The Magnetosphere

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NASA/GSFC
Greenbelt, MD 20771

Overall Objectives

- 1. Why study the magnetosphere?
  - Space weather
  - Fundamental science

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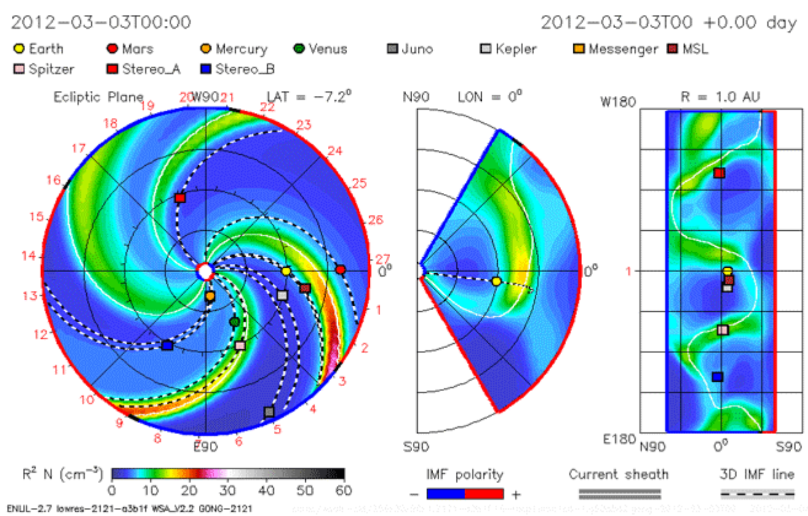
- 1. Why study the magnetosphere?
  - Space weather
  - Fundamental science
- 2. How does solar wind energy enter and circulate through the magnetosphere?
  - Follow the flow of energy, step by step
  - Identify open questions

The Sun-Earth Connection

The Sun continuously emits a supersonic, super-Alfvénic solar wind



NOAA: ENLIL Run doi:10.7289/V5445JGH
https://www.ngdc.noaa.gov/enlil/ run on request service

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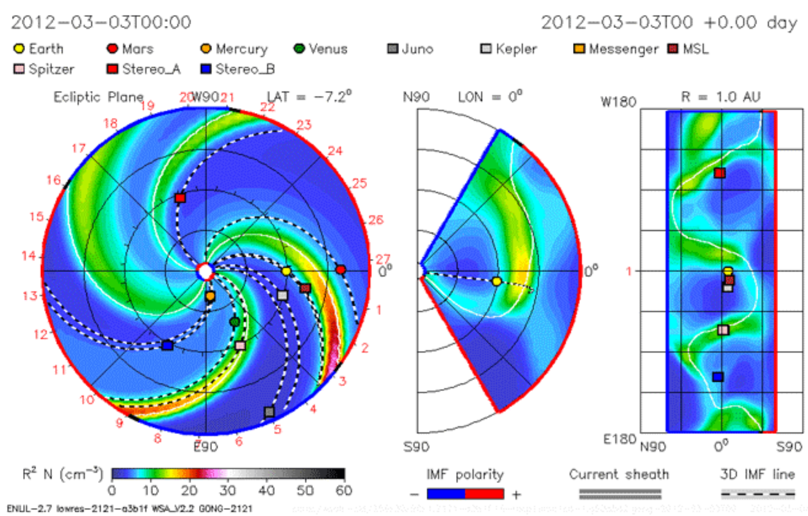
The Earth's magnetic field carves out the magnetospheric cavity in the solar wind



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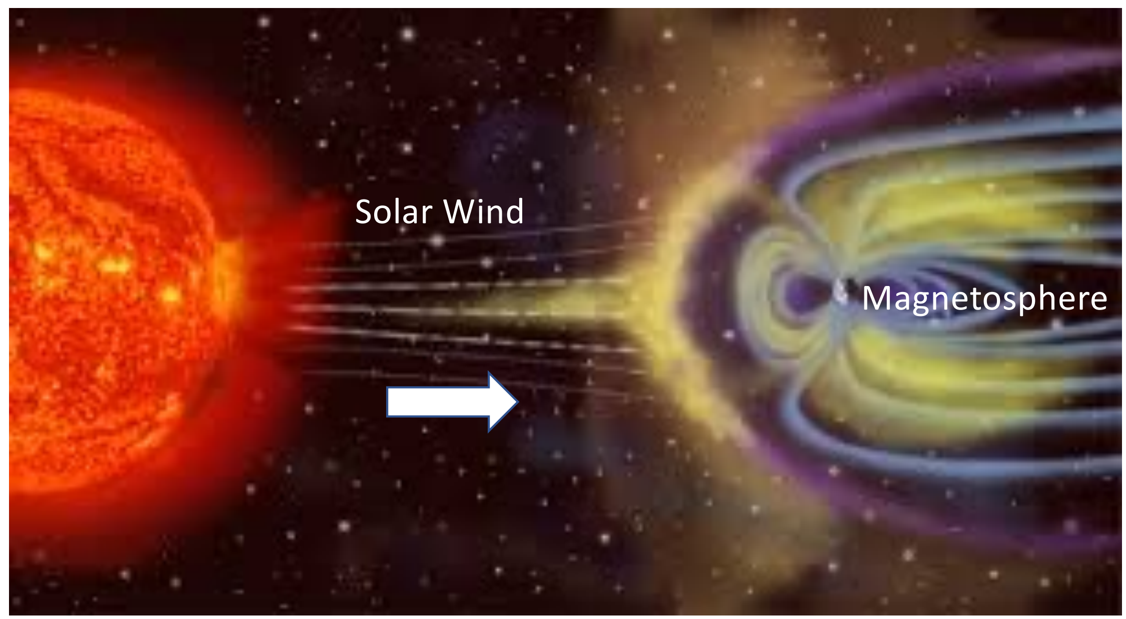

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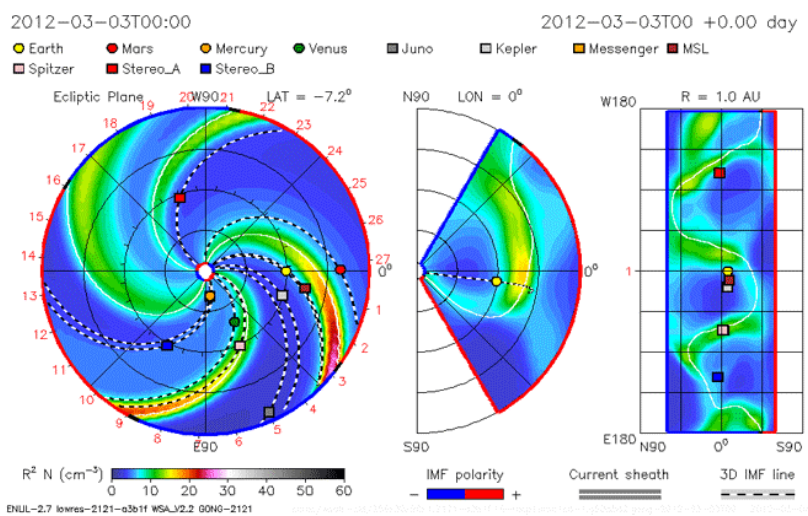
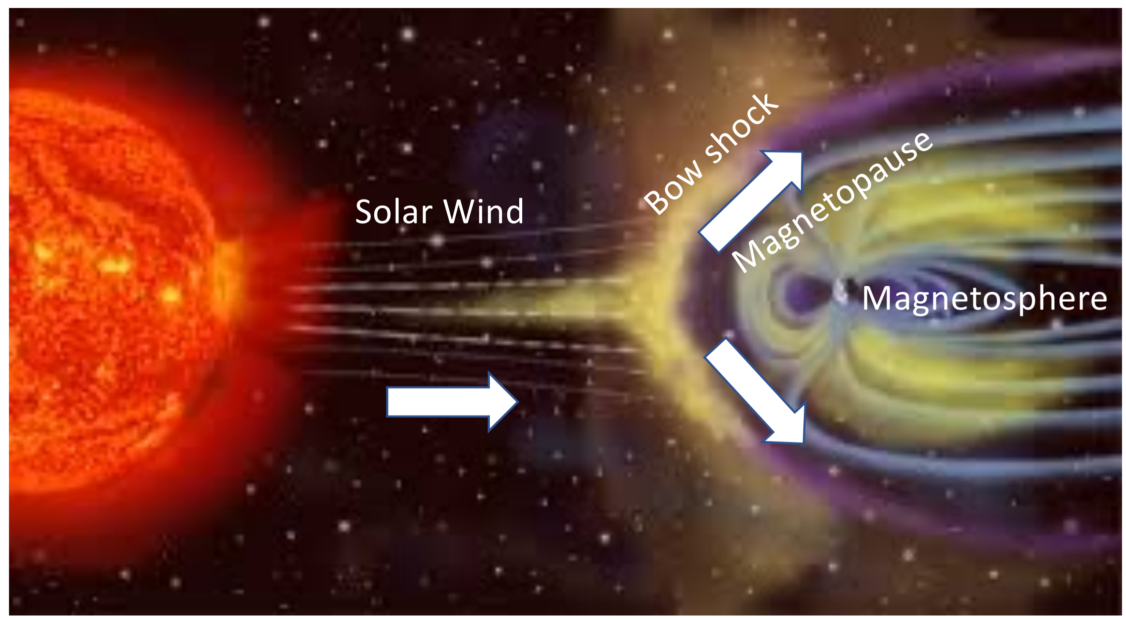
The bow shock slows and deflects the solar wind around the magnetopause





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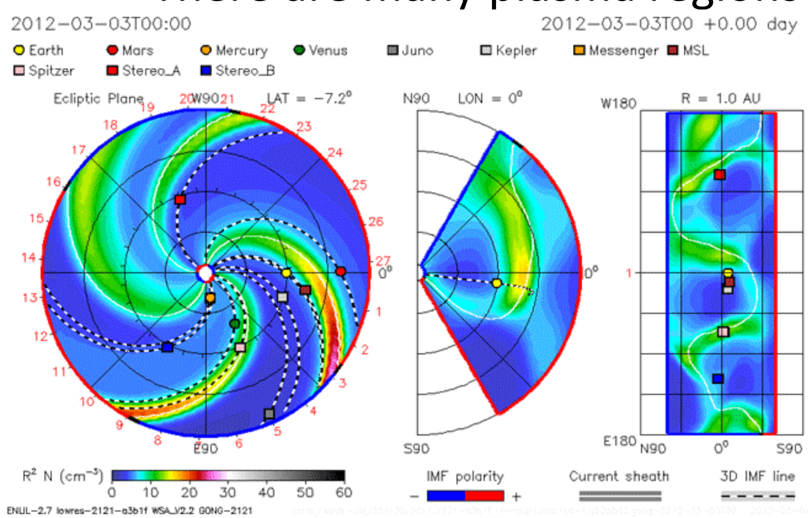
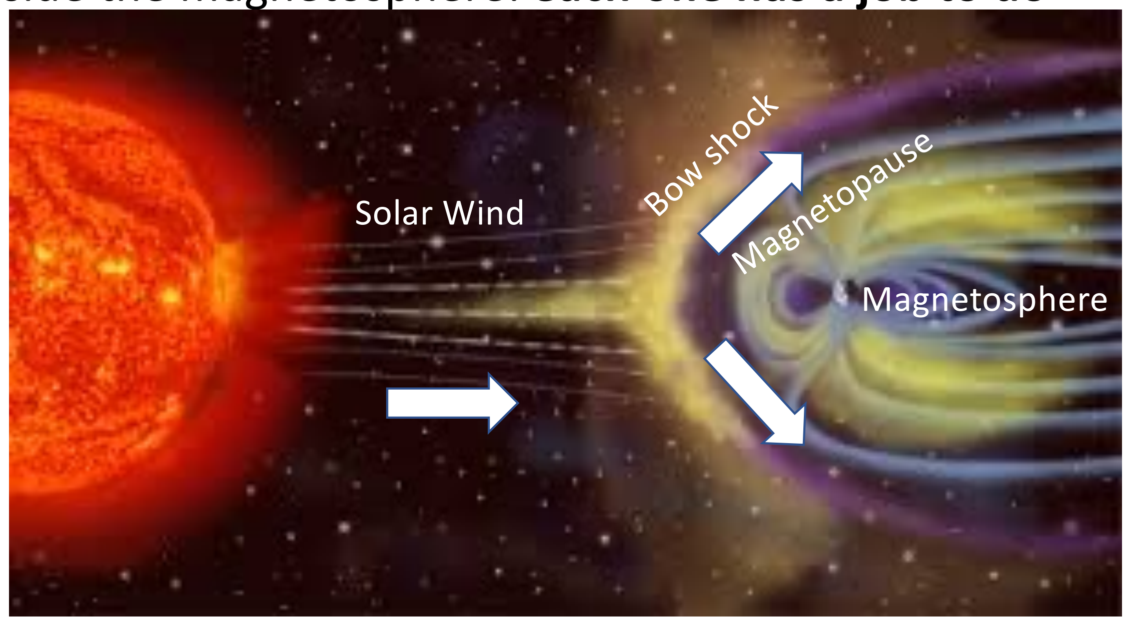
There are many plasma regions inside the magnetosphere: **each one has a job to do**





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- 1. Because we live there: Space Weather

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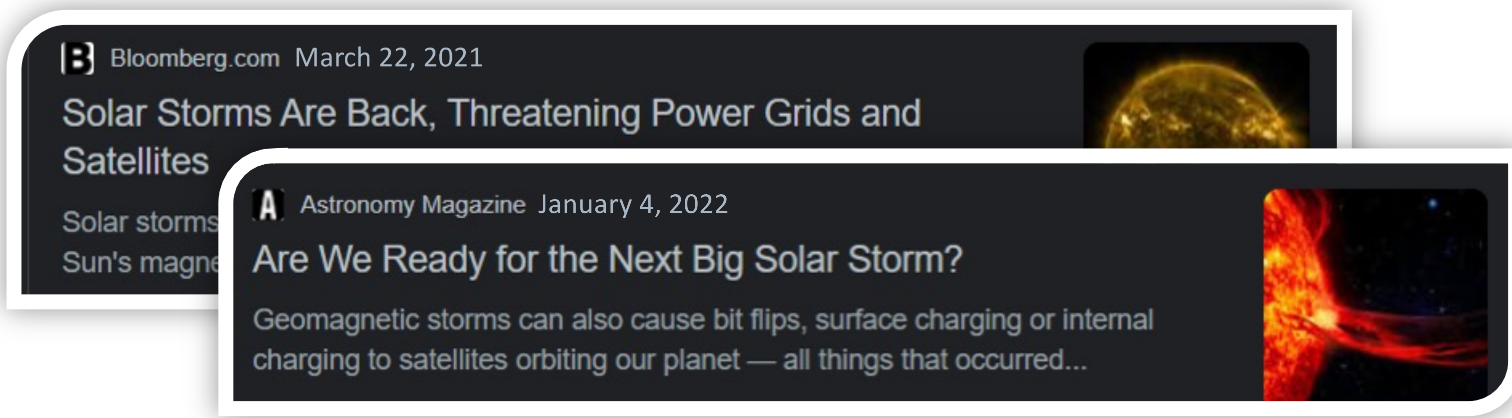
  - Hazardous geomagnetic storms and substorms

Insert created by my team



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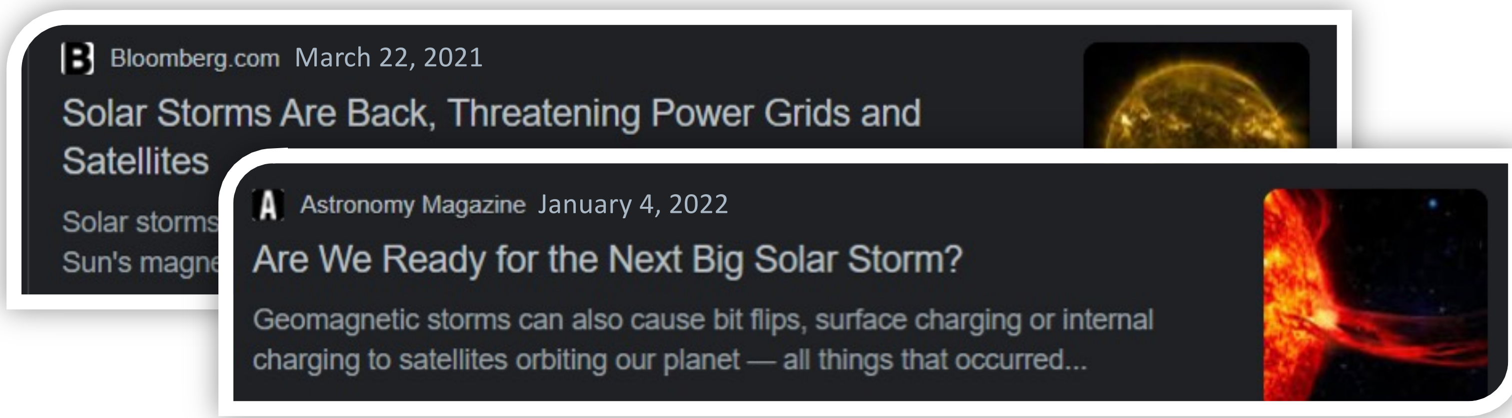
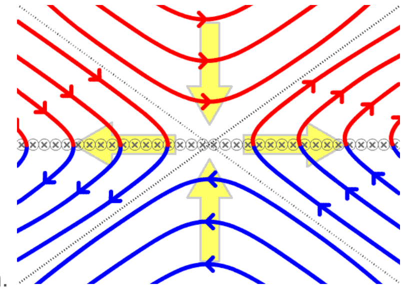


Reconnection



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https://en.wikipedia.org/wiki/Magnetic_reconnection

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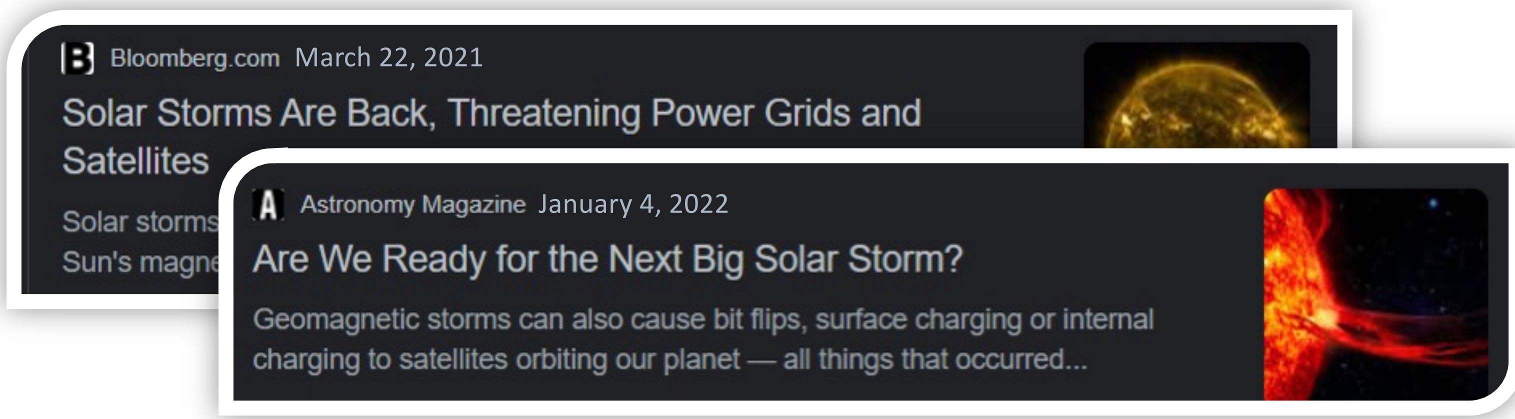

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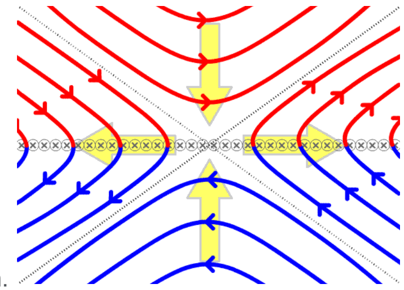

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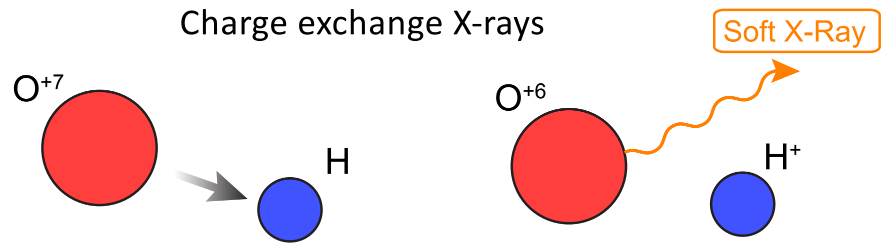
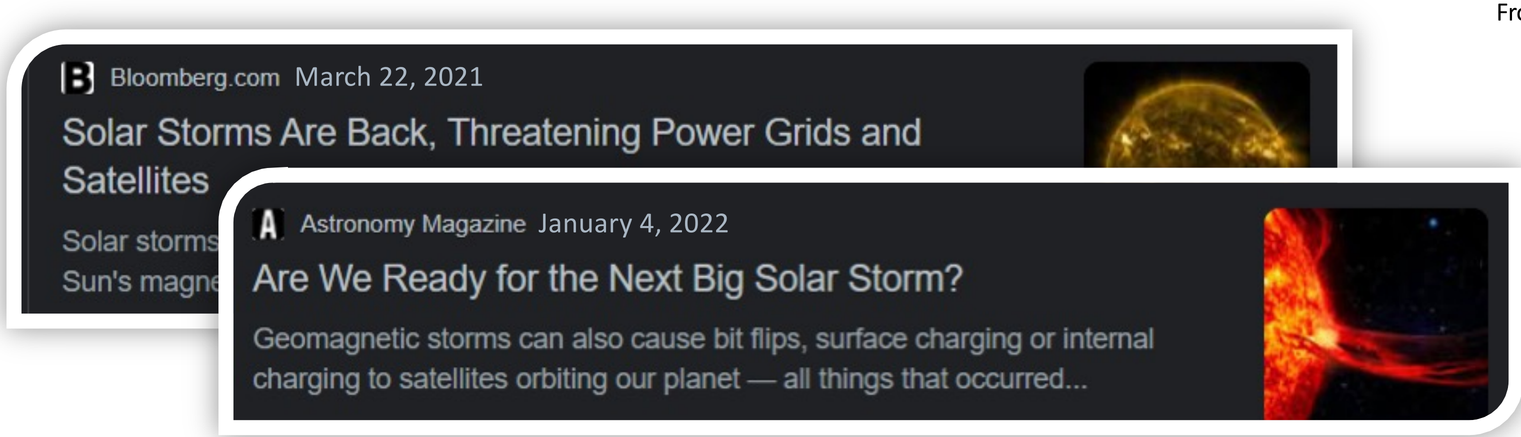
Charge exchange X-rays



From my STORM proposal team



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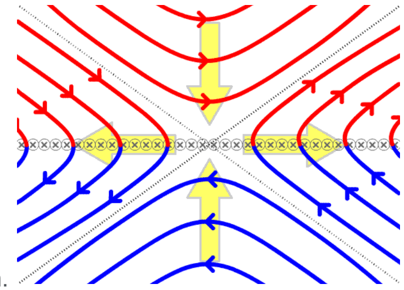
  - Ion-neutral interactions
  - Particle acceleration

Reconnection



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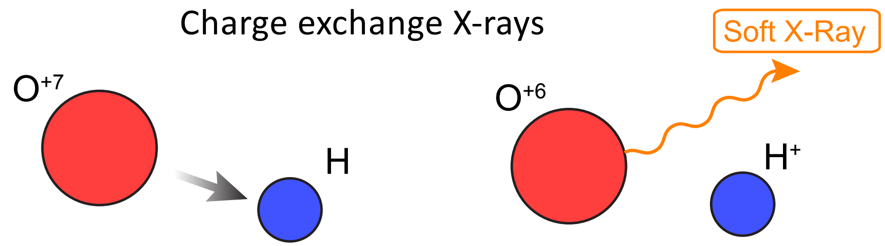

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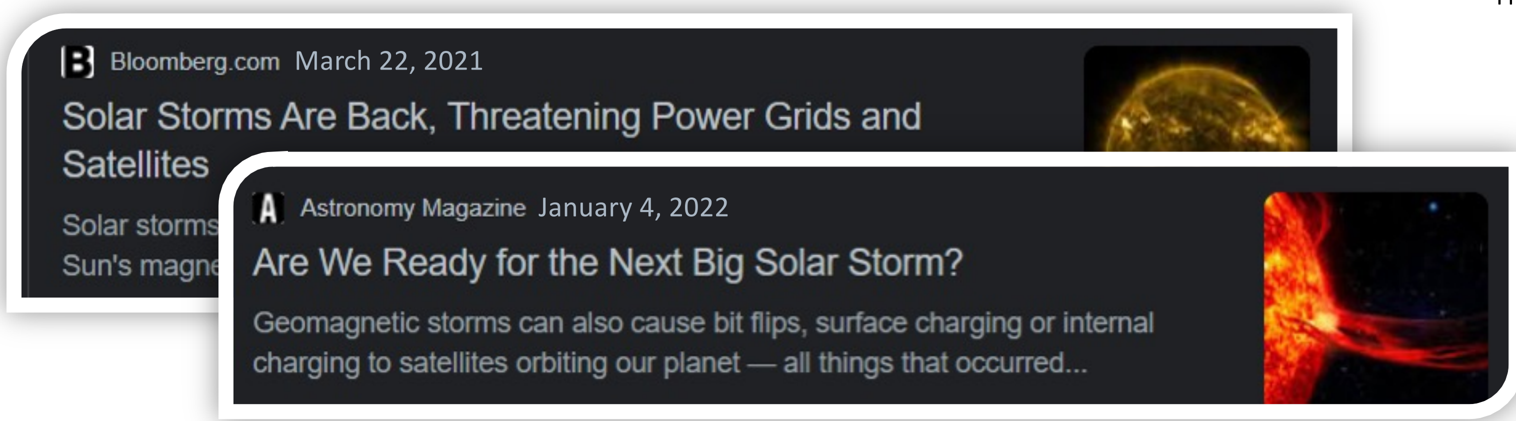
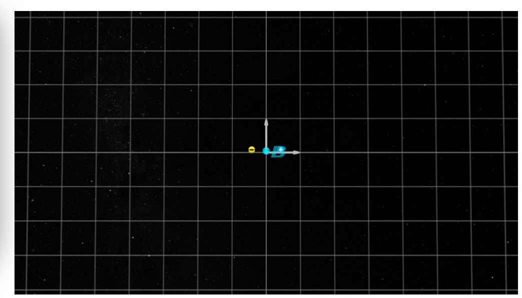


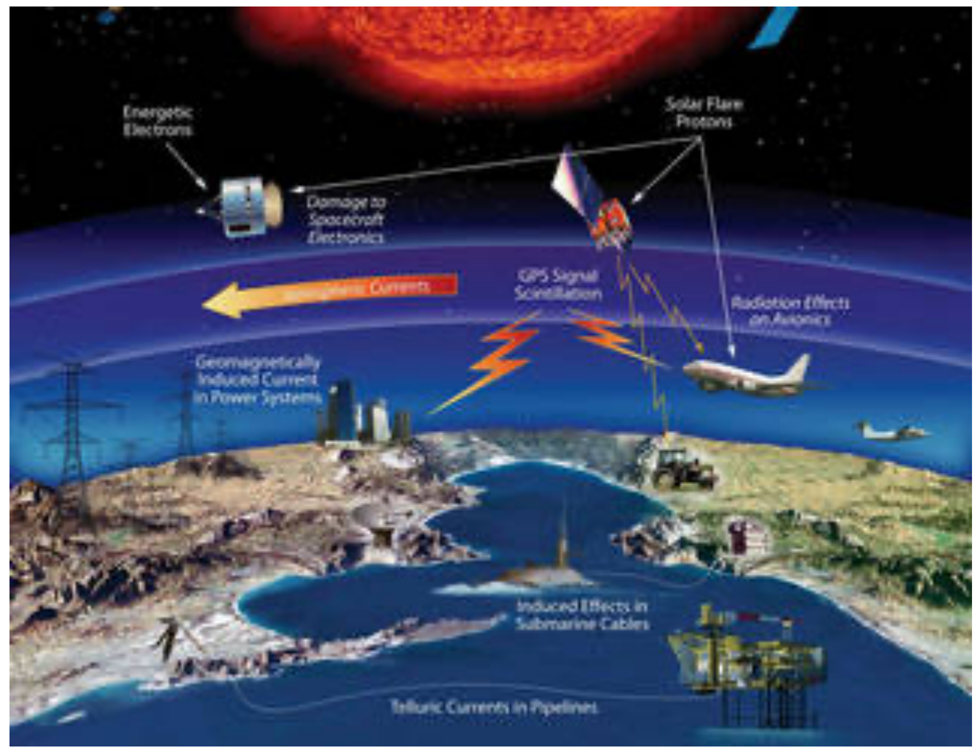
Particle Acceleration
https://svs.gsfc.nasa.gov/4262



Why Study the Magnetosphere?

