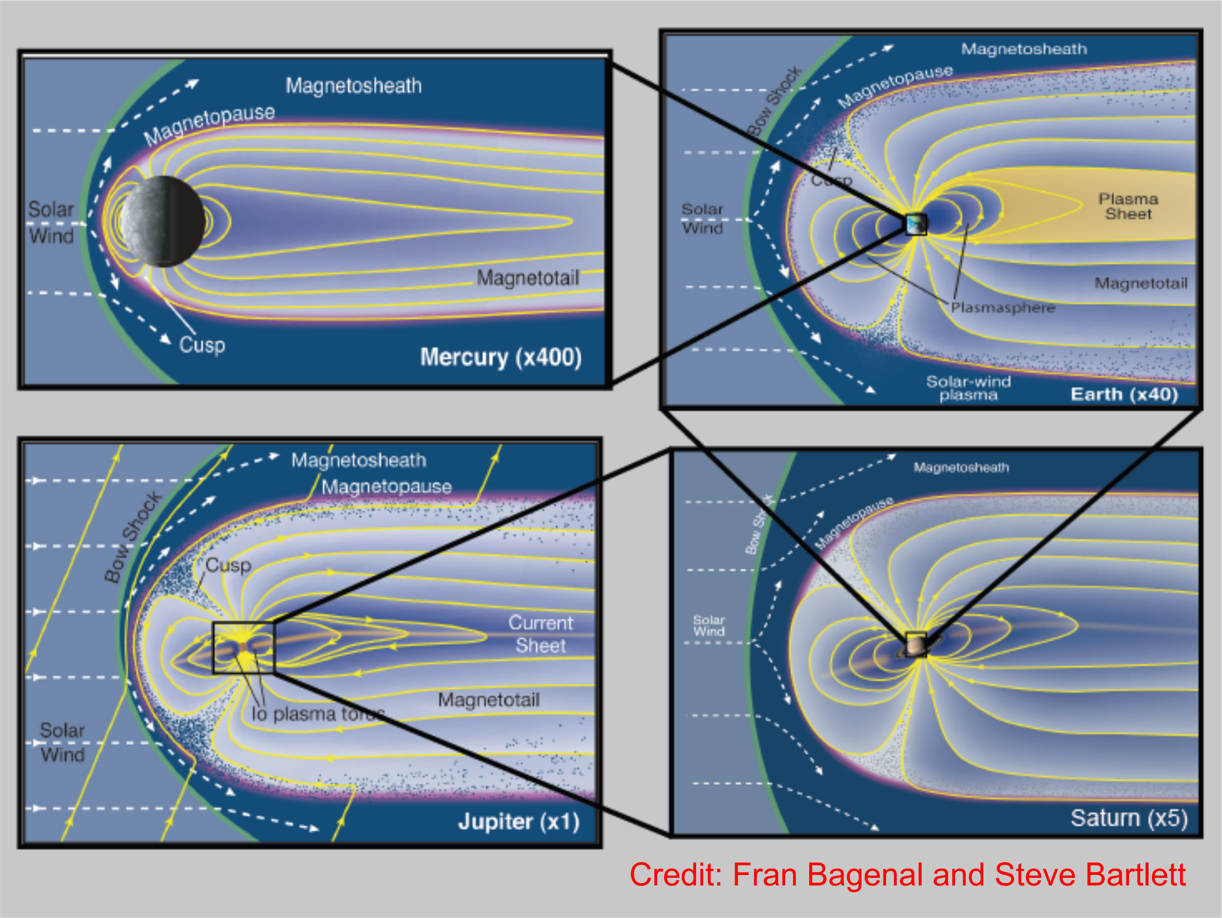
Planetary Plasma Environments



Credit: Fran Bagenal and Steve Bartlett

Dr. Caitríona Jackman

STFC Introductory Solar System Plasma Summer School

Exeter, August 2018

UNIVERSITY OF Southampton

Outline: Planetary Plasma Environments

- Introduction to magnetospheres
- Upstream influence [Sun, Solar Wind, IMF]
- Internal influence [Plasma loading]
- Formation of a magnetosphere

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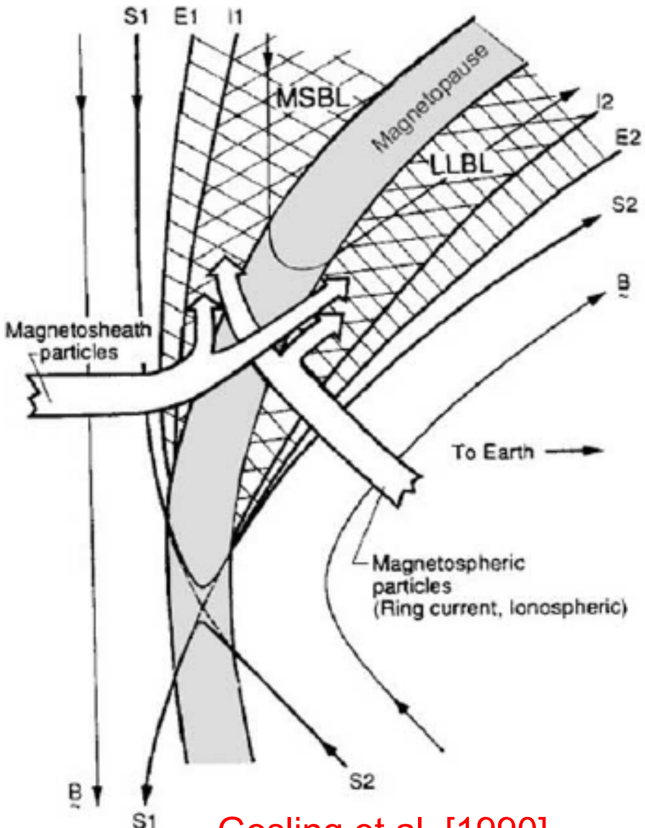
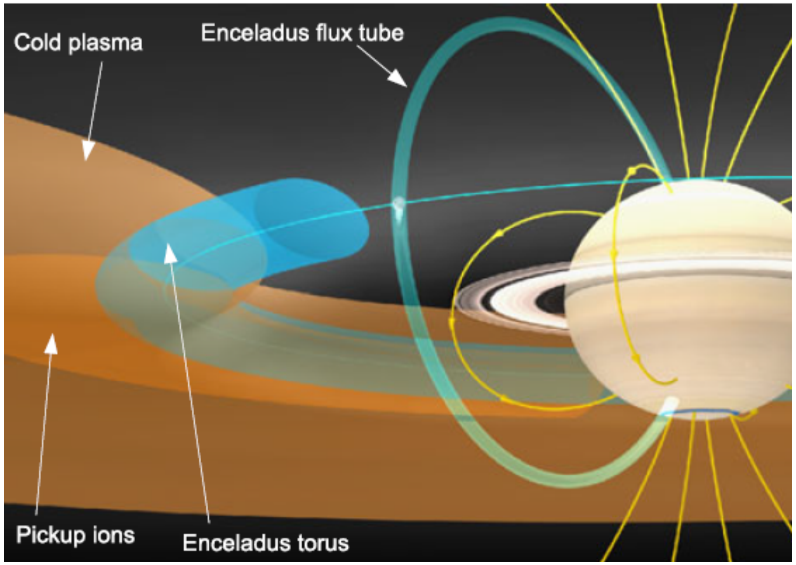
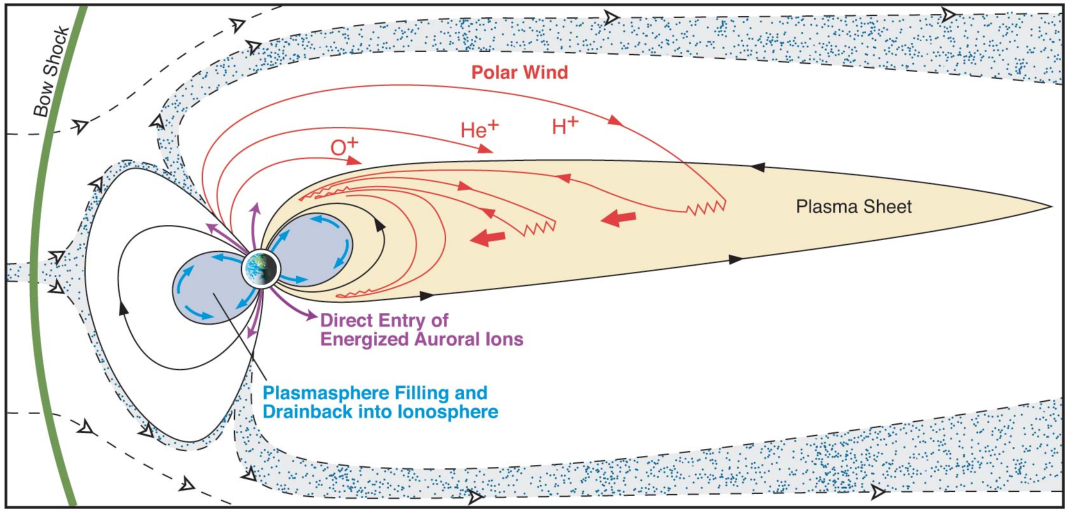
Sources of plasma for magnetospheres



Gosling et al. [1990]



Arridge et al. [2011]



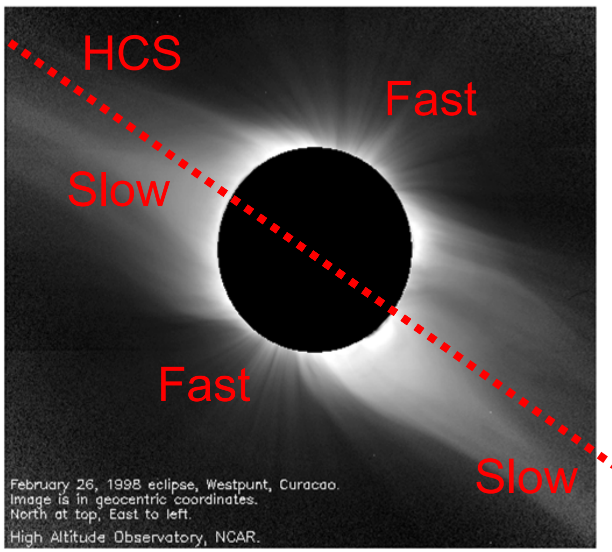
After Chappell [1988]

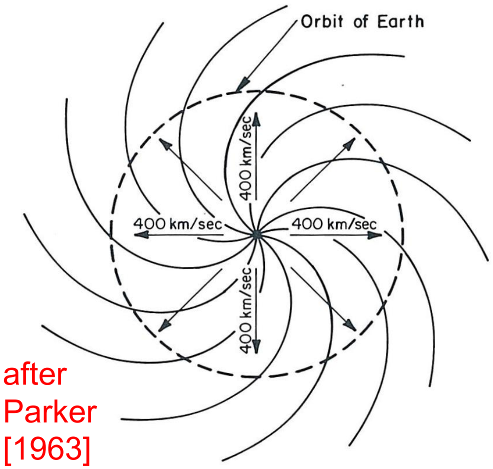
- Solar wind (reconnection, Kelvin Helmholtz)
- Leakage from the ionosphere
- Internal plasma loading (moons)

The Solar Wind

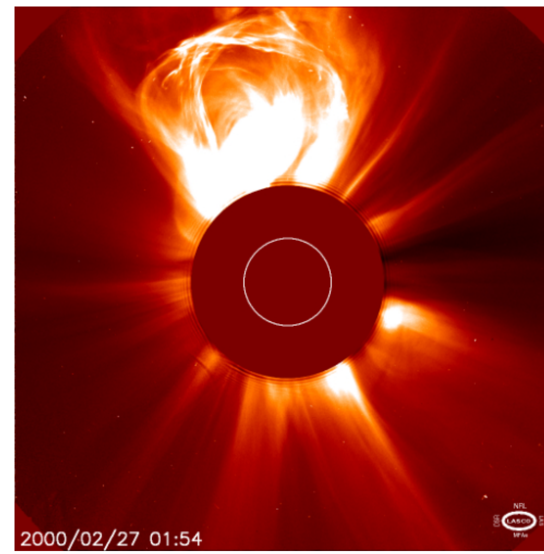
•Character changes with distance in the heliosphere

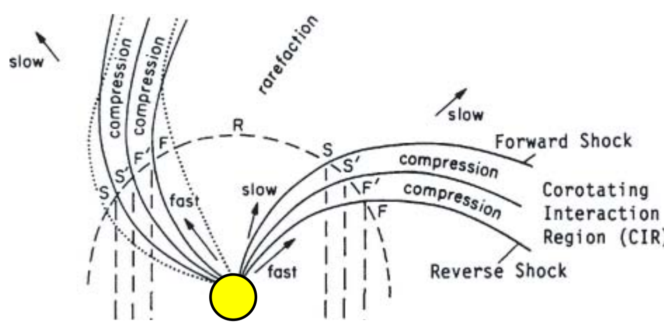
•Interplanetary Magnetic Field structure dictated by:
Parker Spiral, Corotating Interaction Regions (CIRs), Coronal Mass Ejections (CMEs)





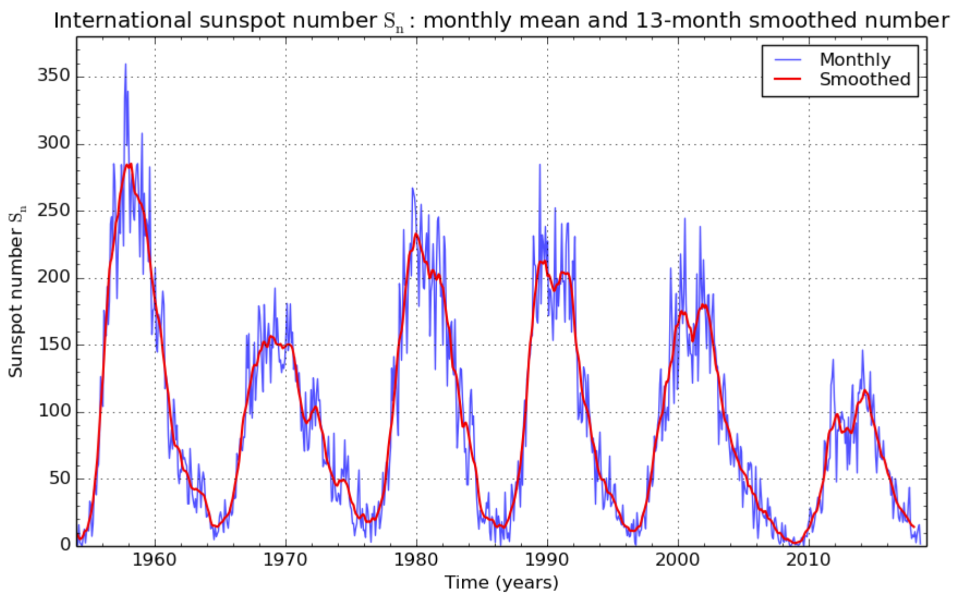
after Parker [1963]





Corotating interaction regions (CIRs): Kunow, [2001]

The Solar Cycle and Seasonal effects



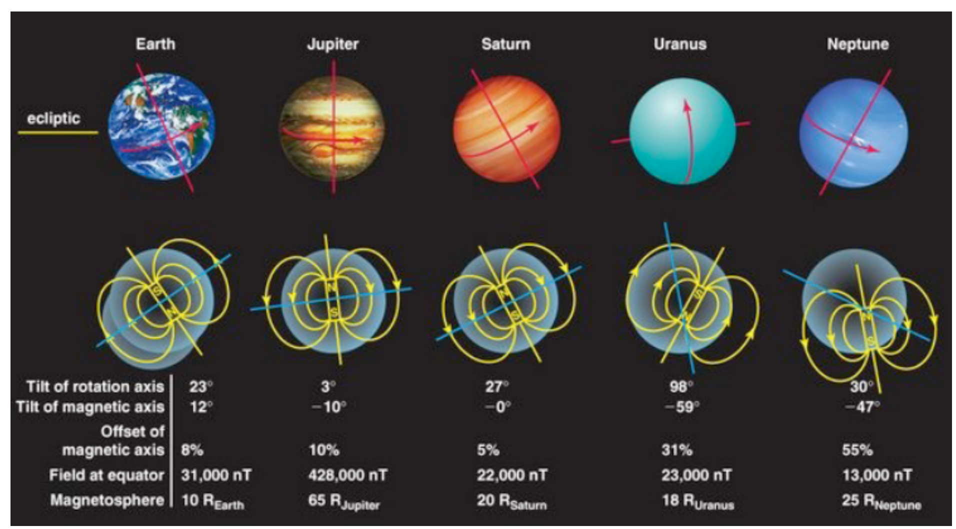
SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium 2018 August 1

Solar Max: Peak CME rate, IMF strength

Not all solar cycles are the same [strength/duration]

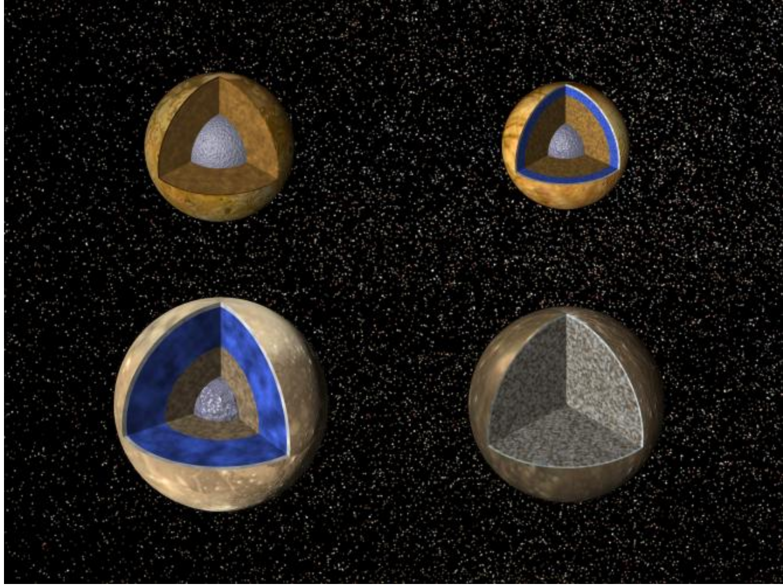
Changes in EUV irradiance (linked to solar cycle and planetary tilt) can alter ionospheric conductivity

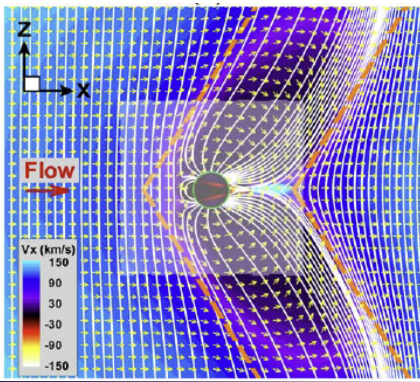
Long duration missions (e.g. Cassini at Saturn) can capture seasonal and solar cycle variability

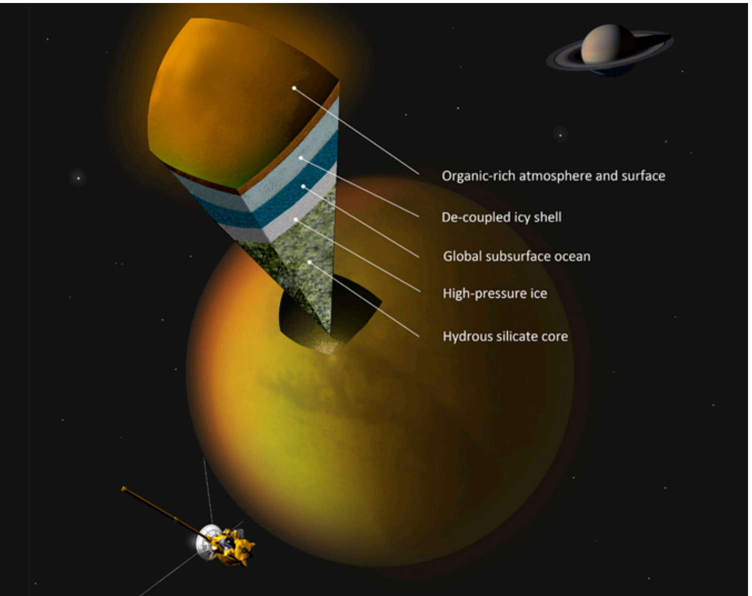


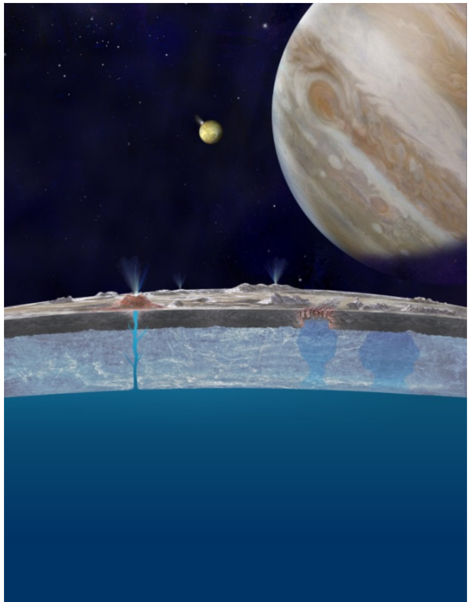
Planetary Moons

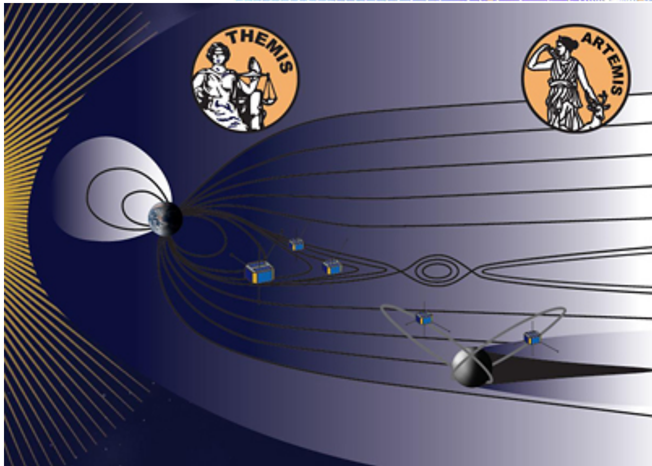
- Huge diversity in solar system moons
- Some are used as gravity assists for orbital missions
- Can play a role in magnetospheric dynamics
- Several act as plasma sources for magnetospheres



