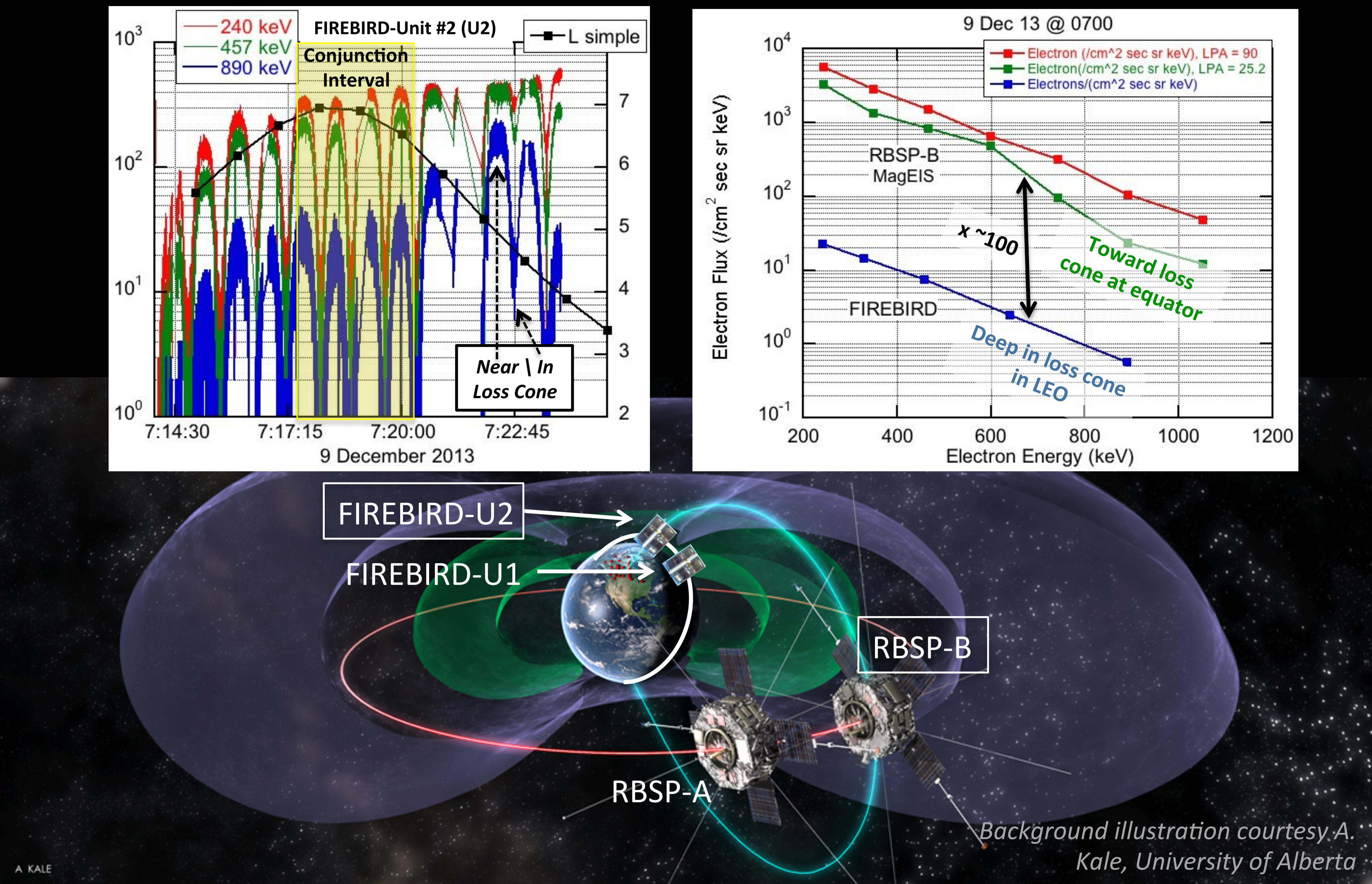
FIREBIRD-II: Flight Units 3 and 4

Improved version of FB-I mission;
Launched and beautiful data since 1/2015

University of New Hampshire
Institute for the Study of Earth, Oceans, and Space

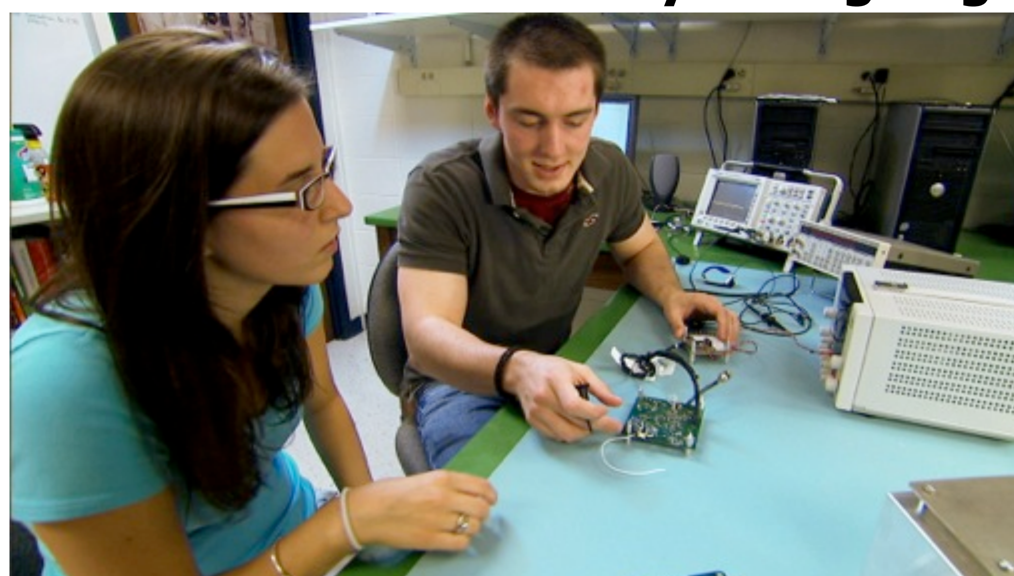
SSEL | MONTANA STATE UNIVERSITY | AEROSPACE | Los Alamos NATIONAL LABORATORY

Comparison of Conjugate Spectral Shape and Electron Intensity (0.25 – 1 MeV) In/Near Loss Cone at LEO (FB-U2) & Equator (RBSP-B) at L ~ 6.5



