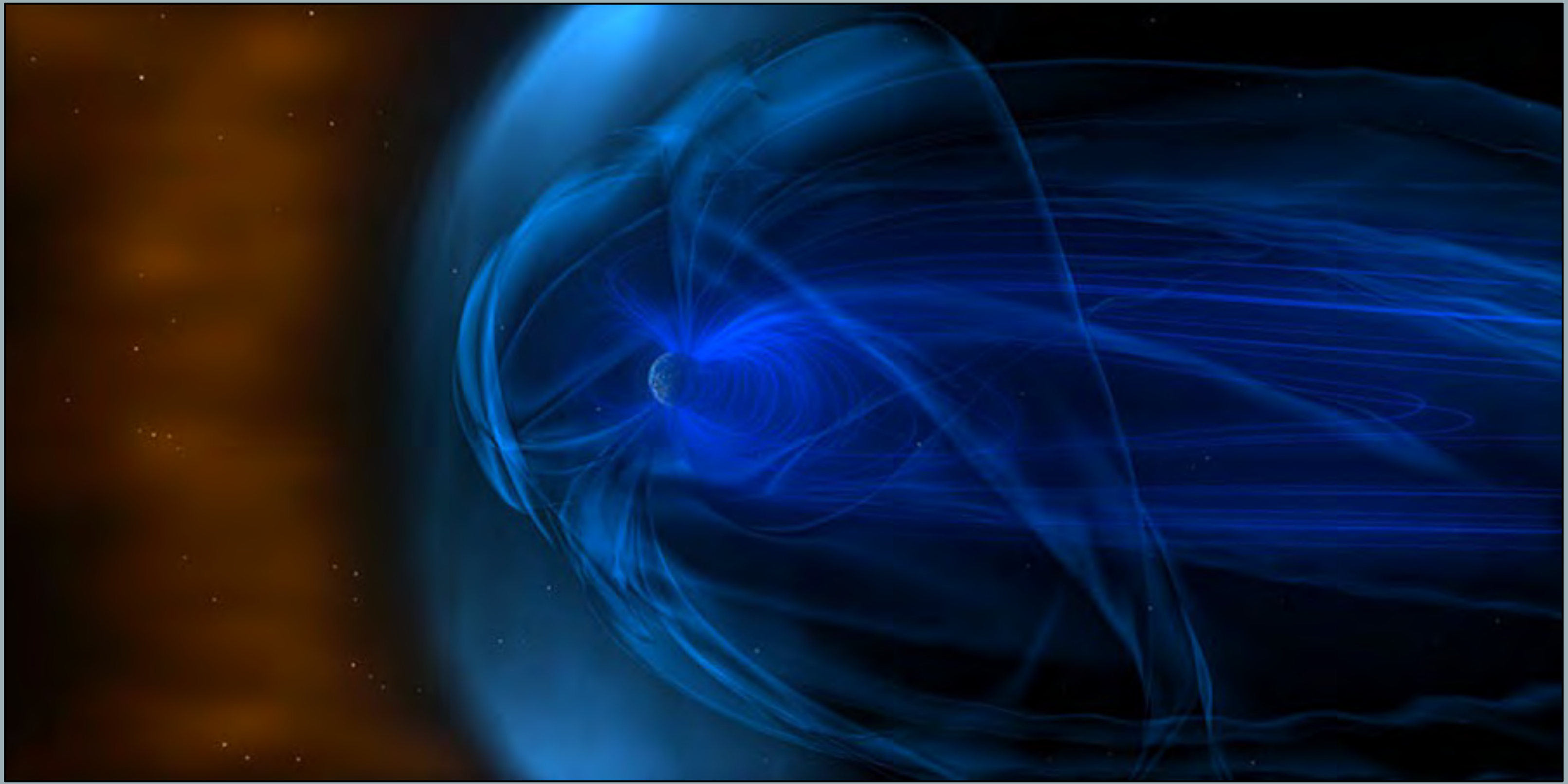
MAGNETOSPHERE – IONOSPHERE SYSTEM

Lauren Blum – lauren.blum@lasp.colorado.edu



A BIT ABOUT MYSELF:

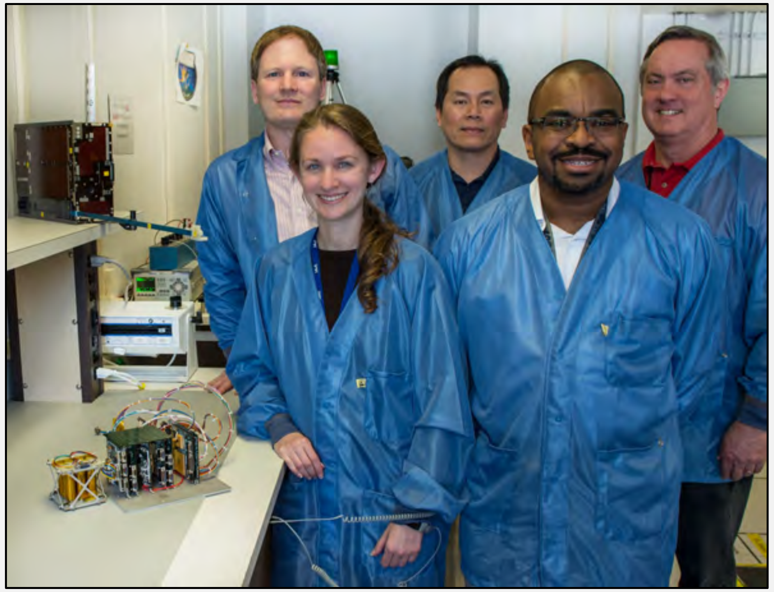
Dr. Lauren Blum, Assistant Professor

(she/her)

Laboratory for Atmospheric and Space Physics,

Astrophysics and Planetary Science Department

- Born/raised in NYC
- Physics major in undergrad, then worked at Los Alamos National Laboratory
- PhD, Aerospace, CU Boulder, 2014
- Postdoc, Space Sciences Lab, UC Berkeley
- Research Scientist, NASA Goddard Space Flight Center, 2016-2020
- Assistant Professor, APS & LASP, CU Boulder, 2020-present
- Research: Planetary magnetospheres, energetic particle dynamics in Earth's radiation belts; charged particle instrumentation and SmallSat design



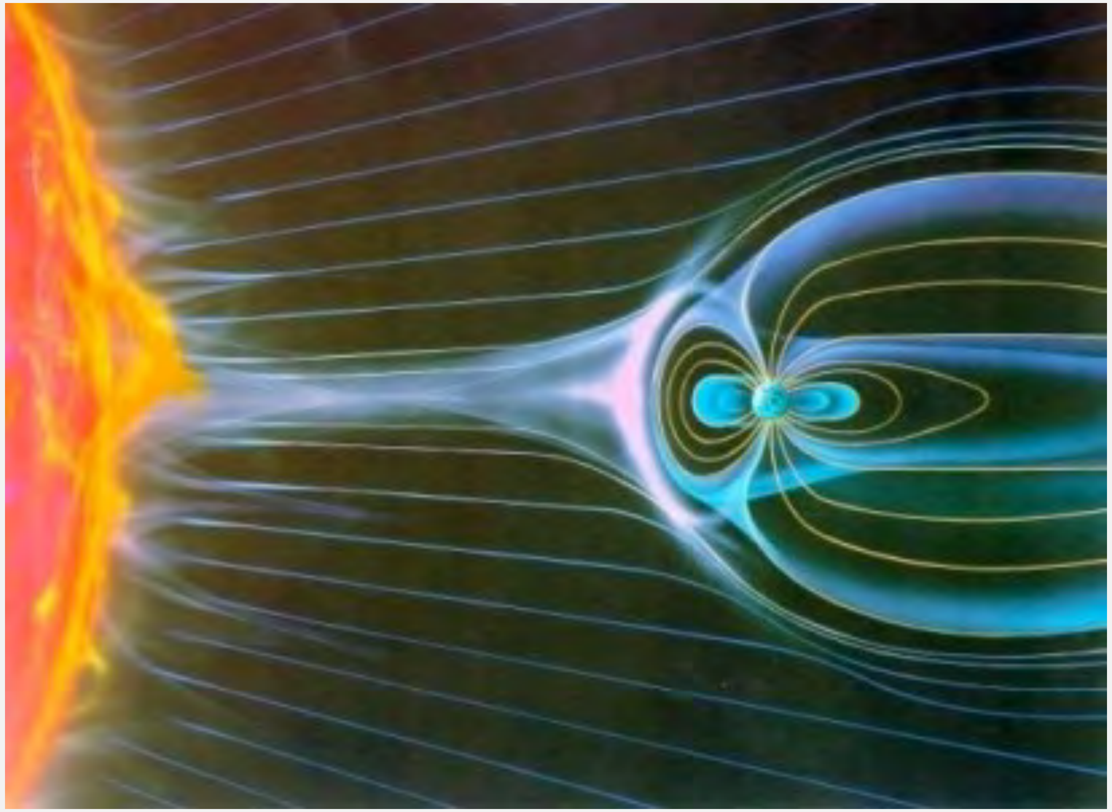
GTOSat CubeSat prototype, NASA Goddard

PLANETARY MAGNETOSPHERES + IONOSPHERES

- What are they?
- What do they look like?
- How do they behave?

1. Earth

2. Other planets – what happens when you:
   - Vary the planet size, mass, rotation rate?
   - Change the solar wind driver?
   - Add volcanic and magnetized moons?



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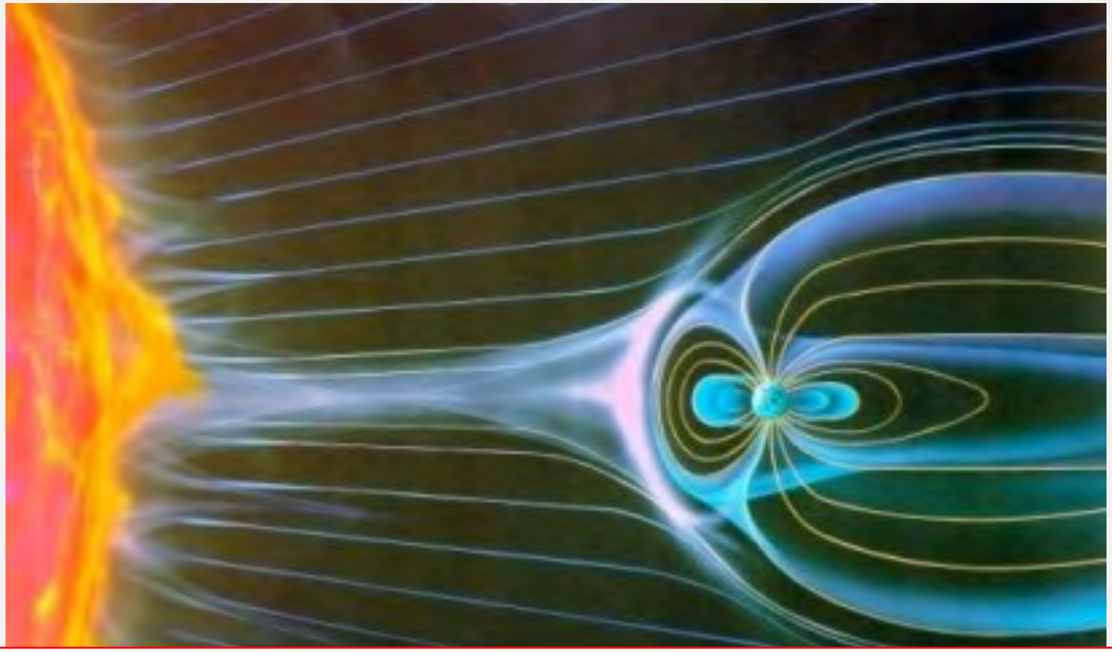


Consider interfaces, cross-region coupling;
How do we observe these regions/processes?

COMPARATIVE MAGNETOSPHERIC SYSTEMS

"Typical of the rigor of physics is the need to change the parameters governing the system studied in order to test whether behavior varies as predicted."

M. Kivelson
GEM 2010, Snowmass, CO

QUICK POLL

What is the primary topic of your research/research interests:

A) Solar/solar wind

B) Earth's magnetosphere

C) Earth's ionosphere/atmosphere

D) Other planetary systems

E) Other/not sure

QUICK EXERCISE:
WHY SHOULD ___ LEARN ABOUT ___?

E.g. why should a magnetospheric physicist learn about the ionosphere or sun?

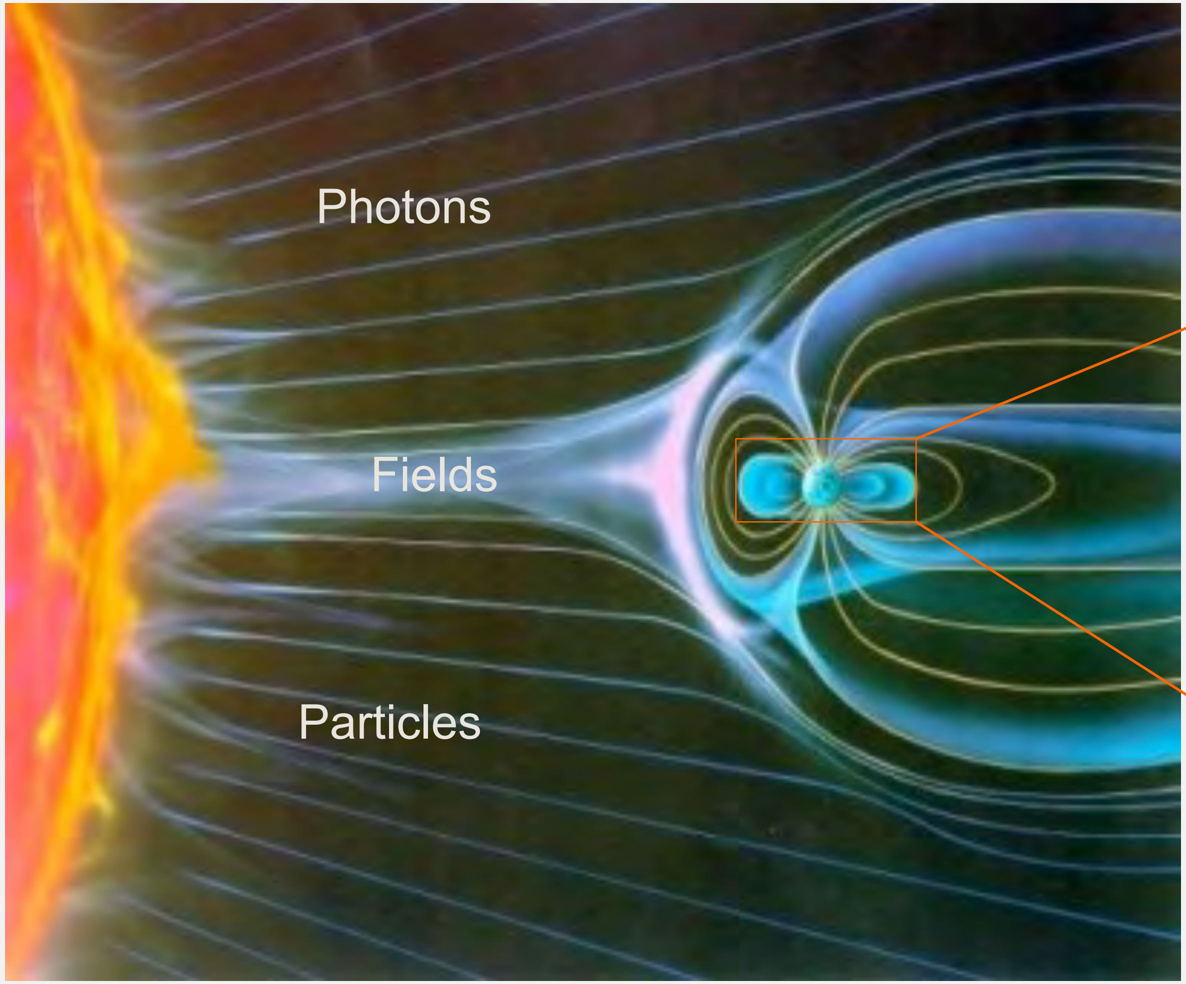
Pick the region seemingly least connected to your own research and think about how the two might interact or relate

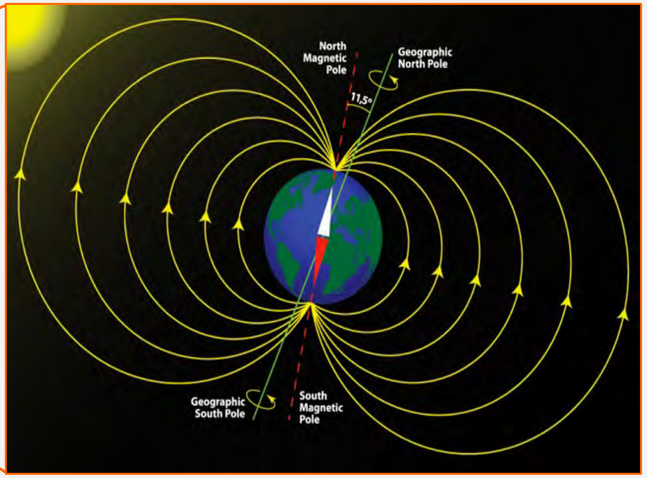
A FEW NOTES:

- Please interrupt at any point with questions, comments, additions from your own research or experience
- My hope is you'll learn as much (more?) from each other as you do from me

Also: Let's consider common questions or misconceptions throughout this talk… please speak up if you think of some!

WHAT IS A MAGNETOSPHERE?





The volume of space from which the solar wind is excluded by a planet's magnetic field, formed by the interaction of a flowing plasma with a magnetized body

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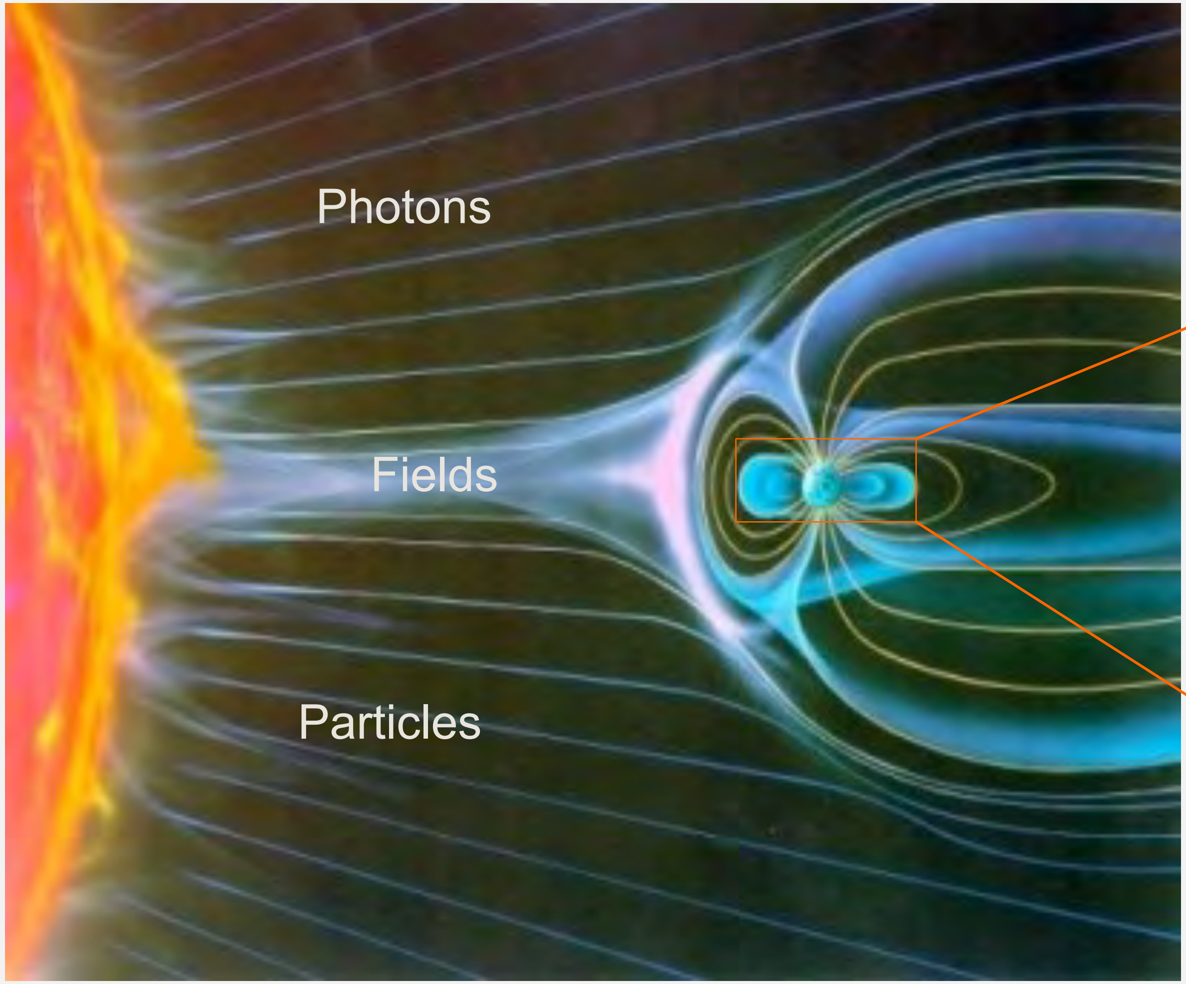
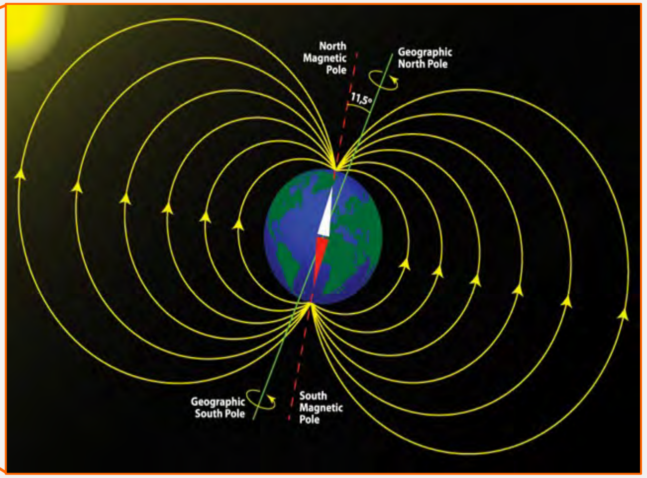
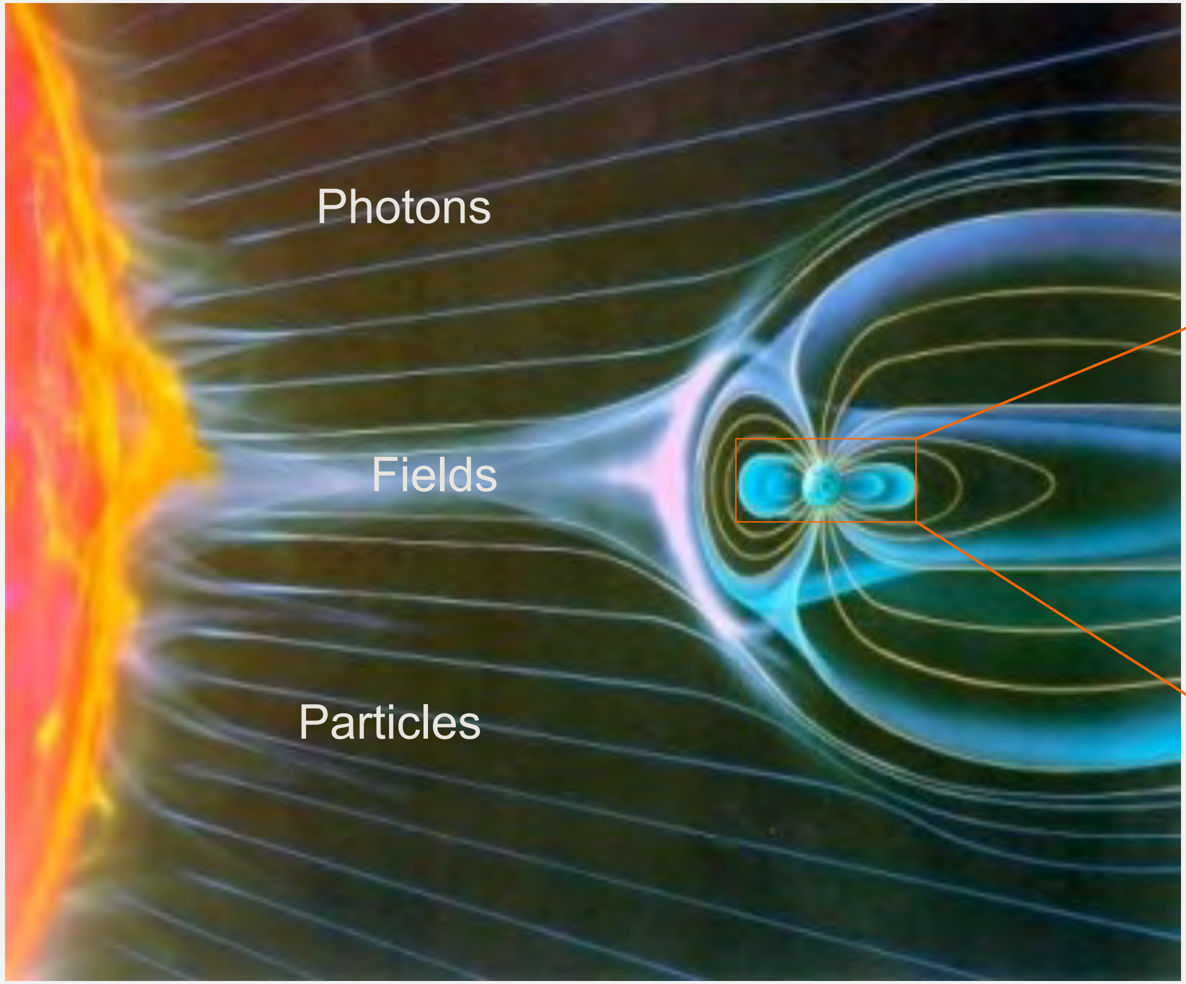


Any caveats/modifications we should make to this definition?



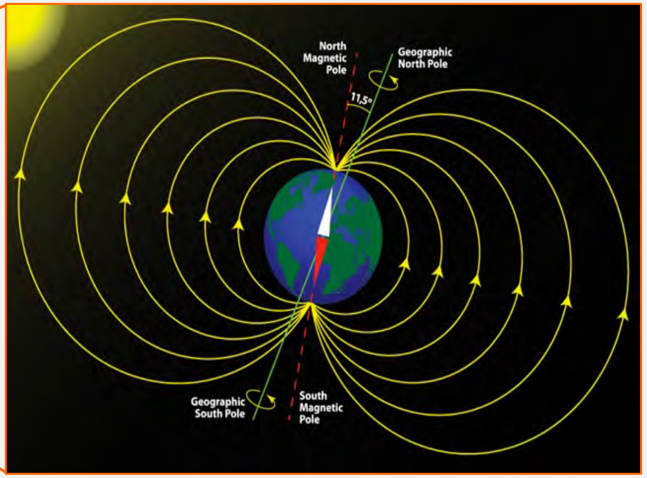
The volume of space from which the solar wind is excluded by a planet's magnetic field, formed by the interaction of a flowing plasma with a magnetized body

EARTH'S MAGNETOSPHERE



The inner field:

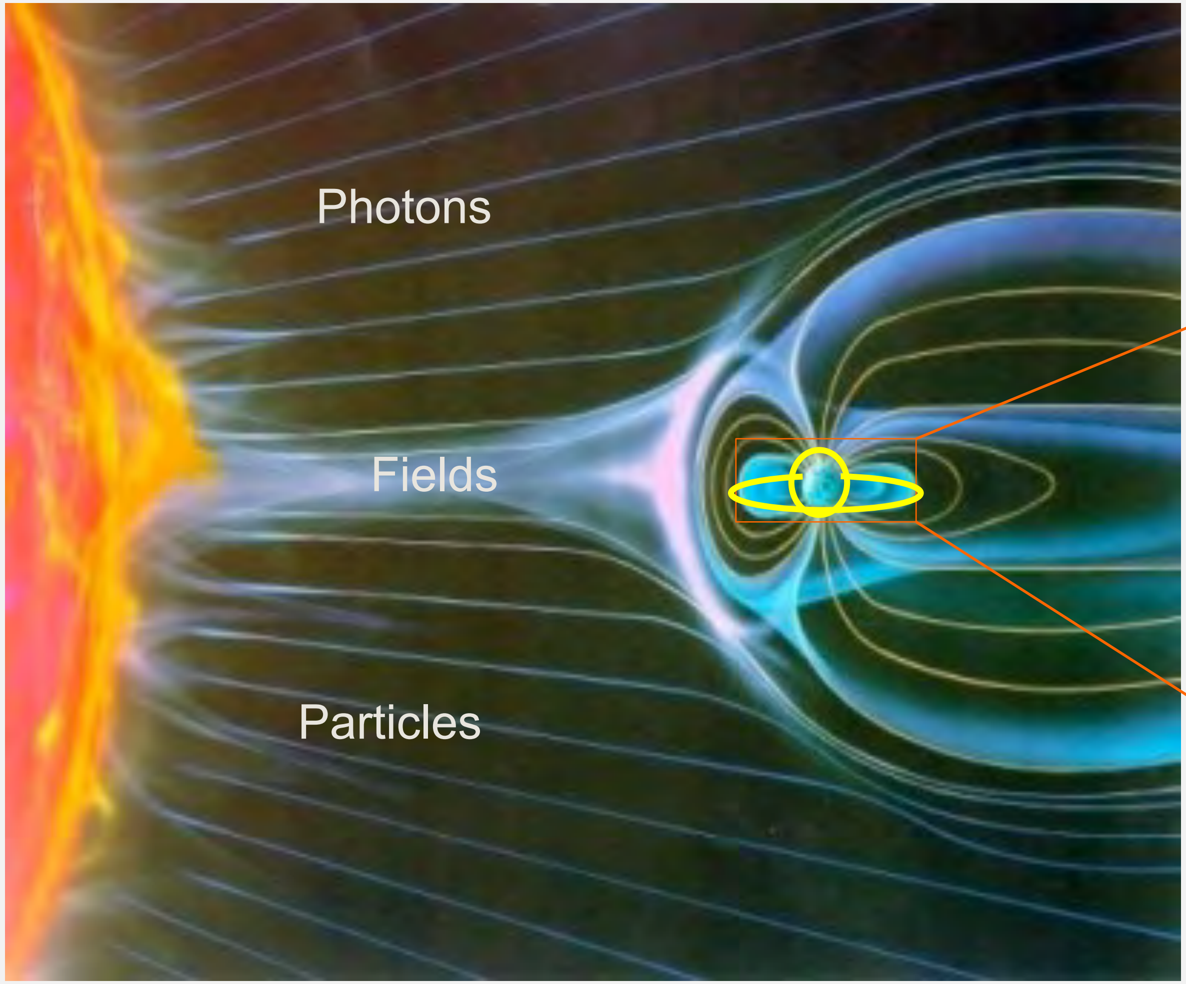
- Originates in a dynamo process inside the Earth's core
- Close to the surface described by as a dipole or a multipole
- Variable in magnitude and direction: polarity reversals approximately all 500 000 years.



