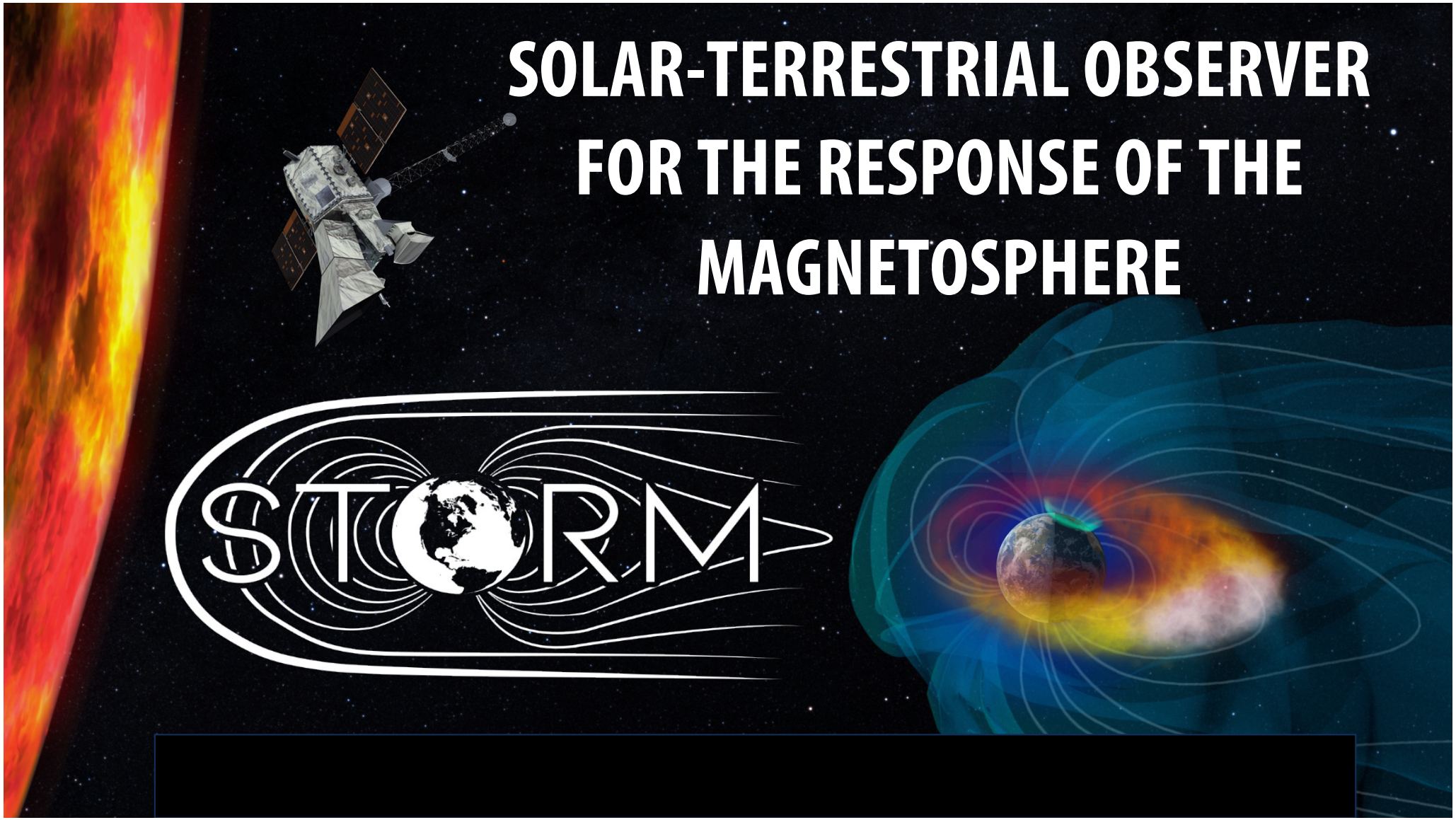
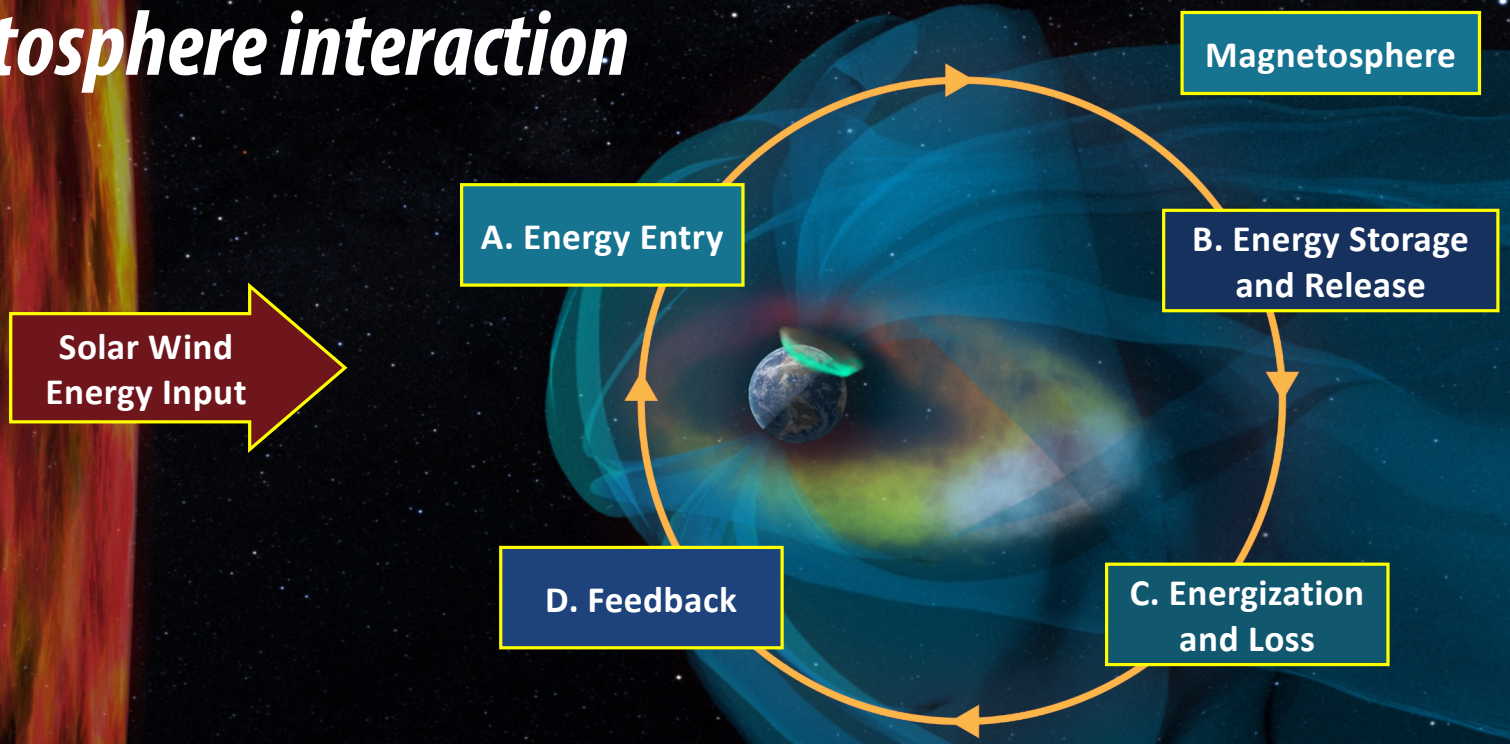
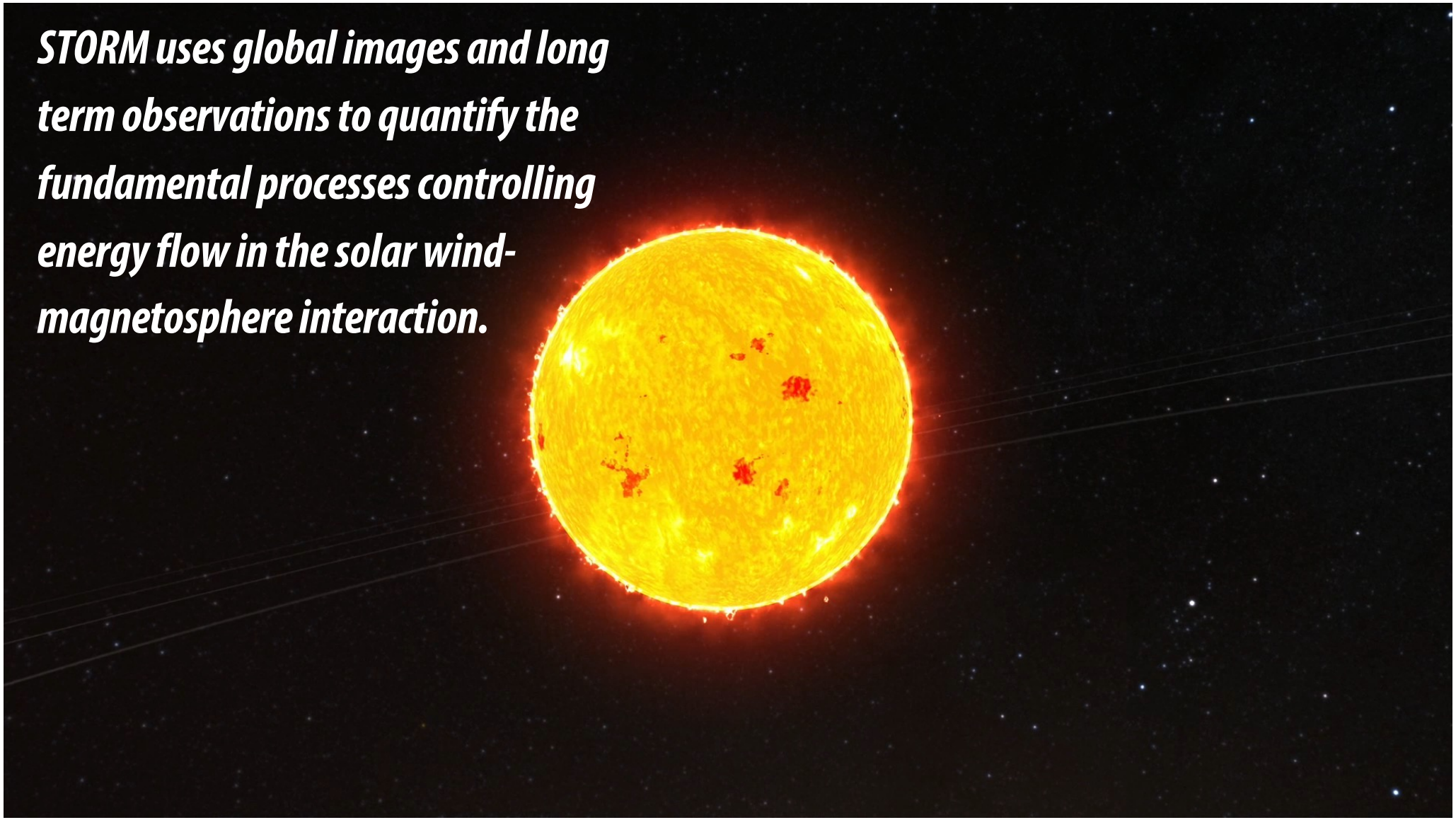

SOLAR-TERRESTRIAL OBSERVER
FOR THE RESPONSE OF THE
MAGNETOSPHERE
STORM

Talk Outline

- 1. Science Drivers
- 2. Observations Needed to Perform the Research
- 3. Instruments and Spacecraft
- 4. Orbit and pointing
- 5. Other Mission Design Parameters
- 6. Writing a proposal and Waiting for the results…

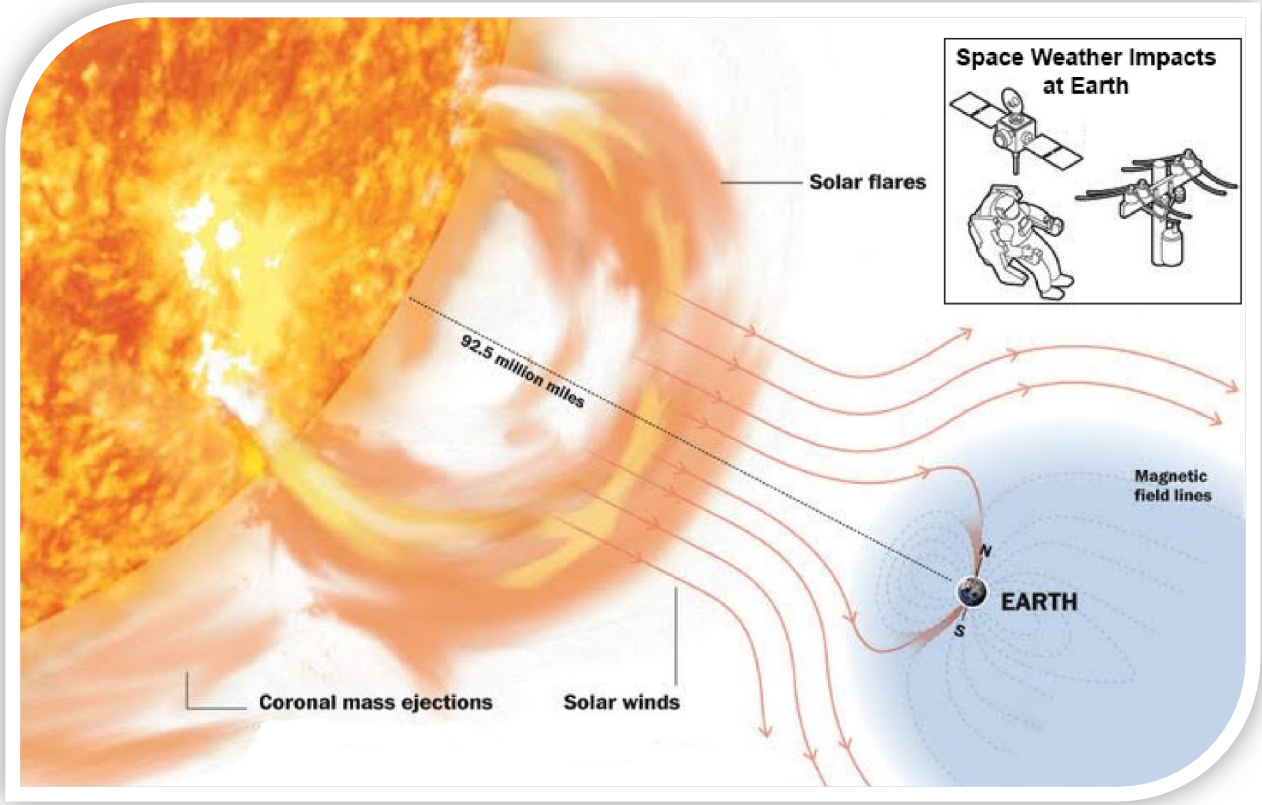
STORM: System Science of the solar wind-magnetosphere interaction