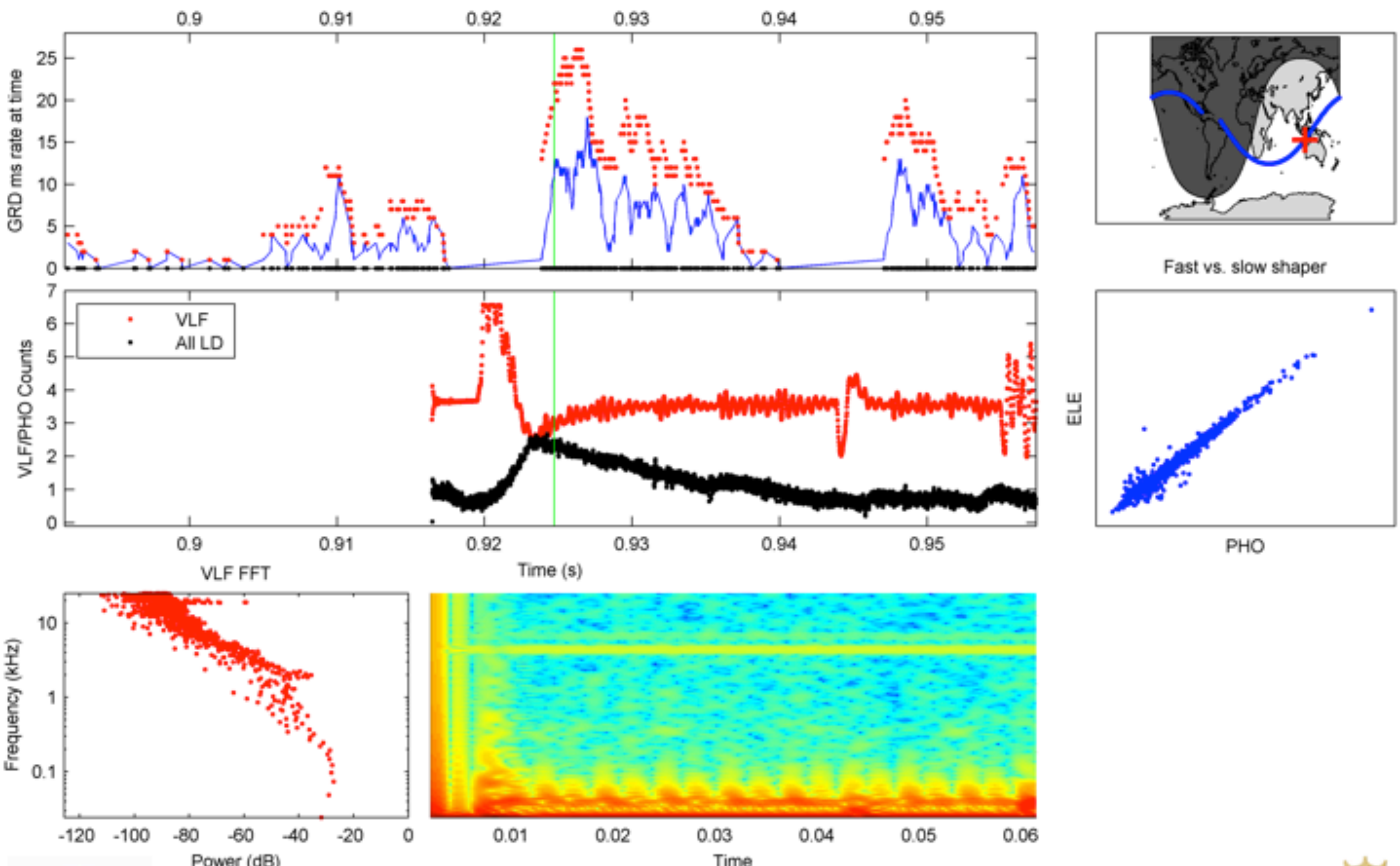
Background illustration courtesy A. Kale, University of Alberta

- **NASA Goddard Space Flight Center & Siena College**
- **Terrestrial Gamma Ray Flashes and Lightning**
  - ❑ **3U cubesat**
  - ❑ **Gamma Rays (to 20MeV); VLF radio and optical**
- **Launched Nov 2013**
  - ❑ **2 months to first contact**
  - ❑ **Data collection and analysis ongoing**