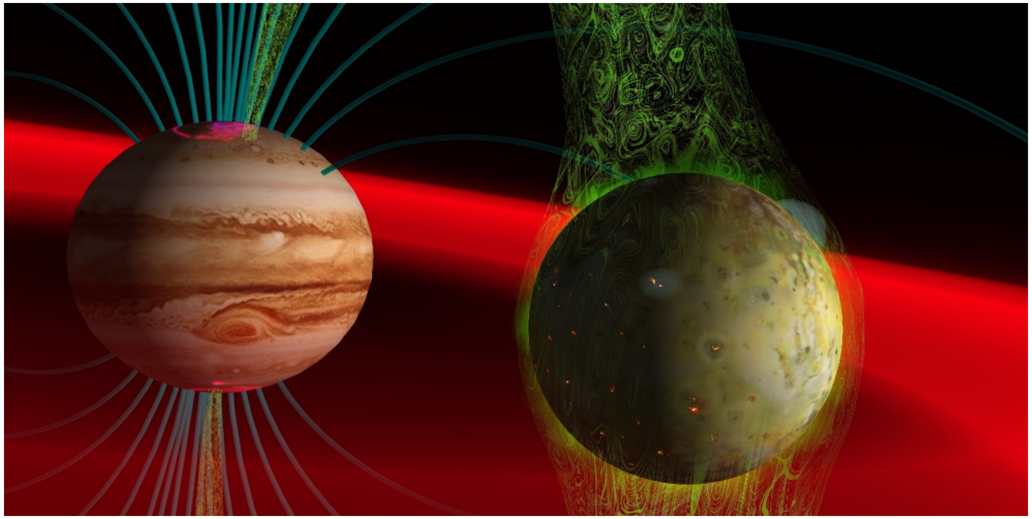




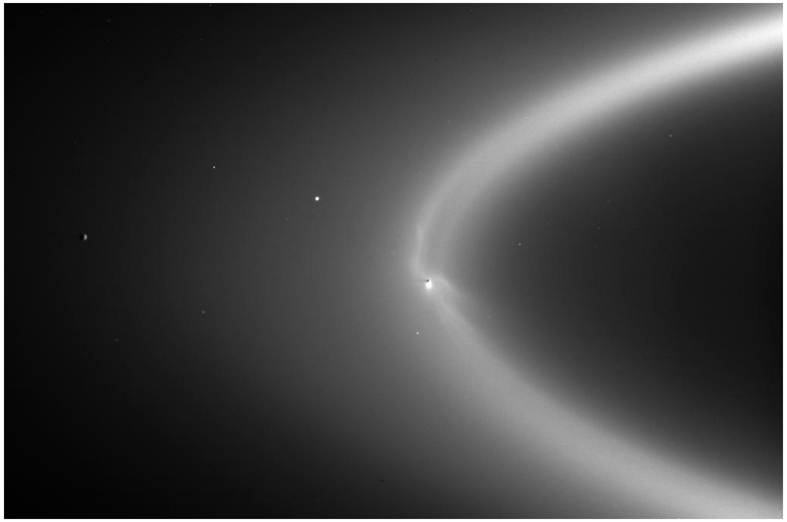




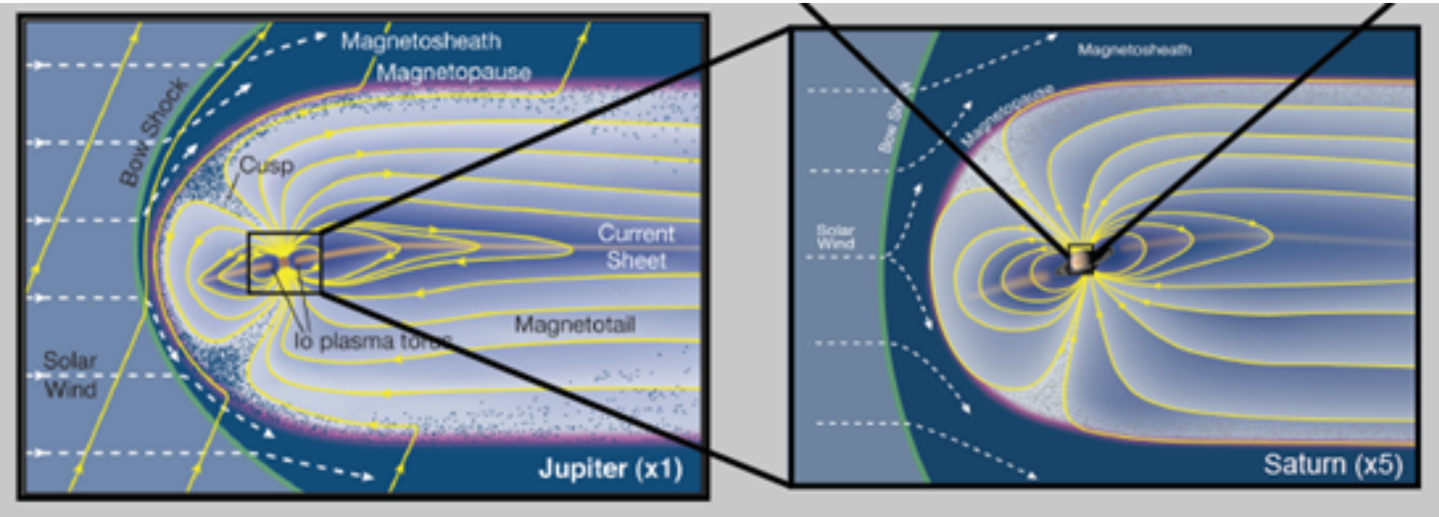
Internal Mass Sources



Ionized plasma from Io at Jupiter



Enceladus forming the E ring at Saturn



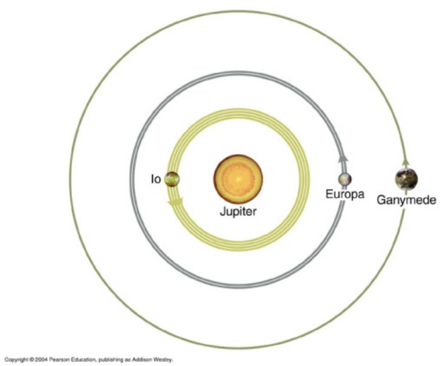
Plasma tori in Jupiter's and Saturn's magnetospheres

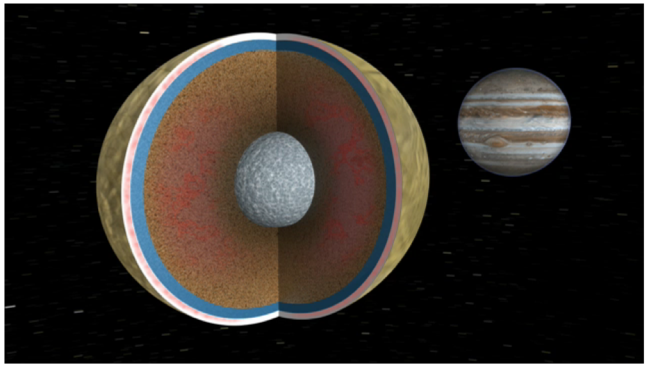
Volcanic Io at Jupiter

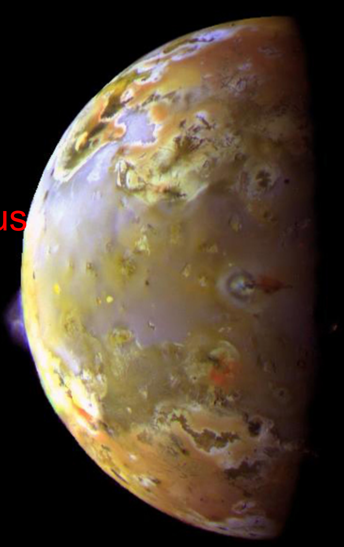
Tidal heating due to proximity to Jupiter and orbital resonance

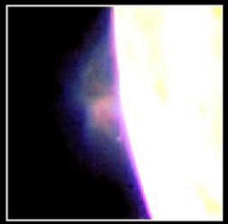
Huge volcanoes

Important source of plasma for Jupiter's magnetosphere

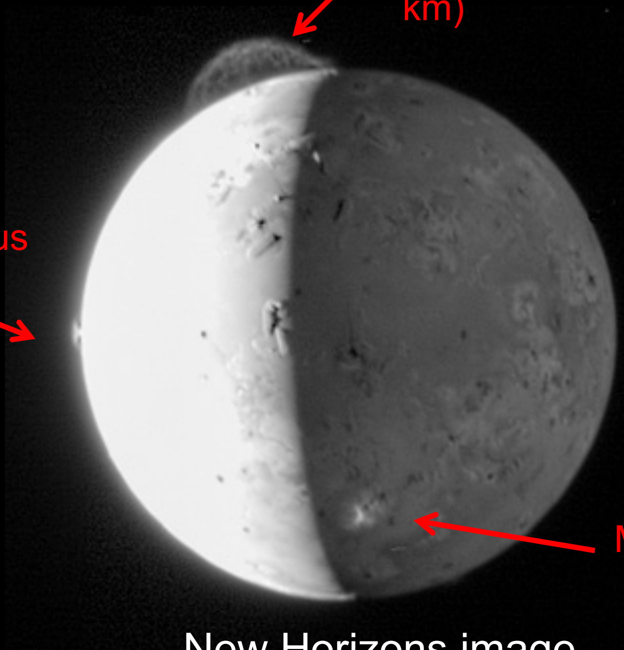






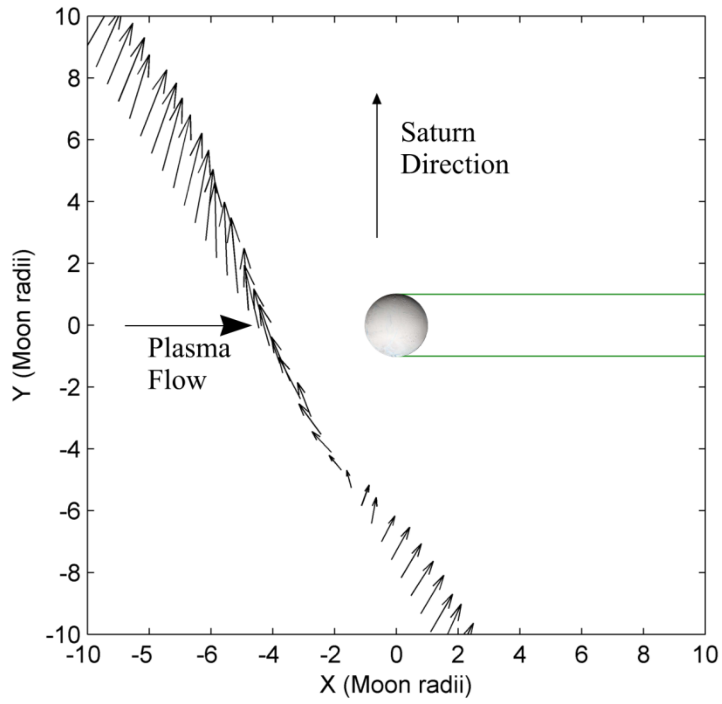


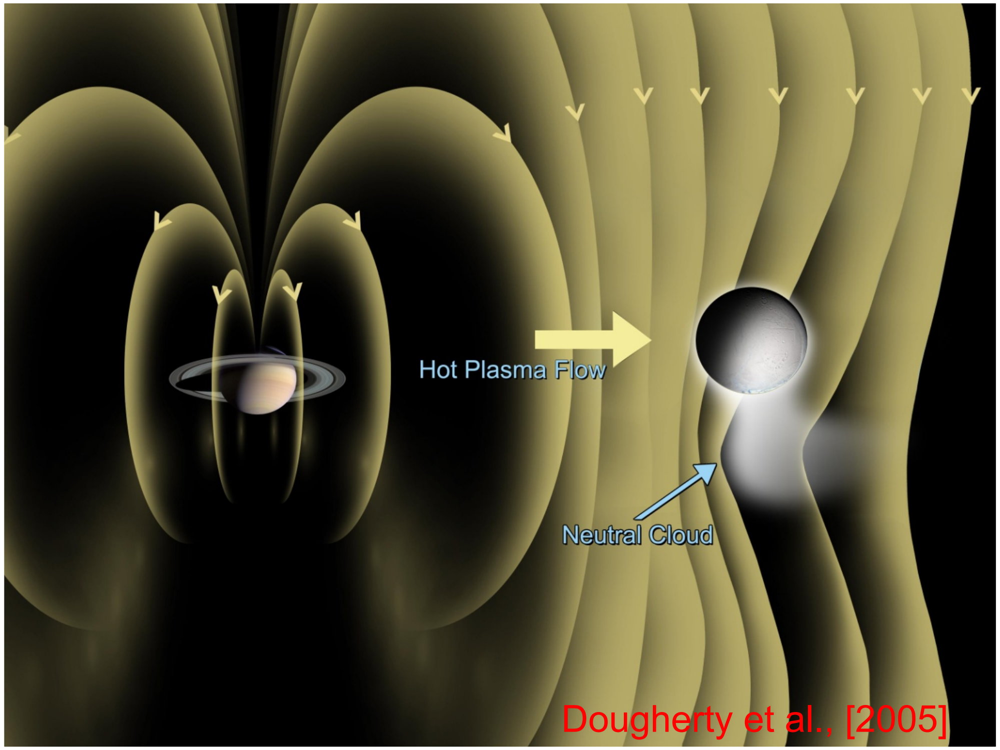
Galileo images



New Horizons image

Enceladus at Saturn: Early flybys

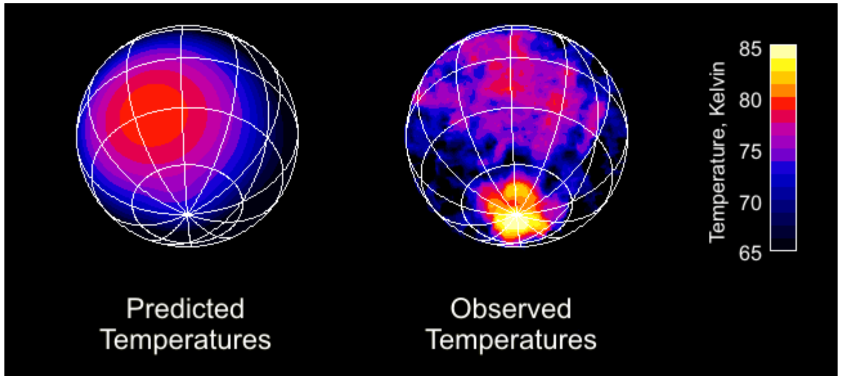




1st flyby/2nd flyby (Feb/March 2005):
Field bent around moon – plasma slowed?

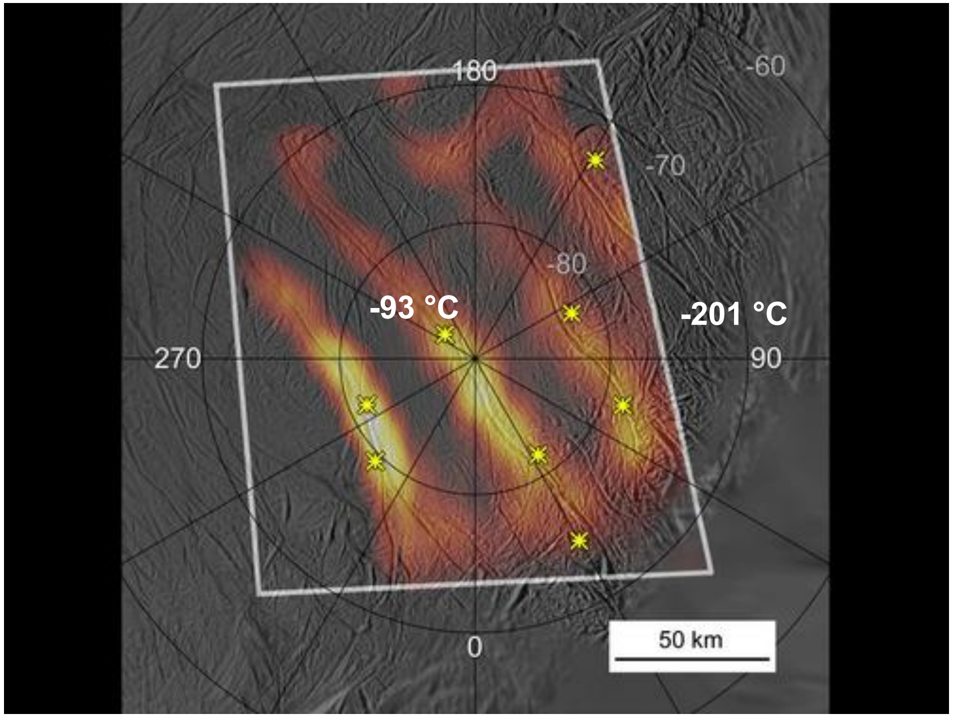
3rd flyby (July 2005):
Out-gassing via a polar plume

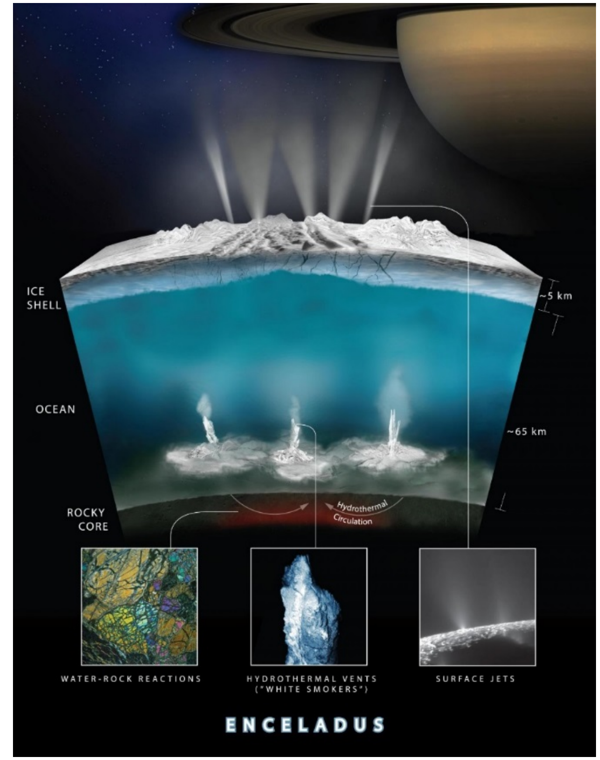
At higher temperatures atmosphere not strongly gravitationally bound



Enceladus at Saturn: Further exploration

Warmest part of fractures coincide with plume jets



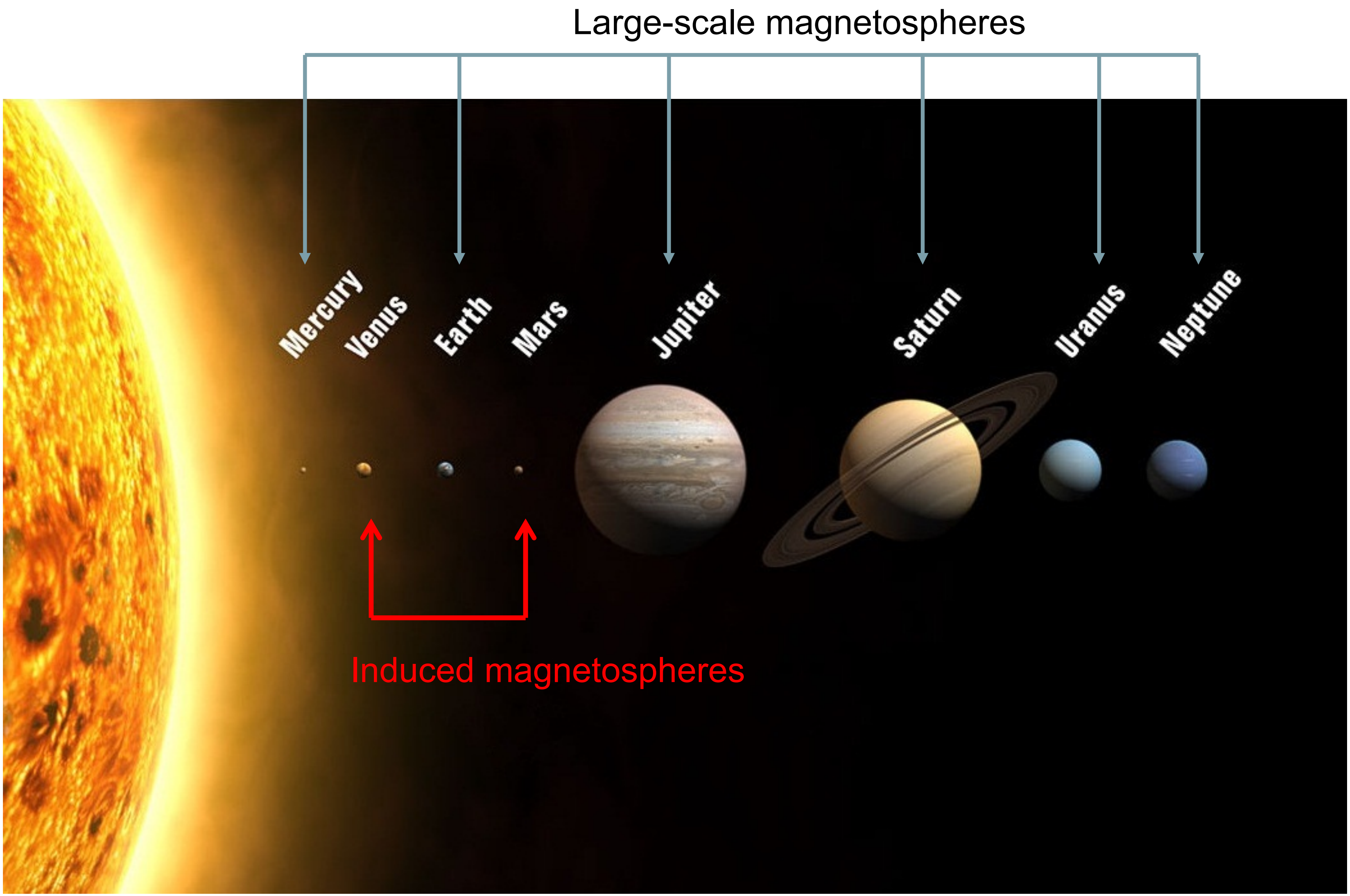


~100 kg/s of water ice ejected and forms the E-ring.