The outer field:

- Originates in current systems in the ionosphere and magnetosphere, driven by the solar wind flow
- Blunted on the sunward ("day") side, long extended tail on the anti-sunward ("night") side

EARTH'S MAGNETOSPHERE



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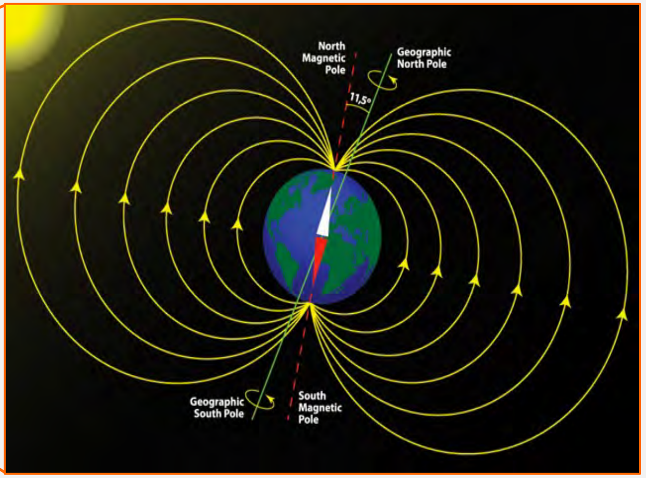

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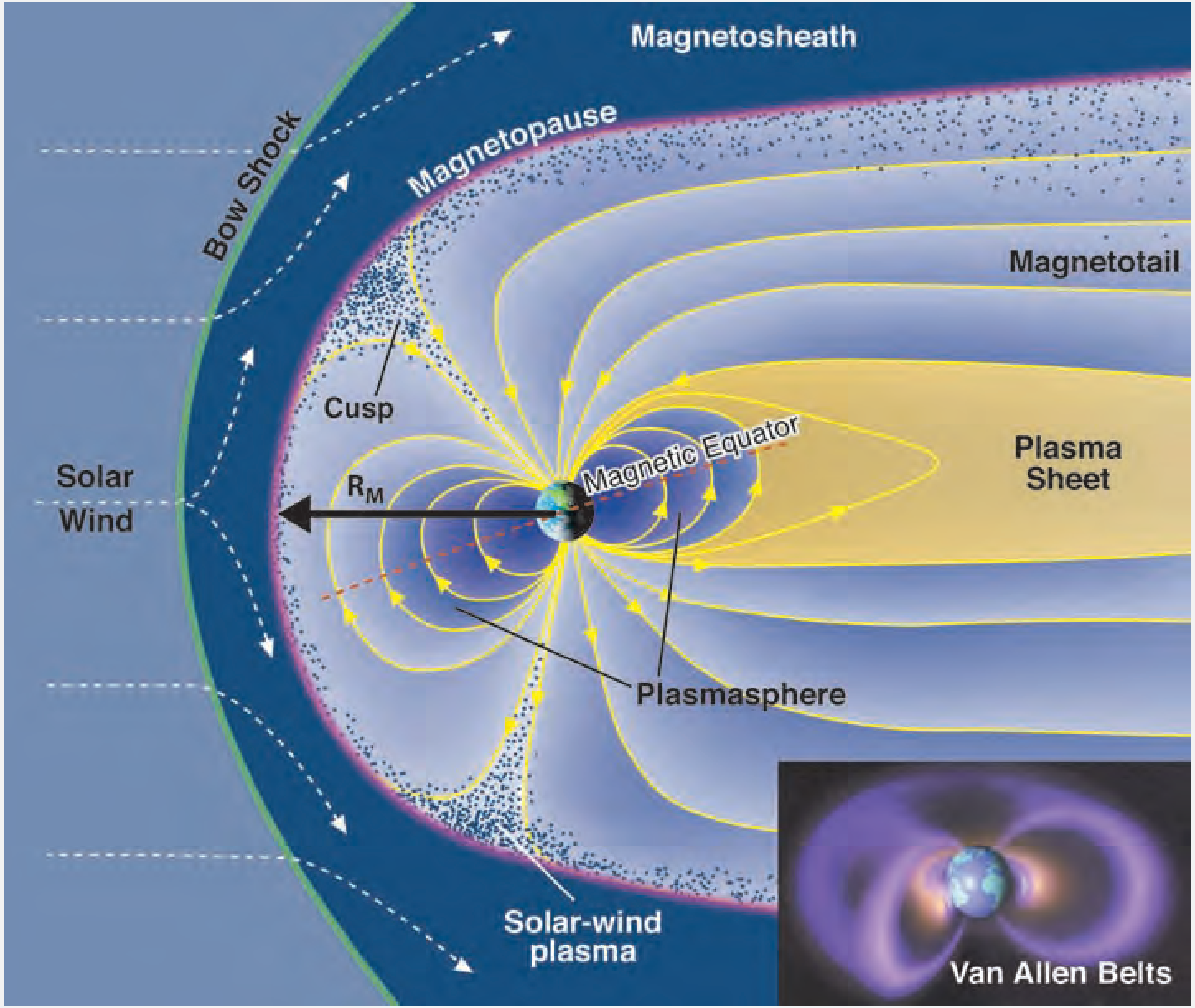

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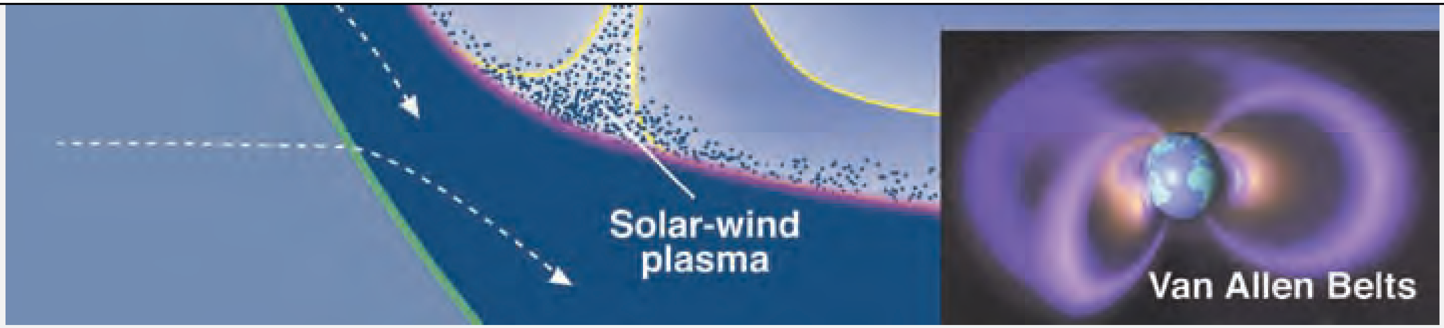
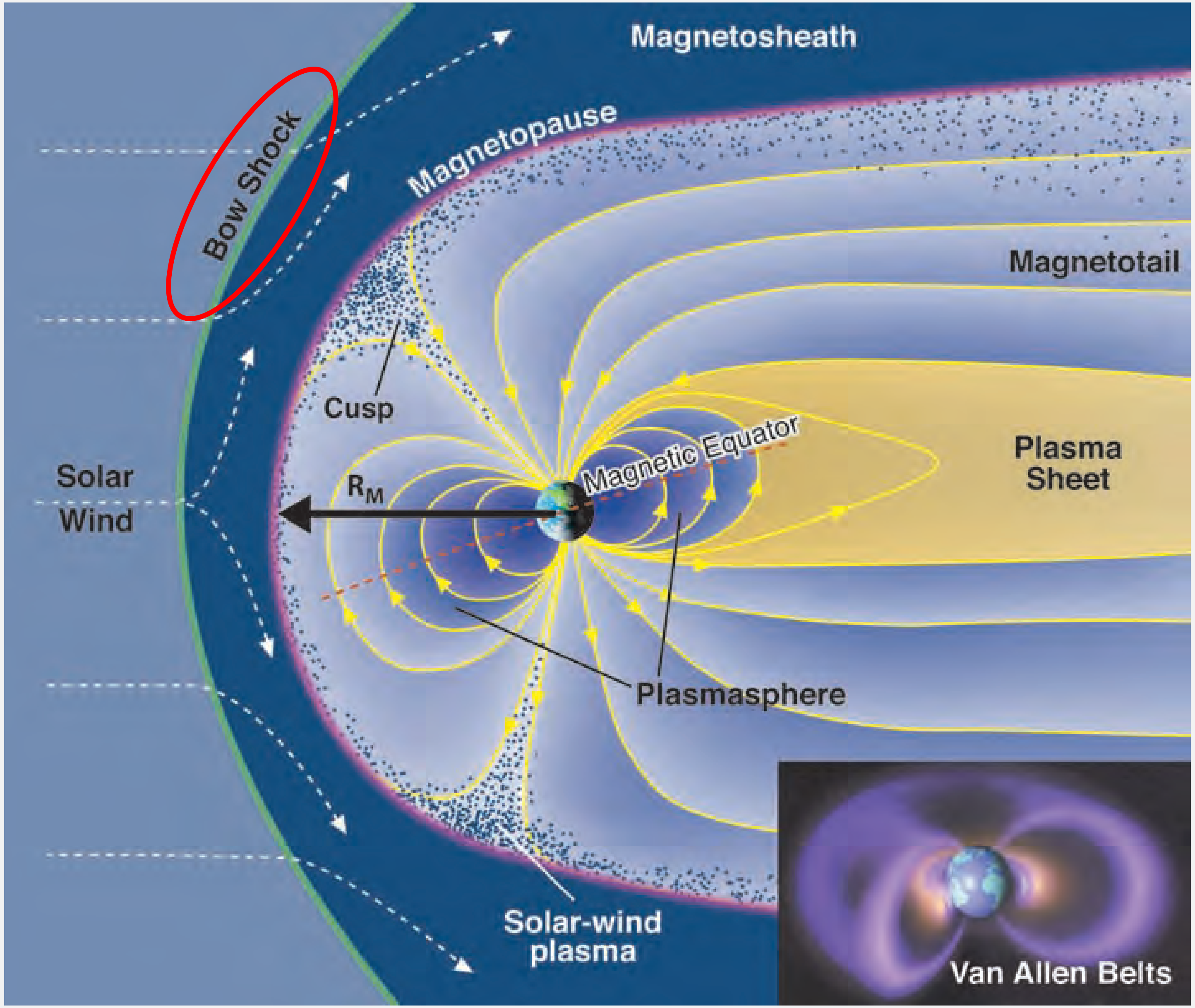
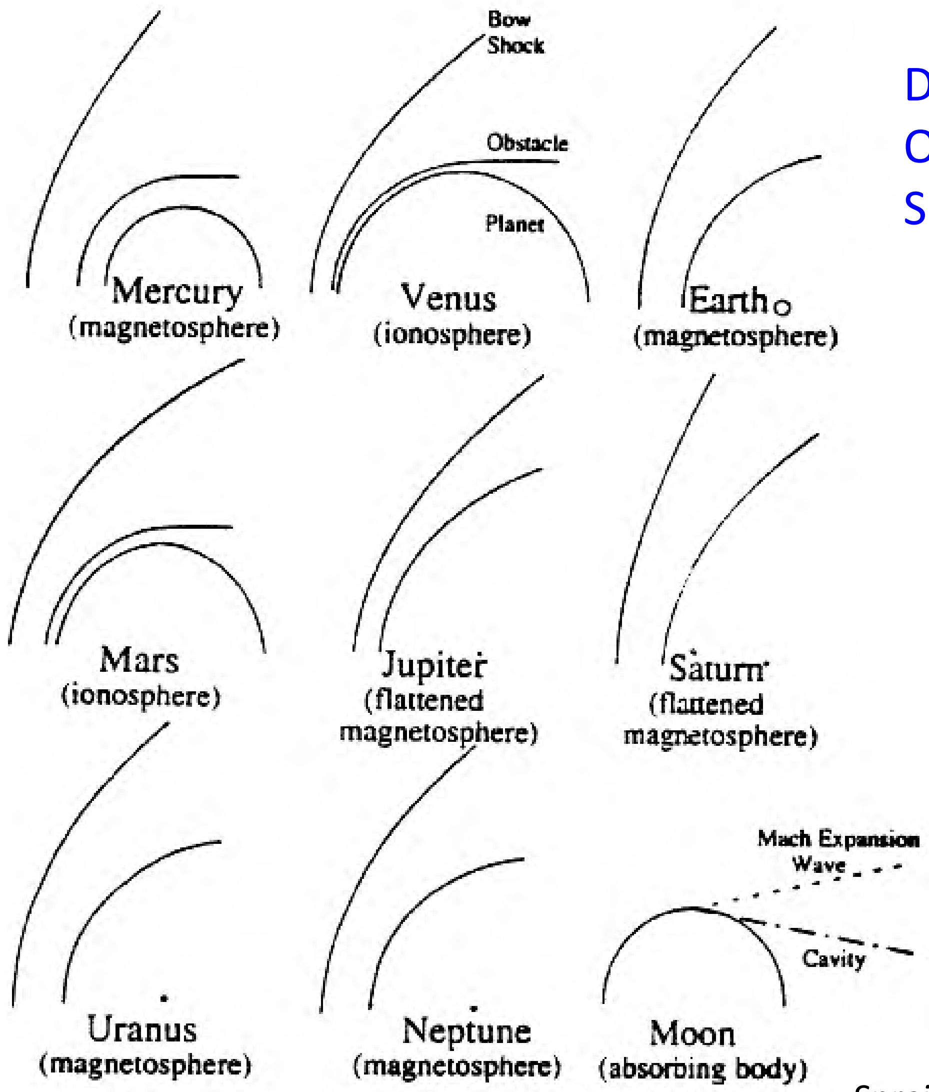


Lockwood (2022) Frontiers
"The Joined-up Magnetosphere"

EARTH'S MAGNETOSPHERE



BOW SHOCK -
COLLISIONLESS SHOCKS IN PLASMAS



Distance of Shock from Obstacle and Shape of Shock depends on....?

Spreiter & Stahara

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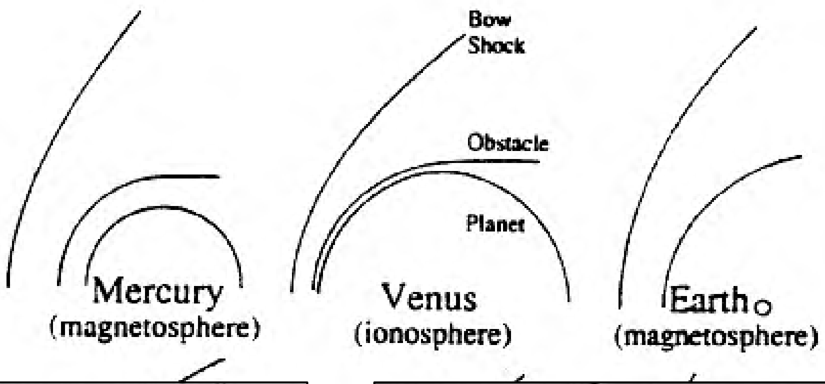

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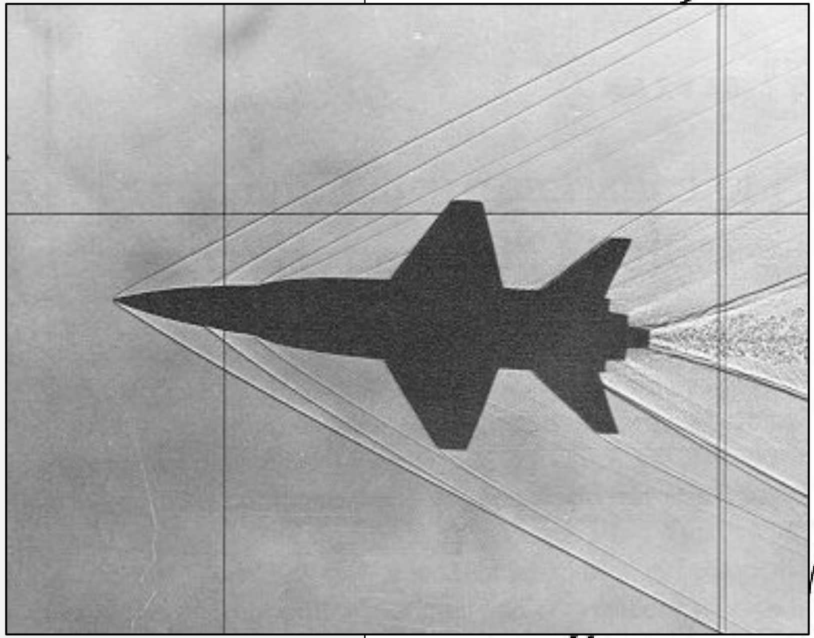

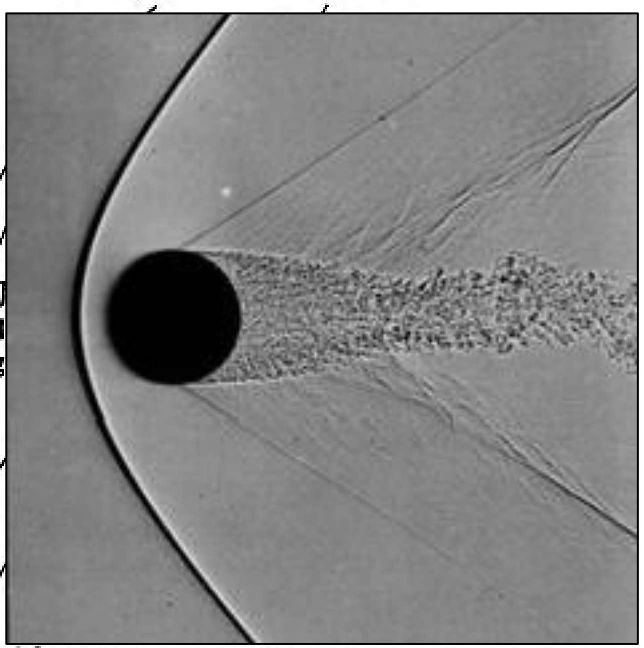

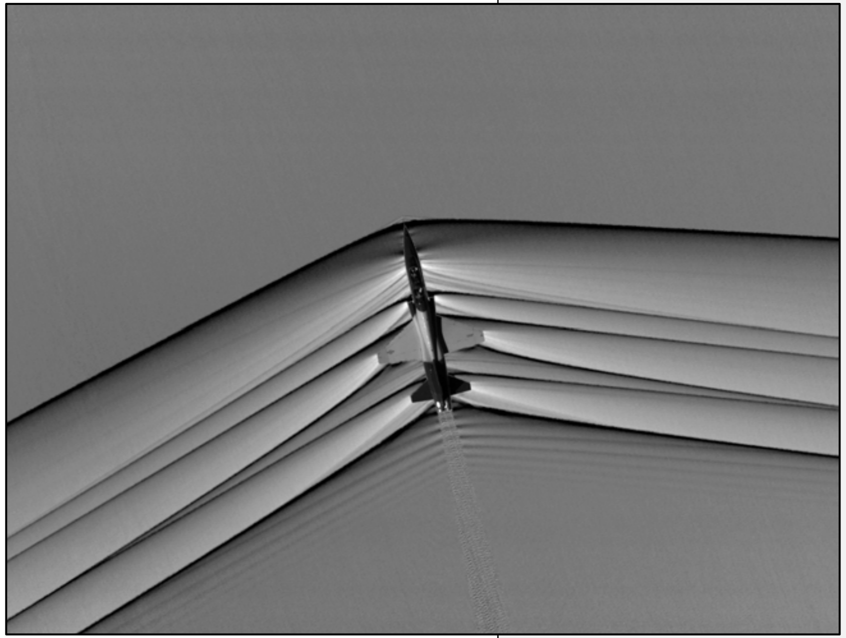

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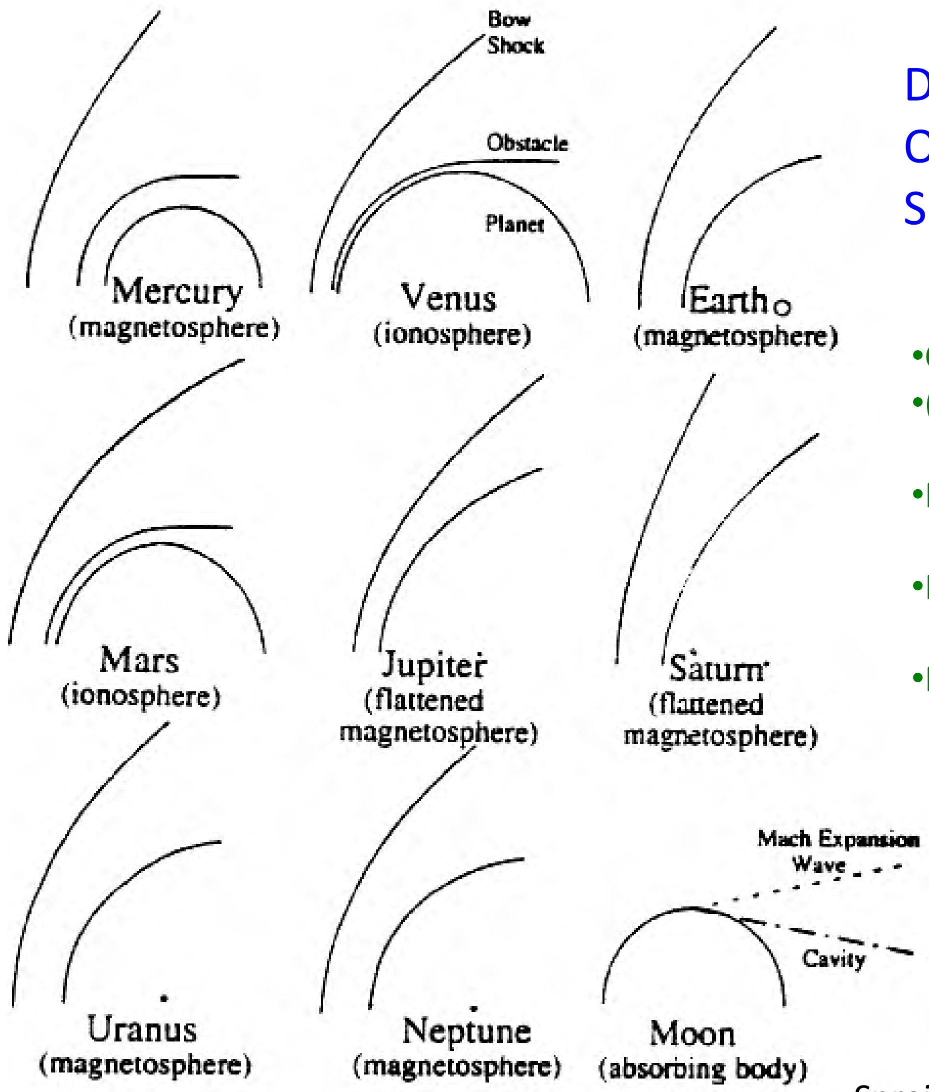
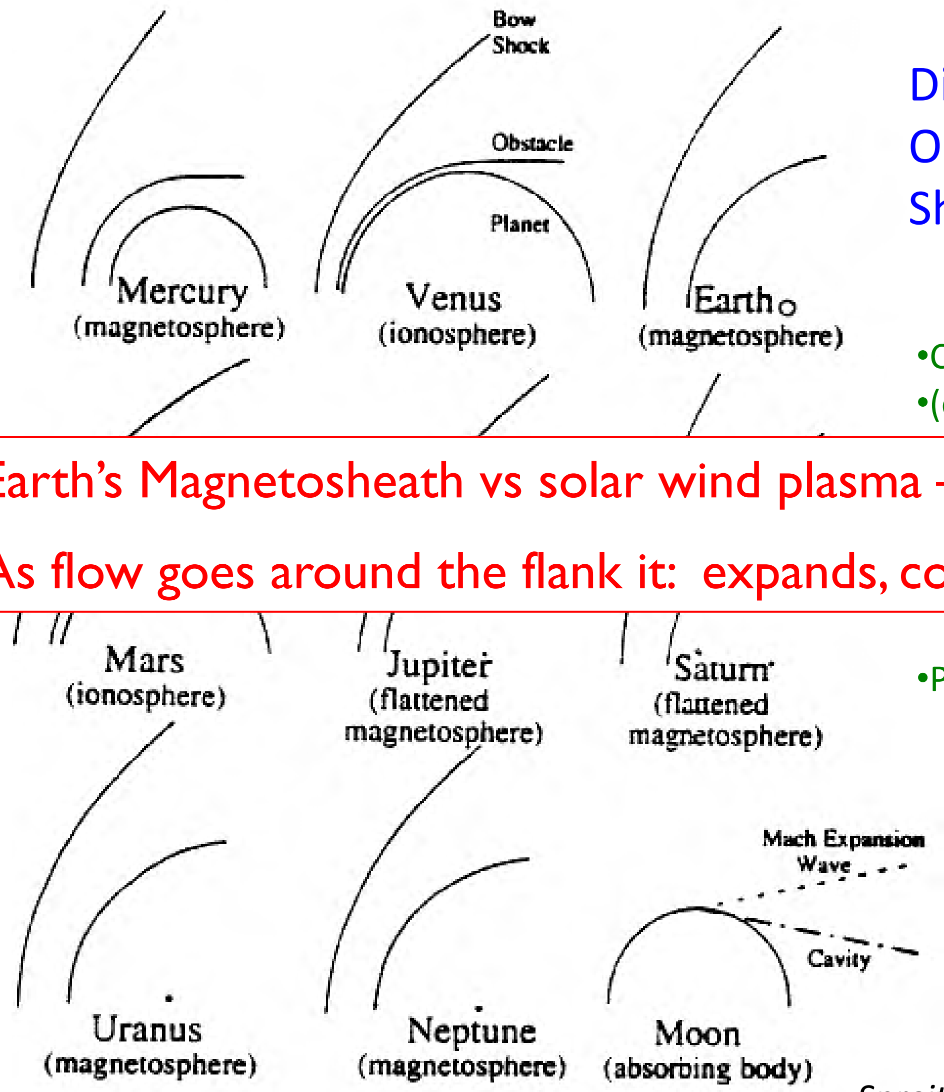


Spreiter & Stahara

Distance of Shock from Obstacle and Shape of Shock depends on....?

- Conductance of body
- (e.g. Moon vs. Mars)
- Magnetic field of planet
- Mach number of solar wind
- Presence of escaping atmosphere

BOW SHOCK - COLLISIONLESS SHOCKS IN PLASMAS



Spreiter & Stahara

Distance of Shock from Obstacle and Shape of Shock depends on….?

- Conductance of body
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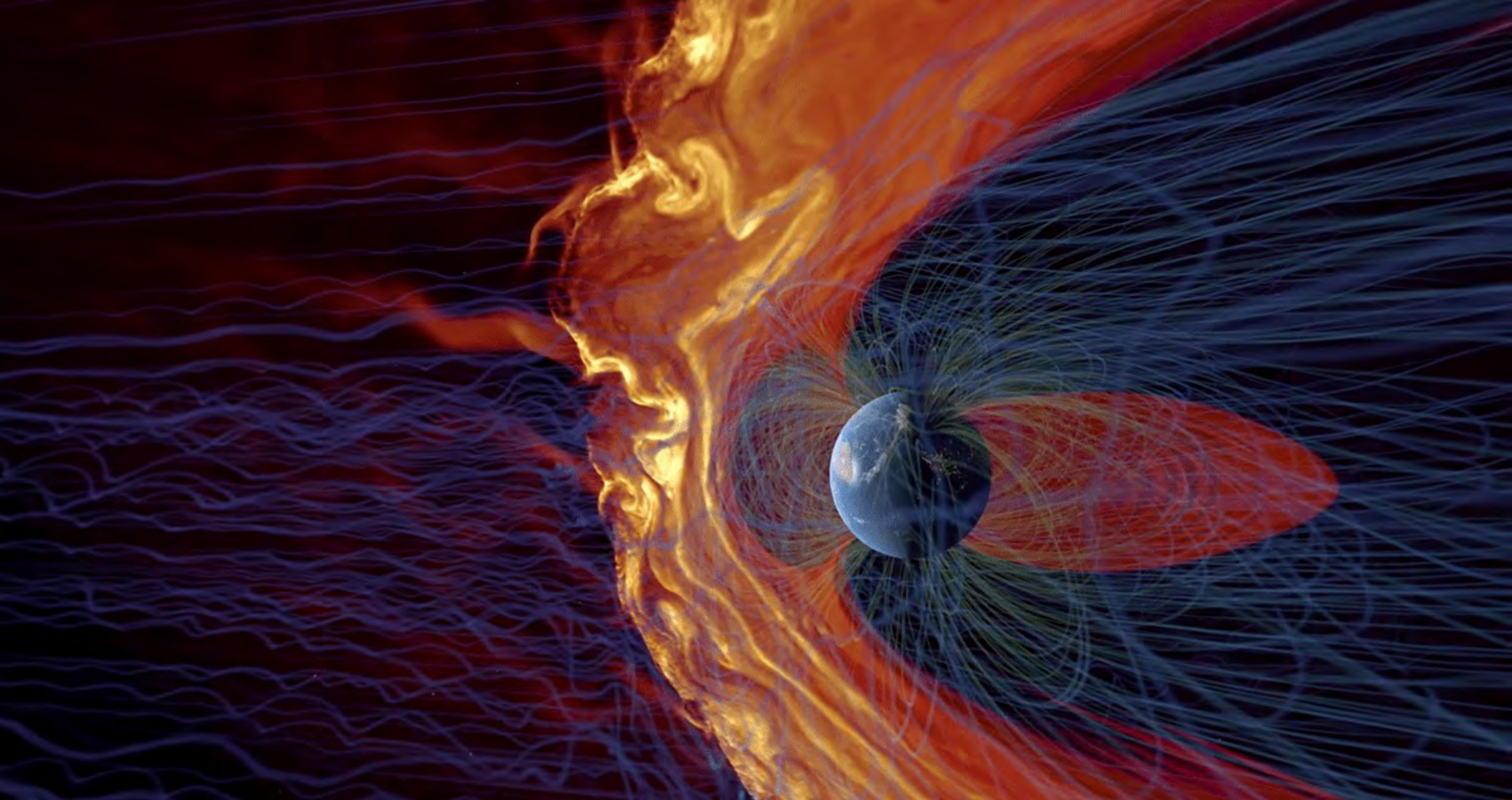
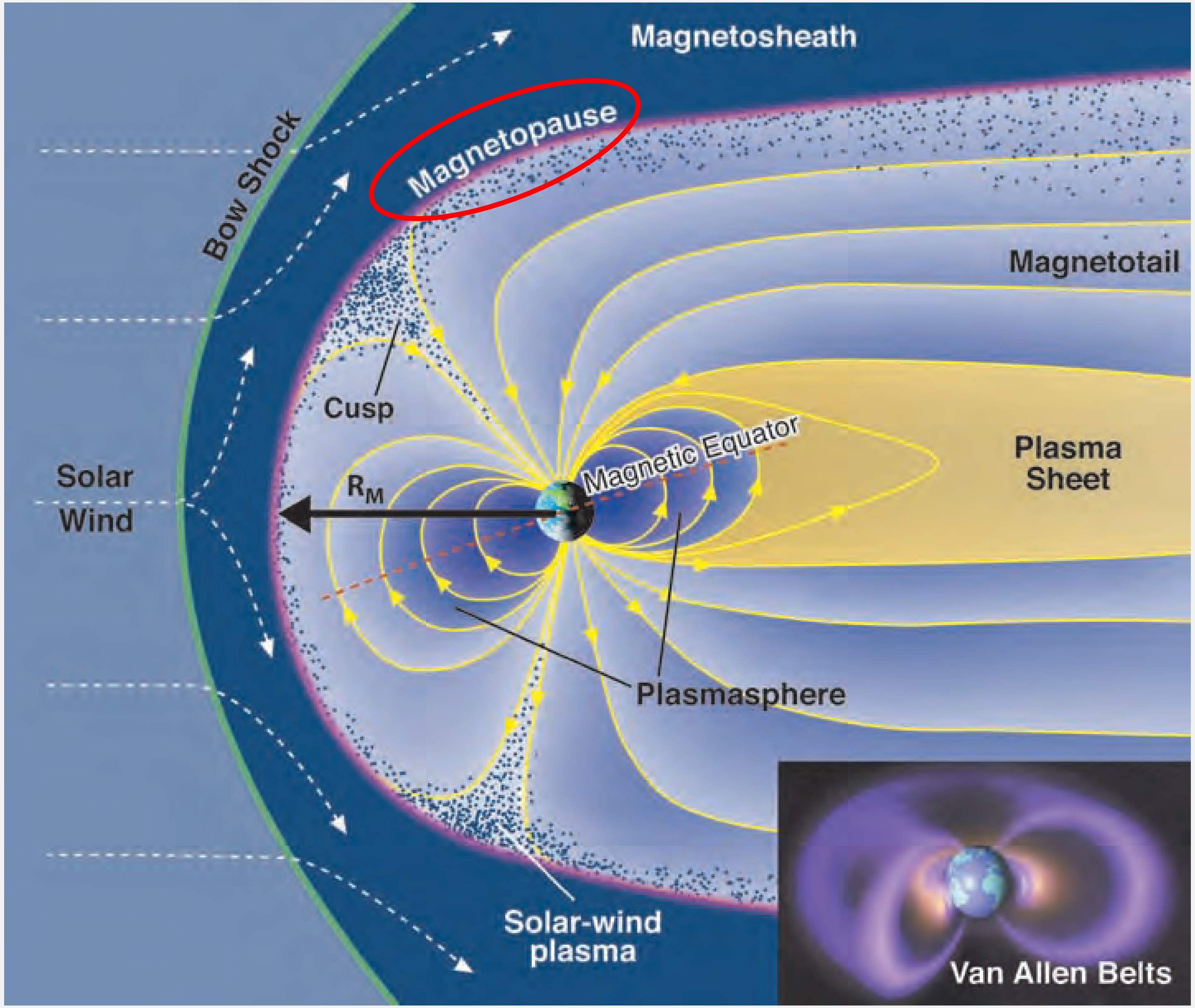
Earth's Magnetosheath vs solar wind plasma – denser, hotter, slower