- Understand and protect against space weather hazards
  - Spacecraft charging
  - Solar cell damage
  - Memory/circuit upsets

https://www.nasa.gov/mission_pages/sunearth/spaceweather/index.html



Why Study the Magnetosphere?

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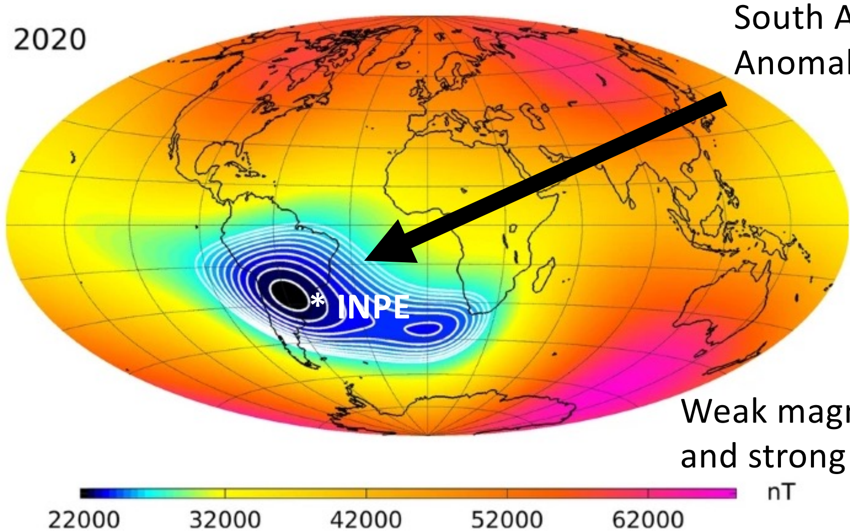
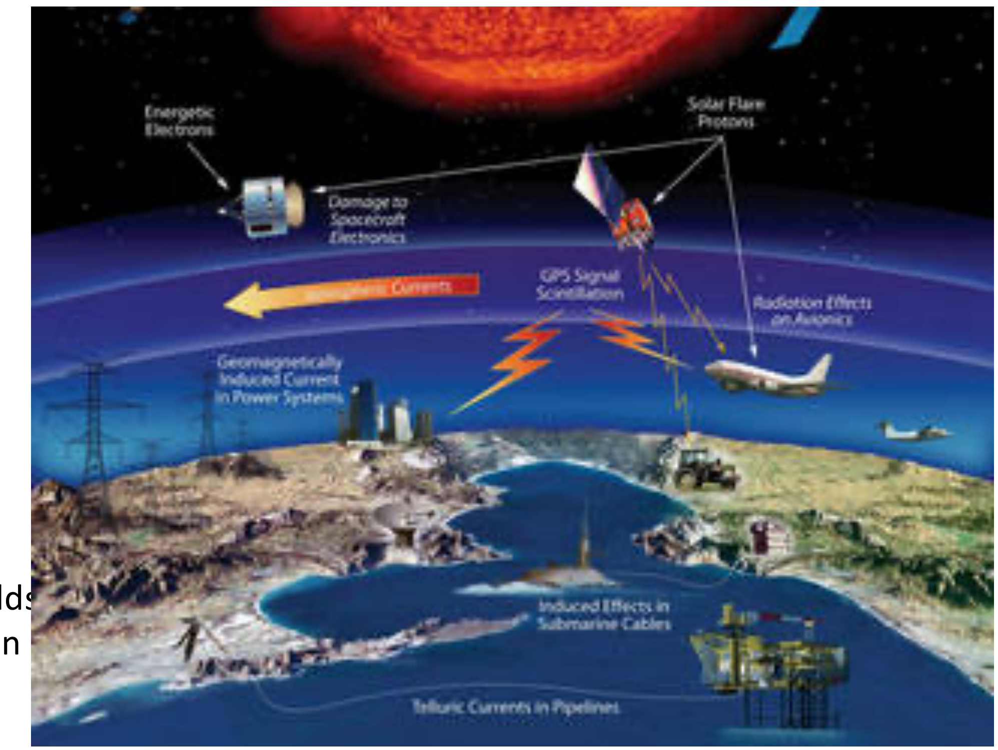


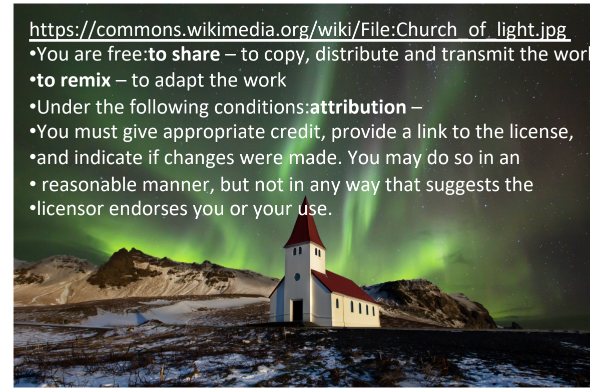
South Atlantic Anomaly

Weak magnetic fields and strong radiation



Why Study the Magnetosphere?

- It is beautiful



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- It is beautiful
- Help others: Guide our Astrophysics and Planetary colleagues
  - We can observe in situ what they must generally observe remotely
  - Plasma is 99.9% of the visible universe

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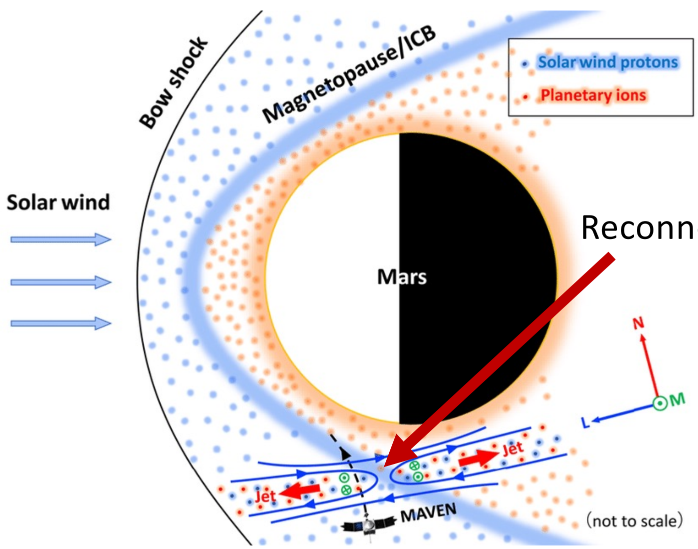

Reconnection at Mars

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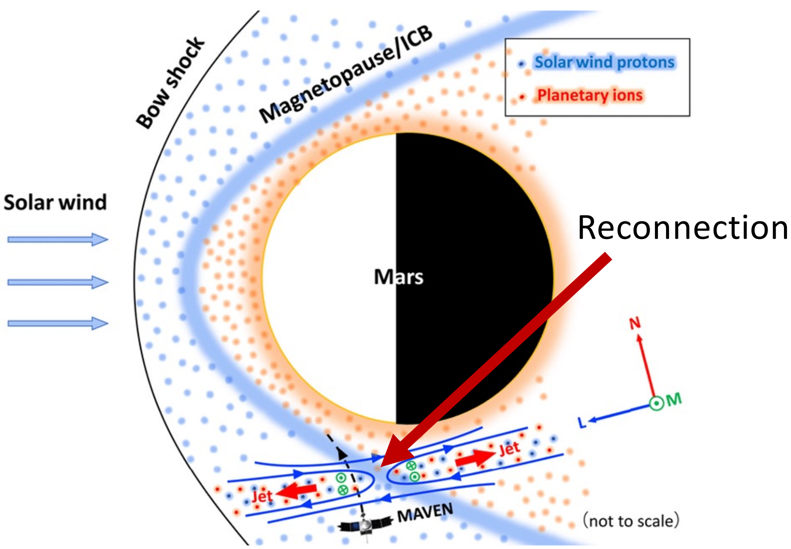
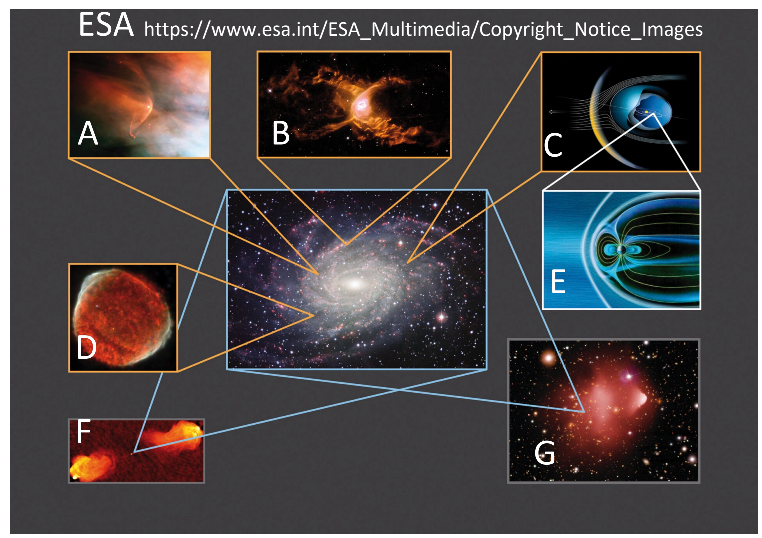


Particle Acceleration at Shock

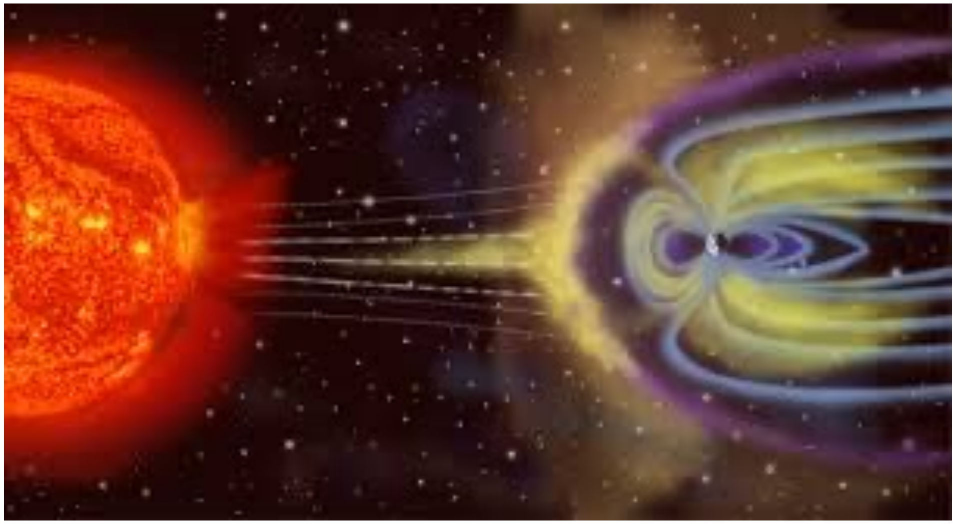
https://www.esa.int/ESA_Multimedia/Images/2011/11/Astrophysical_shocks_are_a_diverse_collection

A LL Ori star
B Red Spider Nebula
C Solar system
D Supernova SN1006
E Earth
F Cygnus A galaxy
G Bullet Merging Galaxy Cluster



Outline

- How do we know there is a Sun-Earth connection?
- The solar wind
- Dungey (substorm) cycle step-by-step
- Geomagnetic storms
- Conclusions



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1769-1859

Sunspots and Storms

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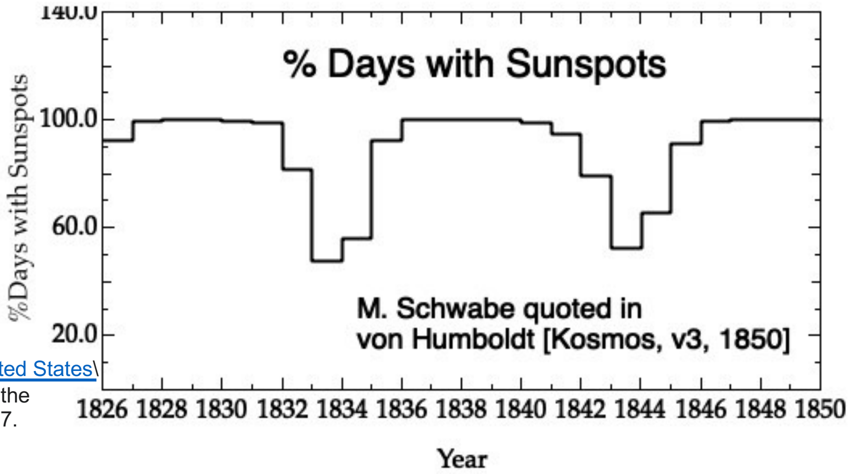

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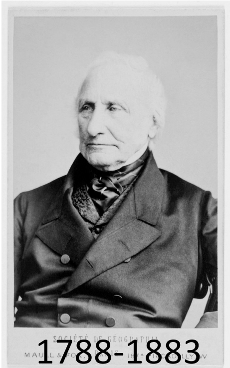

1788-1883

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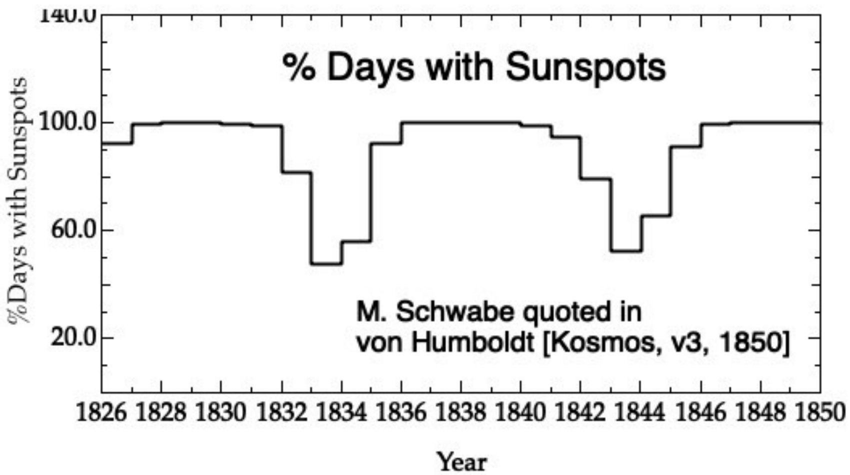
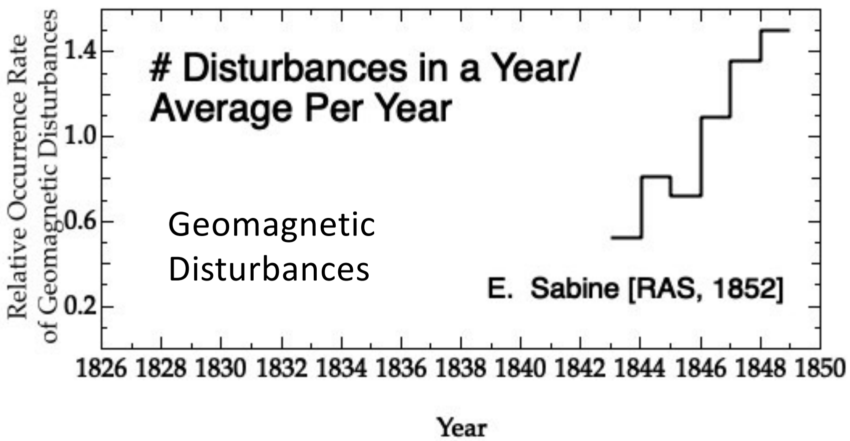
  E. Sabine [Phil. Tran. Royal Soc. May 6, 1852]





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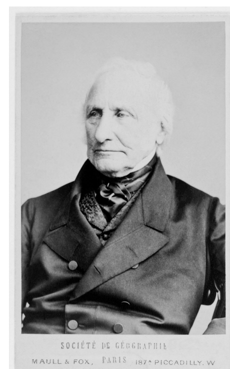

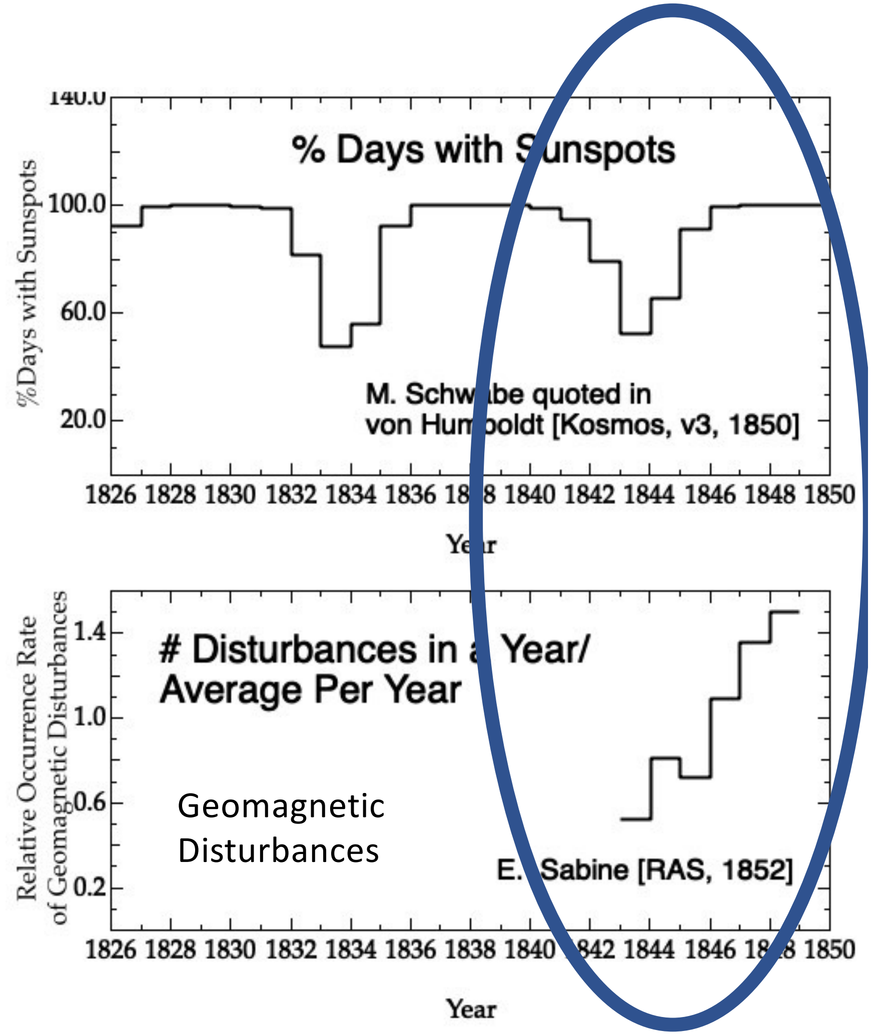

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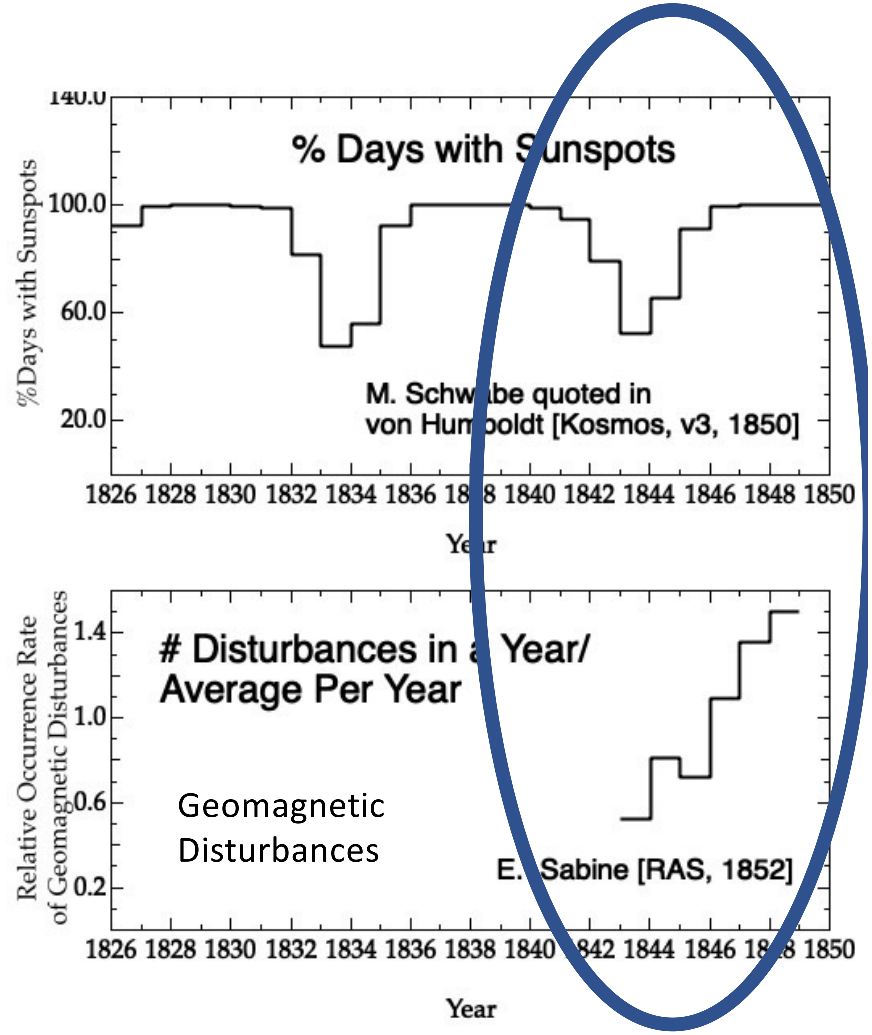
Sunspots and Storms

- → Sabine [1852] concluded:
- "The gaseous envelope of the sun causes magnetic effects at the surface of our planet."



Sunspots and Storms

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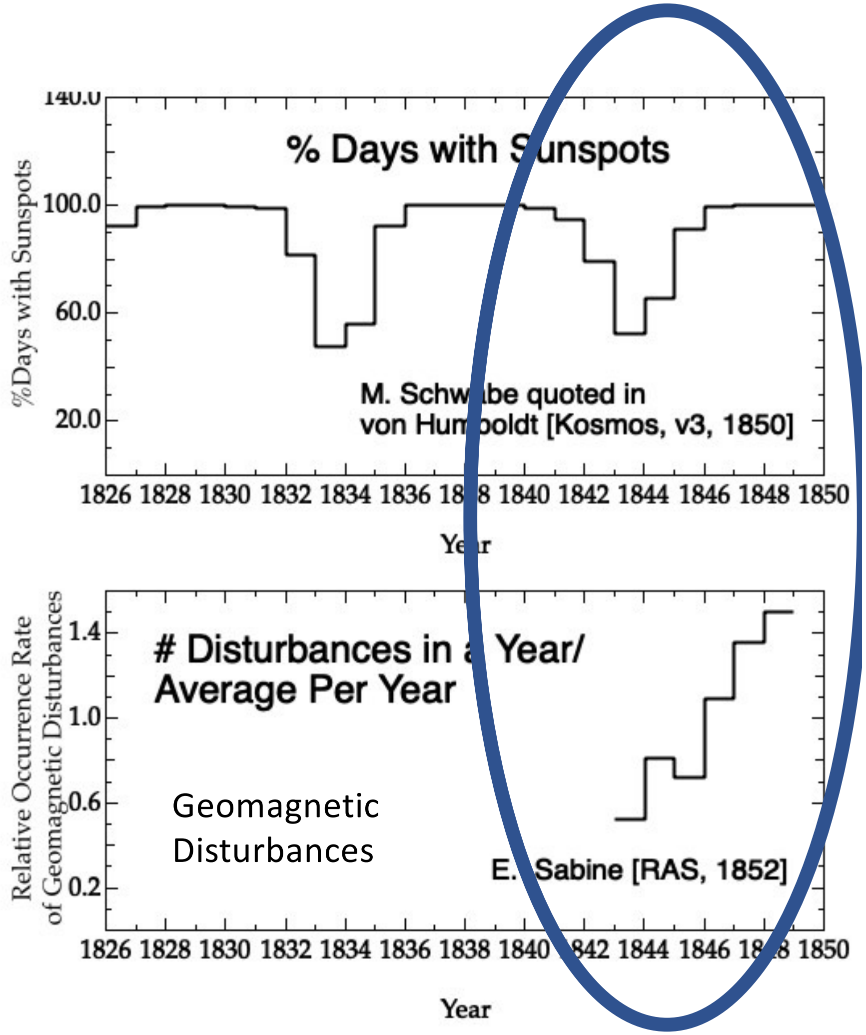
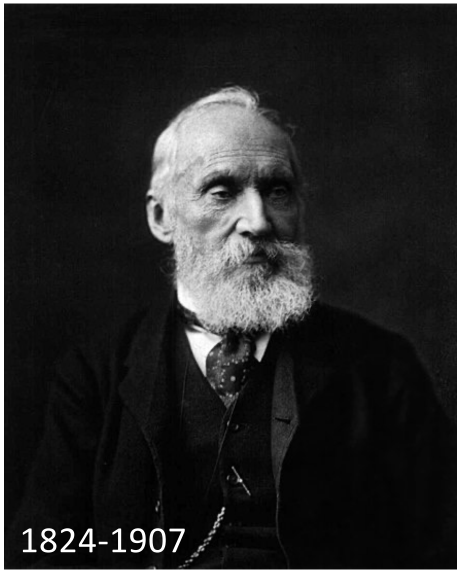
He was certainly a visionary!