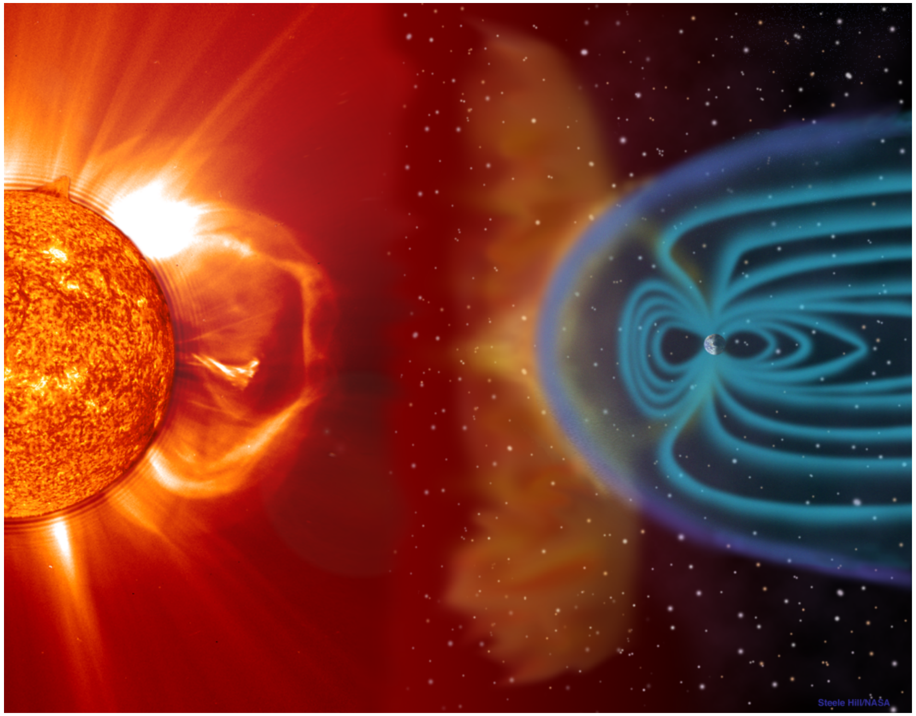
Fissures expand/contract with orbit

Composition of plumes includes molecular hydrogen

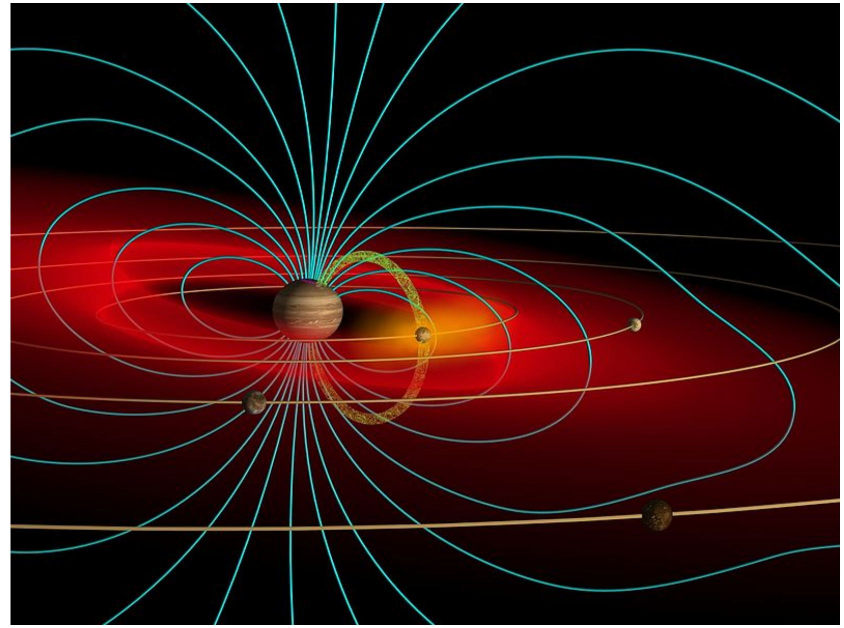
Formation of a magnetosphere?



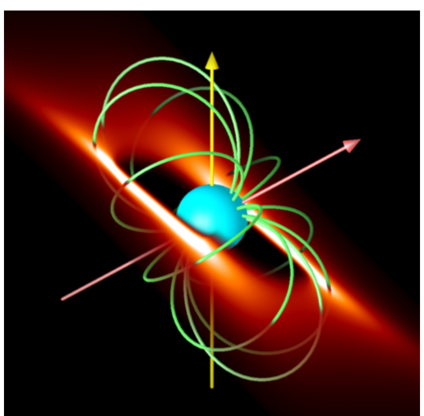
What is a magnetosphere?



protection from space weather

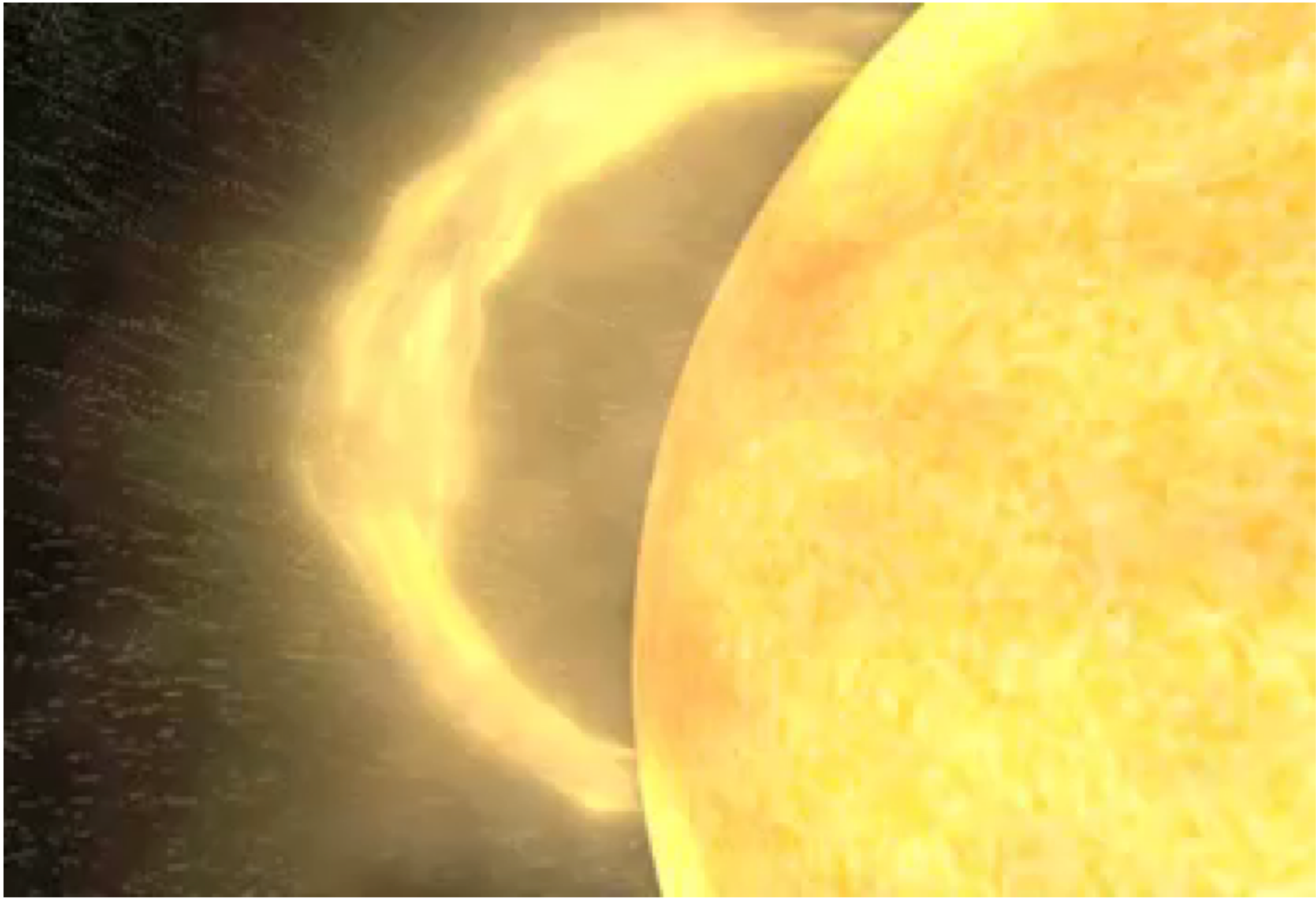


“natural plasma laboratory”



Varying sizes and properties

Formation of a magnetosphere



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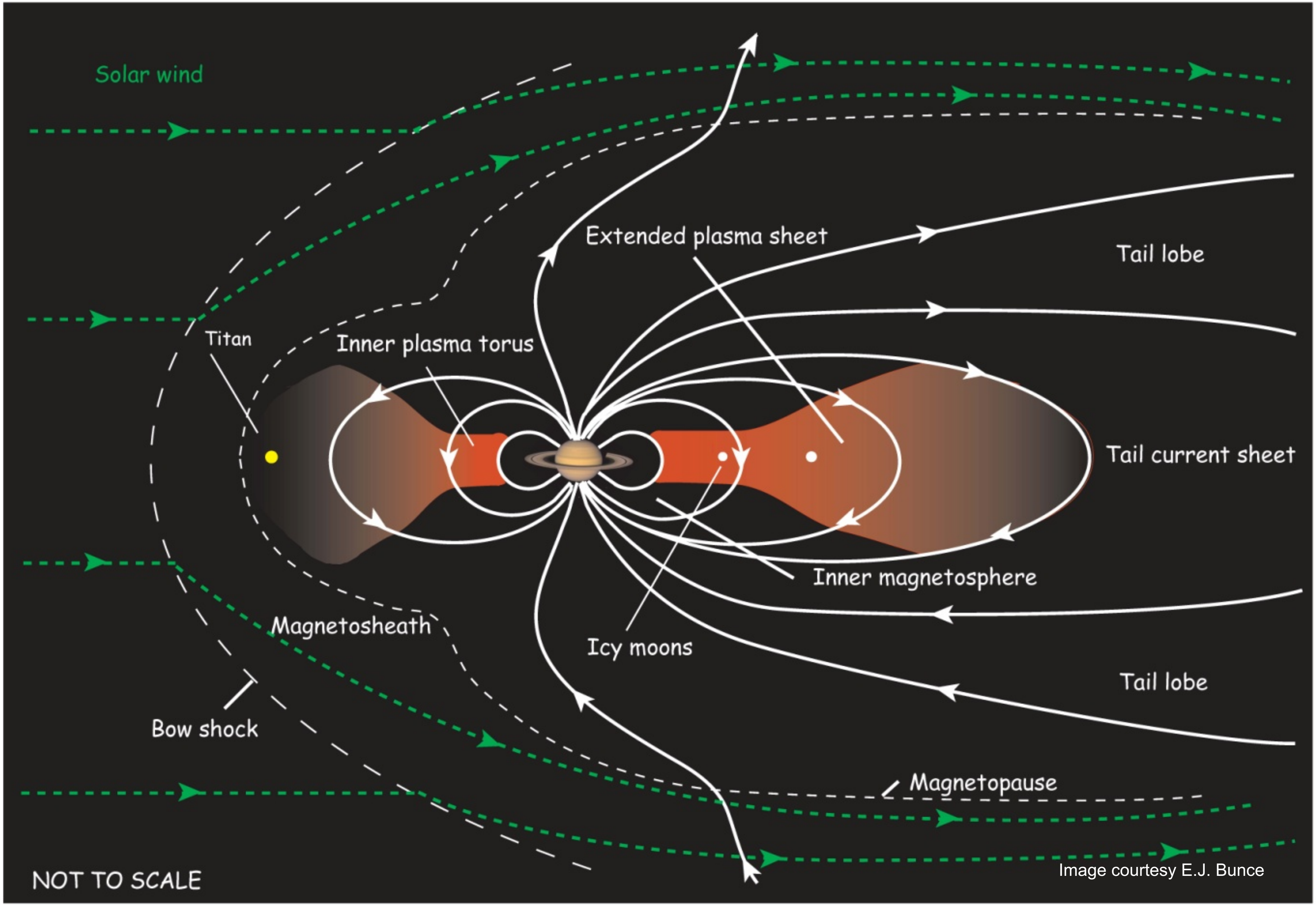

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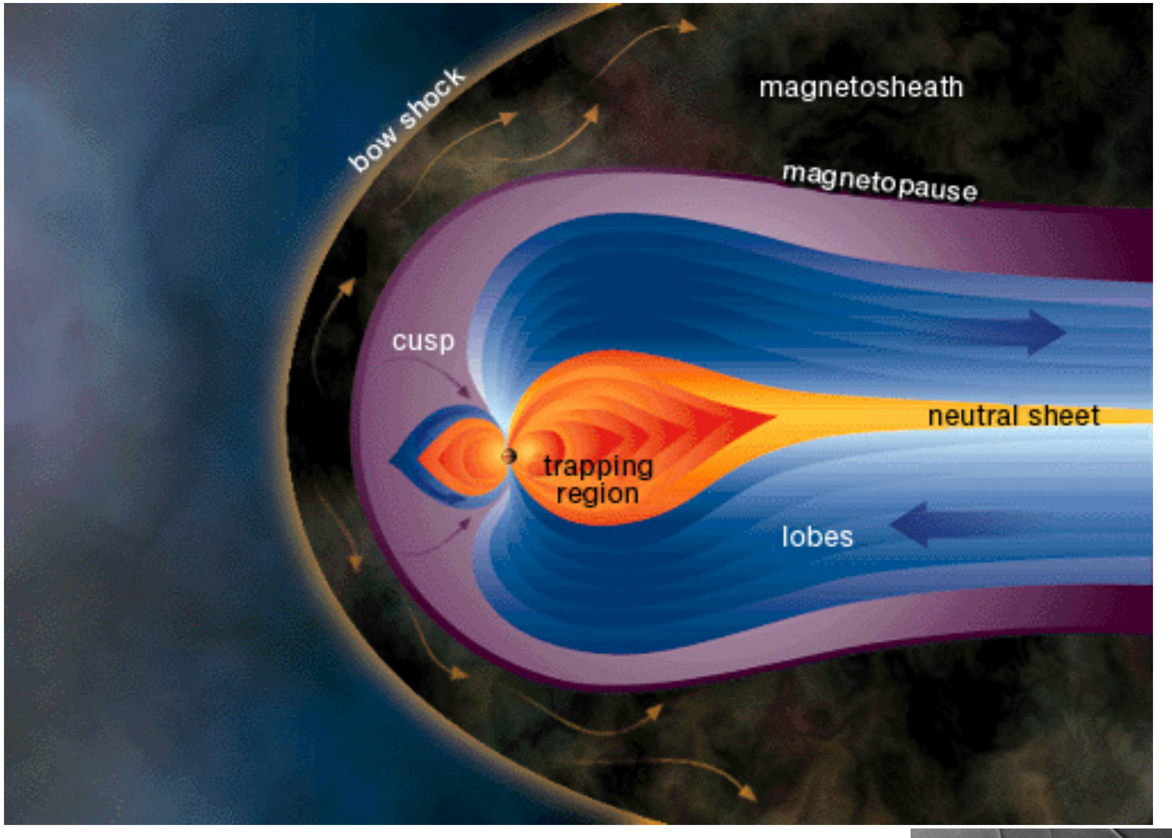
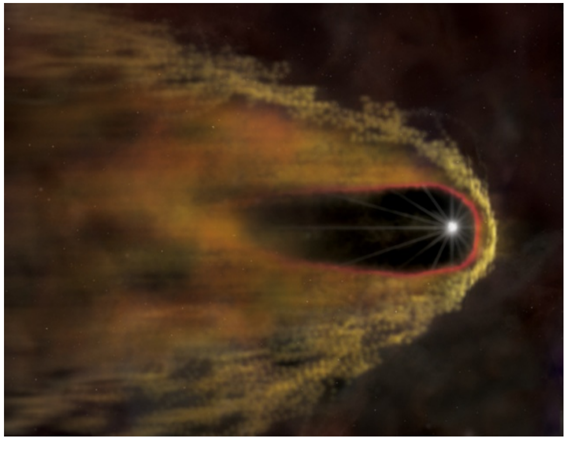
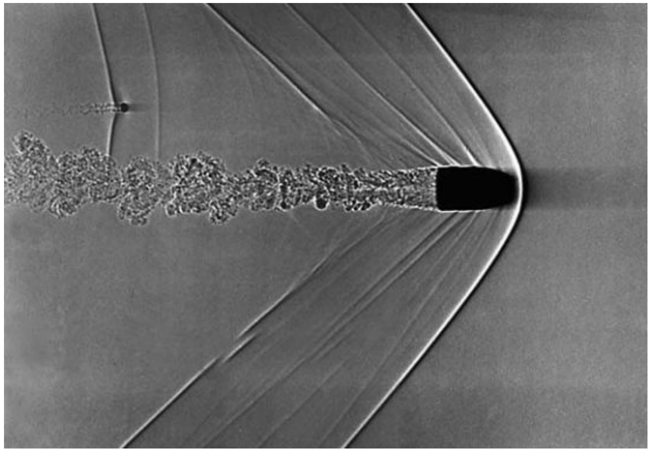
Boundaries: Bow shock – Magnetosheath - Magnetopause



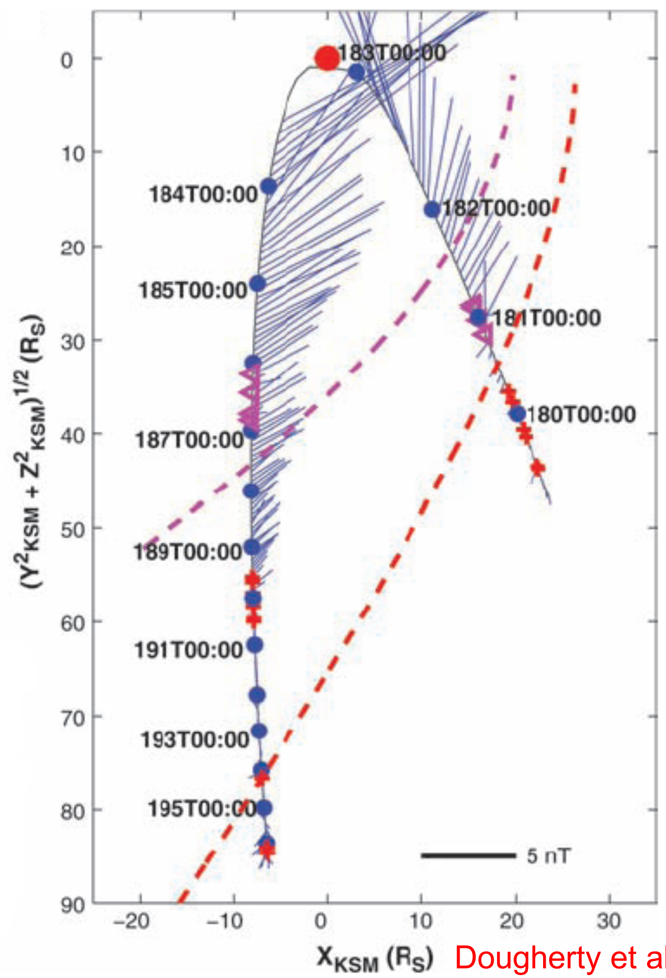


"Black widow" pulsar

Shadowgraph of bullet

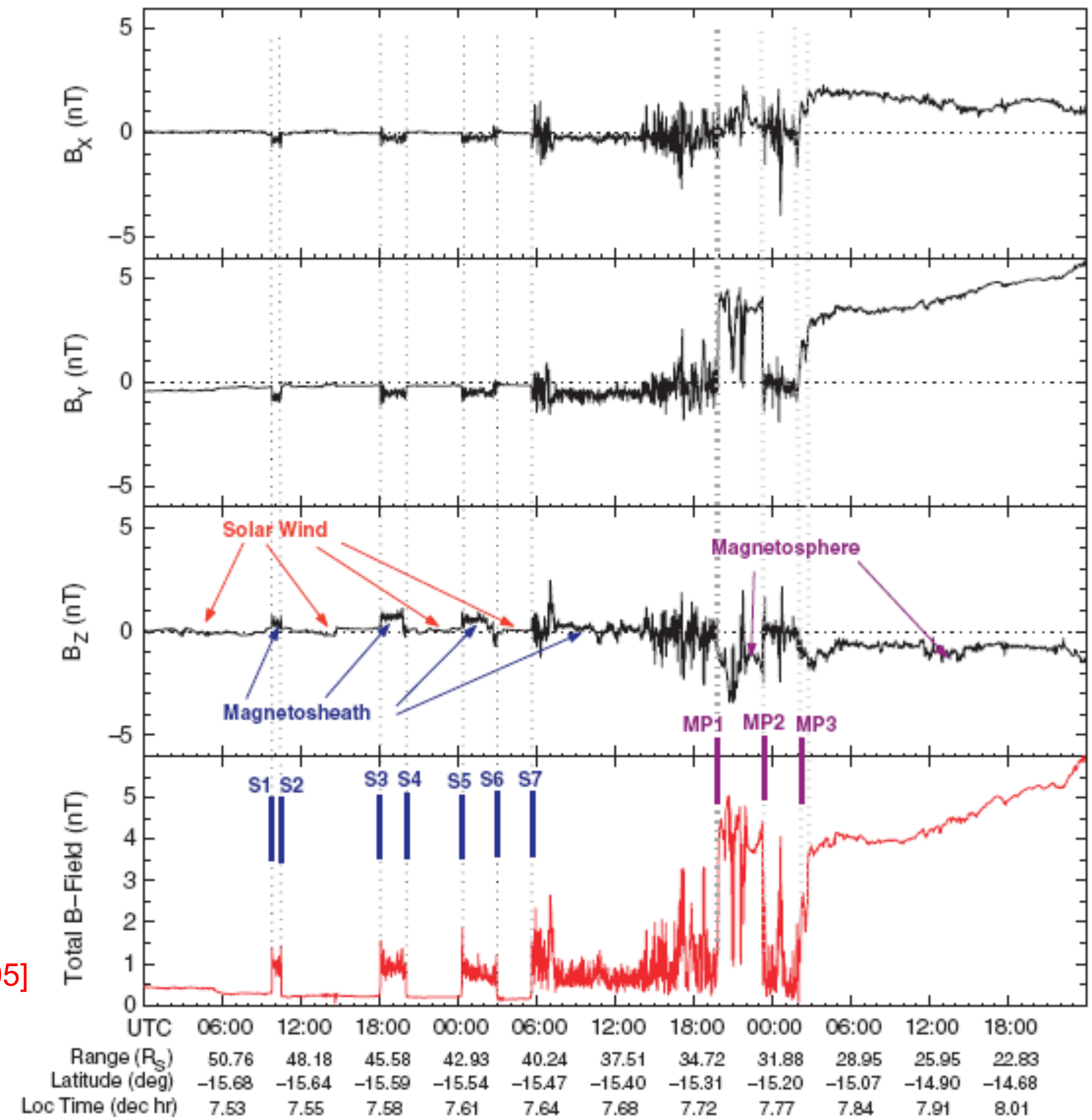


Cassini: Saturn orbit insertion



Dougherty et al., [2005]

