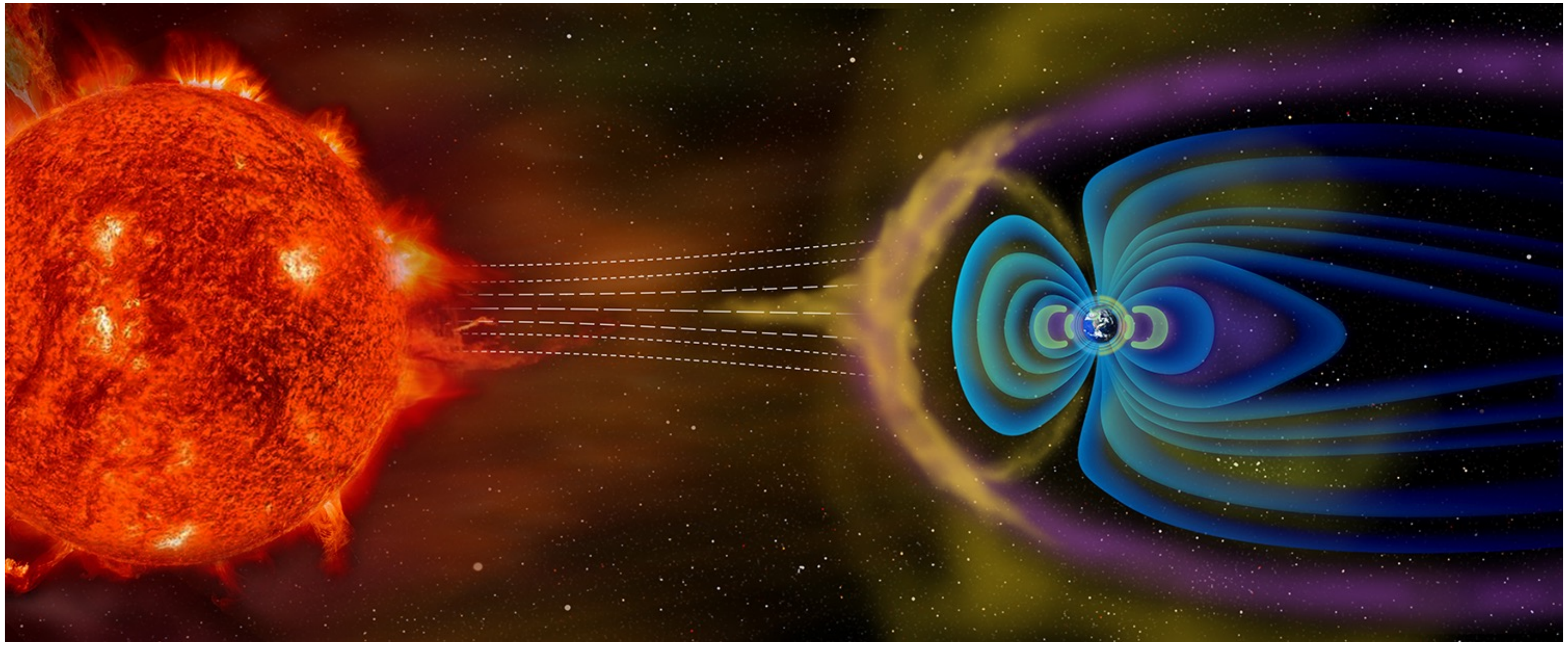

Image Credit: NASA

Global Structure of the Magnetosphere

Michael Hartinger

July 20, 2023

Heliophysics Summer School 2023: Observational Heliophysics

Acknowledgements: Past HSS lectures from Fran Bagenal, Frank Toffoletto, and Nicholas Achilleos

Goal for Today

- High-level introduction to key factors controlling the structure of planetary magnetospheres, with major focus on the Earth’s magnetosphere
- Show of hands: Who is studying the Earth’s magnetosphere?

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- References:
  - "Principles of Heliophysics: a textbook on the universal processes behind planetary habitability," especially Chapter 5.5.4-5.5.7
  - Kivelson, M. G., & Russell, C. T. (Eds.). (1995). *Introduction to space physics*. Cambridge university press.
  - Previous HSS lectures by Fran Bagenal, Frank Toffoletto, and Nicholas Achilleos

What is a magnetosphere?

- Principles of Heliophysics 5.5.5: “The magnetosphere is then the region of space around the central object within which the object's magnetic field has a dominant influence on the dynamics of the local medium”
- Not every planet has a magnetosphere
- Some moons have magnetospheres

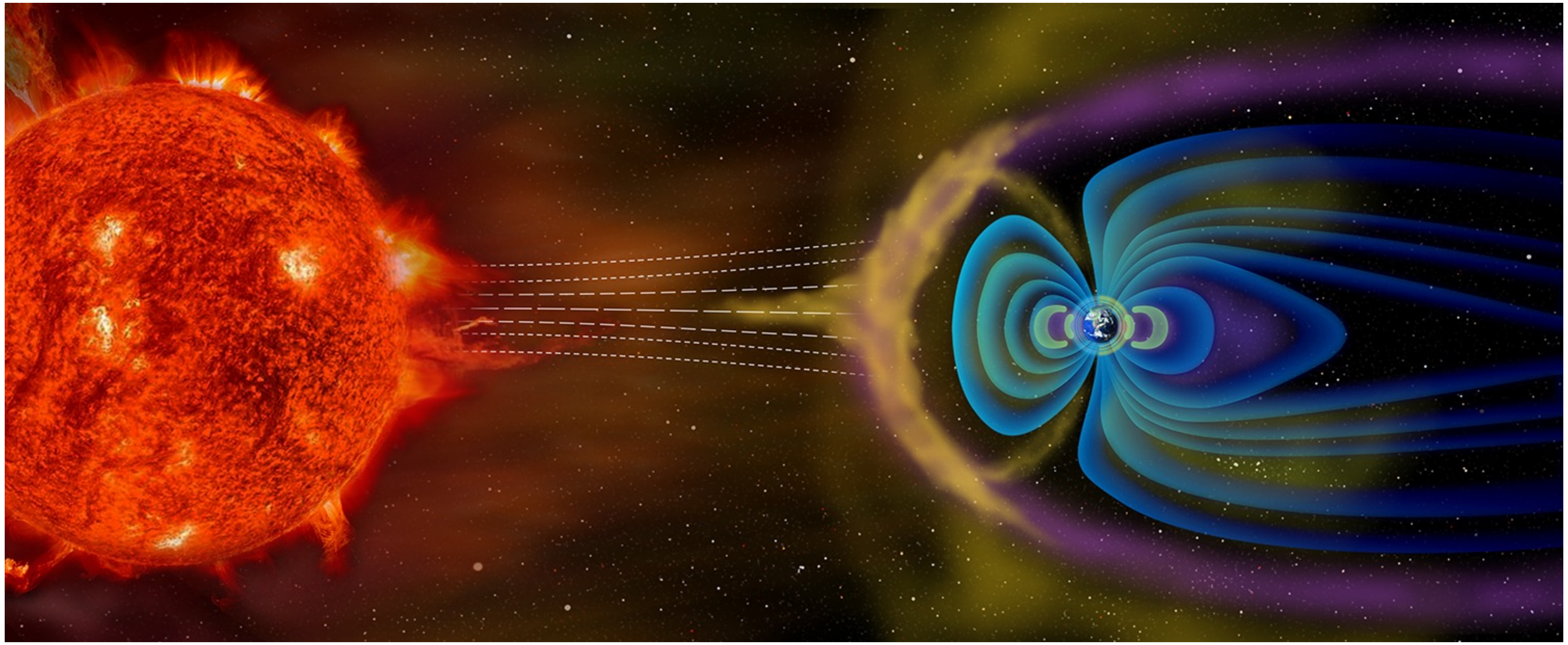


Image Credit: NASA

Major factors controlling the global structure of magnetospheres

- Properties of the ambient medium – example: solar wind dynamic pressure
- Properties of the object's magnetic field – example: magnetic field strength [Can you think of other examples of magnetic field properties that might matter?]
- Object's rotation rate and rotation axis
- Properties of the object's atmosphere

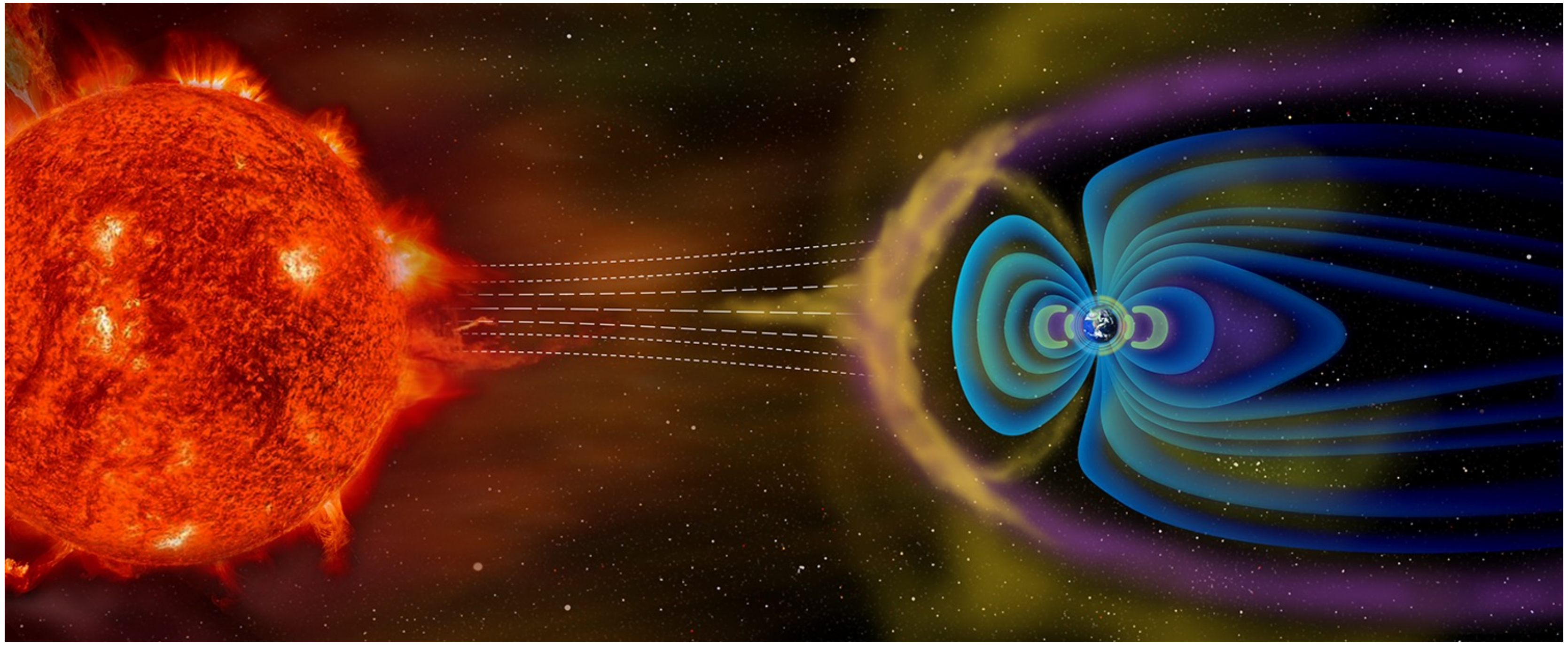
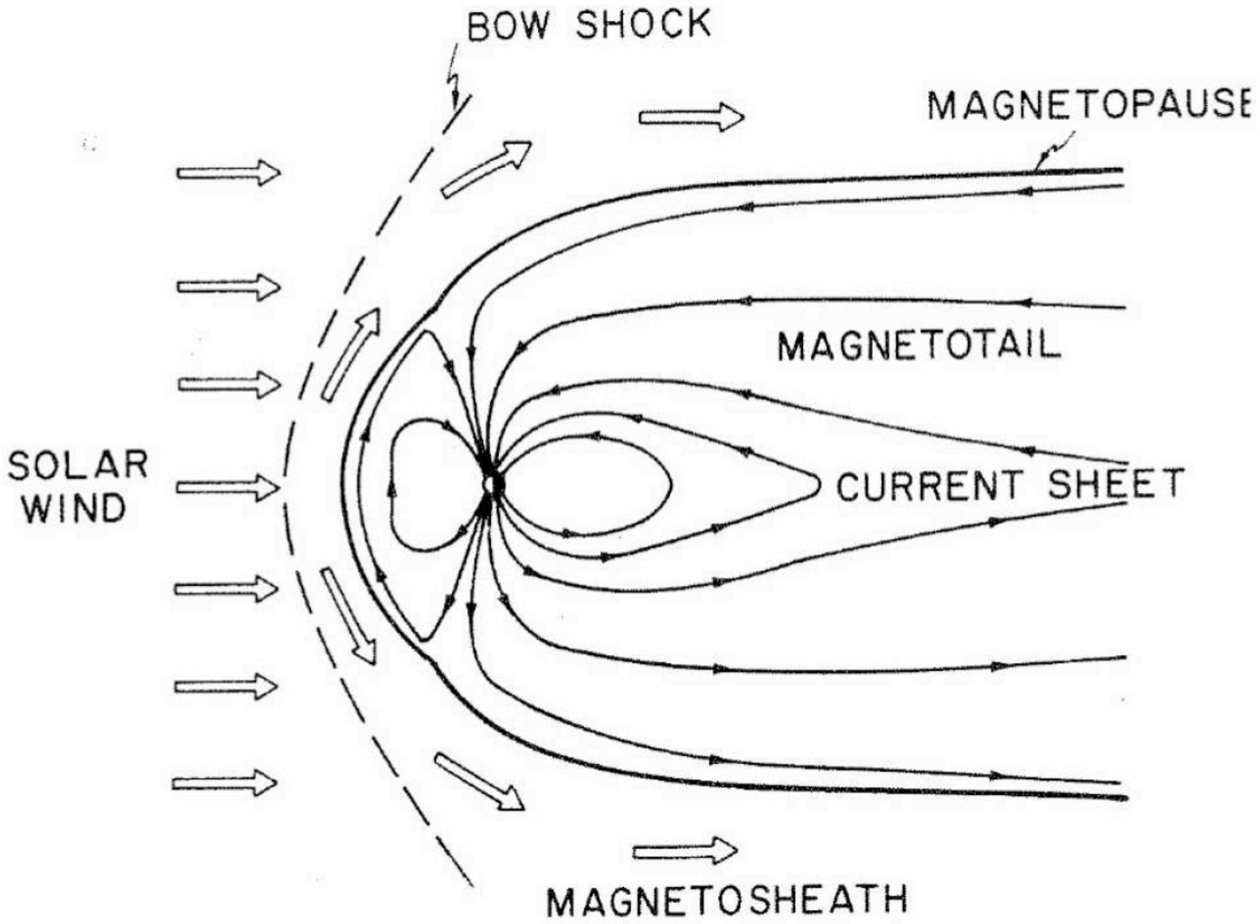