Not everyone believed in his vision…

- "It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sunspots is **unreal**, and that the seeming agreement between the periods has been **mere coincidence**." **Lord Kelvin**, 1892, Royal Society



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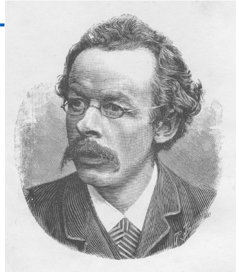


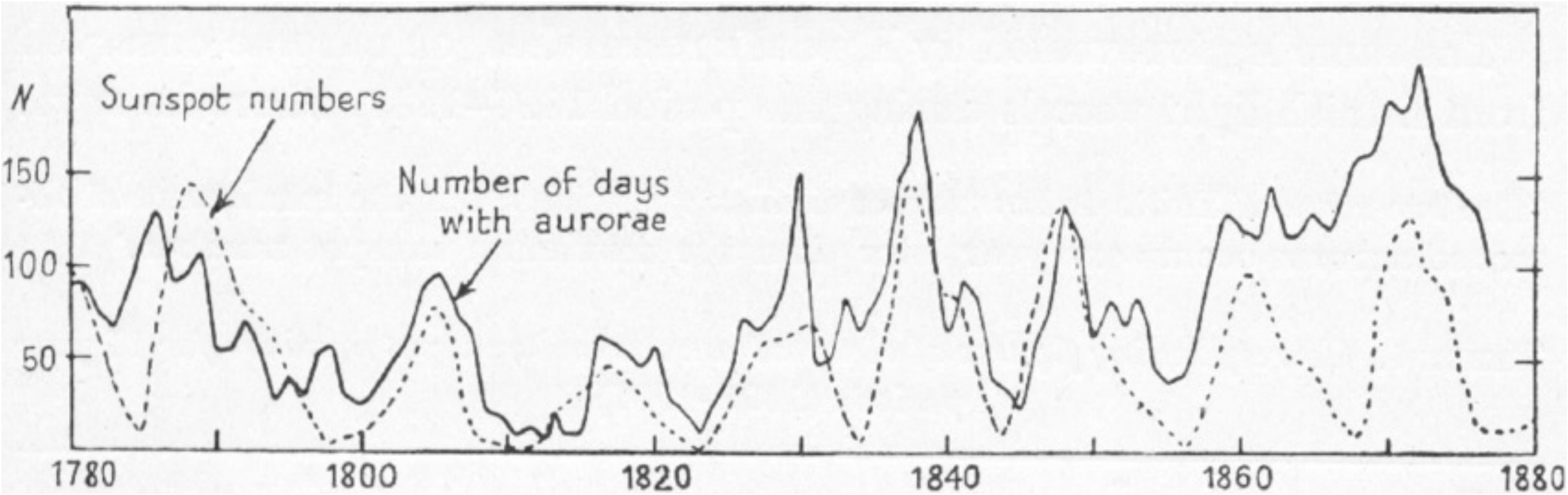
1851-1896

Sunspots and Aurora

- The number of days with aurora tracks the number of sunspots….

https://www.history-of-geo-and-space-sciences.net/policies/licence_and_copyright.html
https://www.researchgate.net/publication/258648038_Sophus_Peter_Tromholt_an_outstanding_pioneer_in_aur oral_research

Tromholt [1898]



Sunspots and Aurora

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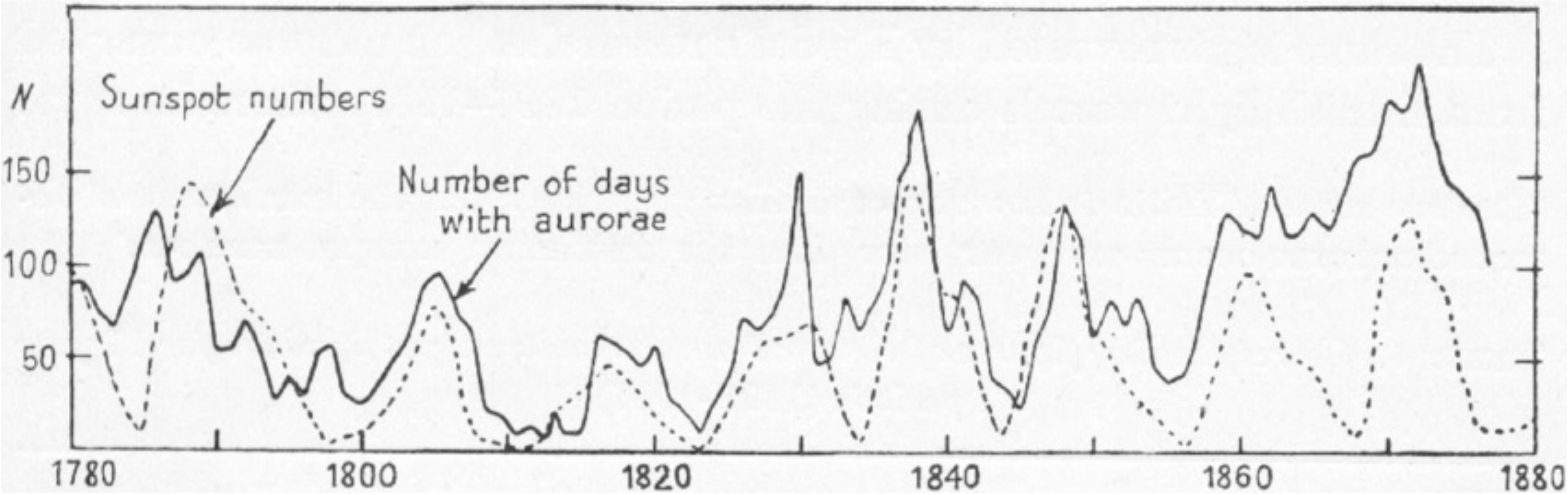
1851-1896

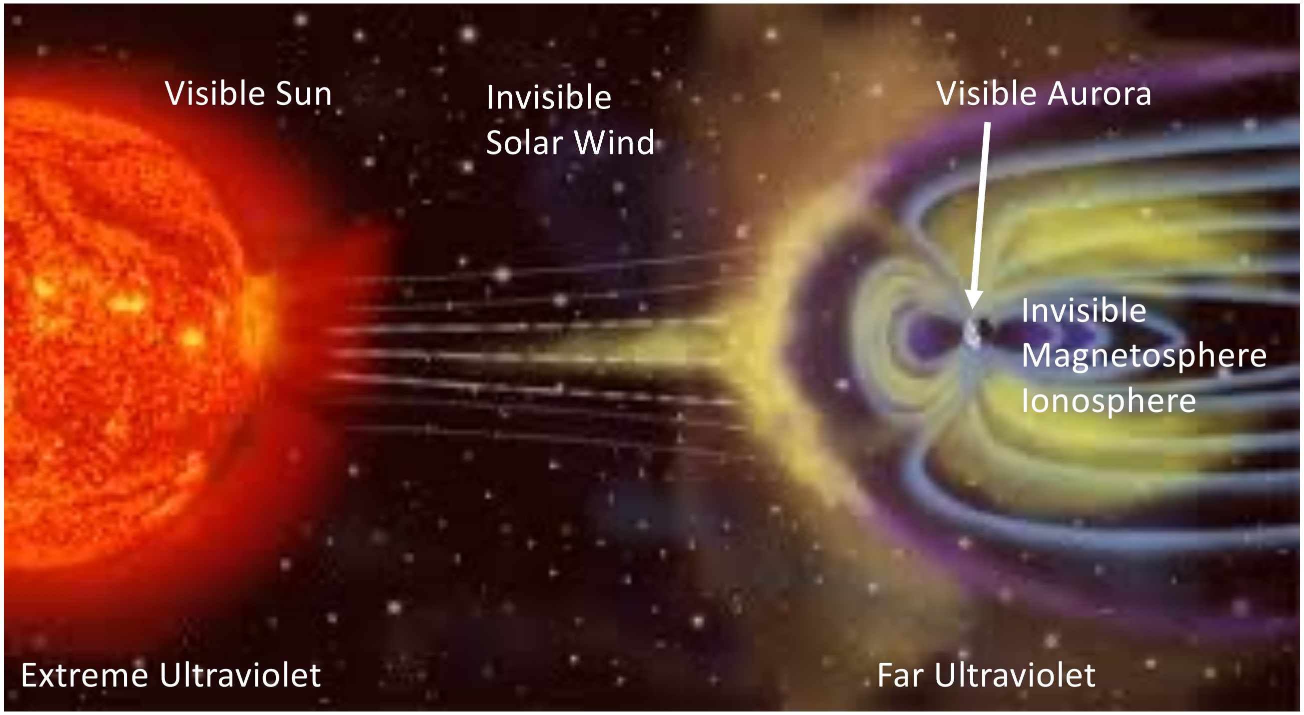
→ Convincing evidence for a connection

Tromholt [1898]
Størmer [1955]



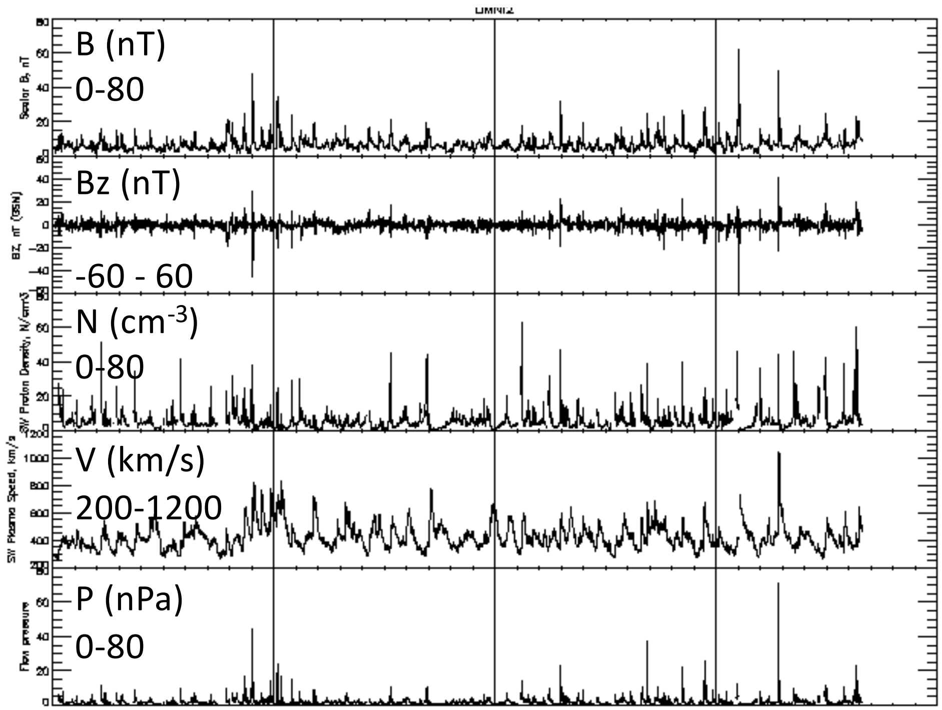
The Sun-Earth Connection

Mediated by the highly variable and generally invisible solar wind…



Episodic Solar Wind Drivers and the Solar Cycle

Solar Maximum **2001**
Hourly Averages



January 1 December 31 January 1 December 31

These figures were made by me

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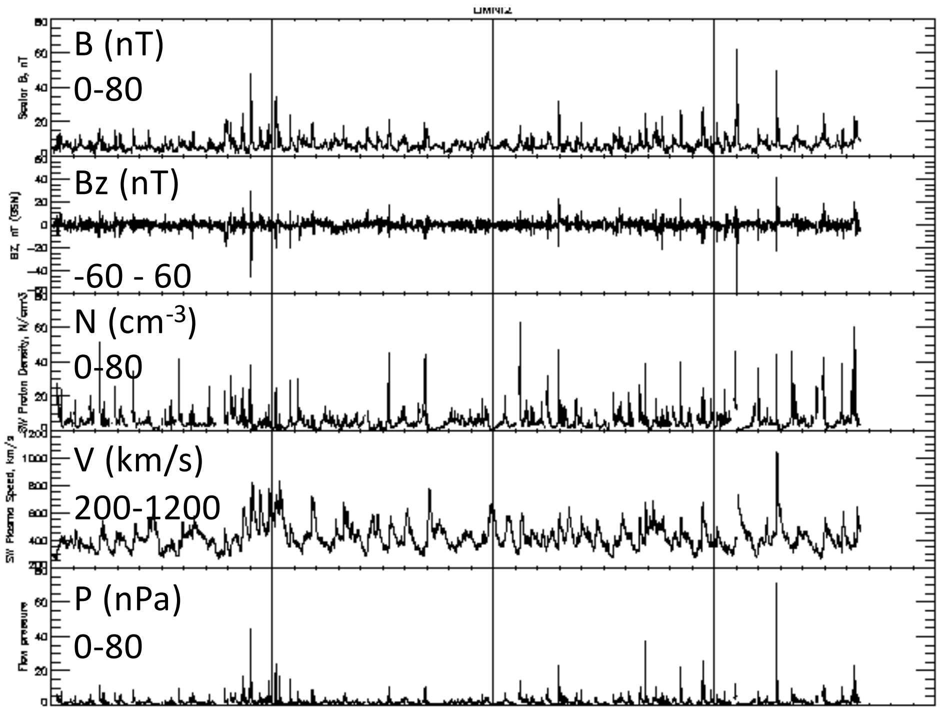
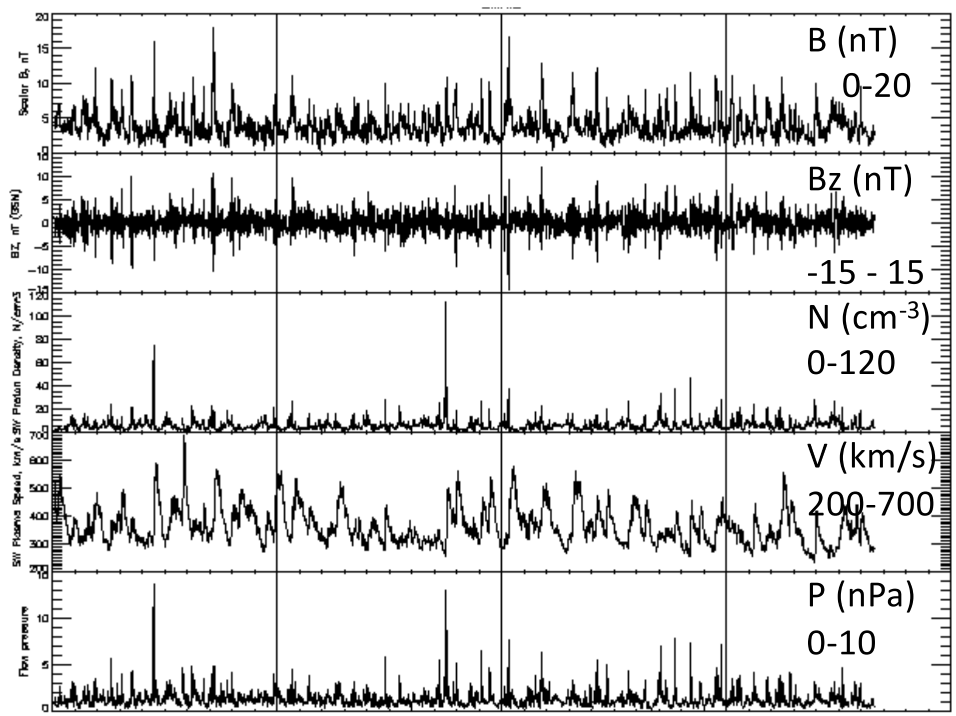


January 1 December 31

Solar Minimum **2009**
Hourly Averages

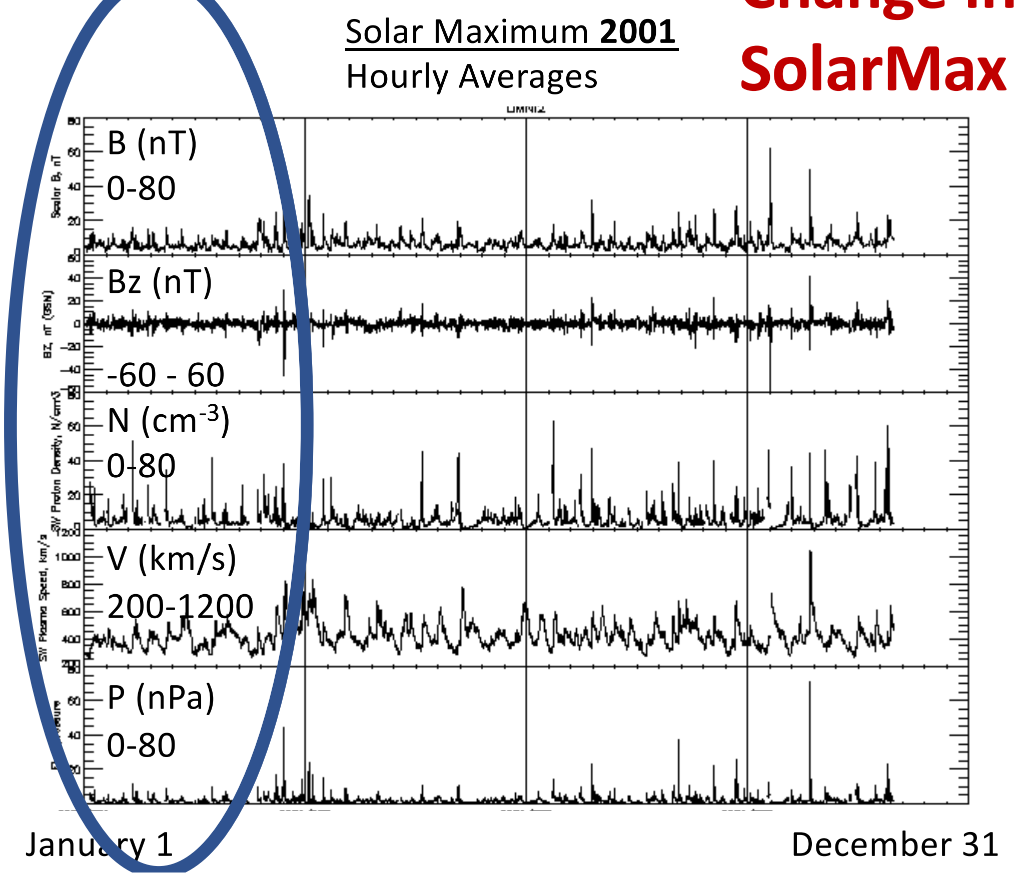


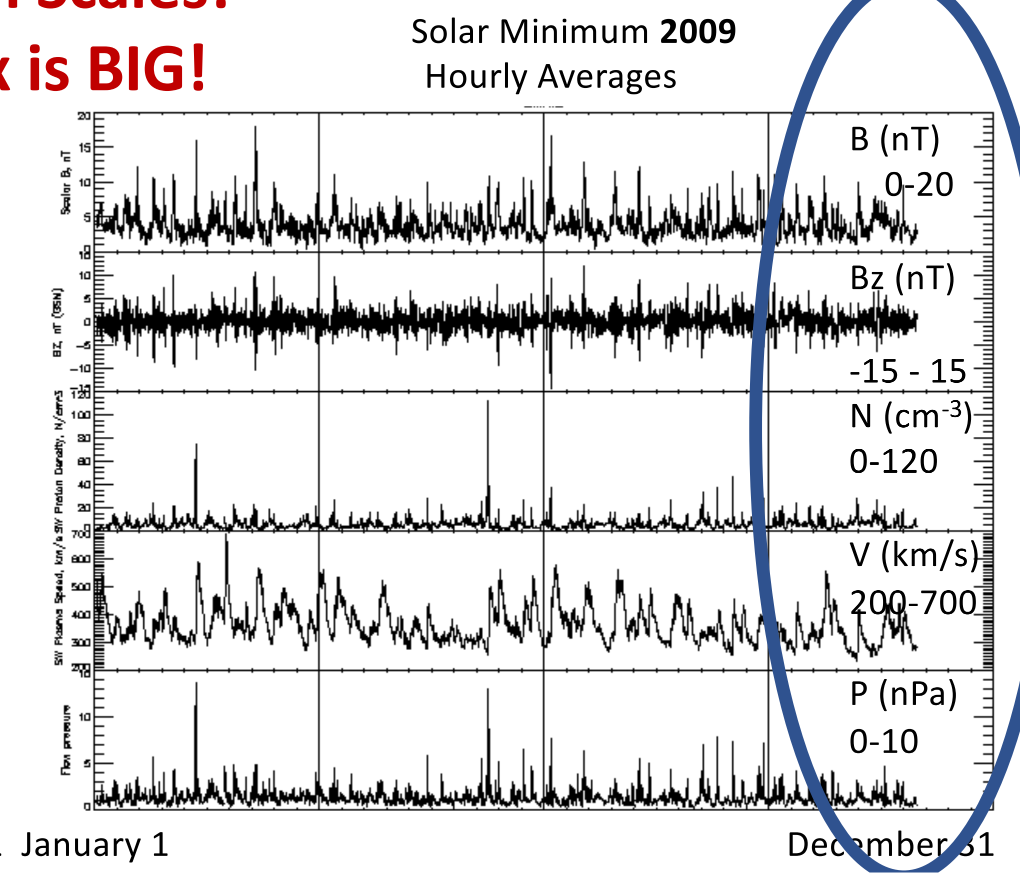
January 1 December 31

Episodic Solar Wind Drivers and the Solar Cycle

Change in Scales!

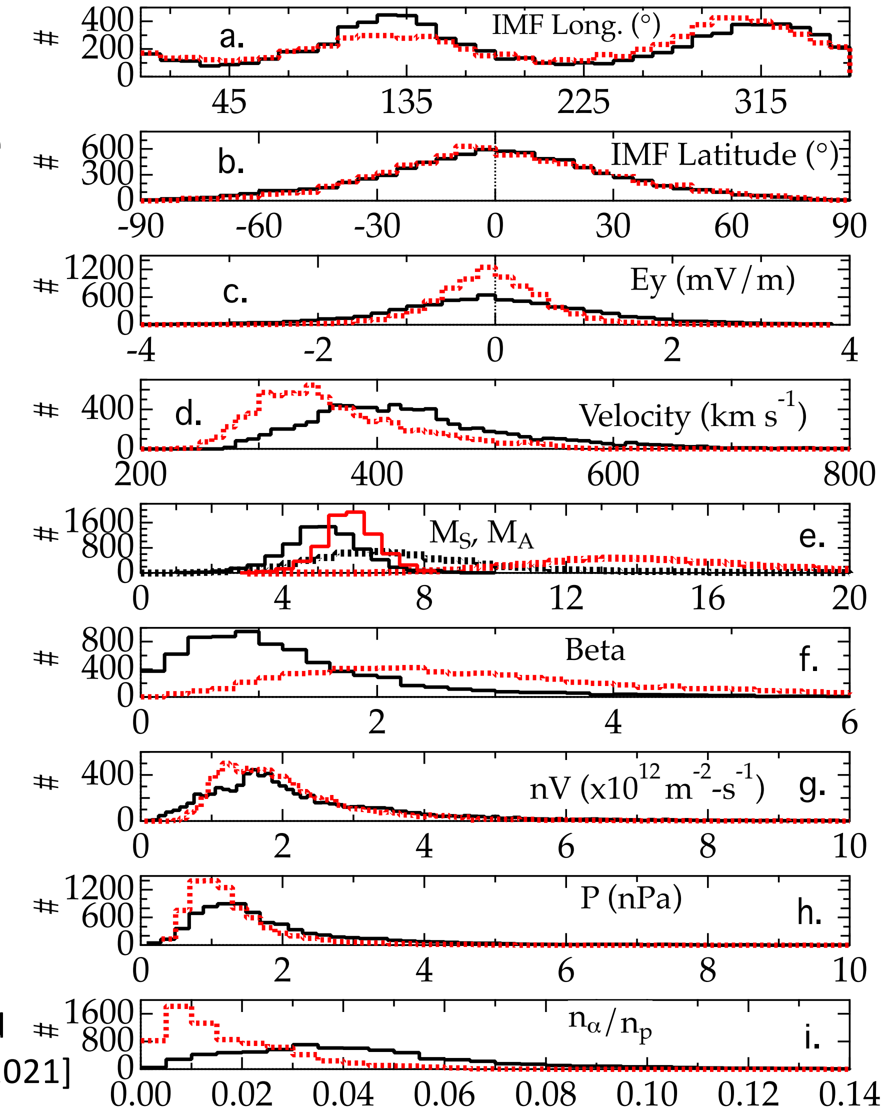
SolarMax is BIG!