As flow goes around the flank it: expands, cools, speeds up again

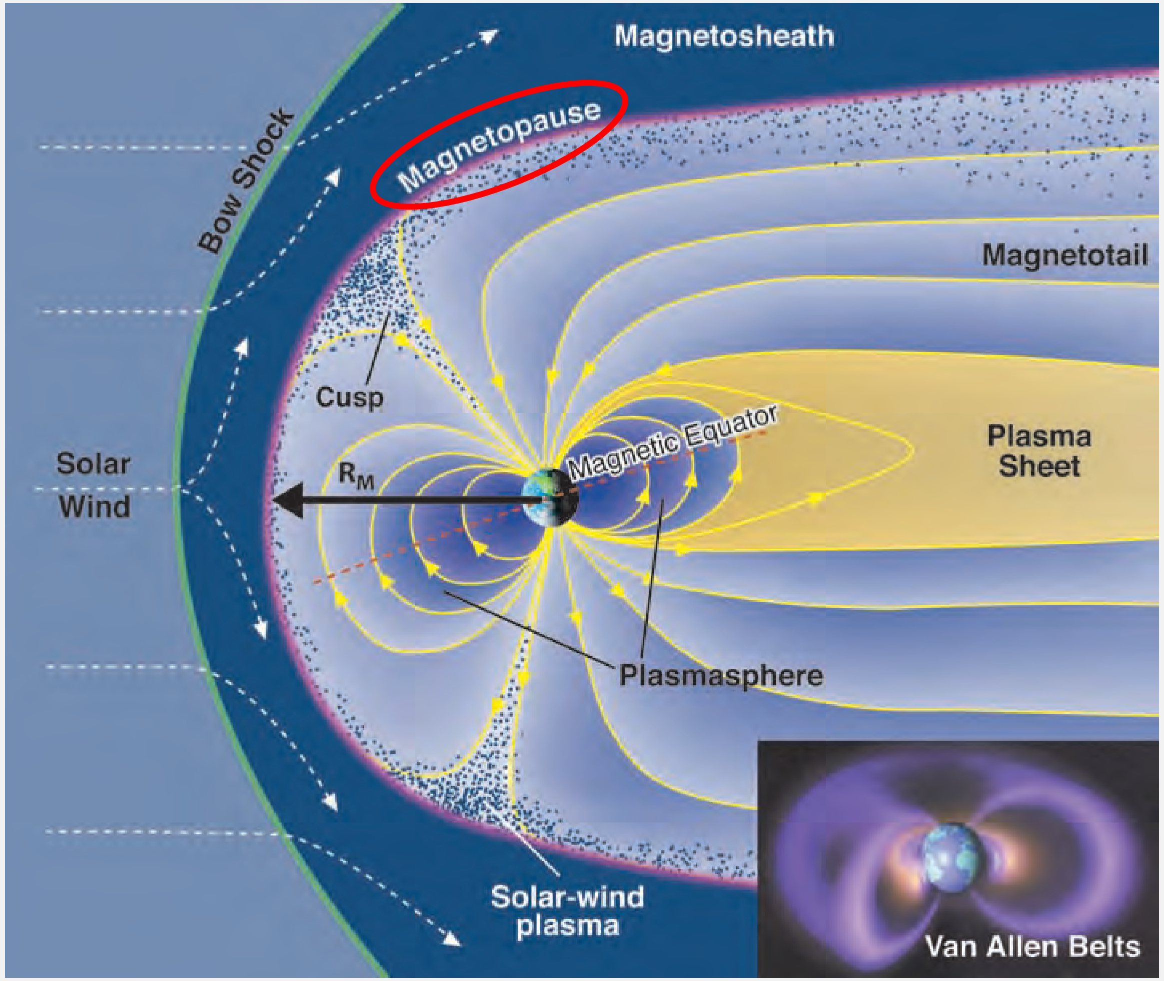


Credit:Advanced Visualization Lab, National Center for Supercomputing Applications, University of Illinois, Urbana-Champaign

EARTH'S MAGNETOSPHERE



MAGNETOPAUSE

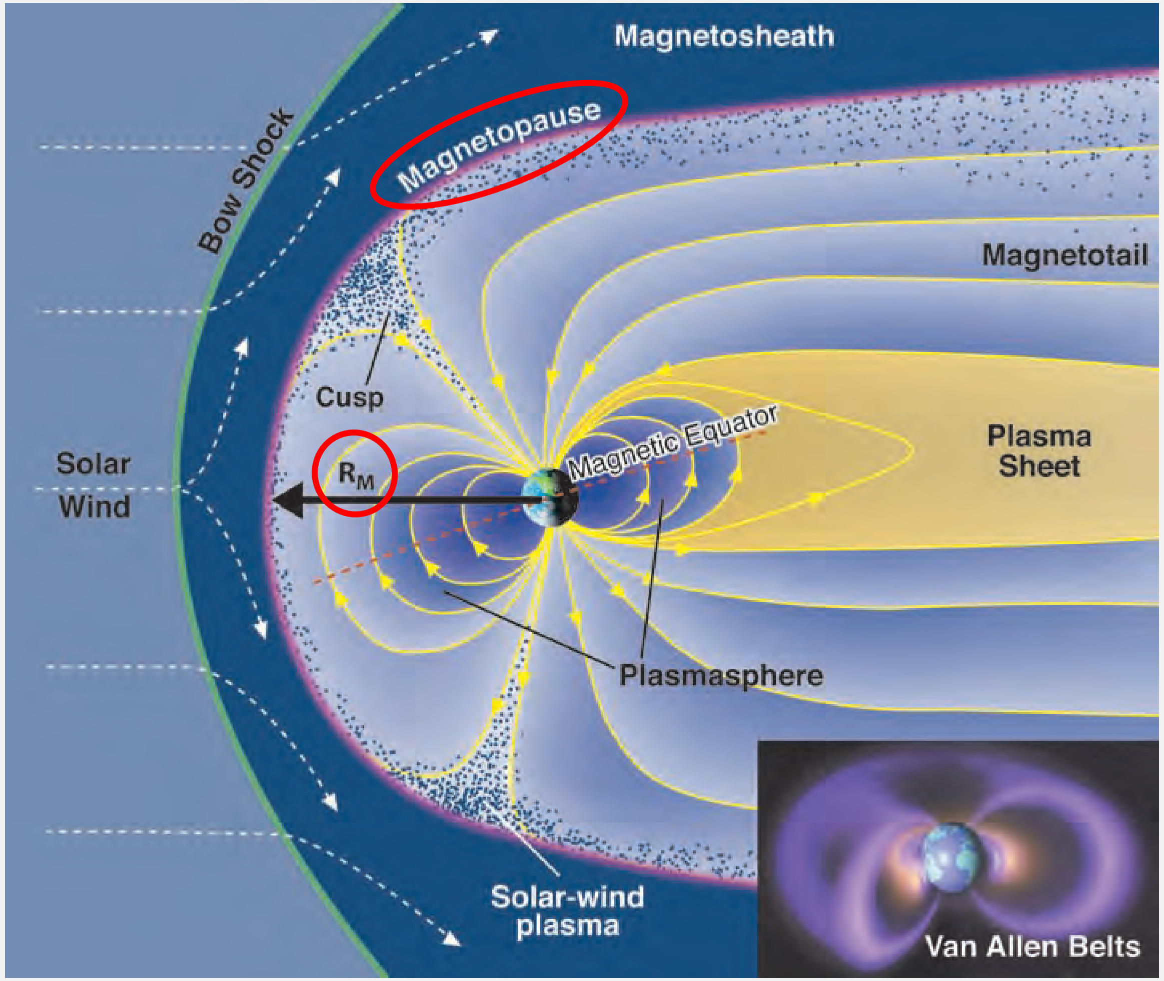


Total pressure P:

$$P = \rho u^2 + p + B^2/2\mu_o$$

- ρu^2: Dynamic pressure
- p: Thermal pressure
- $B^2/2\mu_o$: Magnetic pressure

MAGNETOPAUSE



Total pressure P:

$$P = \rho u^2 + p + B^2/2\mu_o$$

Dynamic pressure (ρu^2)

Thermal pressure (p)

Magnetic pressure ($B^2/2\mu_o$)

Solar wind: Magnetosphere:

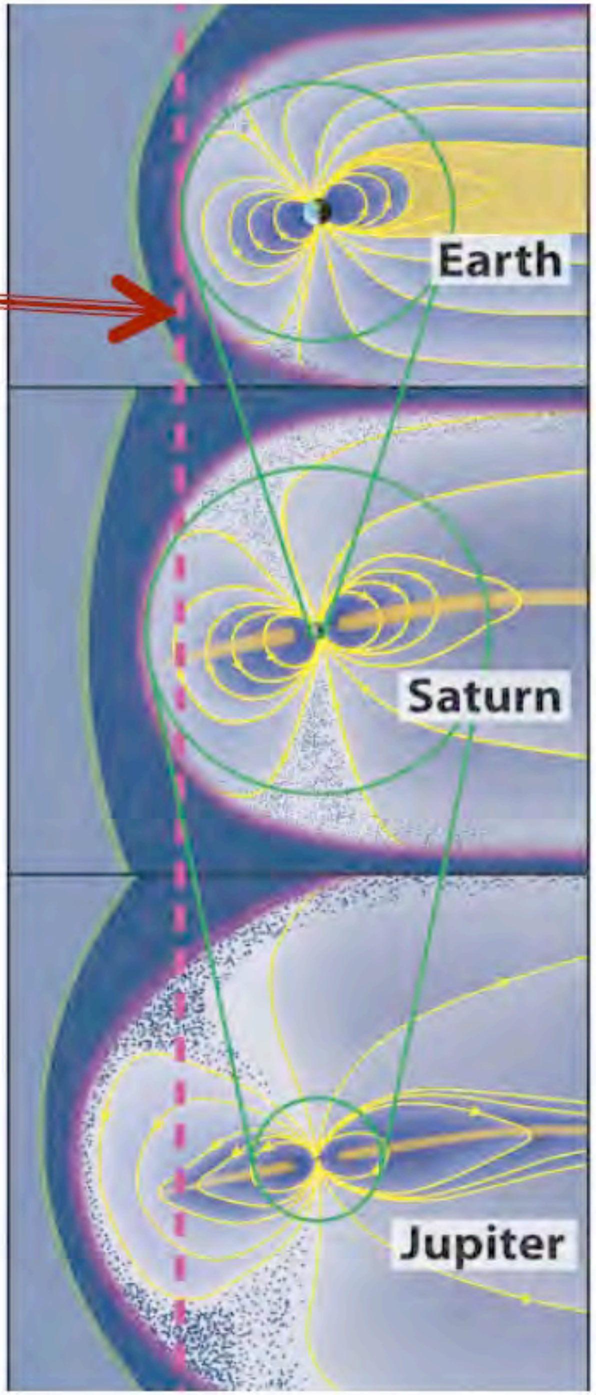
$$\rho u^2 \sim B^2/2\mu_o$$

Is this similar at other planets?

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

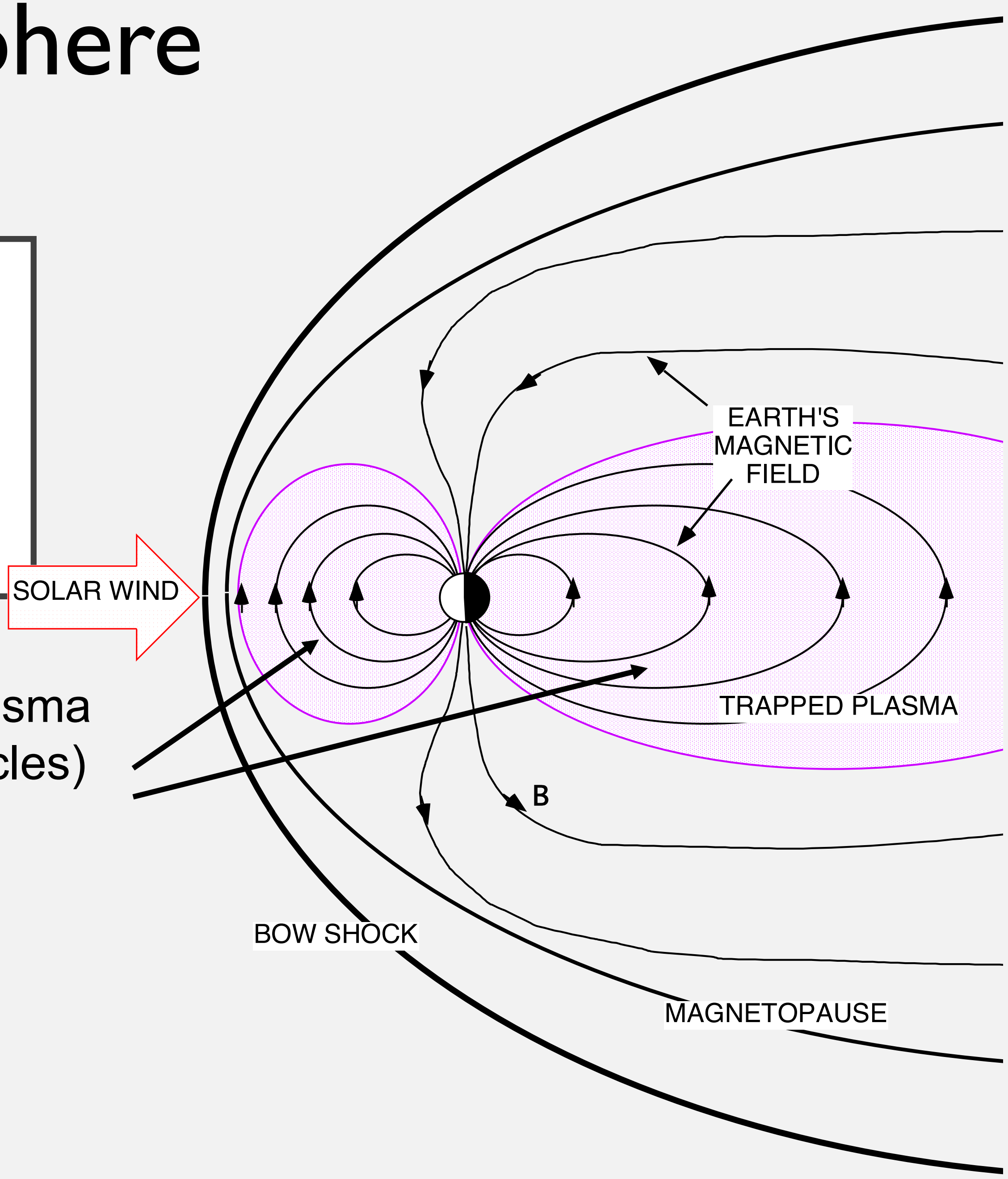


Note bimodal average locations
* *Achilleos et al. 2008*   # *Joy et al. 2002*

Bagenal 2014
HSS lecture

Earth’s Magnetosphere

THE BUBBLE ISN’T EMPTY



Charged particles (plasma and high-energy particles) are trapped in the magnetosphere

Earth’s Magnetosphere

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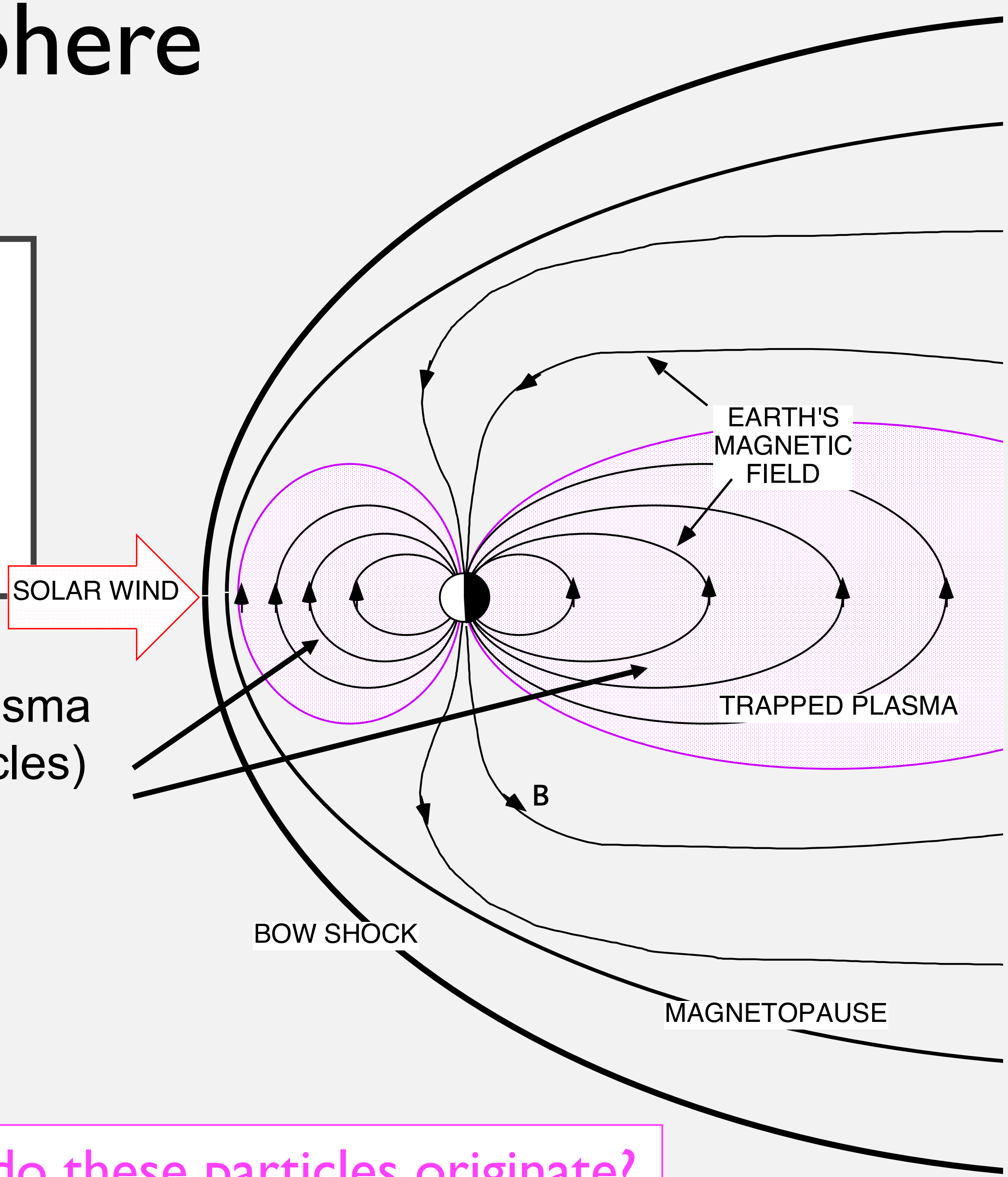


Where do these particles originate?

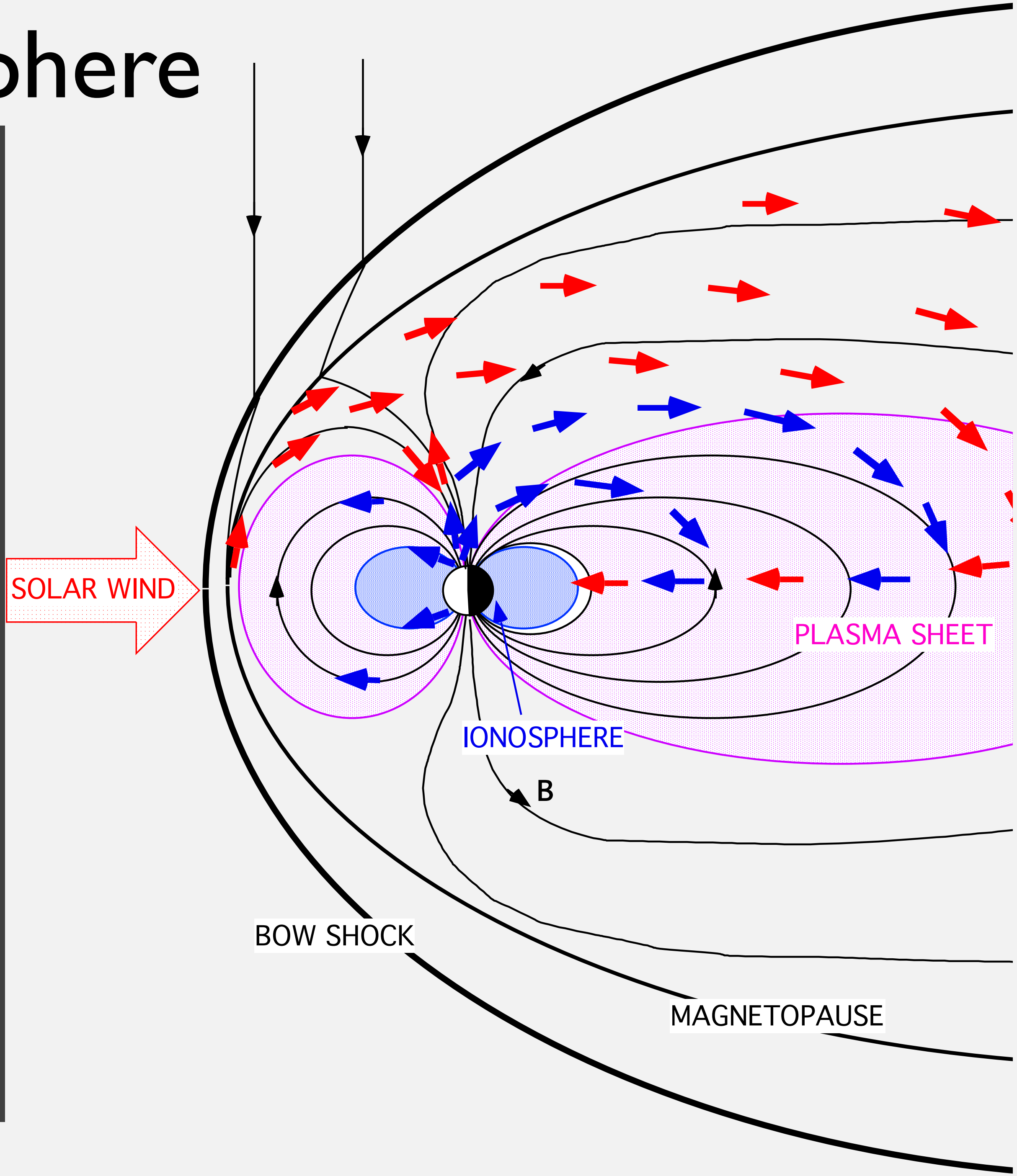
Earth's Magnetosphere

PARTICLE SOURCES:

THE EARTH'S UPPER ATMOSPHERE (RELATIVE IMPORTANCE IS ACTIVELY DEBATED.)

AND

THE SOLAR WIND (HOW? IS ACTIVELY DEBATED.)



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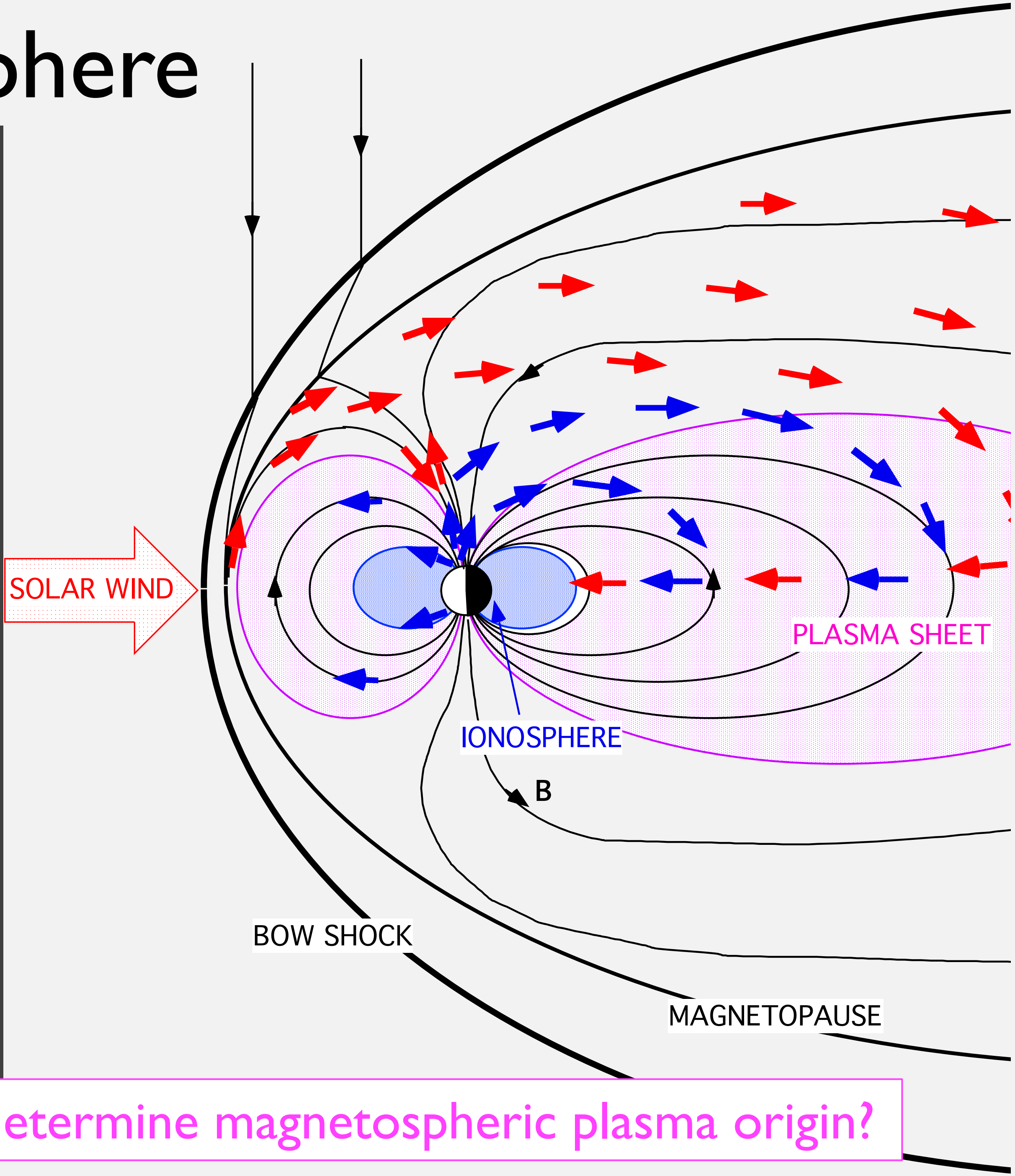
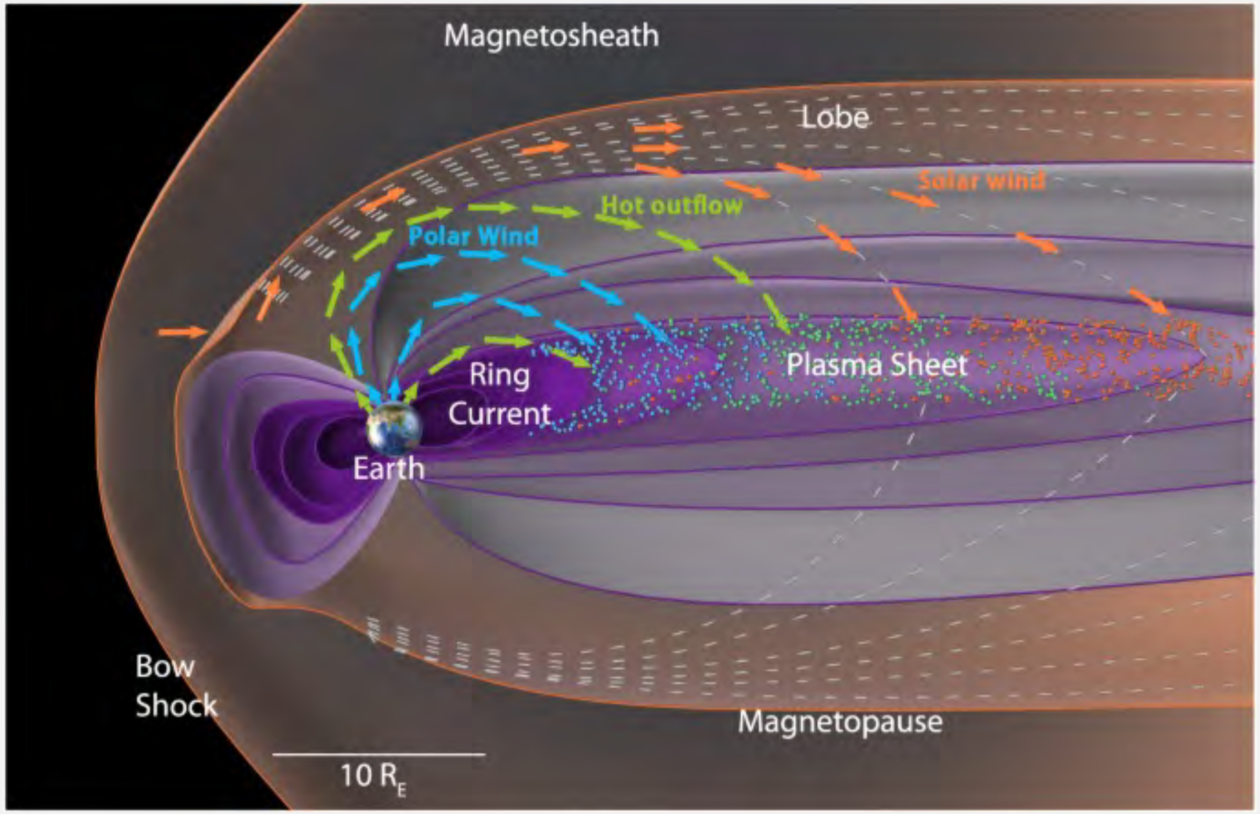
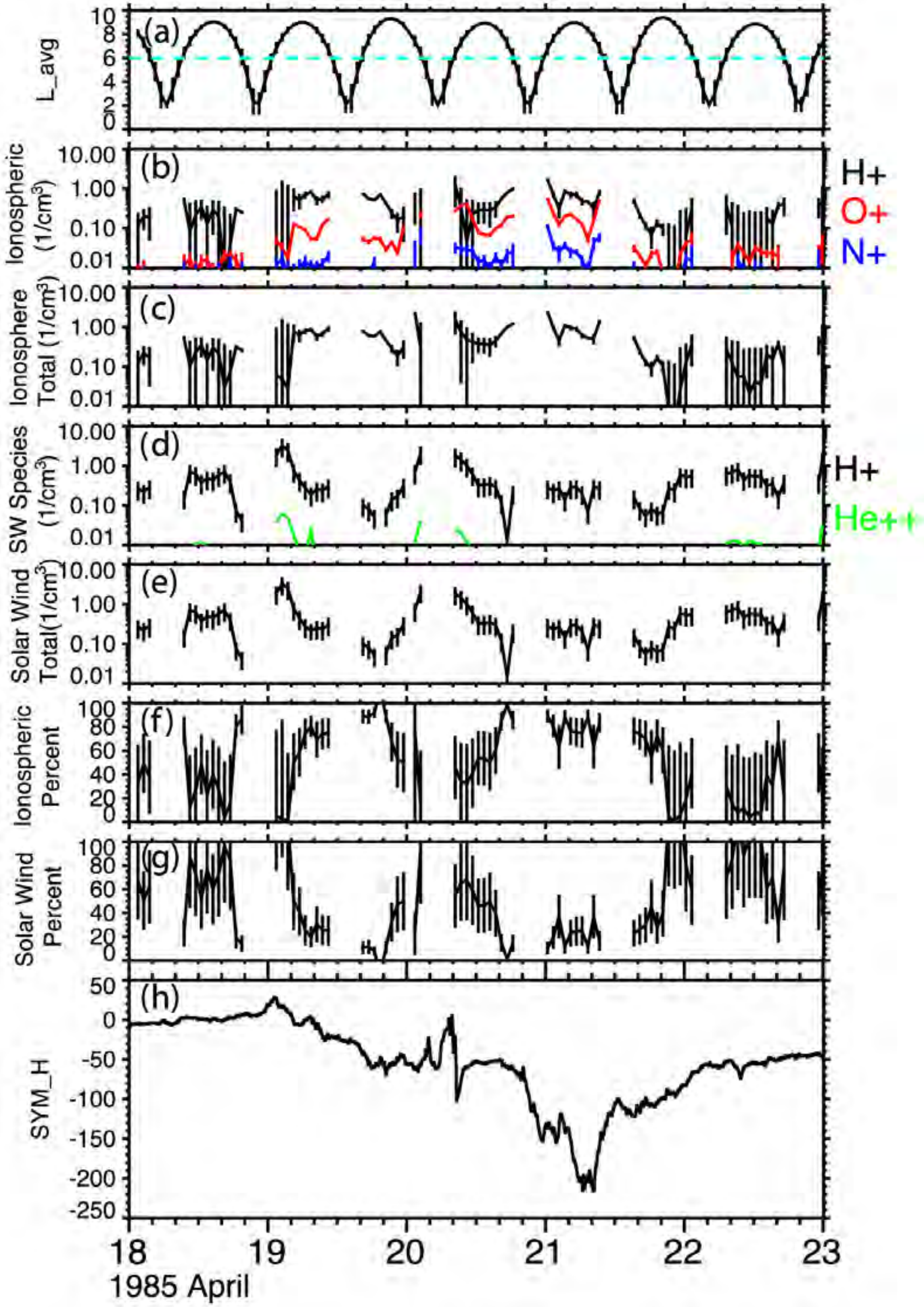


How do we determine magnetospheric plasma origin?

HOW DO WE KNOW THIS?