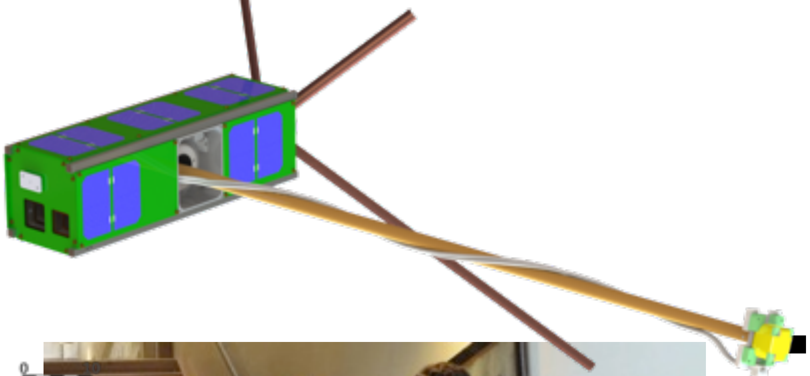
Firefly Combined Survey Plot

UT Time: 2014.05.21 16:55:6.820 Position: -13.905 N 114.178 E, 489 km

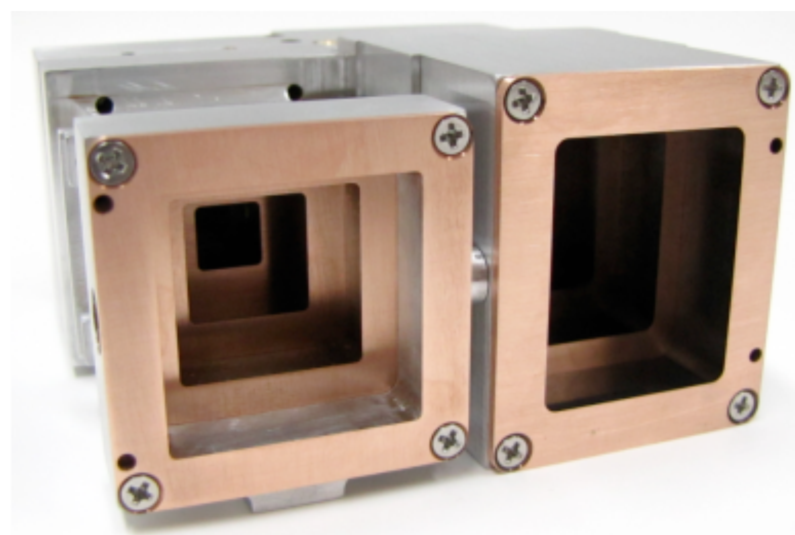


We gratefully acknowledge support from the National Science Foundation

ELFIN



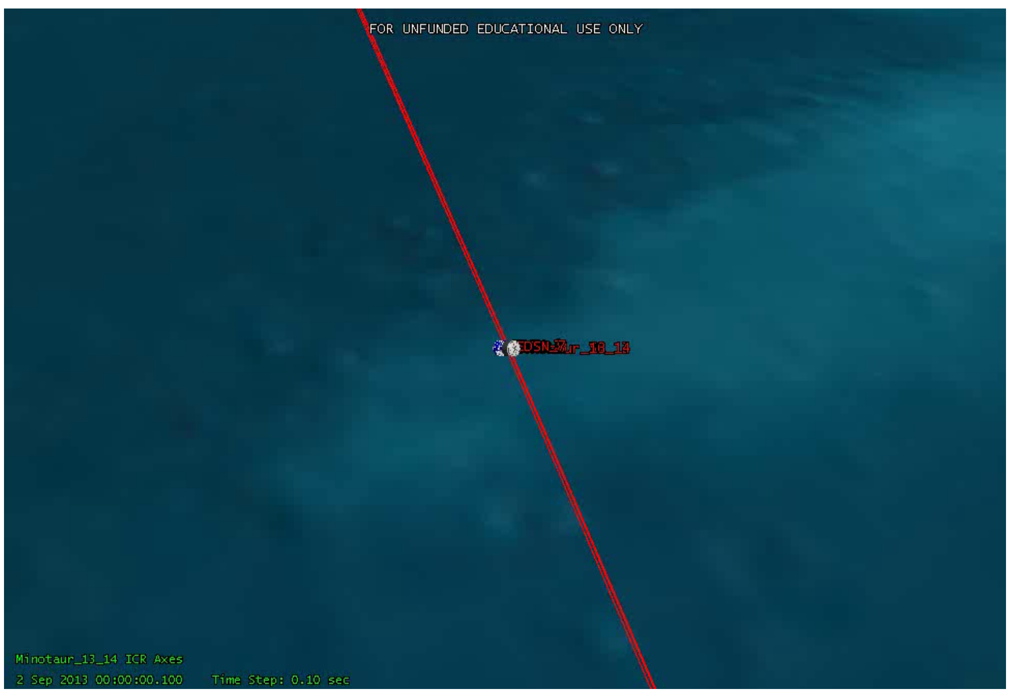
- UCLA
- Pitch angle distribution of relativistic electrons and ions
  - 3U cubesat; spinning @20rpm
  - Full angular distribution of electrons (50keV-5MeV) and ions (50-300keV); Magnetic field
- Project Started August 2014
  - Jointly funded with NASA

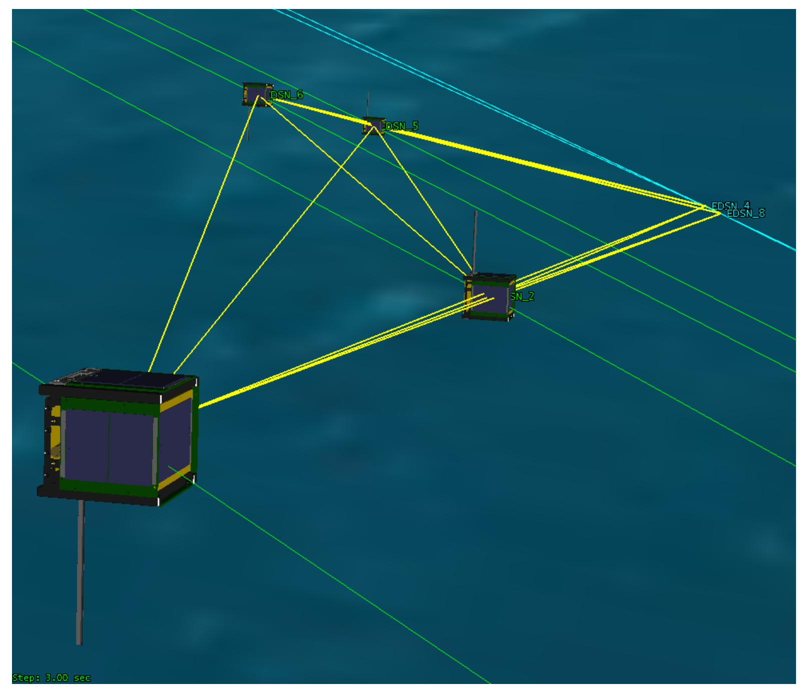


Upcoming EDSN Mission (MSU, D. Klumpar)

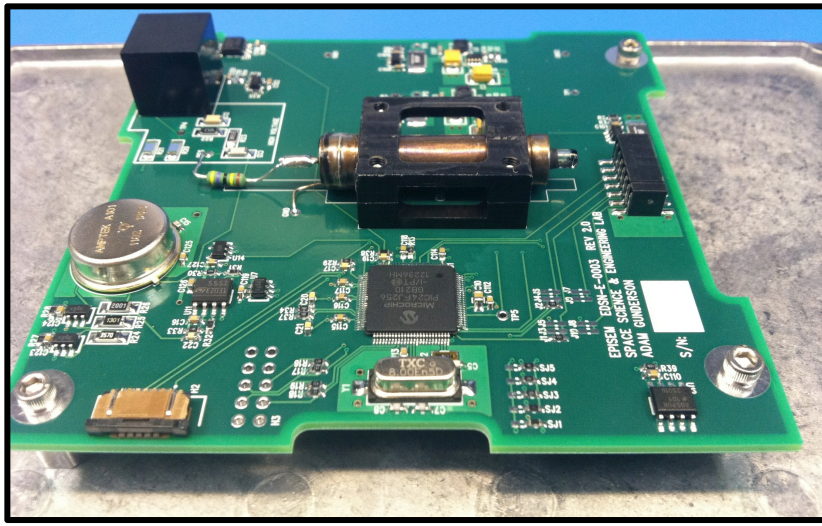
- 14 Space Radiation Payloads for NASA STMD Edison Demonstration of SmallSat Networks (EDSN) – Energetic Particle Integrating Space Environment Monitor (EPISEM)
  - Multi-node network of 8 identical satellites
  - CMD and DWNLNK accomplished through a single "parent" which sends and receives data from the rest of the "siblings."
  - Any of the 8 satellites can become the "parent."
  - Active attitude control through magnetorquers and reaction wheels
  - On board GPS receiver and S-band Comm system