Image Credit: NASA

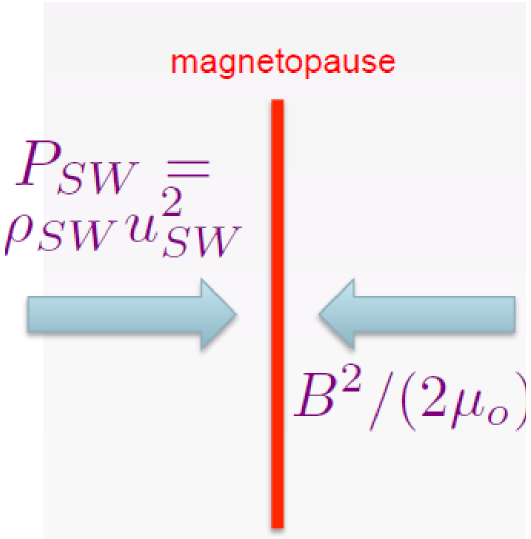
Solar wind-magnetosphere interaction: shock

- [Covered more extensively in Frank Toffoletto's 2011 lecture]
- At Earth and other planetary magnetospheres, the solar wind flow is supersonic → shock formation
- Kinetic energy is converted to thermal energy, flow is diverted around the Earth or other object



"Principles of Heliophysics," Fig I: 10.1

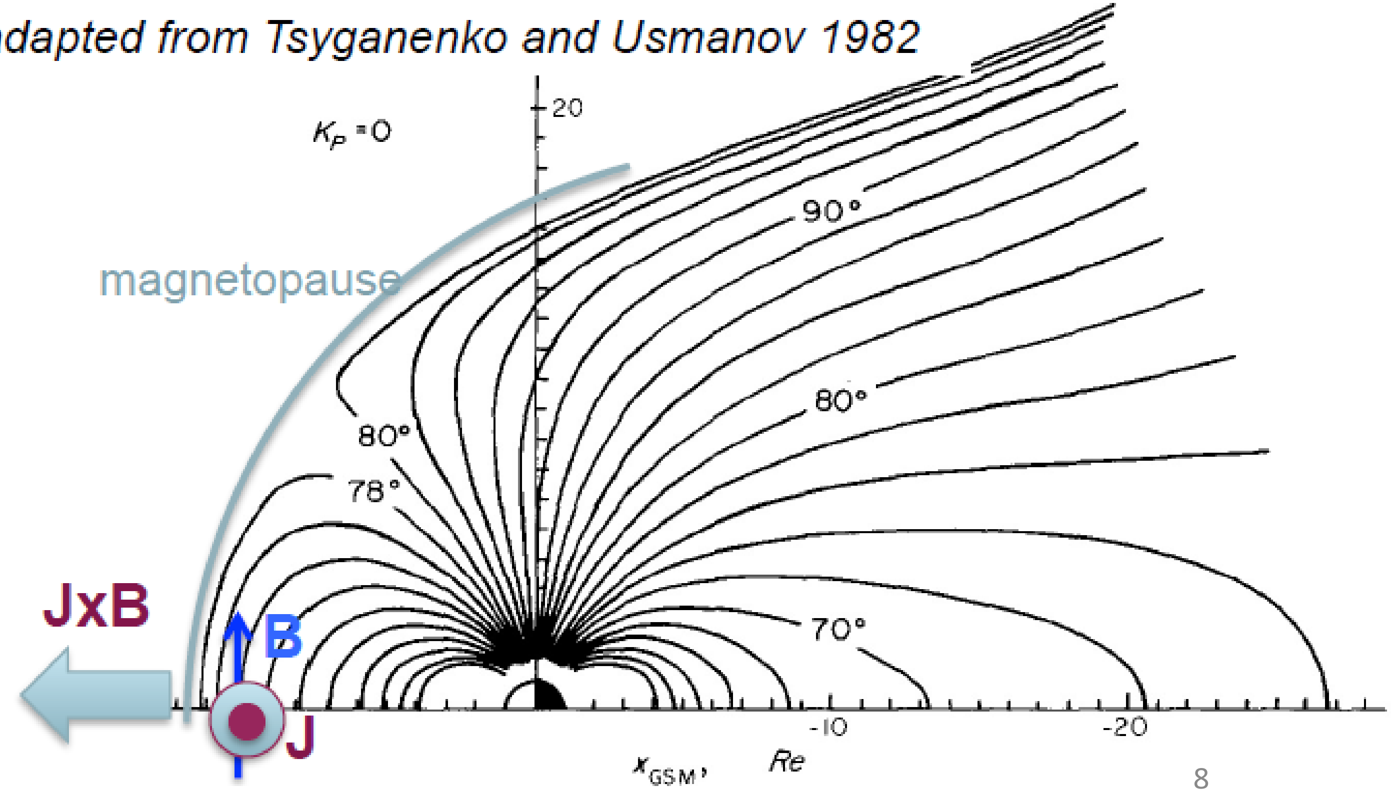
Solar wind-magnetosphere interaction: pressure balance



- Pressure balance is crucial in determining the typical location of the outer boundary, or magnetopause
- At Earth, the pressure balance is dominated by the solar wind dynamic pressure and the Earth's magnetic pressure
- Magnetopause currents reflect this pressure balance
- If the magnetic field is proportional to 1/r^3, then

$$R_{MP} \propto P_{SW}^{-1/6}$$

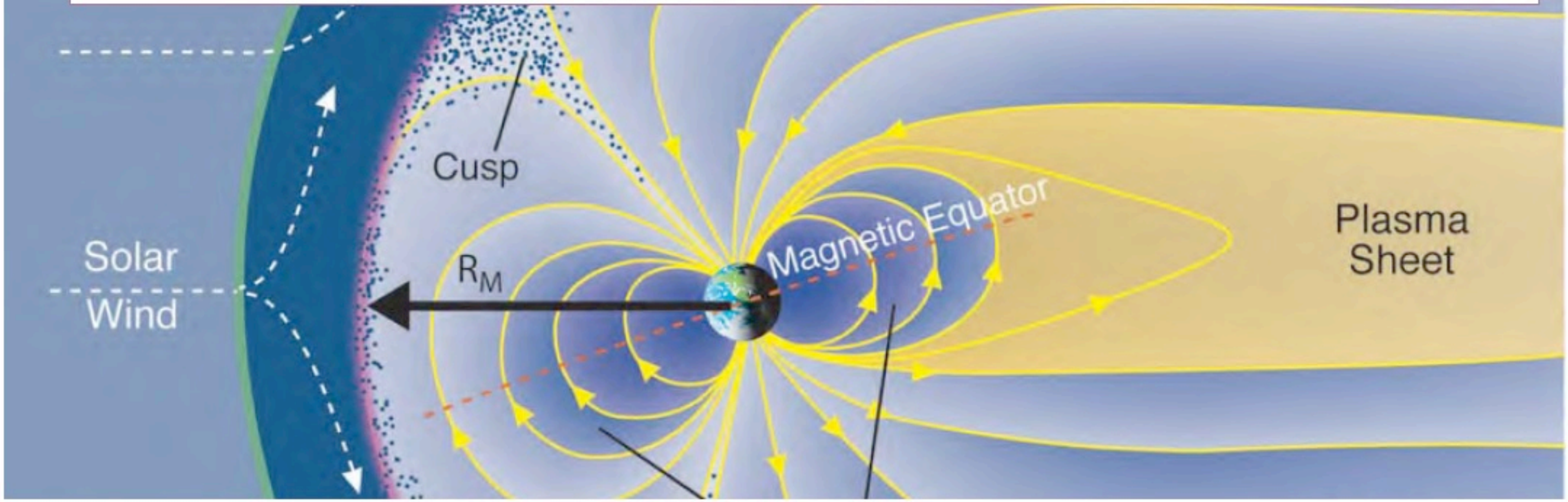
adapted from Tsyganenko and Usmanov 1982



Achilleos 2015
HSS lecture

Dipole Magnetic Field in Solar Wind

SW Ram Pressure ⟷ Magnetic Pressure



$$R_{MP} / R_{planet} \sim 1.2 \left[B_o^2 / 2 \mu_o \rho_{sw} V^2_{sw} \right]^{1/6}$$

Chapman-Ferraro Distance

Bagenal 2014
HSS lecture

$$R_{MP}/R_{planet} \sim 1.2 \{B_o^2 / 2 \mu_o \rho_{sw} V^2_{sw}\}^{1/6}$$

Slide from Fran Bagenal 2014 HSS lecture

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
B_o Gauss	.003	.31	4.28	.22	.23	.14
R_{MP} Calc.	1.4 R_M	10 R_E	46 R_J	20 R_S	25 R_U	24 R_N
R_M Obs.	1.4-1.6 R_M	8-12 R_E	63-92 R_J	22-27 R_S	18 R_U	23-26 R_N

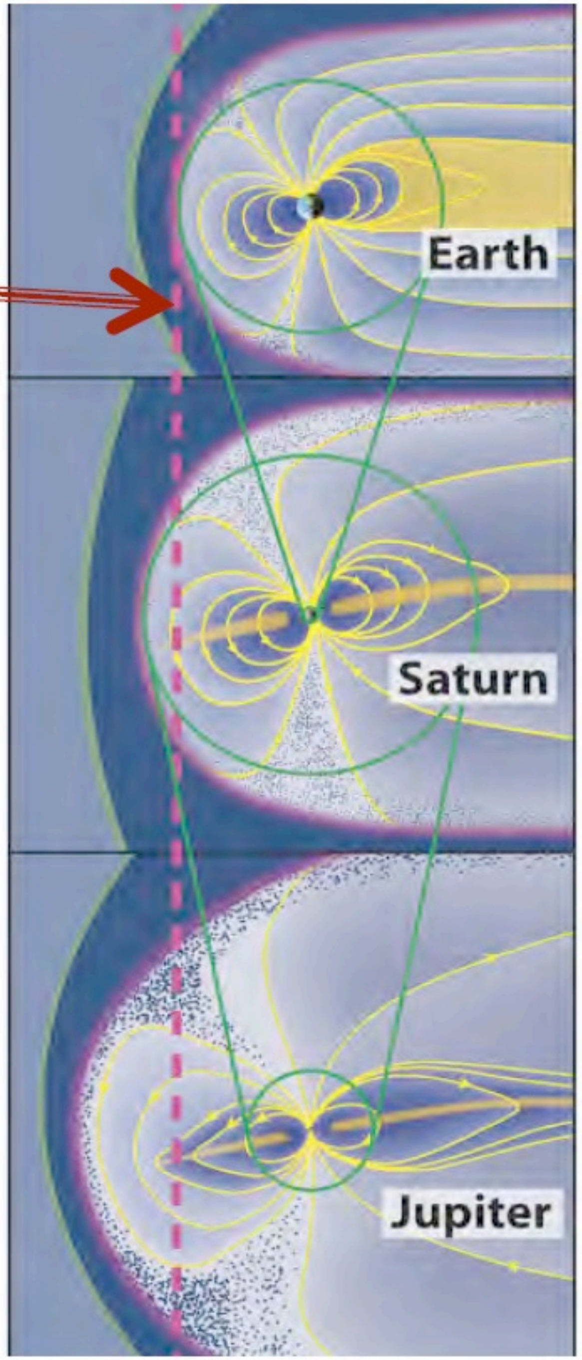
Magnetospheres scaled by stand-off distance of dipole field