Cassini trajectory



Magnetometer data on inbound pass

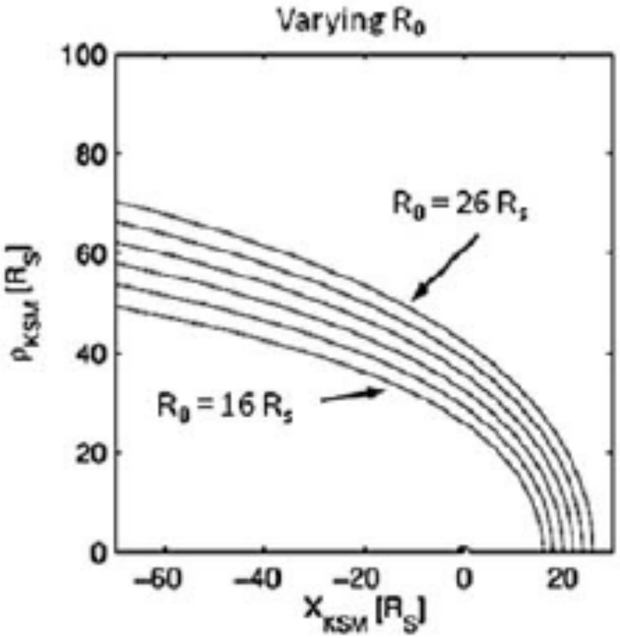
Determining magnetopause position

Magnetopause:

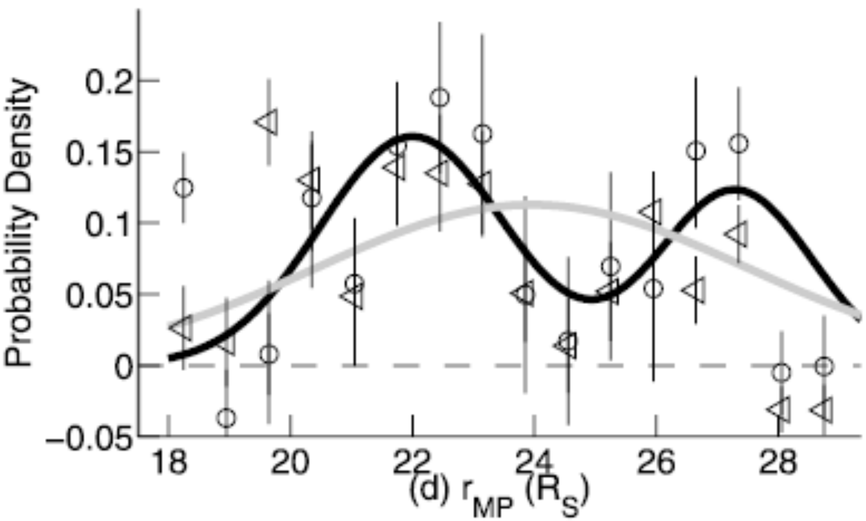
~~IMF magnetic pressure~~ + Solar wind Flow Pressure = Magnetospheric magnetic pressure + ~~Magnetospheric plasma pressure~~

Simple approximation for Earth: $$N_{sh} m_i v_{sh}^{\;2} = \frac{B_{mag}^{\;\;2}}{2\mu_0}$$

For Jupiter/Saturn, need to include magnetospheric plasma pressure



Kanani et al. [2010]



Achilleos et al. [2008]

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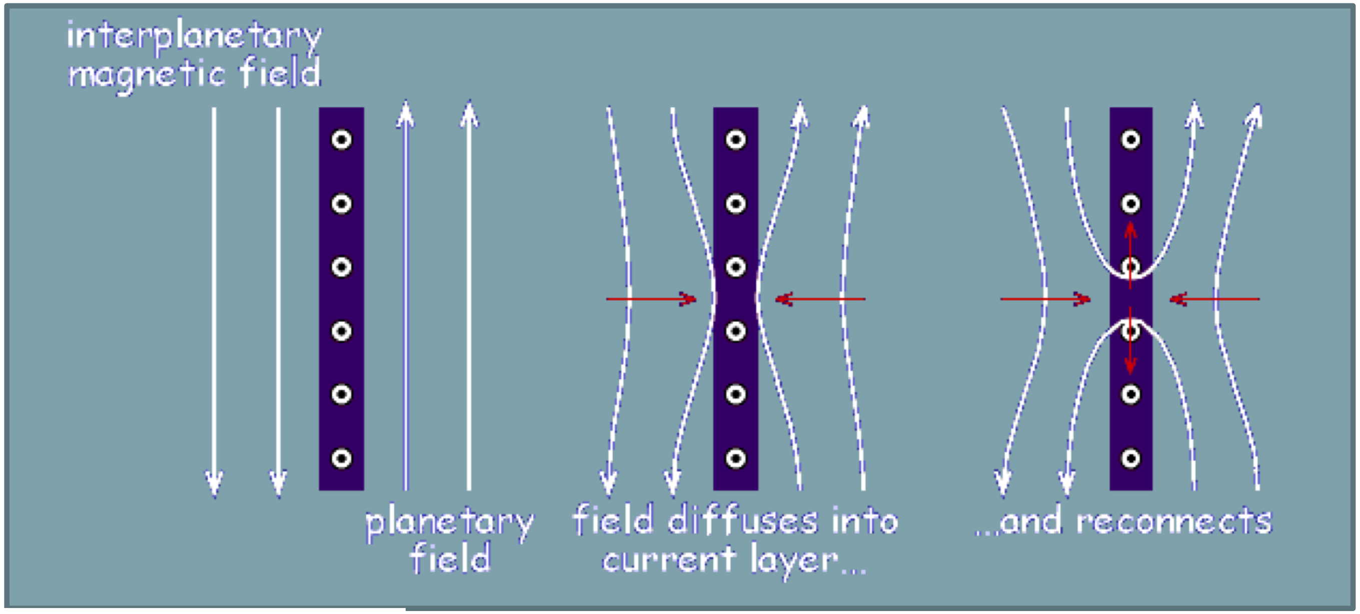
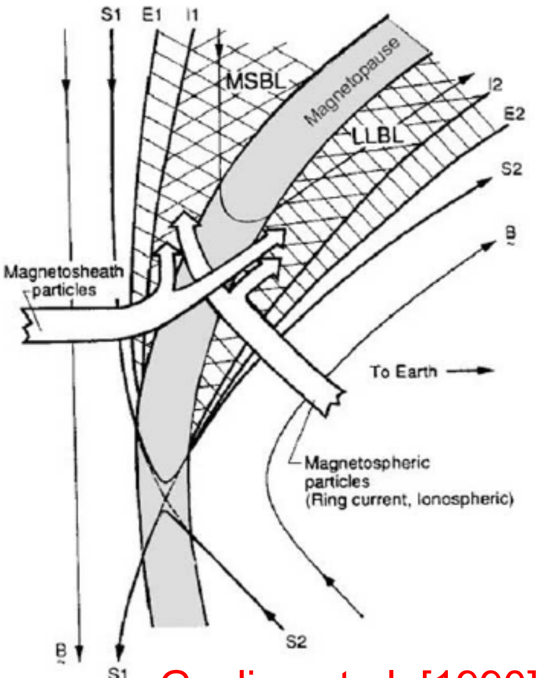
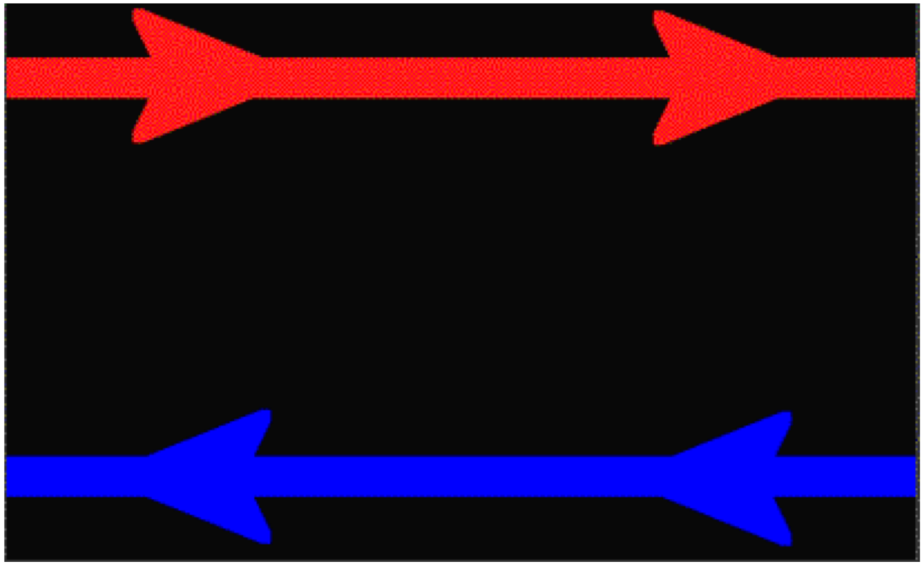
Dayside Reconnection





Gosling et al. [1990]



Dayside reconnection voltage

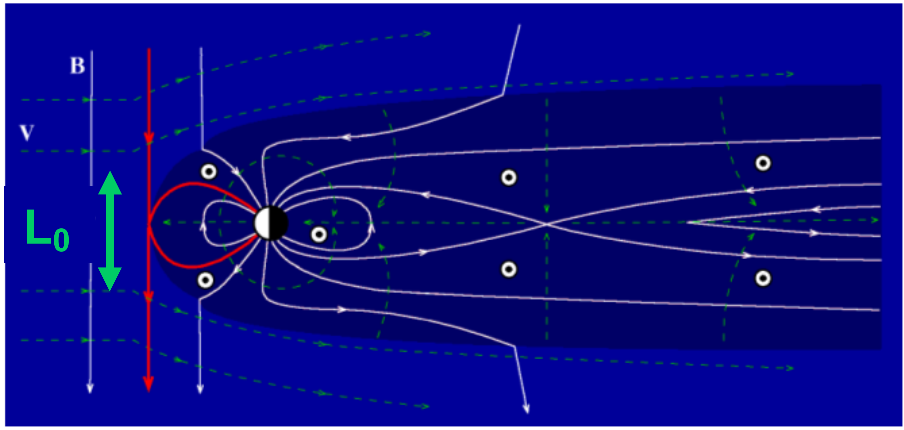
Dayside reconnection voltage, Φ across the magnetopause:

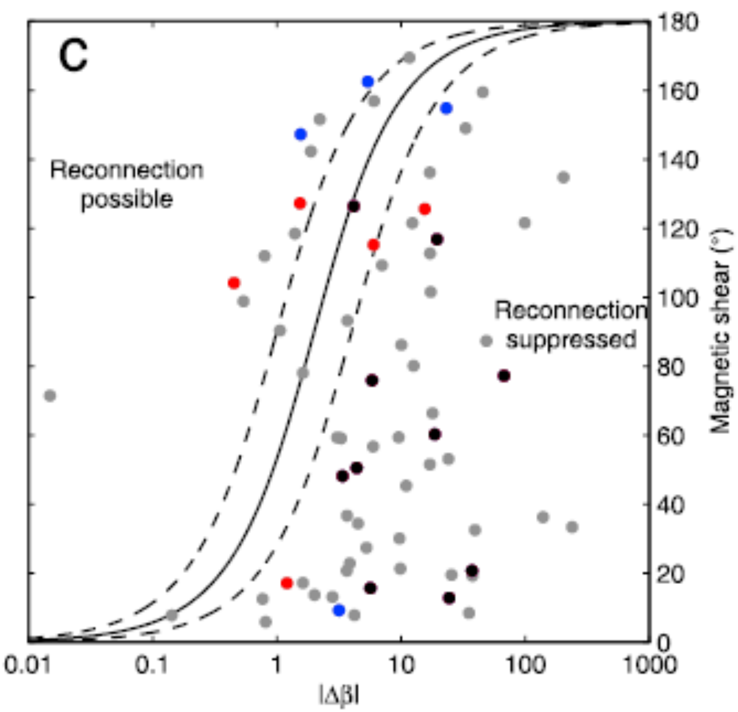
$\Phi = V_{sw} B_{\perp} L$

$B_{\perp}$ – strength of IMF perpendicular to velocity vector

$V_{sw}B_{\perp}$ – motional electric field in the solar wind

L = “length” of reconnection channel in solar wind

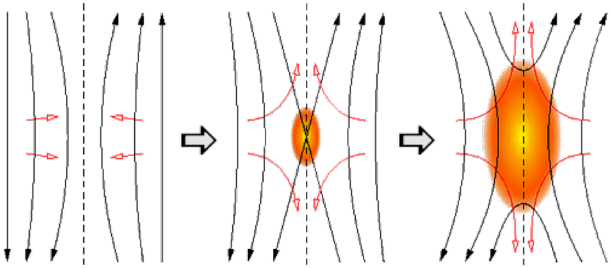




Masters et al. [2012]

Efficiency of reconnection can depend on:

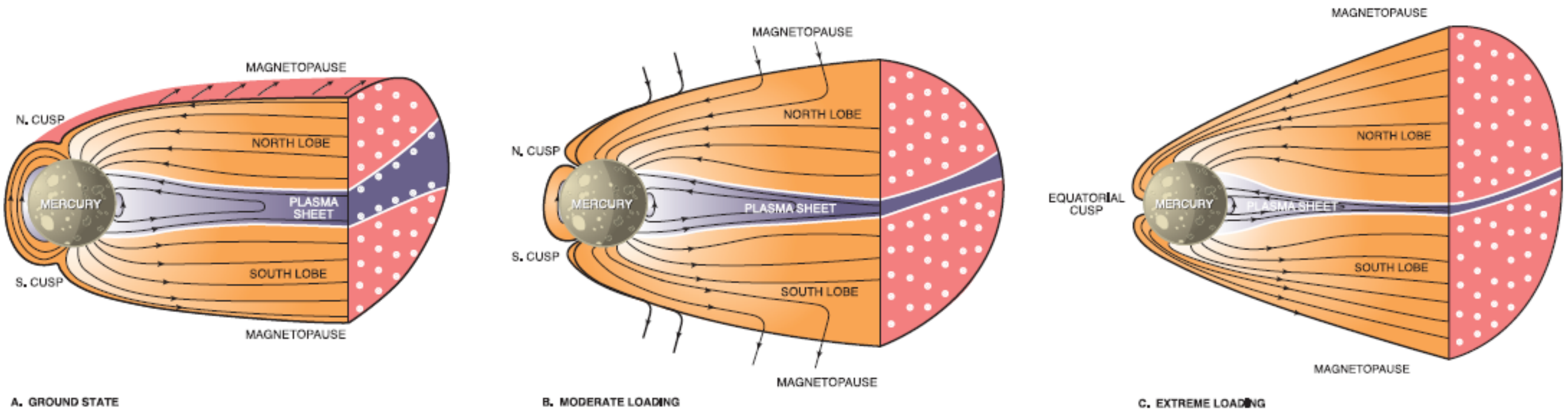
- Magnetic shear
- Plasma beta
- Mach number



Reconnection effect on MP position

Reconnection at the dayside can “erode” the magnetopause

“Extreme loading” at Mercury may be able to strip the dayside magnetosphere, exposing the planetary surface

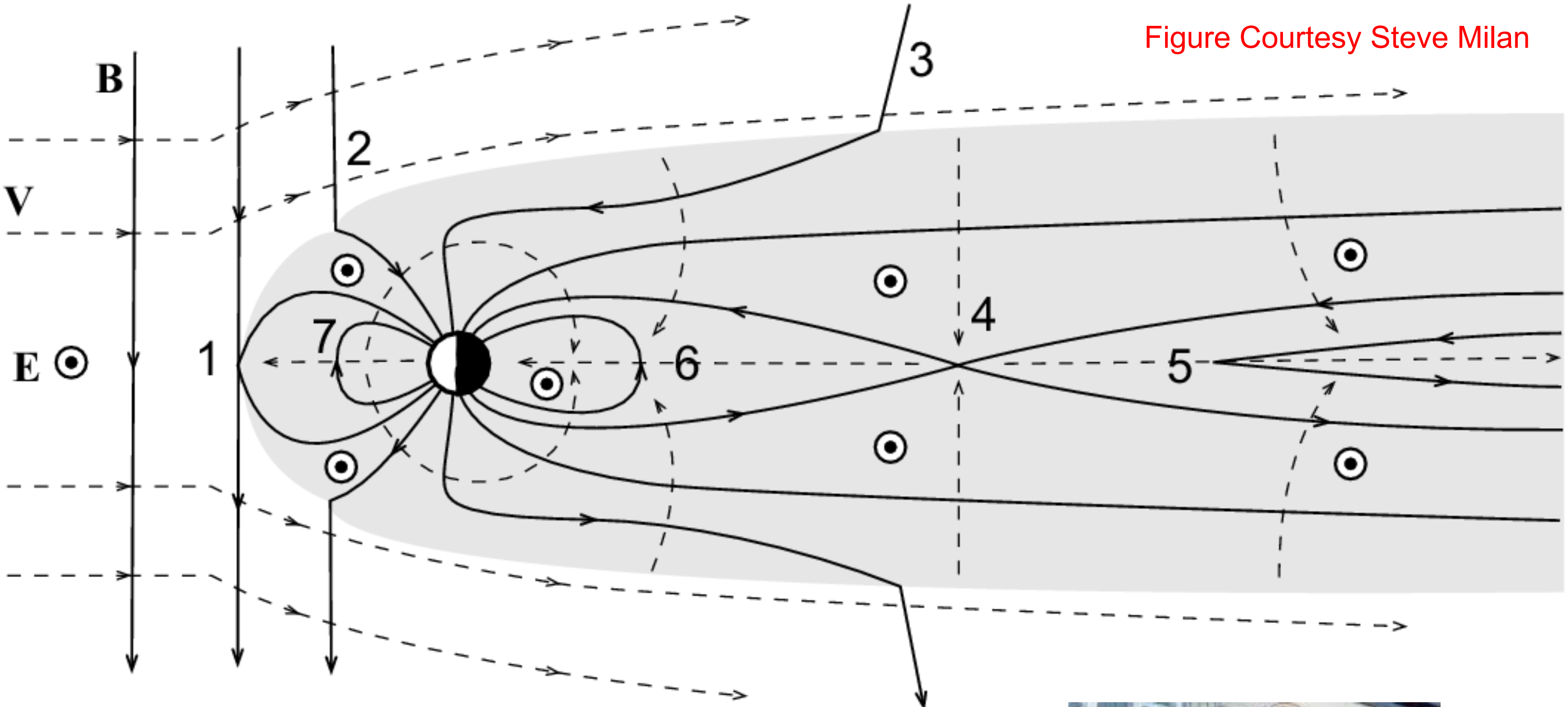


Slavin et al. [2010]

Work at Jupiter has shown MP erosion by reconnection of order ~ a few R_J (compared to 60-90 RJ standoff distance) [Kivelson and Southwood, 2003]