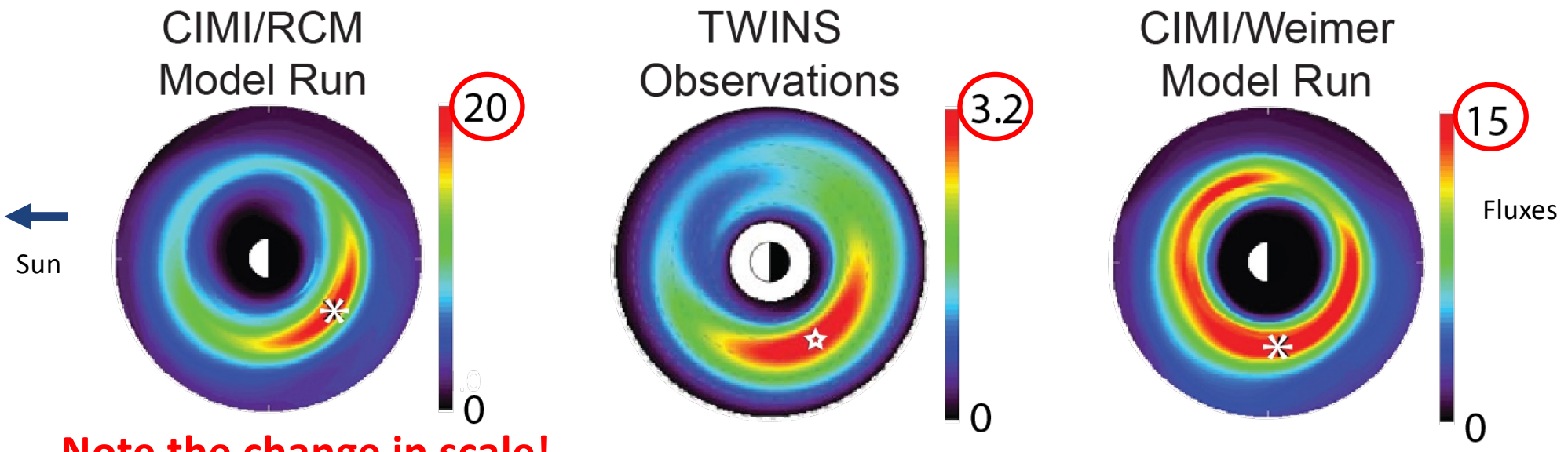

STORM uses global images and long term observations to quantify the fundamental processes controlling energy flow in the solar wind-magnetosphere interaction.

This Dynamic Interaction Drives Hazardous Space Weather

A detailed understanding of the fundamental physics governing space weather at Earth will enable improved modeling, accurate forecasting, and successful mitigation



Incorrect Models:
The Ring Current and Surface Charging

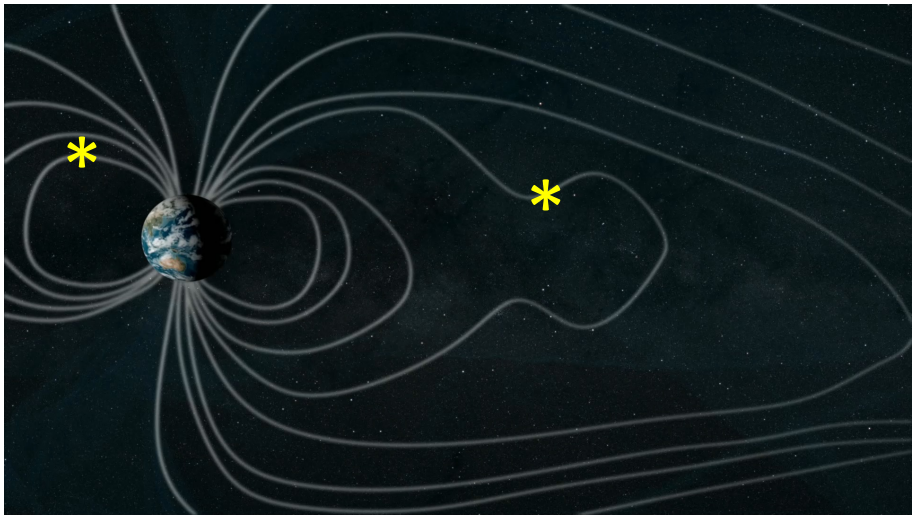


Note the change in scale!

Global models miss fundamental science and produce conflicting predictions

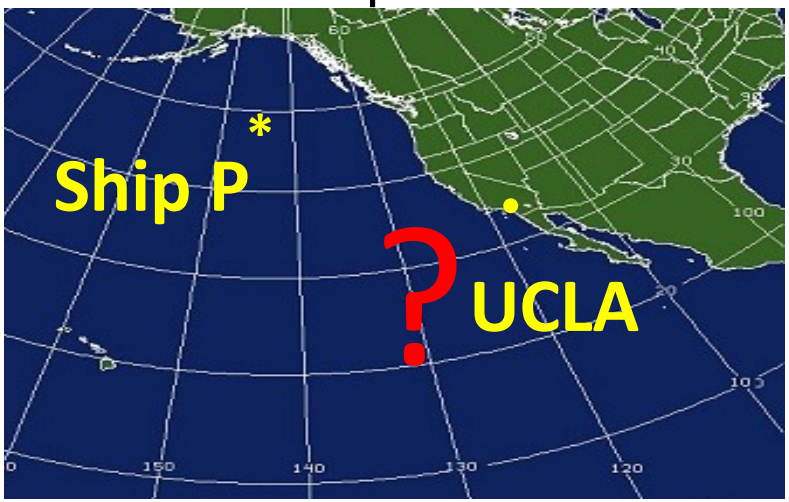
A Paucity of Simultaneous Observations

Magnetospheric Physics Today

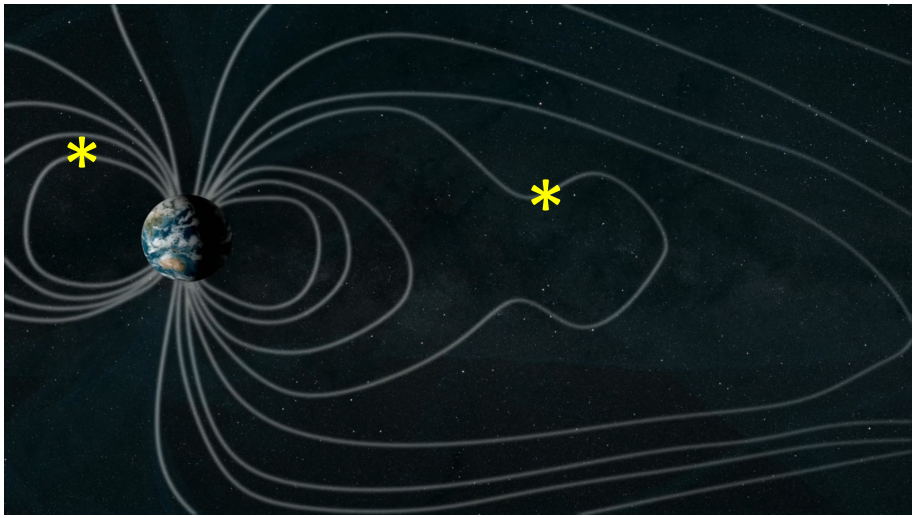


A Paucity of Simultaneous Observations

In-situ meteorology before GOES spacecraft

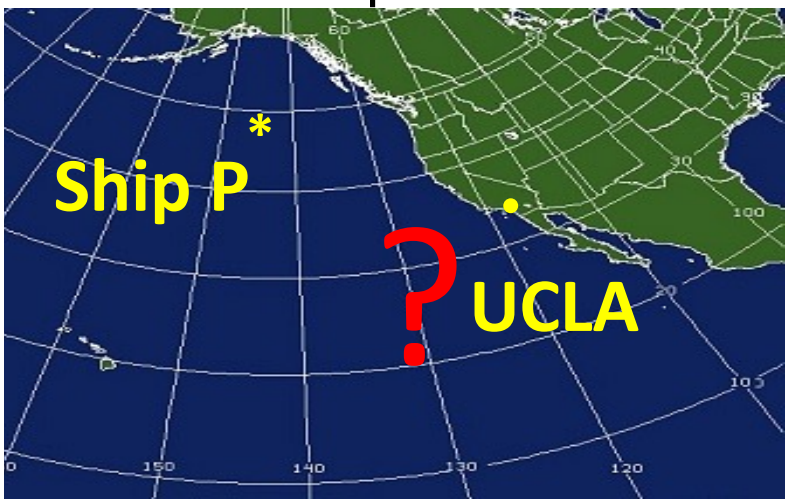


Magnetospheric Physics Today

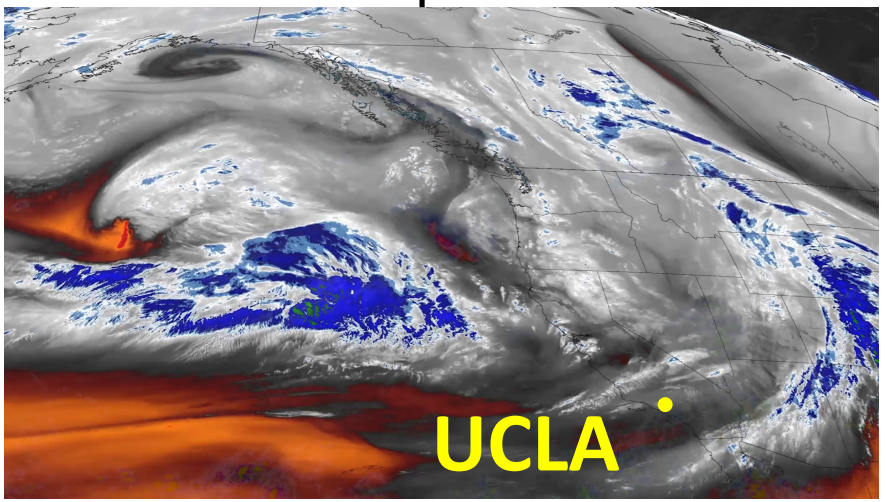


The Argument for Global Imaging

In-situ meteorology before GOES spacecraft



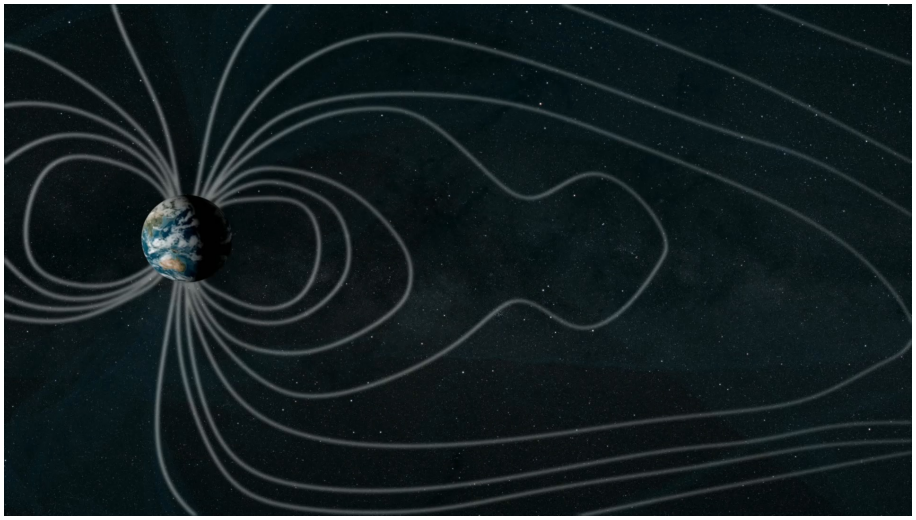
Imaging meteorology after GOES spacecraft

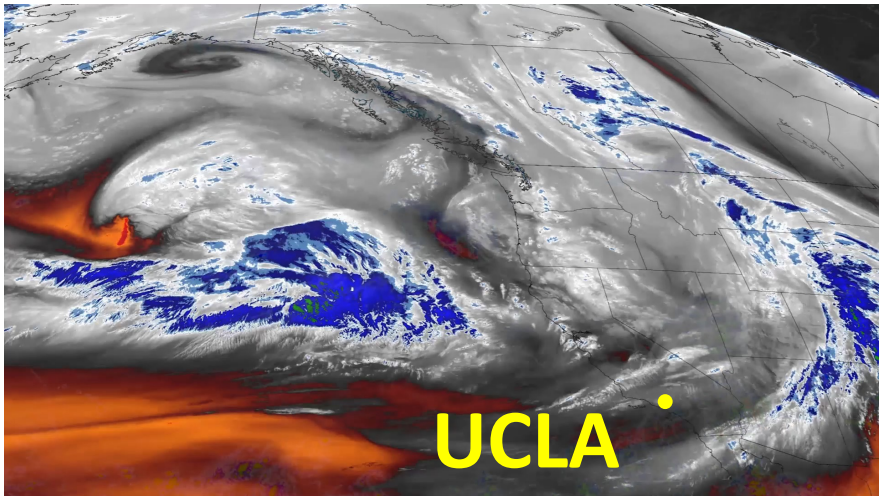


Global imaging revolutionized meteorology with both fundamental physics and the knowledge needed to improve forecasting.

The Argument for Global Imaging

Magnetospheric Physics with STORM

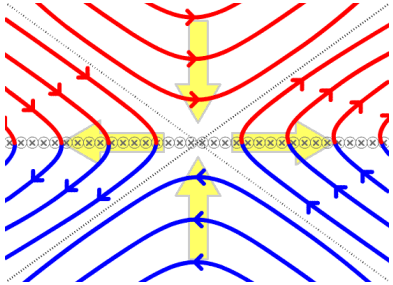




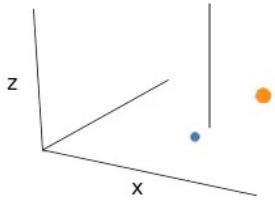
Global imaging and system science will revolutionize magnetospheric physics *with the fundamental physics understanding needed to improve forecasting.*

NASA Studies Fundamental Plasma Physics → Reconnection & Particle Acceleration

Reconnection



Particle Acceleration



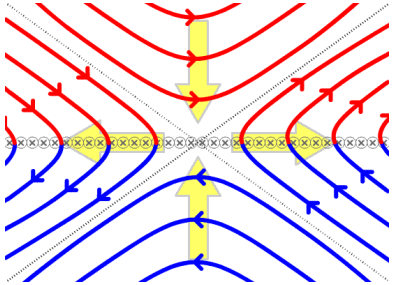
STORM's images resolve fundamental Heliophysics science questions

NASA Studies Fundamental Plasma Physics → Reconnection & Particle Acceleration

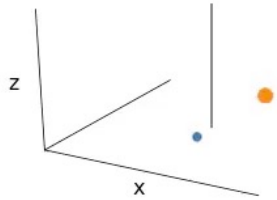
Are reconnection and particle acceleration…

Patchy and Local?	OR	Extended and Widespread?
Steady and Continuous?	OR	Bursty and Sporadic?
Triggered by Solar Wind Features?	OR	Intrinsically Unstable?