Kistler et al. (2023, 2020)

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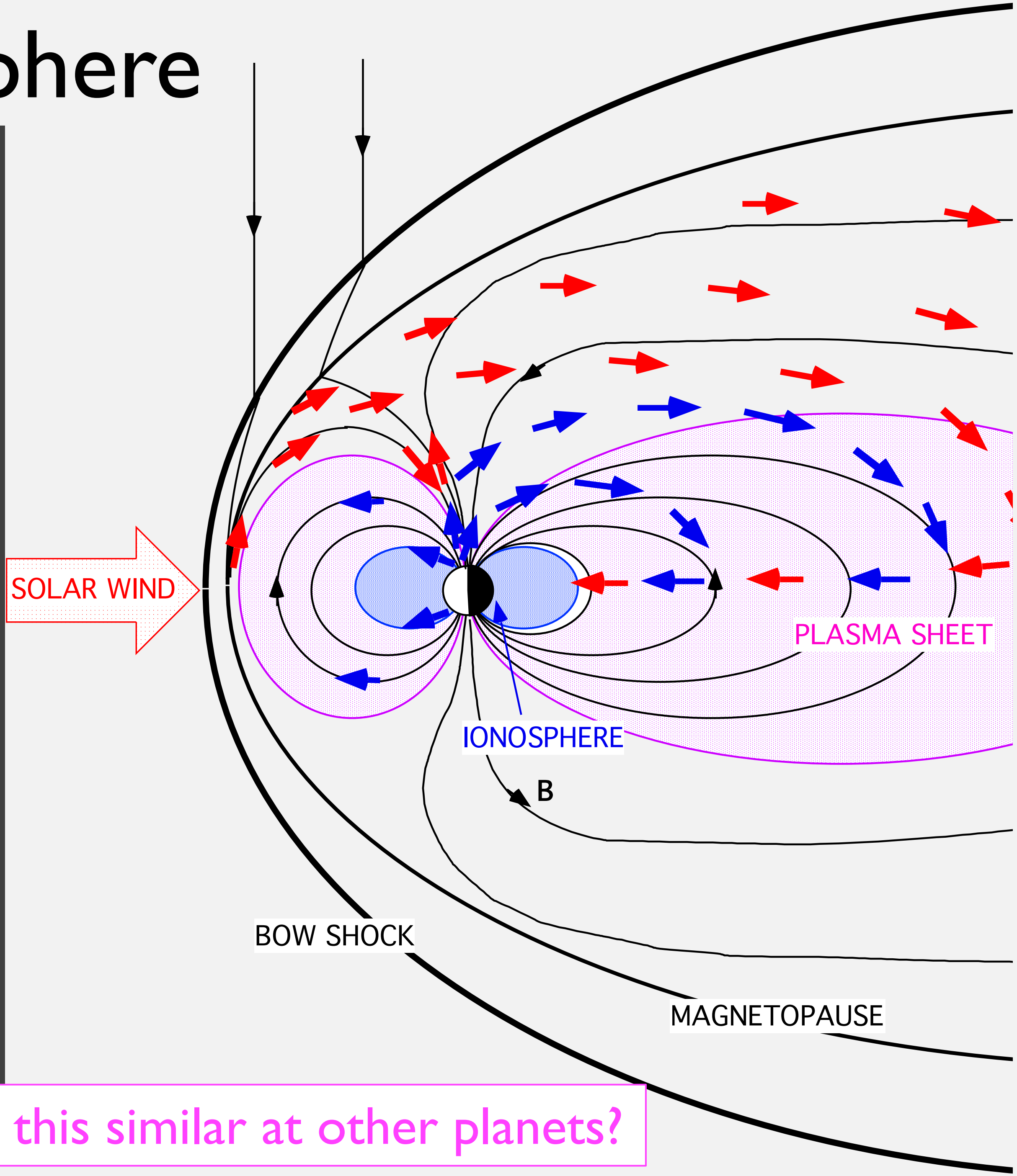
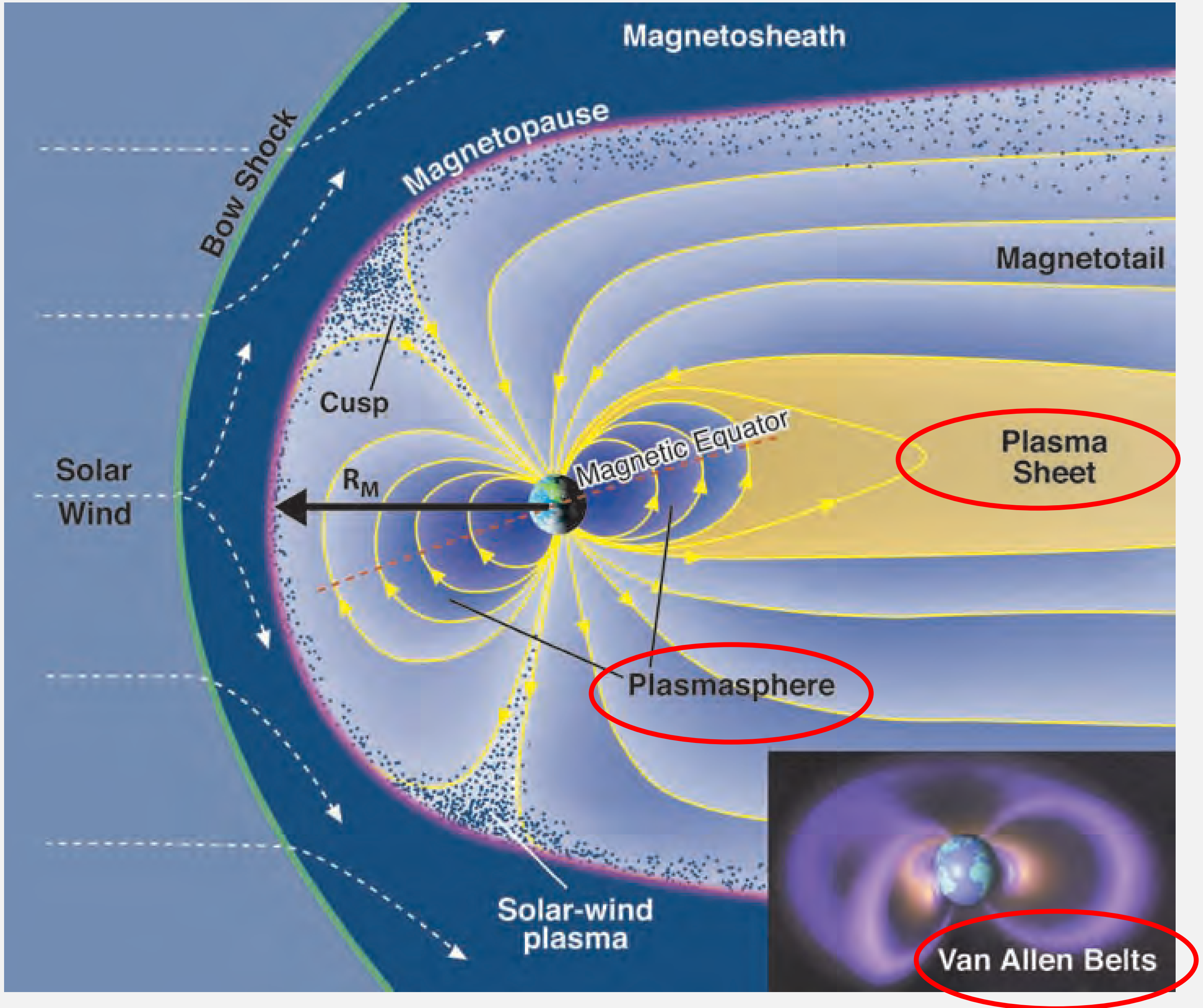
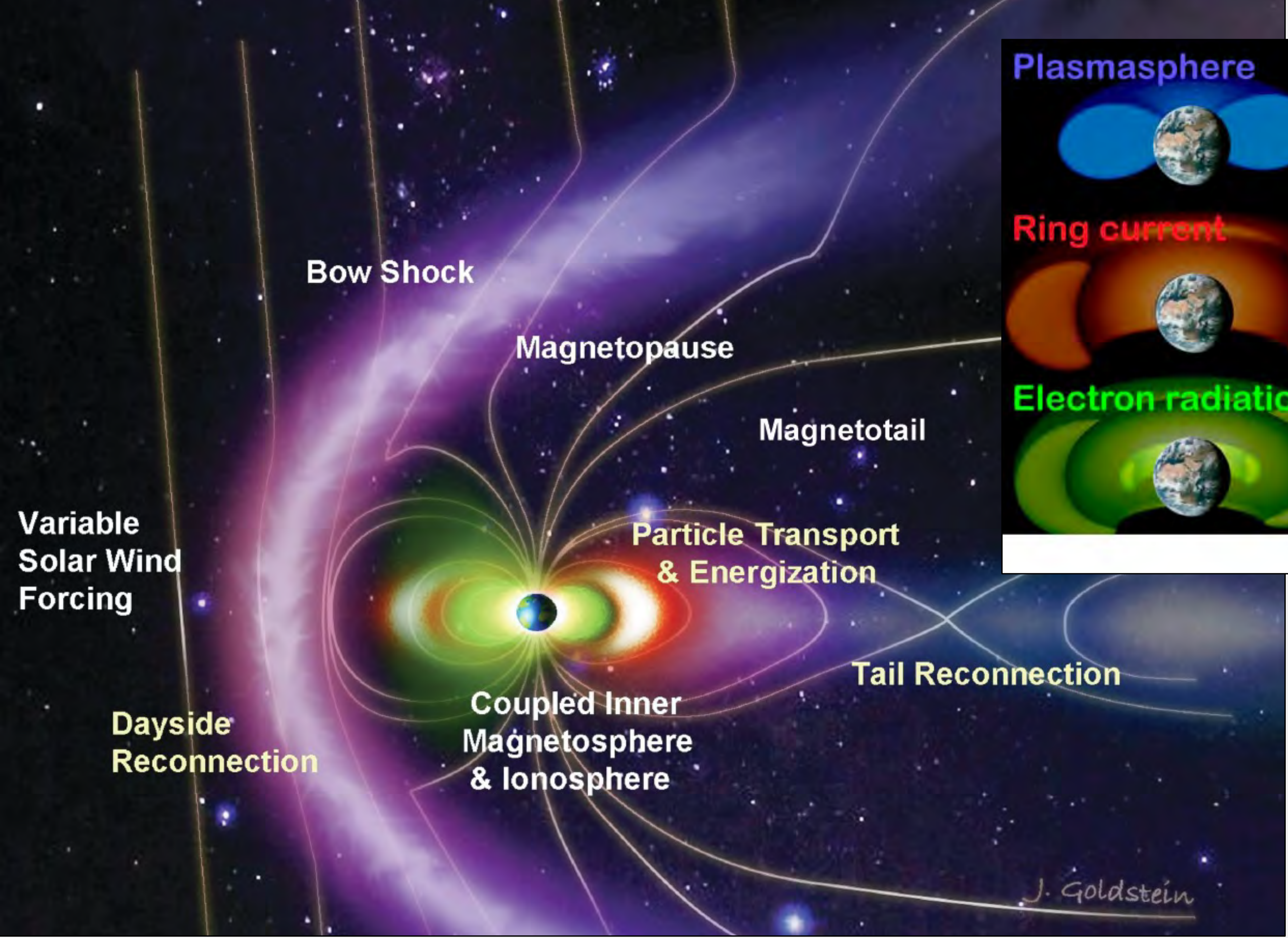
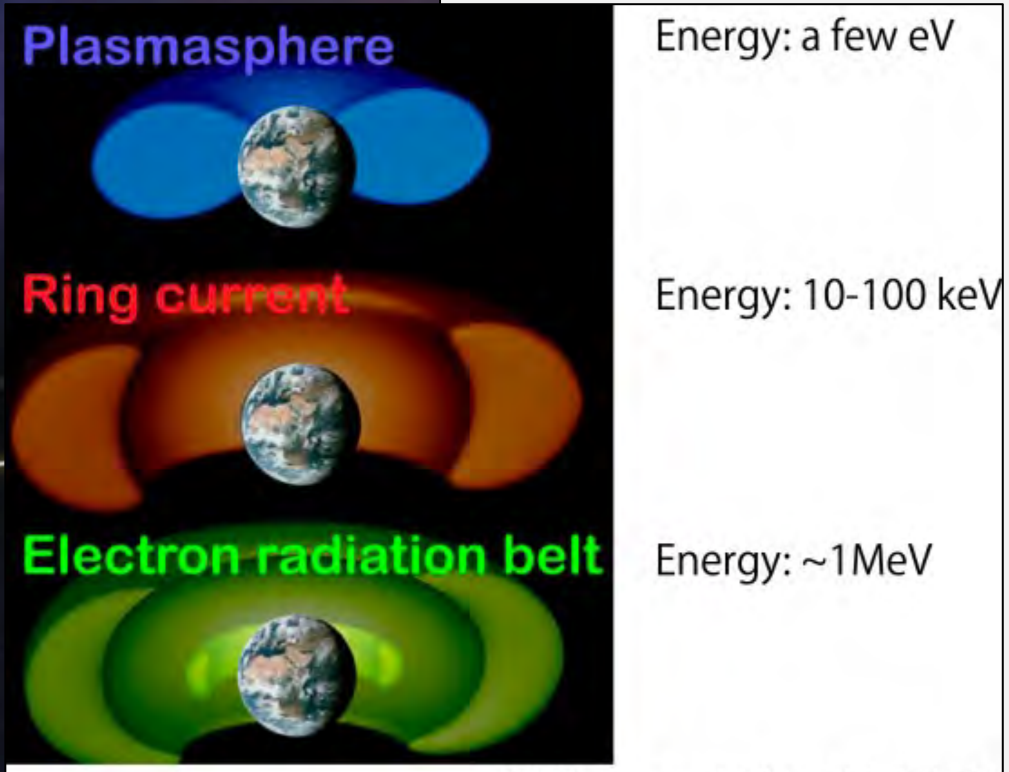


Is this similar at other planets?

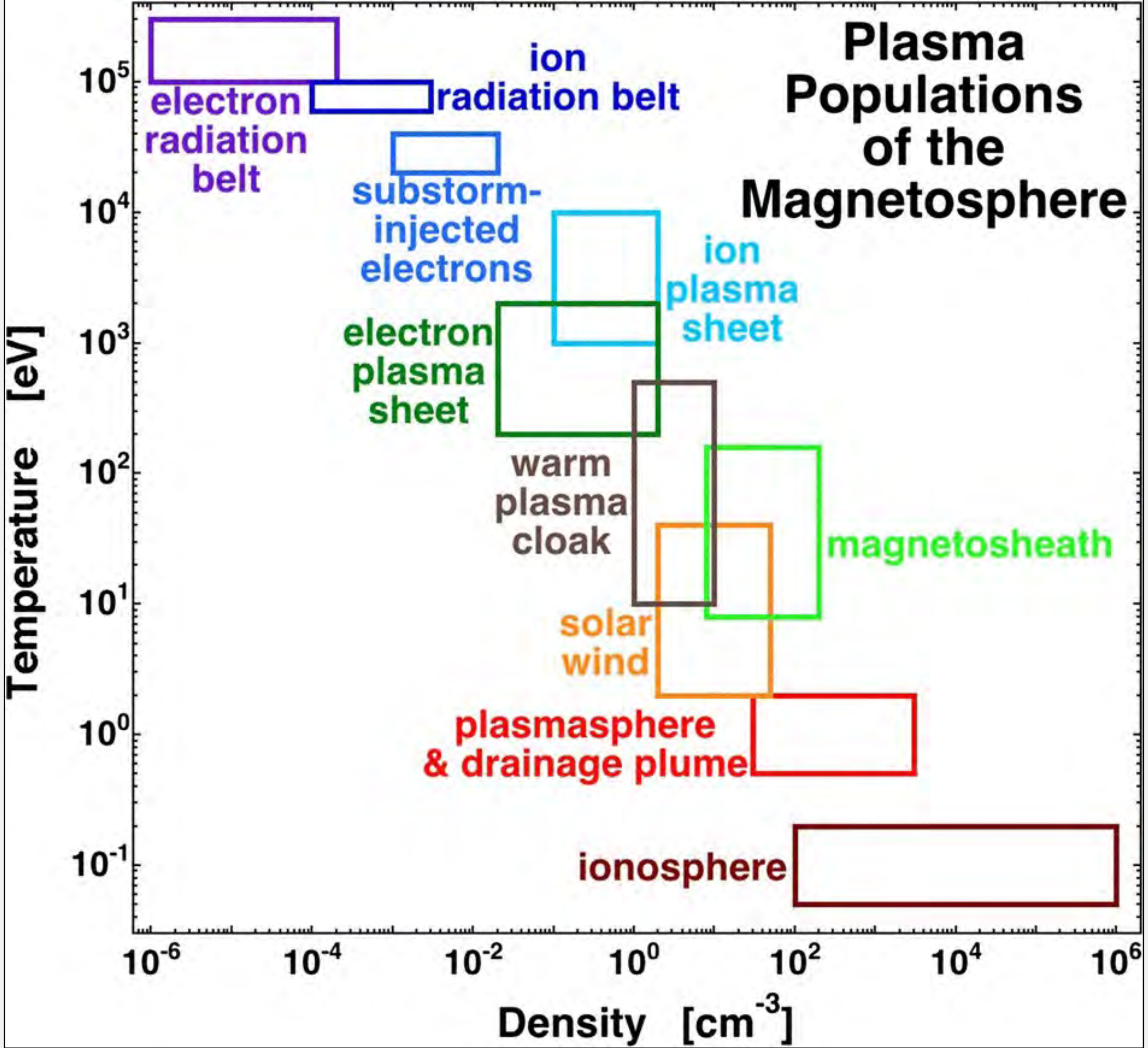
EARTH'S MAGNETOSPHERE



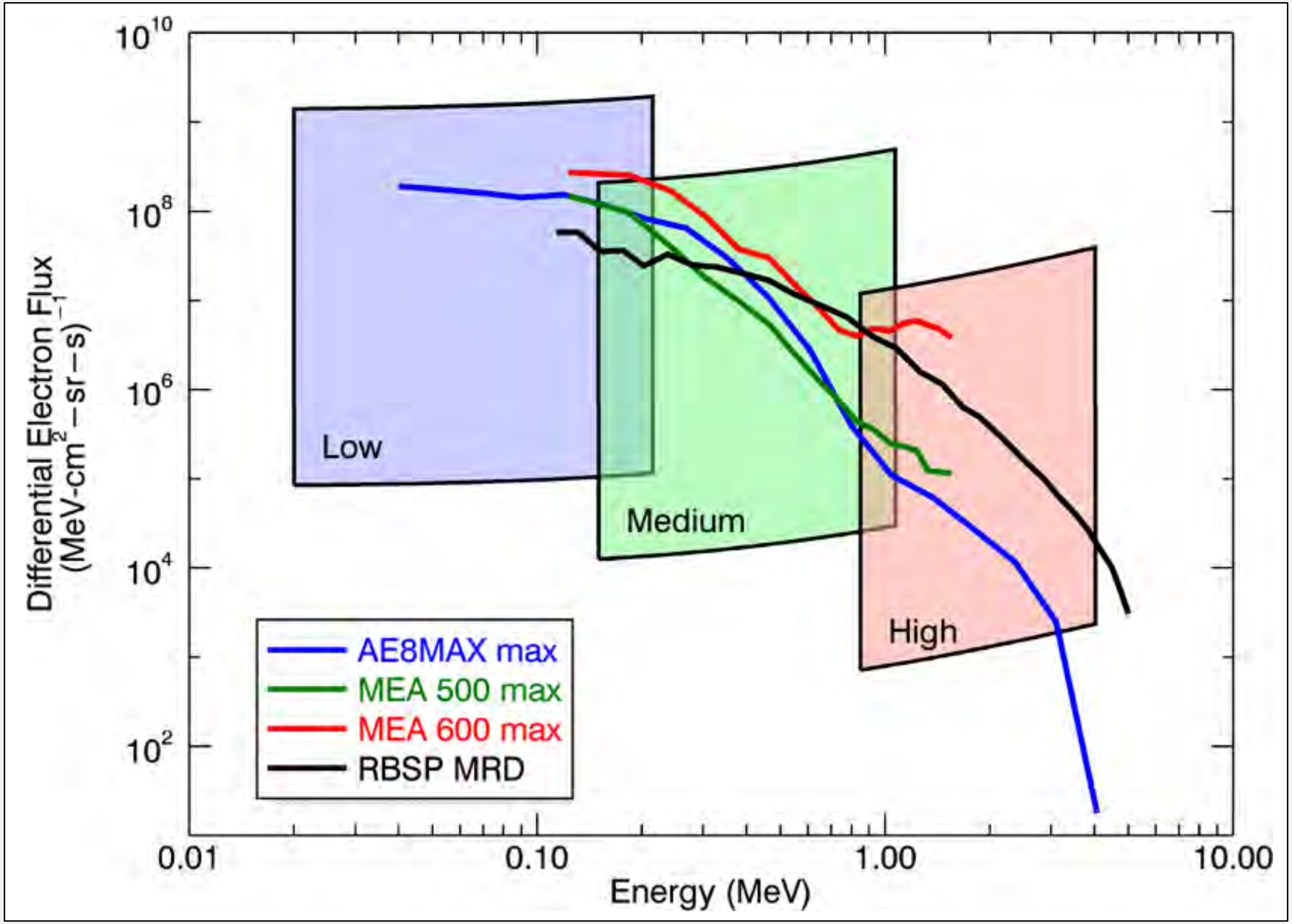




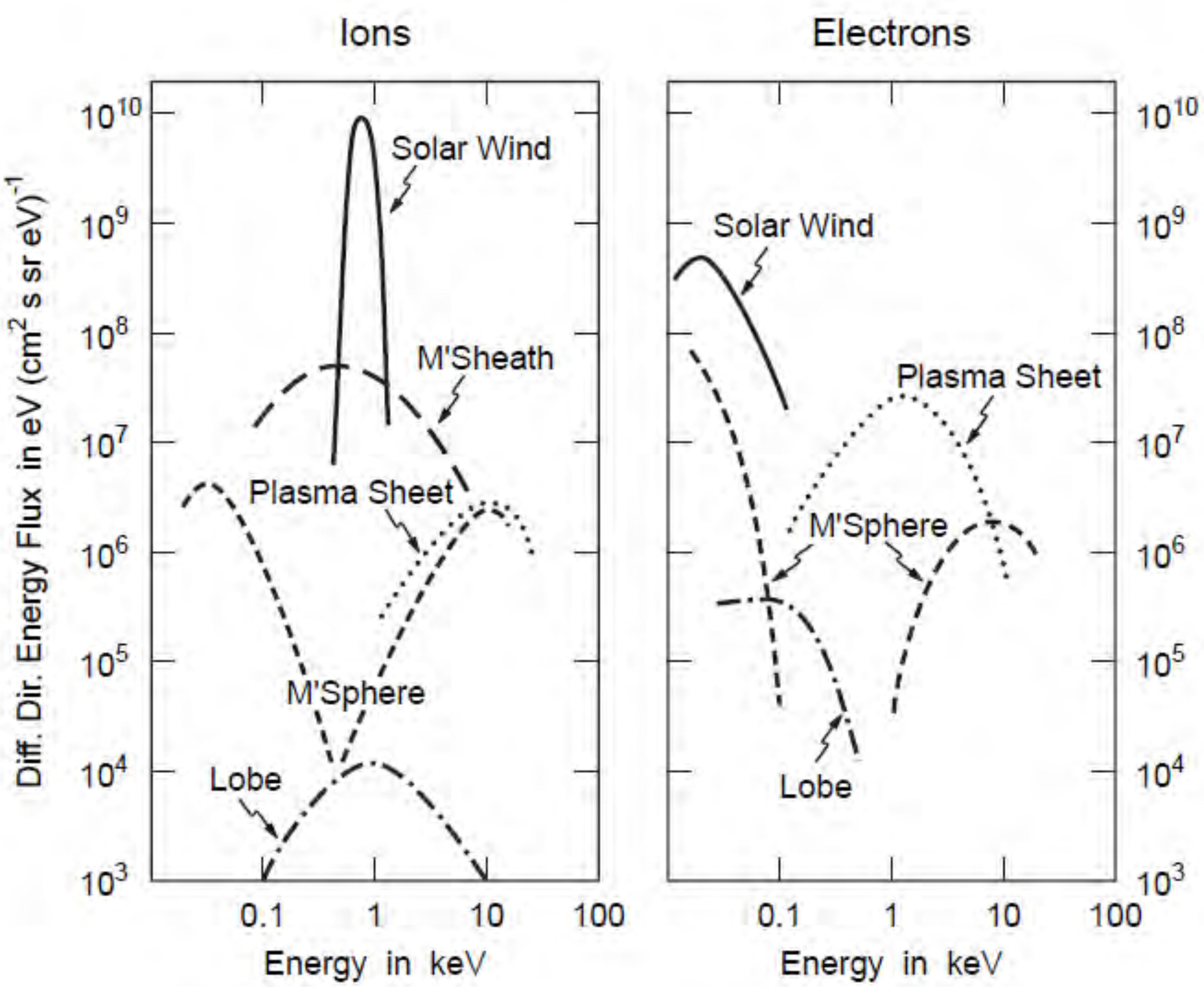
[Ebihara and Miyoshi, 2011]



Borovsky and Valdivia (2018)

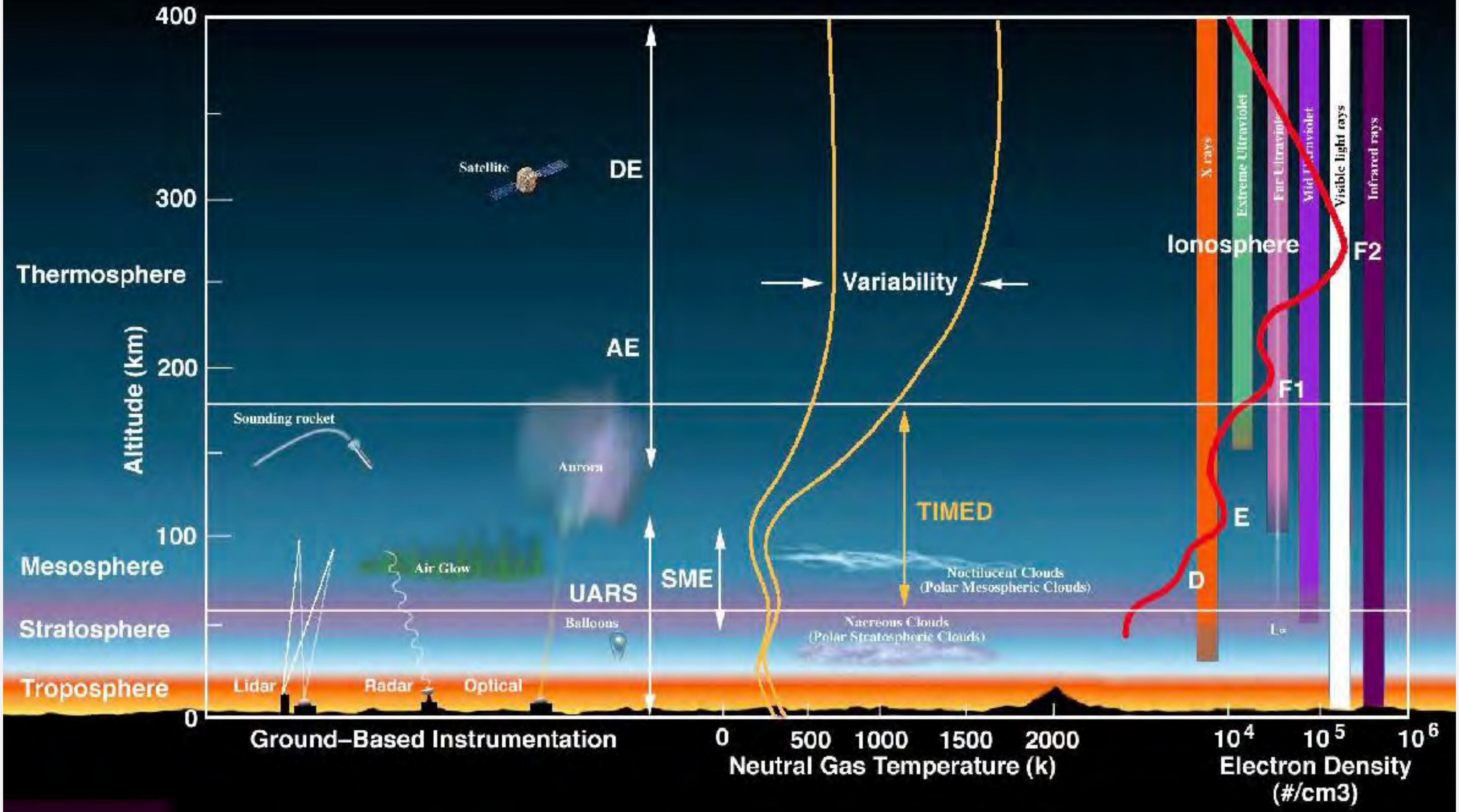


Blake et al. (2013)

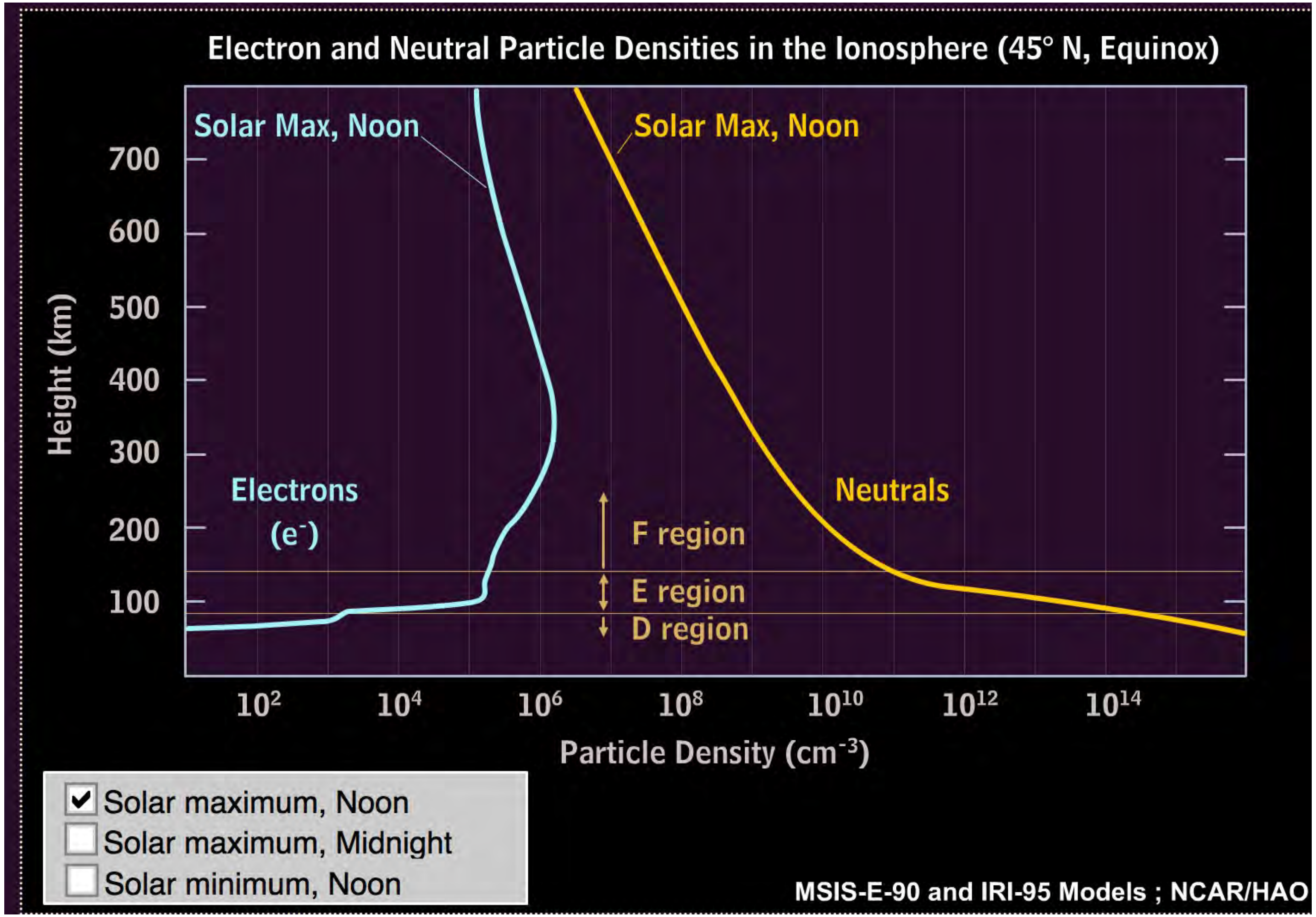


[From Wuest et al., 2007; Cluster mission proposal]

The Atmosphere and Ionosphere

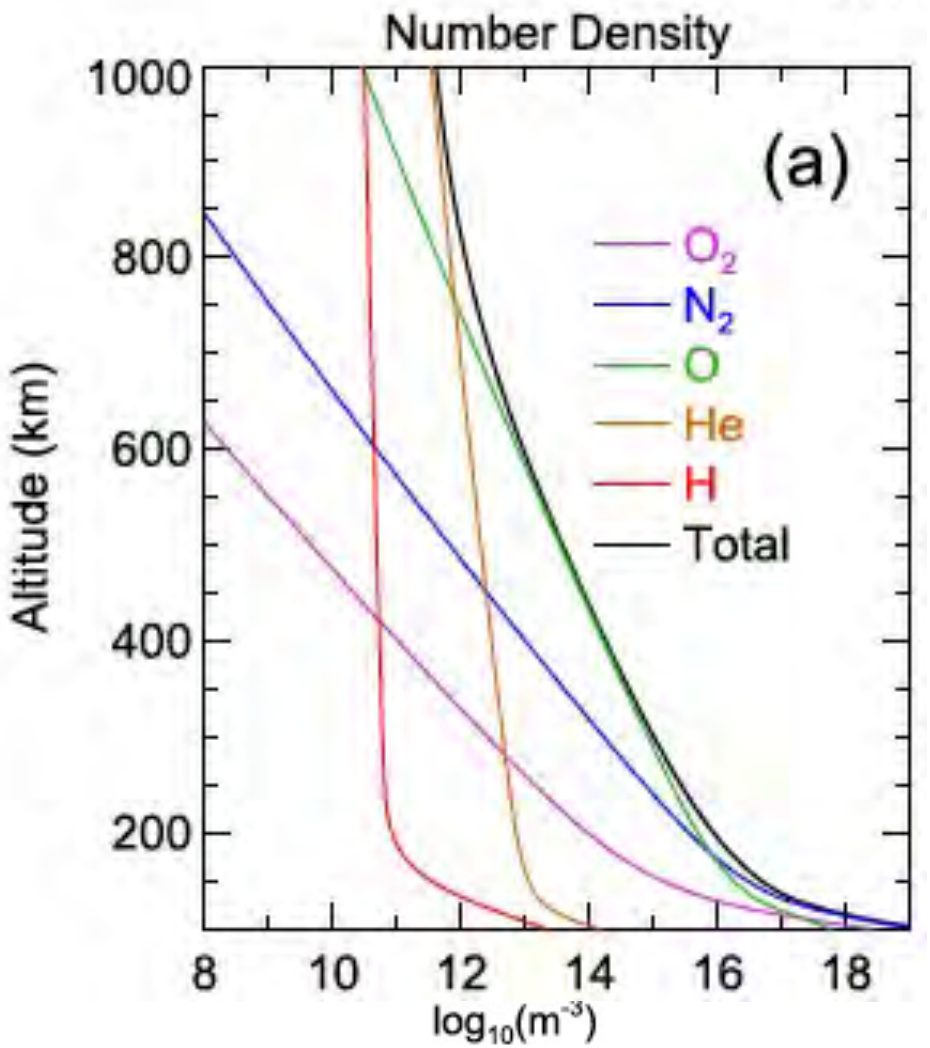


Thermosphere and Ionosphere Density Profiles



- Ionosphere: weakly ionized plasma
- Ion-neutral collisional coupling strongly controls the IT dynamics.