Solar Wind and Solar Cycle

- Hourly averages for 2001 (Black), 2009 (red)
- M_A solid, M_S dashed

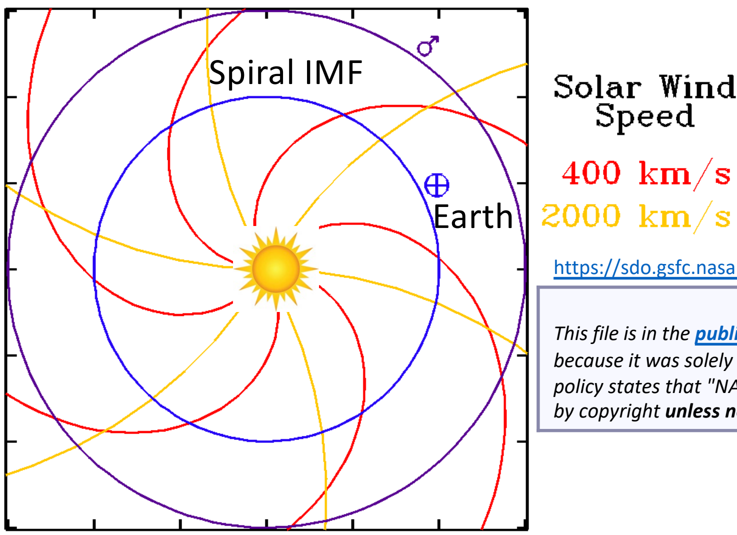


Sibeck and Murphy [2021]

This figure was made by me.

Solar Wind and Solar Cycle

- Hourly averages for 2001 (Black), 2009 (red)
- M_A solid, M_S dashed
- Interplanetary magnetic field is spiral and equatorial
- Solar wind is supersonic, superAlfvénic



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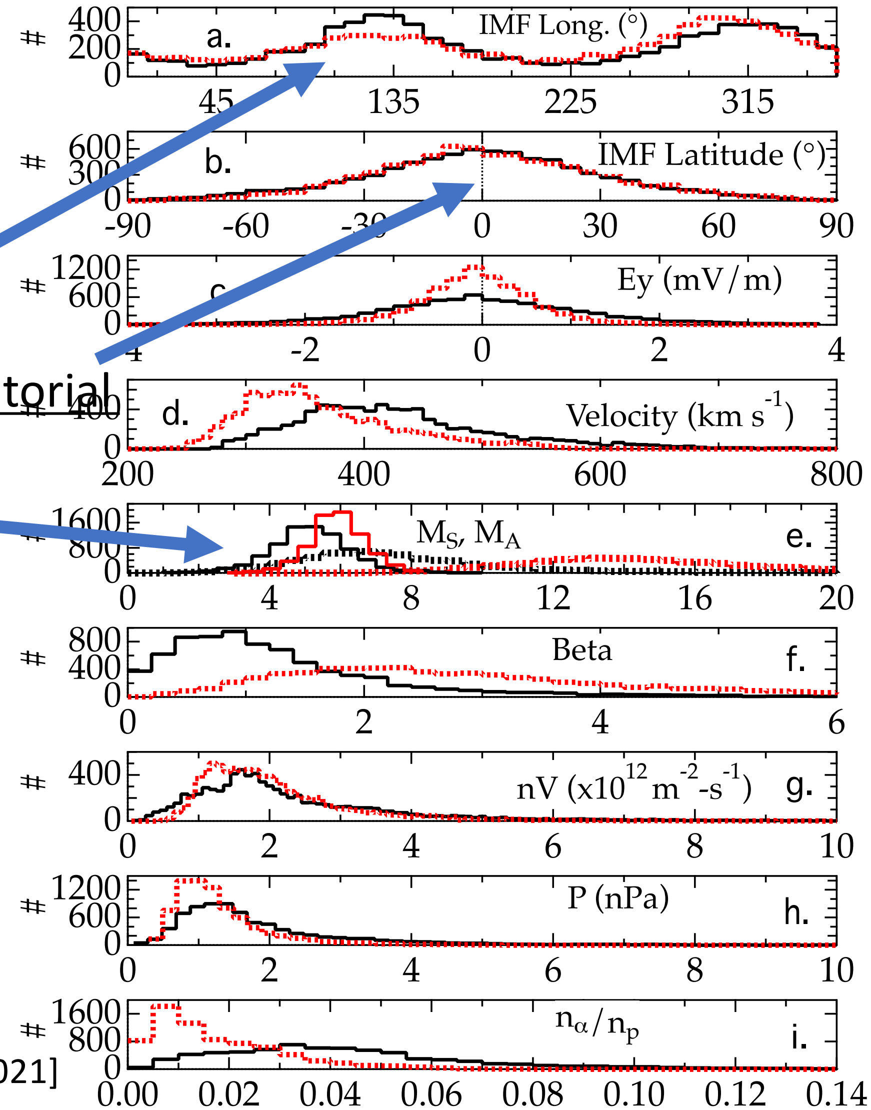
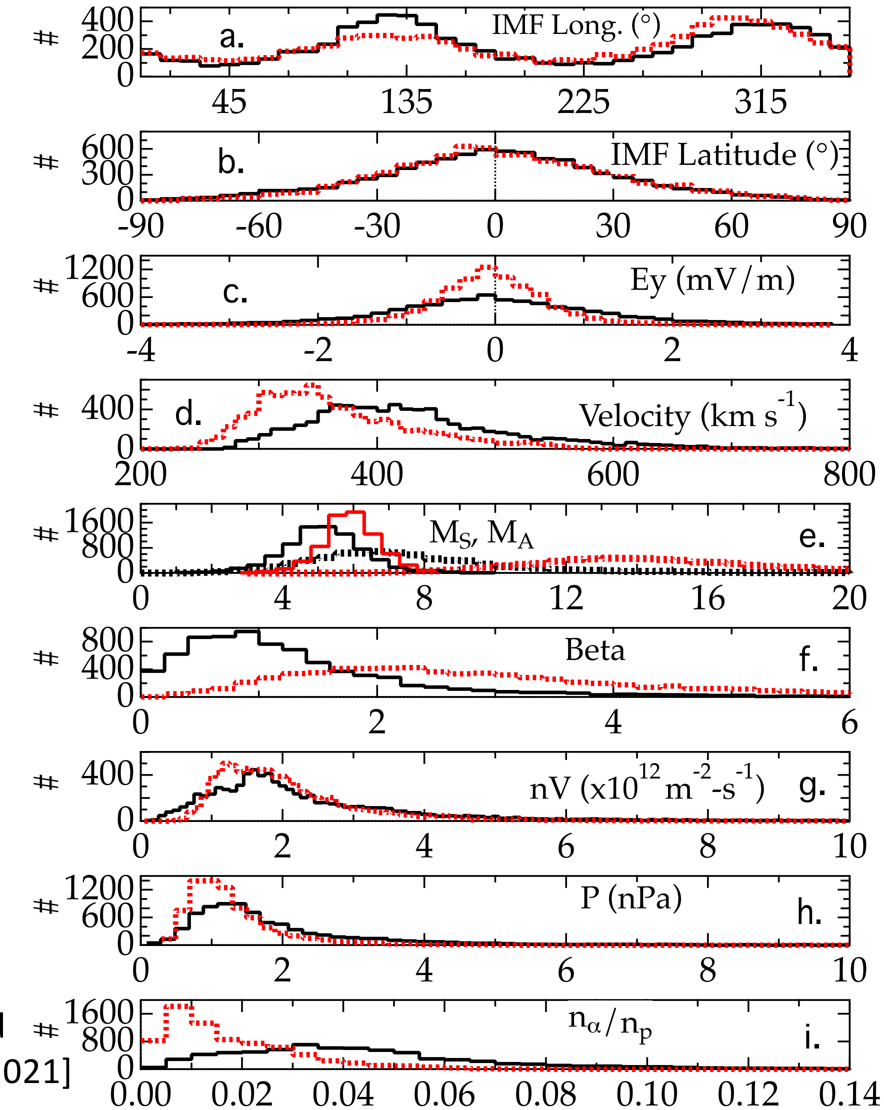


Sibeck and Murphy [2021]

Typical Solar Wind Values

- Hourly averages for 2001 (Black), 2009 (red)
- M_A solid, M_S dashed

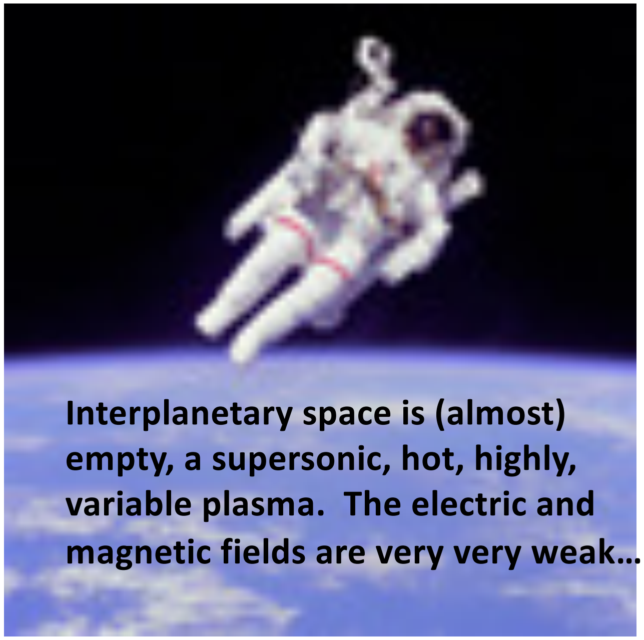
Parameter	Solar minimum	Solar Maximum
Φ_{IMF}	Spiral IMF	Spiral IMF
Θ_{IMF}	1.3 +/- 29°	-0.2 +/- 31°
E_Y	-0.06 +/- 0.73 mV/m	0.01 +/- 1.87 mV/m
V	364 +/- 65 km/s	**425** +/- 90 km/s
M_S, M_A	5.9 +/- 0.9, 12.3 +/- 6.3	5.2 +/ 1.2, 7.8 +/- 3.7
β	**4.4** +/- 8.8	1.45 +/- 1.7
nV	1-3x10^{12} m $^{-2}$ s^{-1}	1-3x10^{12} m $^{-2}$ s^{-1}
nMV^2	1.3 +/- 0.8 nPa	**2.2** +/- 2.6 nPa
n_α/n_P	0.017 +/- 0.013	**0.044** +/- 0.024



Sibeck and Murphy [2021]

You and the Solar Wind

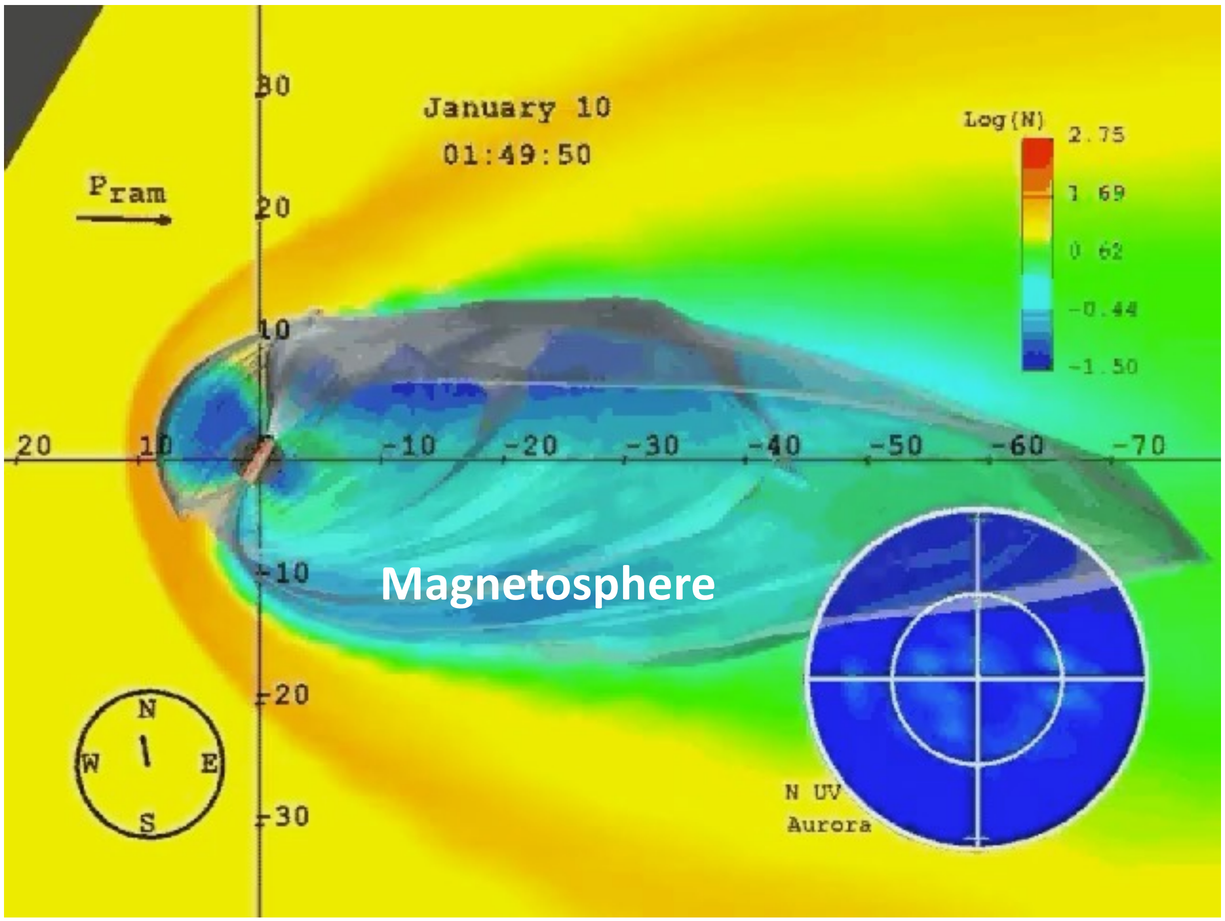
Parameter	Solar Wind	Air outside this meeting room
Density	5 cm^{-3}	2.7×10^{19} cm^{-3}
Velocity	4×10^{5} m s^{-1}	20 m s^{-1} A very windy day
Temperature	1×10^{5} K	3×10^{2} K
Magnetic Field Strength	5 nT	~25000 nT
Electric field strength	0.002 V/m	100 V/m down



http://grin.hq.nasa.gov/ABSTRACTS/GPN-2000-001156.html

Earth’s Magnetosphere Carves out a Cavity

Solar Wind



Solar wind pressure variations buffet the magnetosphere

Global magnetohydrodynamic simulation [C. Goodrich personal communication]

The IMF Drives the Dungey Cycle

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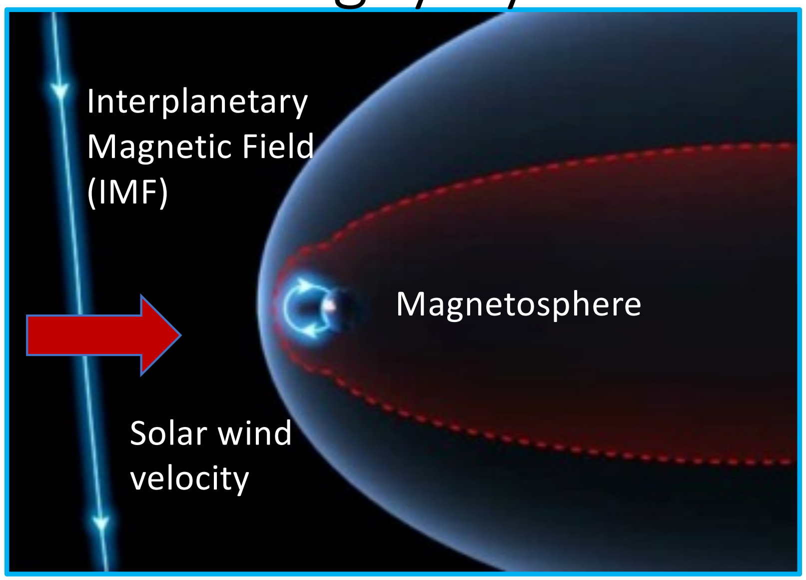
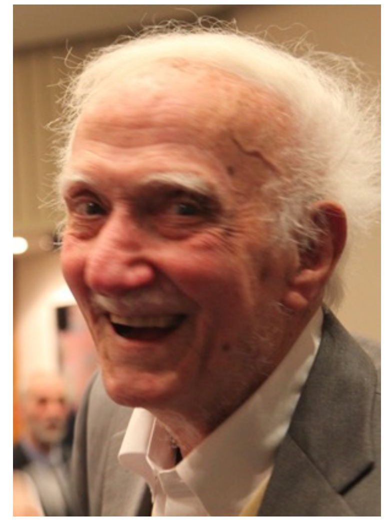
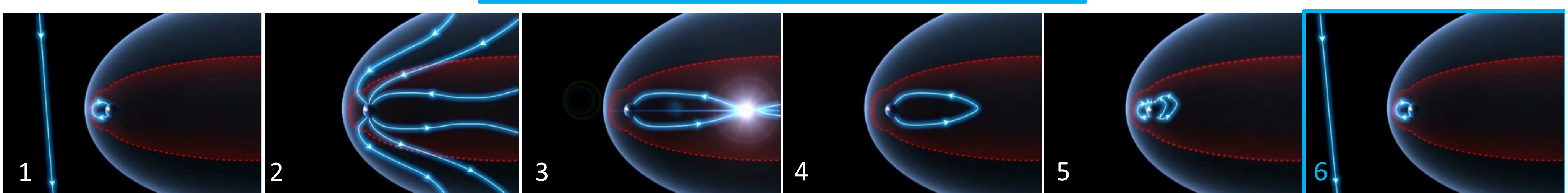