	M/M_E	MP_{Dipole}	MP_{mean}	MP_{Range}
Mercury	~8×10^{-3}	1.4 R_M	1.4 R_M	
Earth	1	10 R_E	10 R_E	
Saturn	600	20 R_S	24 R_S	22-27* R_S
Jupiter	20,000	46 R_J	75 R_J	63-92# R_J

Inflated magnetospheres of Jupiter & Saturn due to HOT PLASMAS

Note bimodal average locations

* *Achilleos et al. 2008* # *Joy et al. 2002*



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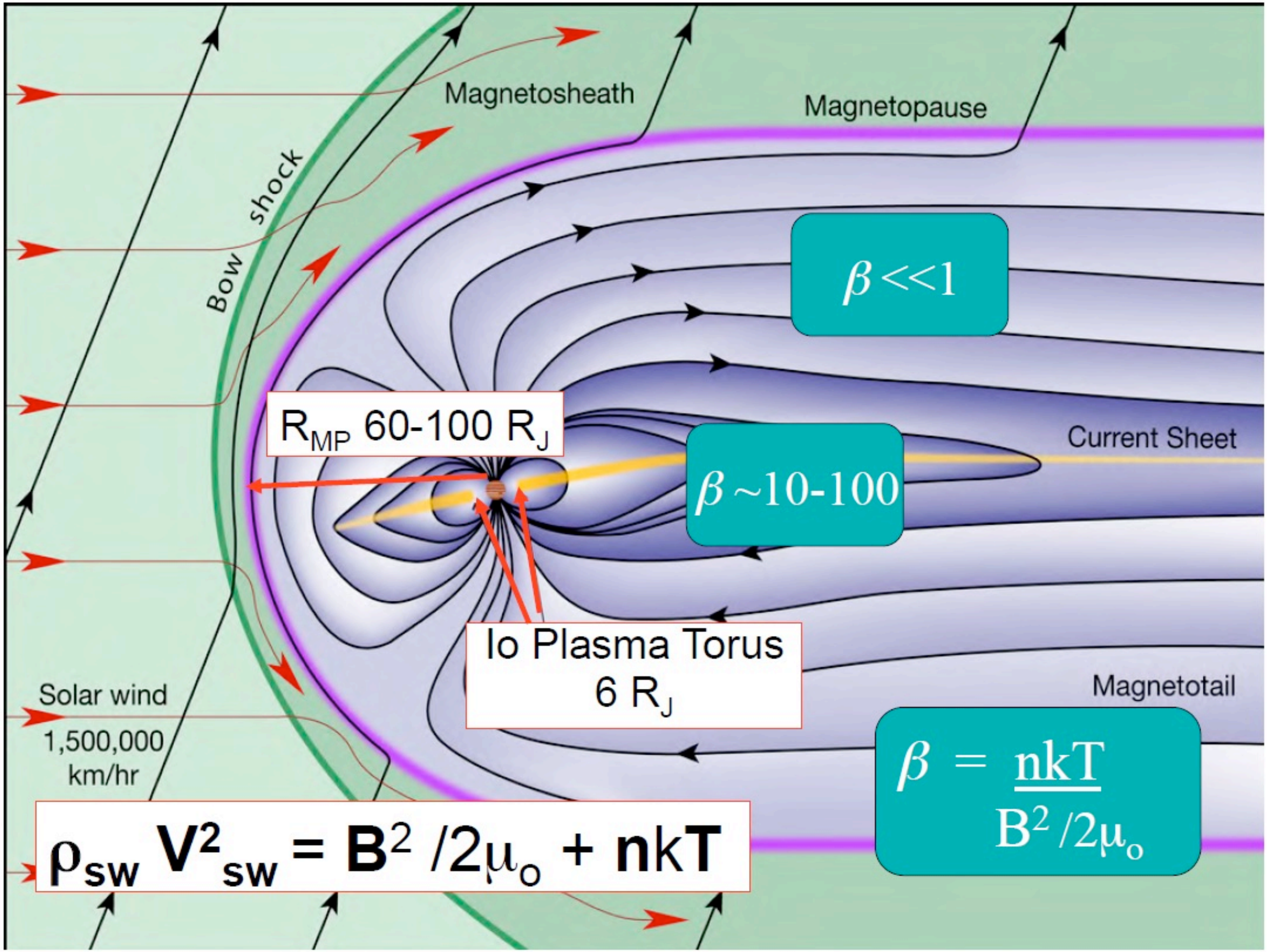

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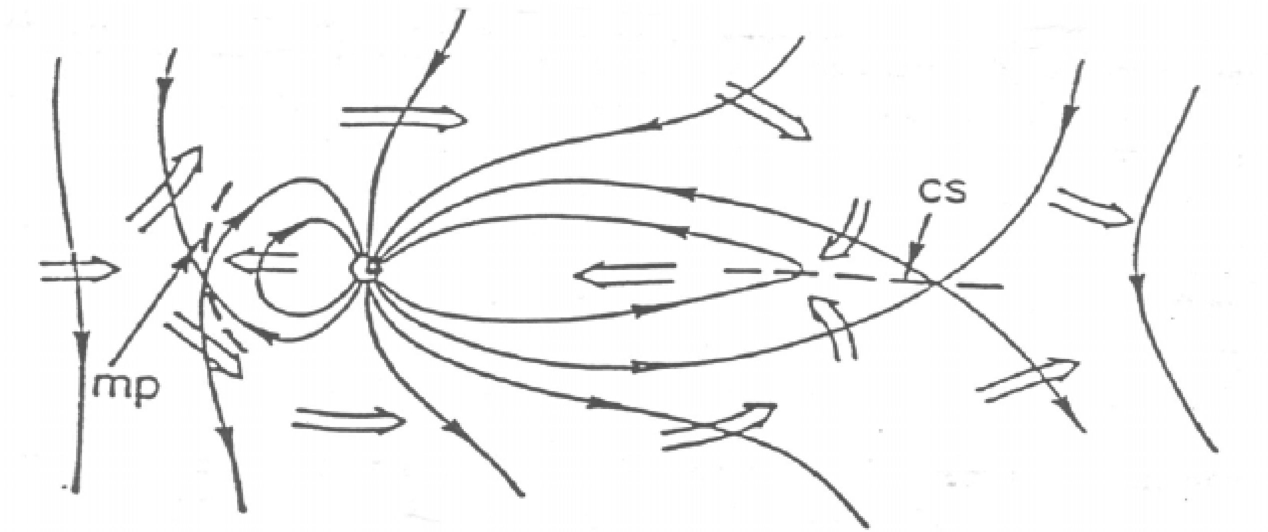
Solar wind-magnetosphere interaction: reconnection

- Magnetic reconnection is the process whereby plasma ExB drifts across a magnetic separatrix, i.e., a surface that separates regions containing topologically different magnetic field lines
  - (Vasyliunas, *Rev. Geophys. Space Phys.*, *13*, 303, 1975)
  - In the original Dungey picture, reconnection occurs both on the dayside magnetopause and in the magnetotail.

Toffoletto 2011
HSS lecture

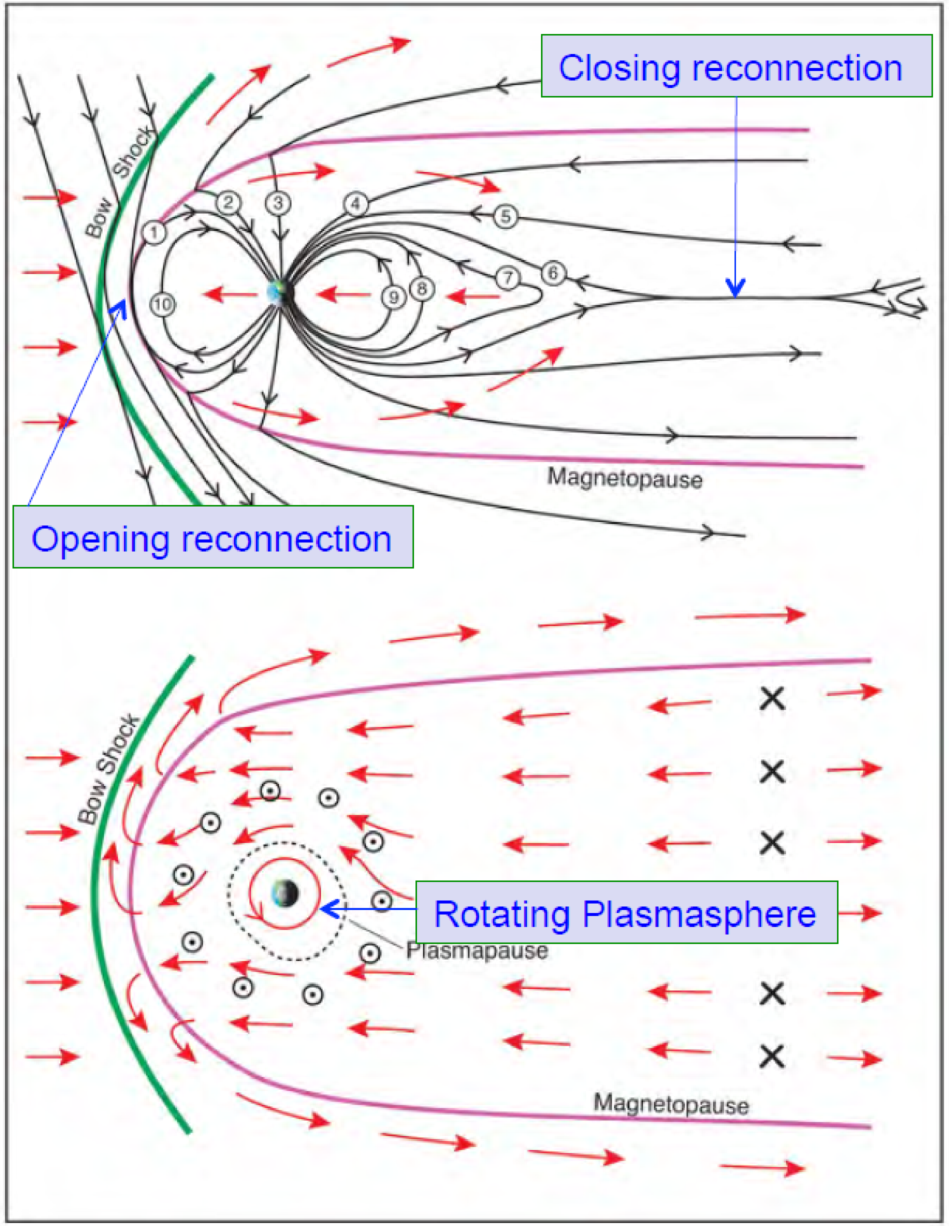


Solar wind-magnetosphere interaction: reconnection

Dungey Cycle

Dynamics at Earth driven by the solar wind coupling the Sun's magnetic field to the Earth's field

- Variable opening & closing rates
- Must be equal over time to conserve magnetic flux



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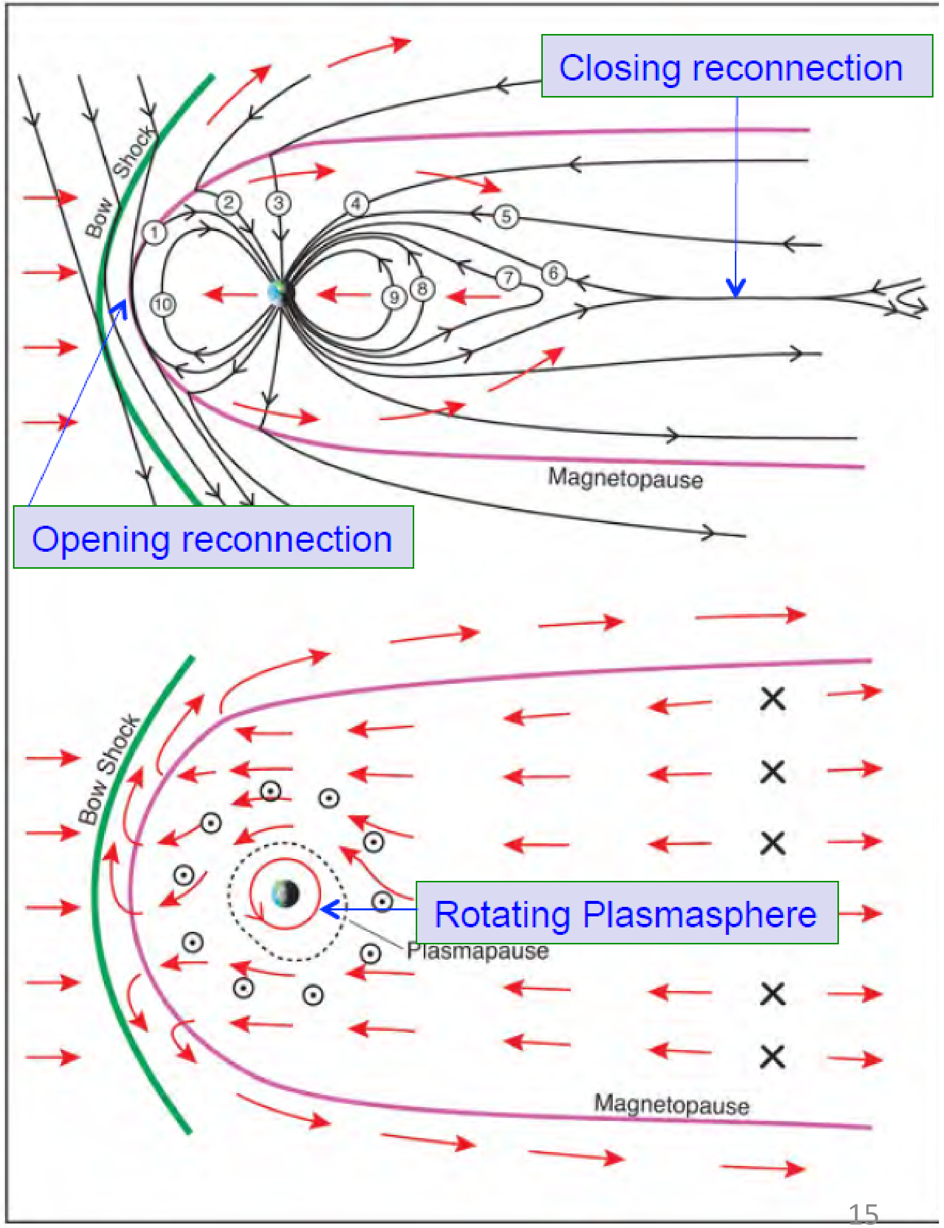
Solar wind-magnetosphere interaction: convection