Reconnection



Particle Acceleration



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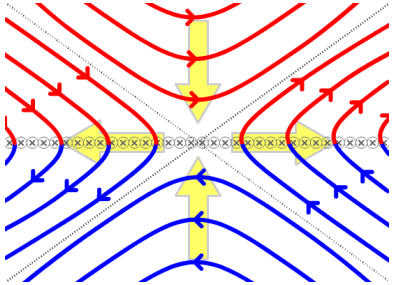
Are reconnection and particle acceleration…

Patchy and Local?	OR	Extended and Widespread?
Steady and Continuous?	OR	Bursty and Sporadic?
Triggered by Solar Wind Features?	OR	Intrinsically Unstable?

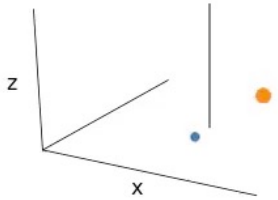
Do these answers depend on solar wind and magnetospheric conditions?

→ The answers matter not just to magnetospheric physicists but also to researchers across the heliophysics, planetary, and astrophysics disciplines

Reconnection



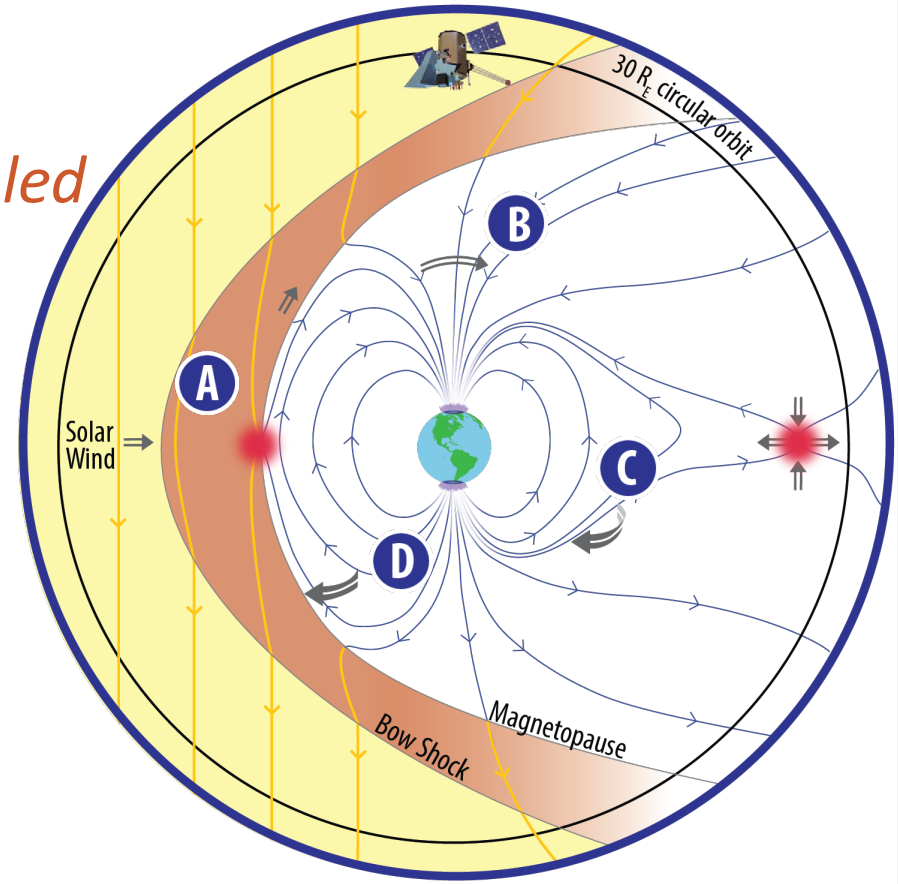
Particle Acceleration



STORM's images resolve fundamental Heliophysics science questions

STORM has Four Science Objectives/Regions that Quantify the Global Flow of Energy Through the Coupled Solar Wind-Magnetosphere system

- **A** Energy Transfer at the Dayside Magnetosphere.
- **B** Energy Circulation and Transfer Through the Tail.
- **C** Energy Sources and Sinks in the Ring Current.
- **D** Energy Feedback from the Inner Magnetosphere.



Science Summary

- We have identified a research problem targeted at:
  - fundamental physics discoveries ✓
  - something of practical use to humankind ✓

Science Summary

- We have identified a research problem targeted at:
  - fundamental physics discoveries ✓
  - something of practical use to humankind ✓

- What do we need to succeed?

2. We need more observations and better models

Requirement	STORM
Information on the dynamics of fundamental processes (reconnection, particle energization)	Continuous global observations to quantify fundamental processes (reconnection, particle energization) ✓
Simultaneous observations of the critical regions	System science view of the magnetosphere ✓
Statistics of where, when, and why processes occur	Self-standing 2-year mission ✓
Incorporation into first principle forecast models	Strong modeling team ✓

STORM's global magnetospheric imaging and system science enable the understanding of physical processes to successfully forecast space weather at Earth

REQUIREMENTS

- 1. Measurements and Payload
- 2. Spacecraft bus
- 3. Launch vehicle
- 3. Orbit
- 4. Pointing and Propulsion
- 5. Thermal
- 5. Power
- 6. Communication
- 7. Radiation
- 8. MOC, SOC, SDC
-

STORM's Observables

- Solar Wind Magnetic Field
- Solar Wind Plasma
- Magnetopause location
- Global Aurora
- Ring Current
- Microscale Aurora

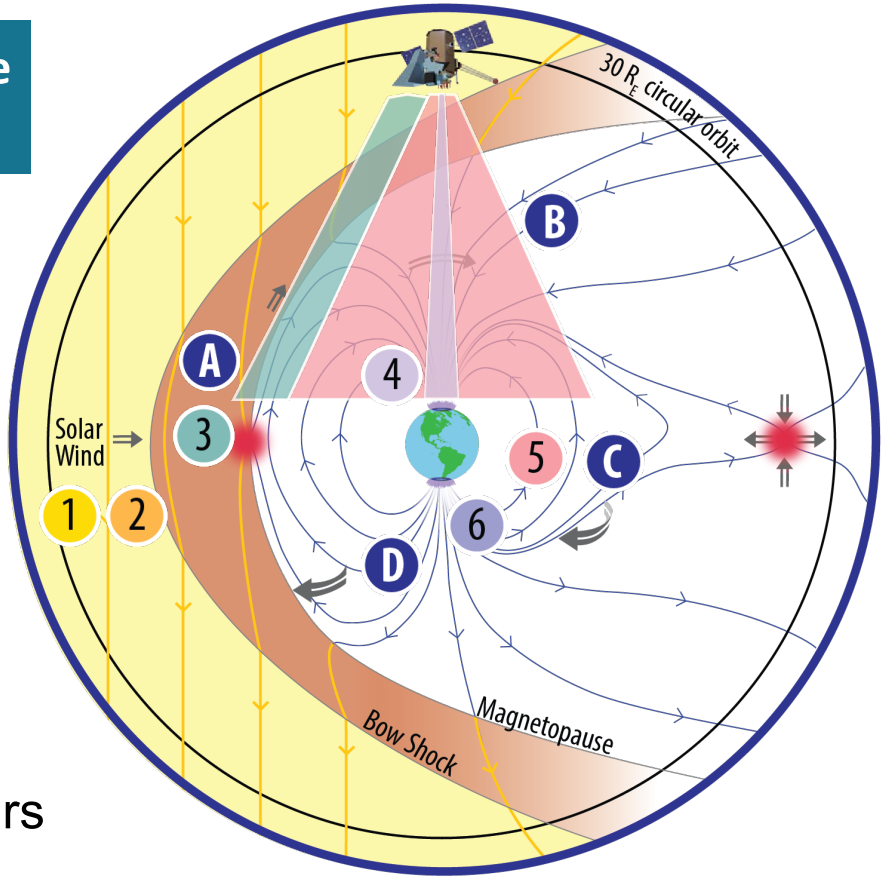
STORM's System Science Instrument Suite

INPUT

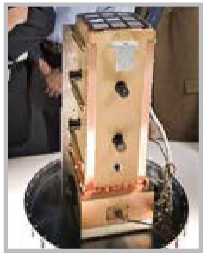
1. MAG IMF — in situ
2. IES Plasma — in situ

RESPONSE

3. XRI X-rays — camera
4. FUV Ultraviolet — camera
5. ENA Neutrals — camera
6. ASI All sky imagers — cameras

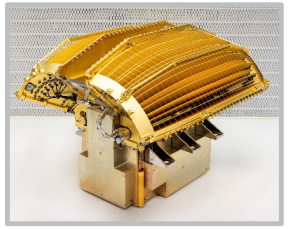


Mission Implementation: High Heritage Instruments



Soft X-ray Imager (XRI) GSFC

Far Ultraviolet Imager (FUV) UCB/SSL

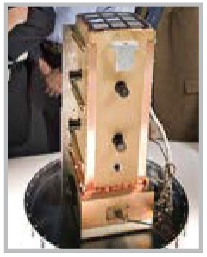


Energetic Neutral Atom Imager (ENA) JHU/APL

Magnetometer (MAG) GSFC

Ion Electron Spectrometer (IES) SwRI

Mission Implementation: High Heritage Spacecraft Instruments



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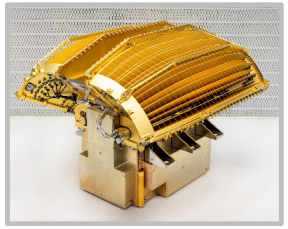

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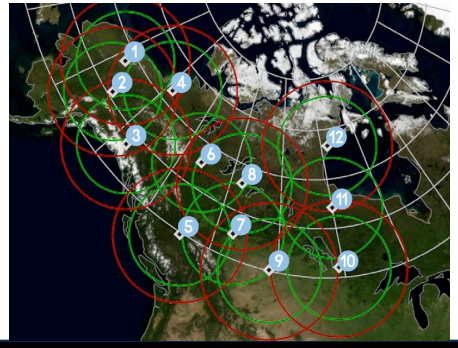
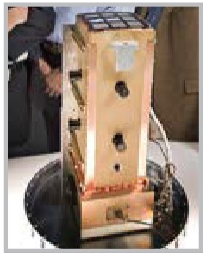
Ion Electron Spectrometer (IES) SwRI

All Sky Imagers (ASI) JHU/APL



Mission Implementation: High Heritage Instruments



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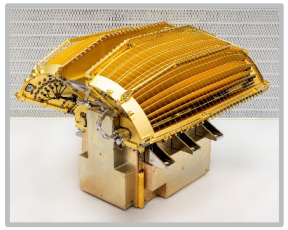

Energetic Neutral Atom Imager (ENA) JHU/APL

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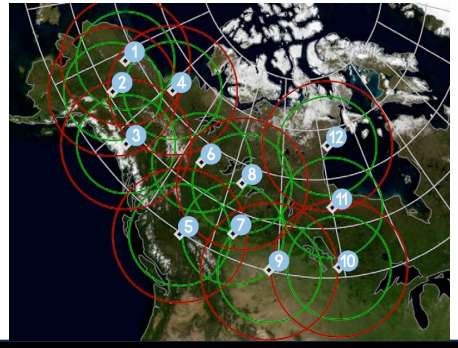
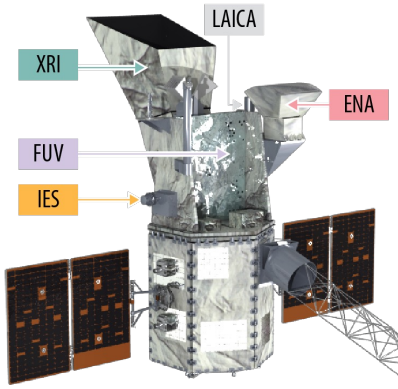
All Sky Imager (ASI) JHU/APL

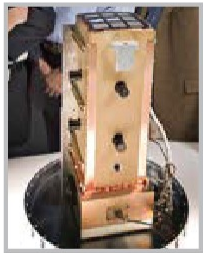
XRI employs Lobster-eye technology transferred from Astrophysics and pioneered by the STORM team (DXL I&II, CuPID, LEXI)



Mission Implementation: High Heritage Instruments and Spacecraft Bus ($250M cost cap)

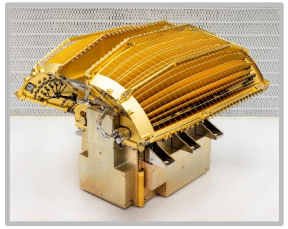


Northrop-Grumman
LEOStar-2 Spacecraft



Soft X-ray Imager (XRI)
GSFC

Far Ultraviolet Imager (FUV)
UCB/SSL



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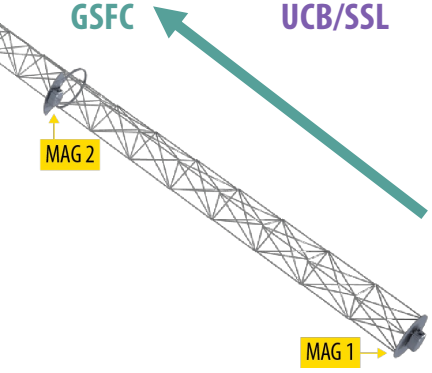

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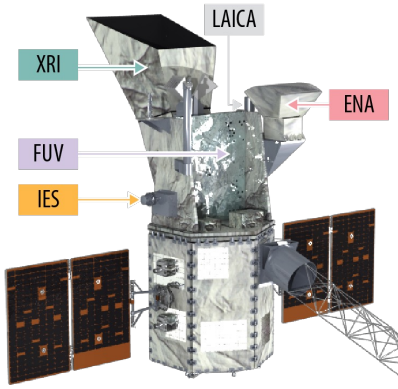
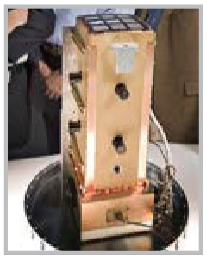


Northrop-Grumman LEOStar-2 Spacecraft

Transiting Exoplanet Surveying Satellite (TESS) heritage in similar orbit.