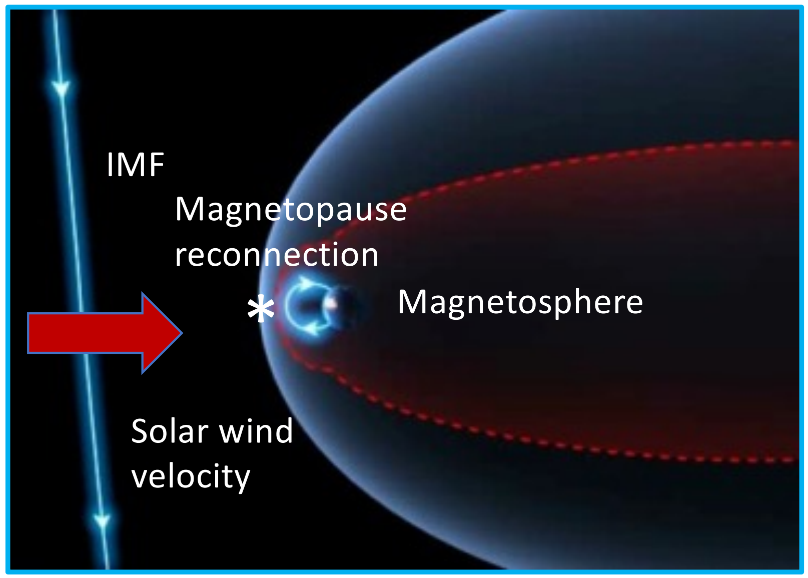
James W. Dungey
1923-2015

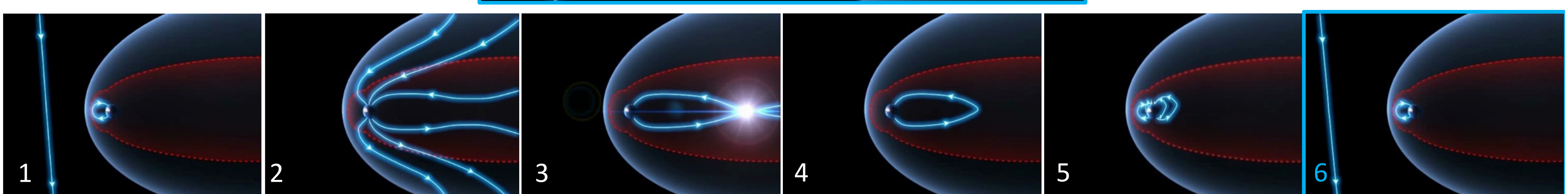
Kyle Murphy
Personal Communication



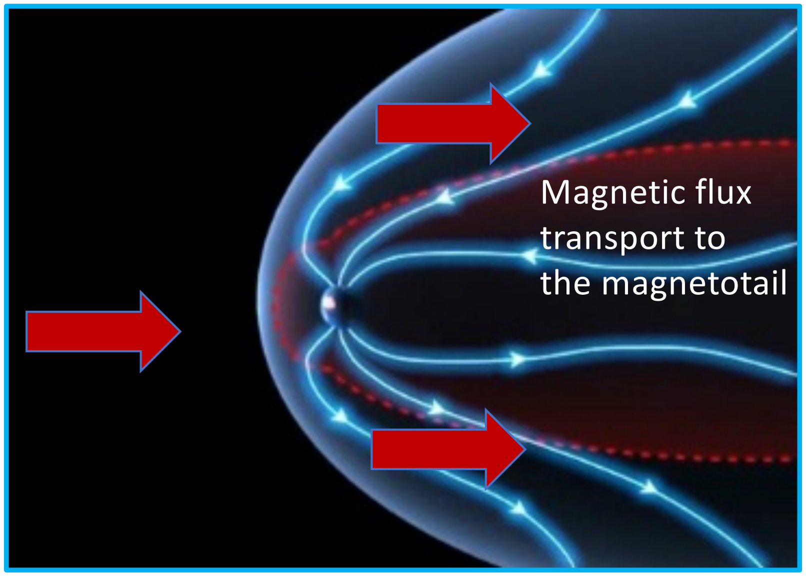
The Dungey Cycle

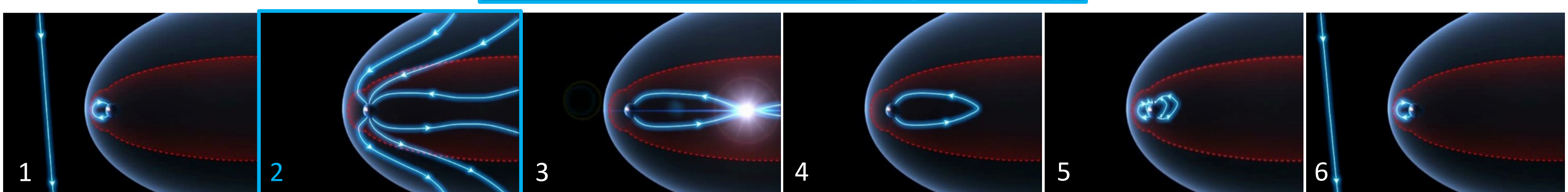
Southward
IMF
turning



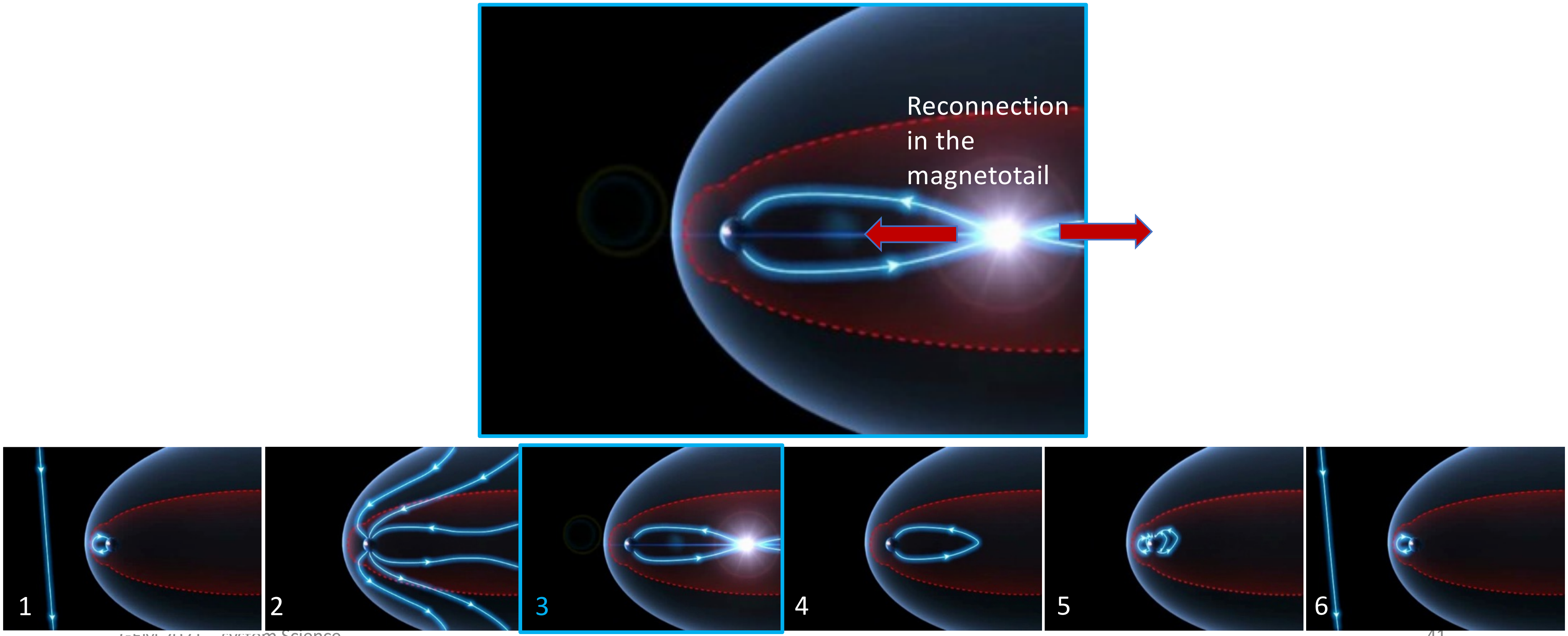


The Dungey Cycle

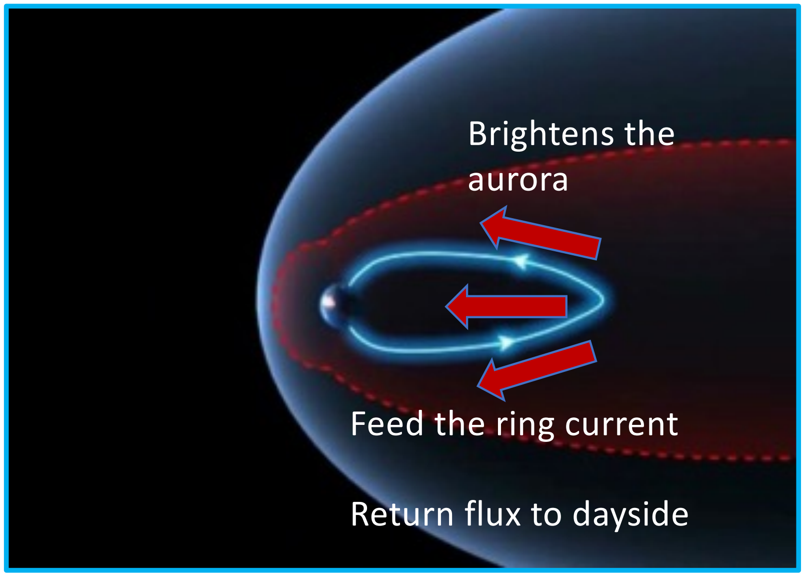


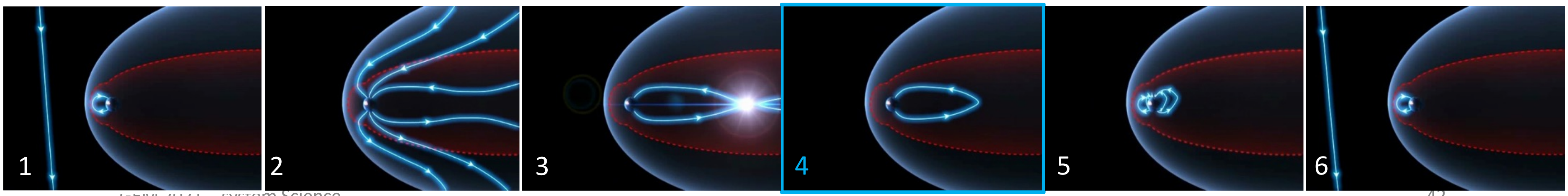


The Dungey Cycle



The Dungey Cycle





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were made by
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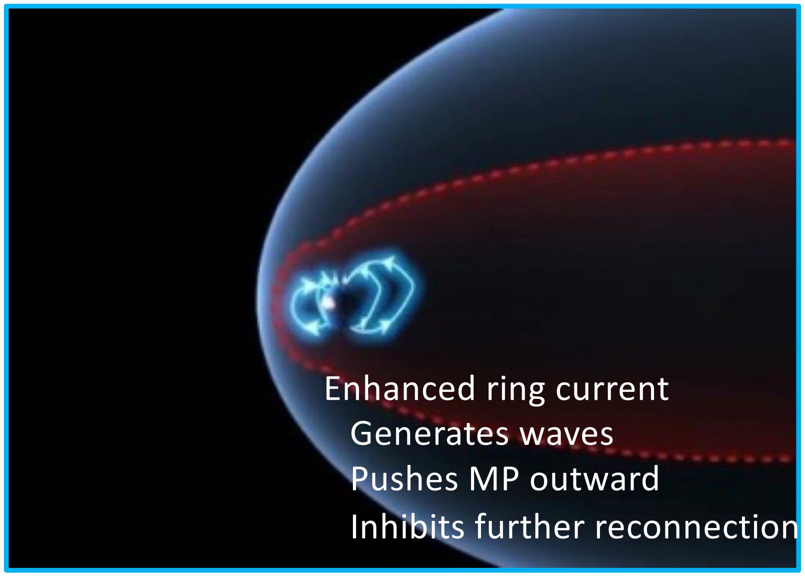
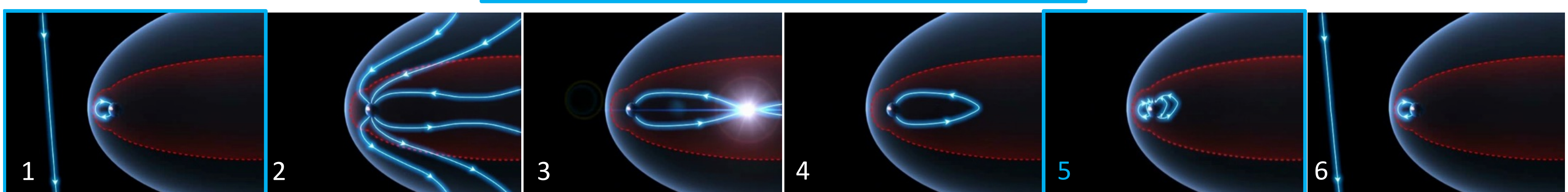
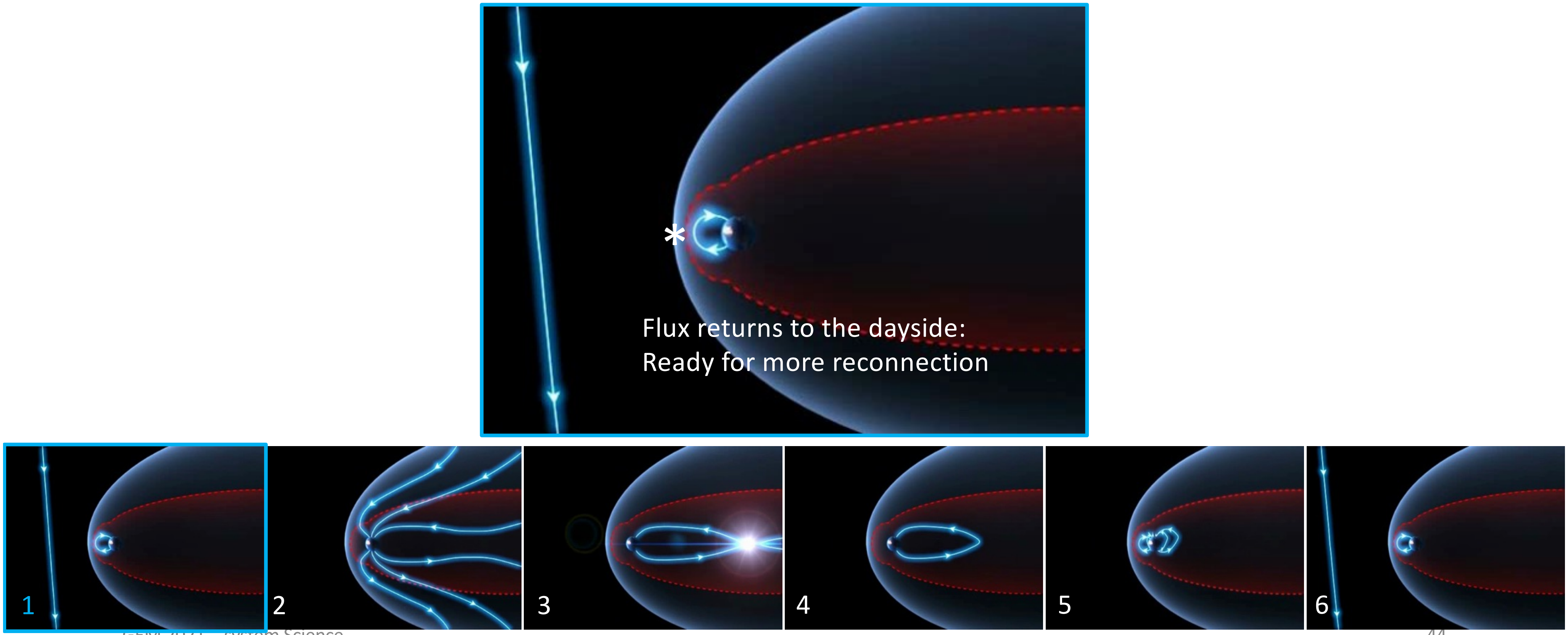
The Dungey Cycle

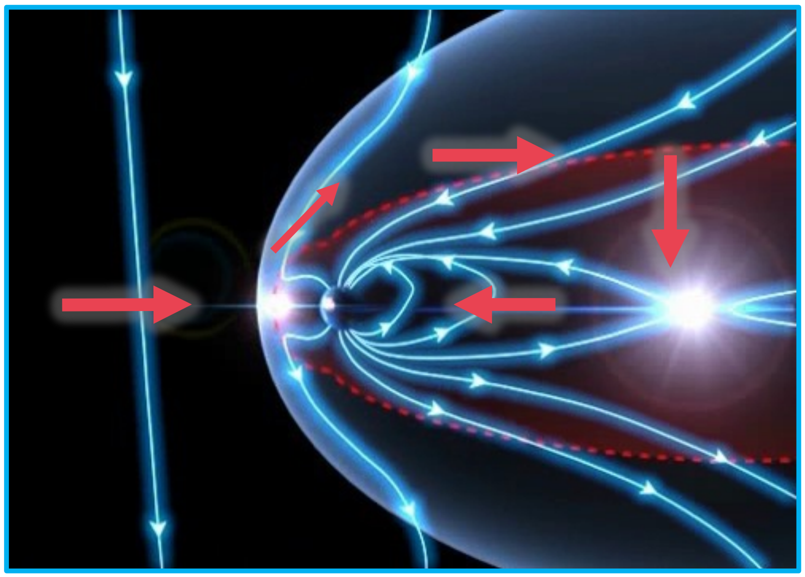




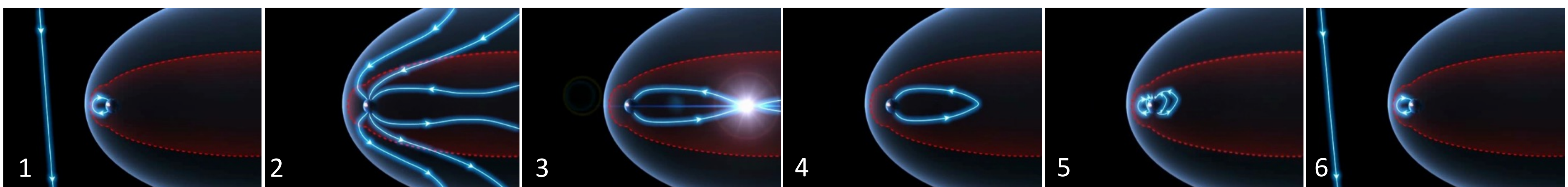
The Dungey Cycle



The Dungey Cycle



- Is a global process
- Driven by solar wind-magnetosphere coupling
- Transfers energy from the solar wind to the magnetosphere
- Circulates this energy throughout the magnetosphere
- Is responsible for nearly all the dynamics in the solar wind-magnetosphere system



Steady Dungey Cycle

- This movie shows steady, balanced,

  dayside and nightside reconnection.

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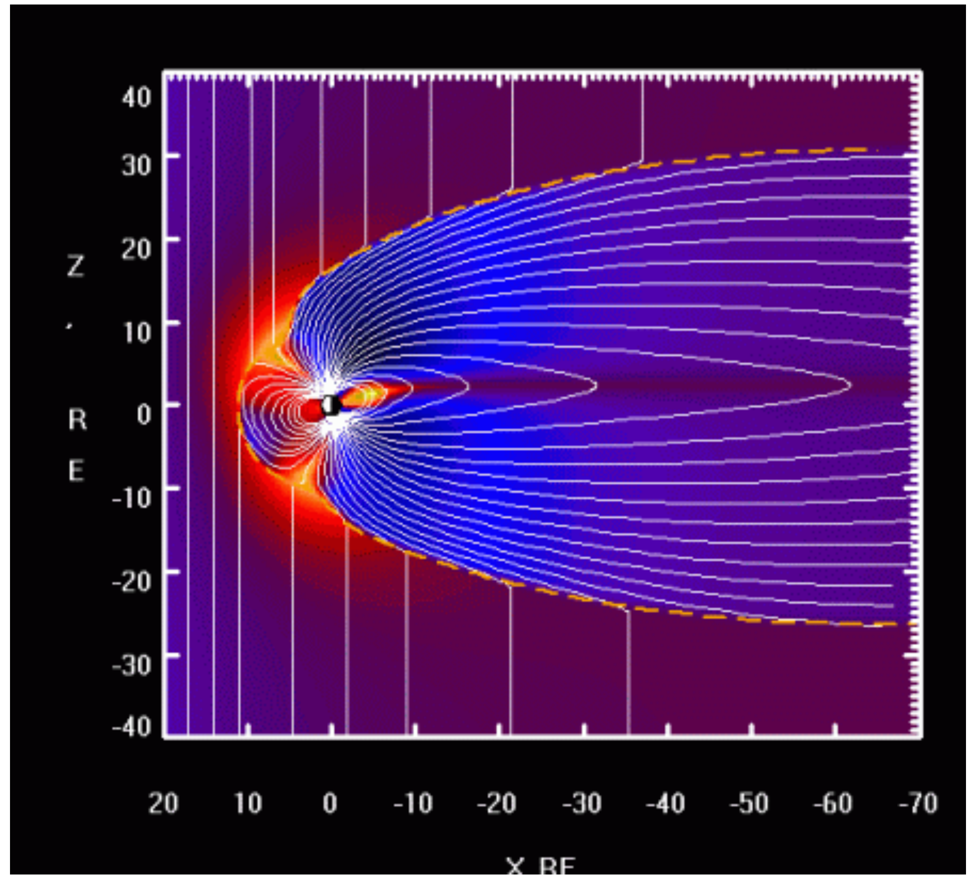

Steady Dungey Cycle

- This movie shows steady, balanced,
  dayside and nightside reconnection.

- **Reconnection is probably unsteady: solar wind variations and intrinsic instabilities**

https://sci.esa.int/web/cluster/-/36448-schematic-of-reconnection
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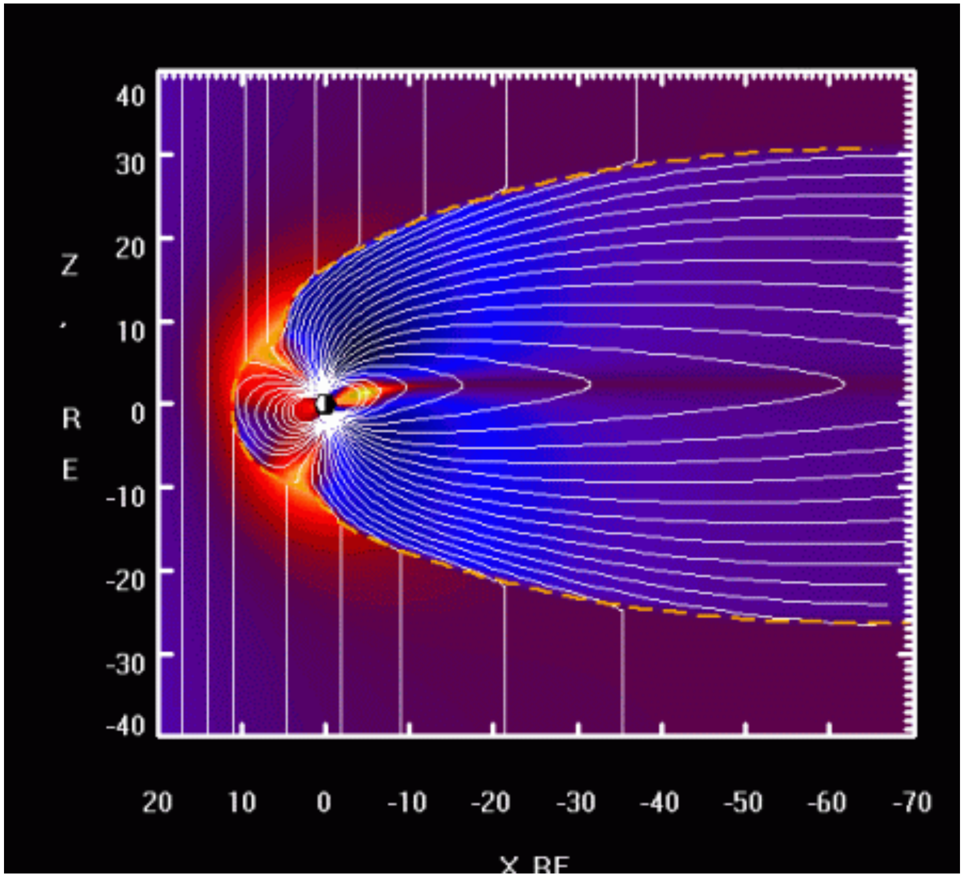
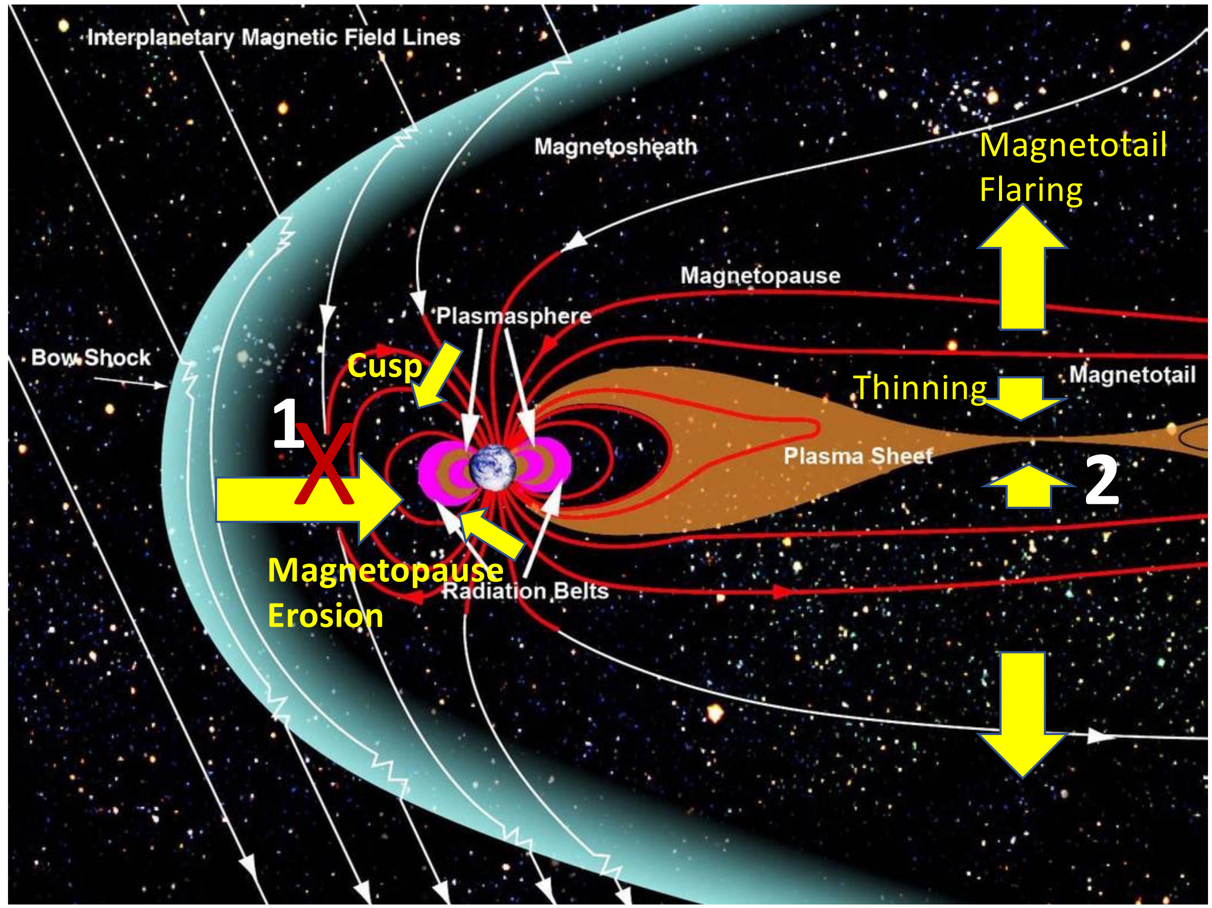


Unsteady Dungey Cycle

- Growth phase:
  - More dayside (1) than
  - nightside (2) reconnection

Magnetopause erodes
Cusps move equatorward
Magnetotail flares
Plasma sheet thins

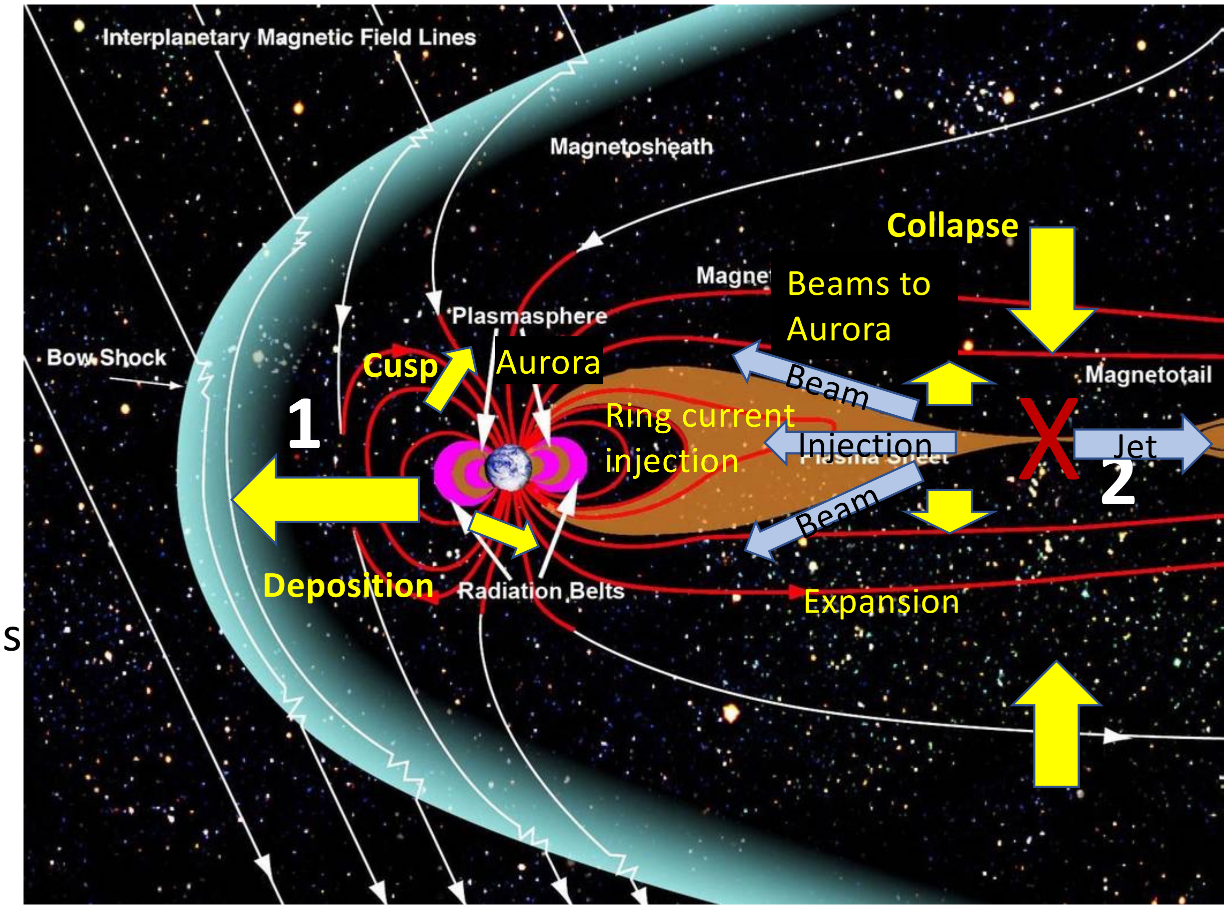


https://www.nasa.gov/mission_pages/sunearth/science/magnetosphere2.html

Unsteady Dungey Cycle

- Expansion phase:
  - More nightside (2) than
  - dayside (1) reconnection

Magnetotail collapses
Injection to ring current
Beams to nightside aurora
Cusps move poleward
Dayside magnetopause moves
outward



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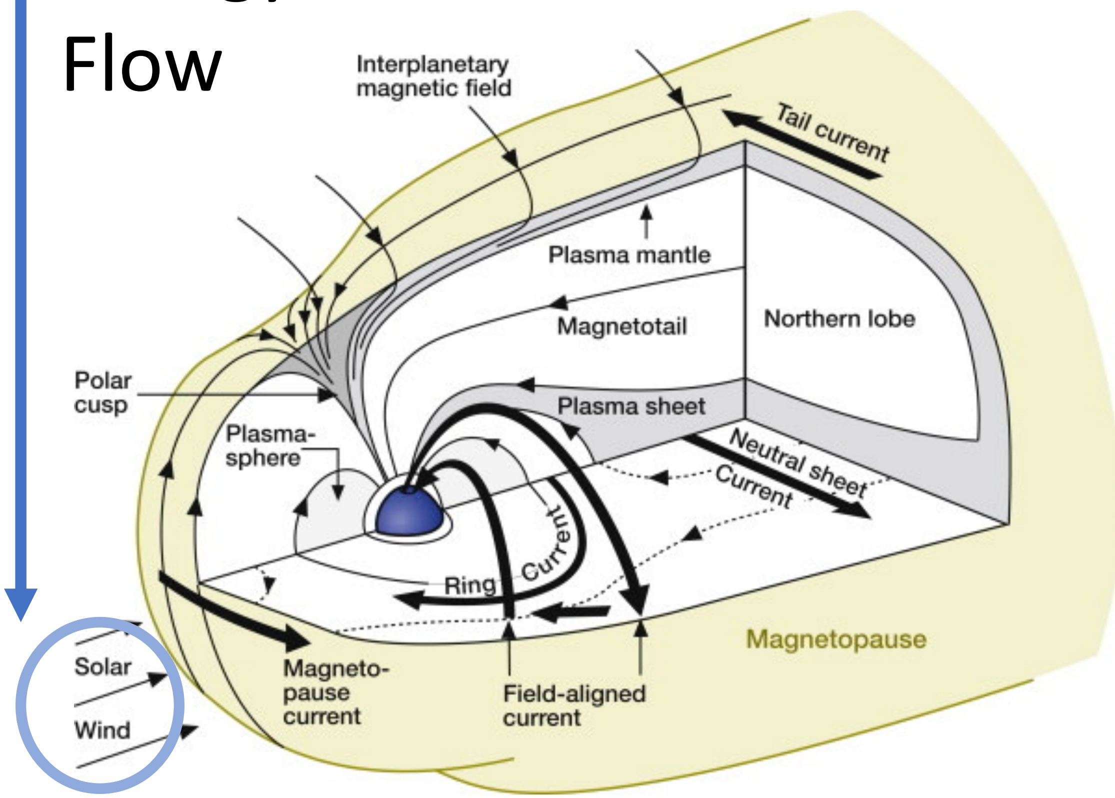
Dungey Cycle Step by Step

- Plasma regions
  - **Solar wind**
  - Bow Shock and Magnetosheath
  - Magnetosphere
    - Magnetopause
    - Cusps
    - Magnetotail lobes
    - Magnetotail plasma sheet
    - Ring current
    - Radiation Belts
    - Plasmasphere