Thermosphere Composition



Global average number density profiles at solar max from the NRLMSISE-00 empirical model. From Emmert, 2015, Advances in Space Research.

- The most abundant neutrals in the lower atmosphere are N_2 and O_2.
- The most abundant neutrals in the thermosphere are O, N_2 and O_2.
- Lighter neutrals, such as H and H_e, become more and more important at higher altitudes.

- All neutral densities decrease exponentially with increasing altitude according to their **scale height (H, in m) above about 100 km**.

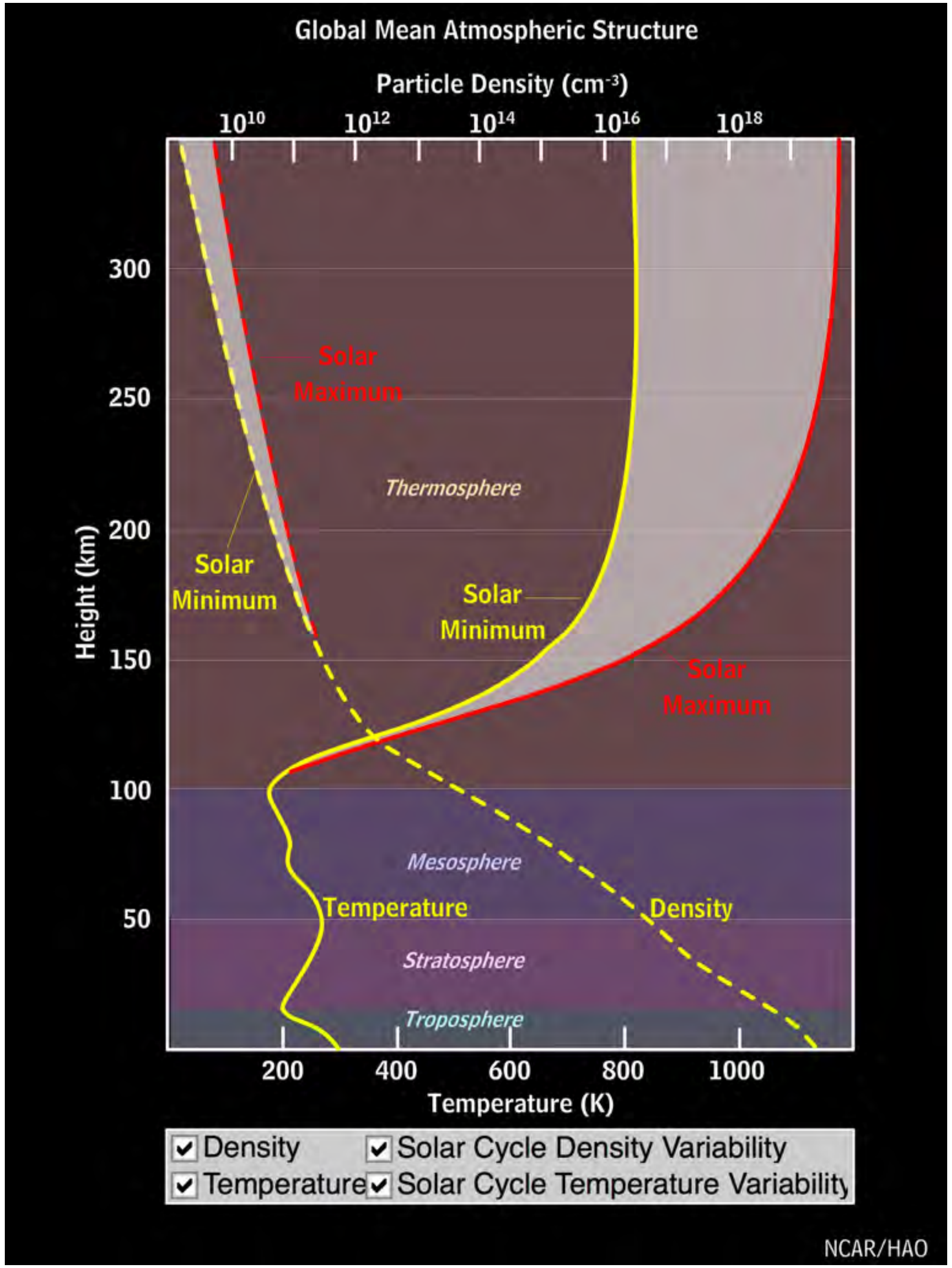
$$n(z) = n(z_0)e^{-\frac{z-z_0}{H}} \qquad H = \frac{kT}{mg}$$

- K is the Boltzmann constant: 1.38 x 10^{-23} J/K
- g is the gravitational acceleration: 9.8 m/s^2
- T is the neutral temperature in Kelvin and m is the neutral mass in Kg.

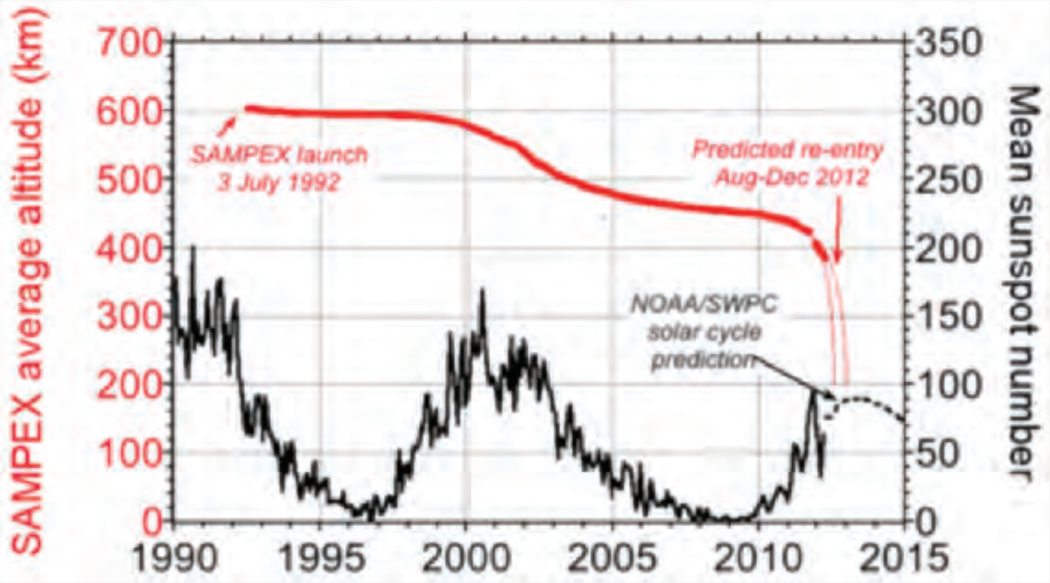
From Shasha Zou, HSS 2021

Solar Cycle Variability of Thermosphere

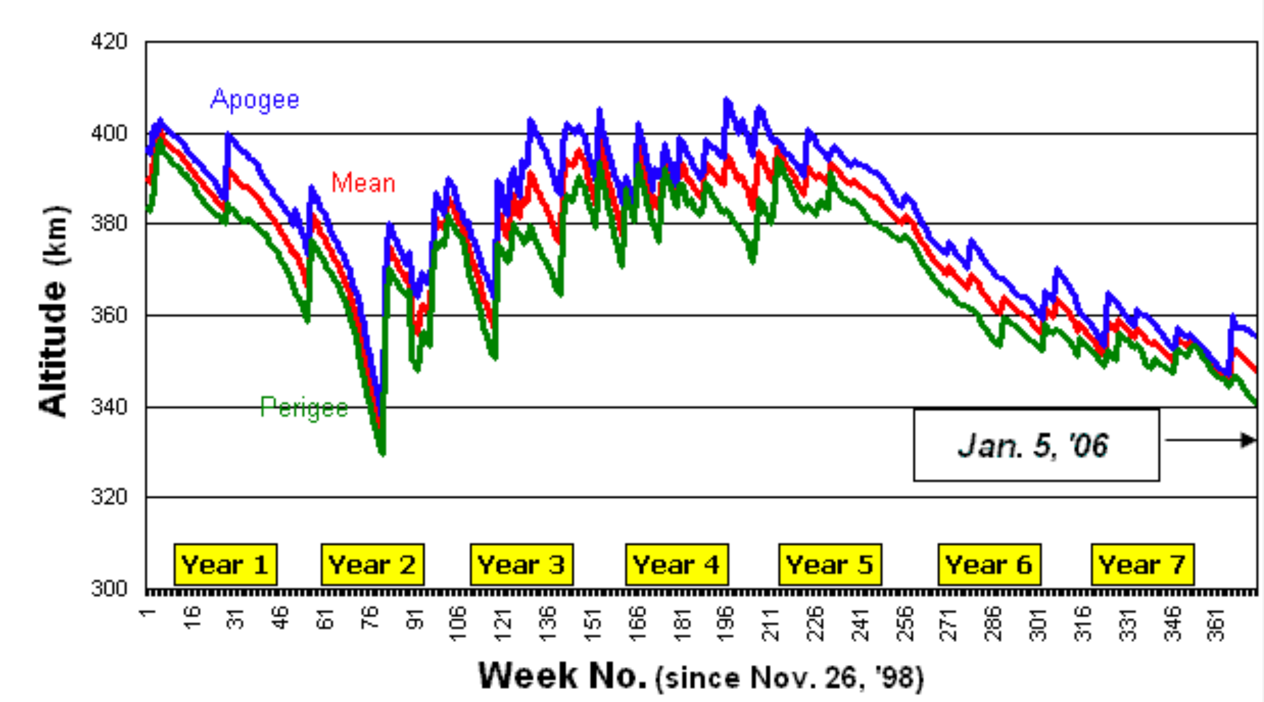
- Near the bottom of the thermosphere (~100 km), the neutrals are well mixed and have the same rate of decreasing.
- Above this height, the neutral densities decrease according to their own scale height.
- During solar maximum, the solar radiation is higher than that during solar minimum. So the thermosphere temperature is higher and the scale height is larger, and then the neutral density is higher.



ATMOSPHERIC DENSITY AND SPACECRAFT DRAG

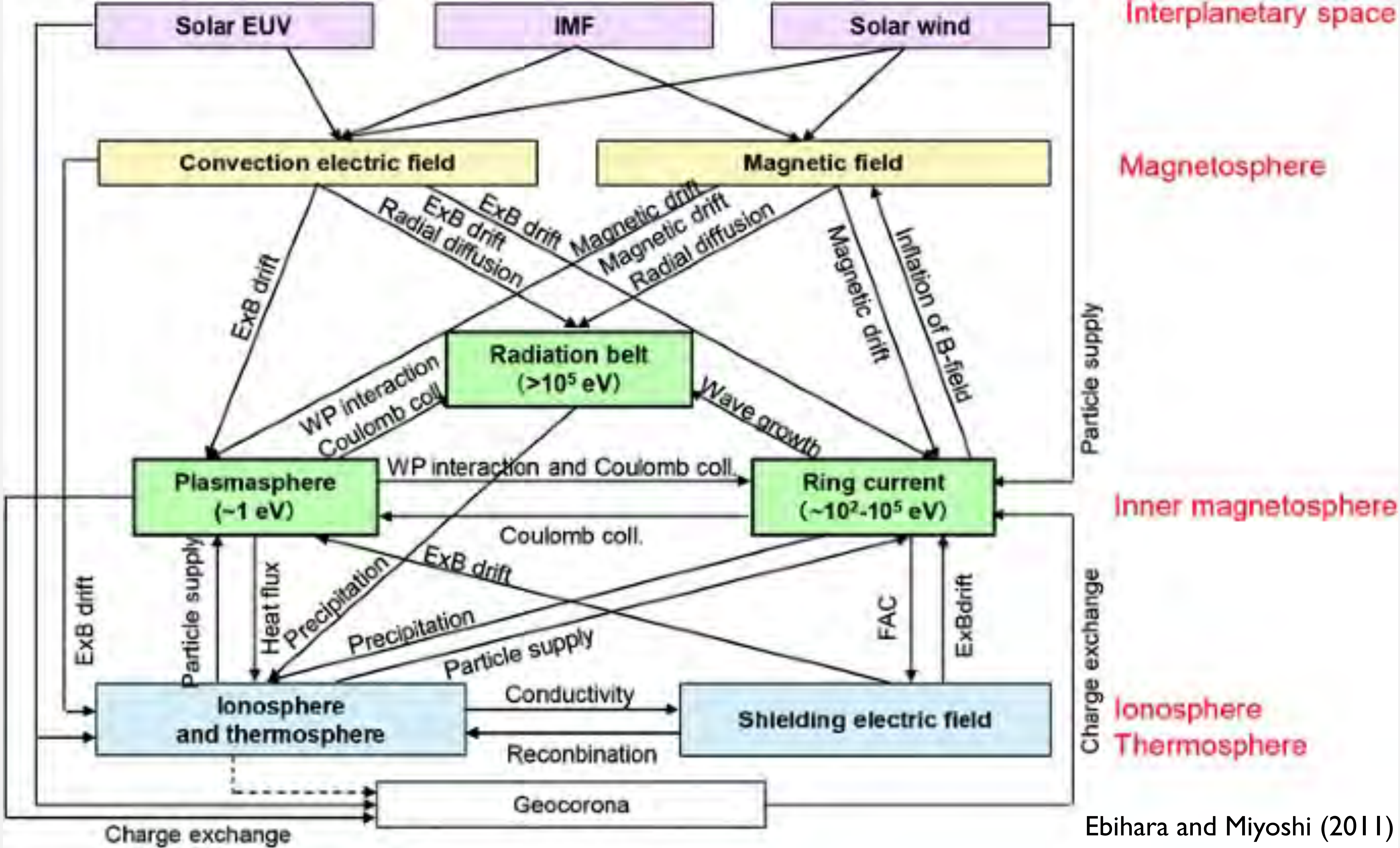


Daily averaged SAMPEX altitude (red) in the context of the past 22 years of solar activity shown by the monthly averaged sunspot number (black). From Baker et al. [2012].



ISS altitude over time. Credit: Heavens_above.com

WHY SHOULD A MAGNETOSPHERIC PHYSICIST CARE ABOUT THE IONOSPHERE?

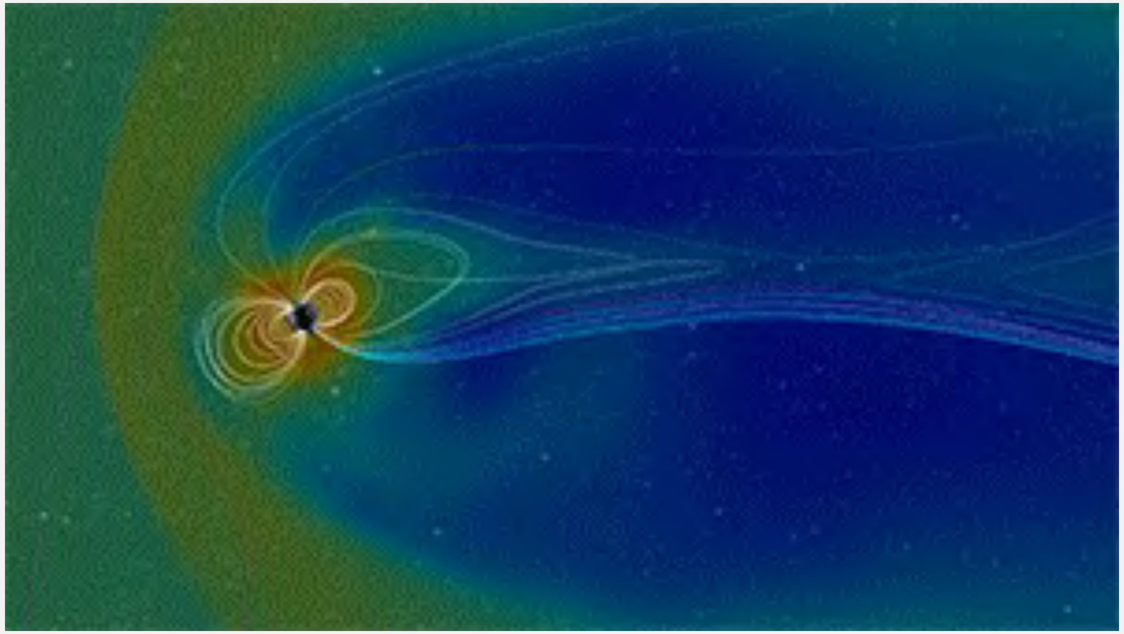


Ebihara and Miyoshi (2011)

PAUSE… QUESTIONS?

MAGNETOSPHERIC DYNAMICS

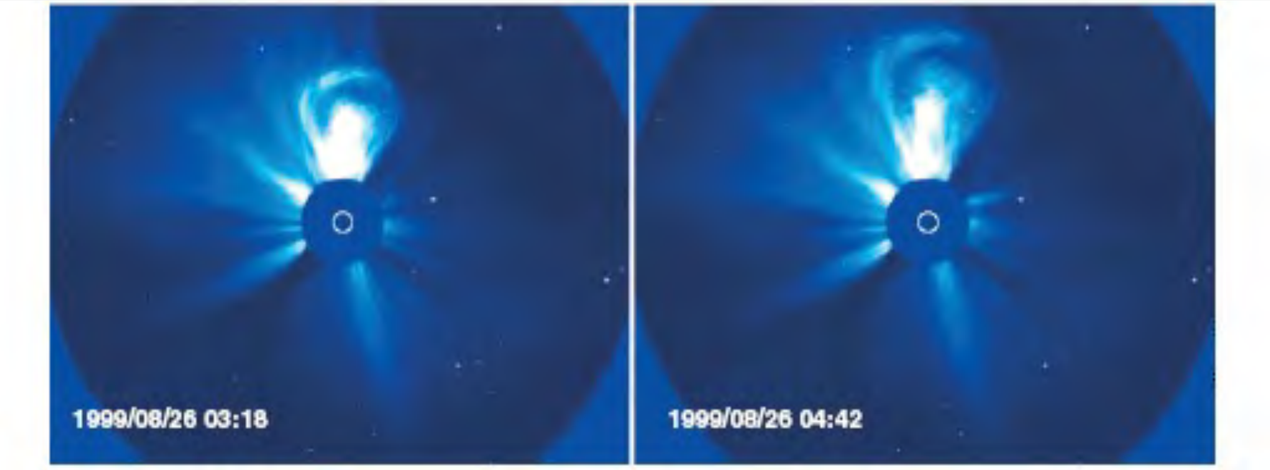
- Particle populations ranging from eV to MeV
- Waves from mHz to kHz
- System responds on timescales of seconds to years

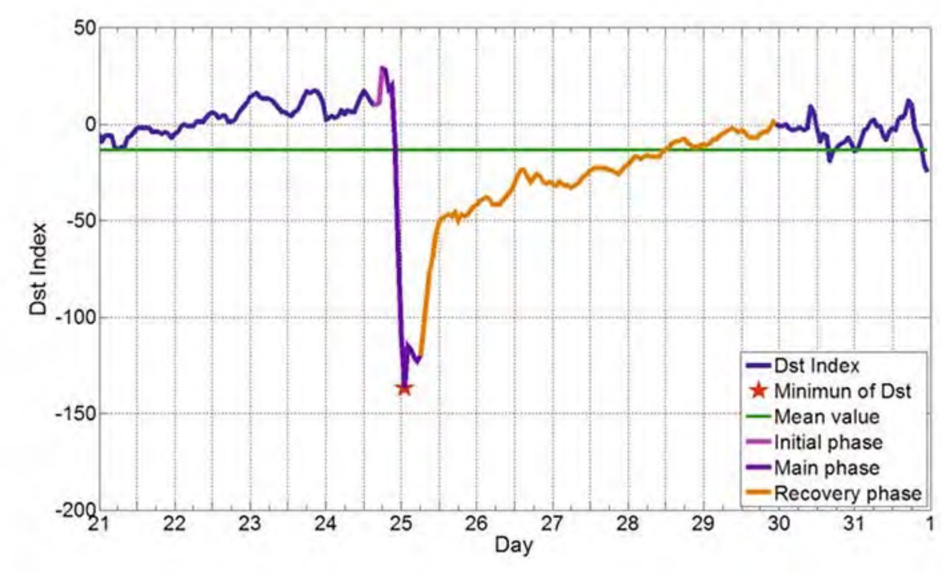


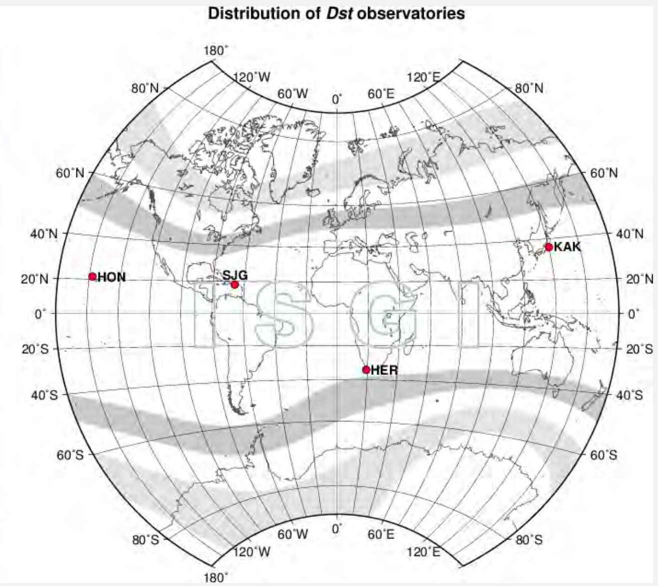
Geomagnetic Activity

Geomagnetic Storms: Temporary (~days) global disturbances of the Earth's magnetosphere caused by conditions in the solar wind

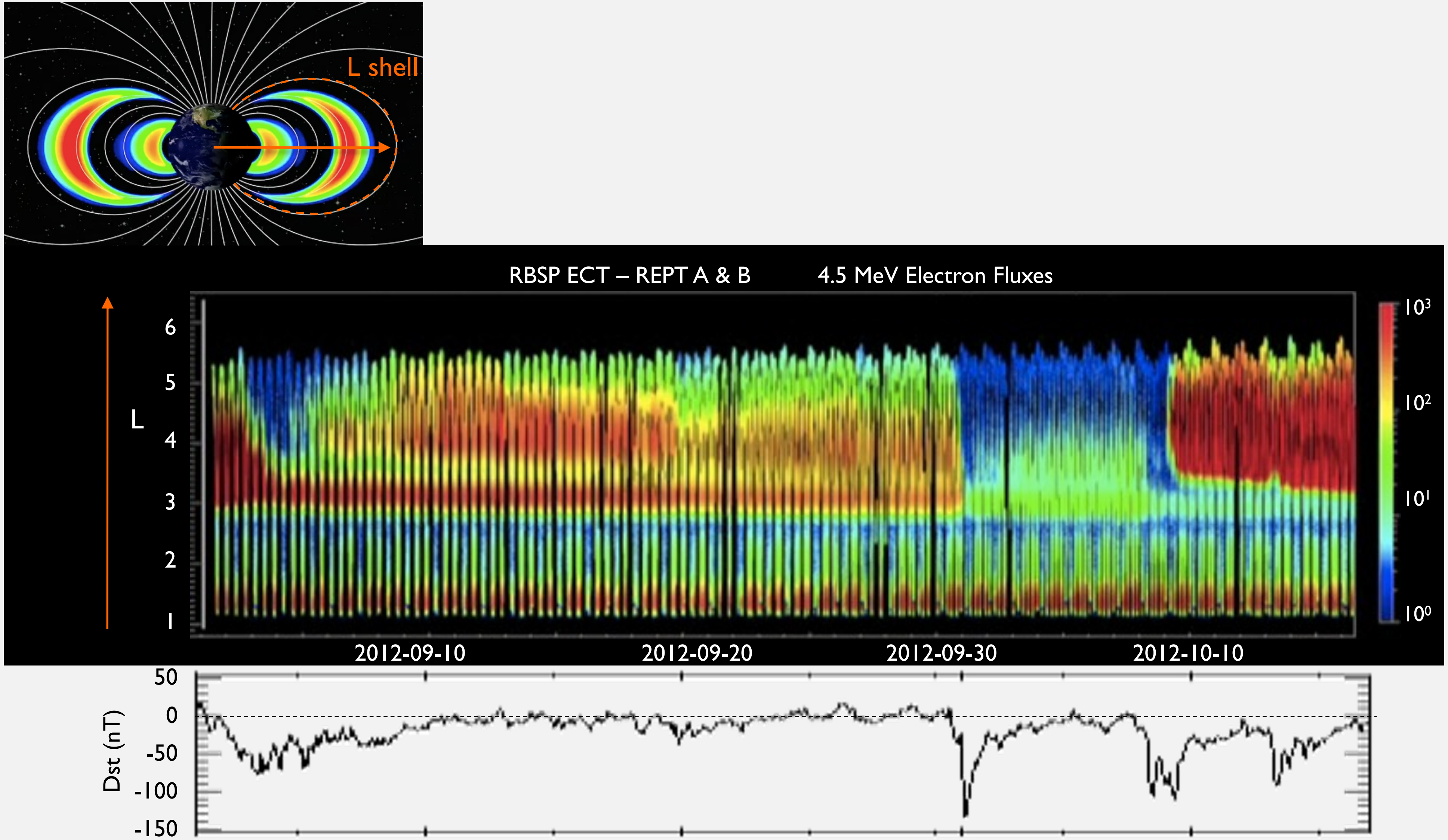
Substorms: Temporary (~hours) more frequent and localized disturbances



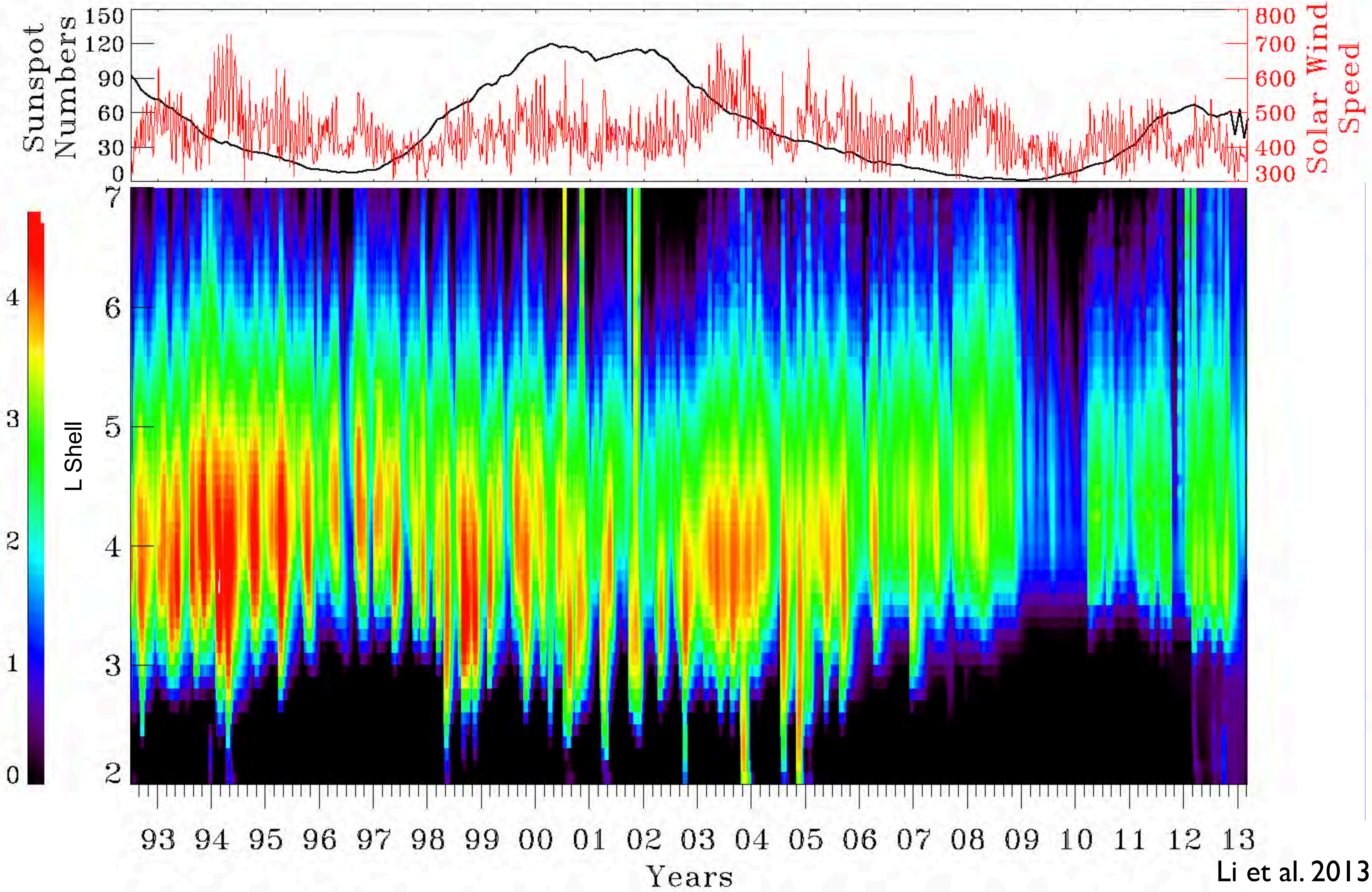




RADIATION BELT DYNAMICS

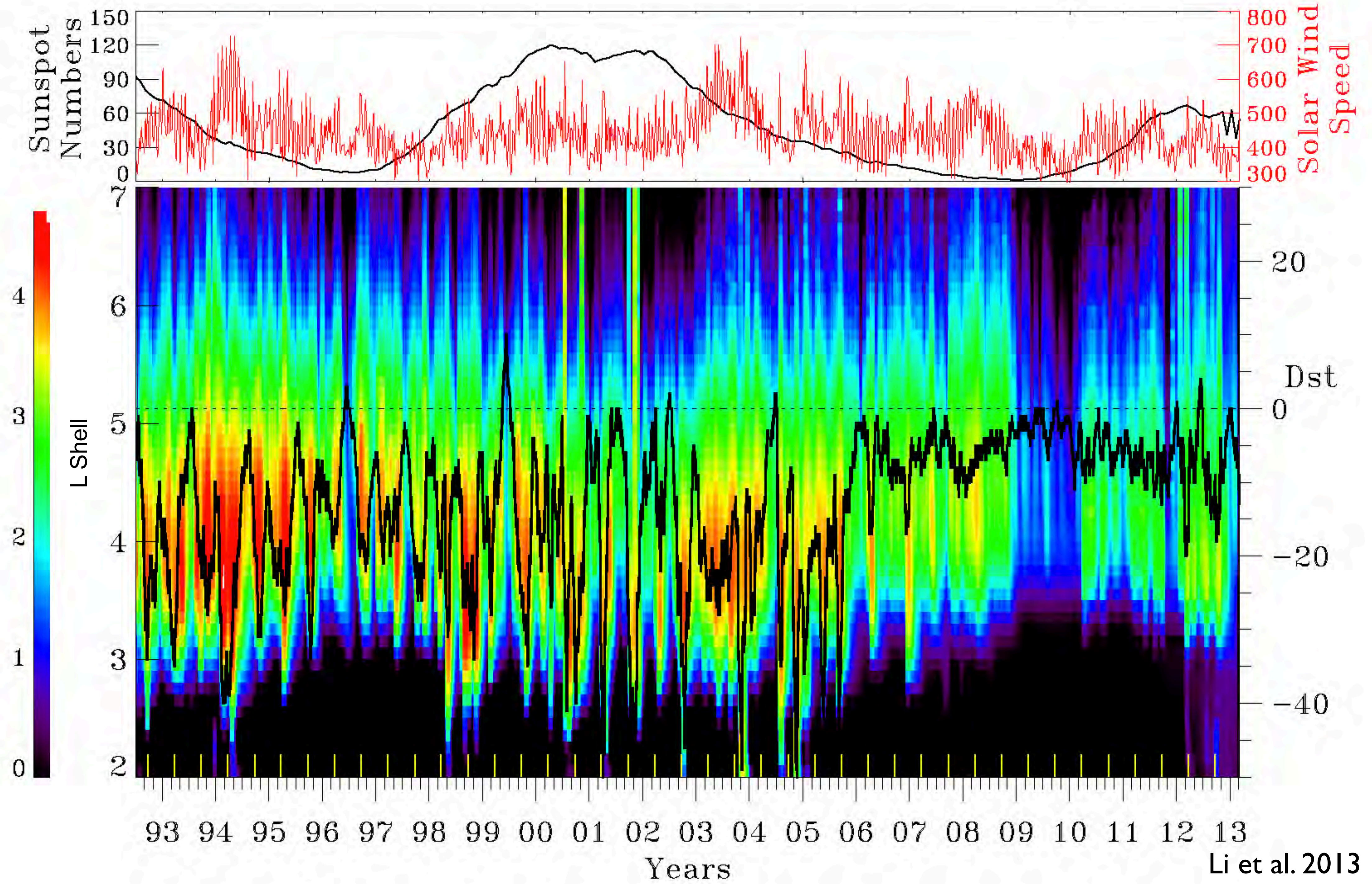


Baker et al., Science (2013)