- Large scale circulation of plasma occurs in magnetospheres due to several processes
- At Earth, magnetic reconnection is crucial though other processes contribute too
- Often referred to as “convection” and being related to a large scale “convection electric field,” though this circulation isn’t convection in the traditional fluid dynamics sense



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Corotation and impact on structure of planetary magnetospheres

$$\mathbf{V}_{co} \sim \Omega \times R$$

$$\mathbf{V}_{convection}$$

$$\sim \zeta V_{SW}(R/R_{MP})^3$$

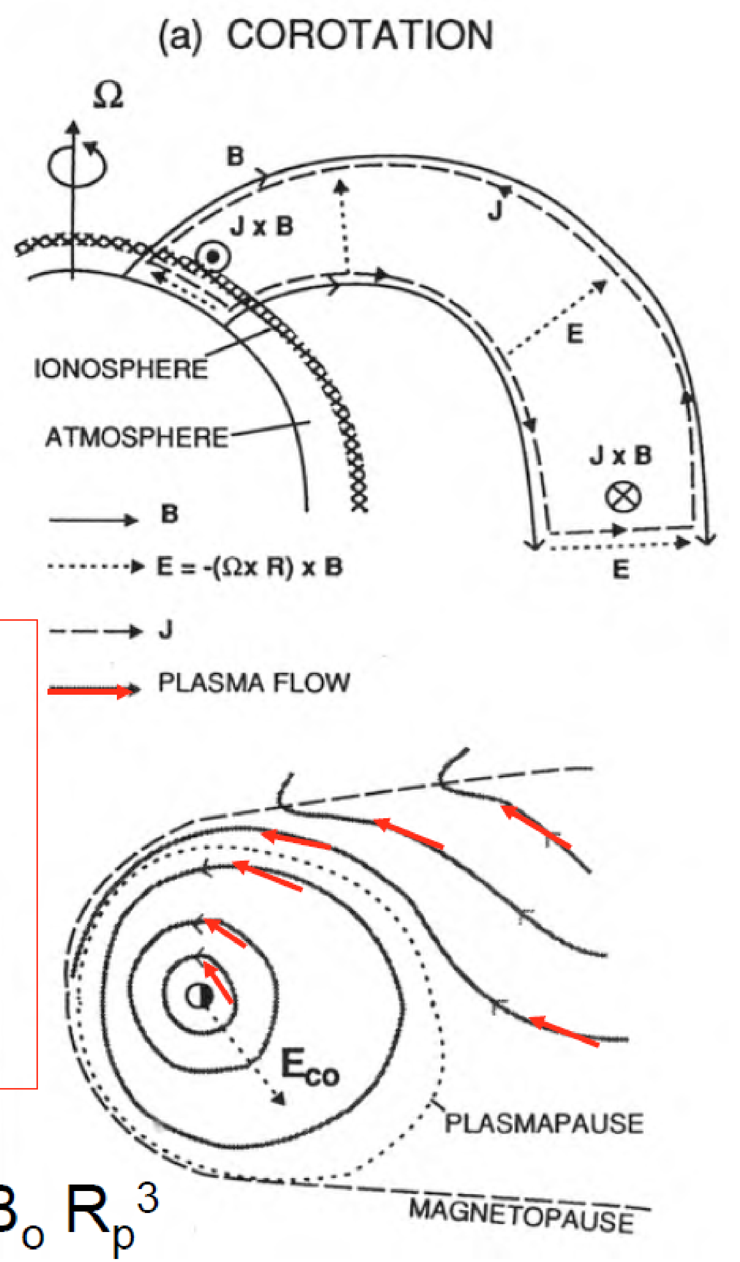
Fraction of planetary magnetosphere that is rotation dominated is…

$$R_{plasmapause}/R_{MP}$$

$$\sim [\, r_p R_{MP}\, \Omega \,/\, \zeta V_{SW}]^{1/2}$$

$$\propto \Omega^{1/2} \mu^{1/6} / (\rho_{sw})^{1/12} V_{sw}^{2/3}$$

r_p = planetary radius
μ = magnetic moment of planet $B_o R_p^3$



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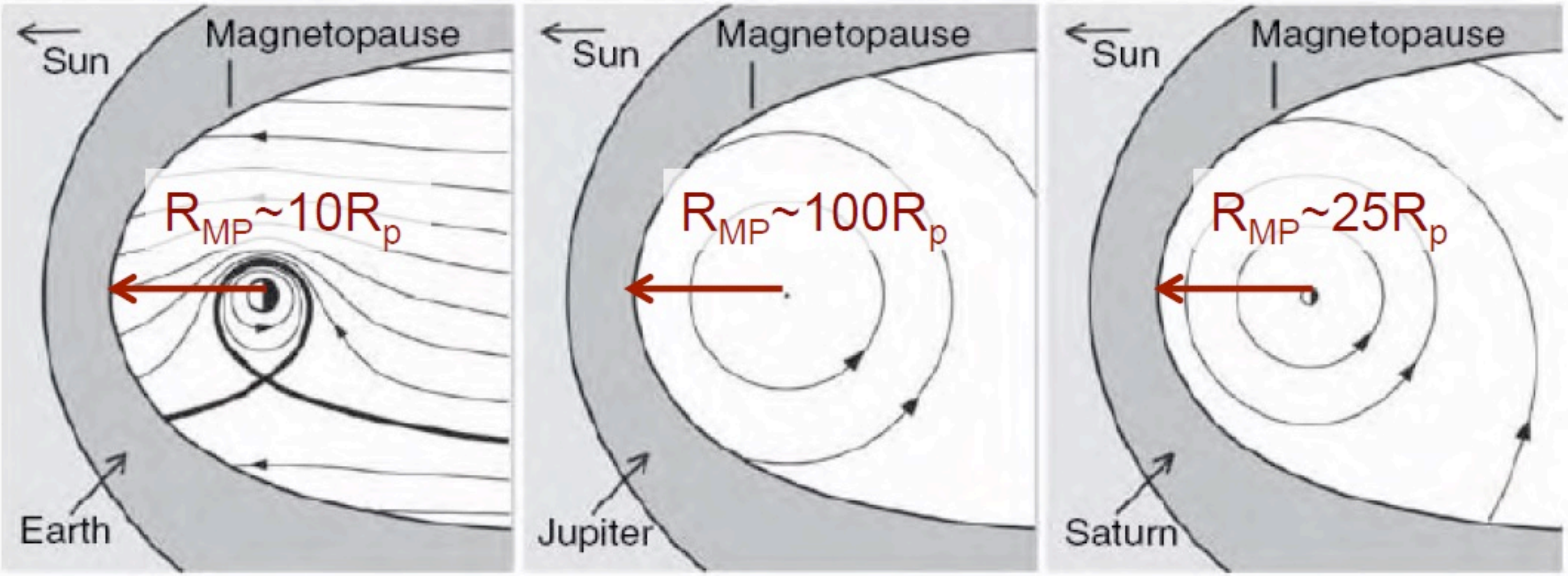
Corotation and impact on structure of planetary magnetospheres

- Many unique processes in rotation-dominated magnetospheres
- See Bagenal 2014 HSS lecture for several examples

Solar-wind vs. Rotation-dominated magnetospheres

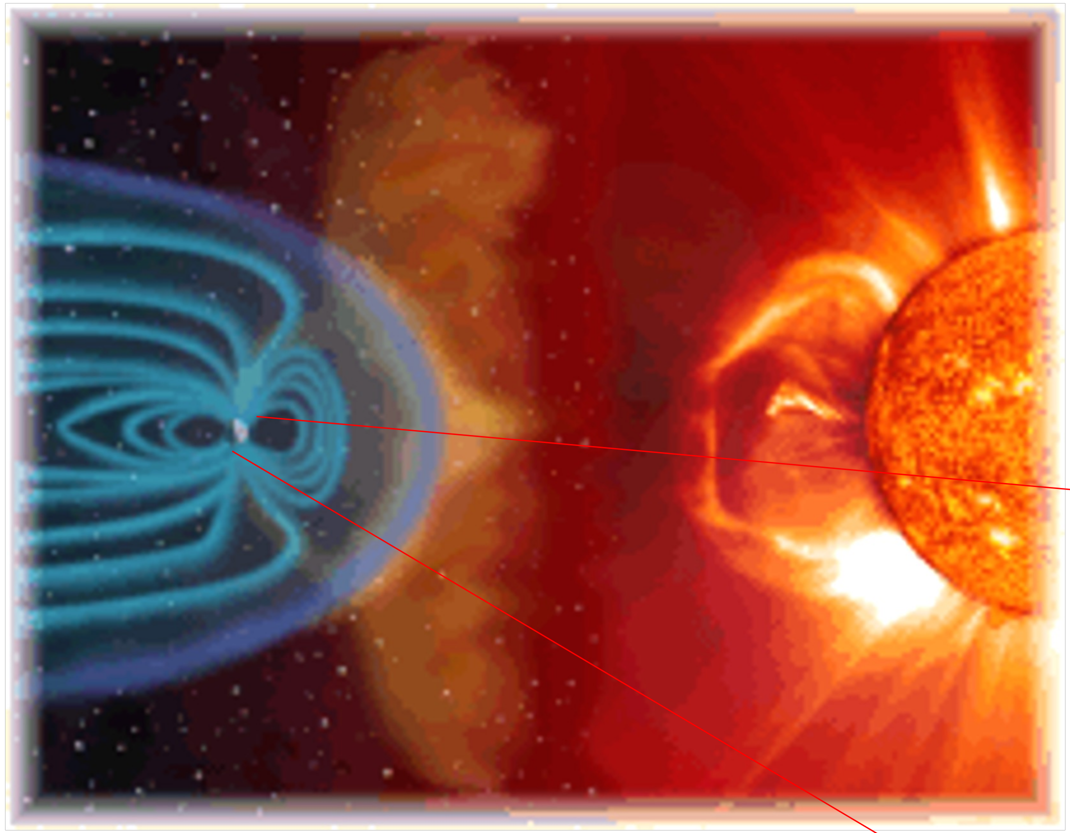


$R_{plasmapause} / R_{Planet}$ =

6.7	350	95

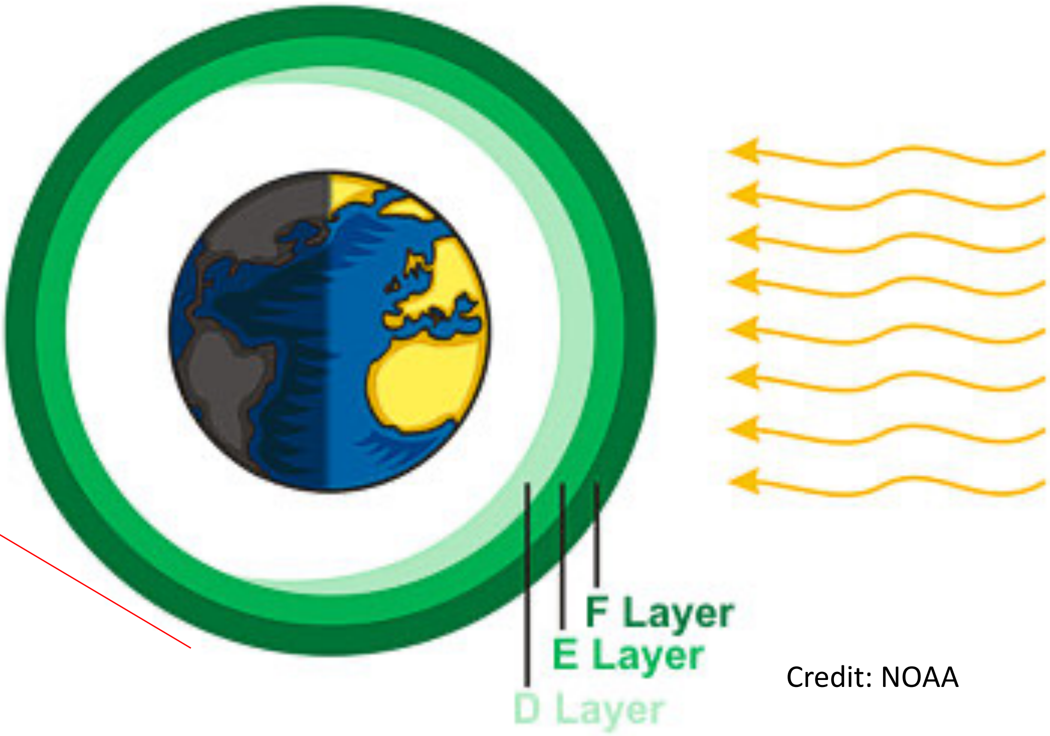
Assumptions:
1. Planet's rotation coupled to magnetosphere
2. Reconnection drives solar wind interaction