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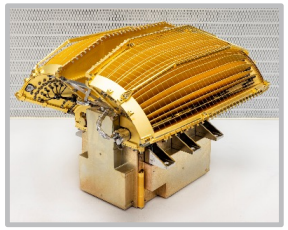

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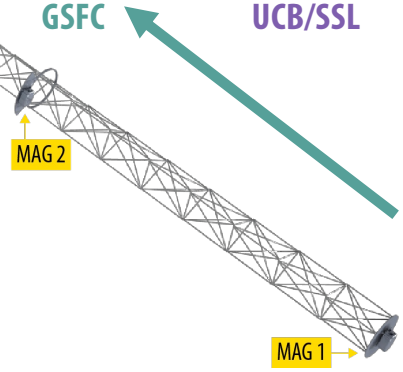

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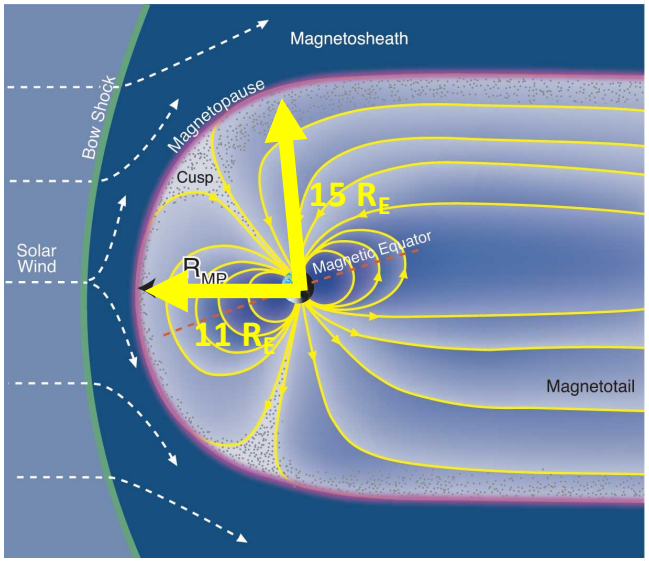
Instrument Requirements

Instrument	Requirement
MAG Magnetometer	Magnetic cleanliness, solar array wiring, location on boom
IES Plasma	Electrostatic cleanliness, grounding
All spacecraft imagers	Sun avoidance (instrument damage), keep out of each other's field of view
XRI	Earth avoidance (too bright)
FUV	Strict particulate cleanliness at all times
All spacecraft instruments	Avoid radiation belts
Ground imagers	Cover 6 hours in LT, Canada, Alaska

Orbit

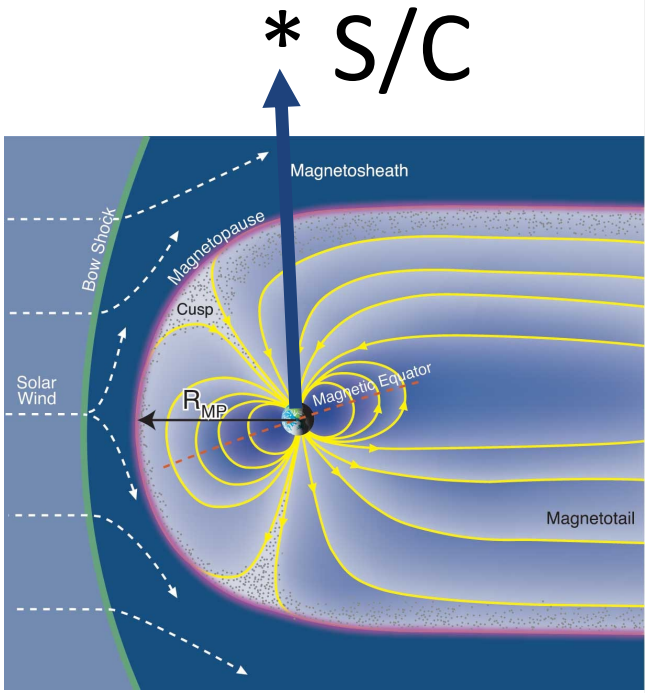
* S/C

- Q. How far out do you want to go?
- A. Outside the target you wish to observe.
  - Subsolar magnetopause at 11 R_E
  - Subsolar bow shock at 15 R_E
  - Flank magnetopause at 15 R_E
  - Flank bow shock at 25 R_E
- Conclude need to observe from a distance of 25-35 R_E from Earth



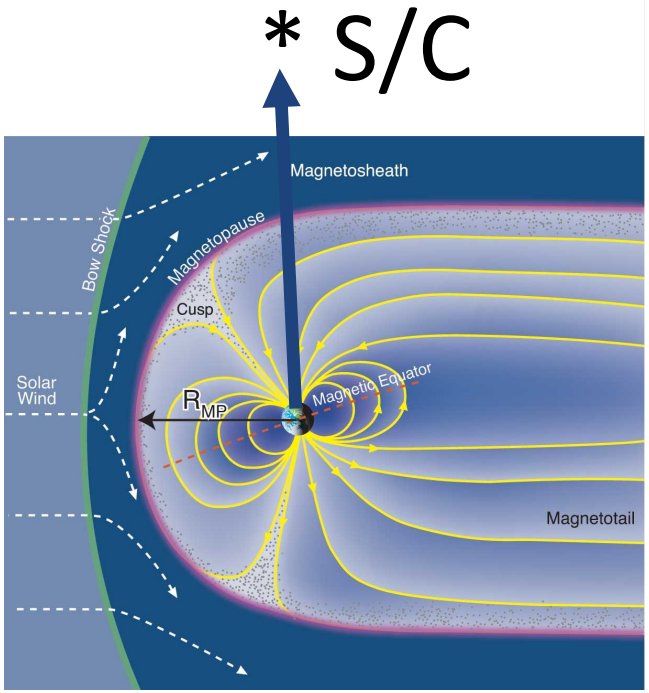
Cancel Gravity?

- Can we just hang out in one place forever?



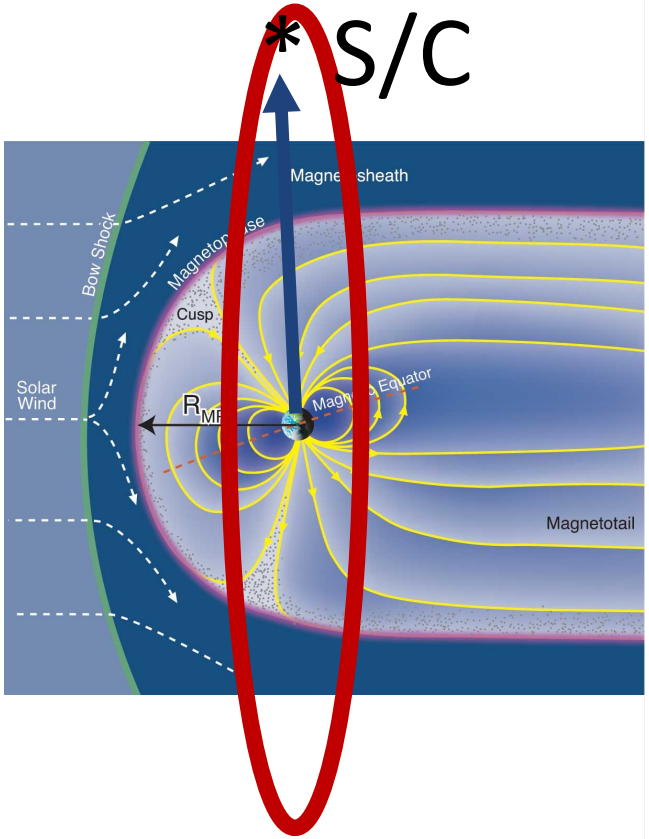
Cancel Gravity?

- Can we just hang out in one place forever?
  - No. That defies gravity. ☹



Halt Precession?

- Can we just hang out in one place forever?
  - No. That defies gravity.
- Can we stay in one meridional plane forever?



Halt Precession?

- Can we just hang out in one place forever?
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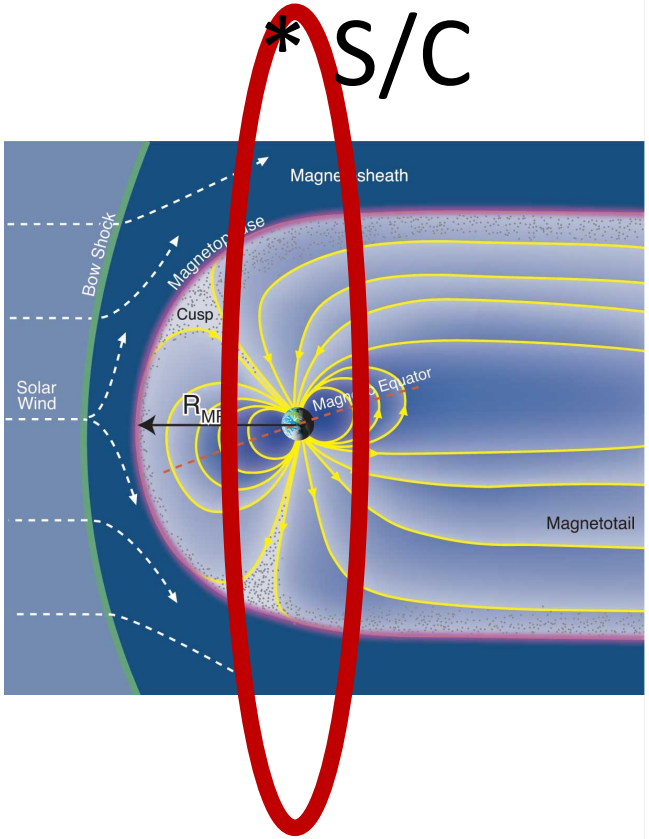
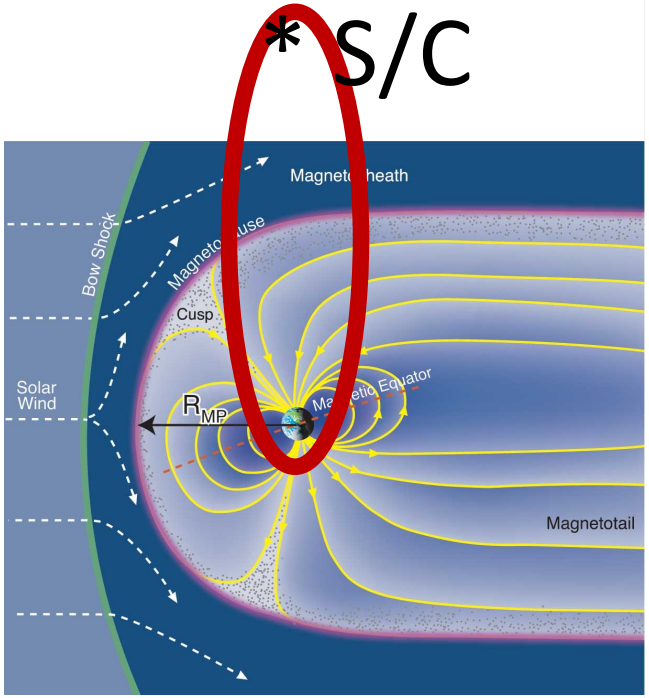
- Can we stay in one meridional plane forever?
  - Do you have infinite propulsion? ☹



Highly Elliptical Polar Orbit?

- Can we just hang out in one place forever?
  - No. That defies gravity.
- Can we stay in one meridional plane forever?
  - Do you have infinite propulsion?
- Can we get into a highly elliptical polar orbit?



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- Can we just hang out in one place forever?
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- Can we stay in one meridional plane forever?
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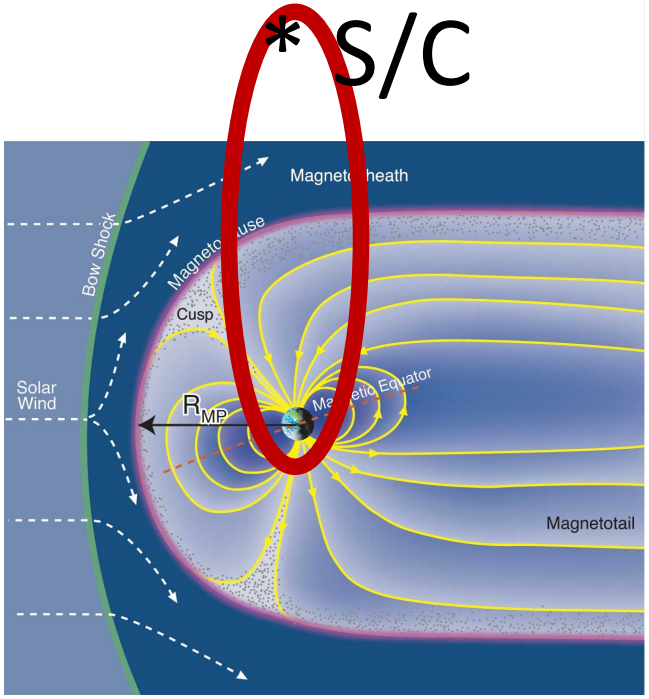
- Can we get into a highly elliptical polar orbit?
  - Sure, is that what you really want?



Large Circular Orbit?

- Can we just hang out in one place forever?
  - No. That defies gravity.
- Can we stay in one meridional plane forever?
  - Do you have infinite propulsion?
- Can we get into a highly elliptical polar orbit?
  - Sure, it that what you really want?
- Can we get into a large radius circular orbit?

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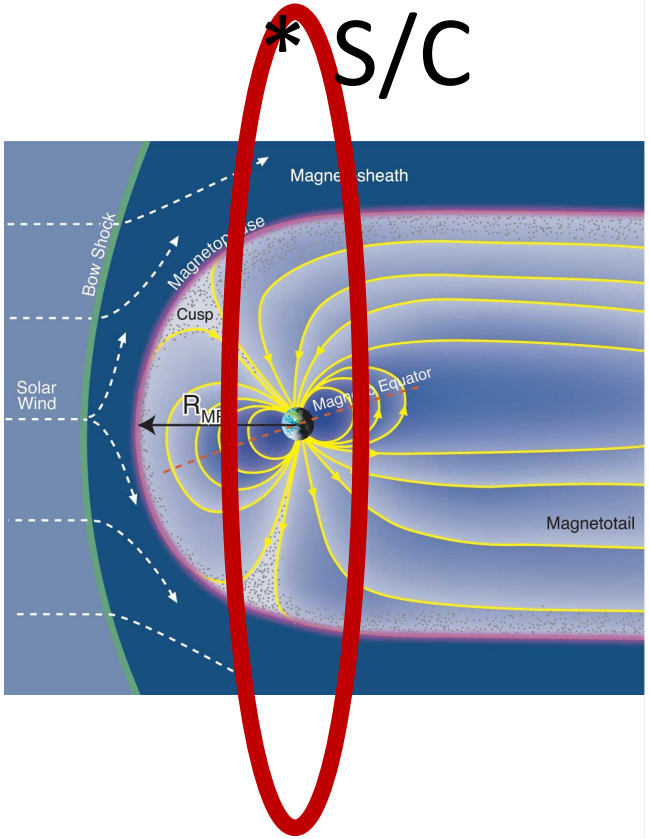
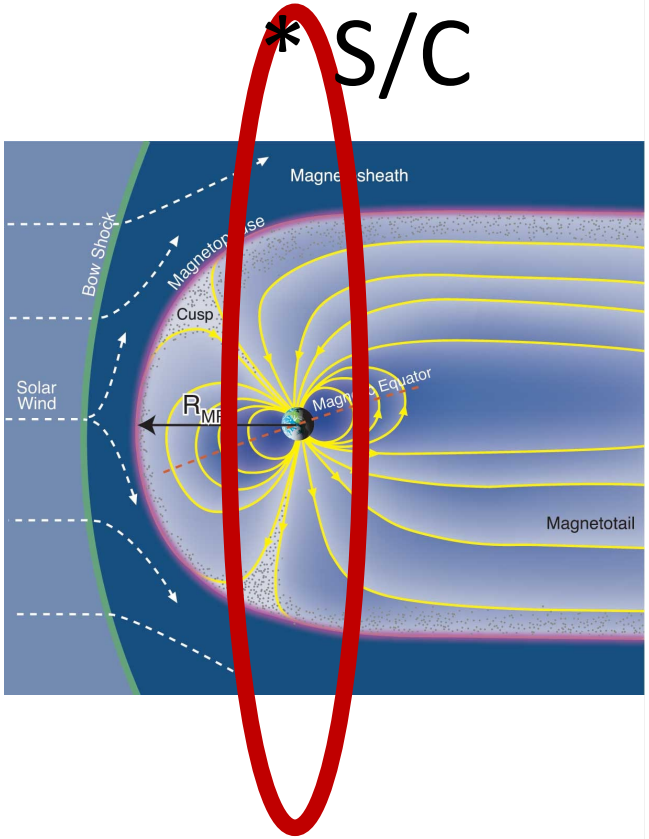