Energy Flow



Dungey Cycle Step by Step

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  - **Bow Shock and Magnetosheath**
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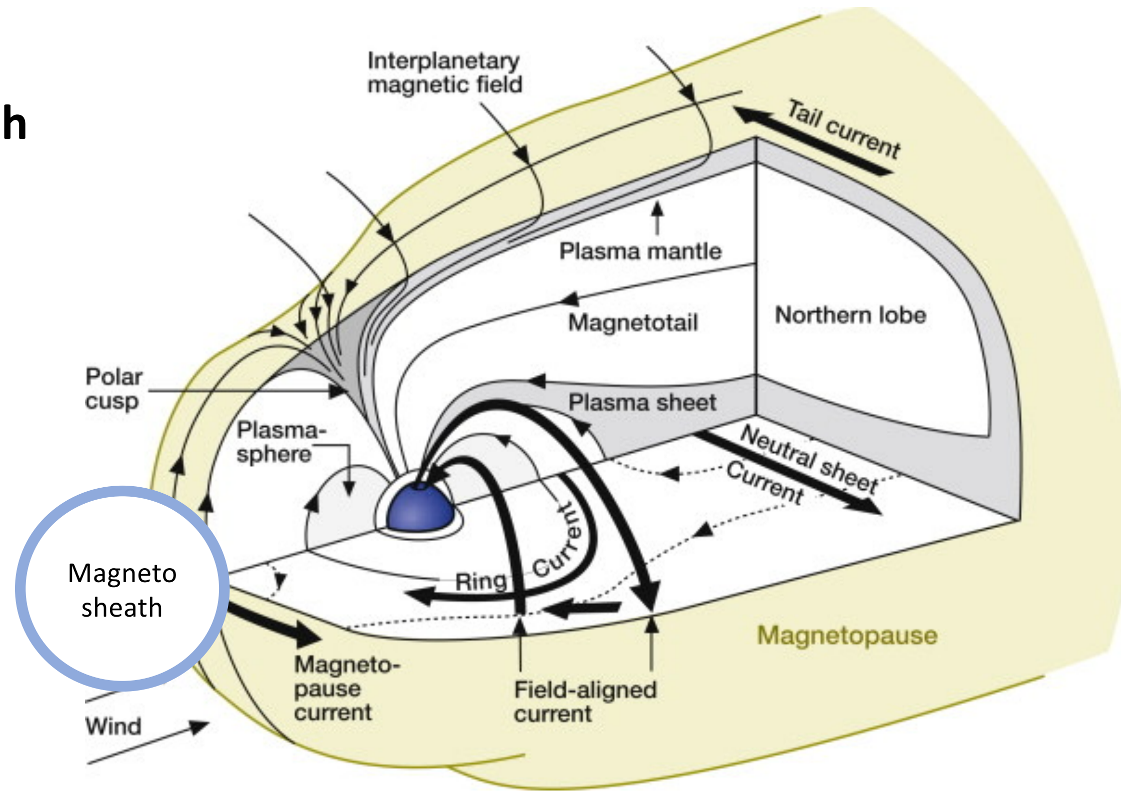

Dungey Cycle Step by Step

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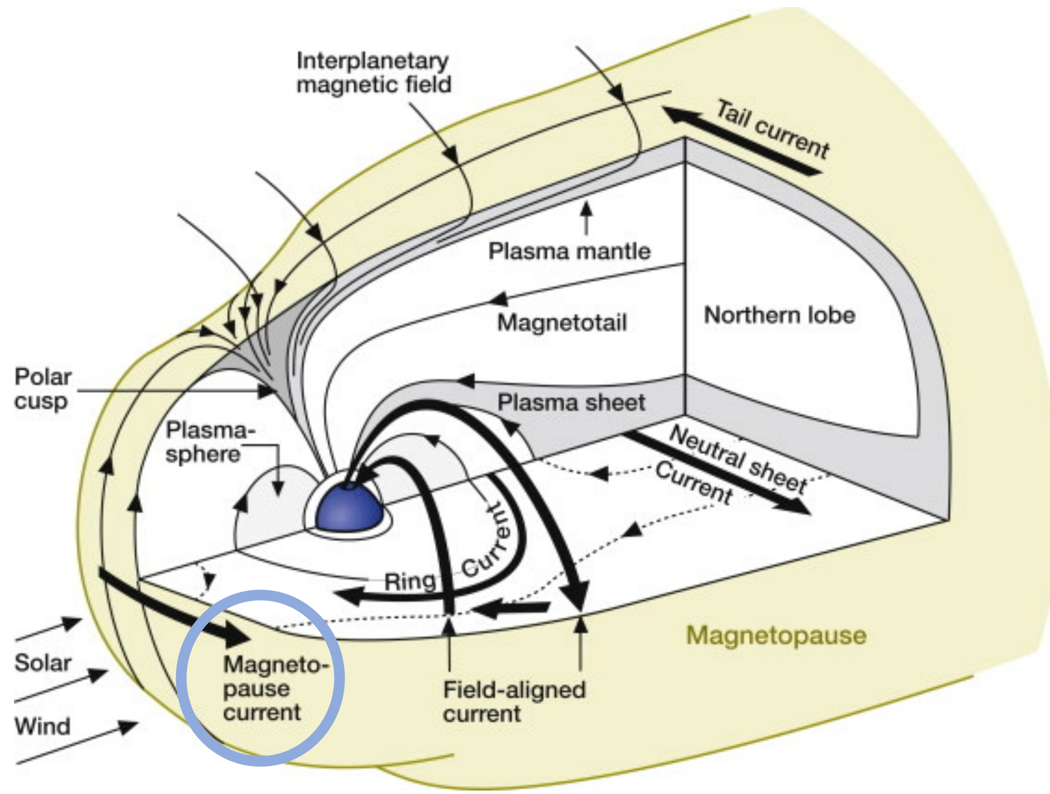

Dungey Cycle Step by Step

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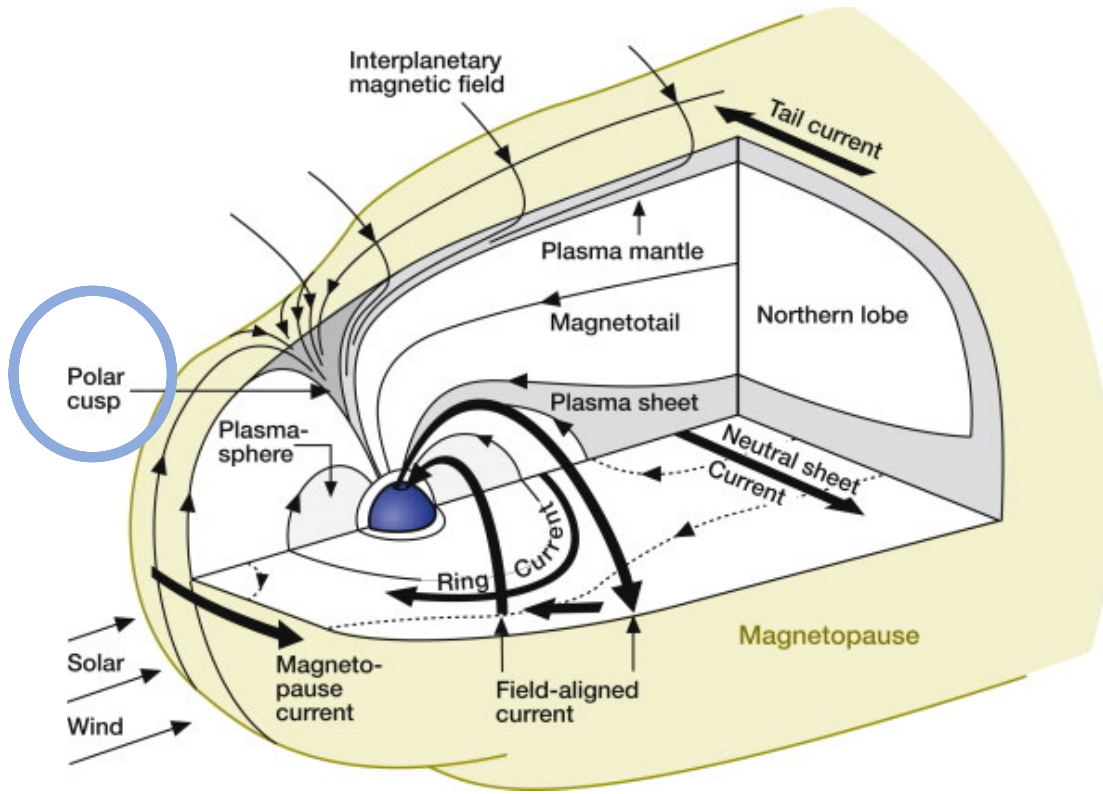

Dungey Cycle Step by Step

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    - Magnetotail Plasma sheet
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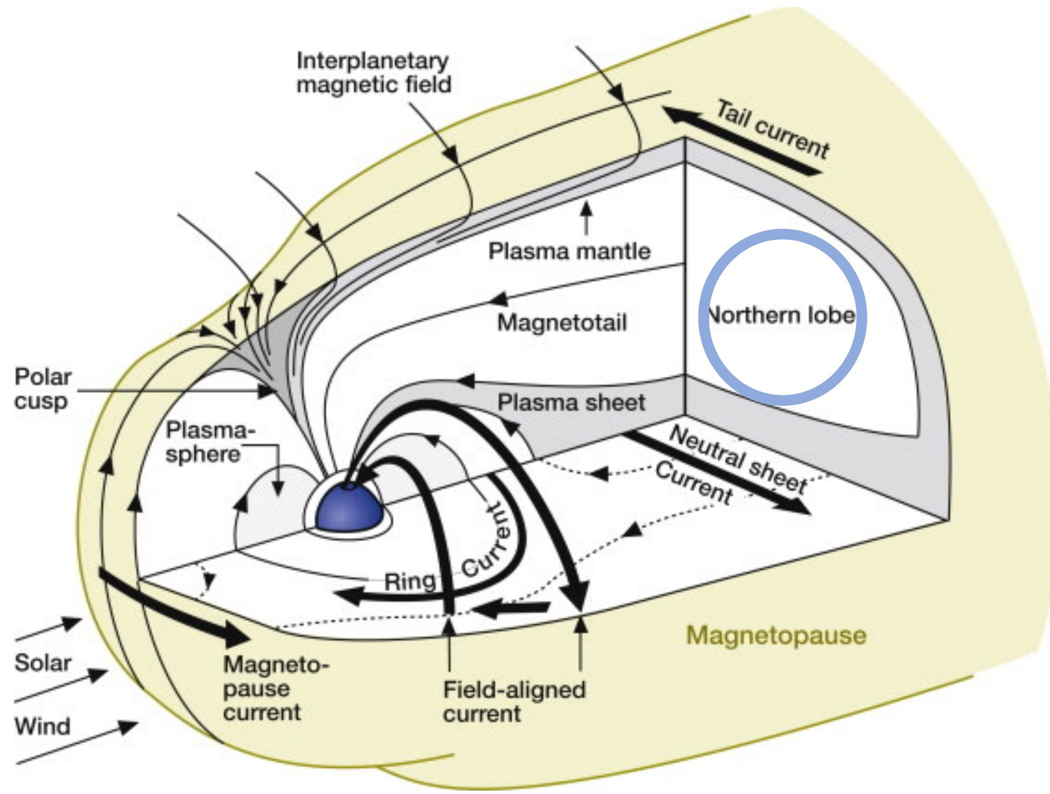

Dungey Cycle Step by Step

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  - Solar wind
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    - **Magnetotail Plasma sheet**
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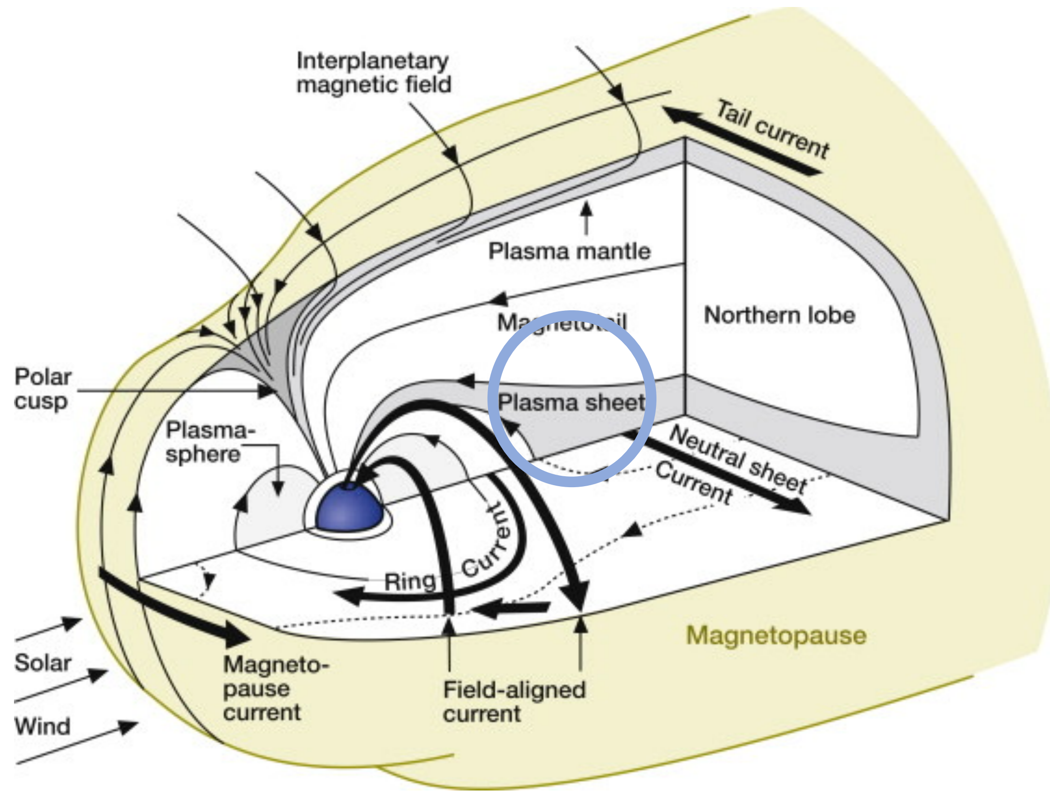

Dungey Cycle Step by Step

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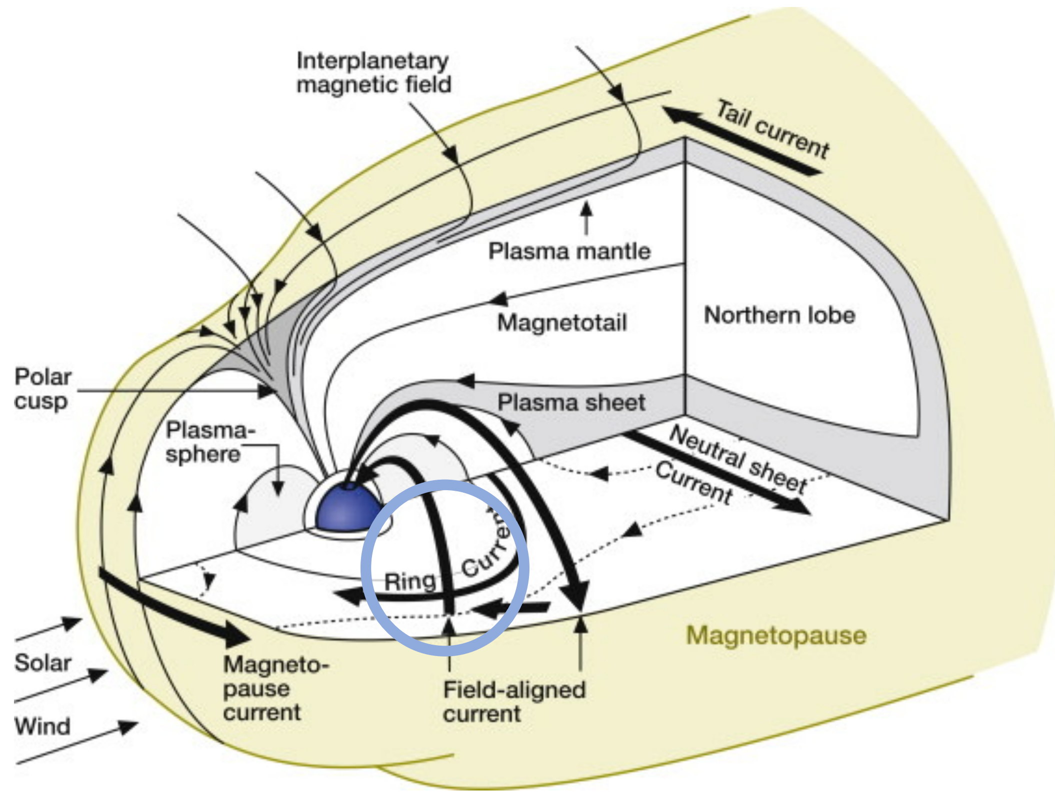

Dungey Cycle Step by Step

- Plasma regions
  - Solar wind
  - Bow Shock and Magnetosheath
  - Magnetosphere
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    - Magnetotail Plasma sheet
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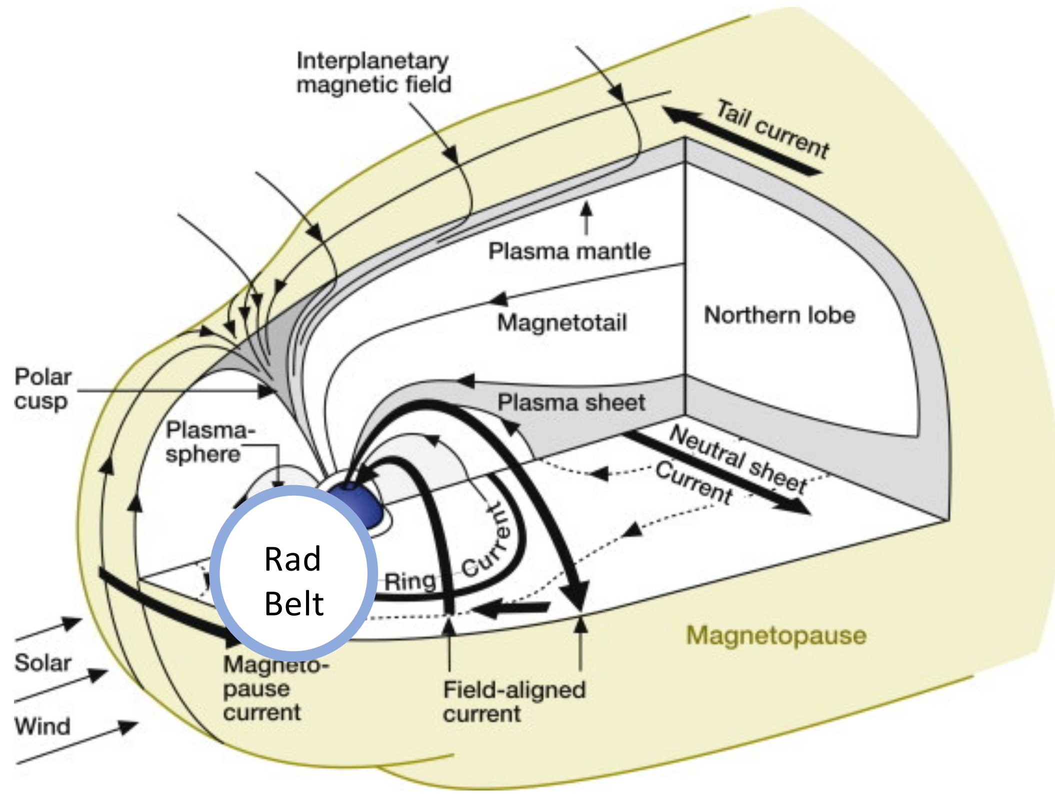
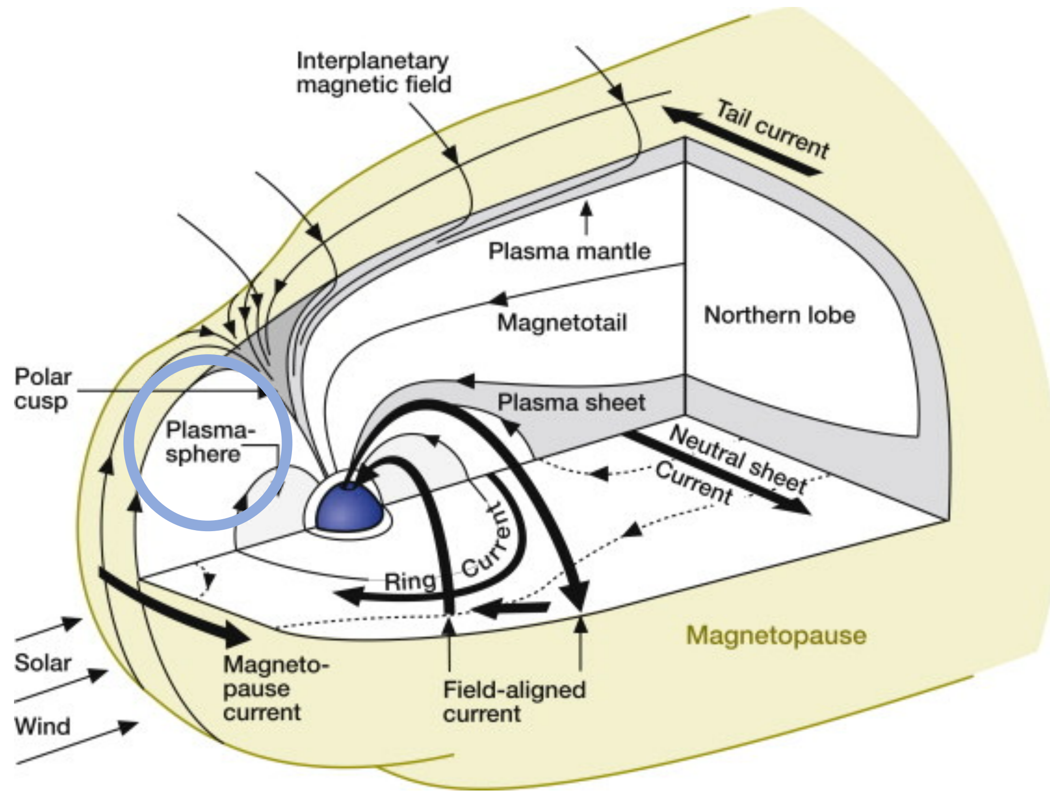
    - **Radiation Belts**
    - Plasmasphere



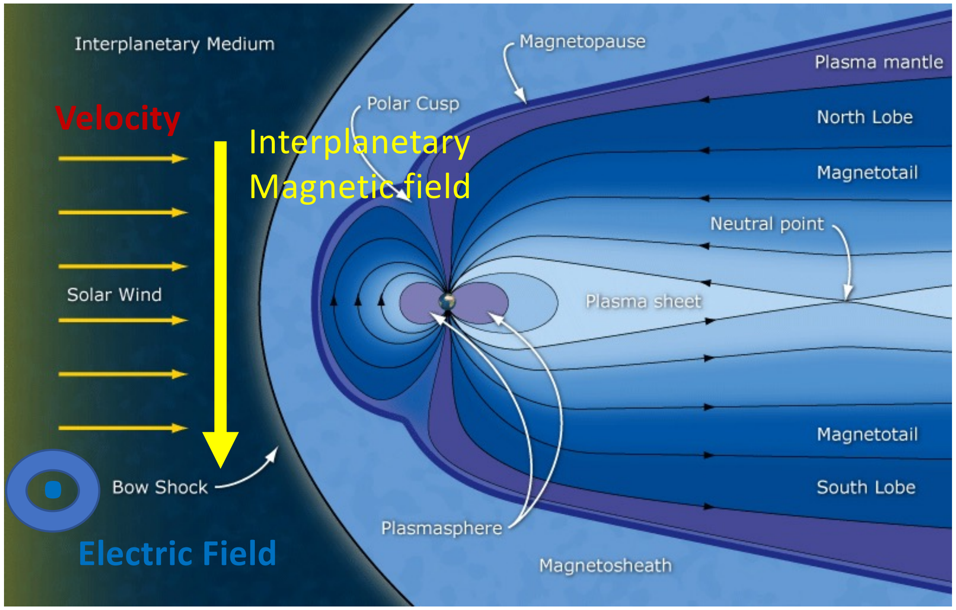
Dungey Cycle Step by Step

- Plasma regions
  - 1. Solar wind
  - 2. Bow Shock and Magnetosheath
  - Magnetosphere
    - 3. Magnetopause
    - 4. Cusps
    - 5. Magnetotail Lobes
    - 6. Magnetotail Plasma sheet
    - 7. Ring current
    - 8. Radiation Belts
    - **9. Plasmasphere**



Dungey Cycle: 1. Solar wind

- Task: Power the magnetosphere



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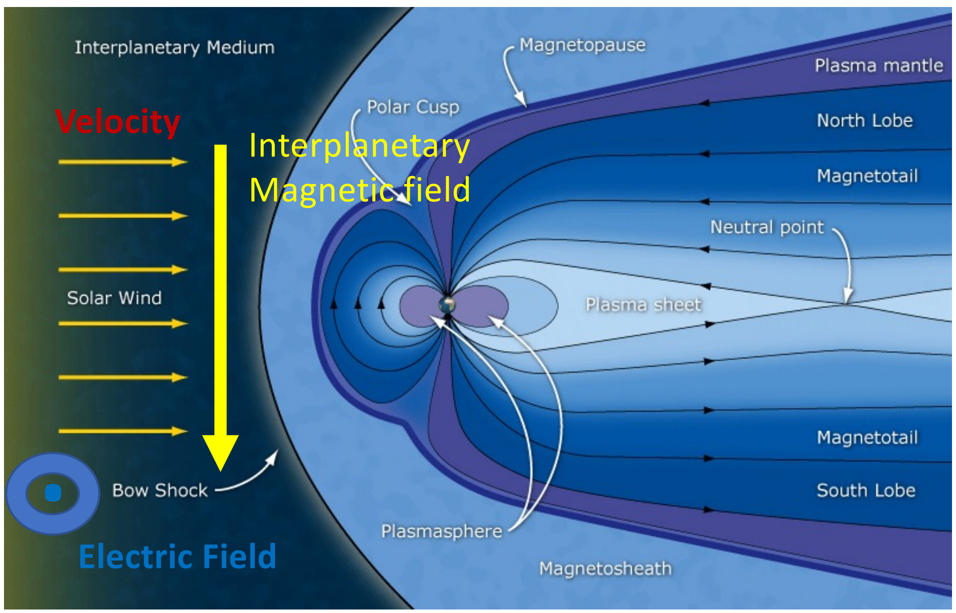
Dungey Cycle: 1. Solar wind