Bagenal 2014
HSS lecture



Credit: NASA

The ionosphere and its impact on the structure of planetary magnetospheres

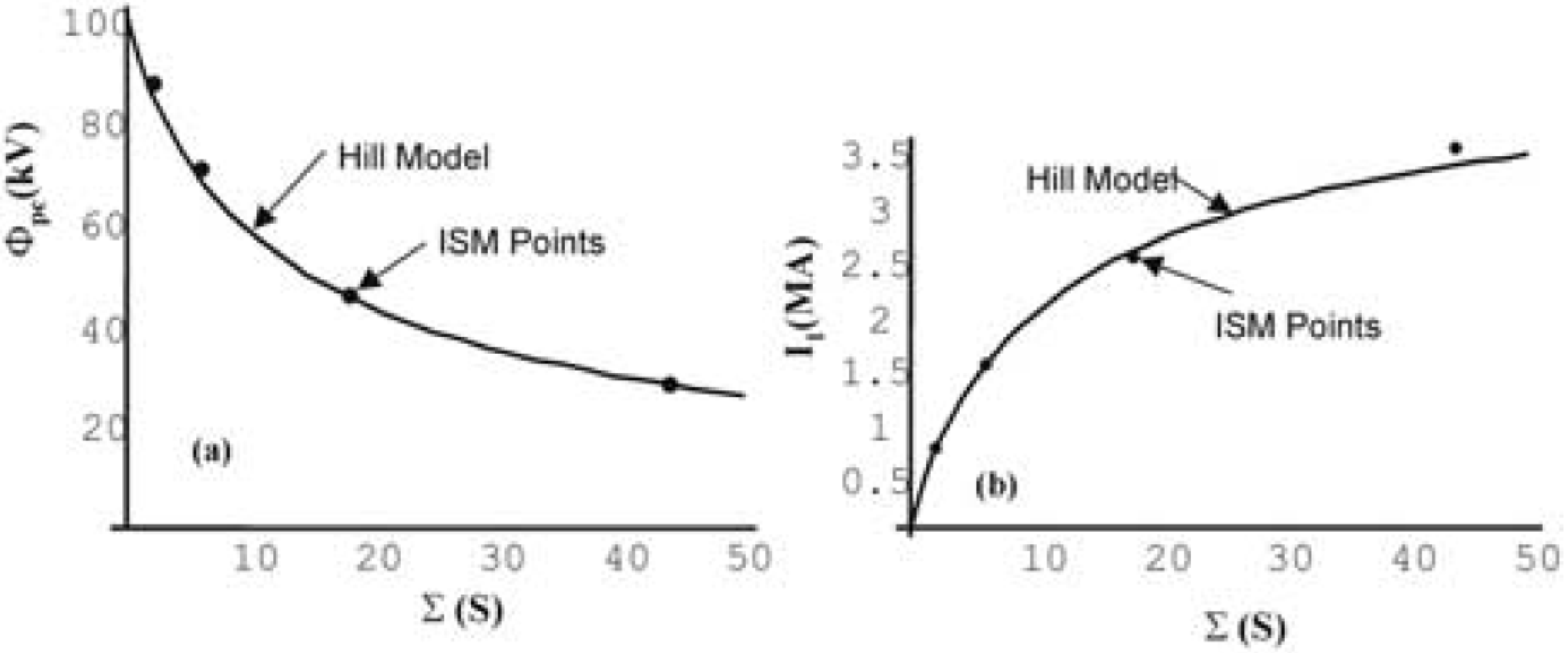


Credit: NOAA

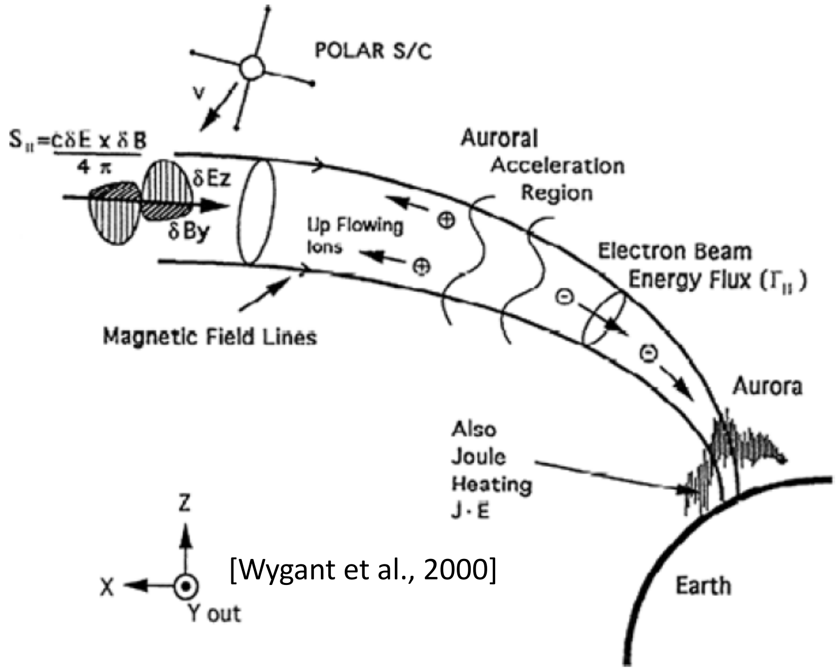
- Ionized portion of upper atmosphere=ionosphere
- Magnetosphere and ionosphere are coupled via many processes
- Example: Large scale magnetospheric current systems closing in the ionosphere

Effect of Ionospheric Conductance

Toffoletto 2011
HSS lecture



- The ionosphere plays an important role on determining the rate of convection on the ionosphere
  - The larger the conductance, the lower the convection rate



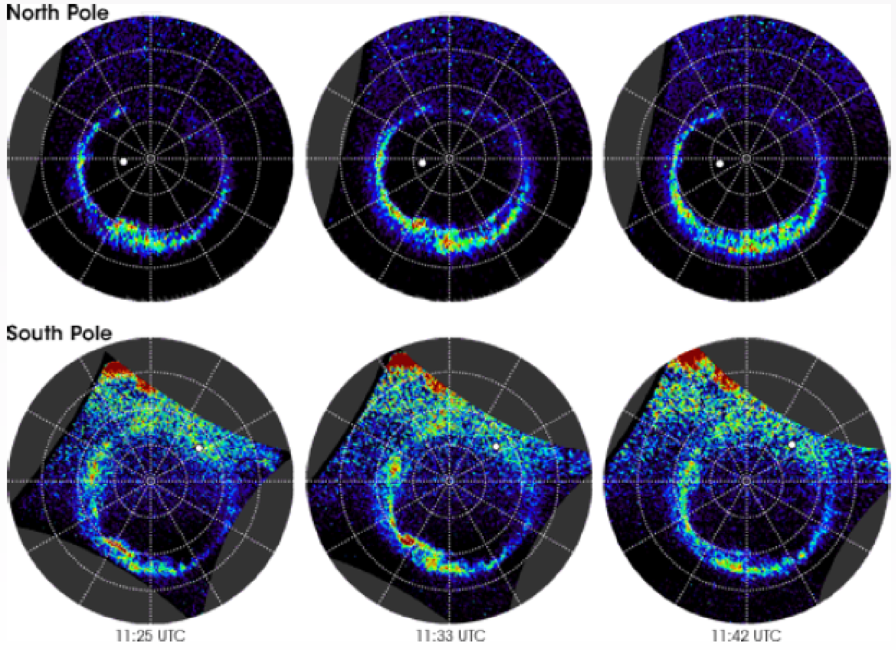
[Wygant et al., 2000]

- Electromagnetic and particle kinetic energy deposition into the ionosphere and atmosphere via many processes
- This in turn affects magnetosphere dynamics – example: precipitation changes ionospheric conductance that in turn affects current systems in the magnetosphere
- Aurora are diagnostics of magnetospheric processes

Magnetosphere-Ionosphere Coupling / Aurorae

Some remarks of relevance, independent of planet:

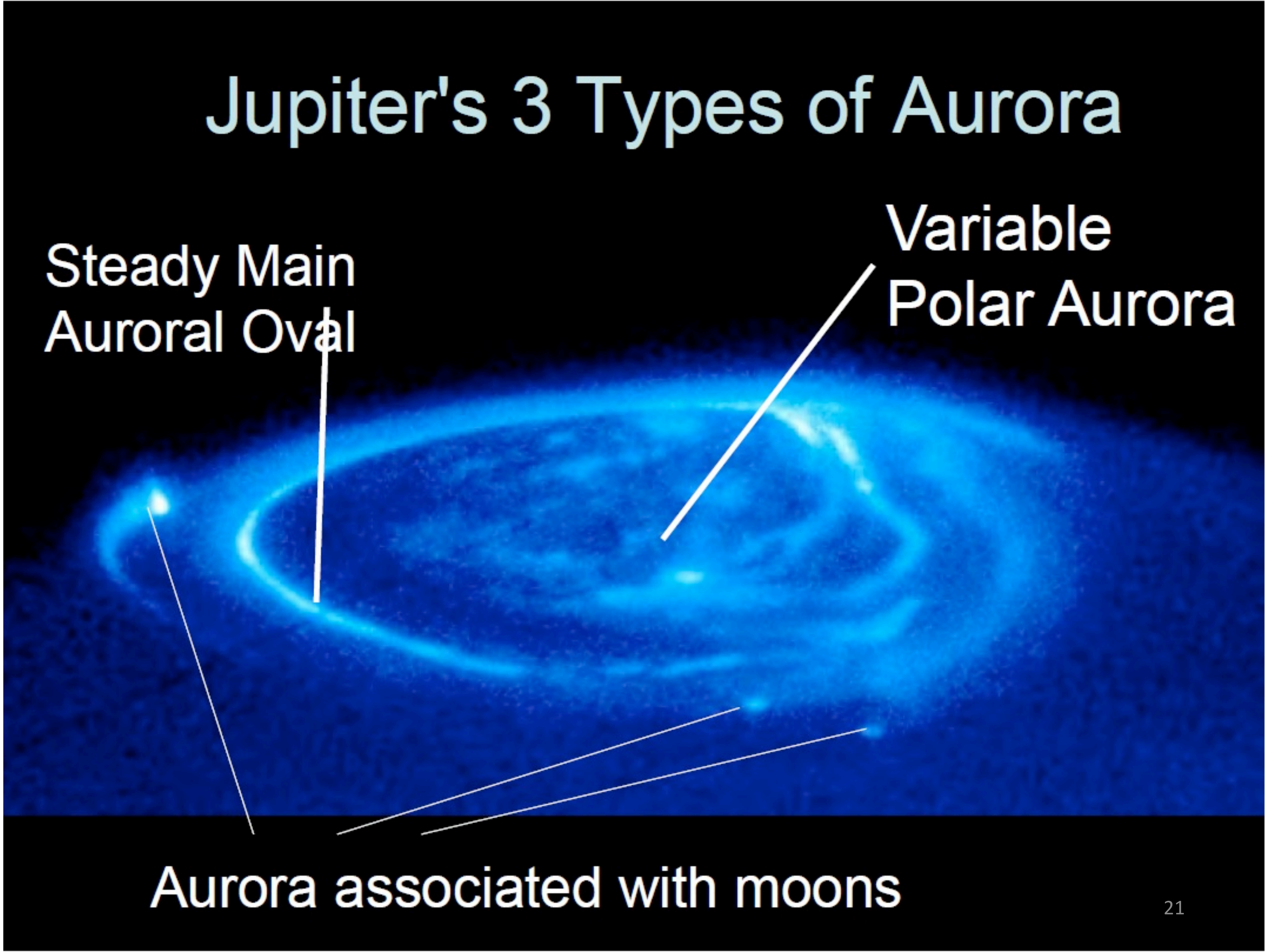
- The most striking difference between planets is which driver produces the brightest, most persistent emission, i.e. the *auroral oval*.
- **Earth:** Magnetosphere-solar wind interaction
  Jupiter: Planetary rotation (source is inside)
  Saturn: Earth-like, with 'secondary' features.