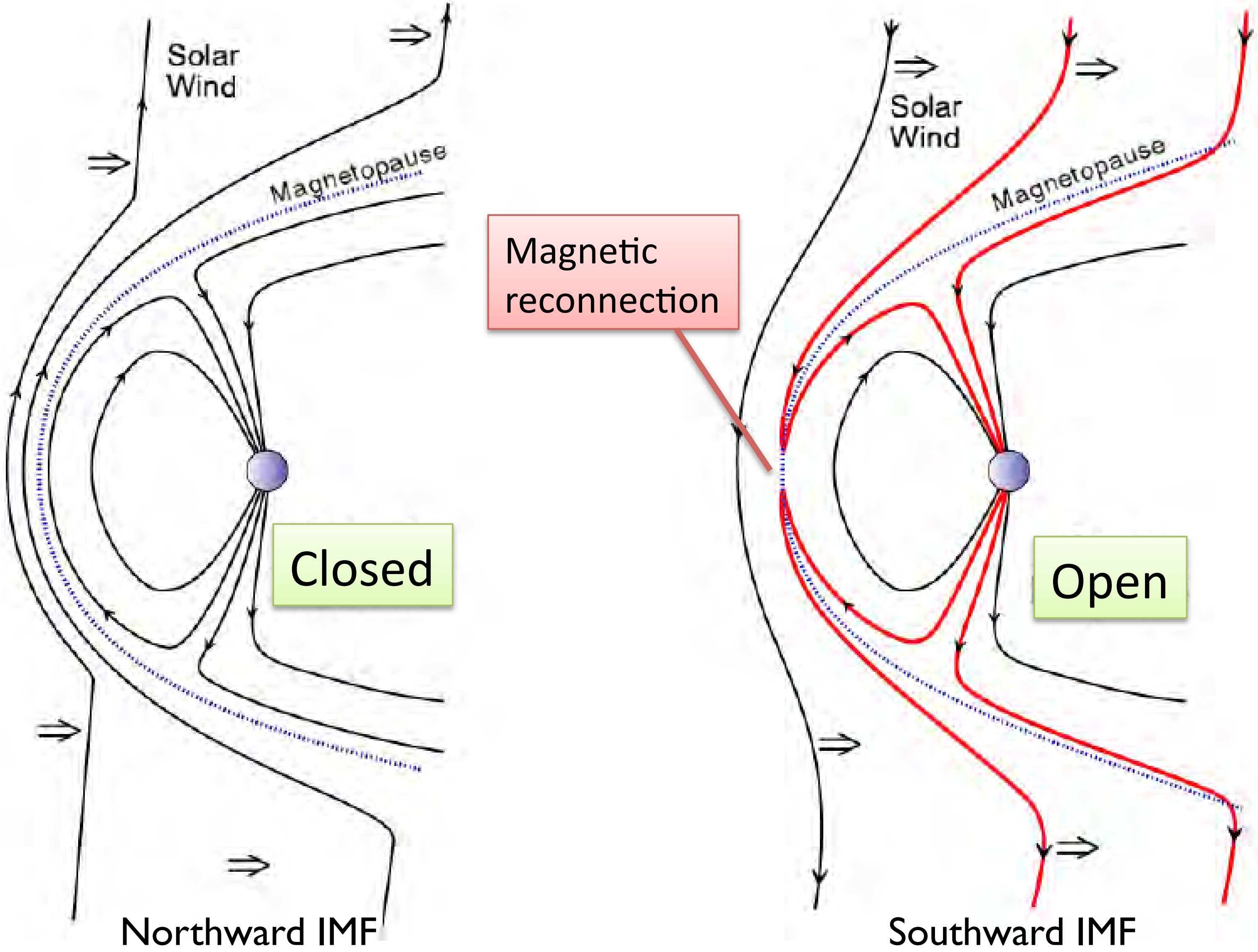
Sunspot Numbers
150
120
90
60
30
0
Solar Wind Speed
800
700
600
500
400
300
L Shell
7
6
5
4
3
2
0
1
2
3
4
93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13
Years

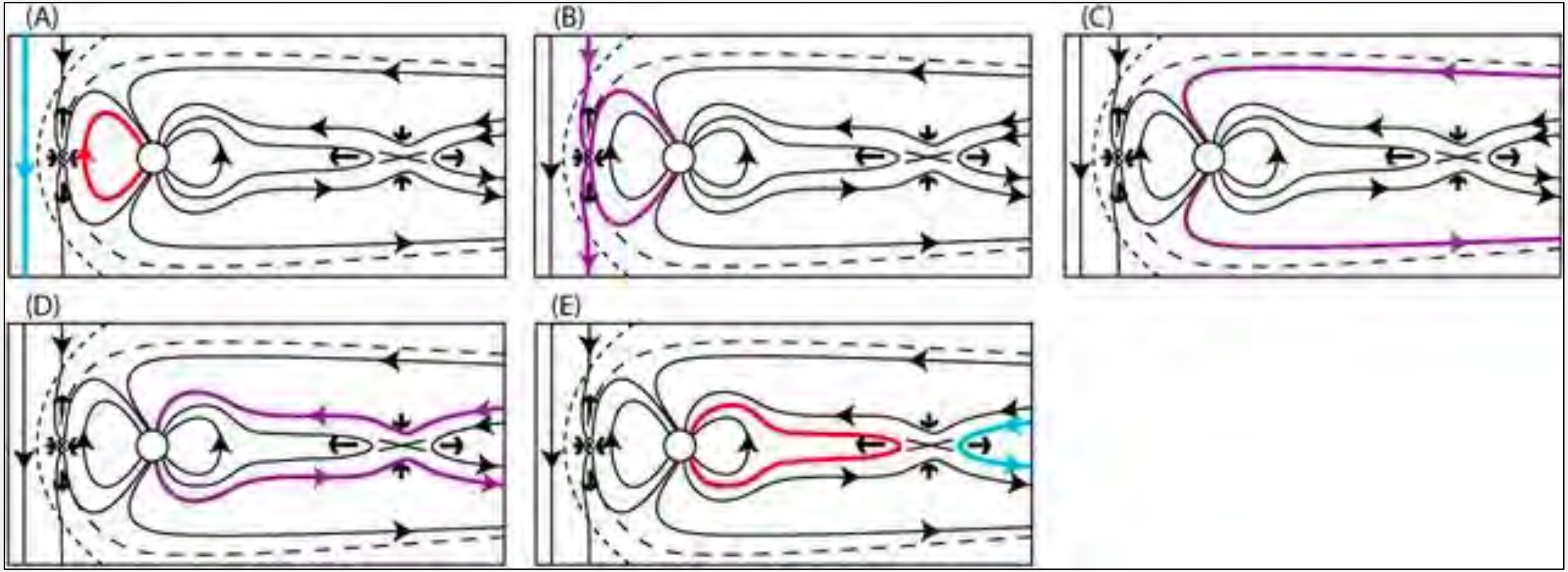
Li et al. 2013



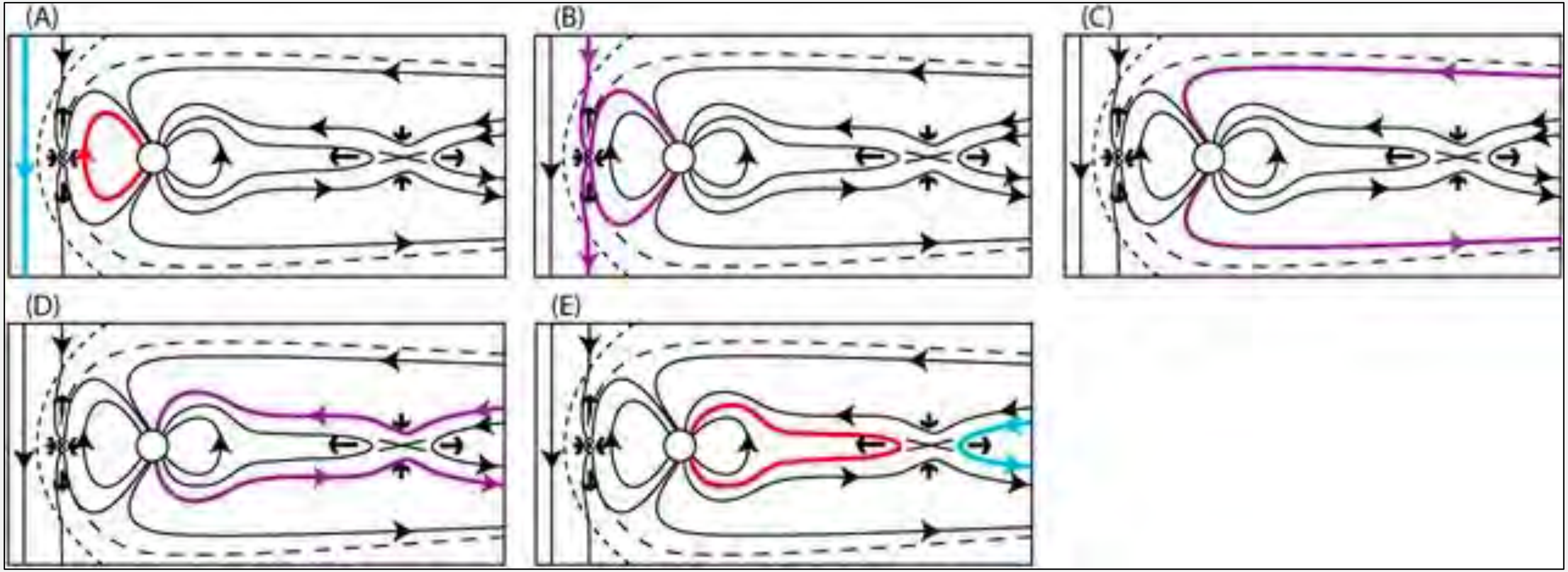
Sunspot Numbers
Solar Wind Speed
L Shell
Dst
Years
93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13
Li et al. 2013

Open vs. closed configurations of the magnetosphere



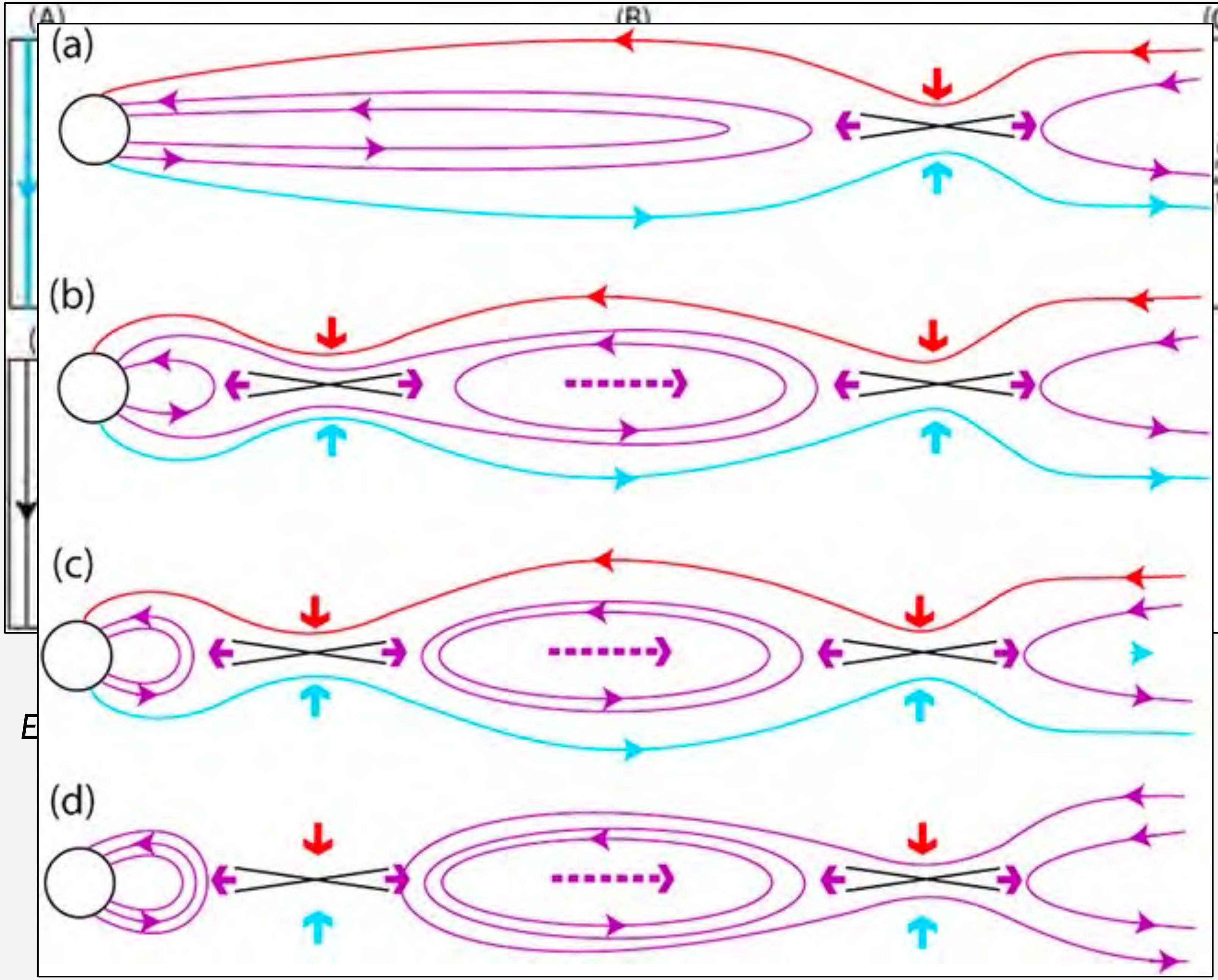


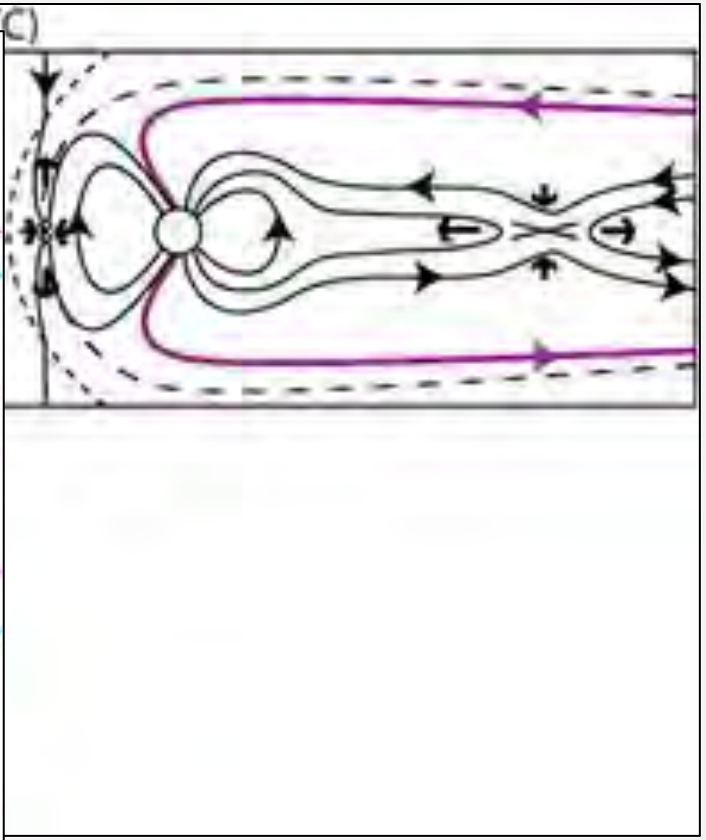
Eastwood et al., Space Sci. Rev., 2015

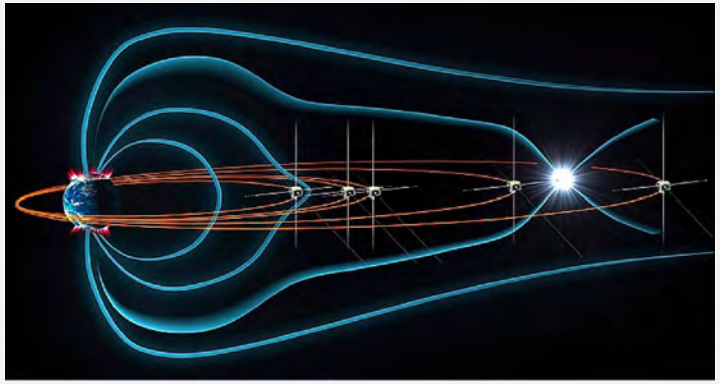


Eastwood et al., Space Sci. Rev., 2015

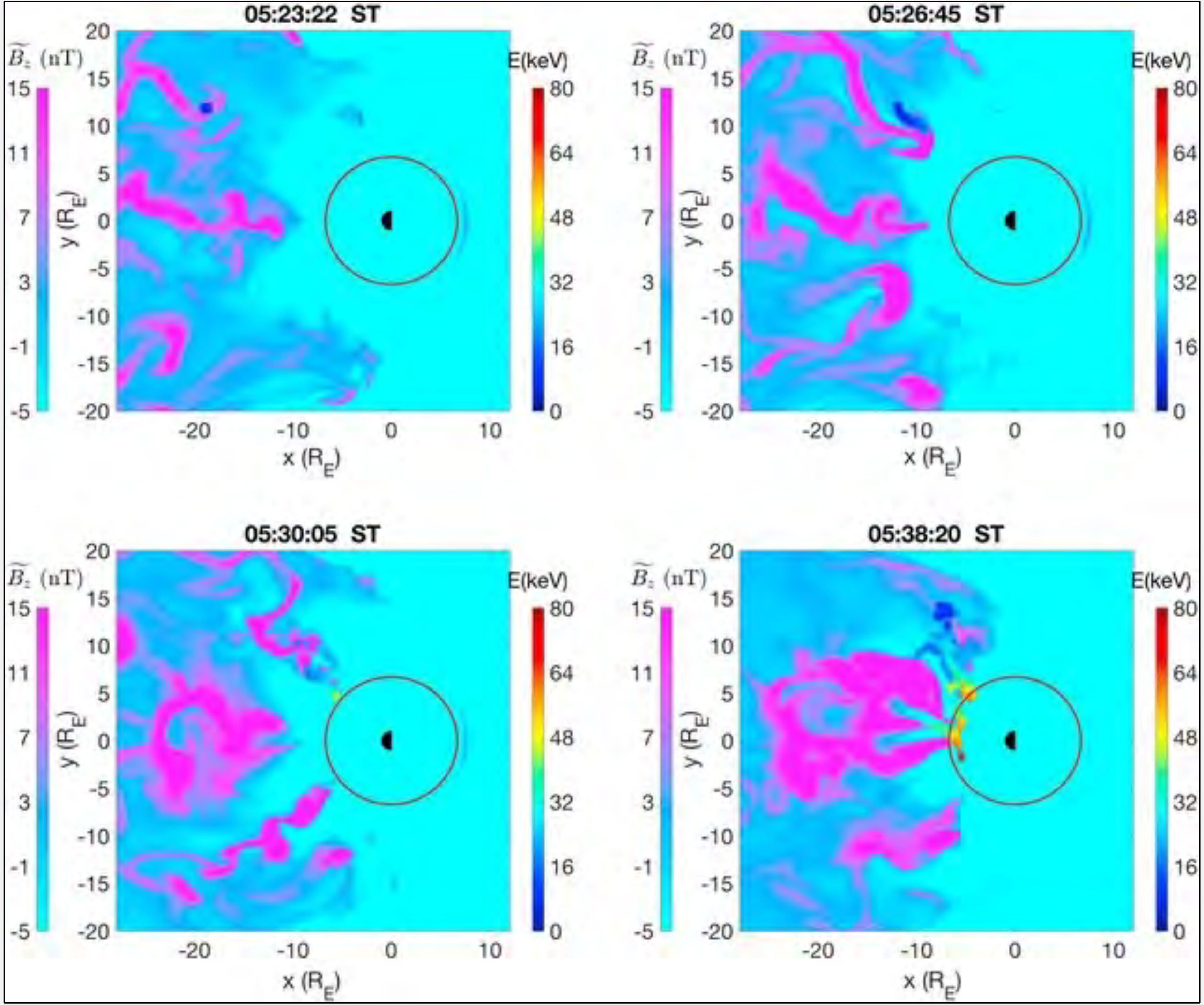
(OPEN QUESTION: relative importance of Dungey cycle at Gas Giants?)





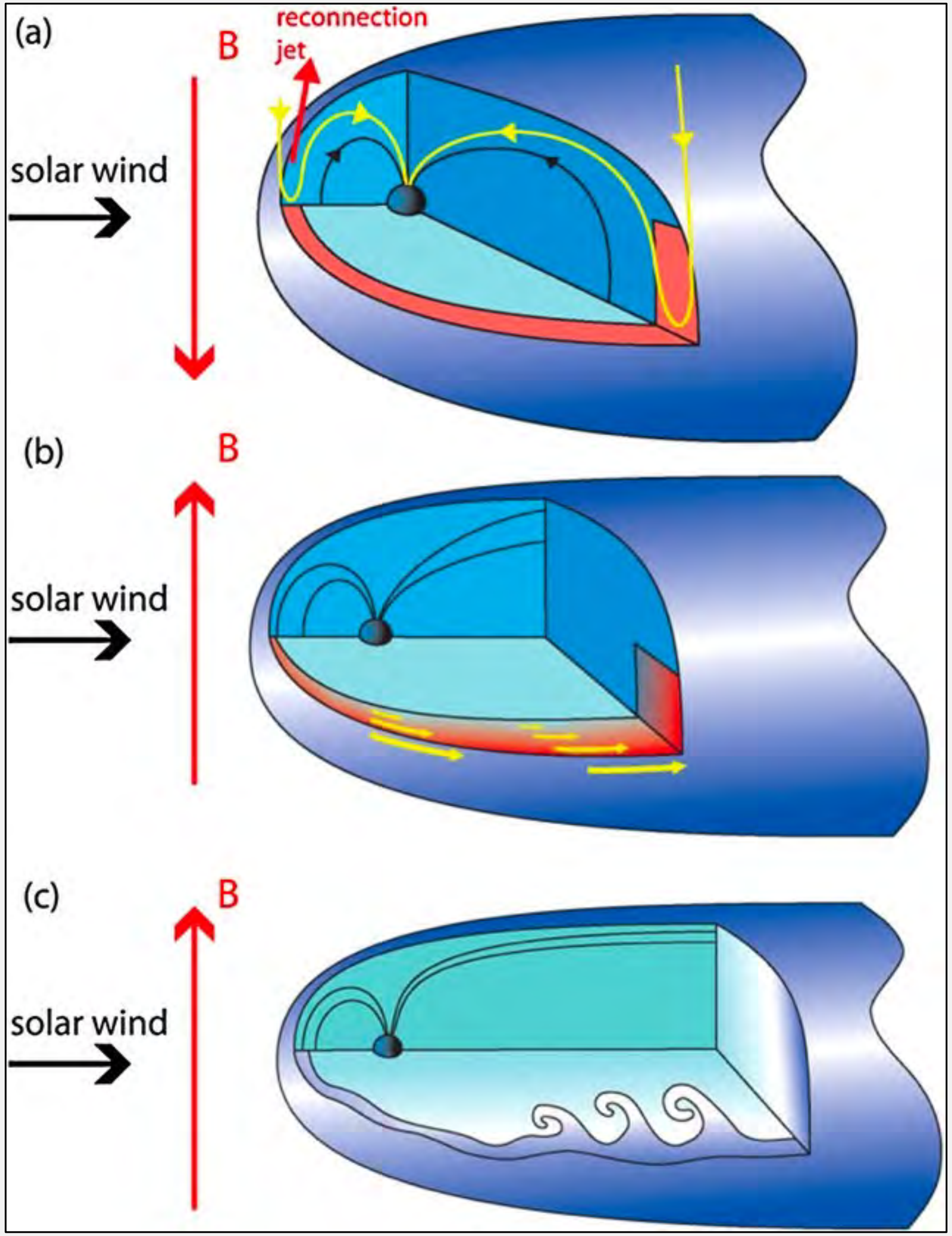


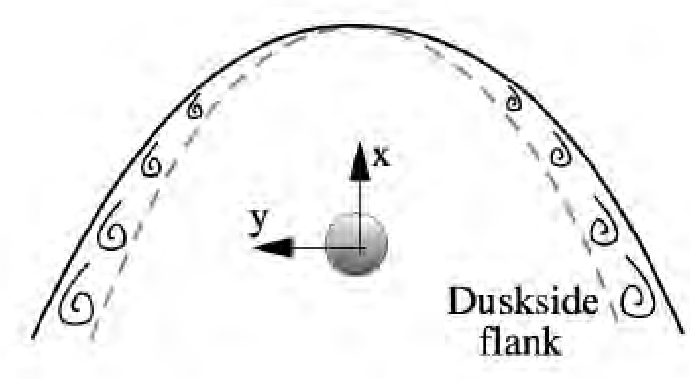
NASA’s THEMIS mission

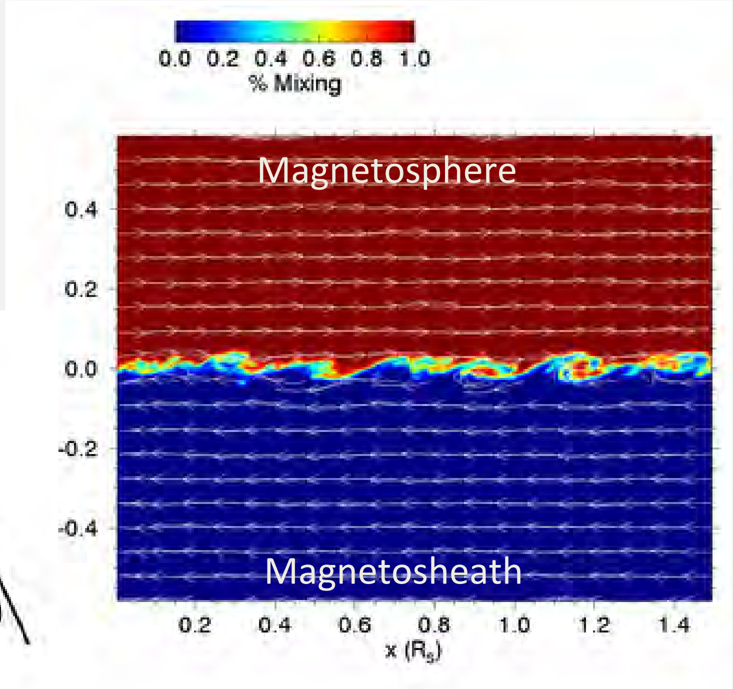


05:23:22 ST
05:26:45 ST
05:30:05 ST
05:38:20 ST
$\widetilde{B_z}$ (nT)
E(keV)
y (R_E)
x (R_E)

SOLAR WIND ACCESS TO THE MAGNETOSPHERE







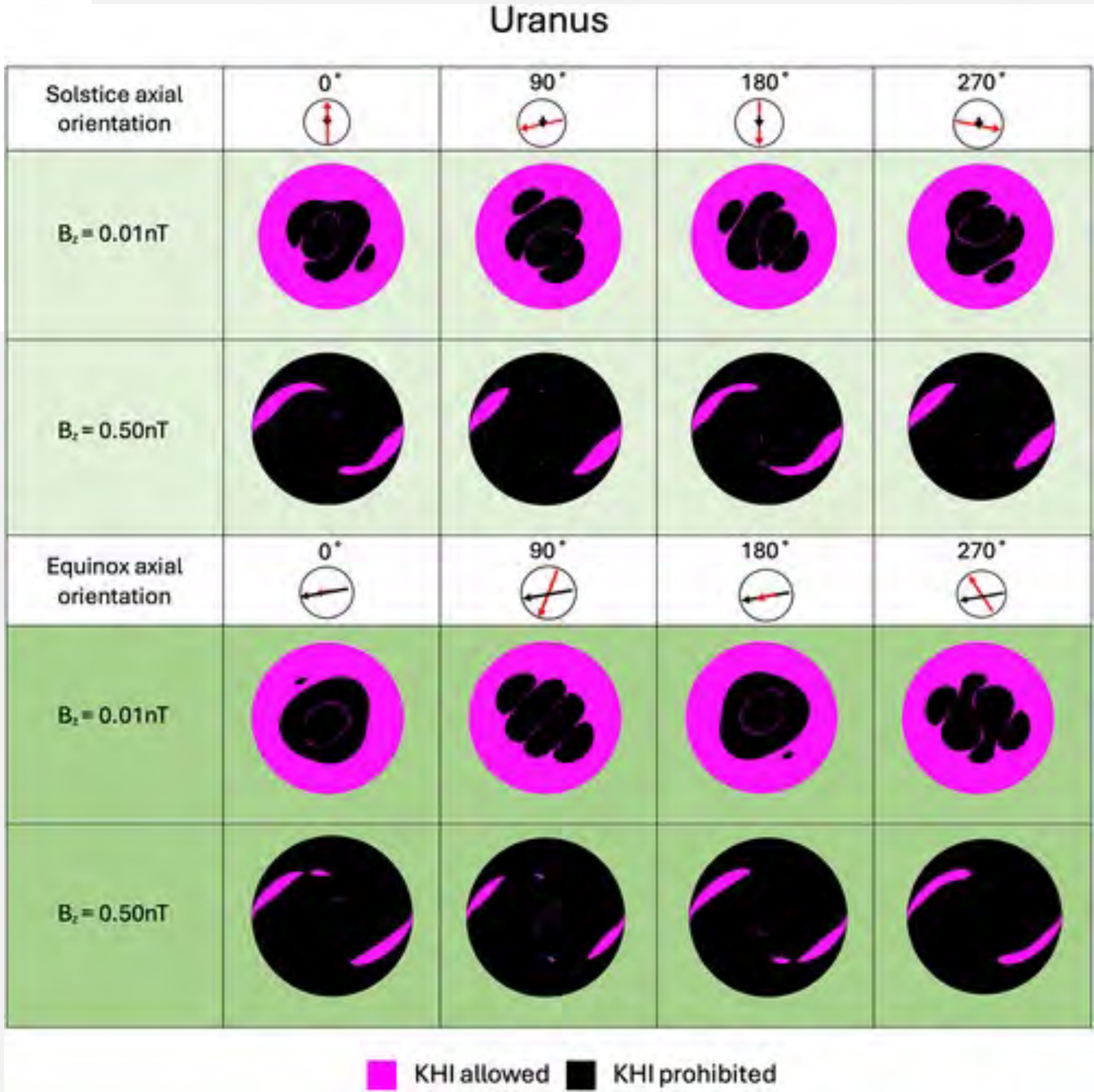
JGR Space Physics

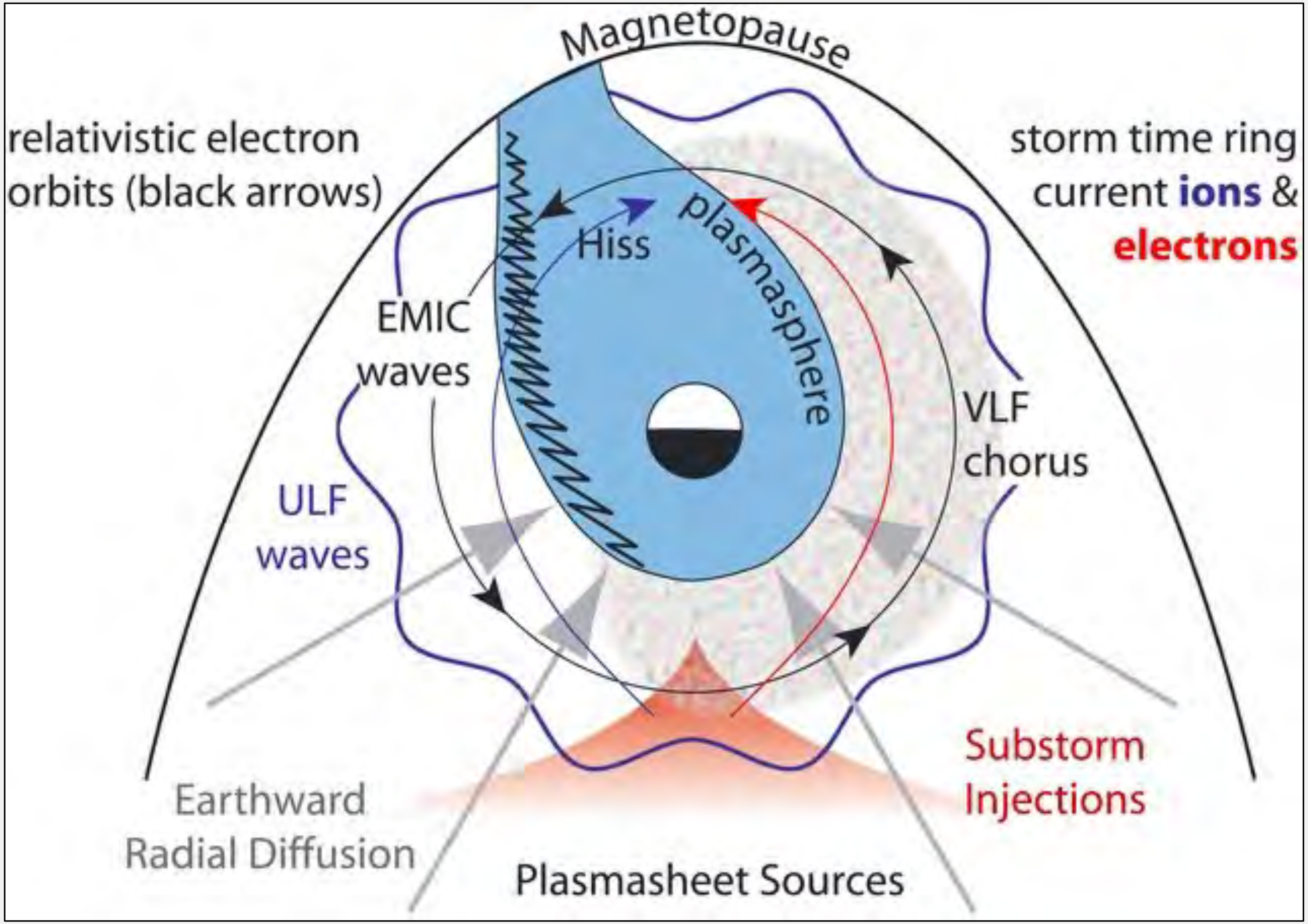
Research Article | Open Access

Characterizing the Solar Wind-Magnetosphere Viscous Interaction at Uranus and Neptune