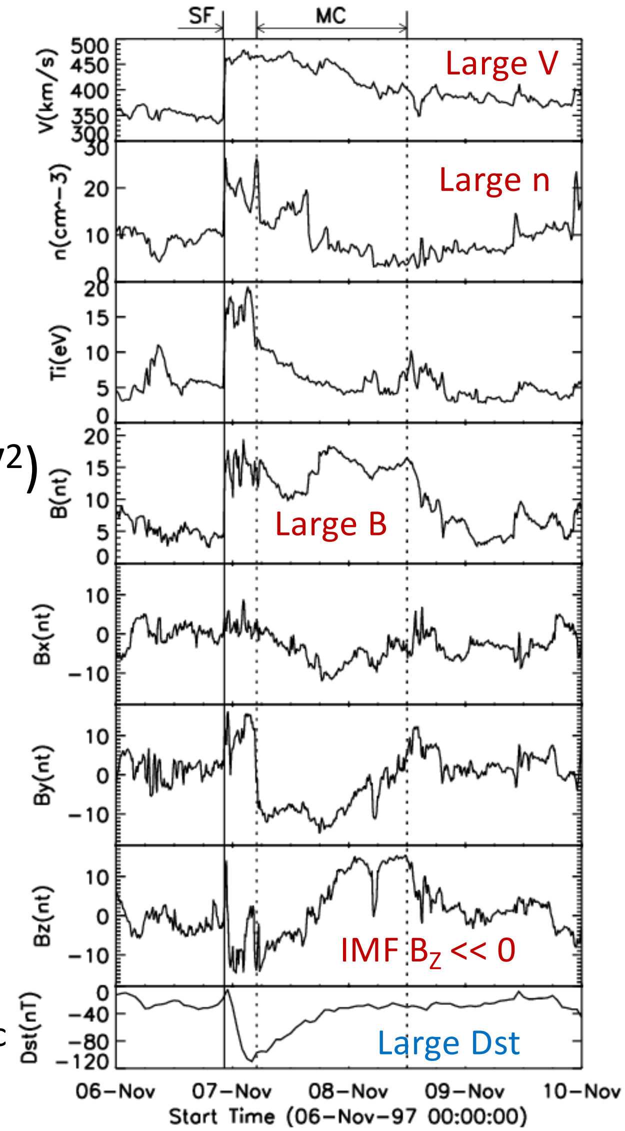
- Task: Power the magnetosphere
- Drivers: IMF B_Z and solar wind dynamic pressure (nMV^2)

Strong Solar Wind Input

Drives Geomagnetic Storms (Dst)

This figure was made by me





Dungey Cycle: 1. Solar wind

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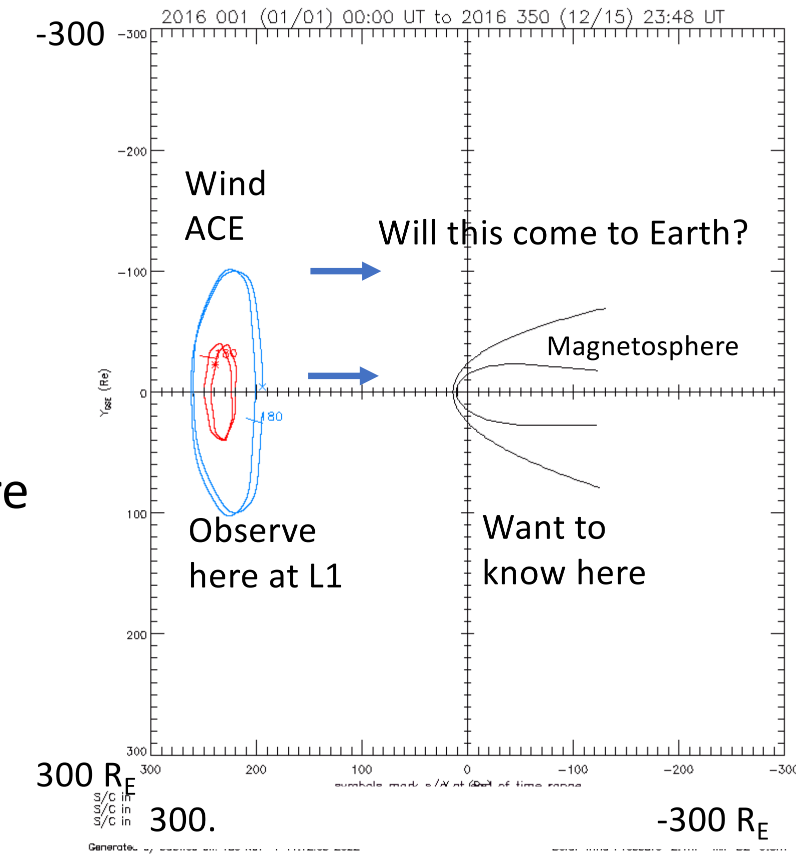

- Task: Power the magnetosphere

- Drivers: IMF B_Z and solar wind dynamic pressure

- Questions
  - When are strong drivers most likely (large nMV^2, $B_Z << 0$)?
  - How well do L1 monitors predict features that arrive at Earth?

Dungey Cycle: 2. Bow Shock and Magnetosheath

- Task: Deflect/energize some incident solar wind ions

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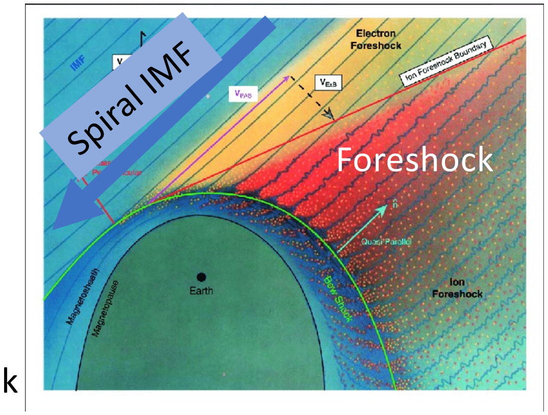

Kinetic effects in the foreshock

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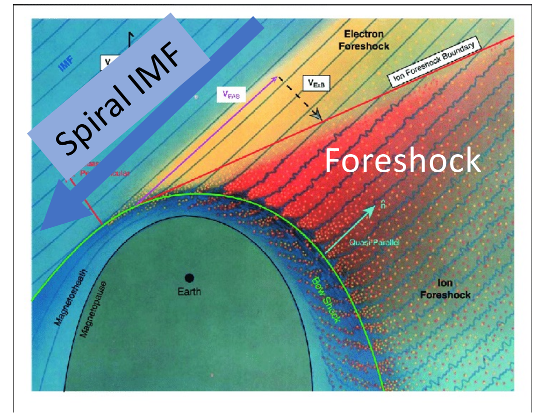
Dungey Cycle: 2. Bow Shock and Magnetosheath



- Task: Deflect/energize some incident solar wind ions

Kinetic effects in the foreshock

- Slow, heat, and deflect solar wind flow
- Outer boundary condition for magnetosphere

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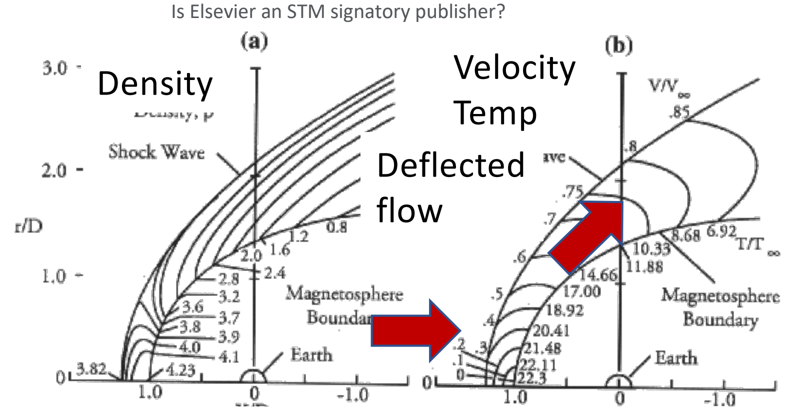

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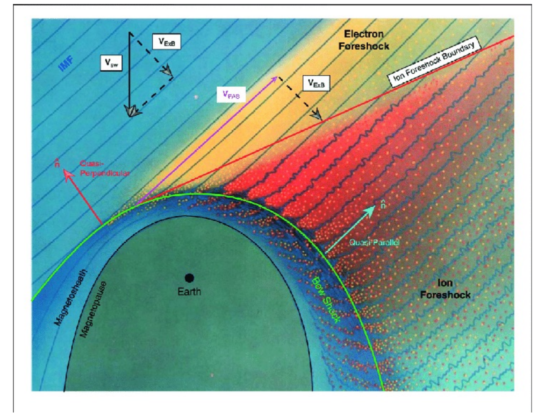
Dungey Cycle: 2. Bow Shock and Magnetosheath



- Task: Deflect/energize some incident solar wind ions

Kinetic effects
in the foreshock

- Slow, heat, and deflect solar wind flow
- Outer boundary condition for magnetosphere

Spreiter et al. [1966] gasdynamic model

Spreiter et al. [1966] gasdynamic model
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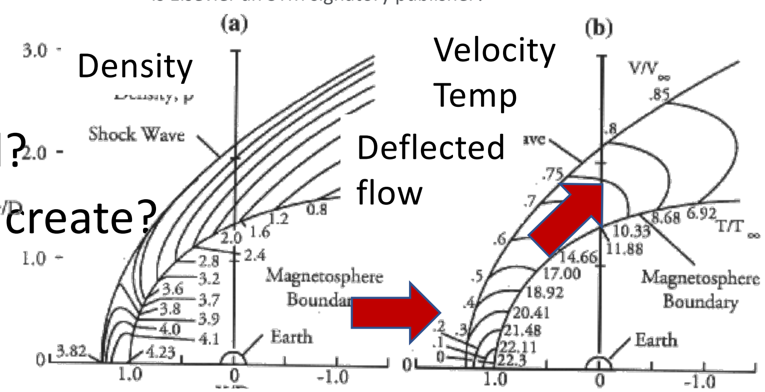
- Questions
  - How does the bow shock energize particles?
  - How does the bow shock process the solar wind?
  - What waves and transients does the bow shock create?



Roelof and Sibeck [1994]
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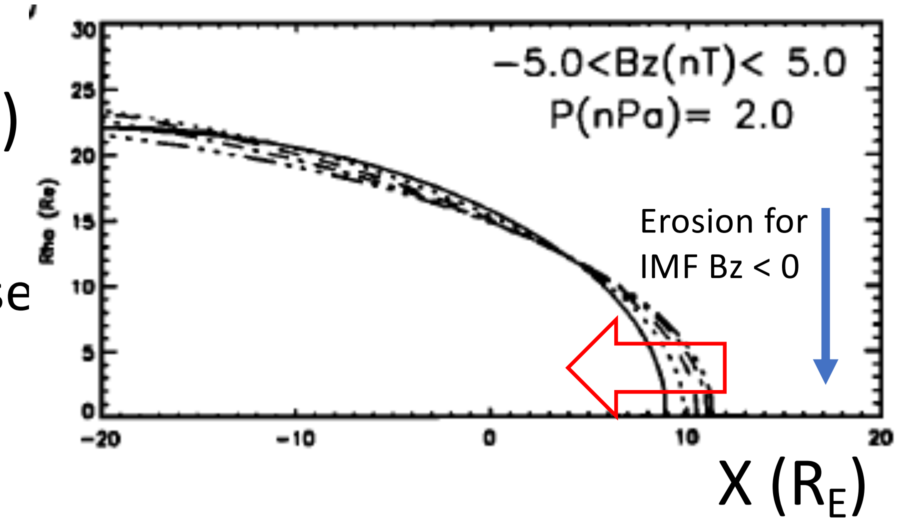
Dungey Cycle: 3. Magnetopause

Magnetopause Erosion for Southward IMF provides evidence for reconnection

- Task: Regulate energy entry
- Reconnection erodes the magnetopause

R (R_E)



Roelof and Sibeck [1994]
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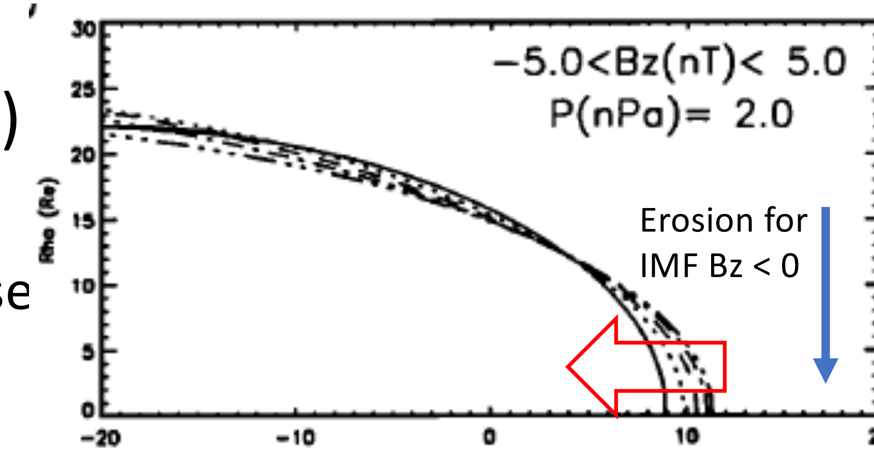
Dungey Cycle: 3. Magnetopause

Magnetopause Erosion for Southward IMF provides evidence for reconnection

- Task: Regulate energy entry
- Reconnection erodes the magnetopause
  - Over extended regions or in patches?
  - Steadily or in bursts?
  - Because of intrinsic instabilities or solar wind triggers?

R (R_E)



X (R_E)

What is the extent of the reconnection line?
Phan et al. [2000]

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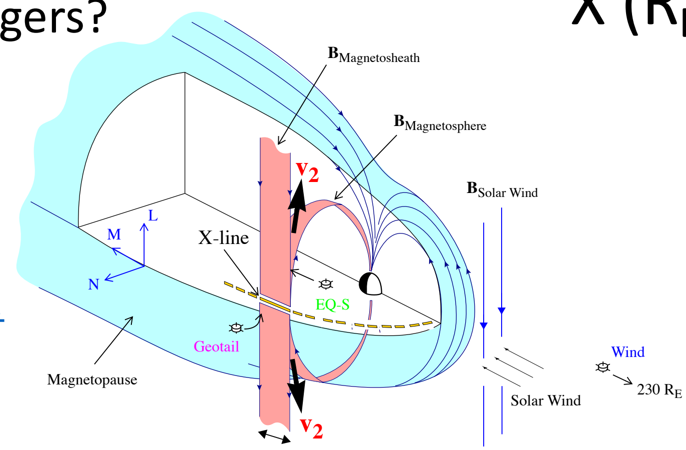


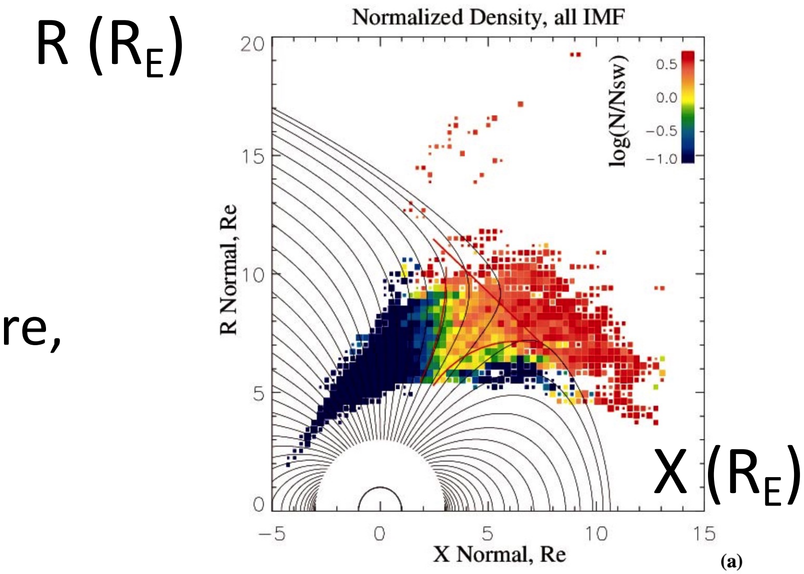
Dungey Cycle: 4. Cusps

- Task: Funnel particles, electric currents,
  waves down to the Earth's atmosphere,
  enhance ionospheric conductivities

- Questions
  - How do cusp properties depend on solar wind conditions?

.

Cluster
Lavraud et al. [2005]



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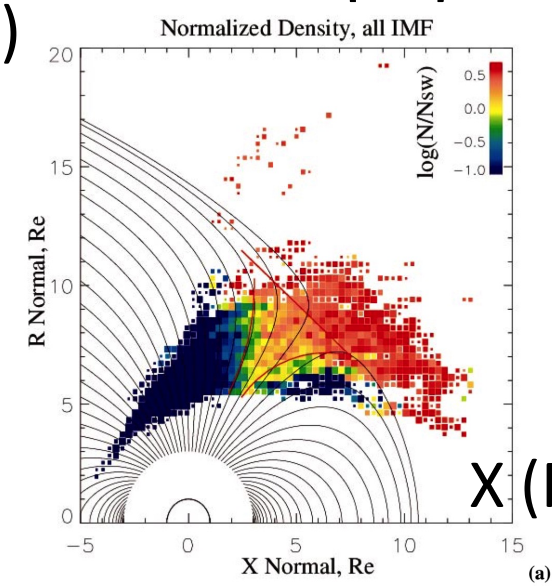
Dungey Cycle: 4. Cusps

- Task: Funnel particles, electric currents,
  waves down to the Earth's atmosphere,
  enhance ionospheric conductivities

- Questions
  - How do cusp properties depend on solar wind conditions?
  - What can we learn about reconnection from cusp observations?

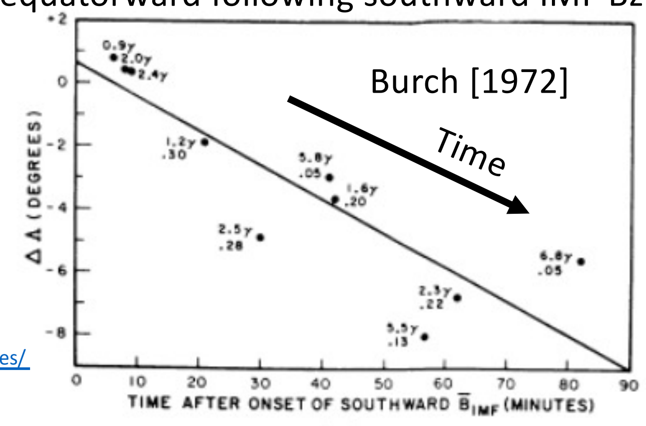
Cluster
Lavraud et al. [2005]

R (R_E)



Cusp moves equatorward following southward IMF Bz

Latitude



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Dungey Cycle: 5. Lobes

- Task: Capture solar wind energy for later release at substorm onset

Eastwood et al. (2015)

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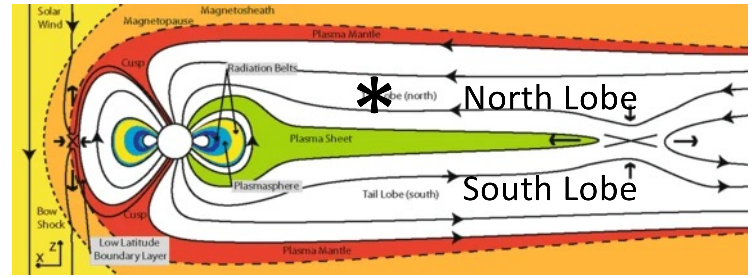
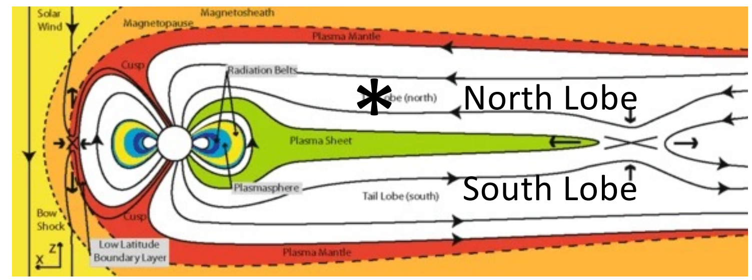


Dungey Cycle: 5. Lobes

- Task: Capture solar wind energy for later release at substorm onset

Eastwood et al. (2015)

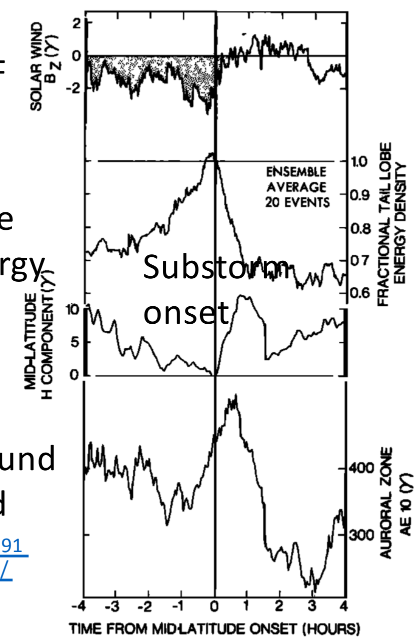
https://s100.copyright.com/AppDispatchServlet?title=What%20Controls%20the%20Structure%20and%20Dynamics%20of%20Earth%E2%80%99s%20Magnetosphere%3F&author=J.%20P.%20Eastwood%20et%20al&contentID=10.1007%2Fs11214-014-0050-x&copyright=The%20Author%28s%29&publication=0038-6308&publicationDate=2014-06-14&publisherName=SpringerNature&orderBeanReset=true&oa=CC%20BY



IMF B_Z

Lobe energy

Ground field



Magnetotail magnetic field strength grows following southward IMF turning, decays after substorm onset

Caan et al. [1975]

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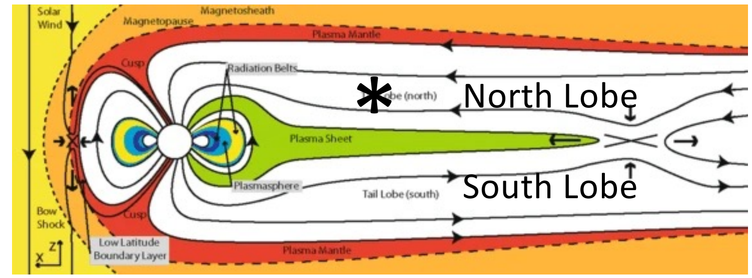
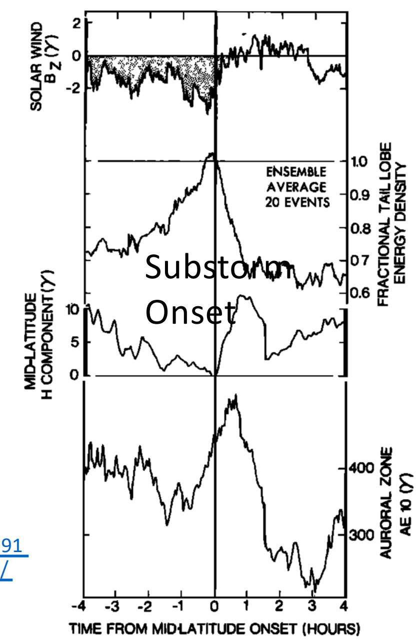
Dungey Cycle: 5. Lobes

- Task: Capture solar wind energy for later release at substorm onset
- Questions:
  - Do the lobes ever close for strongly northward IMF?
  - How much flux is needed to initiate substorm onset?
  - How far downstream do the lobes extend?

Eastwood et al. (2015)

https://s100.copyright.com/AppDispatchServlet?title=What%20Controls%20the%20Structure%20and%20Dynamics%20of%20Earth%E2%80%99s%20Magnetosphere%3F&author=J.%20P.%20Eastwood%20et%20al&contentID=10.1007%2Fs11214-014-0050-x&copyright=The%20Author%28s%29&publication=0038-6308&publicationDate=2014-06-14&publisherName=SpringerNature&orderBeanReset=true&oa=CC%20BY





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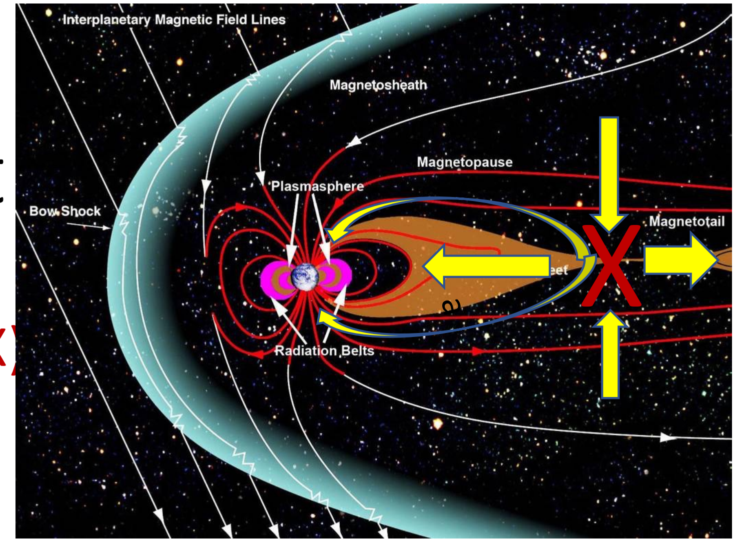
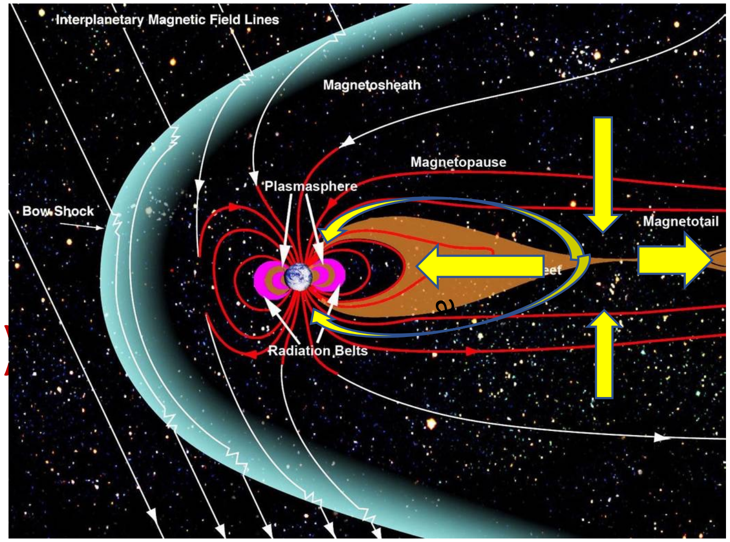
Dungey Cycle: 6. Plasma Sheet



https://www.nasa.gov/mission_pages/sunearth/science/magnetosphere2.html

- Tasks: (1) Release lobe energy via reconnection (X)
  (2) Channel it sunward to the ring current
  (3) Channel it sunward to the auroral oval
  (4) Channel it antisunward

Dungey Cycle: 6. Plasma Sheet



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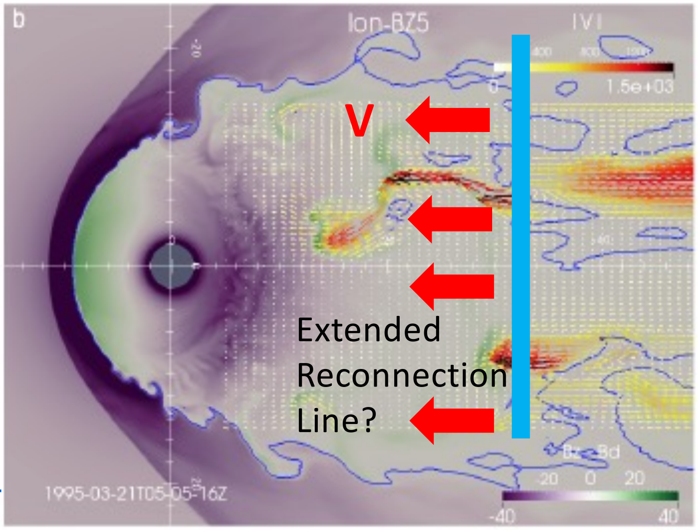
  (3) Channel it sunward to the auroral oval
  (4) Channel it antisunward

- Questions:
  - Is the release global?