Examples of Earth UV auroral images

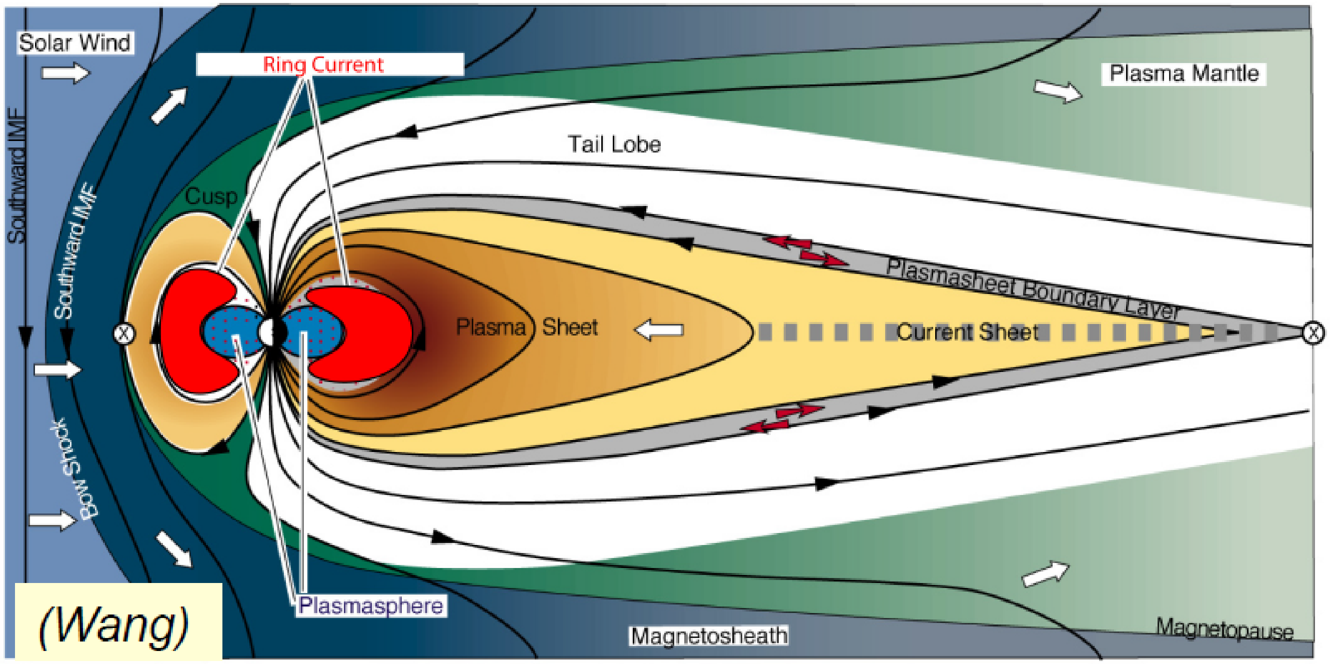
Image credit: T. J. Stubbs / NASA

From Achilleos 2015 HSS lecture



From Bagenal 2014 HSS lecture

Different plasma 'regimes'



	Magneto-sheath	Tail Lobe	PS Boundary Layer	Central Plasma Sheet
n (cm^{-3})	8	0.01	0.1	0.3
T_i (eV)	150	300	1000	4200
B (nT)	15	20	20	10
β	2.5	0.003	0.1	6

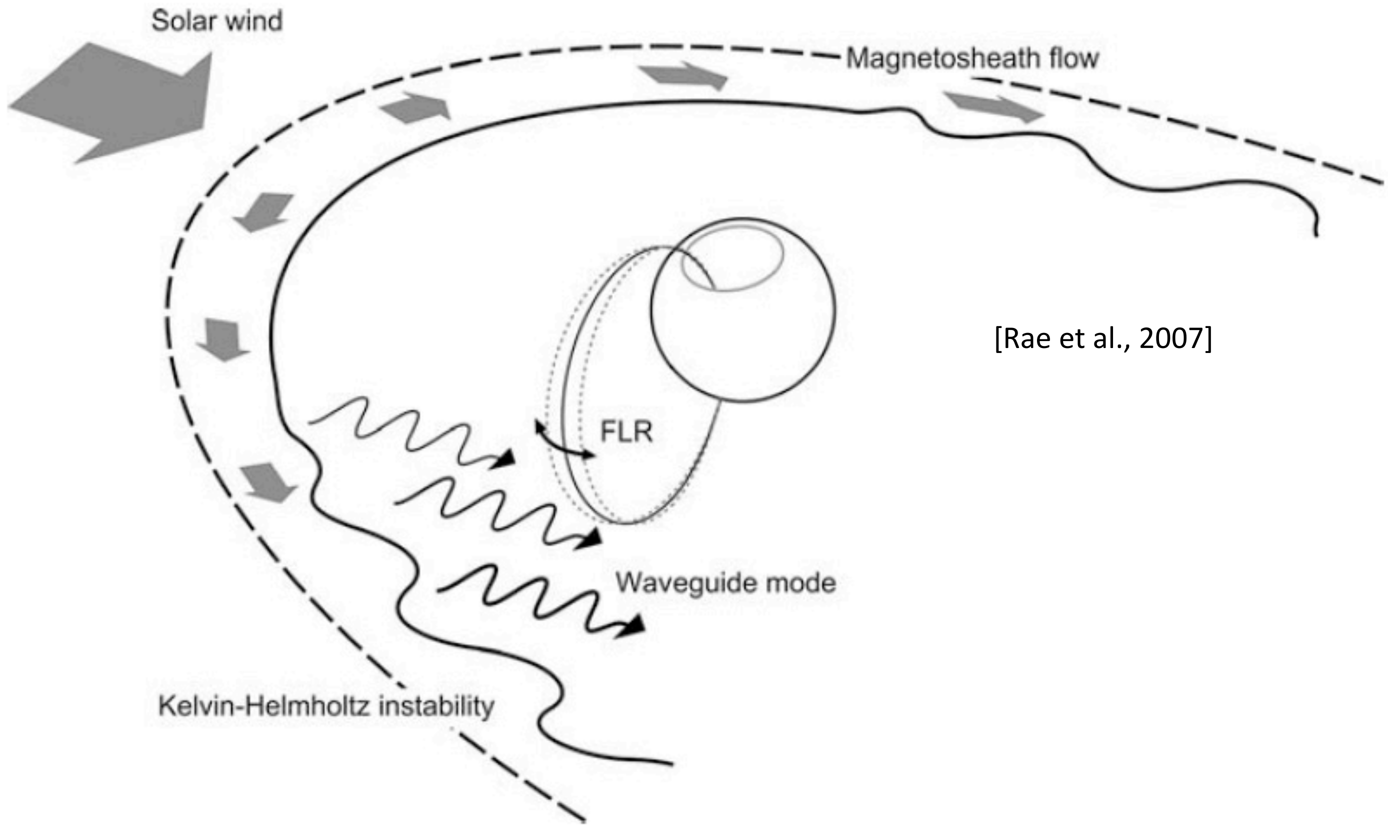
(From chapter by Hughes in 'Intro to Space Phys')

- Tail Lobe: Open field
- PSBL: Prob. Closed field, thermal << flow energy
- PS: hot ~keV particles, flow<<thermal energy
- Reconnection: antisunward plasma streaming to thermal energy of PS
- More PS particles from ionosphere (O+) rel. to solar wind (H+) at 'active' times

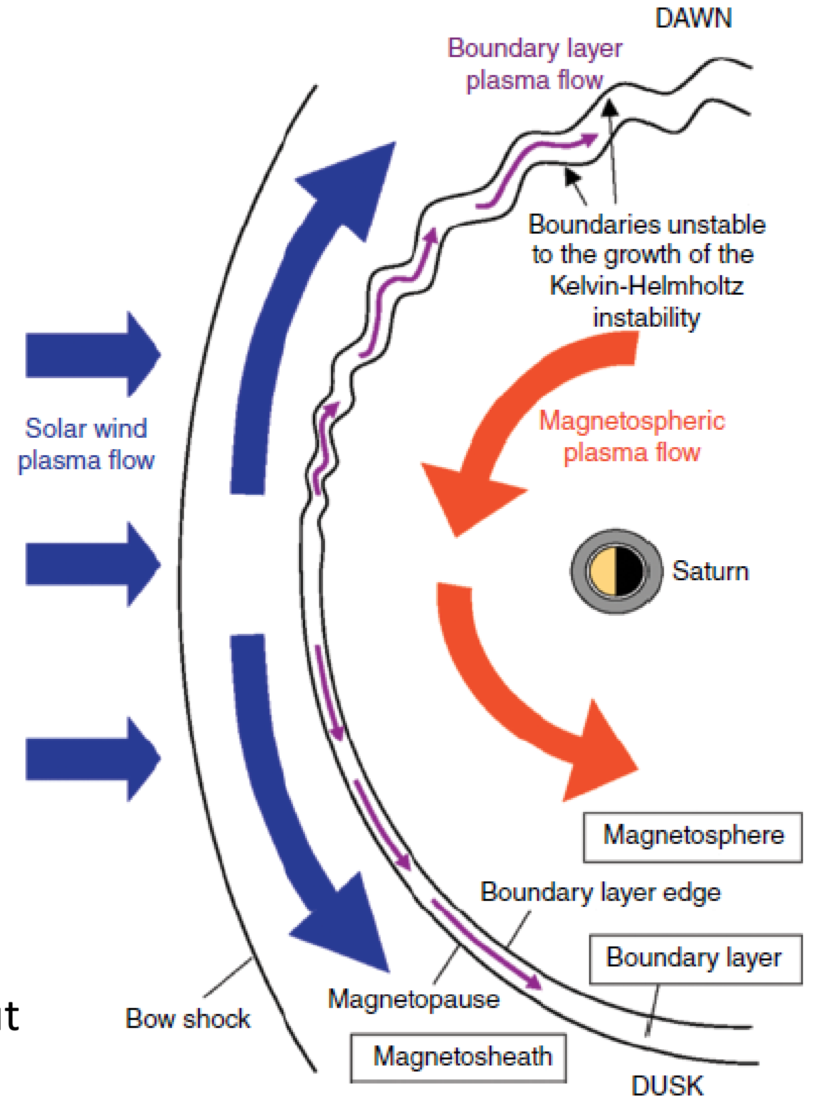
$\beta = P_{PLAS}/P_{MAG}$

Achilleos 2015 HSS lecture

Solar wind-magnetosphere interaction: large-scale waves



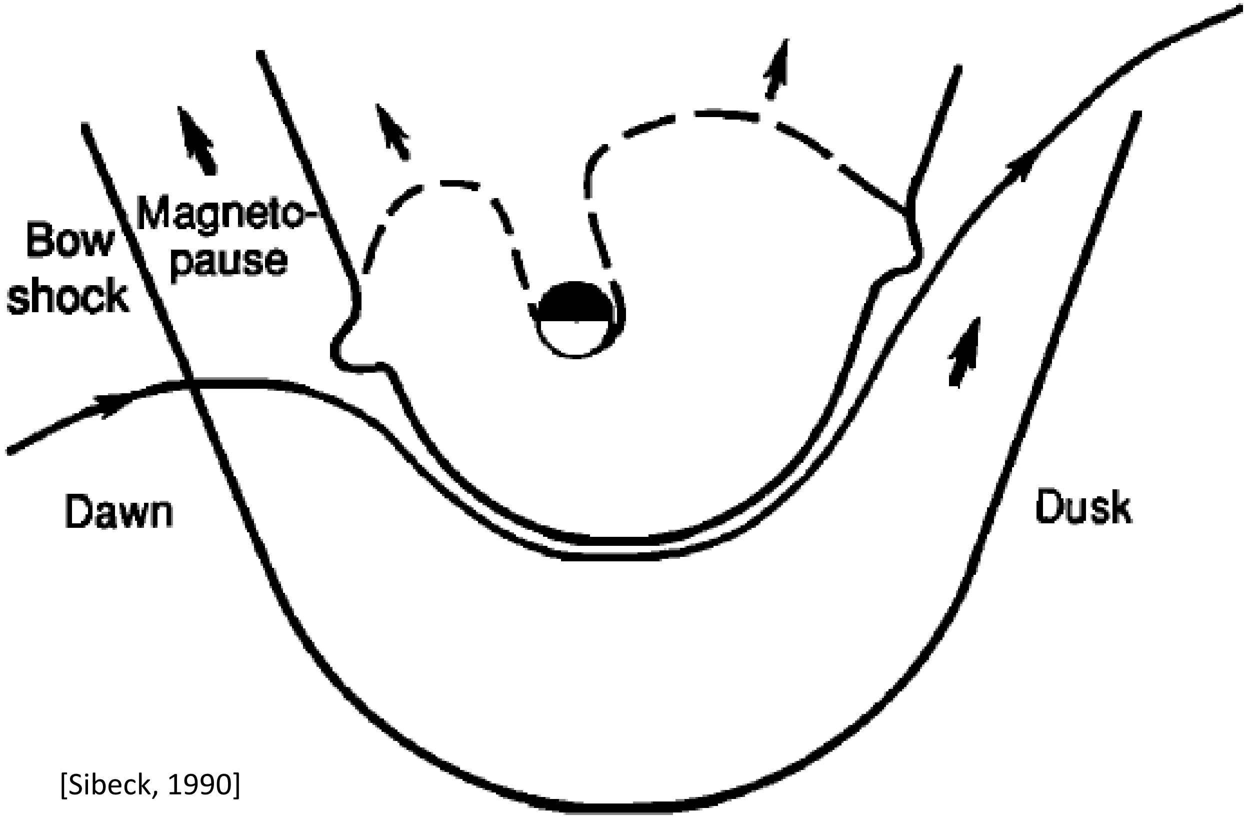
[Rae et al., 2007]