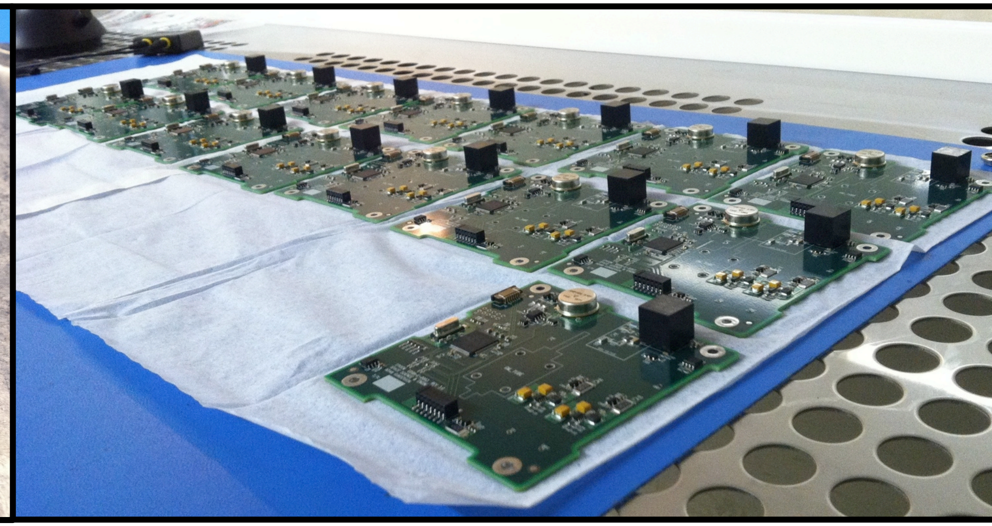
NODES: Two spare EDSN units will launch as a separate 2-element constellation from ISS