Dungey cycle

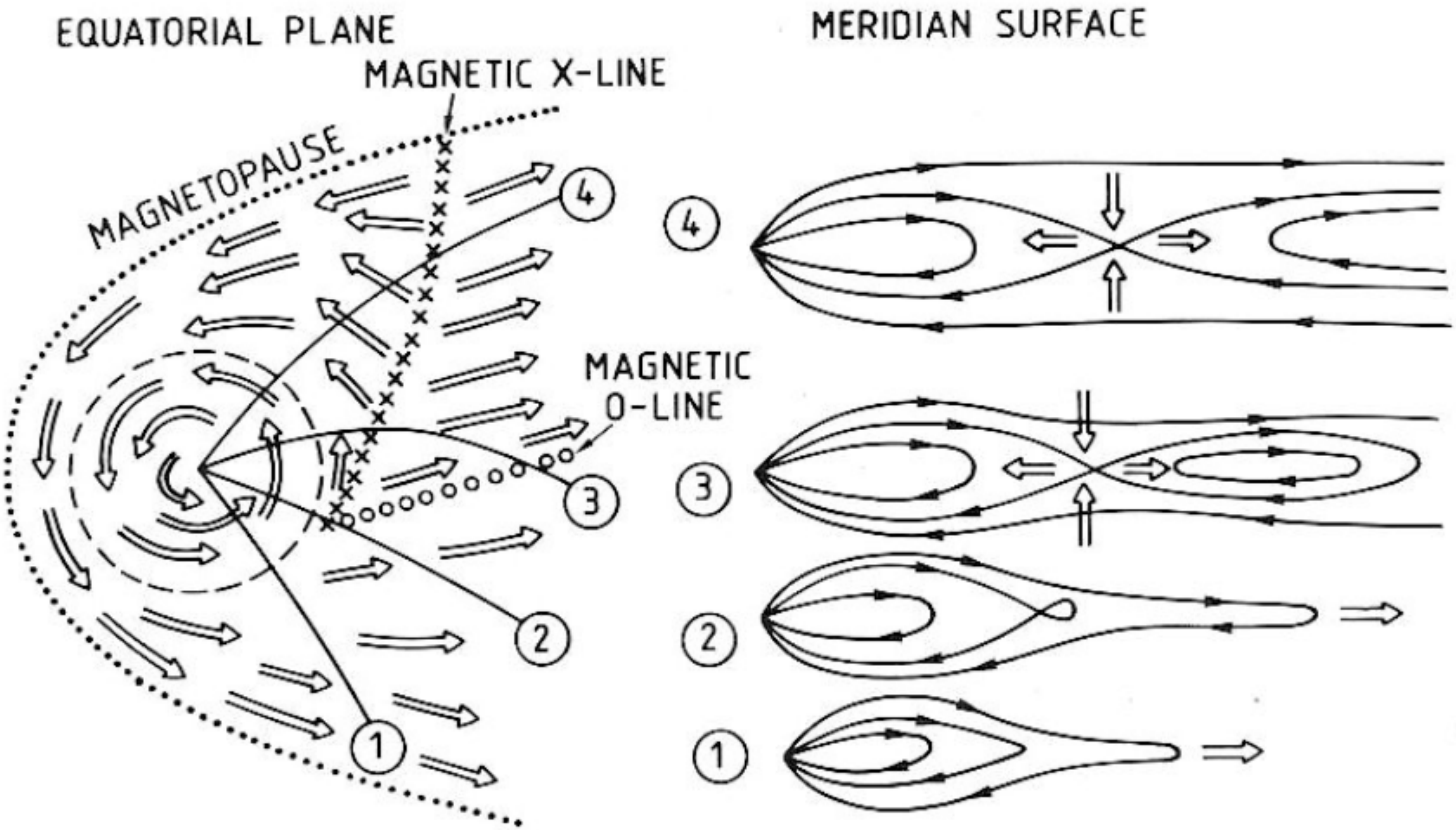
Figure Courtesy Steve Milan



<u>Timescales:</u>

Mercury: ~1-2 min
Earth: ~1 hr
Jupiter: several wks
Saturn: ~1 wk

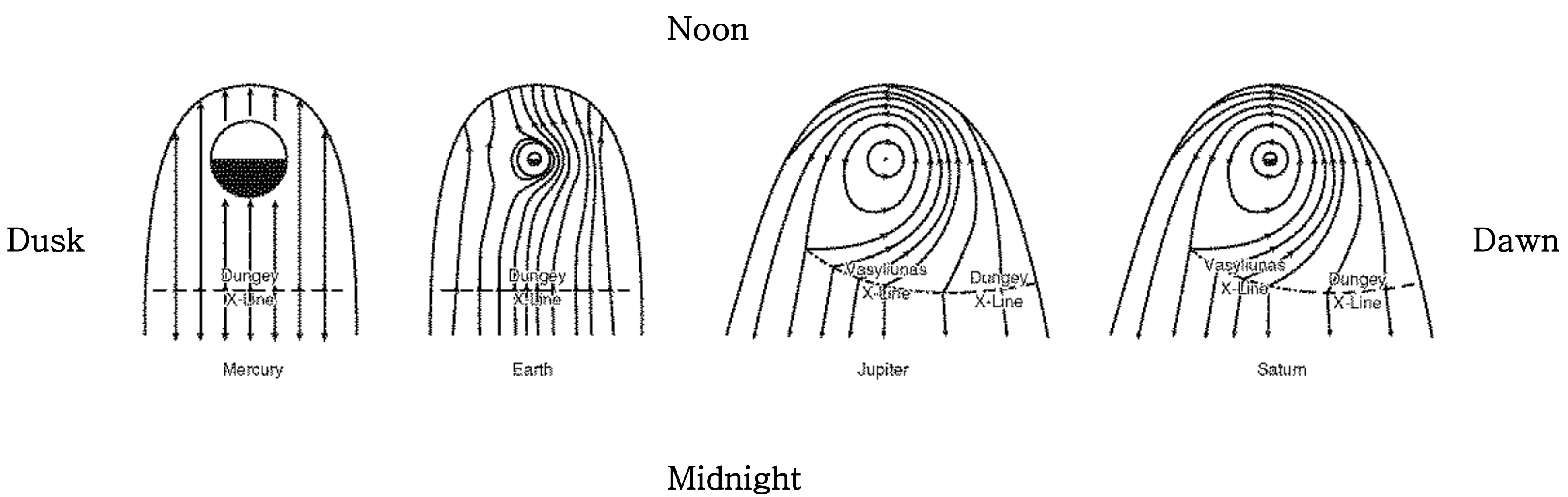
Vasyliunas cycle



- Internally driven
- Important at rapidly rotating planets (e.g. Jupiter and Saturn)
- Involves closed field lines

External vs. Internal competition

Relative importance of Dungey cycle (external/solar wind) and Vasyliunas (internal/rotation) cycle is a big question at giant planets



Can be examined by:

- Mapping auroral emissions to magnetospheric locations
- Tracking particle populations in the magnetosphere
- Charting plasma flow directions
- Models (global MHD, kinetic, etc.)

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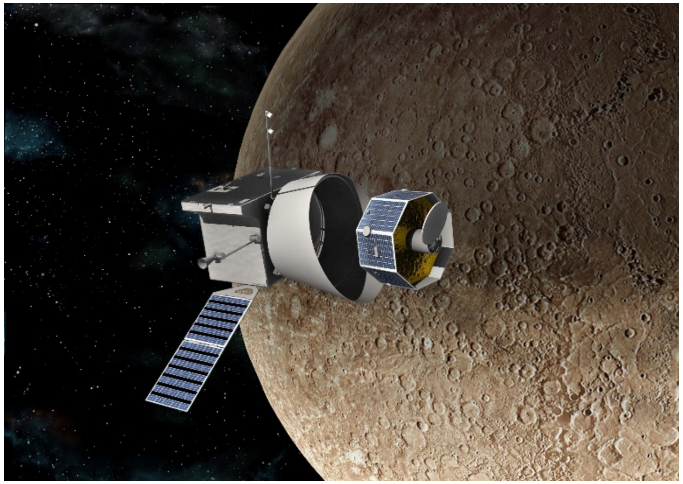
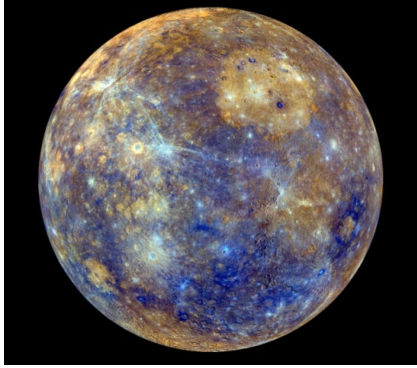
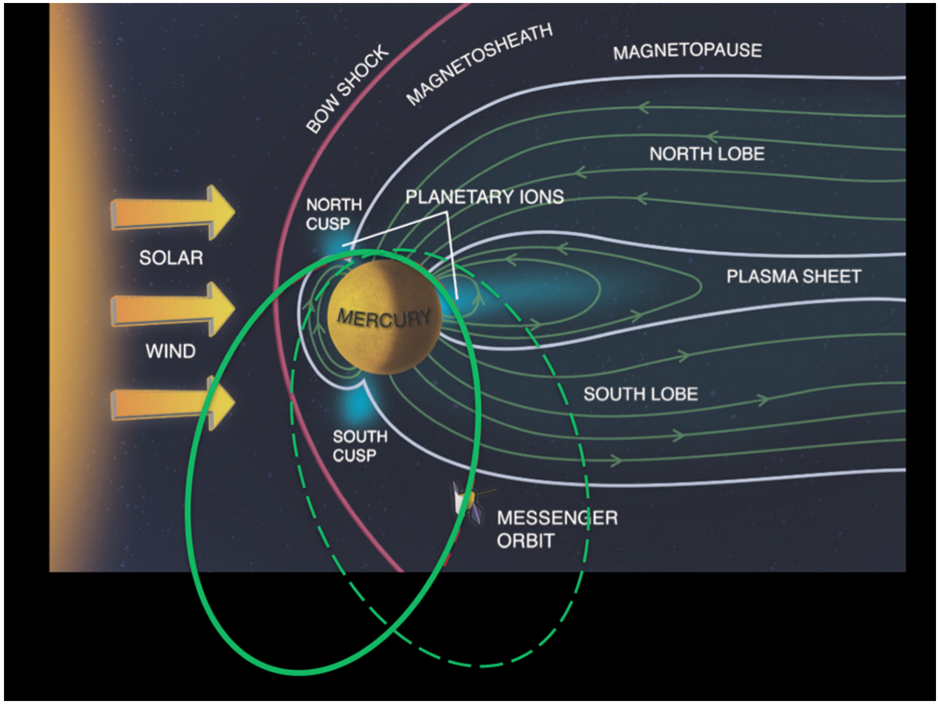
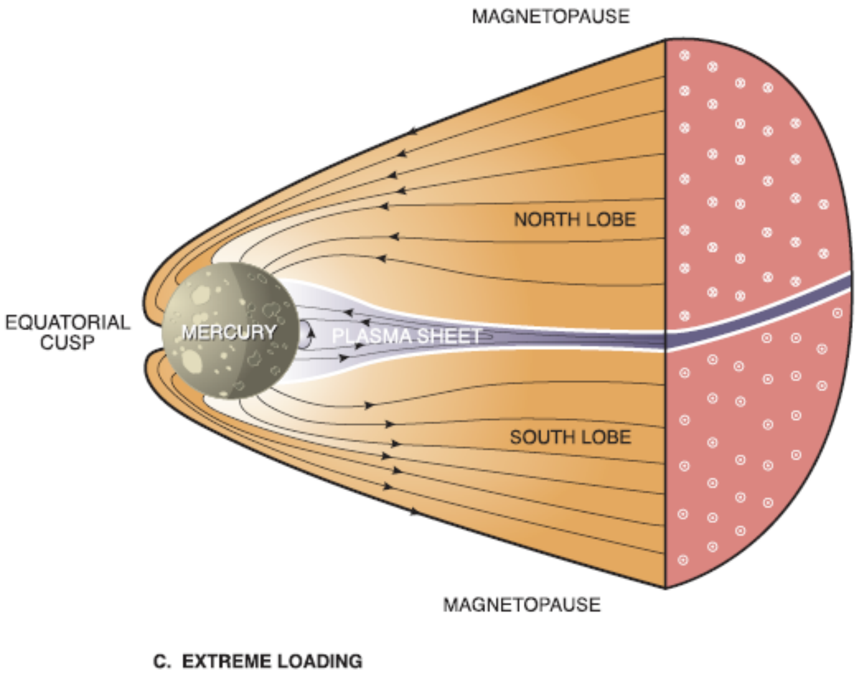
Mercury

- Mariner 10 (1970s)
- MESSENGER (2011-2015)
- BepiColombo (launch 2018, arrival 2025, 2 spacecraft)







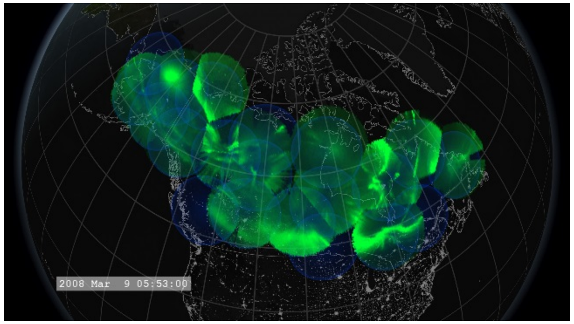


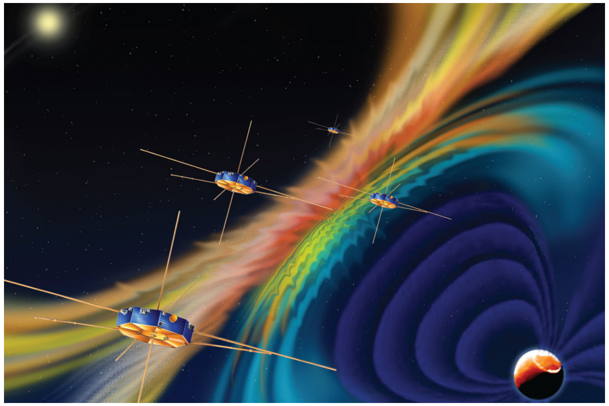
Slavin et al. [2010]

Earth

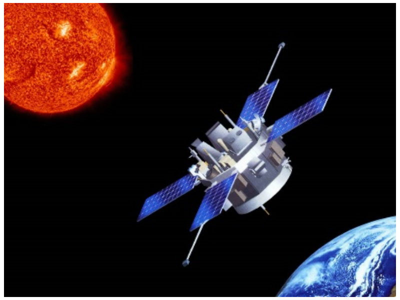
Auroral cameras

Ionospheric radars



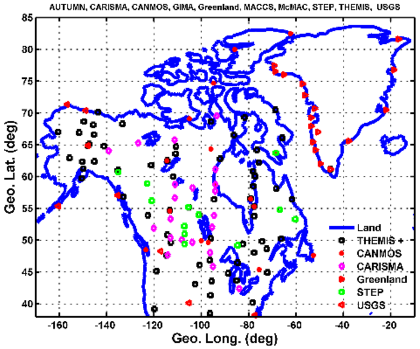


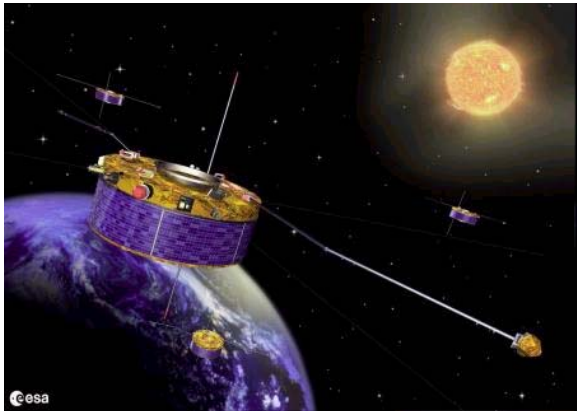
Magnetospheric Multi-Scale



Upstream monitors

Ground-based magnetometers



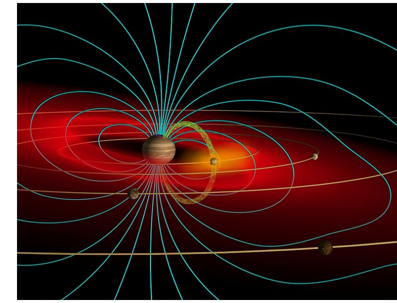


Cluster

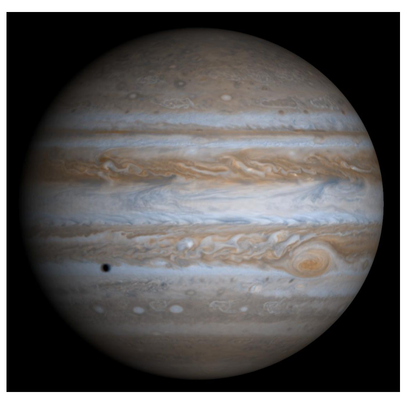
Vast array of ground-based and space-based instrumentation to monitor driving and response of Earth’s magnetosphere and ionosphere

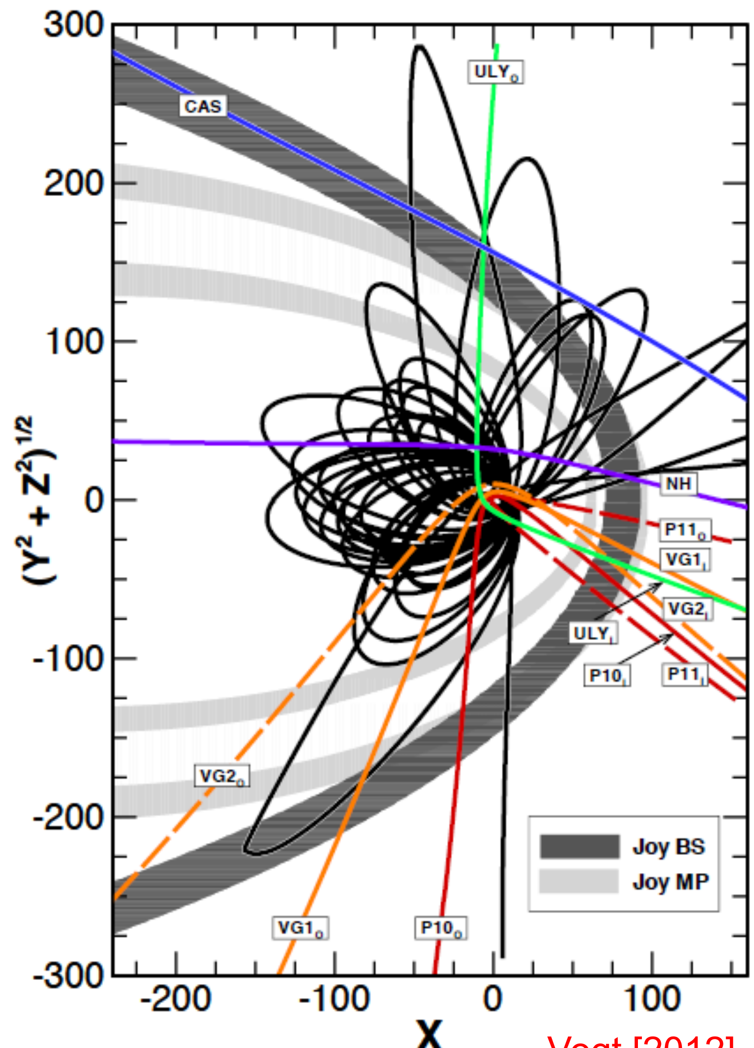
Jupiter

•JUICE (Launch 2022, arrival Jupiter 2030)
•Europa Clipper – in study phase



	Spacecraft Trajectory	Observation Interval
Pioneer 10	Flyby	Nov-Dec 1972
Pioneer 11	Flyby	Nov-Dec 1973
Voyager 1	Flyby	March 1979
Voyager 2	Flyby	August 1979
Ulysses	Flyby	Feb 1992
Galileo	Orbiter	Dec 1995 – Sept 2003
Cassini	Flyby	Dec 2000- Jan 2001
New Horizons	Flyby	Feb-March 2007
Juno	Orbiter	July 2016 - …..

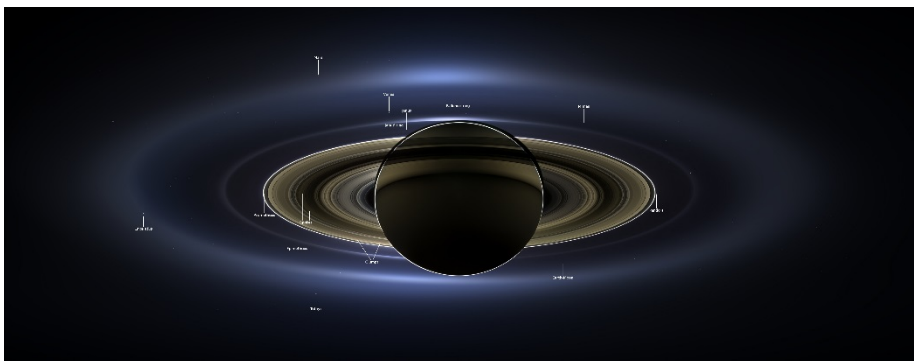


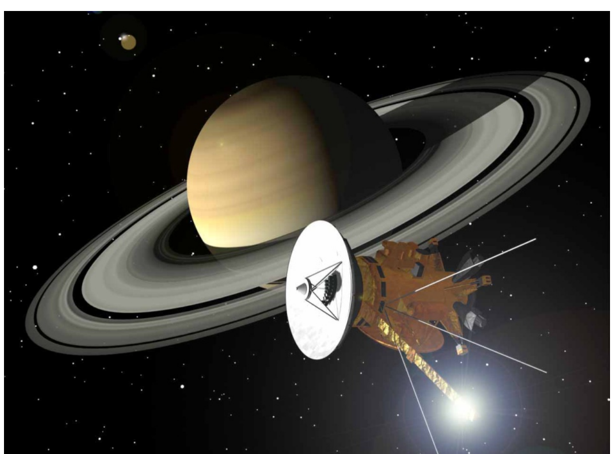


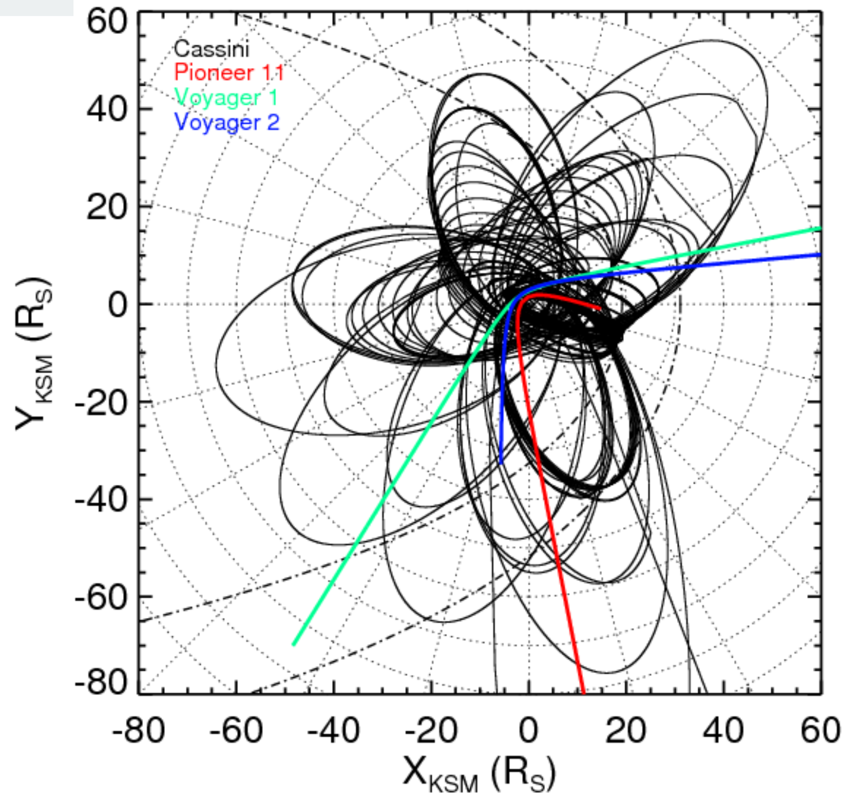
Vogt [2012]