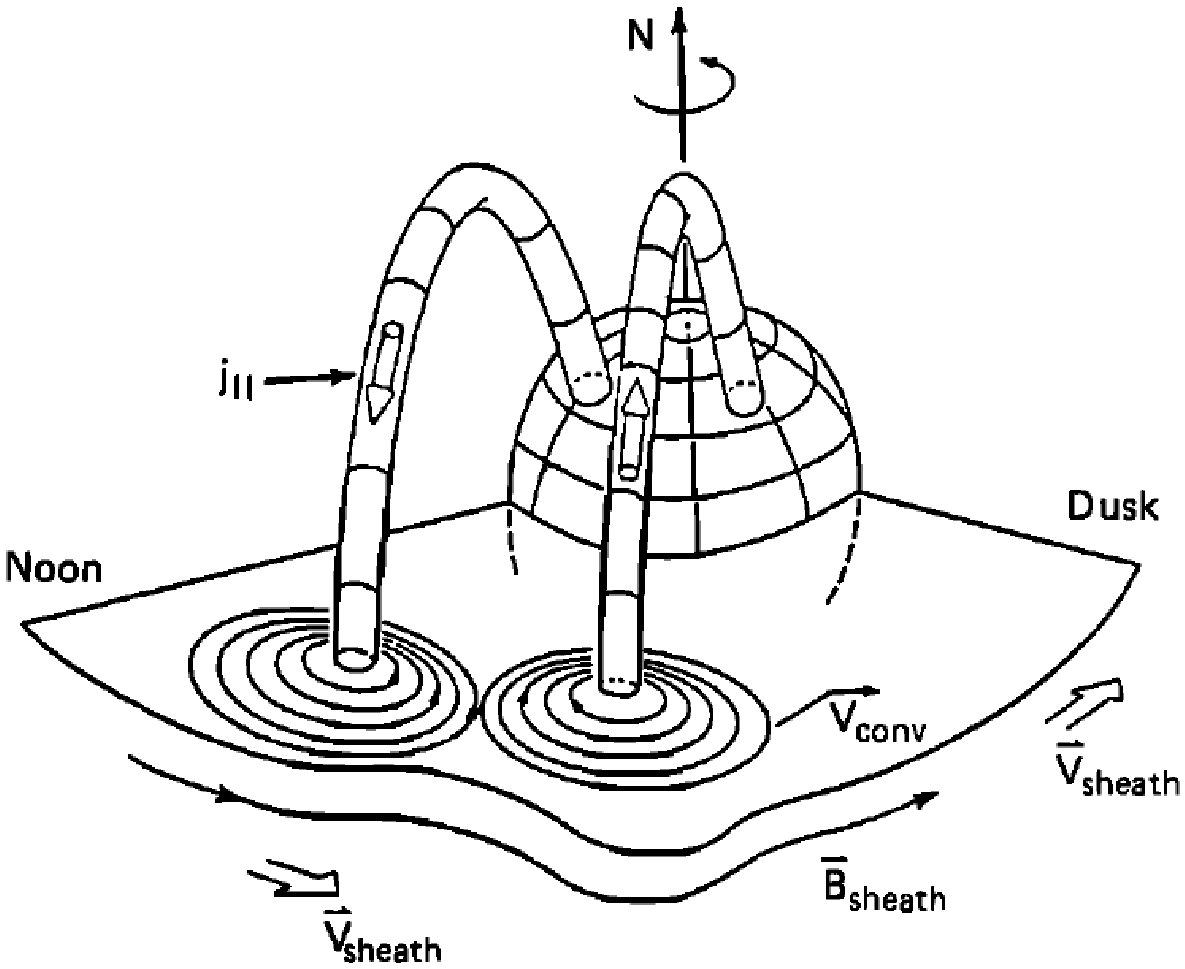
[Masters et al., 2010]

- The system is never static
- Waves carry energy, mass and momentum across boundaries and throughout the system
- Kelvin-Helmholtz instability and related surface waves are important at several magnetospheres

Solar wind-magnetosphere interaction: large-scale waves



[Sibeck, 1990]



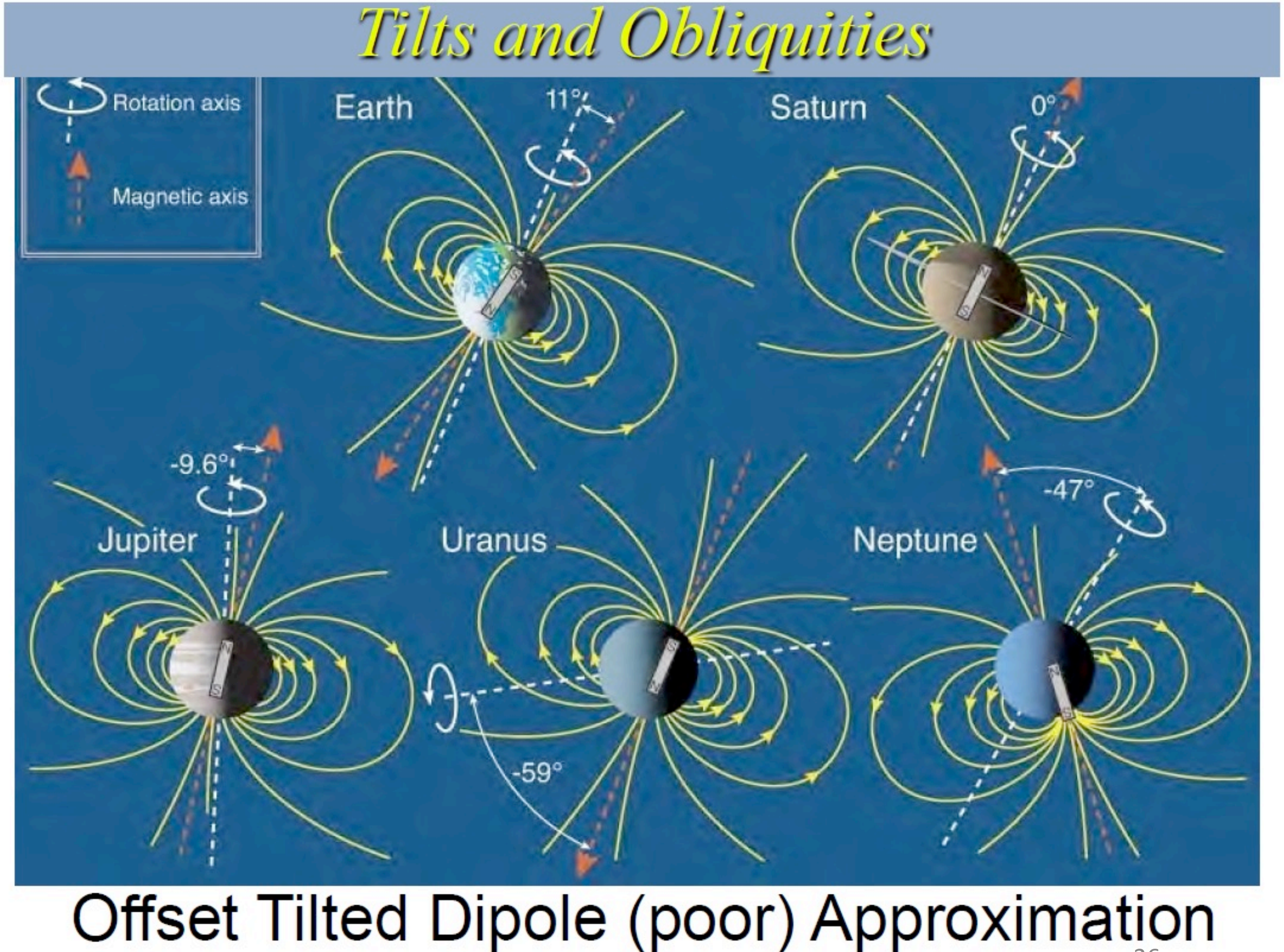
- Dynamic pressure variations in the solar wind --> ripples and other dynamics on the magnetopause, field-aligned currents/Alfven waves
- Very important at the Earth's magnetosphere, also seen at other planetary magnetospheres

Solar wind-magnetosphere interaction: asymmetries

- Many asymmetries internal and external to magnetospheres have profound implications for the magnetosphere’s structure and dynamics
- Affect solar wind-magnetosphere coupling and reconnection rates, pressure balance, dynamics…
- Can you think of some examples of asymmetries in magnetospheres from the material presented so far? Other examples?

Asymmetries in planetary magnetospheres

- Obliquity – angle between rotation axis and ecliptic (orbital) plane
- Various tilts/angles: angle between dipole axis and rotation axis, angle between dipole axis and ecliptic,…
- Offset of dipole and/or dipole isn't a good approximation
- All these factors vary across at different planets/moons
- They play important roles in determining reconnection rates, pressure balance, magnetosphere-ionosphere coupling, and overall magnetosphere structure



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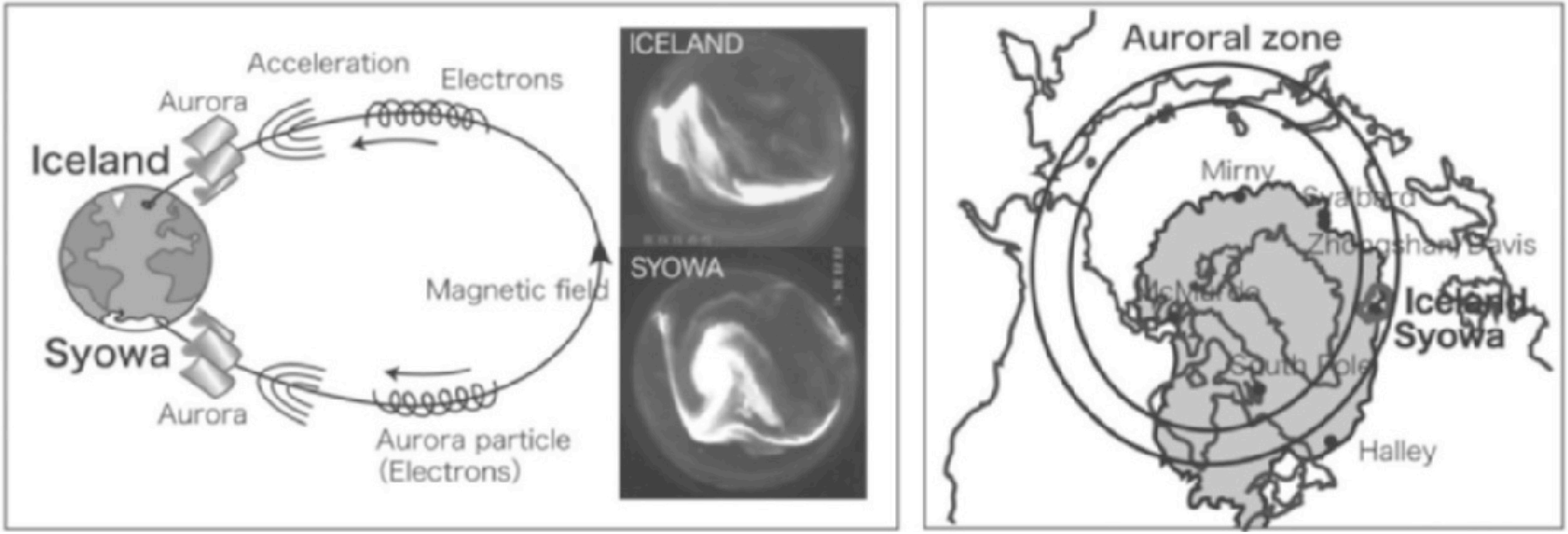
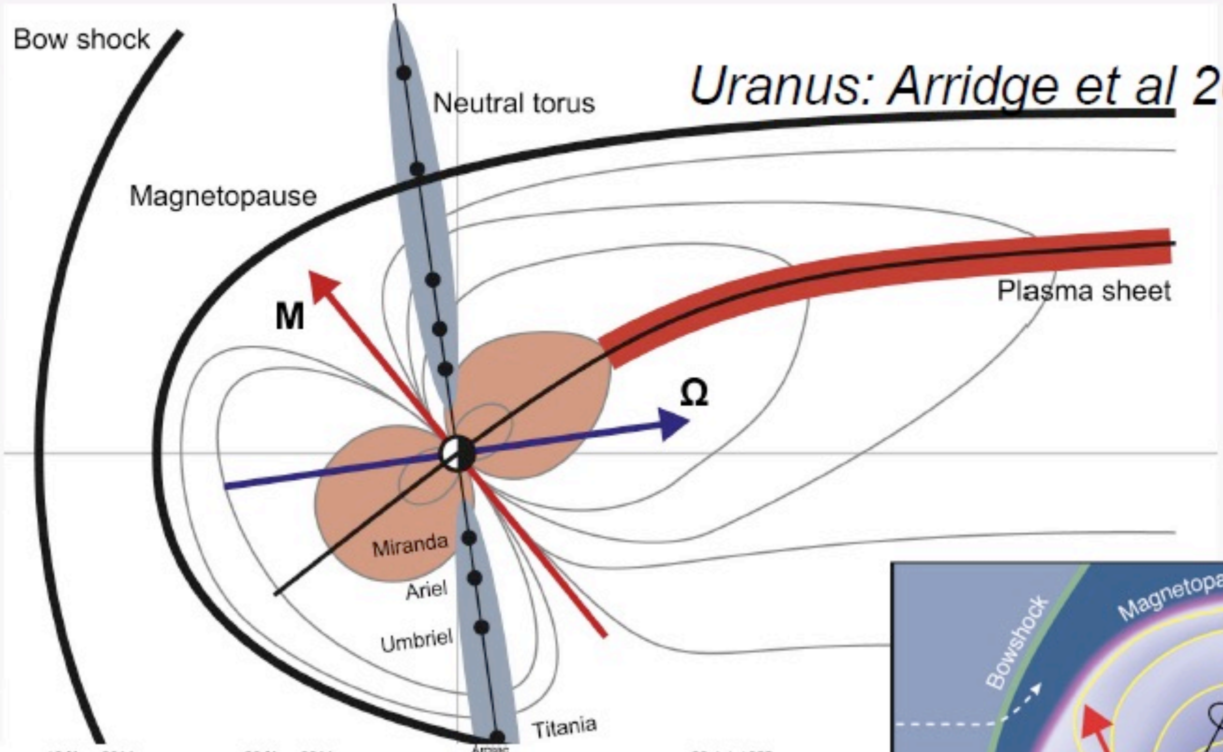
Asymmetries in planetary magnetospheres