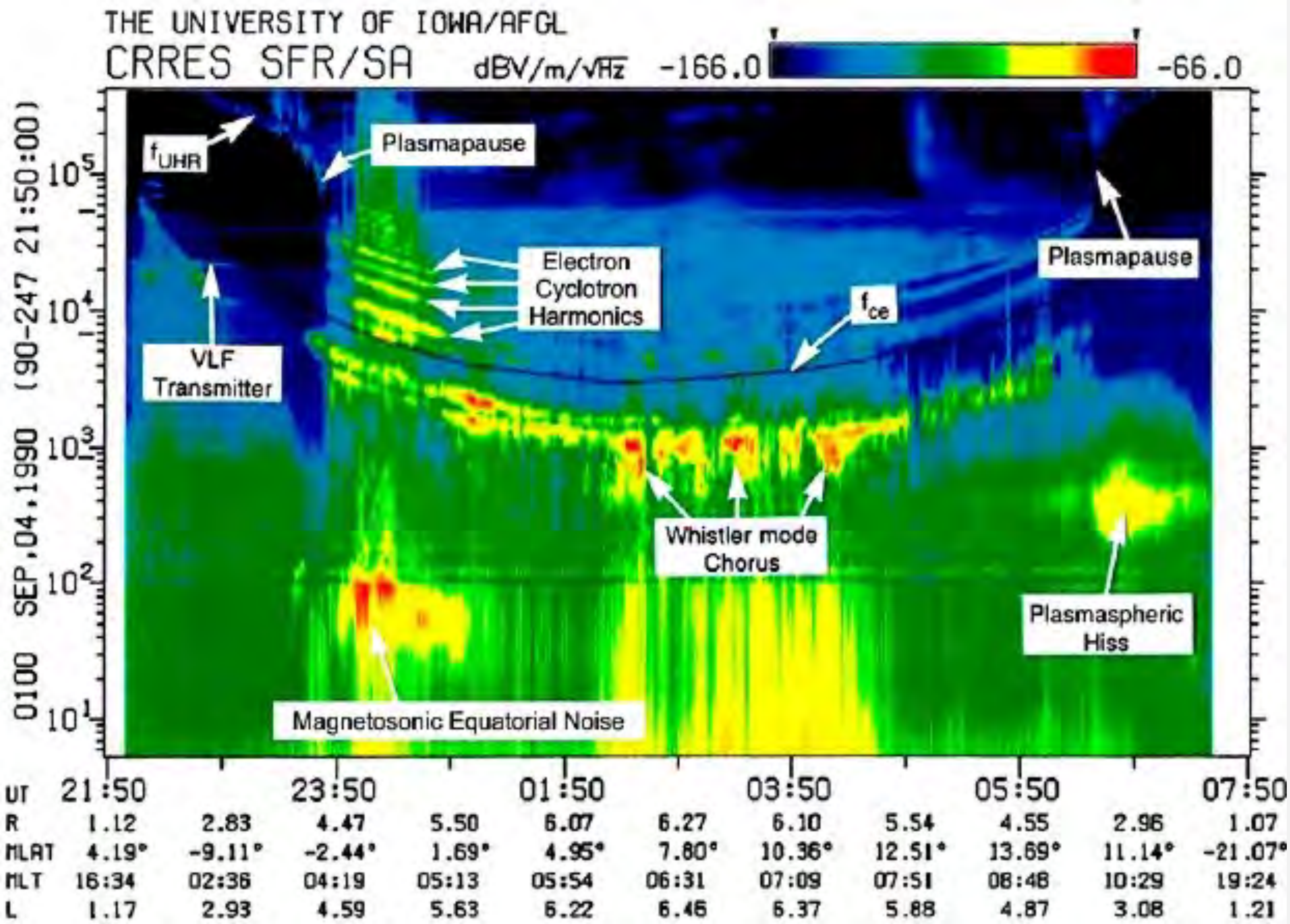
Katelin Donaldson, Angela J. Olsen, Carol S. Paty, Joe Caggiano

First published: 03 August 2024 | https://doi.org/10.1029/2024JA032518





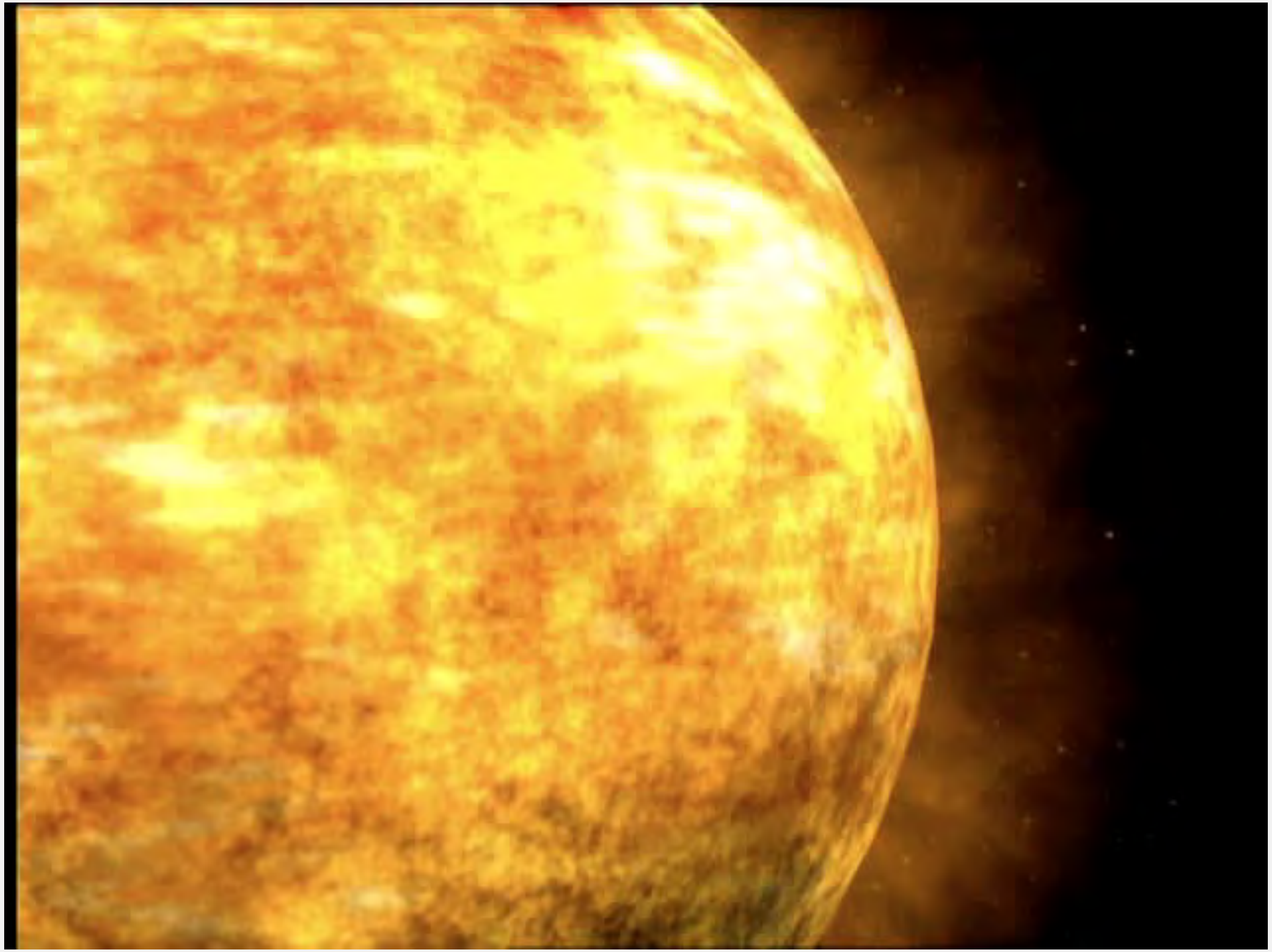
Reeves et al. (2016)



Kletzing et al. (2013)

THE AURORA

SUN-EARTH SYSTEM

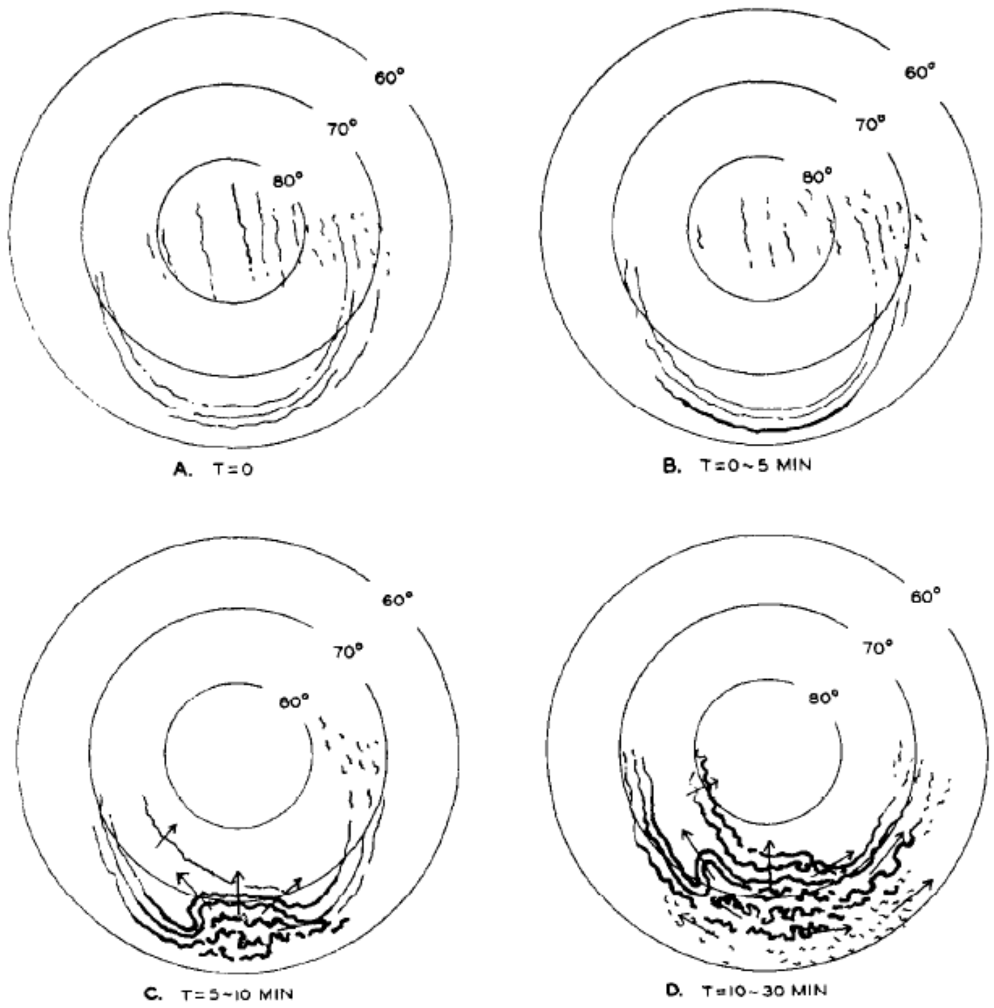


Why I like aurora (part I)

Credit: Longzhi Gan; Boulder CO May 2024

Why I like aurora (part II)

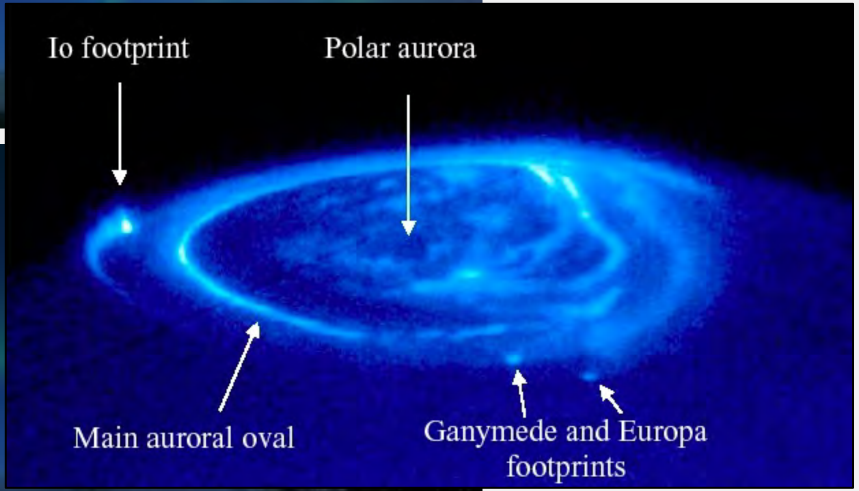
Auroral Onset



Adapted from Akasofu
(Planetary and Space Sciences, 1964)
886—1578 citations

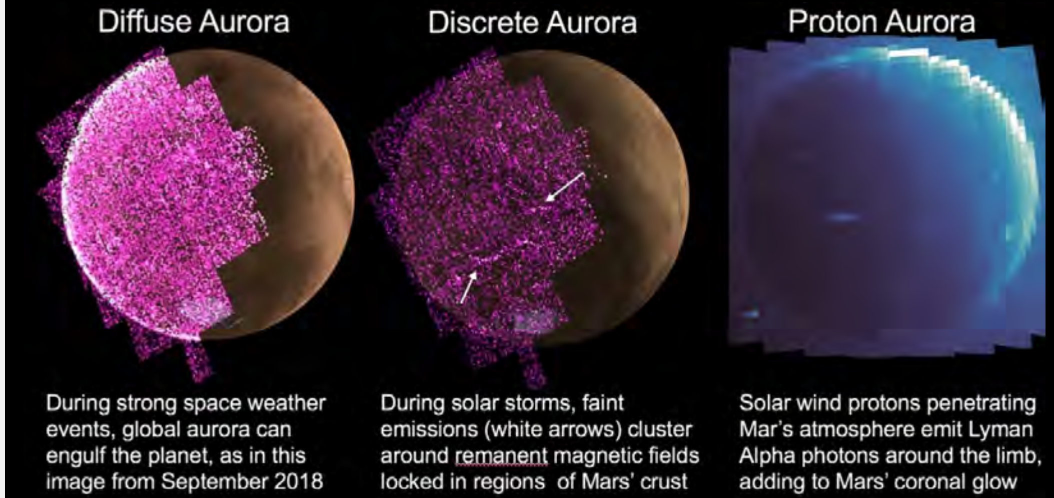
Why I like aurora (part III)

Aurora at Jupiter

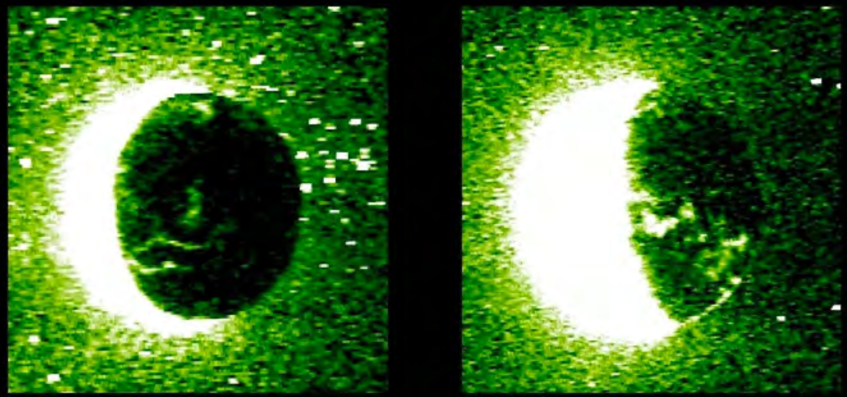


Why I like aurora (part III)

Aurora at Mars

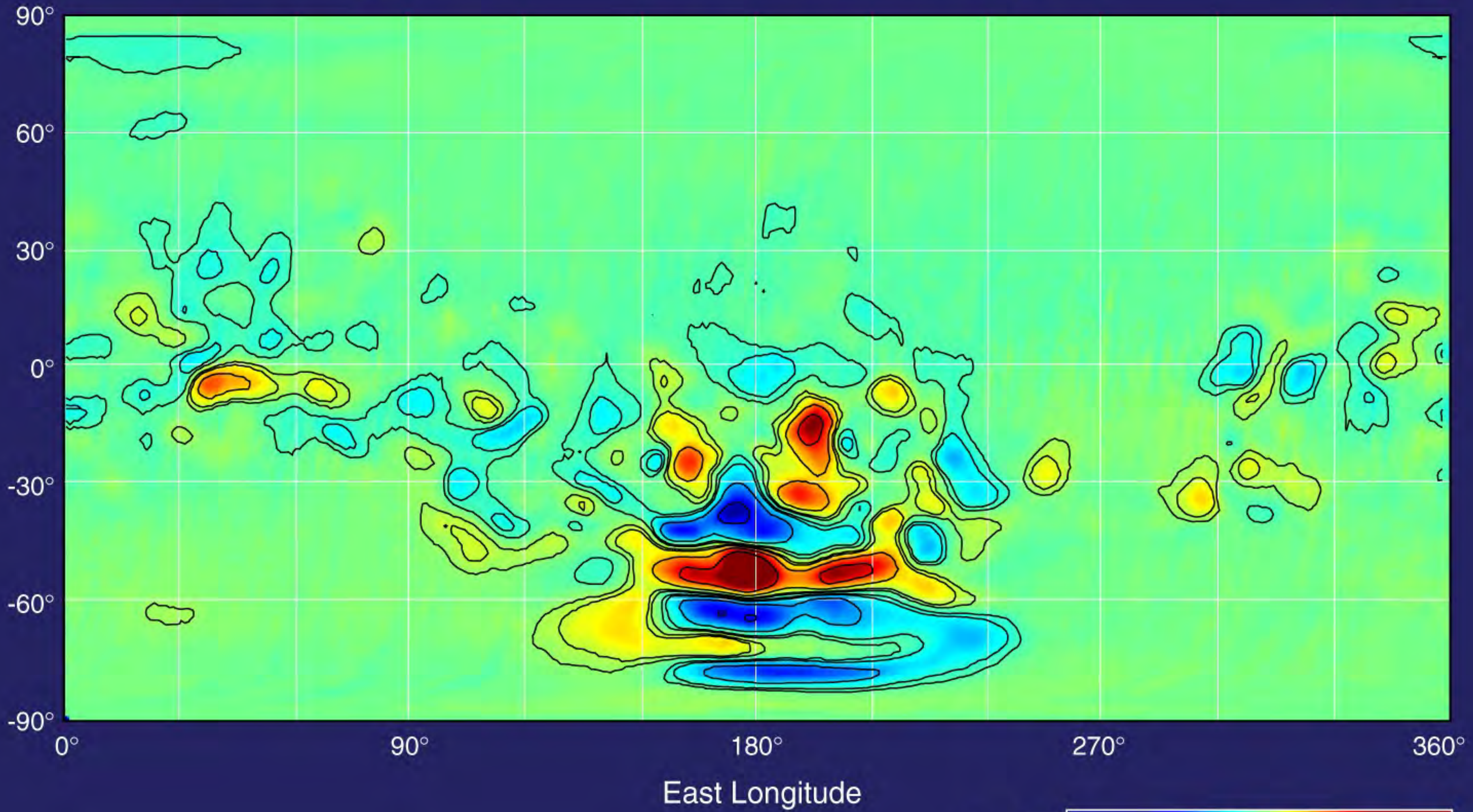


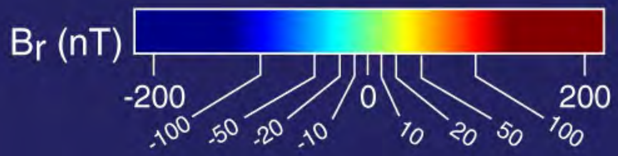
Three types of aurora on Mars, as observed by the Imaging UltraViolet Spectrograph on MAVEN – Schneider et al. 2019



Auroras on Mars imaged by the Hope orbiter Emirates Mars Mission

Mars Crustal Magnetism | Mars Global Surveyor | MAG/ER

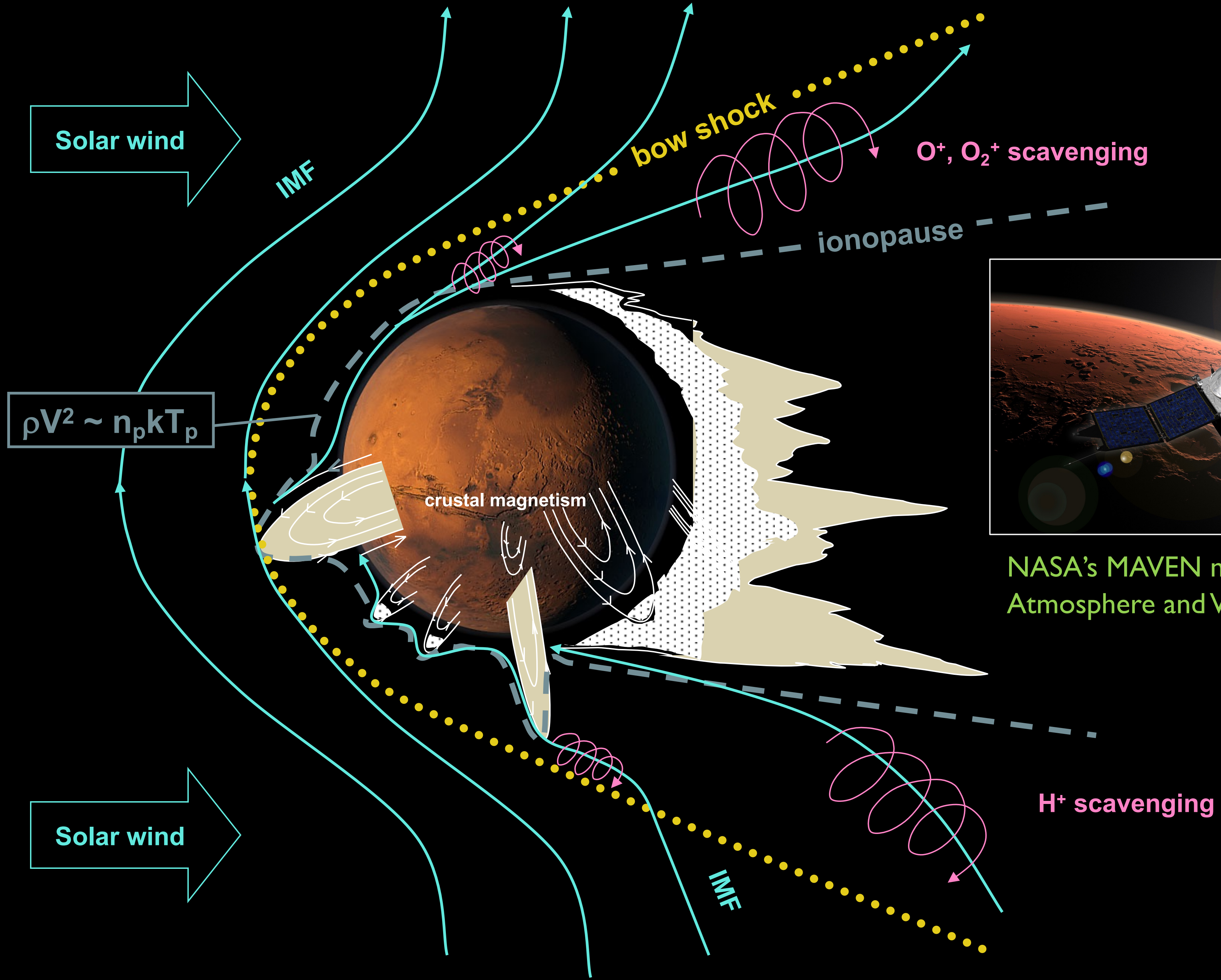


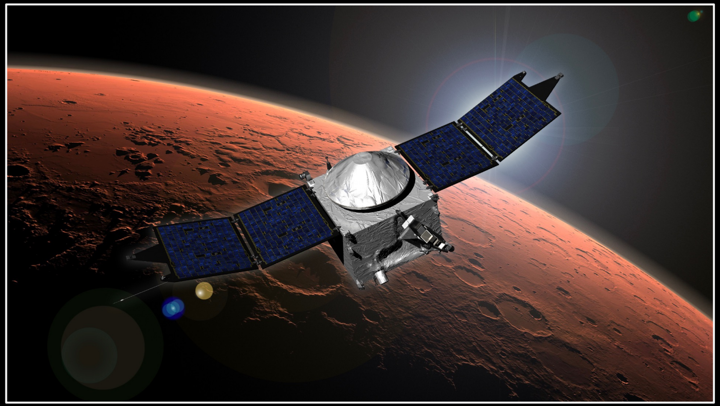


Measurements from 400 km altitude

Connerney et al., *Geophys.Res. Lett., 28,* 4015-4018, 2001.

ConJ2001187.001v





NASA's MAVEN mission– Mars Atmosphere and Volatile EvolutioN

PAUSE – QUESTIONS?

WHAT PARAMETERS GOVERN MAGNETOSPHERIC CHARACTERISTICS?

- If we move to other planets/stellar systems, how might things vary?

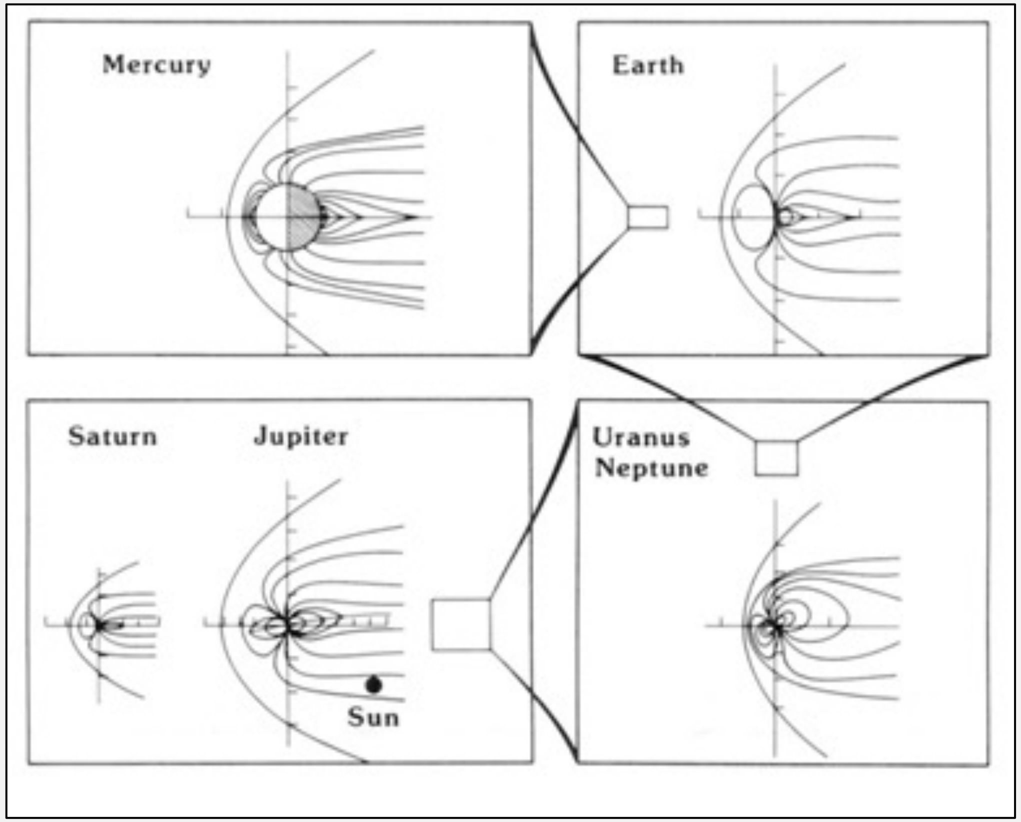
WHAT PARAMETERS GOVERN MAGNETOSPHERIC CHARACTERISTICS?