Saturn

	Spacecraft Trajectory	Observation Interval
Pioneer 11	Flyby	September 1979
Voyager 1	Flyby	November 1980
Voyager 2	Flyby	August 1981
Cassini	Orbiter	July 2004 – Sept. 2017



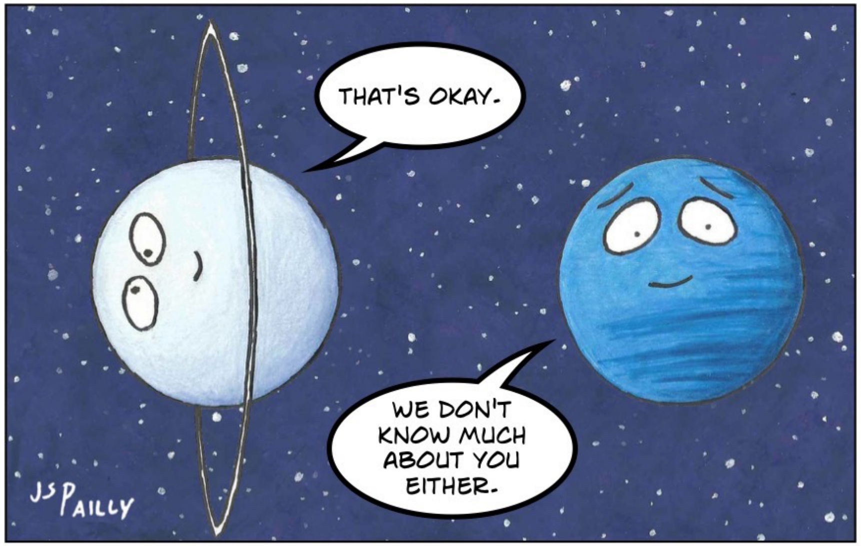


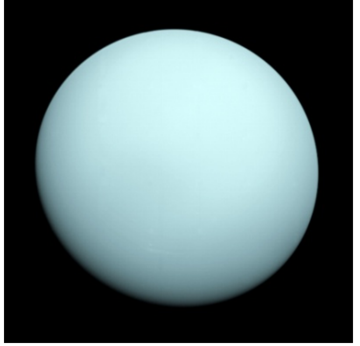


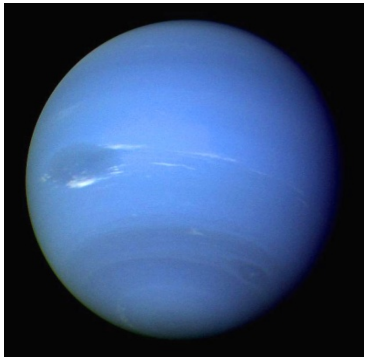
Jackman [2015]

Uranus and Neptune

NASA formed Science Definition Team for Ice Giants future missions







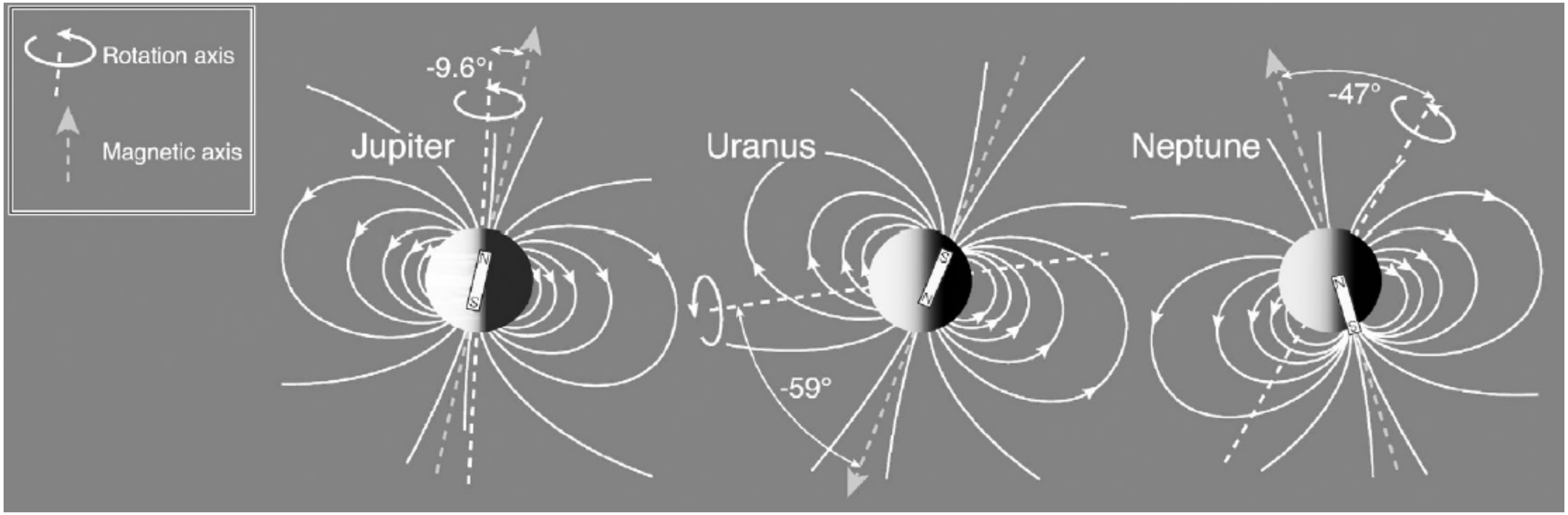


Image Courtesy Fran Bagenal

Outline: Planetary Plasma Environments

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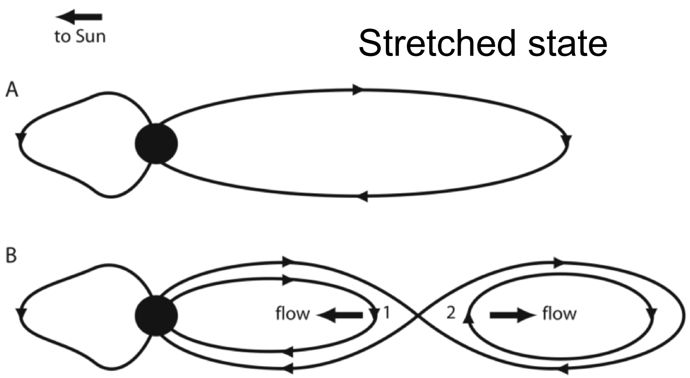
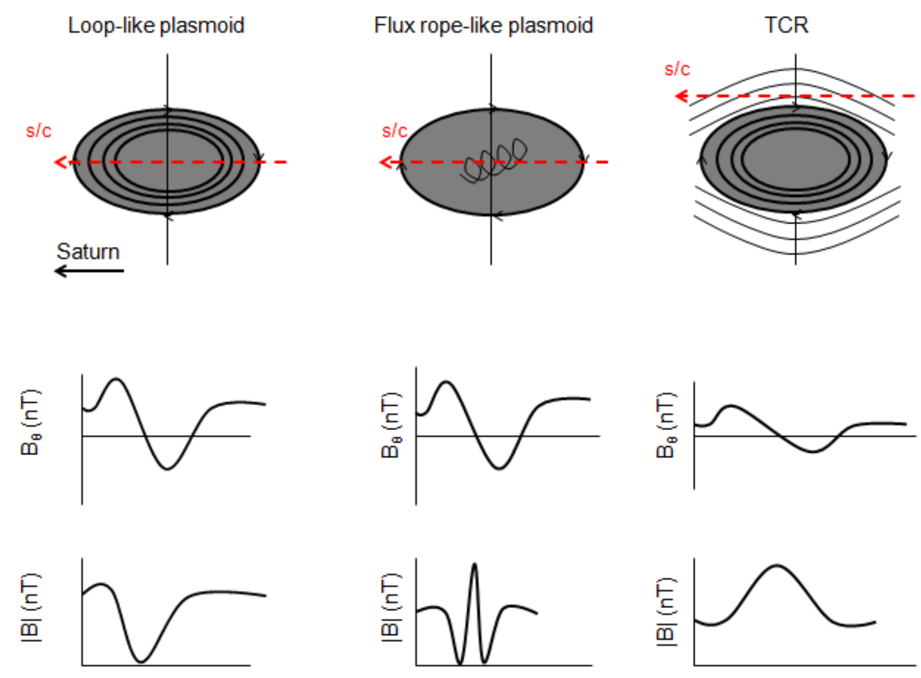
Reconnection signatures in situ



Vogt et al. [2010]

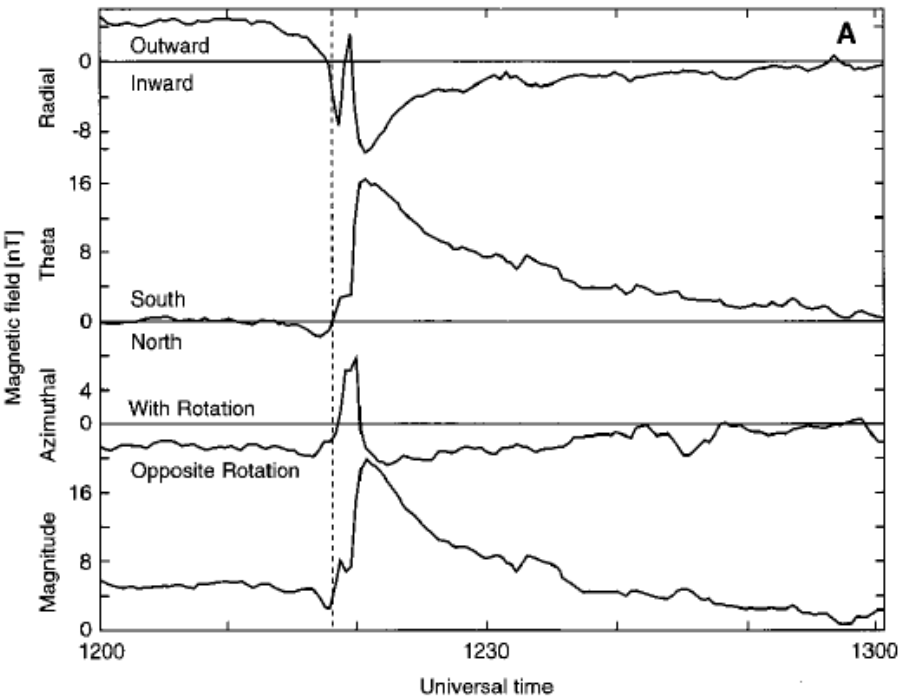
After reconnection, deflection in the north/south (B_θ) magnetic field component

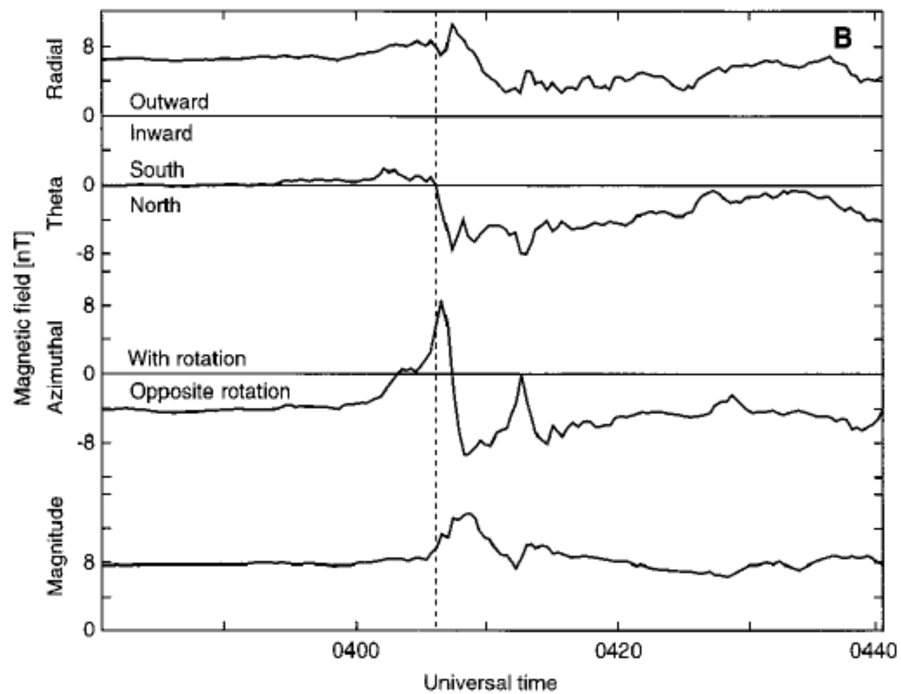


Jackman et al. [2014]

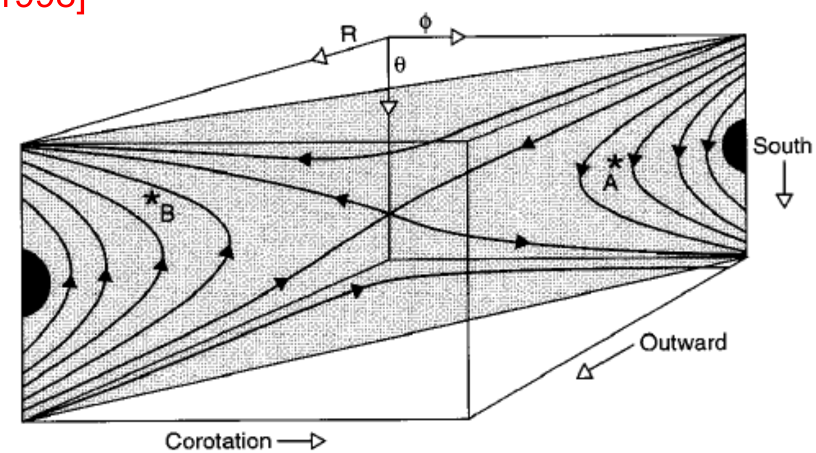
Plasmoid formation and ejection compresses adjacent regions of the magnetosphere to create Travelling Compression Regions (TCRs)

Reconnection signatures at Jupiter





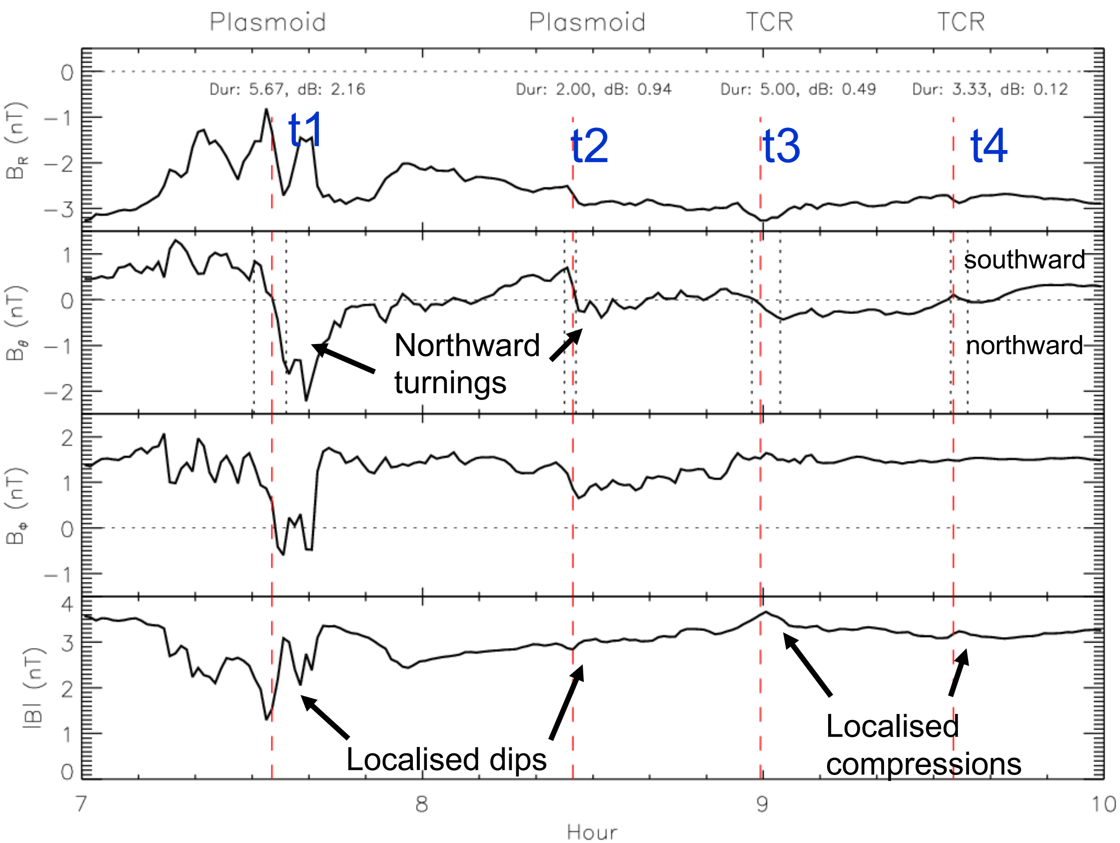
Russell et al., [1998]



Southward/northward turnings of field observed from Galileo data.

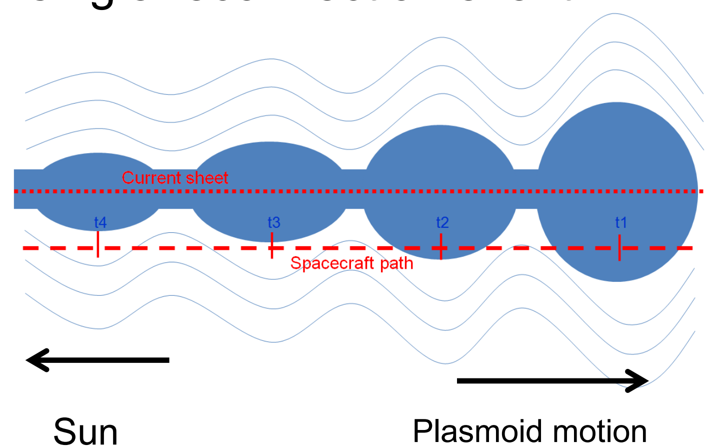
Interpreted as *in situ* evidence of reconnection.

Reconnection signatures at Saturn

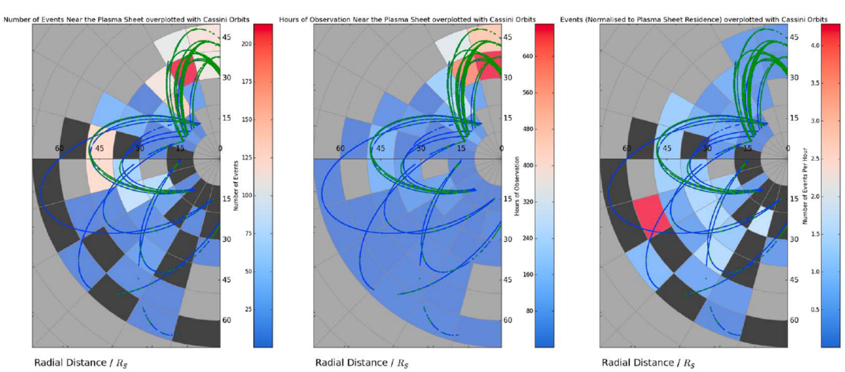


Cassini deep tail orbits rich dataset for finding plasmoids and TCRs

Multiple plasmoids released from single reconnection event.



Jackman et al., [2014]

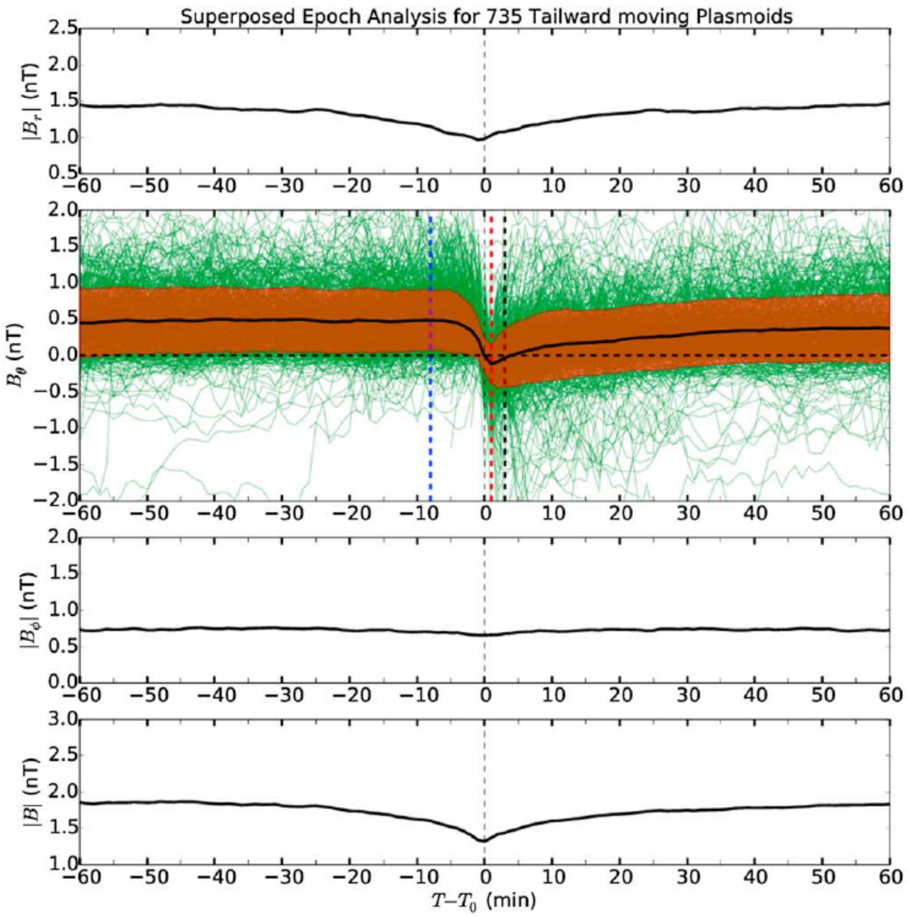


Smith et al., [2017]

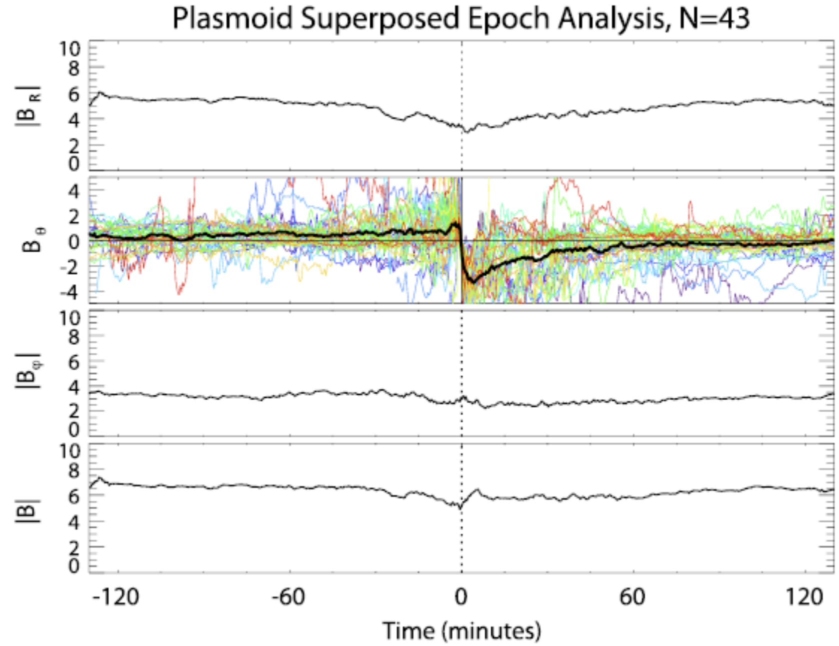
Huge catalogue of reconnection events in planetary magnetotails.