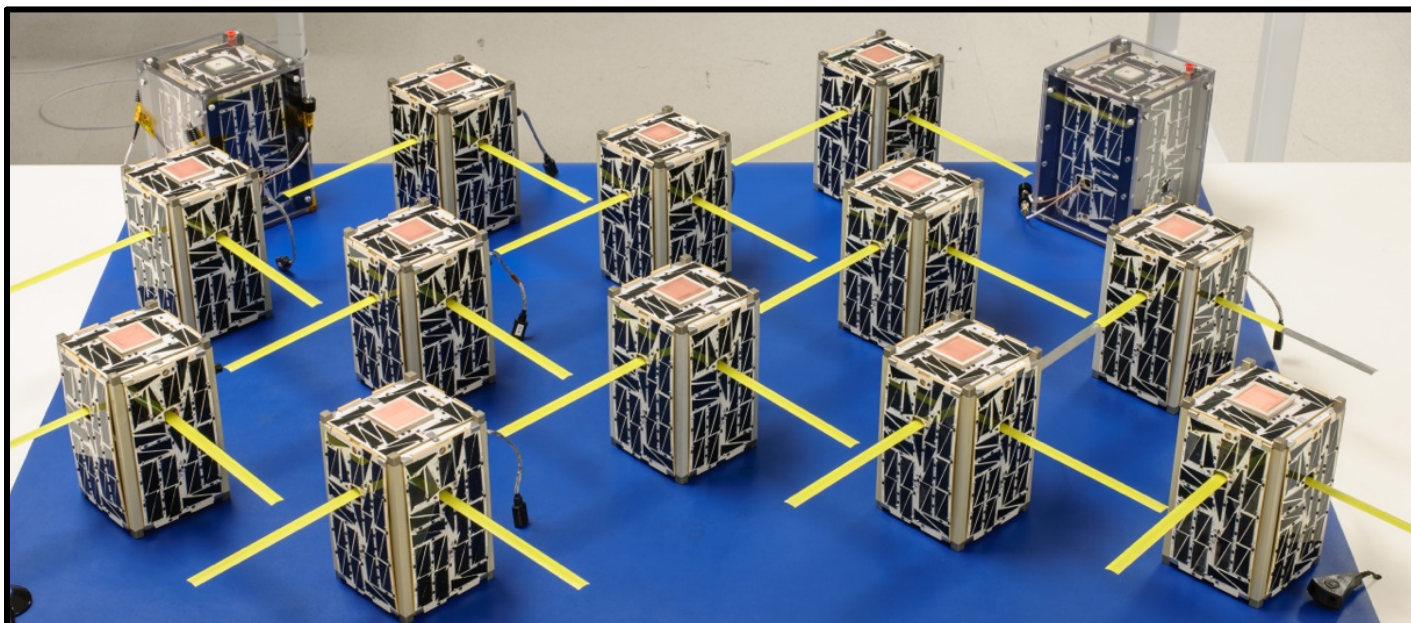




The EDSN/NODES CubeSats



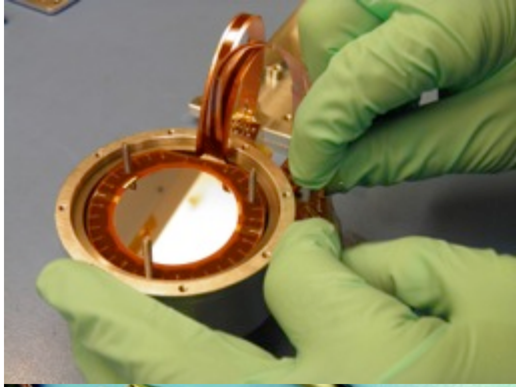


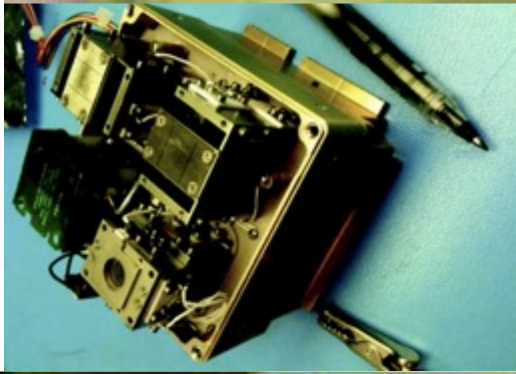


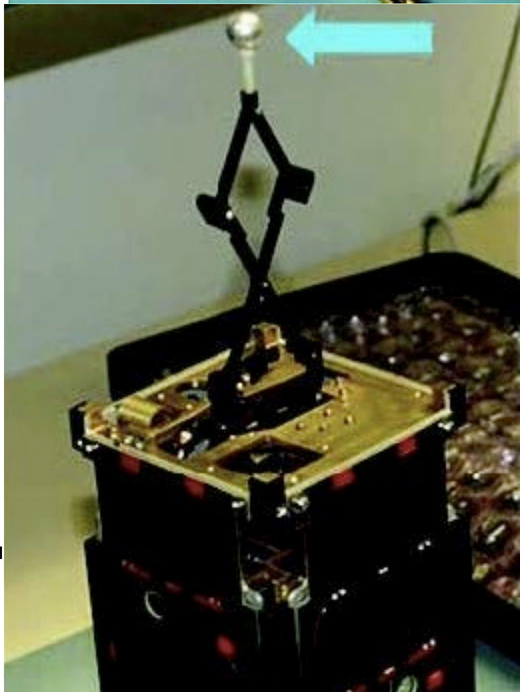
Energetic
Particle
Integrating
Space
Environment
Monitor

Cubesats in LEO

- **can provide most desired space physics parameters**
  - **Capability already demonstrated, or will be soon for: in-situ fields, energetic and supra thermal particles, plasma and neutrals densities, winds, and composition, VLF and UHF receivers, and gamma ray detectors**
  - **Capability documented and will be demonstrated soon for: remote sensing of aurora, air-glow, radio occultation, and simple solar imaging and flare observations (e.g. X-ray)**







Cubesats in HEO & Beyond

- **Exciting potential**
  - **realize mag-con type missions and multi-point solar and solar wind monitoring; even planetary**
- **Main technical challenges include:**
  - **communication and power (related) – laser communication**
  - **radiation hardiness**
  - **maneuverability (propulsion and formation flying) – in-space propulsion**

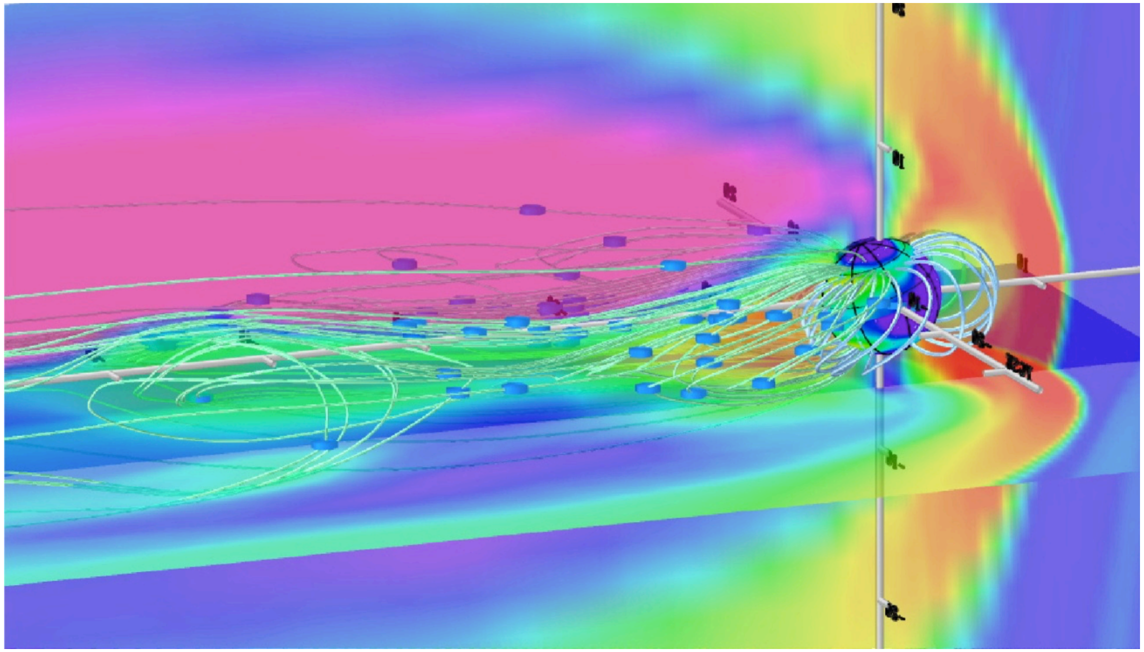
Decadal Survey Committee Reports – Fodder for CubeSat Science Opportunities!

- Committee reports contain additional science topics that are high priority but did not rise to the top based on either science merit or technology/cost/risk concerns
- A common theme in many reports is that constellation missions are an imperative, but implementation poses challenges – hence recommendation in main report to "Venture"
- GDC represents a "modest" constellation while others require bolder implementations that would lead to truly transformative scientific understanding

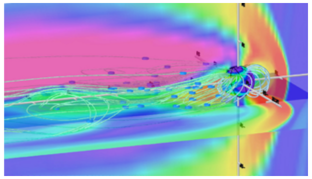
A Retrospective Look Forward on Constellation-Class Geospace Missions

Harlan E. Spence[1,2] and Thomas E. Moore[3]

1. *Center for Space Physics, Boston University*
2. *Space Science Center, University of New Hampshire*
3. *Goddard Space Flight Center, NASA*



Historical Backdrop: 1960's



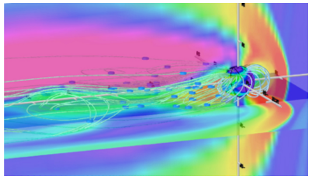
"Looking to the future I believe that progress requires bunches of satellites, though these are as yet in no published program. One is continually conscious of this need for reasons which have a direct analogue on the ground...[S]ince satellites are being launched singly, the scientific returns are less than they could be." *J. Dungey [1966]*[1]

"Most of the important phenomena involve simultaneous variations in space and time. In some cases simultaneous measurements made at two well-chosen locations will provide unambiguous results. In other cases, it may be necessary to make simultaneous measurements at several hundred locations." *C.E. McIlwain [1967]*[2]

....Yesterday's Future is Now!