Large Circular Orbit

- Can we just hang out in one place forever?
  - No. That defies gravity.
- Can we stay in one meridional plane forever?
  - Do you have infinite propulsion?
- Can we get into a highly elliptical polar orbit?
  - Sure, it that what you really want?
- Can we get into a large radius circular orbit?
  - **Yes with a lunar gravitational assist.**



Large circular orbit

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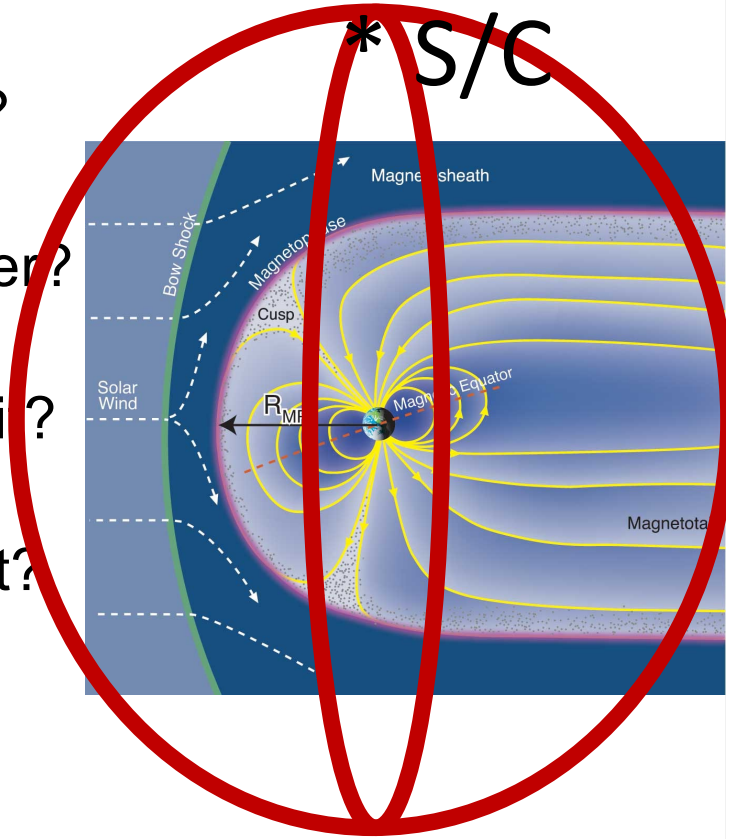
  - Sure, it that what you really want?
- Can we get into a large radius circular orbit?
  - **It will precess, ok?**



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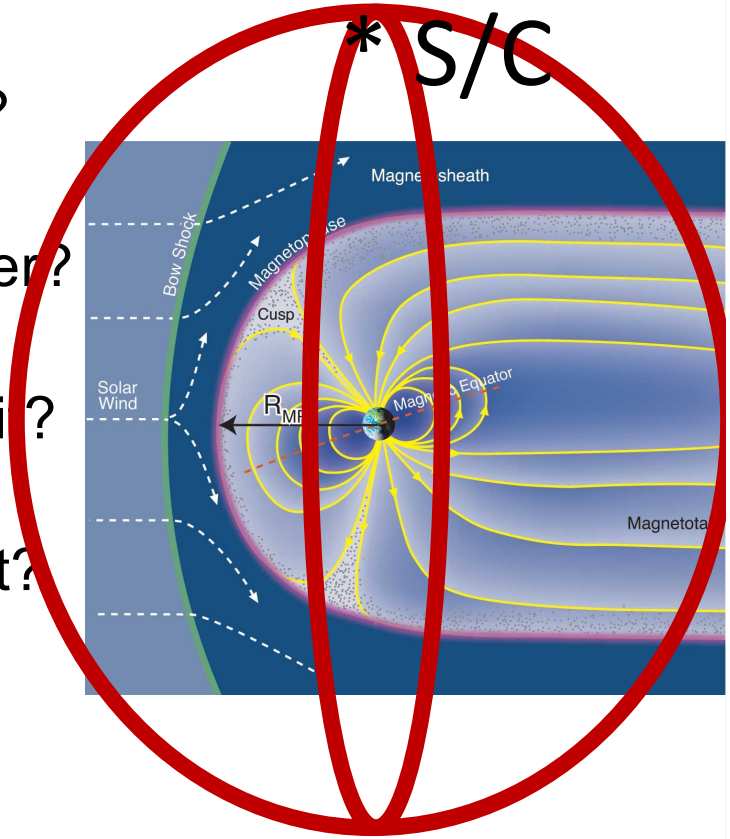
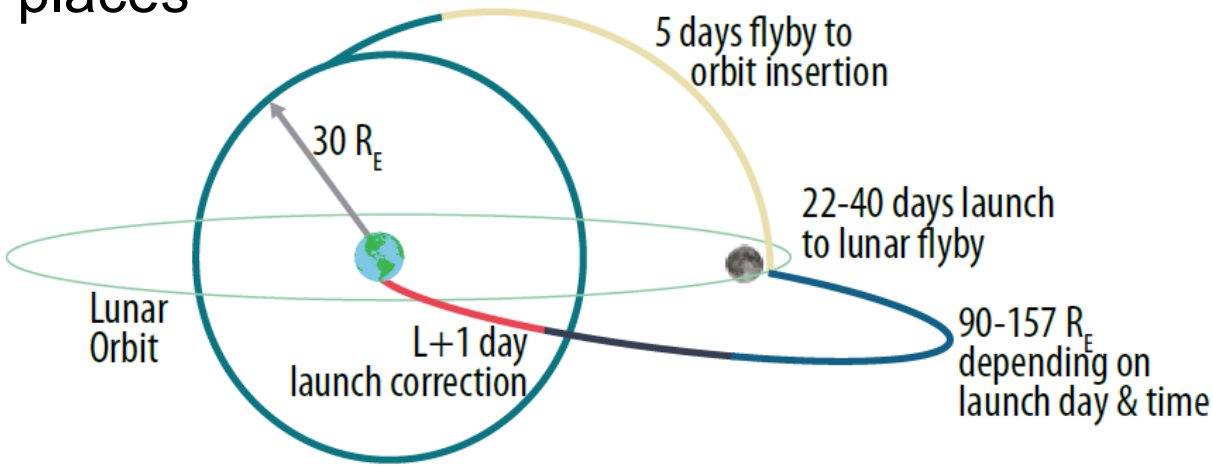


Lunar Gravitational Assist

- A single lunar gravity assist places the STORM spacecraft in
  - high-inclination circular orbit
  - 30 R_E radius
  - 9.65 day period
- Global observations
- Uninterrupted observations
- Perspectives from all viewpoints
- 60 day commissioning and then two-year mission for statistics



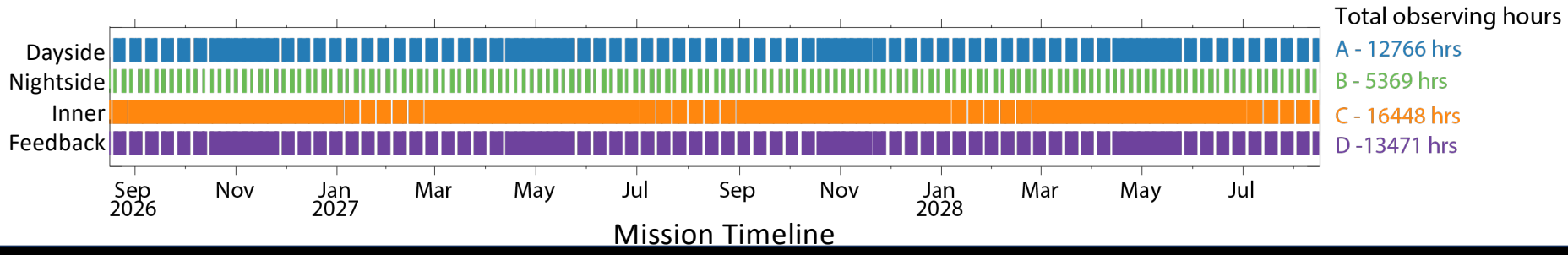
Heritage and Duty Cycle

- **High heritage instruments and software**

Instrument	Heritage
MAG	Parker Solar Probe, Van Allen Probes
IES	Rosetta, MMS
XRI	DXL, DXL-II, CuPID,
FUV	IMAGE, ICON
ENA	IMAGE, JUICE
ASI	THEMIS, TREx, Golono

All must be TRL 6 by PDR:
'a fully functional prototype or representational model'

Duty cycle by objective…



Spacecraft requirements

- Mass, hydrazine propellant, power margins all ~50%
- Survival heaters for all instruments and passive radiators
- 2 star-trackers, 1 inertial measurement unit provide 60 arcsec pointing knowledge and stability. Auroral structure is the driver. Gives about 50-60 km resolution. 1° lat = 110 km.
- 4 x 22 N and 4 x 5 N thrusters provide for orbit insertion and maintenance.

Battery and Shadows

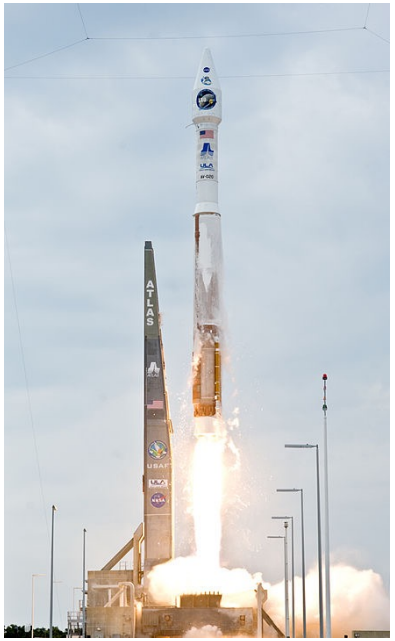
- By design, spacecraft will never enter Earth's shadow (worst case 2.4 hours will never occur)
- However, lithium ion batteries provide sufficient Amp-hours (two days) to power through any such encounter.
- Battery lifetime far exceeds that needed for 2-year mission

Communications

- S-band (2-4 GHz), compatible with
- Near Earth Network
  - 4 stations in continental USA, 1 Asia, 2 Antarctica, 2 Alaska, 2 Europe, 1 Africa, 1 S. America, 1Australia, 1 Hawaii
- Deep Space Network
  - Canberra, Goldstone, Madrid
- Space Network
  - Tracking and Data Relay Satellites (TDRS) at geosynchronous orbit

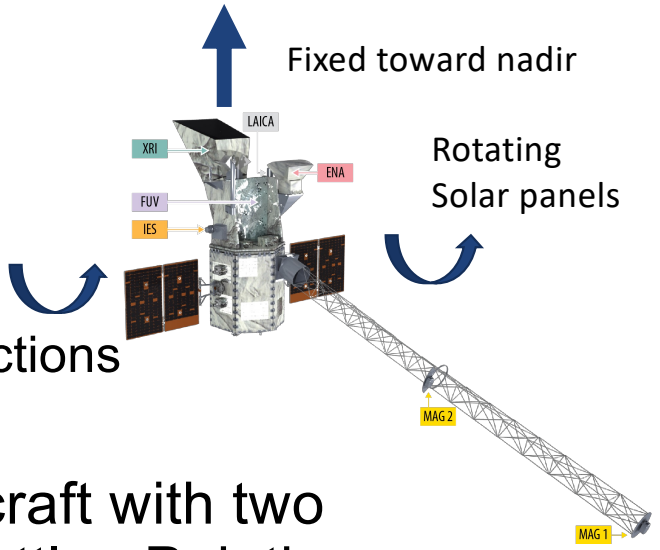
Launch Vehicle

- STORM fits within the fairings of the following nominal launch vehicles. :
  - Falcon-9
  - Antares
  - Atlas-V



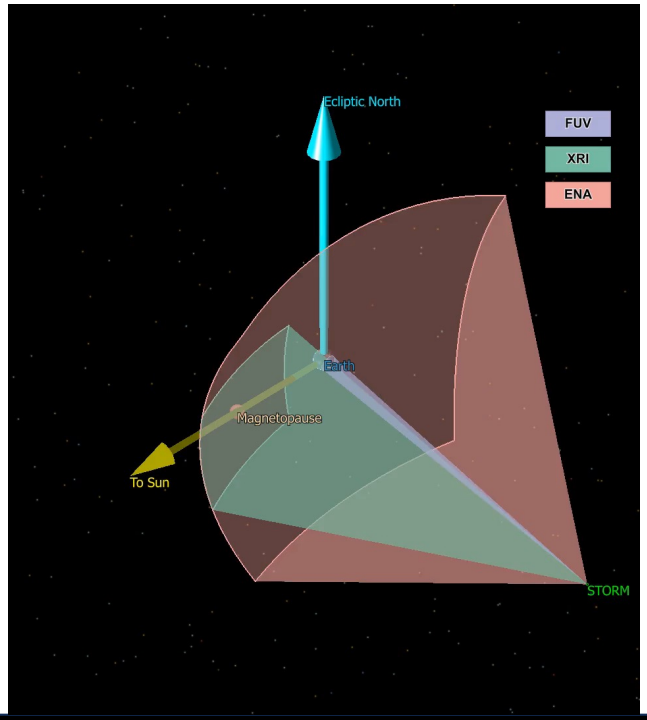
Pointing

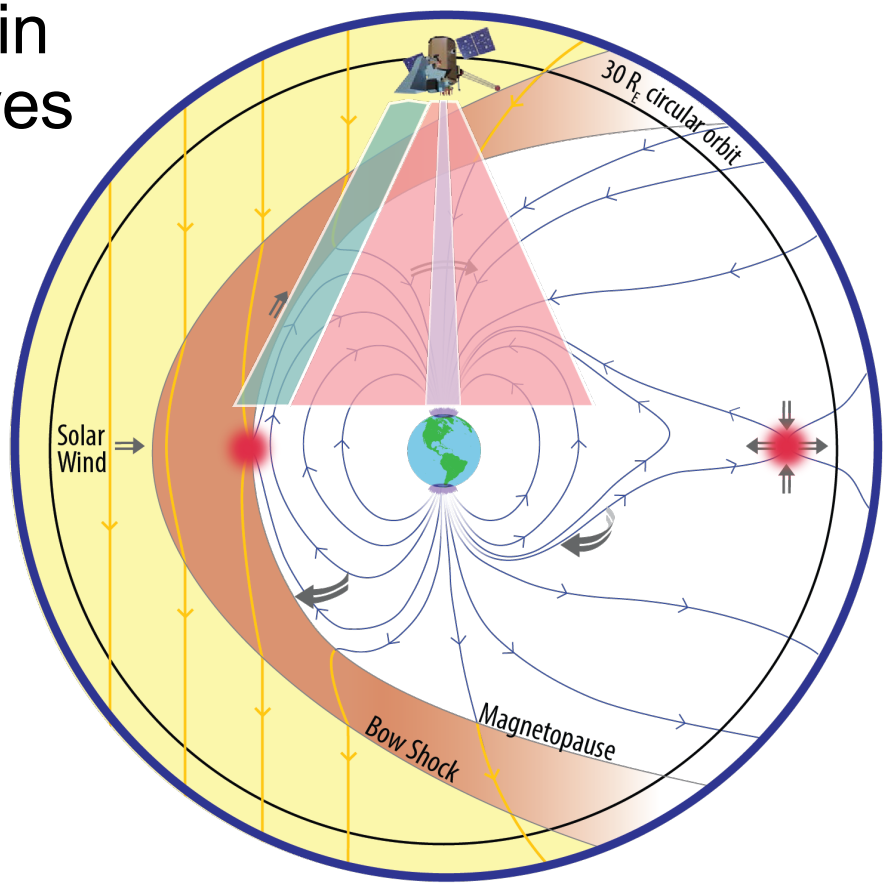
- 1. XRI, FUV, ENA telescopes must not point Sunward.
- 2. FUV and ENA point toward nadir
- 3. XRI pointed slightly sunward from Earth.
- 4. Spinning spacecraft?
  - No: Imagers want more counts
  - Yes: Plasma instrument wants to survey all directions
  - Yes: Magnetometer wants easier calibration



- 5. Conclusion: Three-axis stabilized spacecraft with two deployable rotating solar panels wins this battle. Pointing stability/accuracy is not a problem as this is not an astrophysics mission.