Automated algorithms and advanced machine learning techniques being developed to speed up the search

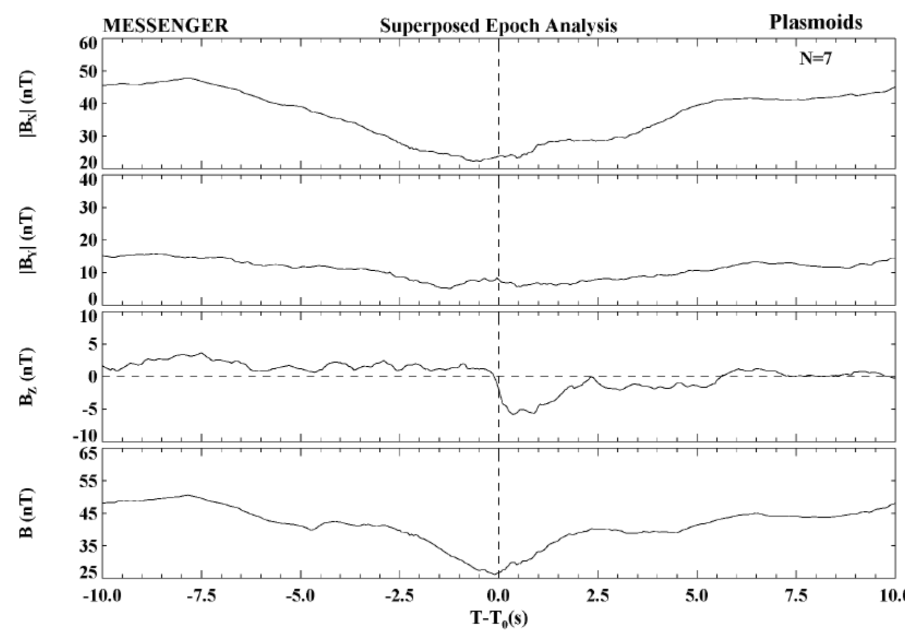
Average field signatures



Saturn: Smith et al. [2017]

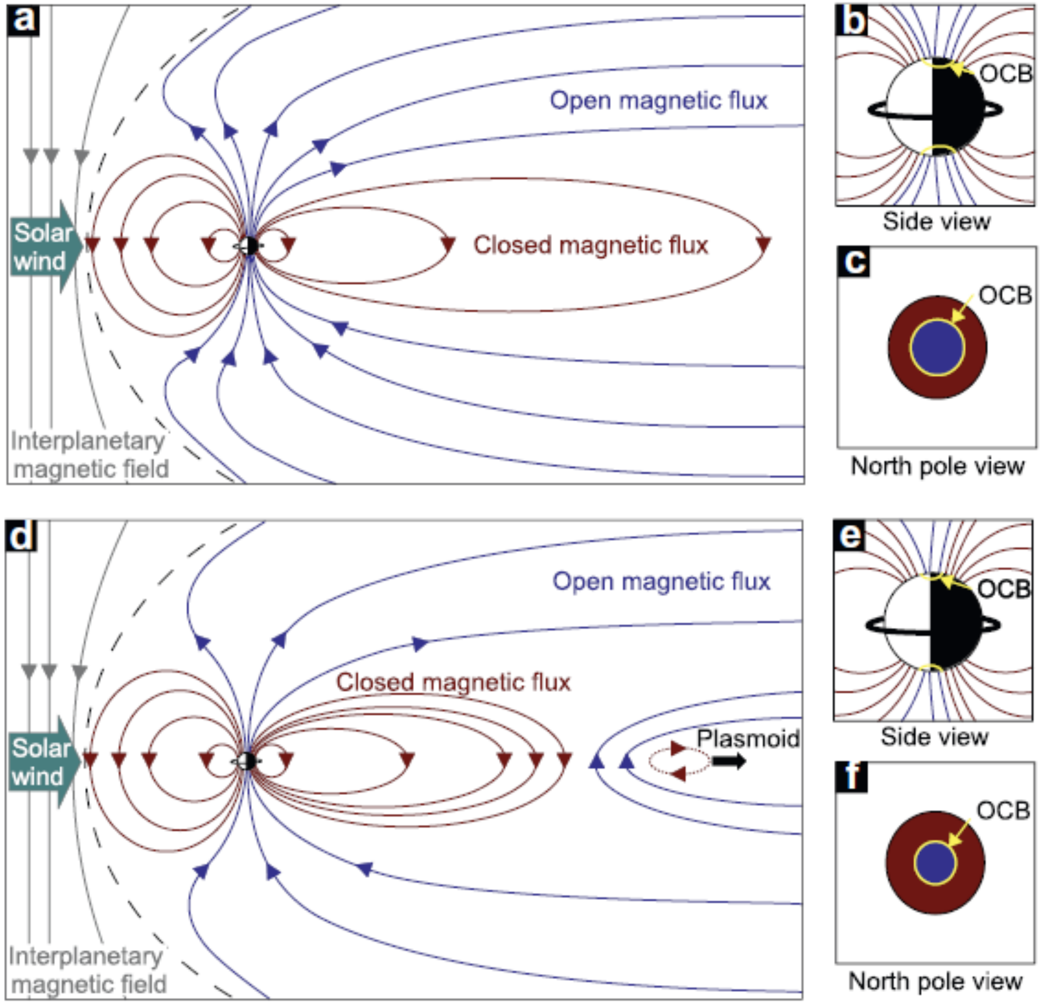


Jupiter: Vogt et al. [2014]



Mercury: Slavin et al. [2012]

Flux transport 1:



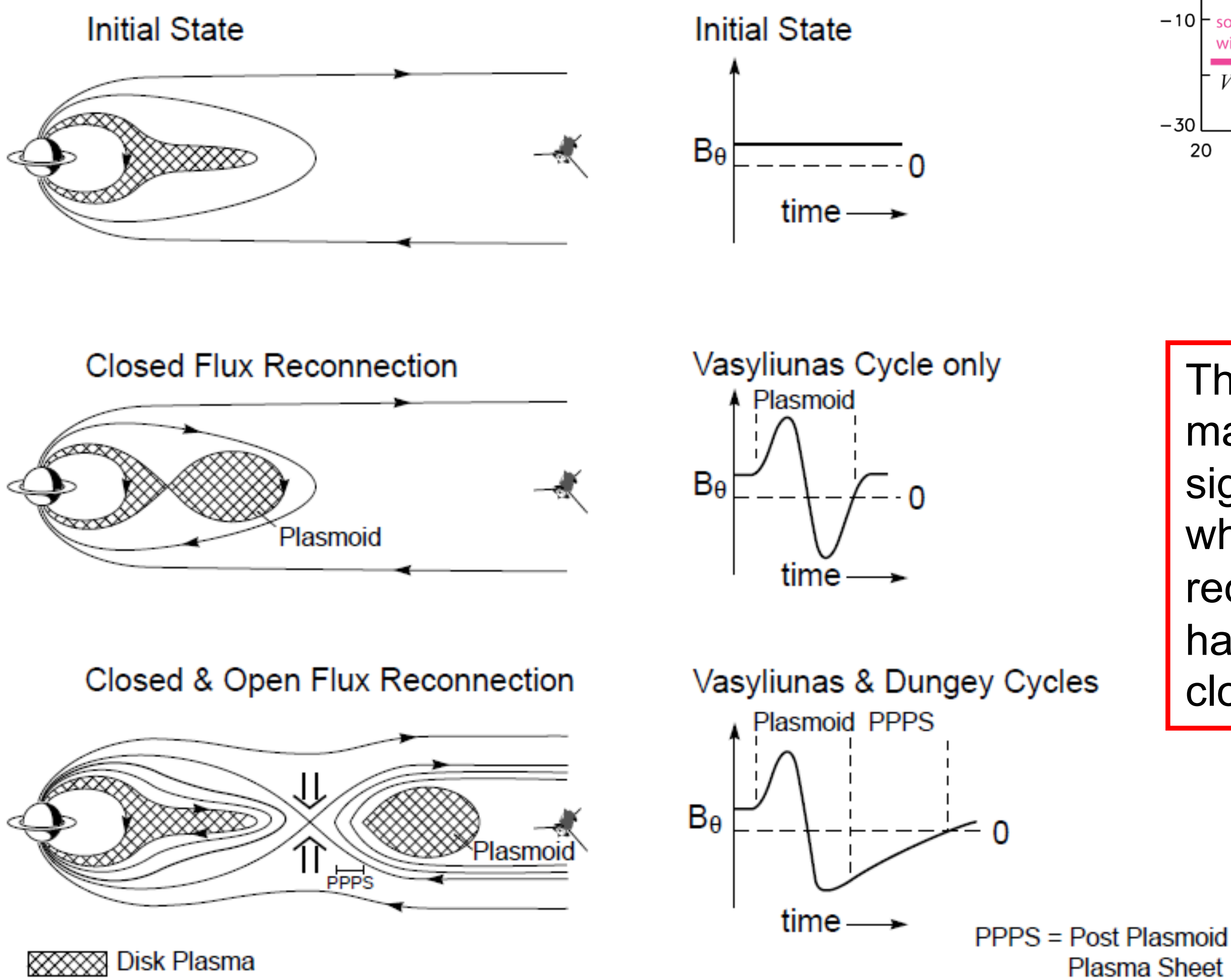
Badman et al. [2014]

Magnetic reconnection at the dayside adds open flux to the magnetosphere.

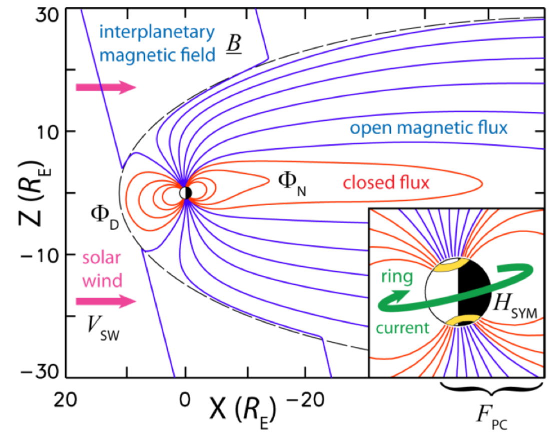
An equal flux must ultimately be closed through reconnection at the nightside.

This flux balance tells us about the dynamics of the magnetosphere.

Flux transport 2:



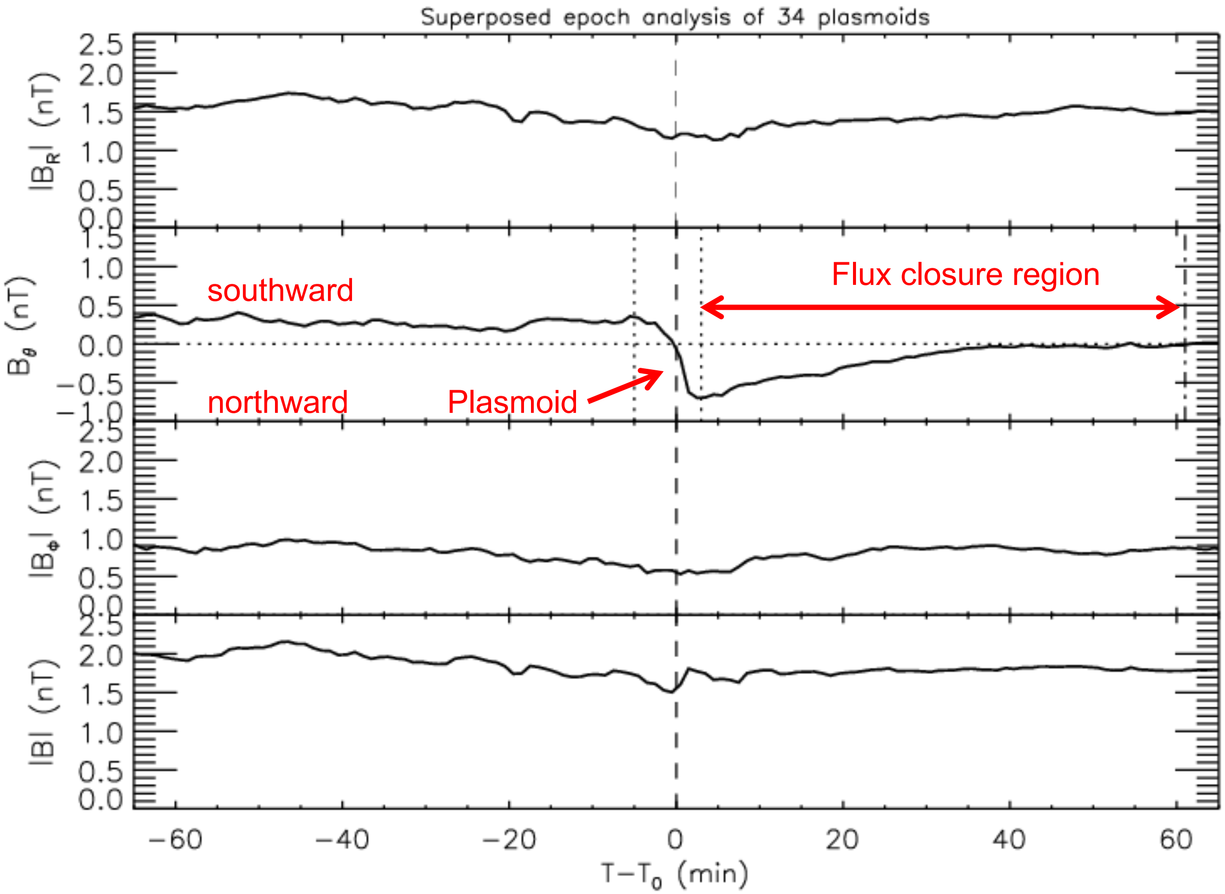
Jackman et al., [2011]



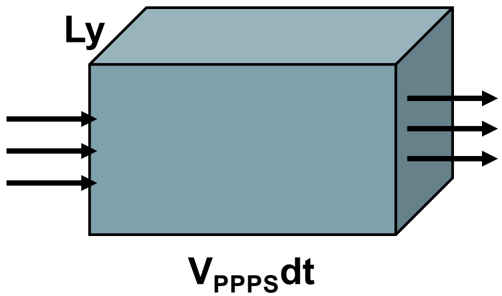
Milan [2009]

The nature of the magnetic field signature can tell us which type of reconnection is happening (open vs. closed field lines)

Flux closure: Saturn



Extended interval of northward field: flux closure



$\Phi_{PPPS}/Ly = \int B_\theta V_{PPPS} dt$

Jackman et al. [2011]

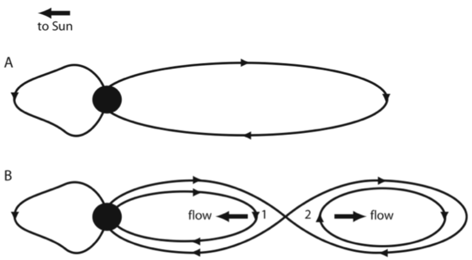
Assumptions: Plasma velocity: V_{PPPS} = 800 km/s [Hill et al., 2008]

Azimuthal extent of reconnection region (upper limit tail width): Ly = 90 R_S

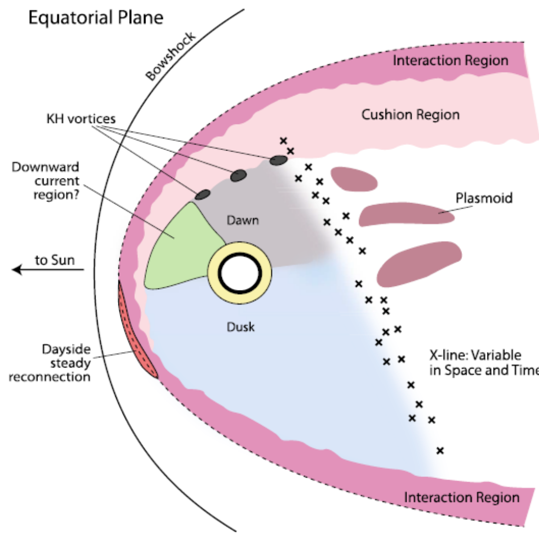
dt = 58 min, Φ_{PPPS}/Ly = 0.555 Wb/m

For Ly=90 R_S, Each event closes ~3 GWb (~7% of typical tail flux content)

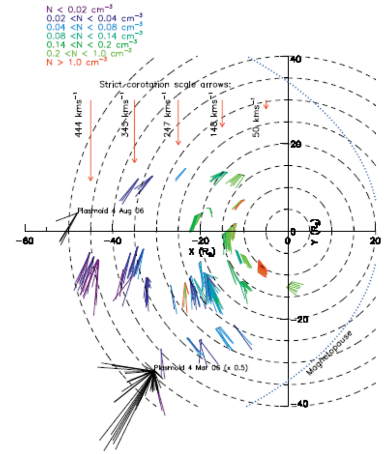
The Mass Budget Problem: Jupiter and Saturn



Vogt et al. [2010]



Delamere and Bagenal [2010]

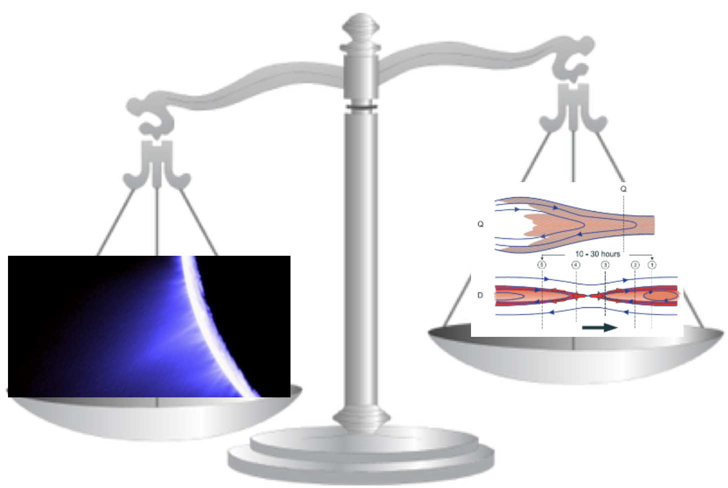


McAndrews et al. [2009]

What goes in:

Jupiter Io loading:
~500 kg/s

Saturn Enceladus loading:
~100 kg/s



What comes out:

Large-scale plasmoid release:

Jupiter:
Up to ~120 kg/s

Saturn:
Up to ~40 kg/s

Alternative mass loss mechanisms required to “balance” budget?

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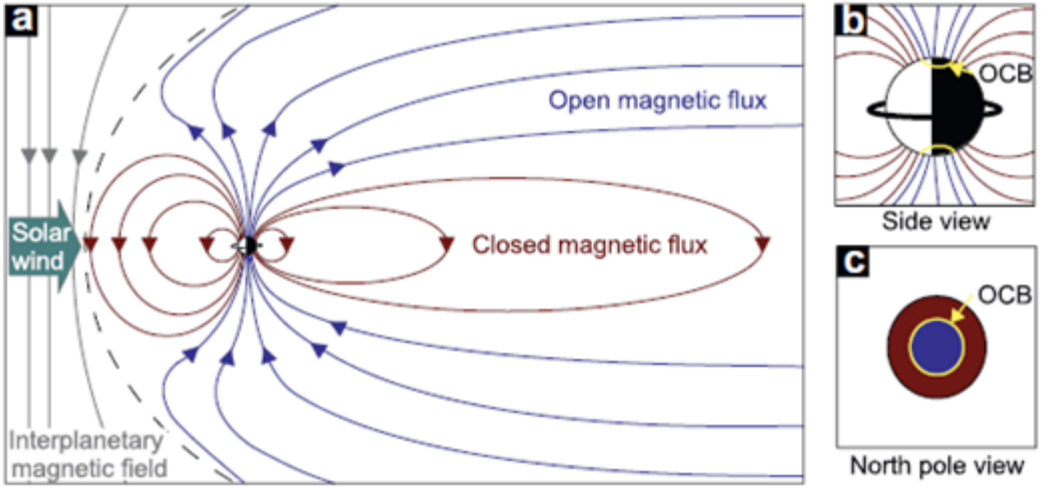
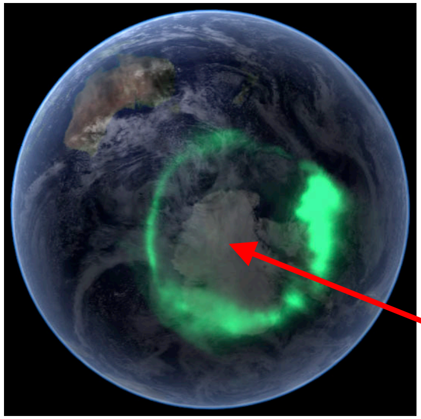
Auroral imaging

UV aurora:
Caused by precipitating particles.