Equatorial Magnetosphere



Wiltberger et al. [2015]

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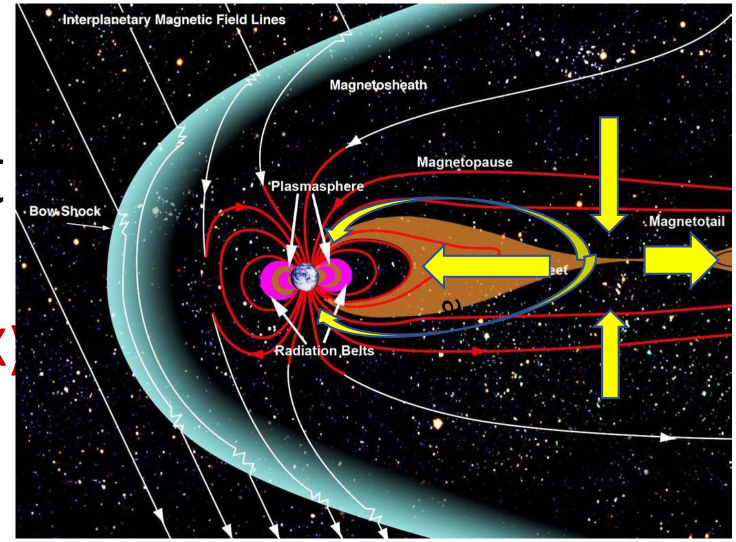
Dungey Cycle: 6. Plasma Sheet



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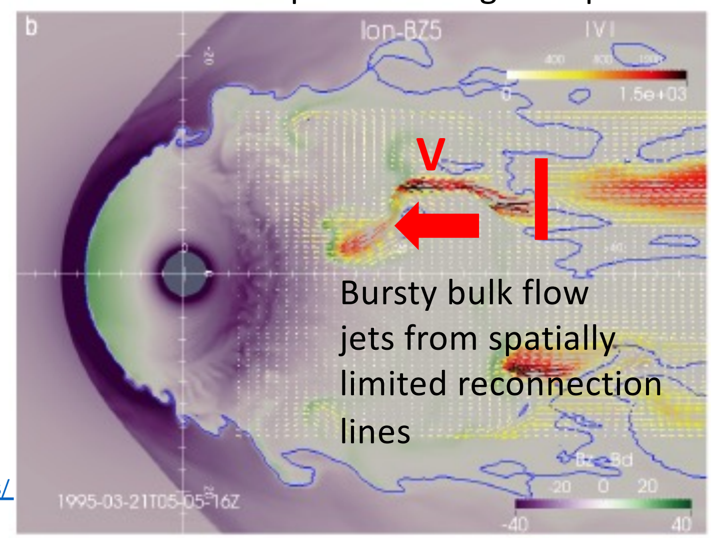
Equatorial Magnetosphere



- Questions:
  - Is the release global or local?
  - Steady or in bursts?

Wiltberger et al. [2015]

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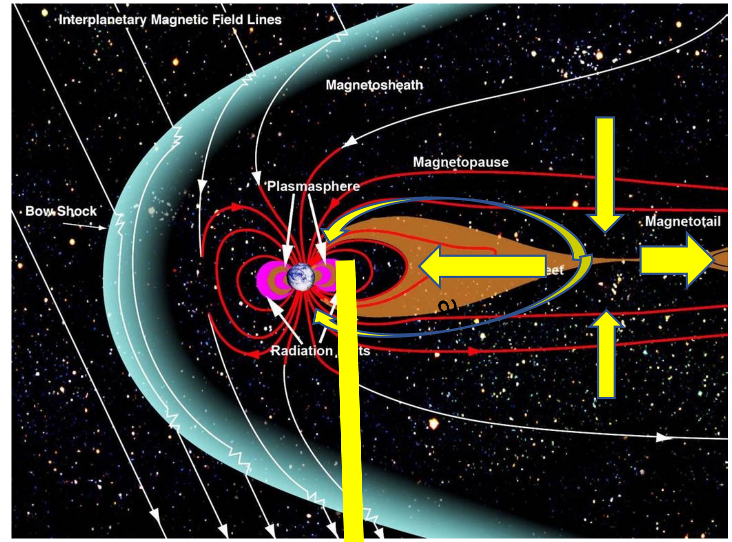
Dungey Cycle: 6. Plasma Sheet



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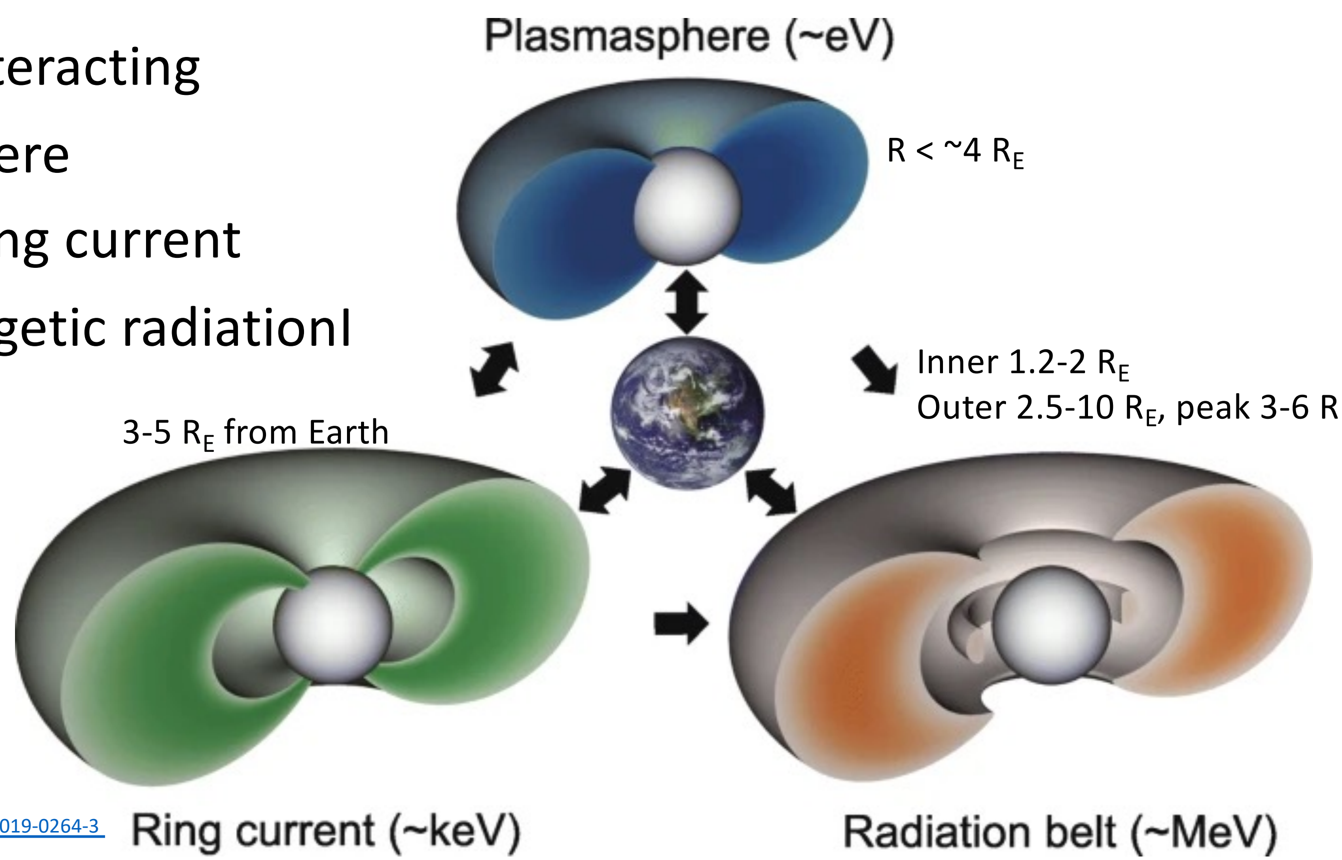
- Questions:
  - Is the release global or local?
  - Steady or in bursts?

Nightside Aurora

Spectacular aurora

Dungey Cycle: 7, 8, 9. The Inner Magnetosphere

- Nested regions of interacting
  cold plasmasphere
  suprathermal ring current
  and highly energetic radiationl
  belt plasmas



Ebihara
[2019]

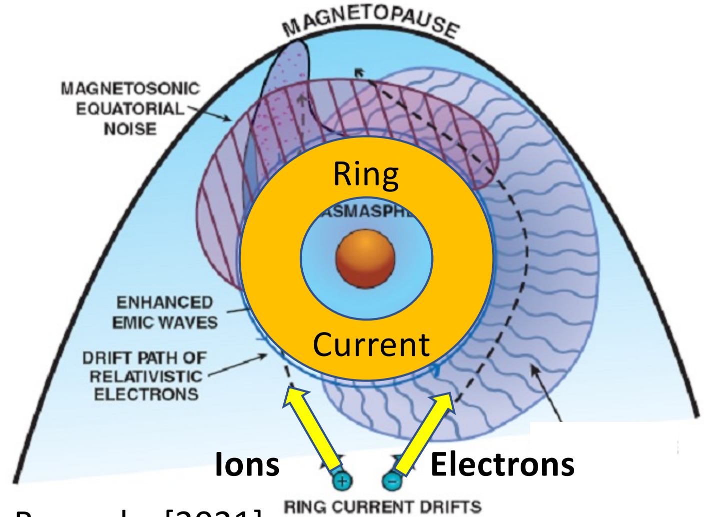
https://progearthplanetsci.springeropen.com/articles/10.1186/s40645-019-0264-3
https://www.springeropen.com/

Dungey Cycle: 7. Ring current

- Store energy that powers geomagnetic storms

- Injected electrons drift eastward,

  ions eastward



Borovsky [2021]

https://www.frontiersin.org/articles/10.3389/fspas.2021.780321/full
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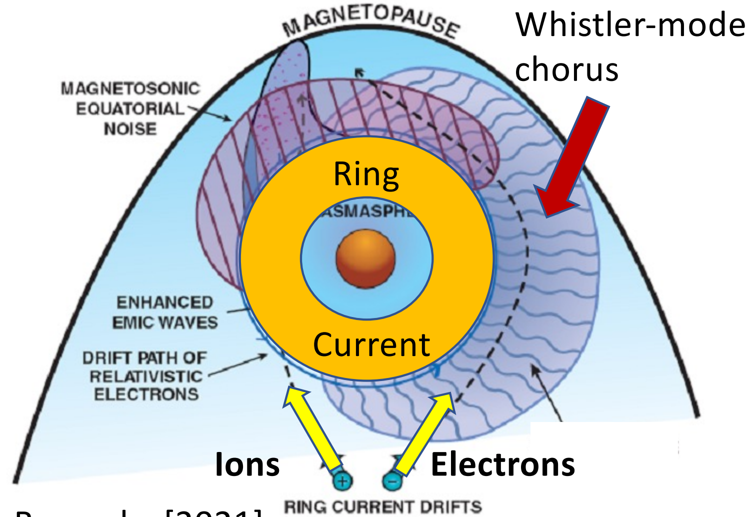
Dungey Cycle: 7. Ring current



Borovsky [2021]

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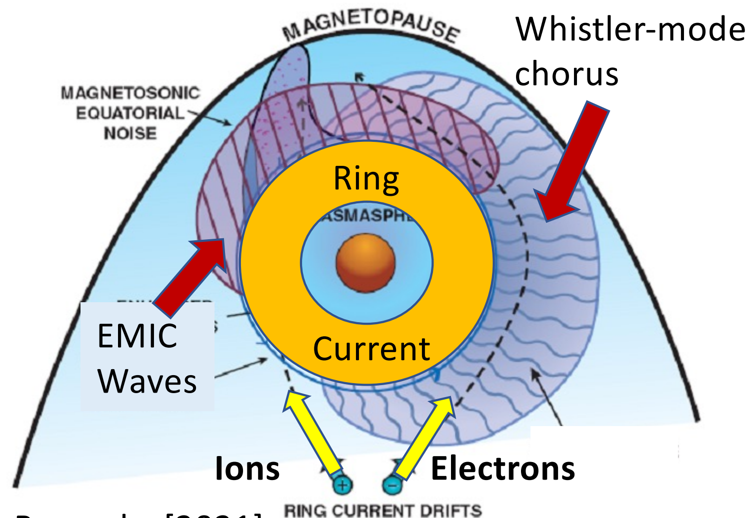
- Store energy that powers geomagnetic storm

- Injected electrons drift eastward,

    ions eastward

- Unstable electron distributions generate chorus waves that energize radiation belt electrons

Dungey Cycle: 7. Ring current



Borovsky [2021]

https://www.frontiersin.org/articles/10.3389/fspas.2021.780321/full
https://www.frontiersin.org/guidelines/policies-and-publication-ethics

- Store energy that powers geomagnetic storm

- Injected electrons drift eastward,

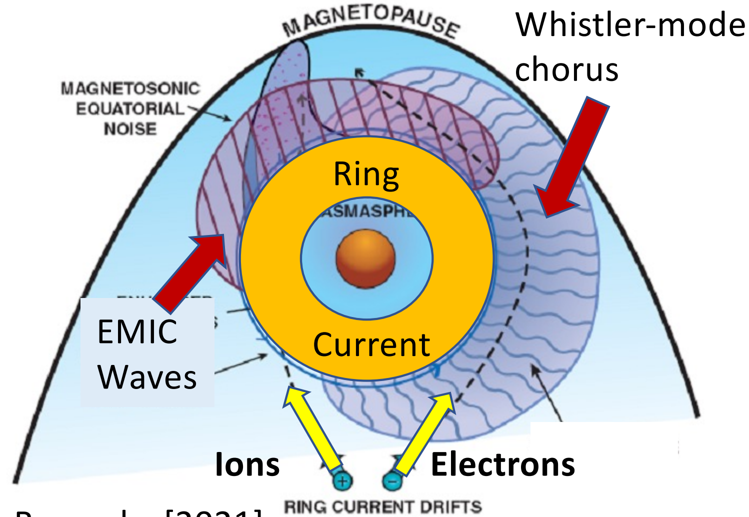
  ions westward

- Unstable electron distributions generate chorus waves that energize radiation belt electrons
- Unstable ion distributions generate EMIC waves that scatter and remove radiation belt electrons

Dungey Cycle: 7. Ring current

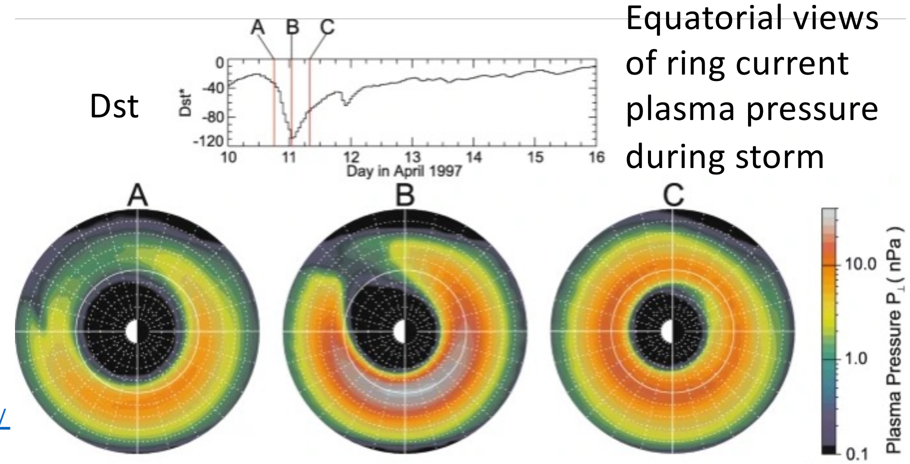
- Store energy that powers geomagnetic storms

- Questions:
  - What source dominates enhancements?
    - Steady, bursty, local, global tail reconnection?
  - What loss mechanisms dominates losses?
    - Precipitation, magnetopause outflow, charge exchange?



Borovsky [2021]

Phases:
A. Initial
B. Main
C. Recovery

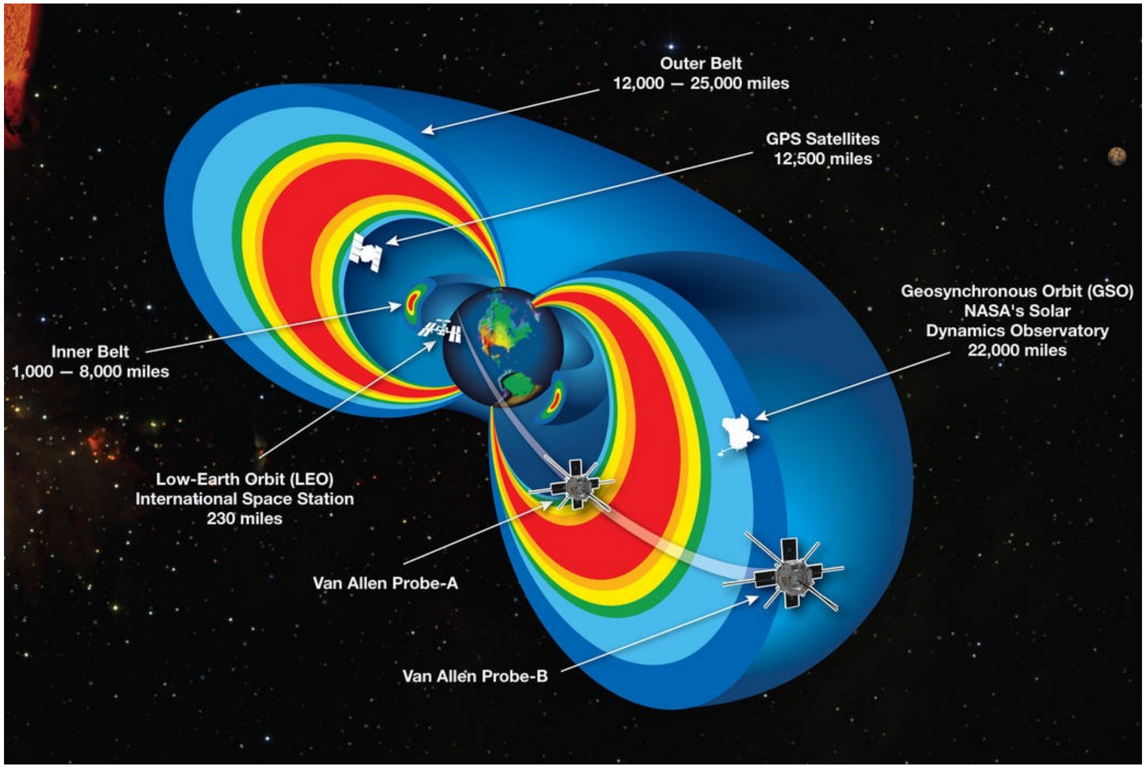


Equatorial views of ring current plasma pressure during storm

Ebihara & Ejiri (2000)
https://www.agu.org/Publish-with-AGU/Publish/Author-Resources/Policies/Permission-policy#:~:text=AGU%20grants%20permiss

Dungey Cycle: 8. Radiation Belts

- Task: Inner and Outer Radiation belts pose a hazard to spacecraft



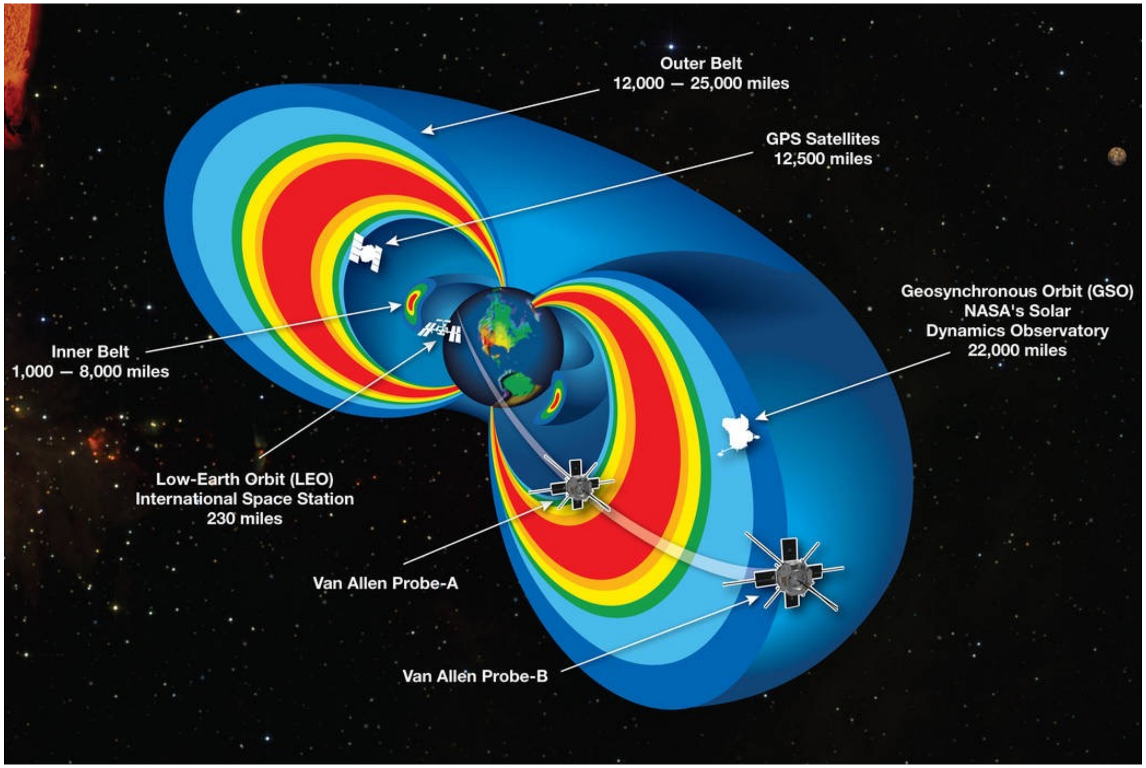
https://www.nasa.gov/mission_pages/sunearth/news/gallery/20130228-radiationbelts.html

Dungey Cycle: 8. Radiation Belts

- Task: Inner and Outer Radiation belts pose a hazard to spacecraft

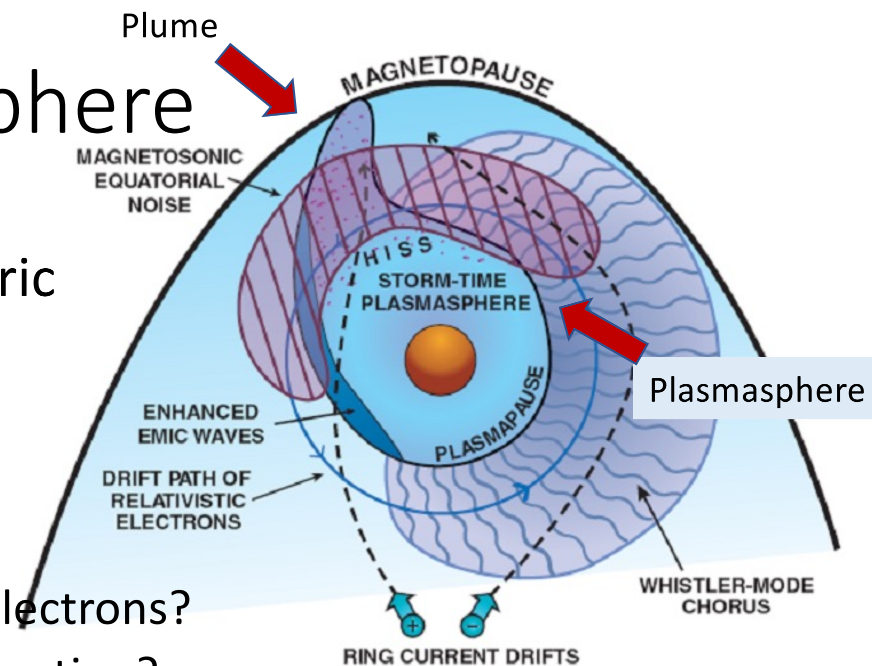
- Questions:
- 1. Energization processes
  - ULF waves?
  - Chorus waves
- 2. Loss processes
  - Magnetopause outflow
  - Precipitation (Hiss, EMIC)

https://www.nasa.gov/mission_pages/sunearth/news/gallery/20130228-radiationbelts.html



Dungey Cycle: 9. Plasmasphere

- Task: Reservoir of cold dense ionospheric plasma



- Questions:
  - Do plumes + EMIC remove radiation belt electrons?
  - Do plumes regulate magnetopause reconnection?

Summary

- Reasons to study magnetosphere
  - Basic physics
  - Practical applications → Space Weather
- End-to-end Dungey cycle
  - The flow of energy through the magnetosphere
  - Steady or unsteady?
  - Drives geomagnetic storms, substorms, aurora