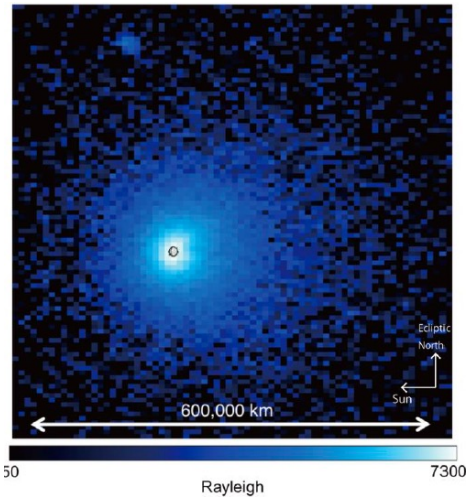
STORM S/C rolls along orbit to obtain continuous views from all perspectives





STORM's International Partner: JAXA

LAICA & the exosphere

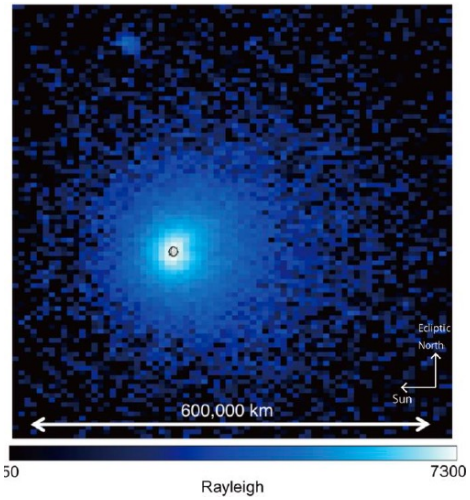


LAICA images the Exosphere

- LAICA is a wide field-of-view camera that observes Lyman-α emissions to determine exospheric neutral densities
- LAICA supplements STORM, partners with GLIDE
- LAICA flies on a do-no-harm basis

STORM's International Partner: JAXA

LAICA & the exosphere



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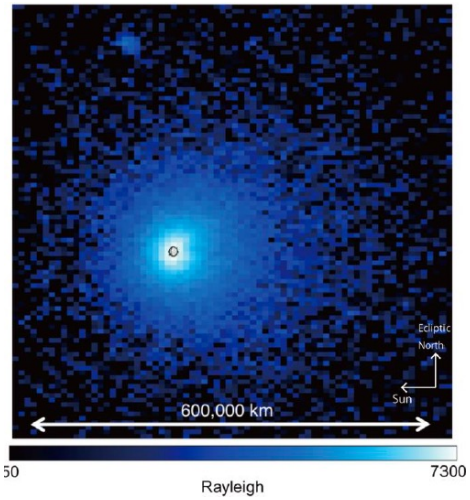

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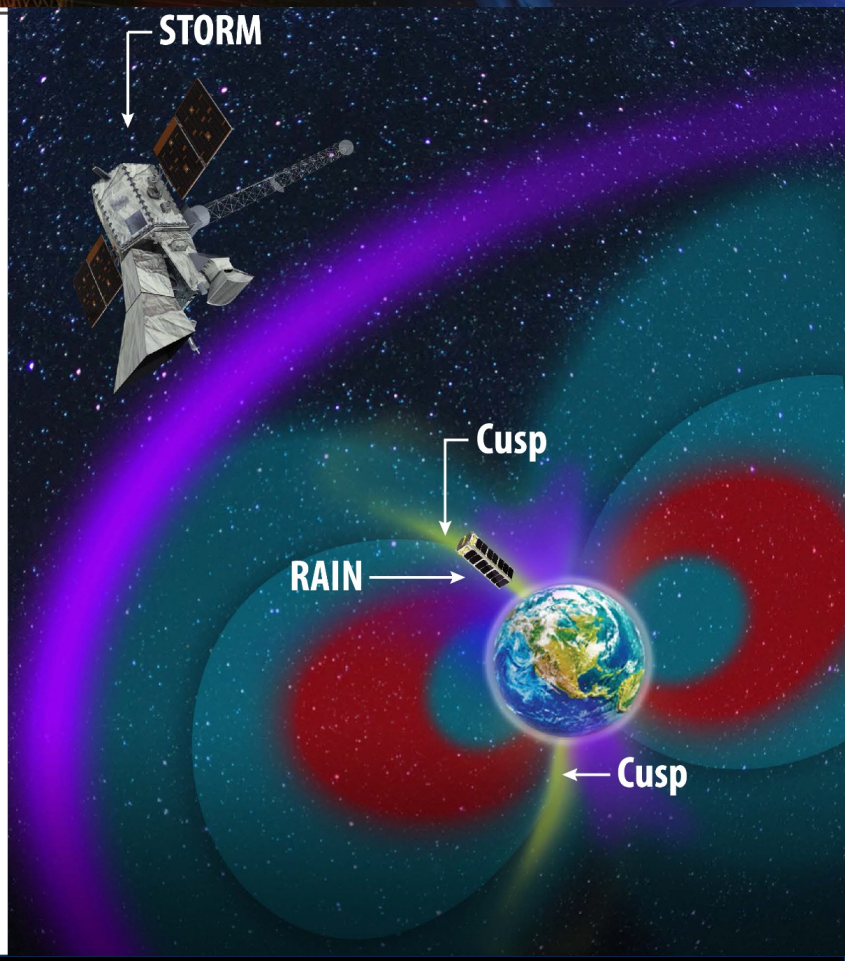
Why LAICA on this Mission?

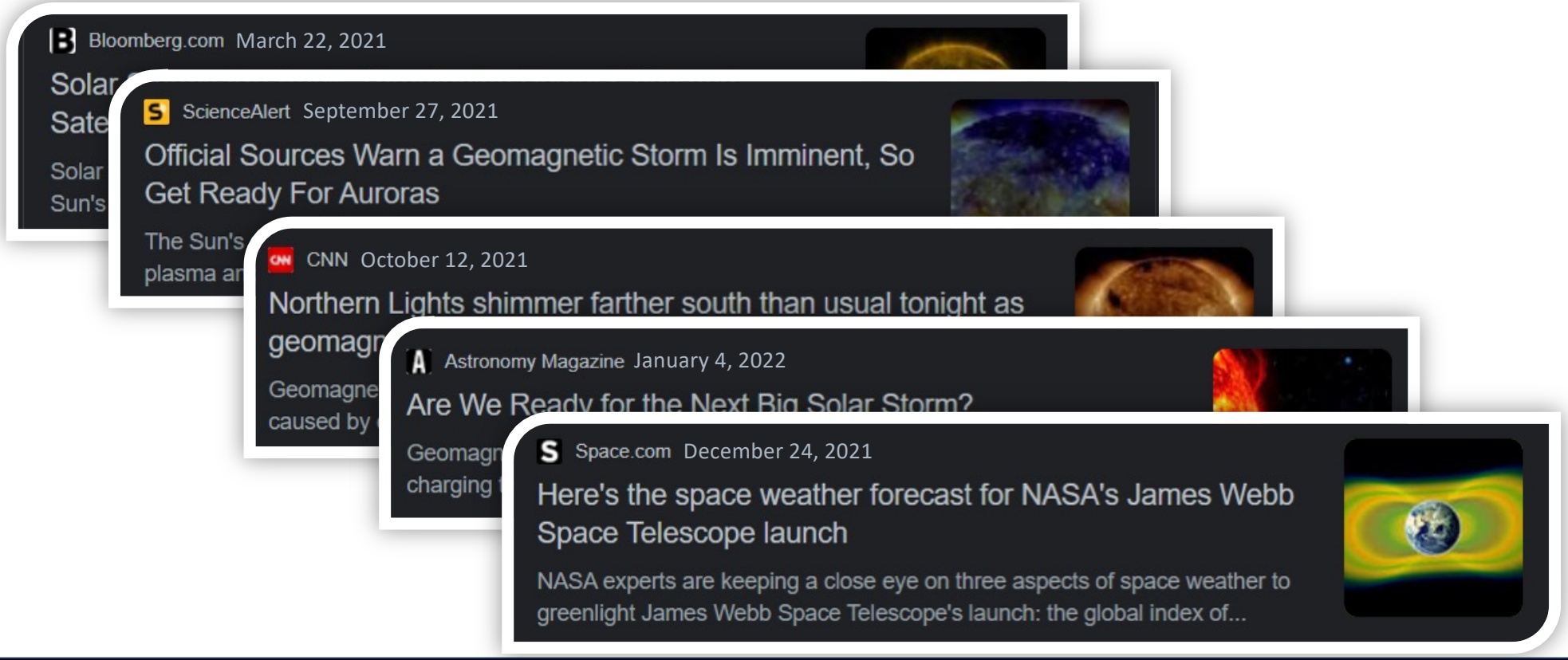
Charge exchange with neutrals produces ENA, XRI signals!

STORM's Student Collaboration: RAIN

- Boston University led student CubeSat
  - RAIN single pixel looks up into the cusp from low Earth orbit while
  - STORM's XRI looks down
  - RAIN measures emission line spectrum and tells solar wind composition
  - RAIN engages underrepresented groups at BU and all STORM partners

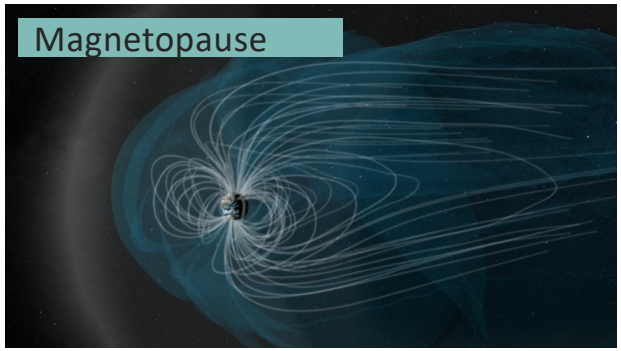


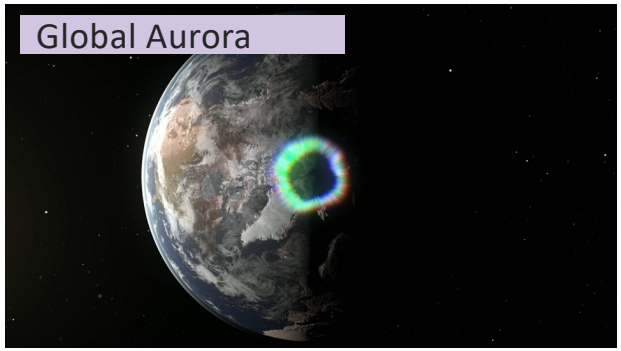
Geomagnetic Storms Engage the Public

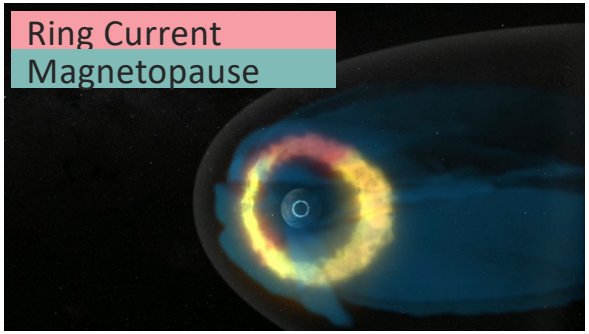


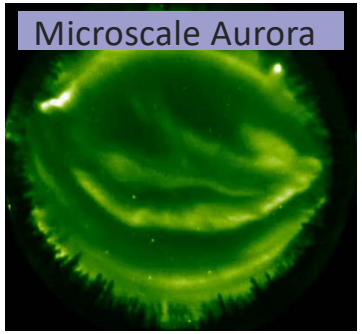
STORM Images Geomagnetic Storms

STORM's dynamic images and movies make space weather tangible.