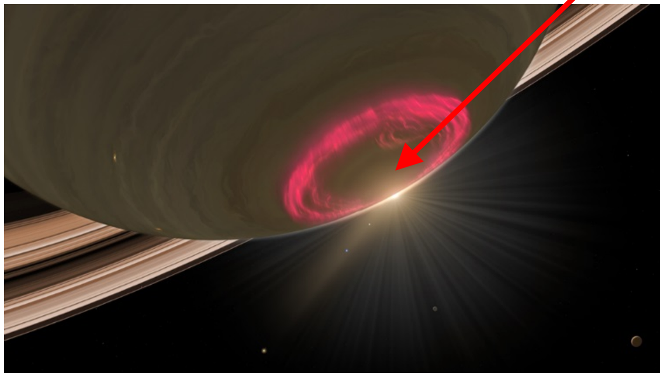
Currents generated by:
1) Velocity shear at open-closed field line boundary

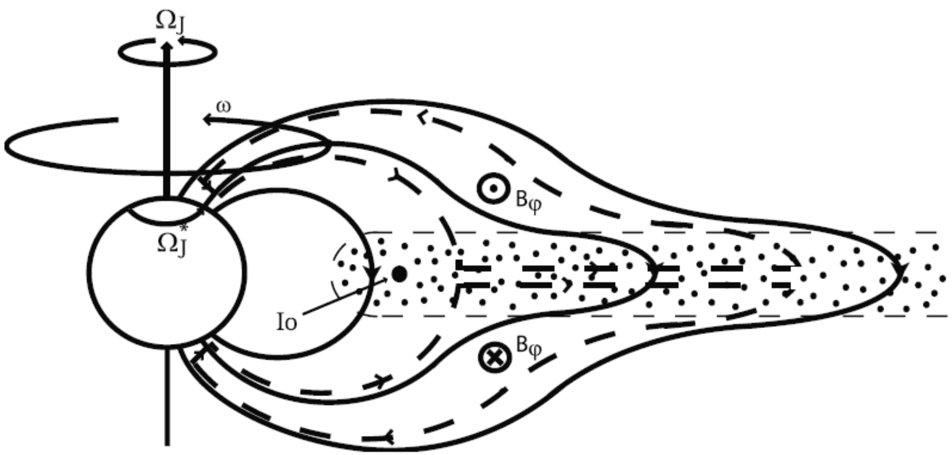


Badman et al. [2014]



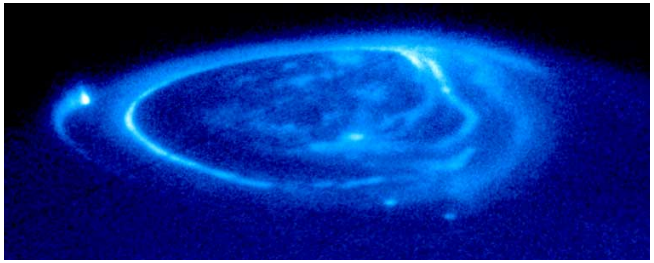
Polar cap



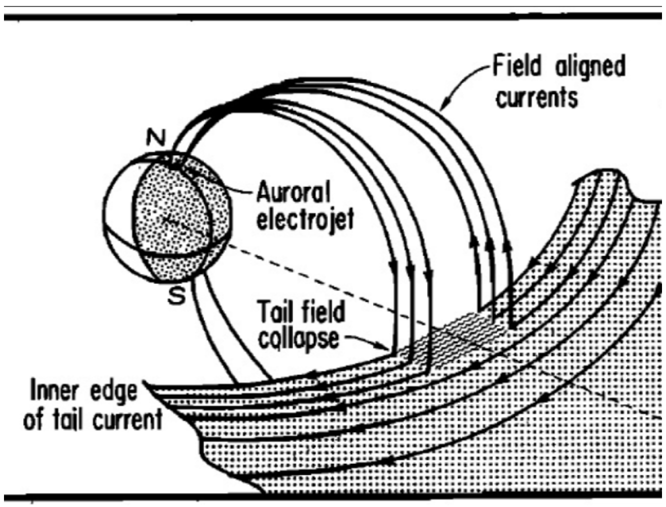


Cowley and Bunce [2001]

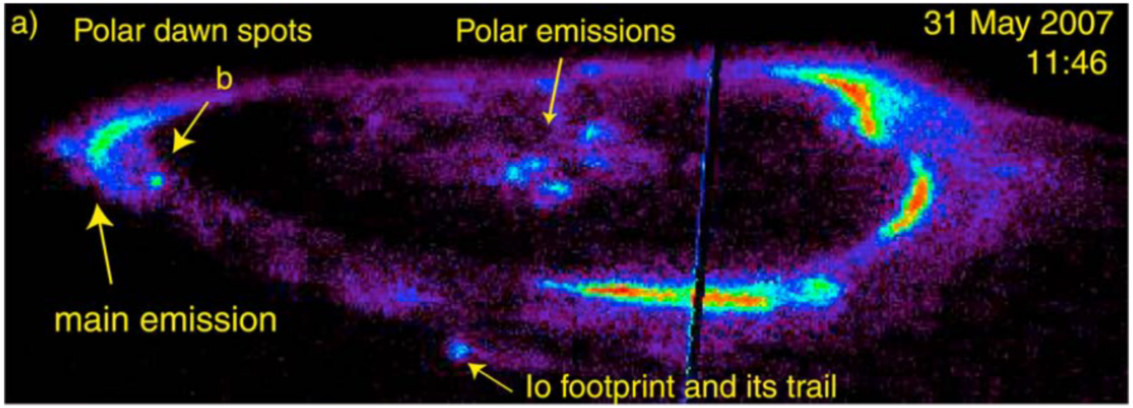
2) Corotation breakdown/ angular momentum conservation



Smaller-scale auroral features

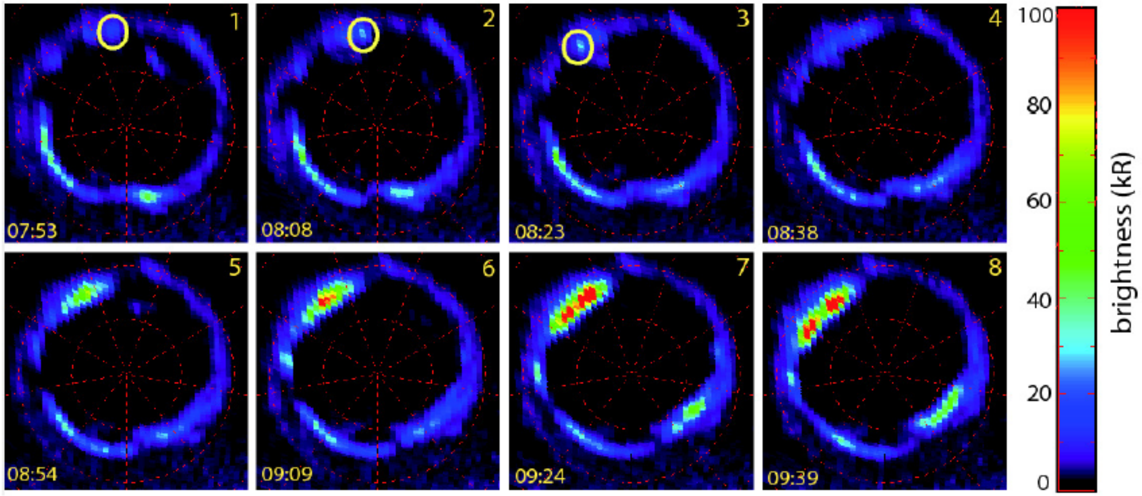


McPherron et al., [1973]



Radioti et al., [2010]

- Tail reconnection
- Diversion of cross-tail current
- Field-aligned currents flow into ionosphere
- Spots formed near auroral oval



Jackman et al., [2013]

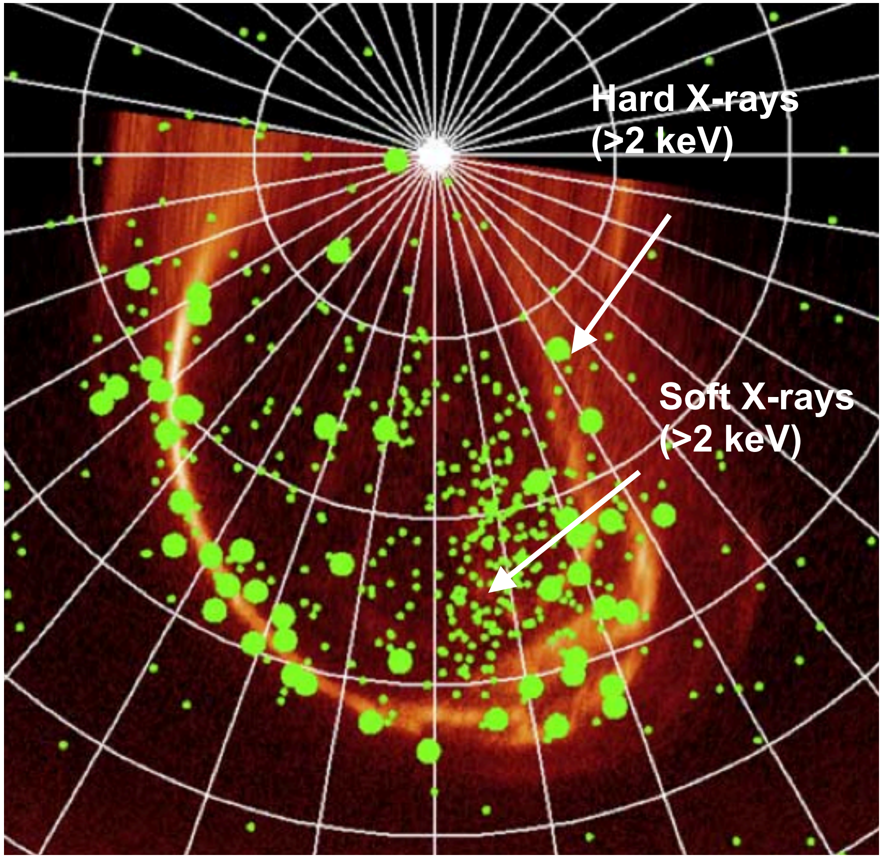
Auroral imaging

X-ray aurora:

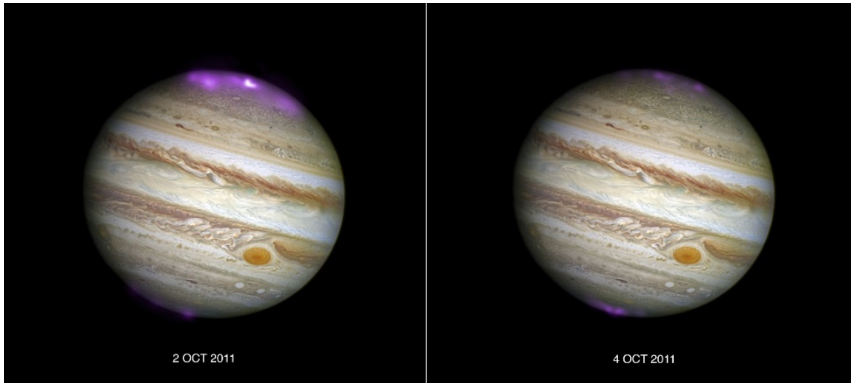
Jupiter:

(1) Disc emission: Scattering of solar X-ray photons in the upper atmosphere

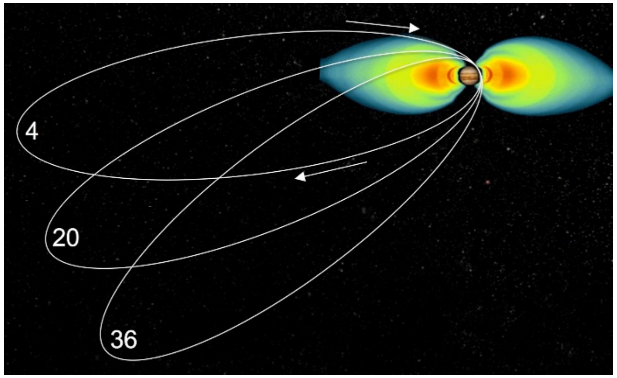
(2) Polar emission: charge exchange between precipitating ions (source??) and atmospheric neutral hydrogen molecules



Branduardi-Raymont et al. [2008]



Dunn et al. [2015]



Juno trajectory: Polar magnetosphere coverage

Radio emissions

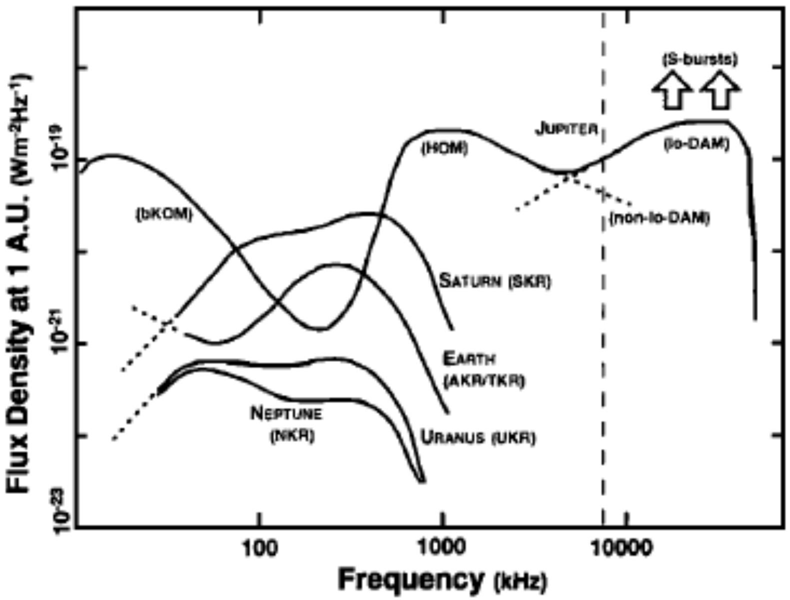
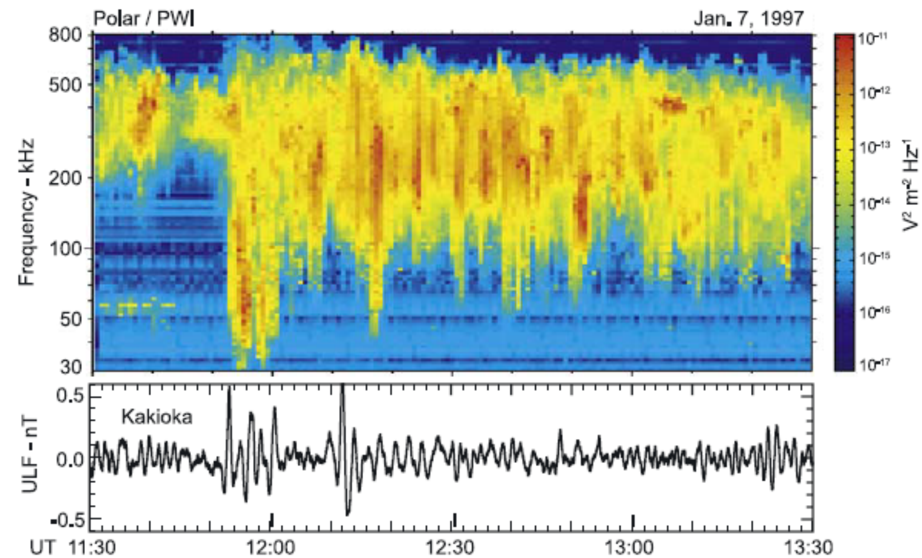


Figure 1. Comparative spectra of auroral radio emissions. Average emission levels are sketched, normalized to a distance of 1 AU from the source. They are based on 2-6 days of Voyager/PRA measurements for each spectrum, recorded from a 100-500 planetary radii range, with LH and RH polarizations mixed together. Errors about ±3 dB are due to PRA calibration. Peak flux densities are ≥10 times higher than the displayed levels, and Jovian S bursts up to ≥100 times higher. The low-frequency limit of DAM control by Io is somewhere about 1 MHz (not accurately known). That of other planetary radio emissions is a few kHz. ITKR extends the TKR range below ~50 kHz, down to ~10 kHz. The displayed curves may vary with time and observer location (adapted from *Zarka* [1992a]).

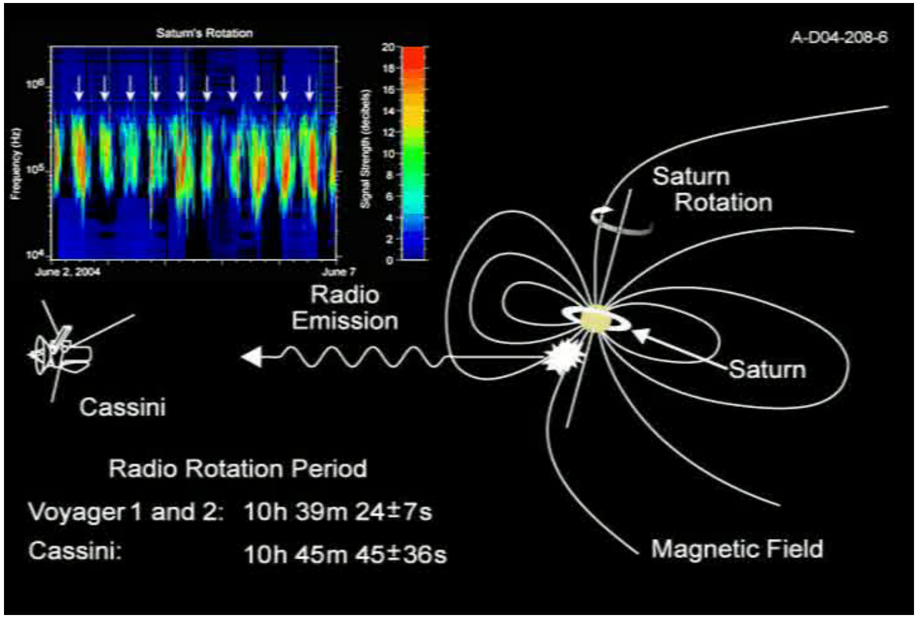
Zarka et al. [1998]

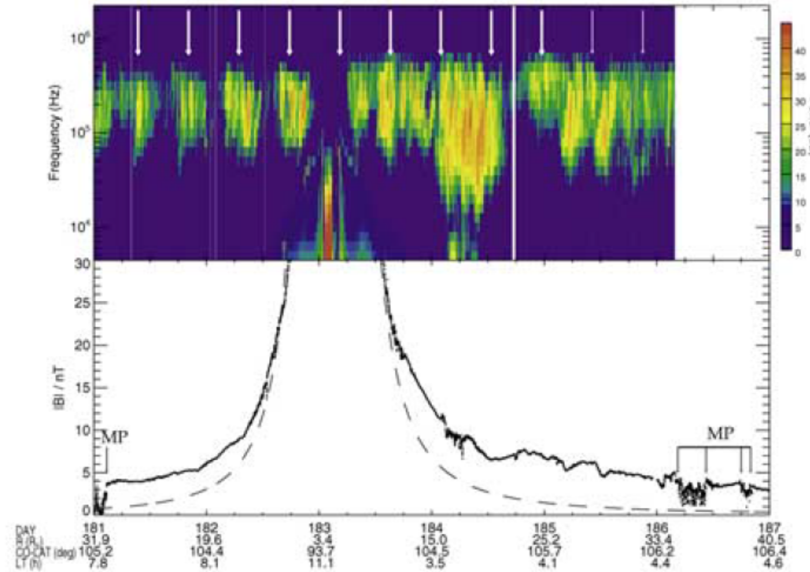


Can be used as a remote proxy for magnetospheric dynamics
(e.g. intensification and low frequency extensions of AKR linked to substorm onset at Earth)

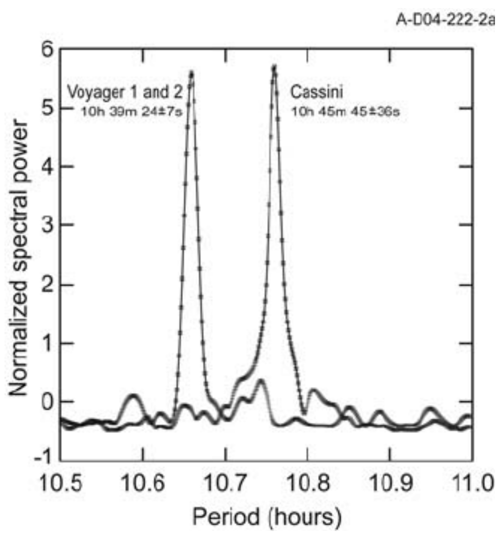
Morioka et al. [2007]

Saturn's puzzling radio emissions

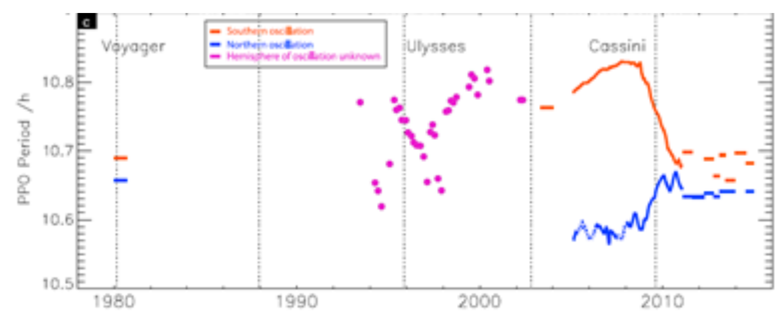




Bunce et al. [2005]



Gurnett et al. [2005]



Provan et al. [2015]

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