(1) from "Inaugural Lecture as Professor of Physics at Imperial College," 1966; quote courtesy of W. J. Hughes.
(2) from "Comments and Speculations Concerning the Radiation Belts," page 303 (Proceedings of the Joint IQSY/COSPAR Symposium, London, 1967, Part 1), MIT Press, 1967; quote courtesy of R. B. Sheldon.

Historical Backdrop: 1990's

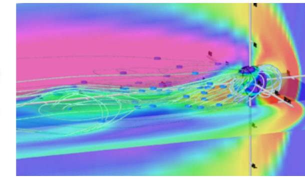


- NASA's New Mission Concept AO in mid-1996 prompted from the community many mission ideas using multiple satellites

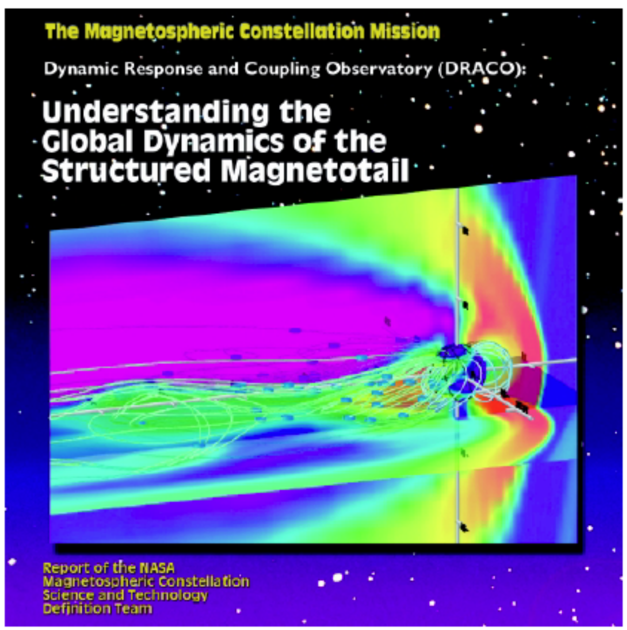
- Geospace "Multiprobe" team formed to identify and prioritize mission concepts

- Magnetospheric Constellation (MC) science and **technology** definition team (STDT) formed in 1999

Historical Backdrop: Early 2004

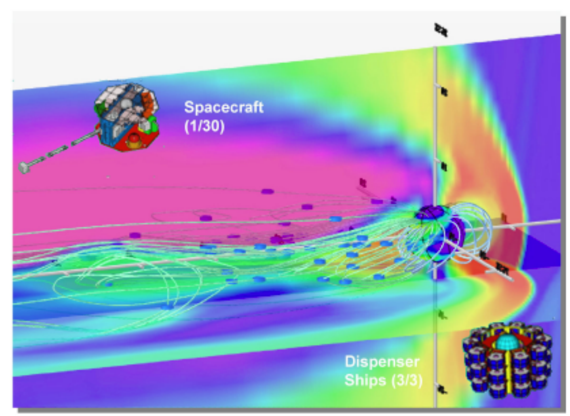


- Magnetospheric Constellation report published ‘01
- Updated report published in late 2004 (MC, MMC)



NASA/TM—2001–209985

May 2001



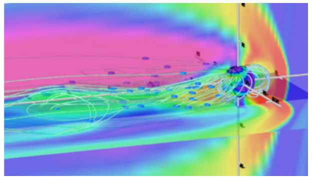
The Magnetospheric Constellation (MC)

Global Dynamics of the Structured Magnetotail

Updated Synopsis of the
Report of the NASA Science and Technology Definition Team
for the Magnetospheric Constellation Mission

October 2004

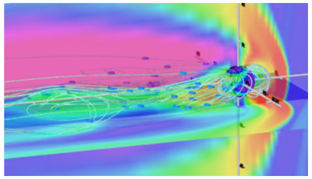
Geospace Science Motivations



- Observations and simulations show global magnetotail is highly structured in space and time (L > ~1 Re; t >~ 10 sec)
- Driven by reconnection which is bursty in time and patchy in space and other structured macroscale instabilities

A constellation of simply instrumented spacecraft required to resolve space/time ambiguities which conceal the governing physical processes in this complex magnetized fluid.