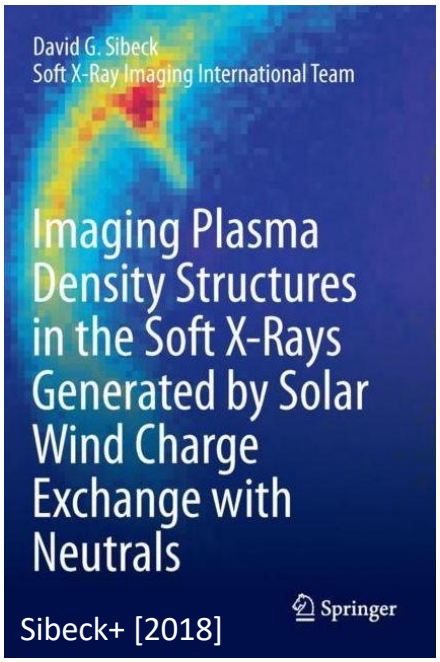




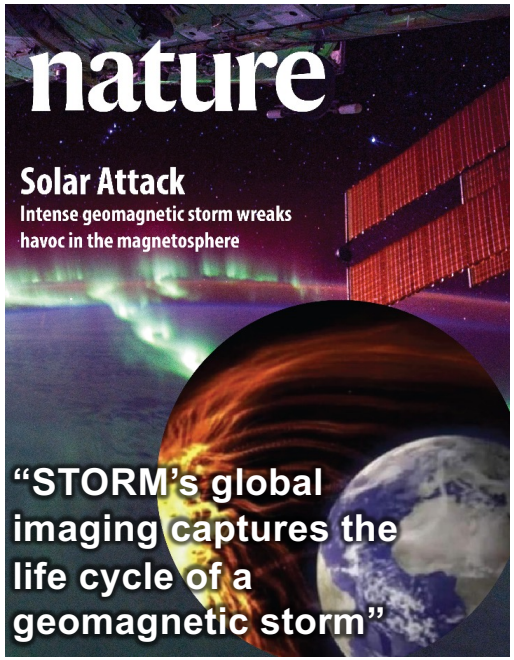


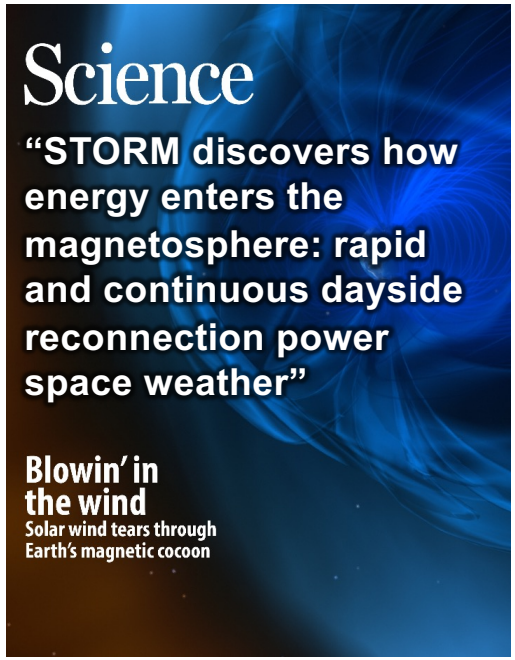


STORM Drives Novel Research



Sibeck+ [2018]





Core science objectives are only the beginning

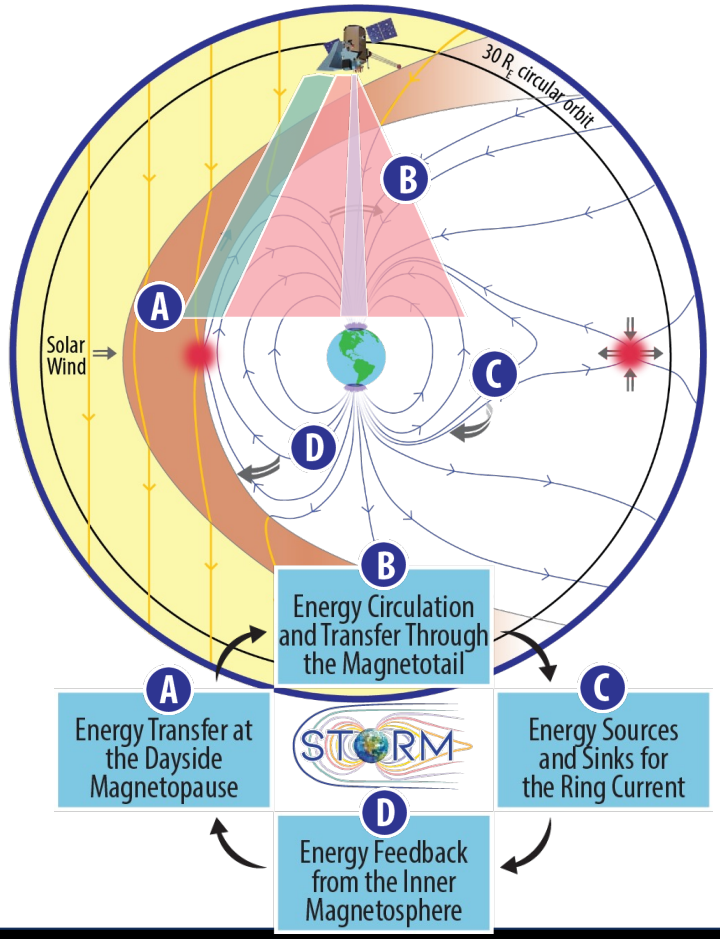
Laying the ground work, over 30 research articles → **for STORM's first simultaneous global observations of a geomagnetic storm and the magnetopause!**

PROGRESS: First ***end-to-end system science*** to understand the complete global solar wind-magnetosphere interaction.

BENEFITS: Provides the pathway to revolutionize space weather forecasting with ***global imaging*** and system science.

IMPACT:

- ***Cross-disciplinary*** technology transfer between astrophysics and magnetospheric physics paves the way for future missions across Heliophysics and NASA.
- STORM resolves the global response of the magnetosphere to ***fundamental physical processes***.
- STORM provides the first principal understanding needed to ***validate and improve*** space weather models and forecasting.



The Proposal Process

- Began thinking about a mission in 2005
- Employed GSFC's Instrument Design Laboratory in 2009 (XRI Cost, mass, power…)
- Did not succeed in 2010 MIDEX competition (science good, but not compelling)
- Continued holding weekly meetings from 2011-2018. Launched DXL-1,2 in 2012, 2015
- Wrote and published a book (2018) and papers on the topic
- Began forming team and meeting engineers in 2018
- Made our (successful case) for investment to GSFC management in 2018.
- Submitted proposal in Fall 2019.
- Downselected by NASA HQ in Fall 2020. One of 5 competitors in Phase A.
- Submitted proposal in July 2021 and held site visit in Fall 2021. CuPID launch.
- Final presentation to Associate Administrator in January 2022. Launch ready July 2026.

What Happens Next?

- STORM was not selected.
- STORM had no major weaknesses
- STORM had no significant minor weaknesses.
- STORM can be resubmitted at the next opportunity with minor updates!
- STORM looks forward to working with YOU!

STORM and X-ray Optics: Developed for Astrophysics, Adopted for Heliophysics

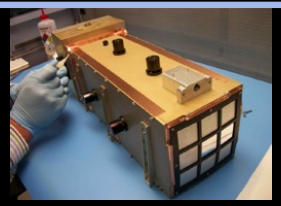
A timeline of X-ray Optics

STORM's Collaborations

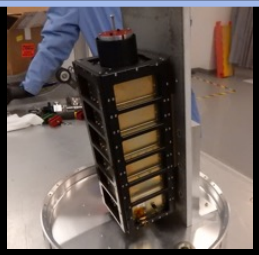
Proposed 1978
Roger Angel

Optics developed in 90s

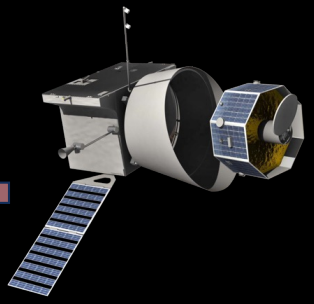
Helio Pioneer early 2000's



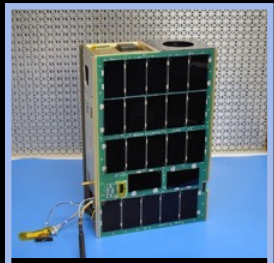
2012 DXL/STORM



2015 DXL/CuPID



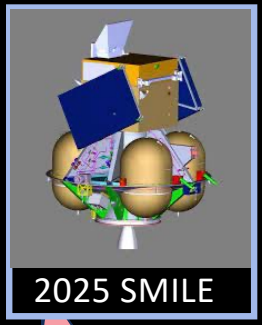
2018 BepiColumbo



2021 CuPID

2024 LEXI

2023 SVOM



2025 SMILE

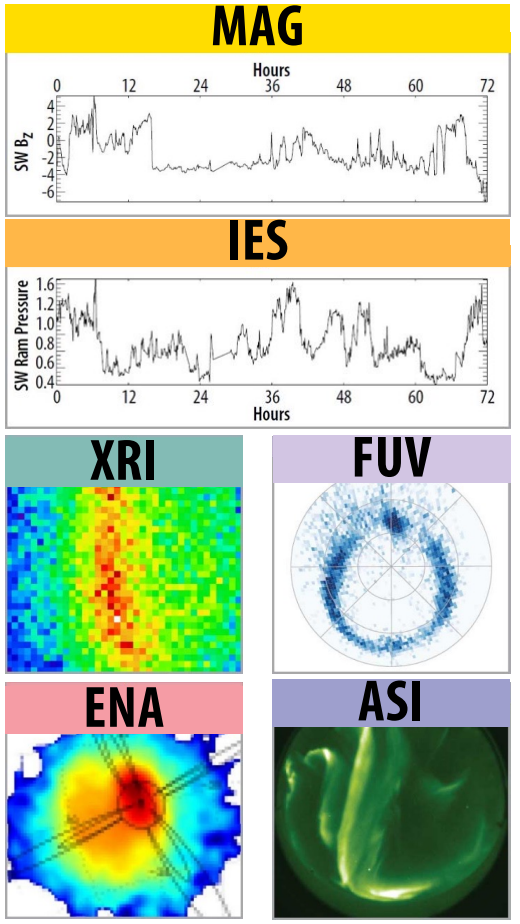
20??


STORM
SOLAR-TERRESTRIAL OBSERVER FOR THE RESPONSE OF THE MAGNETOSPHERE

Methodology

Quantify the significance of fundamental physical processes in the global solar wind-magnetosphere interaction

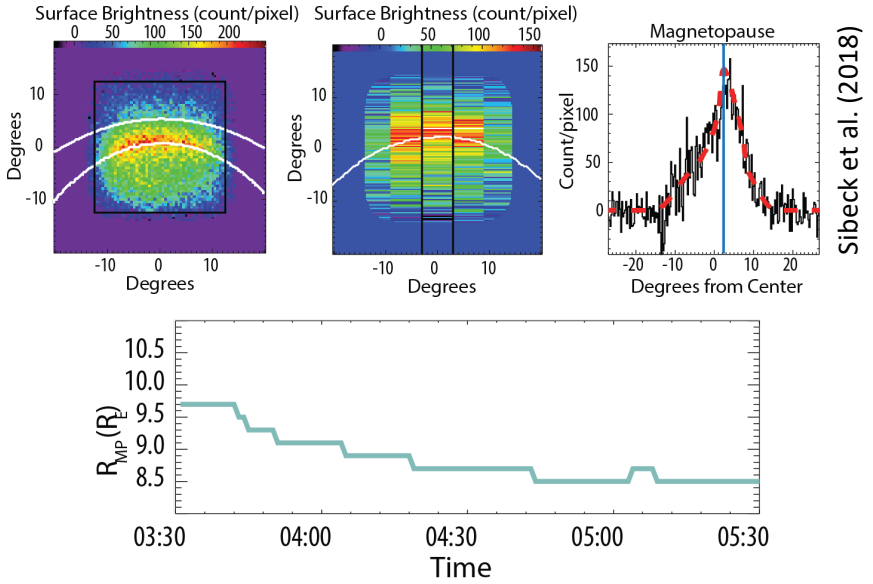
1. Identify the signatures of fundamental processes in the images
2. Quantify the amplitude of
   - Boundary motion
   - Brightness/emission variations
3. Specify when, where, why, and how these processes occur as a function of solar wind input
4. Compare with model predictions



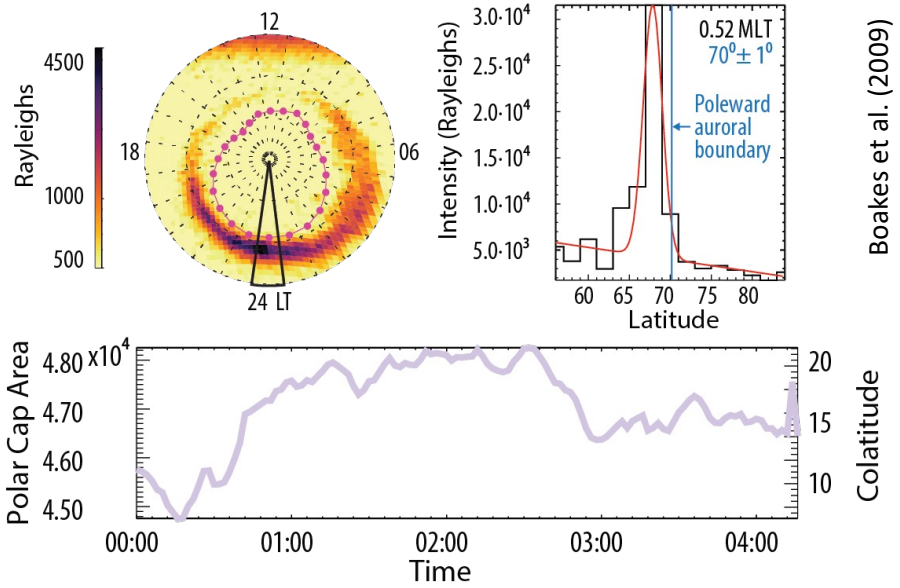
Methodology

A Specifying energy transfer modes at the dayside magnetopause

XRI Tracks the Magnetopause Location



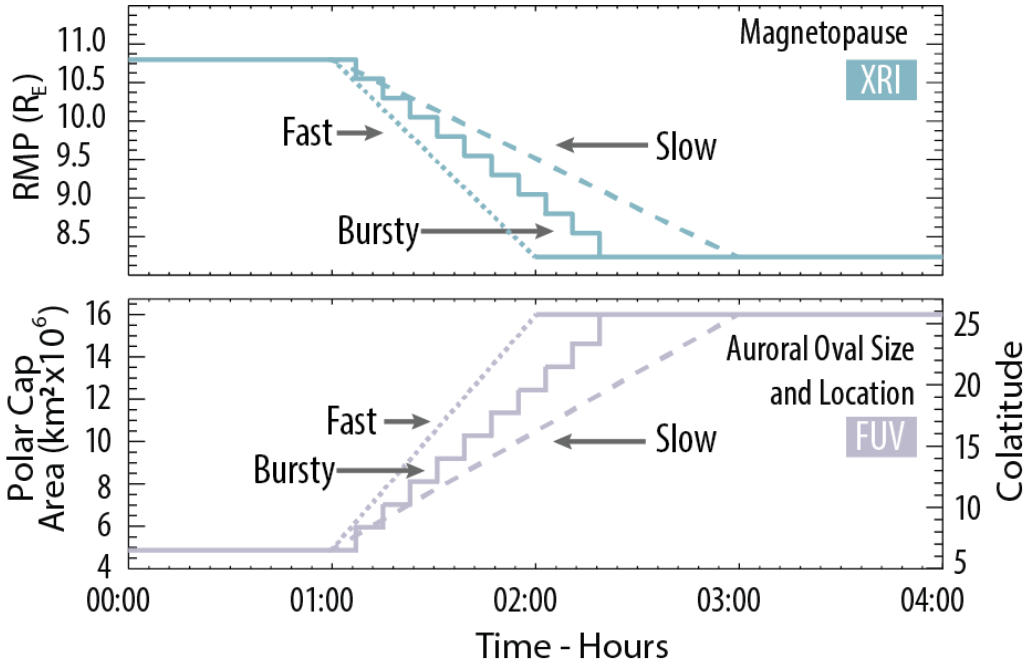
FUV Quantifies Auroral Oval Dynamics



STORM employs sophisticated image processing algorithms to achieve its science

Methodology

A Specifying energy transfer modes at the dayside magnetopause



STORM employs sophisticated image processing algorithms to achieve its science

Methodology

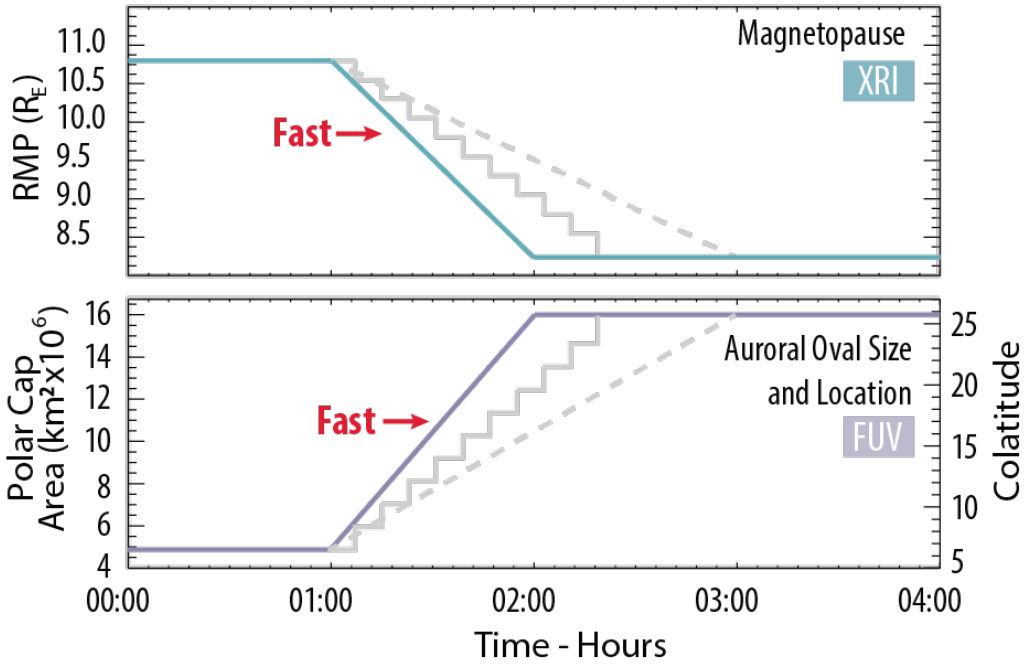
A Specifying energy transfer modes at the dayside magnetopause