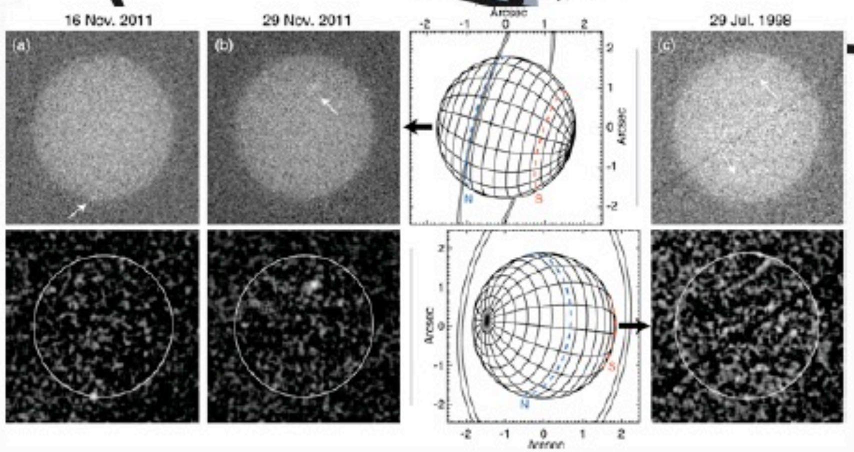
[Sato et al., 2013 – taken from Sato et al, 2005 (left) and Lanzerotti et al., 1987 (right)]

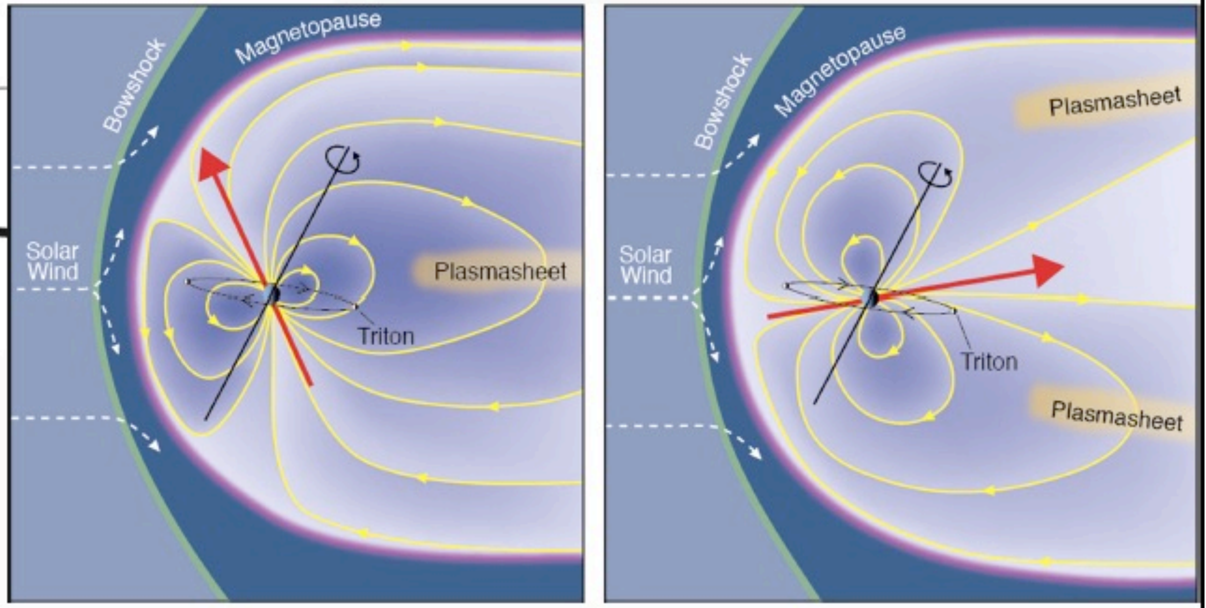
- Example north-south hemisphere asymmetry: aurora at Earth
- The solar wind distorts/twists the Earth’s magnetic field, asymmetries in precipitation rates…



Uranus: Arridge et al 2014

- ***Complex*** **B-fields**
- Large dipole-rotn axis angles predict dramatic magnetospheric 'reconfigurations'





Uranus Aurora: Lamy et al 2012

Neptune: Bartlett / Bagenal, Masters et al (2014)

Achilleos 2015
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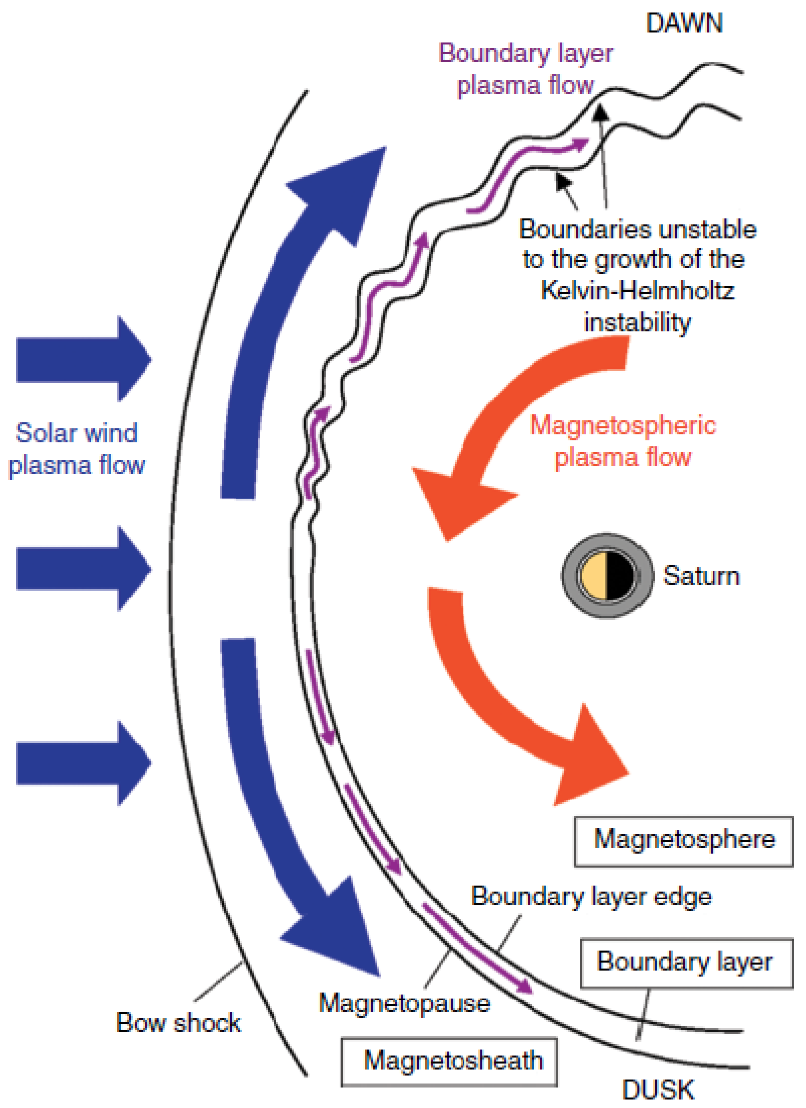
Asymmetries in planetary magnetospheres

- Example east-west hemisphere asymmetry: magnetopause surface waves at Jupiter due to larger rotation rate → larger flow shear relative to other planets like Earth



[Masters et al., 2010]

Summary

- Many factors control the structure of magnetospheres: ambient medium, magnetic field properties, rotation rate, atmosphere, asymmetries
- The interplay of these factors lead to a wide range of structure and dynamics in different magnetospheres

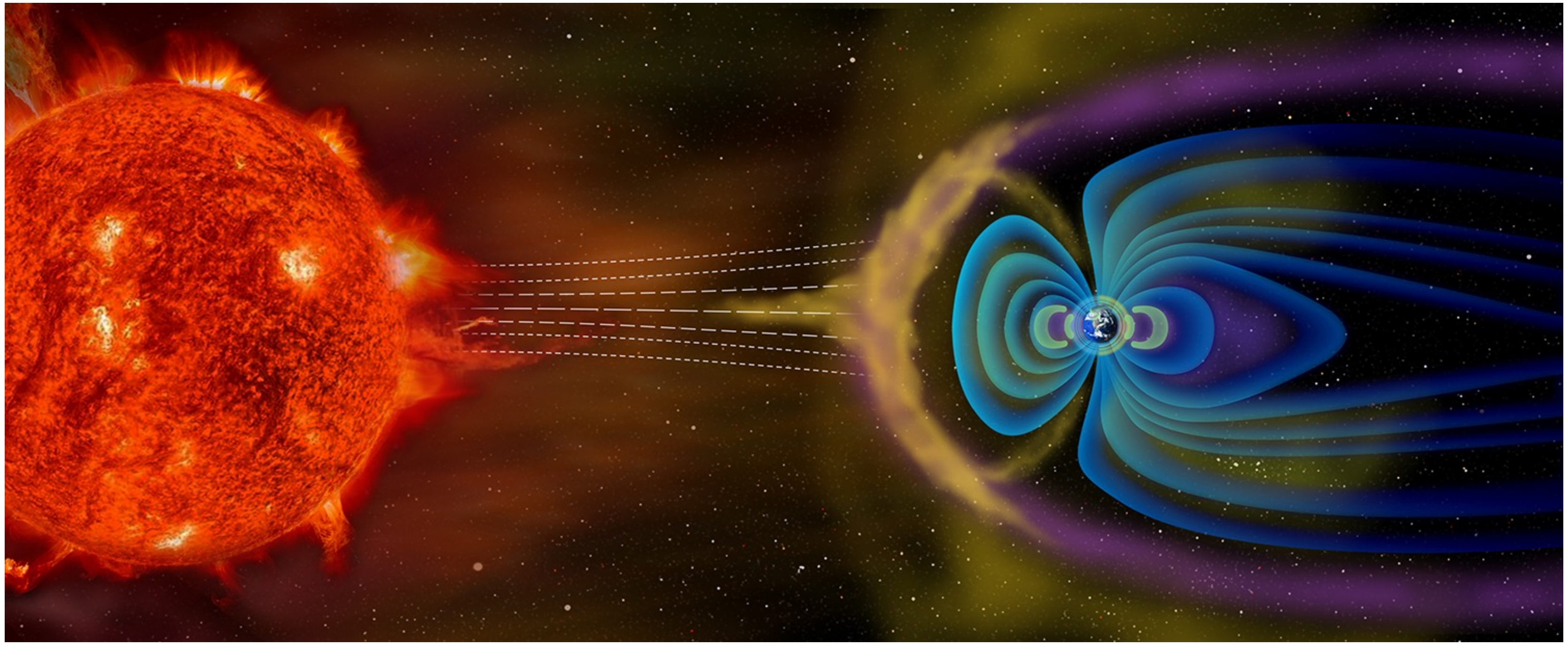


Image Credit: NASA