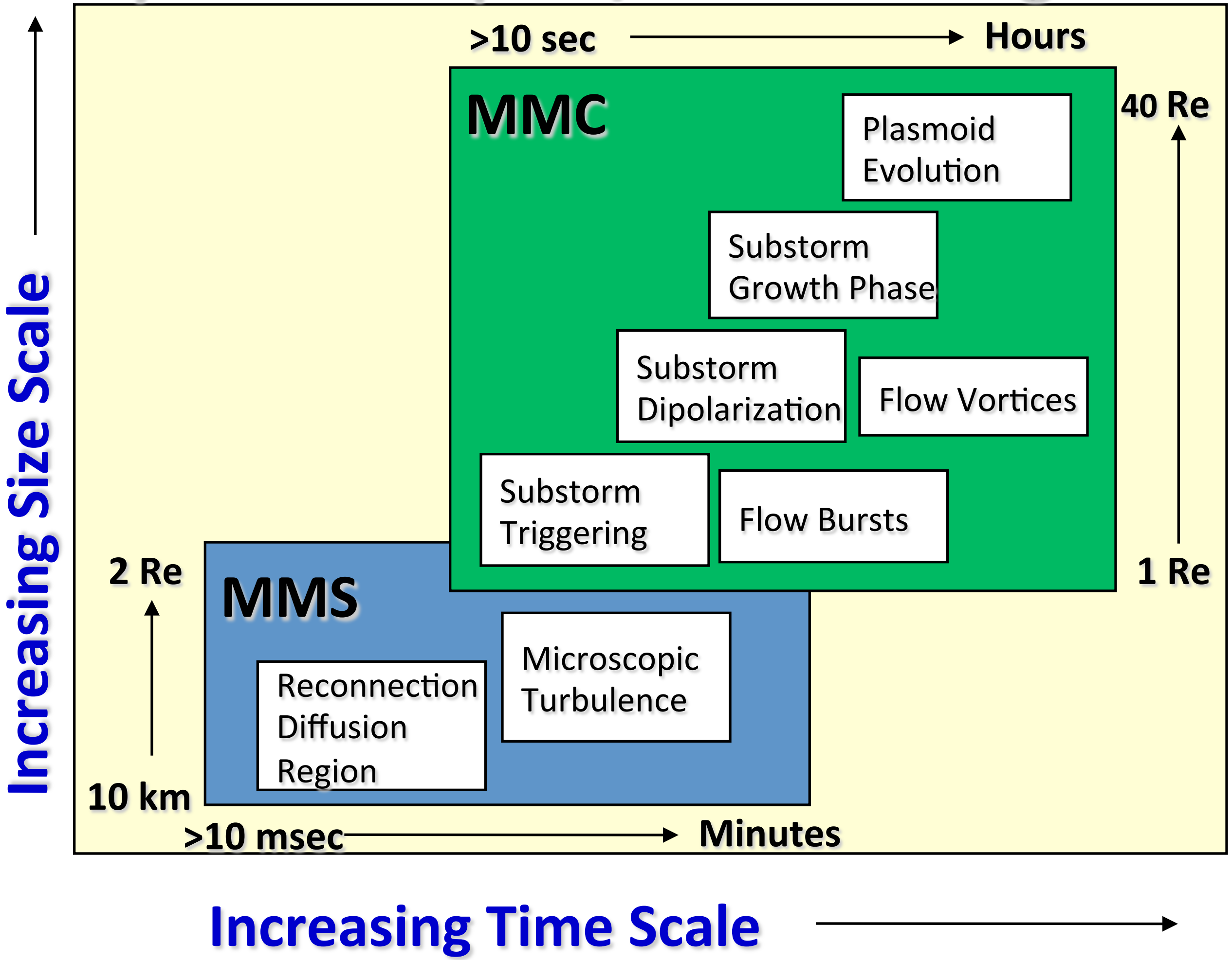
Regional flow bursts projected in the equatorial plane of a dynamic plasma sheet; simulation courtesy of C. Goodrich.



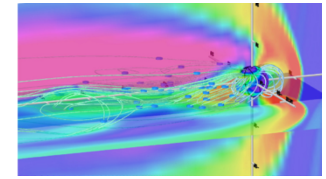
Sampling Configuration Space

- Single spacecraft only glimpse micro- and macro-physics.
- Next logical step is to deploy spacecraft "networks" and requires both:
- <u>MMS/Cluster</u> to resolve small size and short time scales
- <u>THEMIS</u> provides 1D array focused on substorm chronology
- <u>MMC</u> to resolve larger size and longer time scales processes