In this case, we find that Space Weather energy enters the magnetosphere rapidly rather than slowly or in small bursts.

→ *Closes Science Objective A.*

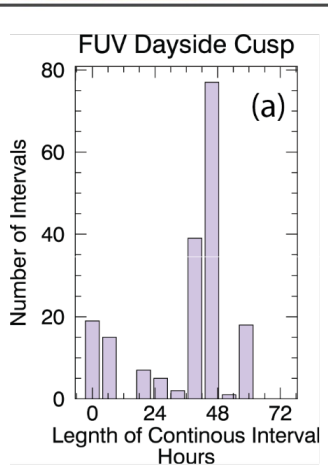
Provides the foundation for complete system science picture.

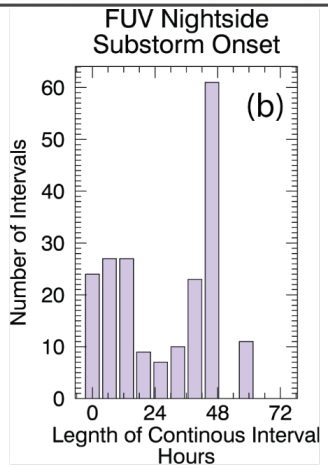
Identifies correct global magnetospheric model for forecasting.

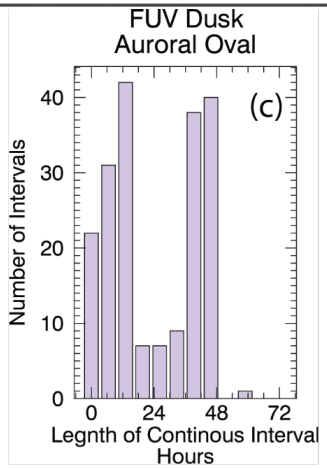


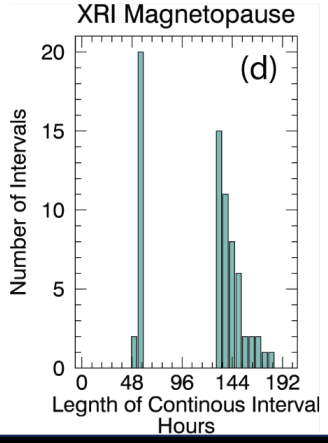
STORM System Science and Data Sufficiency

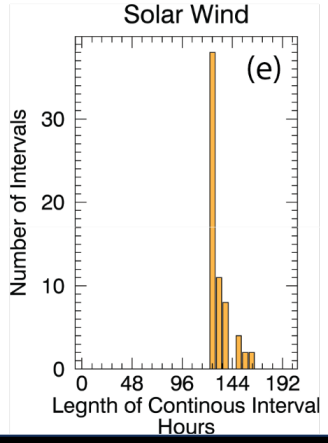
Objective	Observable	Instrument	System Science 1: Breakdown and Rebuild	System Science 2: Global Continuous Observations
A Energy Transfer at the Dayside Magnetosphere	Magnetopause location Global Aurora Solar Wind Magnetic Field Solar Wind Plasma	XRI FUV MAG IES	12766 observation hours	Over 5000 hours of simultaneous observations from all instruments to observer the solar wind-magnetosphere interaction as a complete system.
B Energy Circulation and Transfer Through the Tail	Magnetopause location Global Aurora Microscale Aurora Solar Wind Magnetic Field Solar Wind Plasma	XRI FUV ASI MAG IES	5369 observation hours	
C Energy Sources and sinks in the ring current	Magnetopause location Global Aurora Microscale Aurora Ring Current	XRI FUV ASI ENA	16448 observation hours	
D Energy Feedback from the Inner Magnetosphere	Magnetopause location Global Aurora Solar Wind Magnetic Field Solar Wind Plasma Ring Current	XRI FUV MAG IES ENA	13471 observations hours	

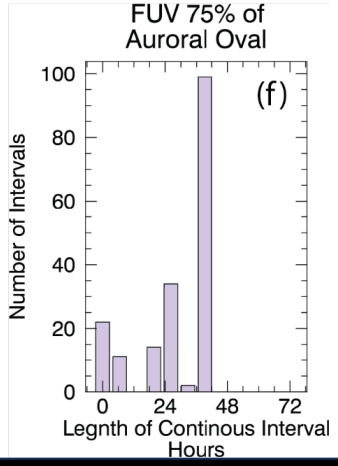

FUV Dayside Cusp
(a)
Number of Intervals
0
20
40
60
80
0
24
48
72
Legnth of Continous Interval
Hours


FUV Nightside
Substorm Onset
(b)
Number of Intervals
0
10
20
30
40
50
60
0
24
48
72
Legnth of Continous Interval
Hours


FUV Dusk
Auroral Oval
(c)
Number of Intervals
0
10
20
30
40
0
24
48
72
Legnth of Continous Interval
Hours


XRI Magnetopause
(d)
Number of Intervals
0
5
10
15
20
0
48
96
144
192
Legnth of Continous Interval
Hours


Solar Wind
(e)
Number of Intervals
0
10
20
30
0
48
96
144
192
Legnth of Continous Interval
Hours


FUV 75% of
Auroral Oval
(f)
Number of Intervals
0
20
40
60
80
100
0
24
48
72
Legnth of Continous Interval
Hours

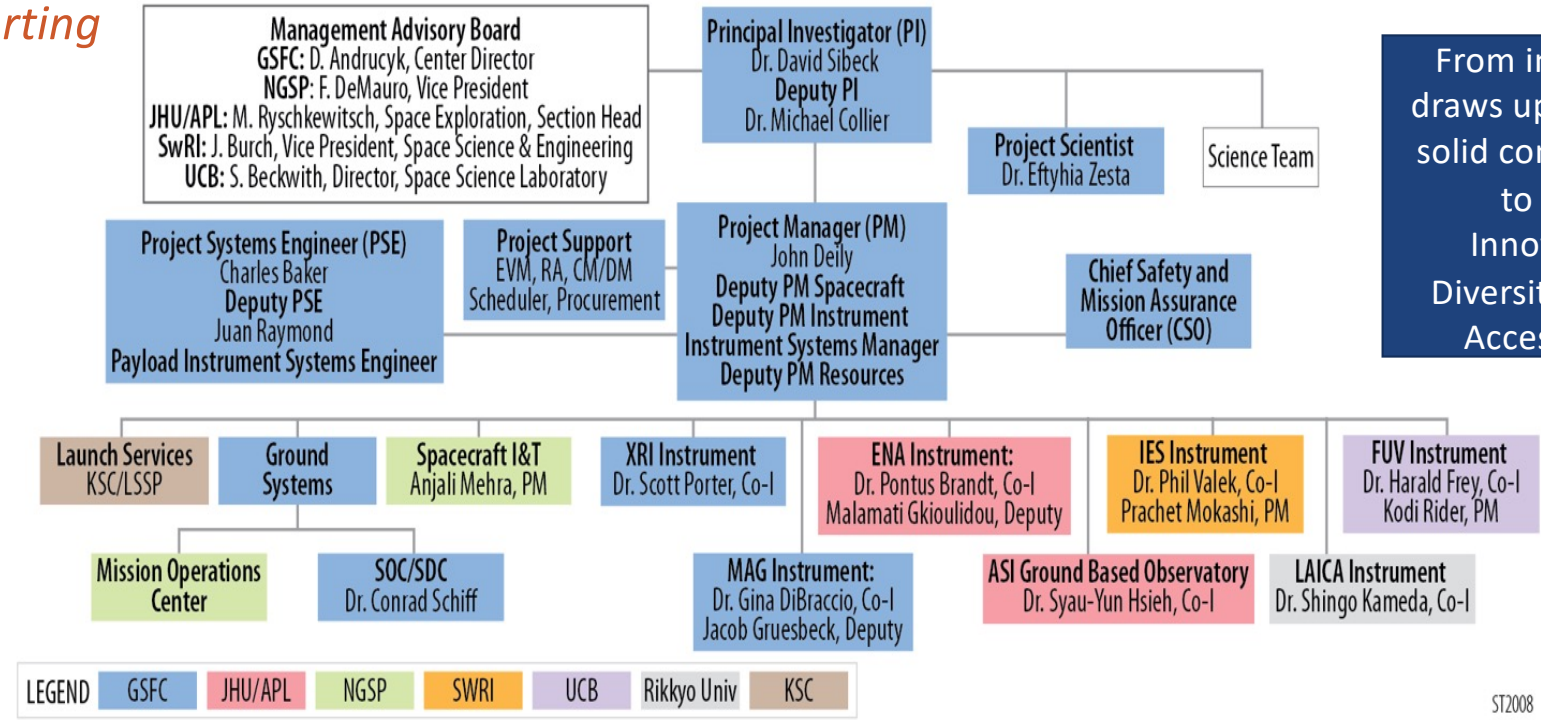
Data Sufficiency based On Objective

Science Objective	STORM Event/ Geomagnetic Condition	Number of Events		
		Required for closure	Observed by STORM (based on DRM Sim)	Margin (%)
A	Strong Magnetopause Erosion	100 hr	384 hr (XRI)	284
			272 hr (FUV)	172
B	Substorm (SS) Onset Triggers	100 SS	1879 SS	1779
			365 SS	265
B	Subsolar Magnetopause outward motion	100 SS	292 SS	192
C	STORM observes a geomagnetic storm	10 GS	29 GS	190
C	STORM observes an intense ring current	100 hr	196 hr	96
C	Substorm injections	100 SS	1667 SS	1567
C	Magnetopause Shadowing (6-minute intervals)	50 6m int.	312 6m int.	524
D	Ring Current Effect on Substorm Onset	50 SS	402 SS	704
D	Ring Current effect on MP location	1000 6m int.	1512 6m int.	51

STORM will observe ample events to answer all science questions

STORM's Team

Lean management approach fosters autonomy, communication across and up/down all partner organizations, and timely and thorough decision making, accurate status and reporting



From inception, draws upon GSFC's solid commitment to IDEA Innovation, Diversity, Equity, Accessibility

Science Requirements: Instrument Capabilities

Instrument	Required Resolution	Projected Resolution
XRI Porter, GSFC	**0.25 R_E, 3 min**	**0.20 R_E, 3 min**
FUV Frey, UCB SSL	**100 km, 3 min (e- and p)**	**40 km, 30 sec (e-)** **80 km, 30 sec (p)**
ENA Brandt, JHU/APL	**2 R_E ring current** **3 R_E plasma sheet** **30 min**	**1 R_E ring current** **2 R_E plasma sheet** **10 min**
IES Valek, SwRI	**0.5 – 4 keV, 2 min**	**0.05 – 10 keV, 1 min**
MAG DiBraccio, GSFC	**0.5 nT, 1.5 sec**	**0.05 nT, 0.1 sec**
ASI Hsieh, JHU/APL	**630 nm (red), 20 km, 30 sec**	**630 nm (red), <10 km, 6 sec** **557.7 nm (green), <10 km, 3 sec**

STORM's Instrument Suite Satisfies All Observational Requirements with Margin

SMILE (magnetopause science) and STORM (system-science)

Topic	SMILE	STORM	STORM Advantage
Measures solar wind input?	20 R_E apogee rarely in SW	30 R_E radius often in SW	**STORM is self-standing**
Continuous imaging	Perigee pass every 51 hrs, limited continuous obs.	Median cont. obs. 5.75 days, can exceed 40 days	**STORM observes throughout storms**
Auroral Conjugacy	Views only the N aurora	Views both N & S aurora	**Conjugacy studies possible**
FUV capability	Only electron aurora	Proton and electron aurora	**Study dayside reconnection and ring current precip**
XRI capability	5 min cad., 0.5 R_E res. For SW nV > 4.9×10^8 cm^{-2} s^{-1} 5.5x9.3 R_E (at apogee)	3 min cad., 0.25 R_E res. For SW nV > 2.5×10^8 cm^{-2} s^{-1} 13.5x12.2 R_E (fixed)	**XRI FOV covers entire dayside region with needed cadence & resolution**
Ring current	----------	STORM ENA	**End-to-end science**
All Sky Imagers	----------	STORM ASI	**Substorm onset triggers**
Exosphere	----------	LAICA	**3-D exosphere studies**

STORM's mission design and instruments and objectives exceed those of SMILE

Leadership Team

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(Some of) Our Diverse Early Career Team Members

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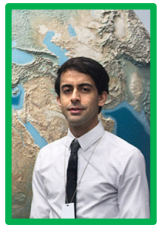

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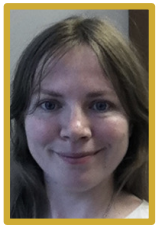

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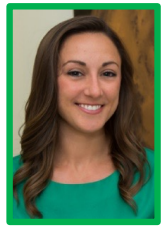

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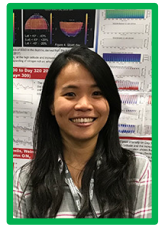

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Early Career