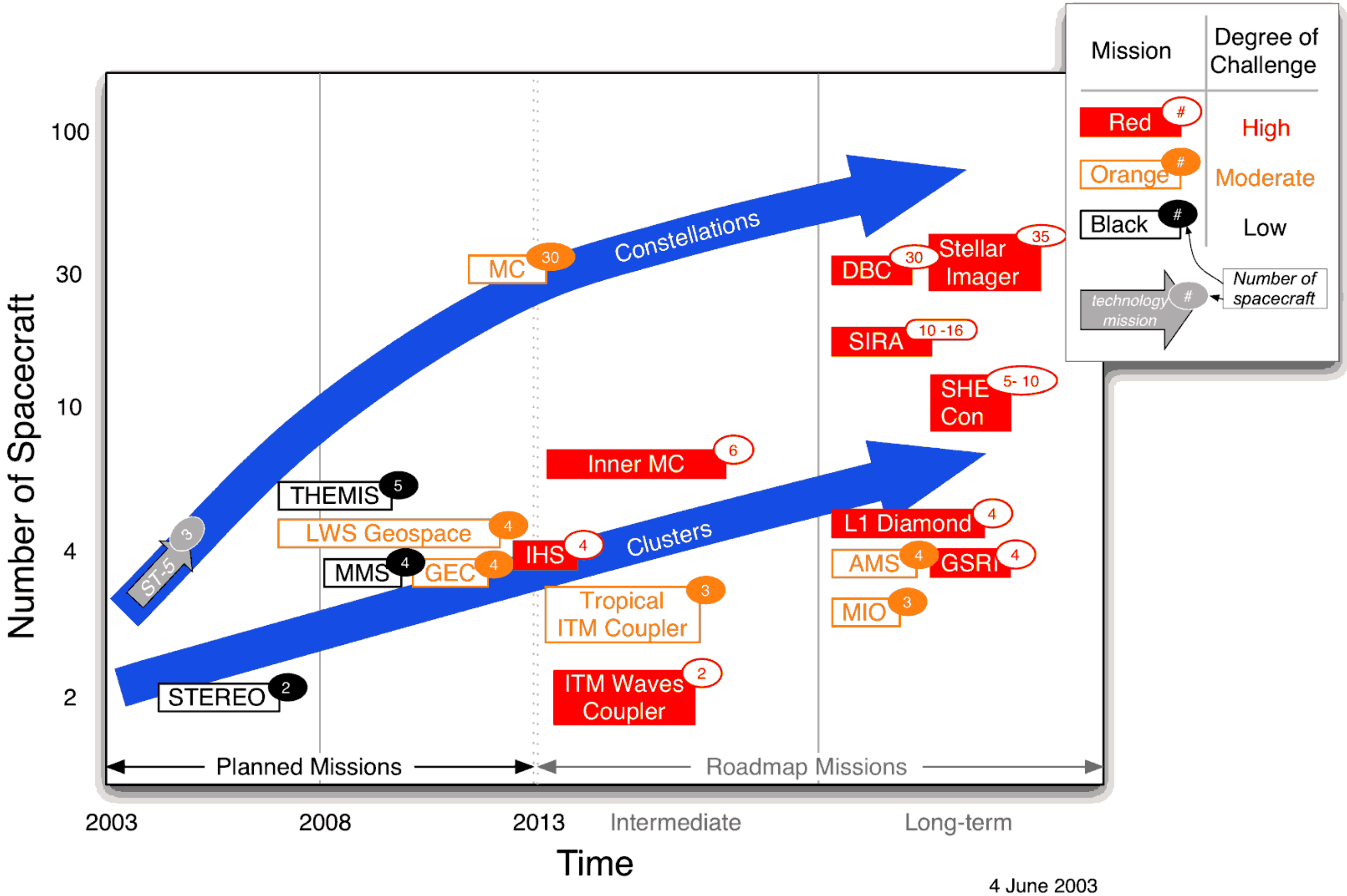
Systematic Space/Time Coverage



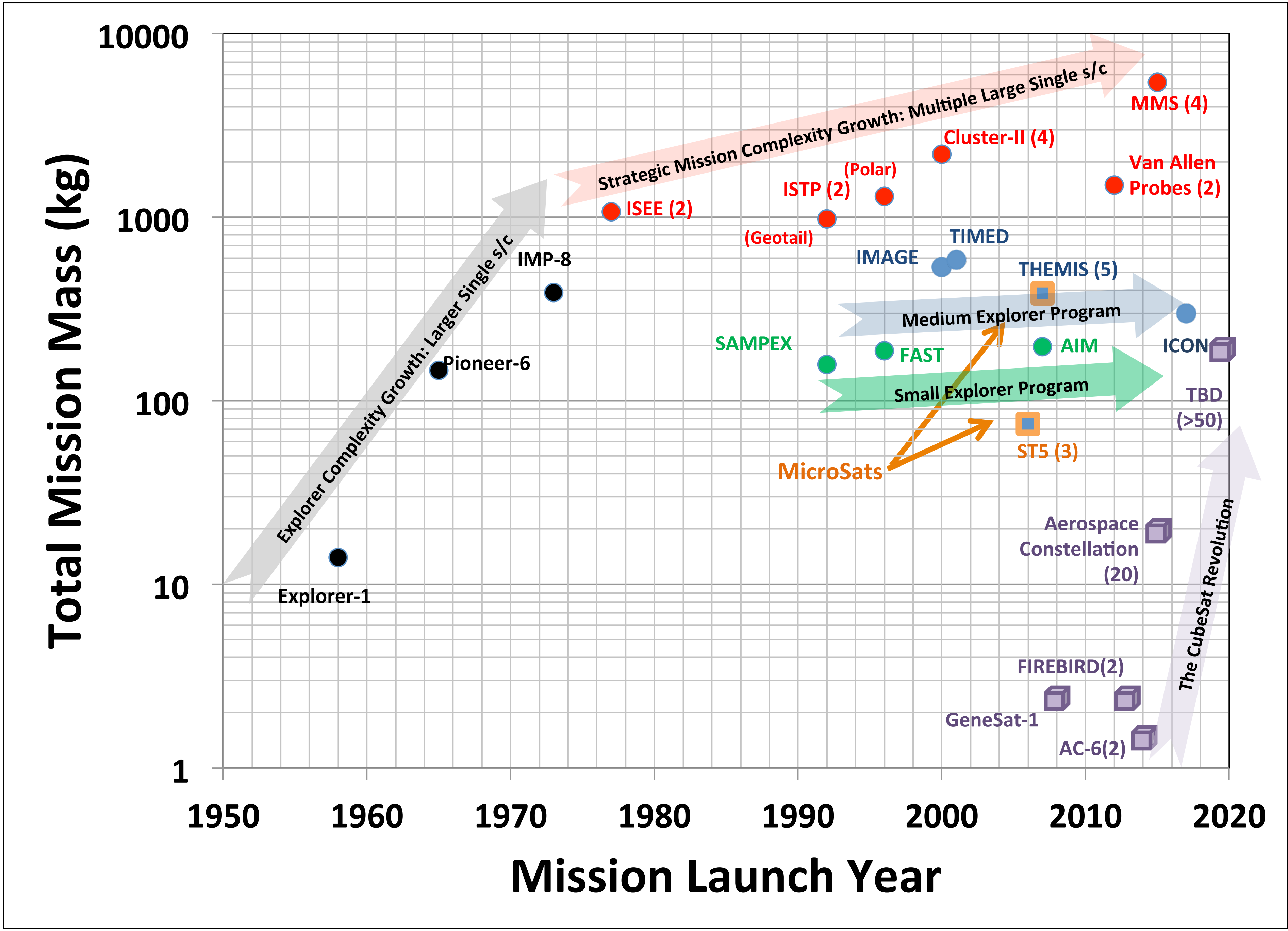
How Many Spacecraft?



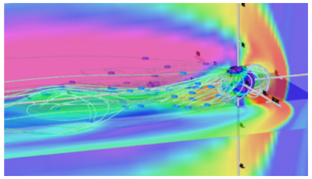
- MCC requires an order of magnitude more s/c than previous vector missions
- Creates 2D array of inner plasma sheet.
- 25 to 30 s/c would let us see the *dynamics* in the most interesting part of tail, based on estimates from the IRM data.



The Challenge of "Economical" Spacecraft: *Develop affordable clusters and constellations of spacecraft for multi-point measurements of the connected Sun-Earth System.*


Total Mission Mass (kg)
10000
1000
100
10
1
1950
1960
1970
1980
1990
2000
2010
2020
Mission Launch Year
Explorer Complexity Growth: Larger Single s/c
Strategic Mission Complexity Growth: Multiple Large Single s/c
Medium Explorer Program
Small Explorer Program
The CubeSat Revolution
Explorer-1
Pioneer-6
IMP-8
ISEE (2)
ISTP (2)
(Geotail)
(Polar)
Cluster-II (4)
MMS (4)
Van Allen
Probes (2)
IMAGE
TIMED
THEMIS (5)
ICON
SAMPEX
FAST
AIM
TBD
(>50)
MicroSats
ST5 (3)
Aerospace
Constellation
(20)
FIREBIRD(2)
GeneSat-1
AC-6(2)

Concluding Remarks



- Science drivers for constellation-class missions have existed since dawn of space age
- Many of same science drivers remain unaddressed in 40 years because push to tackle microphysics (more accessible with single s/c or cluster of s/c)
- Technology development (especially over the past decade) now enables many elements needed for a constellation-class mission
- Originally envisioned as 25-kg class s/c – revisit again given emergence of CubeSats… Cheaper?...Sooner?

Those who assert that "It cannot be done", should never interrupt those who are already doing it.