- Planet radius and rotation rate
- Planetary internal magnetic field
- Spin axis, magnetic field axis orientation
- Flowing (solar/stellar wind) plasma properties; distance from sun/star
- Plasma sources (e.g. moons, atmosphere)
- …

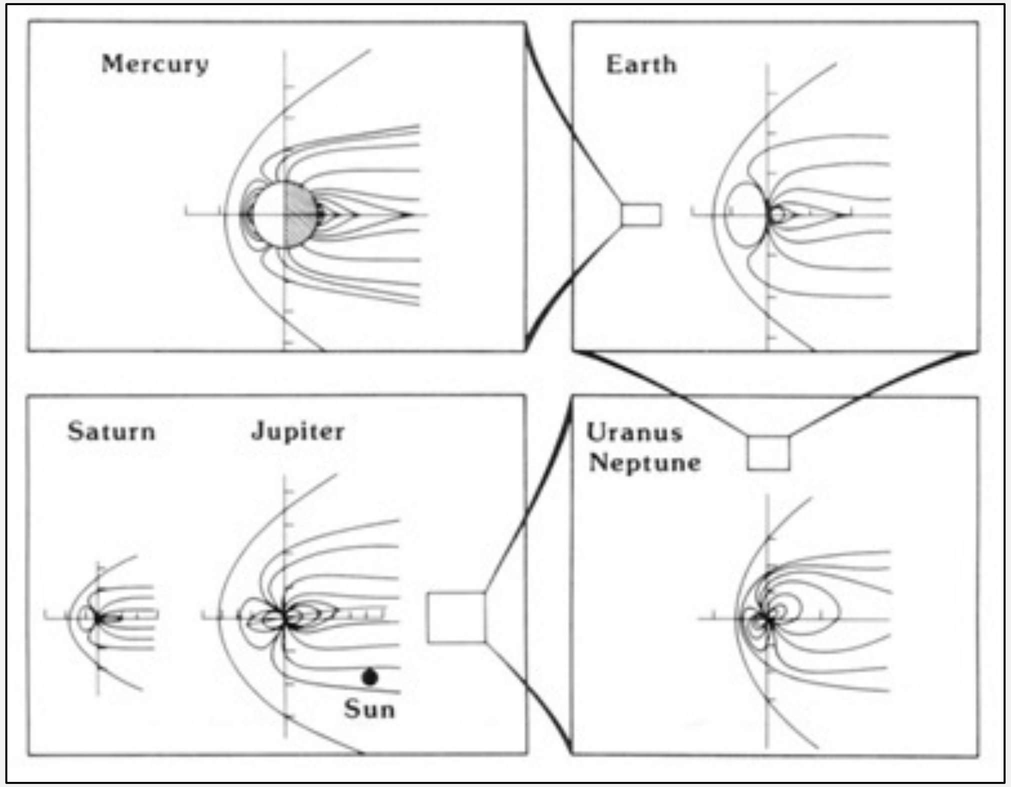
	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Distance, a_{planet} (AU)[a]	0.31–0.47	0.723	1[b]	1.524	5.2	9.5	19	30	30–50
Solar wind density (amu cm^{-3})[b]	35–80	16	8	3.5	0.3	0.1	0.02	0.008	0.008–0.003
Radius, R_P (km)	2,439	6,051	6,373	3,390	71,398	60,330	25,559	24,764	1,170 (±33)
Surface magnetic field, B_0 (Gauss = 10^{-4} T)	3×10^{-3}	$<2 \times 10^{-5}$	0.31	$<10^{-4}$	4.28	0.22	0.23	0.14	?
Planetary radii, R^c_{MP}	1.4–1.6 R_M	—	10 R_E	—	42 R_J	19 R_S	25 R_U	24 R_N	
Observed size of	1.4 R_M	—	8–12 R_E	—	50–100 R_J	16–22 R_S	18 R_U	23–26 R_N	?
magnetosphere (km)	3.6×10^3	—	7×10^4	—	7×10^6	1×10^6	5×10^5	6×10^5	

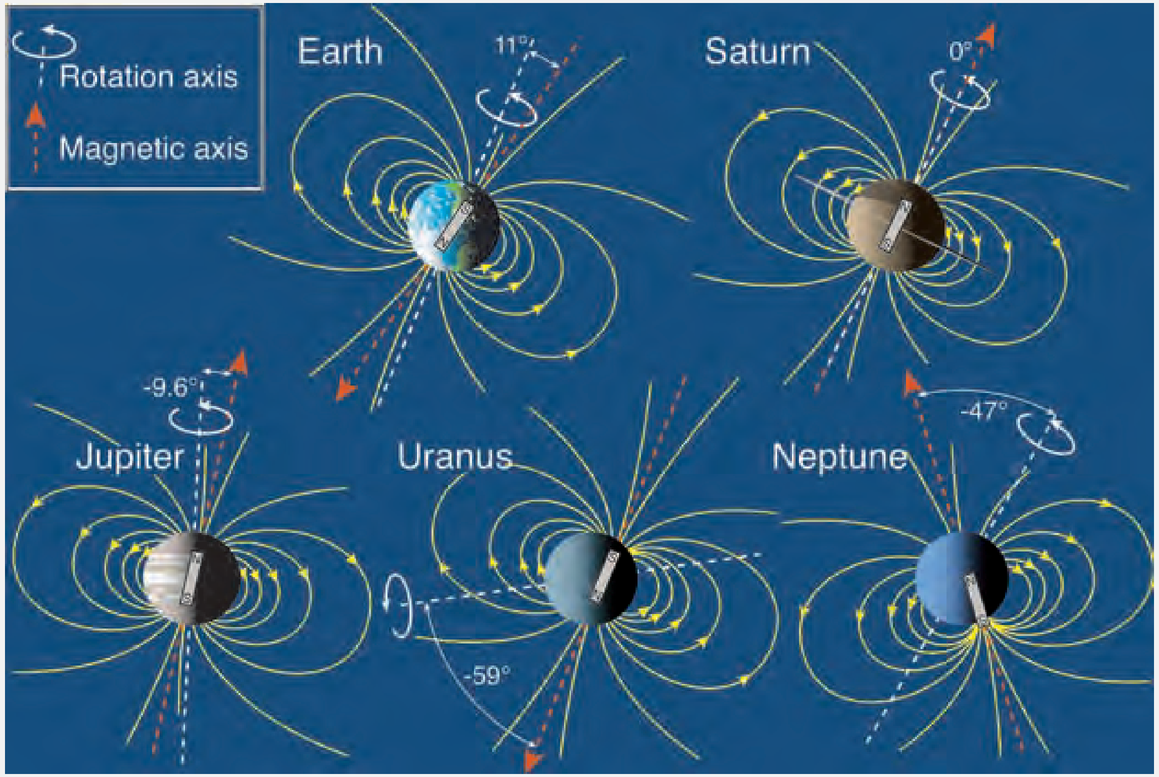
Giant Planets

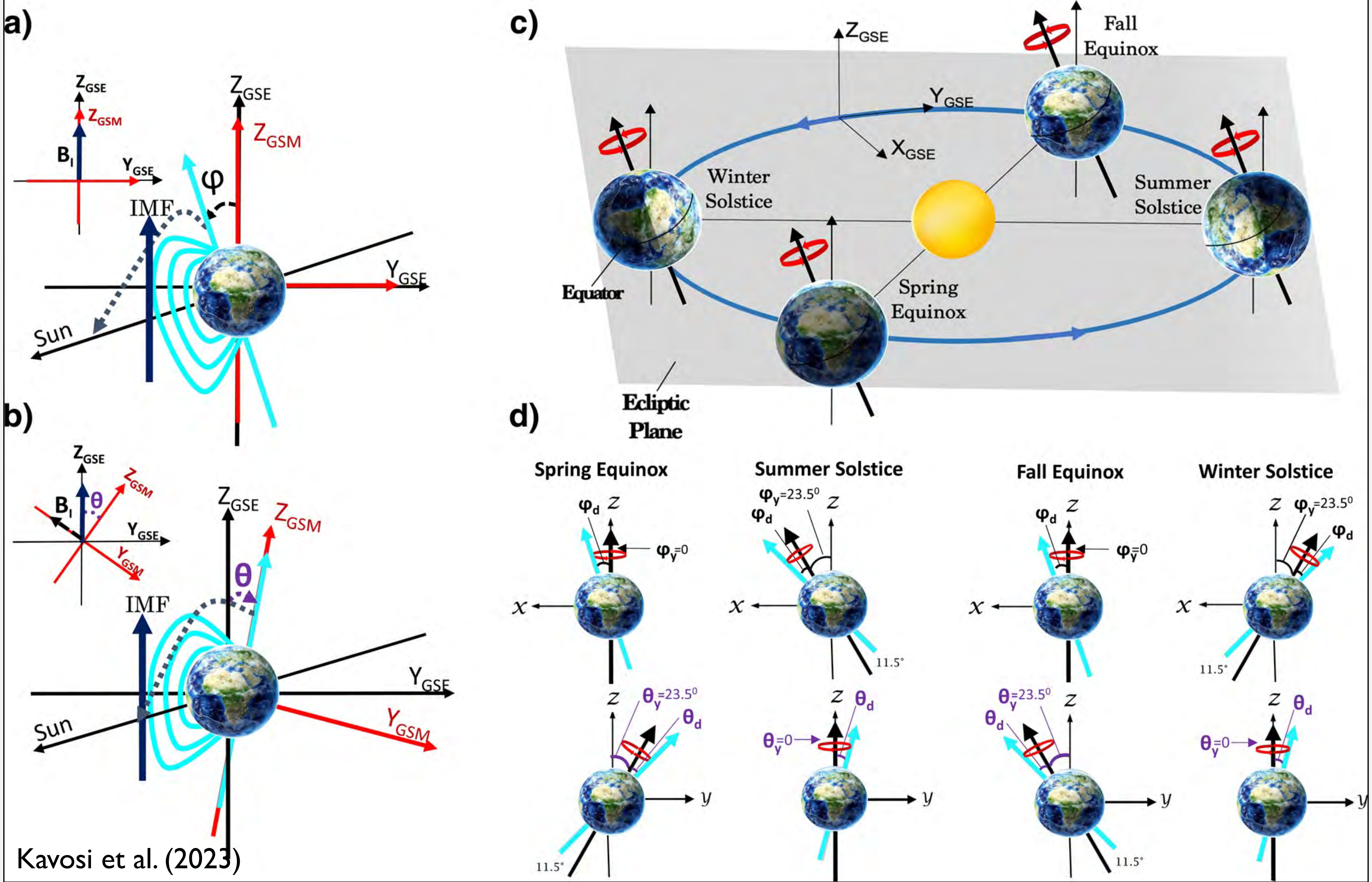
		Distance AU	Mass Earth Mass	Radius Earth Radii	Density 1=water	Composition % by mass
	Jupiter	5.20	318	11.2	1.33	90% H, He
	Saturn	9.54	95	9.46	0.71	75% H, He
	Uranus	19.2	14	3.98	1.24	10% H, He Water Ammonia Methane
	Neptune	30.1	17	3.81	1.67	10% H, He Water Ammonia Methane



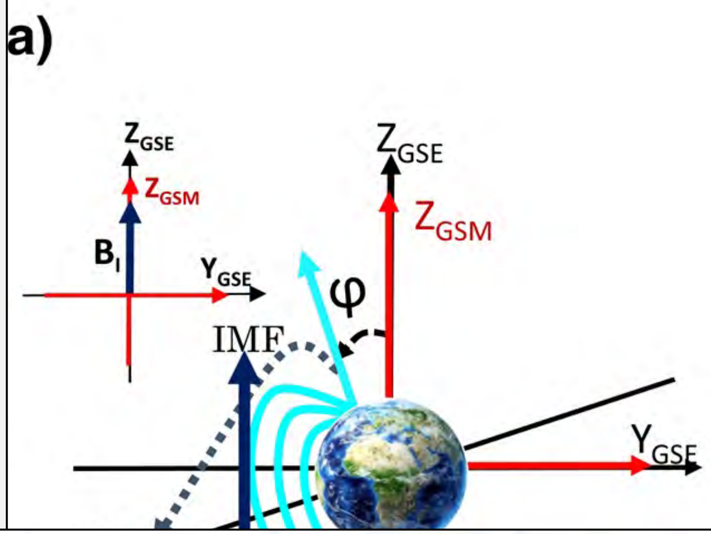
GIANT PLANET MAGNETOSPHERES – URANUS AND NEPTUNE

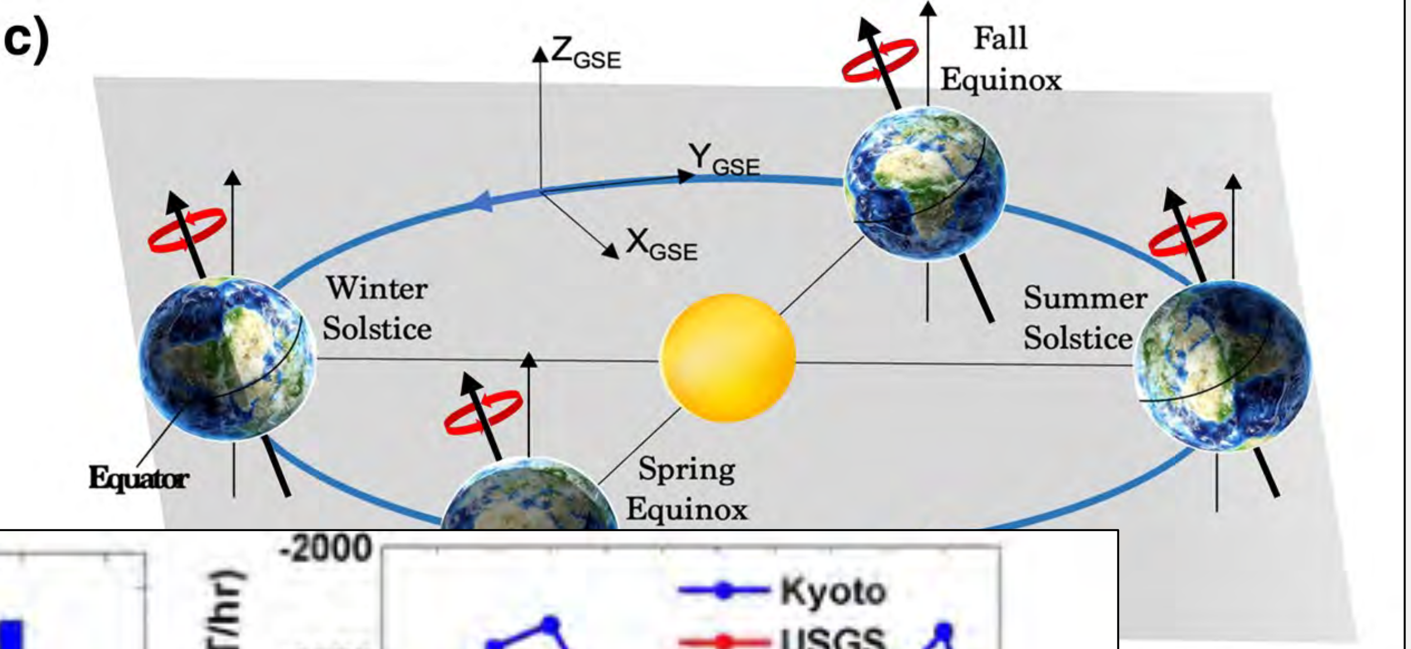


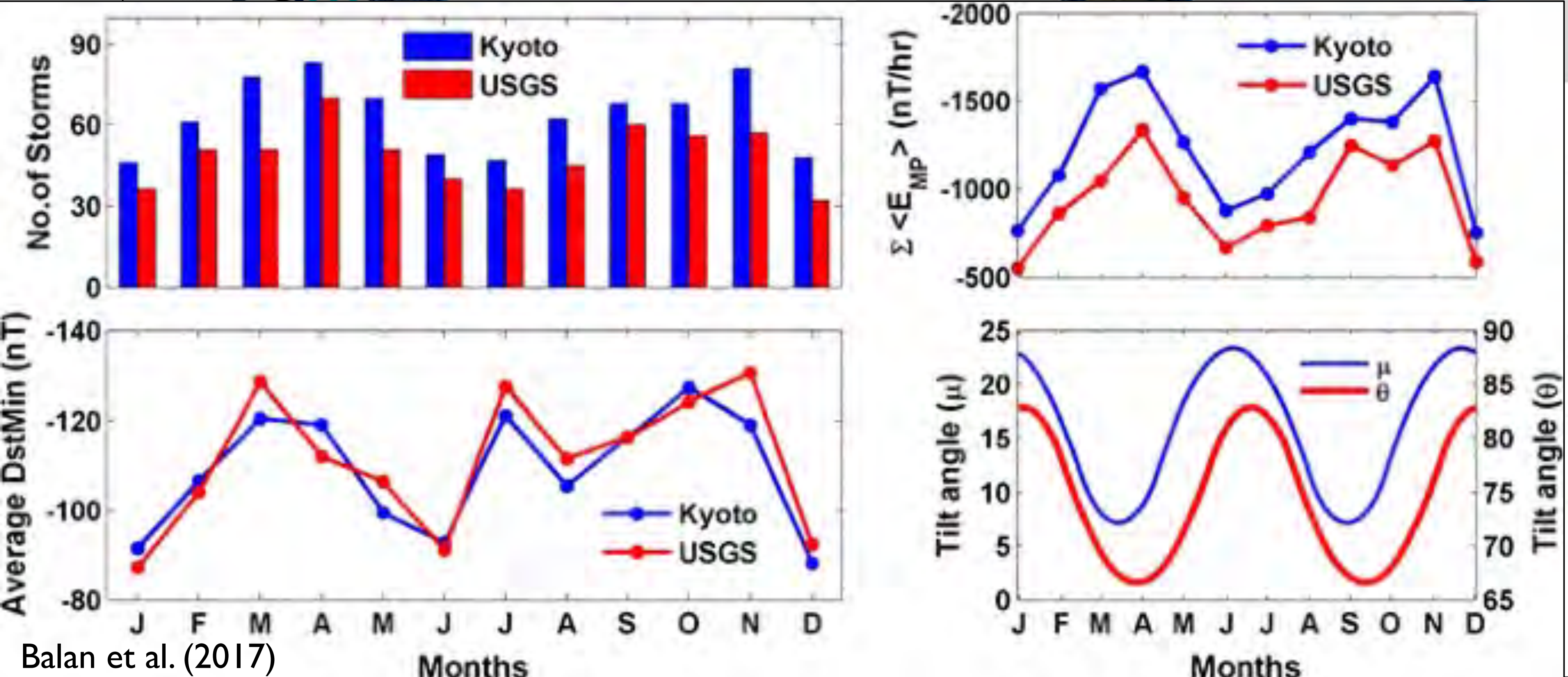


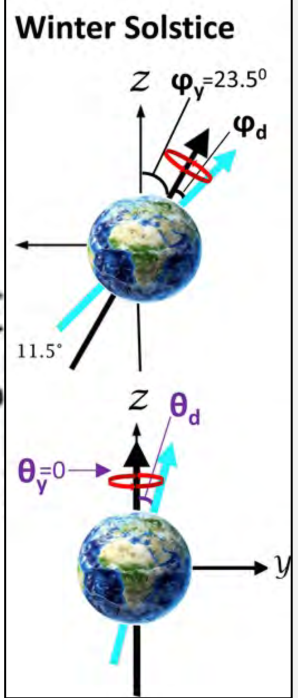


Kavosi et al. (2023)



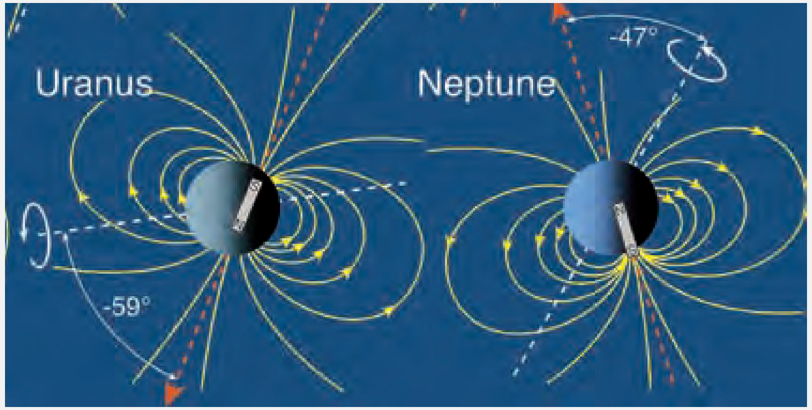




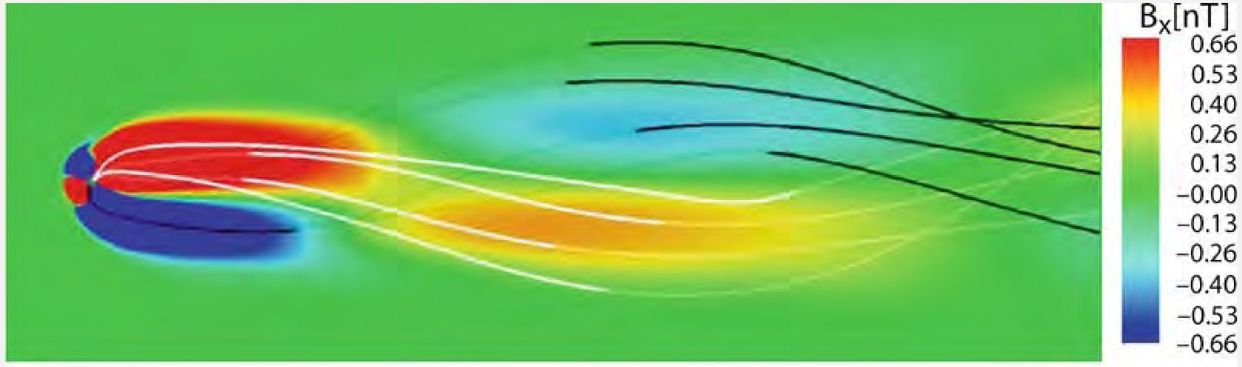


Balan et al. (2017)

ROTATION AND MAGNETIC AXES



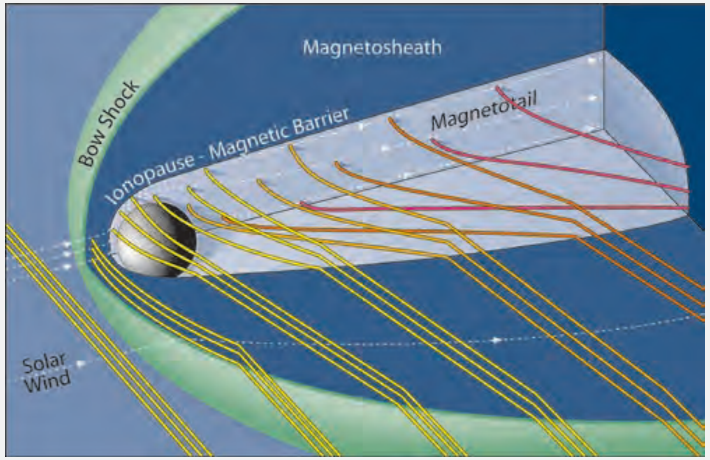
Uranus:



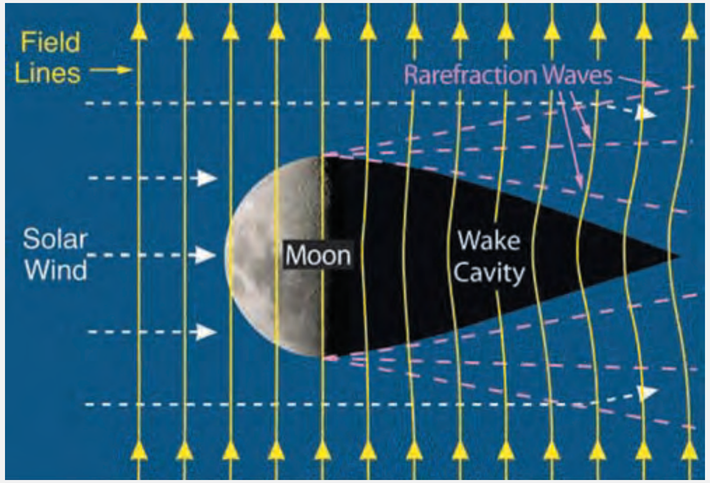
Neptune:

WHAT WE DIDN'T DISCUSS…

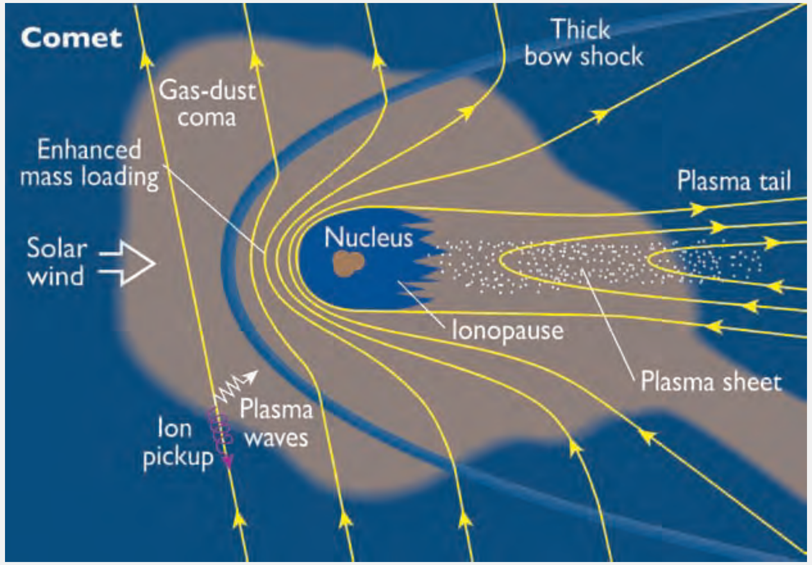
Unmagnetized conducting bodies (e.g. Venus):



Unmagnetized non-conducting bodies (e.g. the Moon):



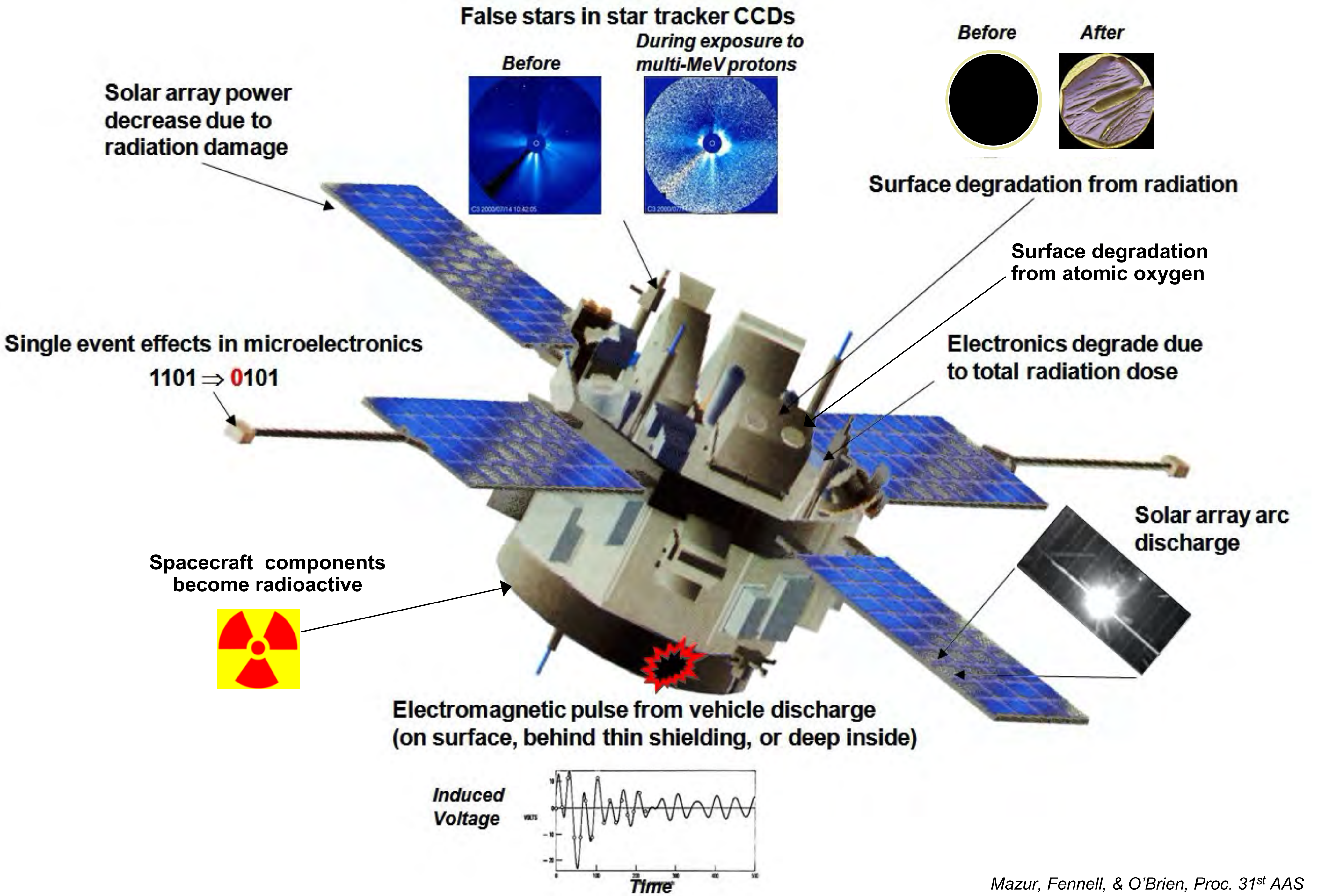
Comets:



SPACE WEATHER IMPACTS

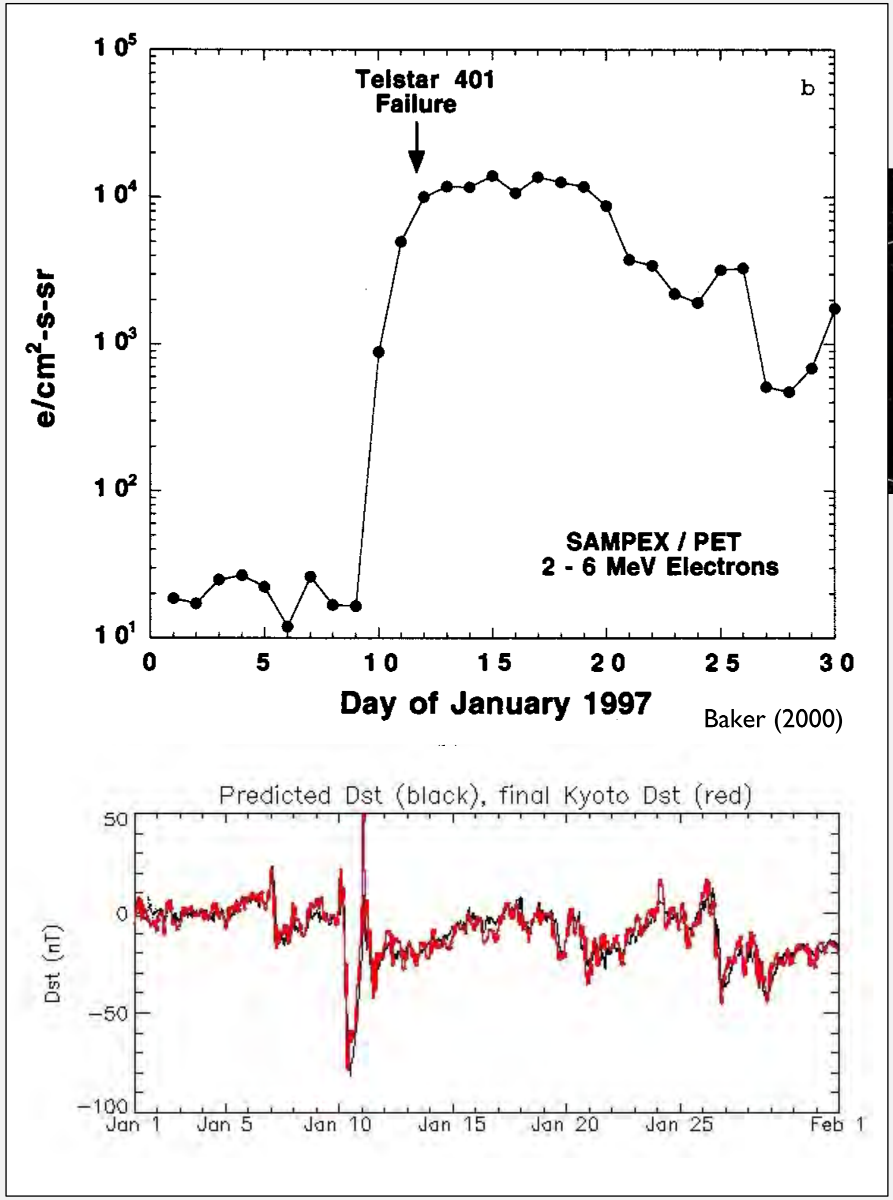
SPACE WEATHER

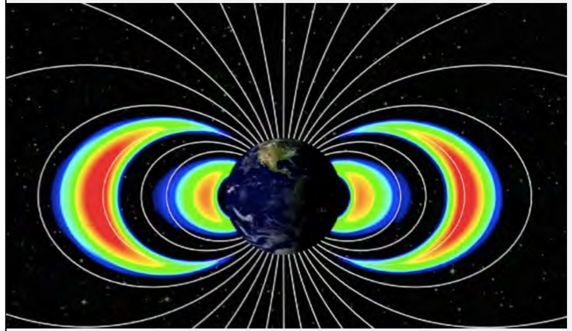
The variable conditions on the Sun and in the space environment that can influence the performance and reliability of spaceborne and groundbased technological systems, as well as endanger life or health.



Mazur, Fennell, & O'Brien, Proc. 31st AAS Guidance and Control Conf., vol 131, 2008

SPACE WEATHER IMPACTS





TAKE-AWAYS

- The near-Earth space environment is fascinating both from a pure physics as well as applied perspective
  - Studying our own magnetosphere can teach us a lot about planetary magnetospheres and star-planet interactions in general

- The system is complex and interconnected
  - Other star-planet/moon interactions provide a laboratory to learn how different variables affect the overall system, how well we really understand our own system

BEFORE WE LEAVE…

Write down:

1. one thing you found interesting
2. one question about today's material

EXTRA

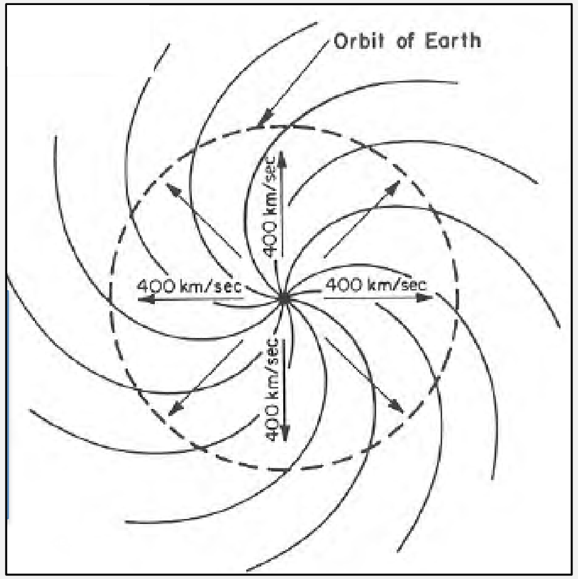
COMMON MISCONCEPTIONS…

SOLAR WIND

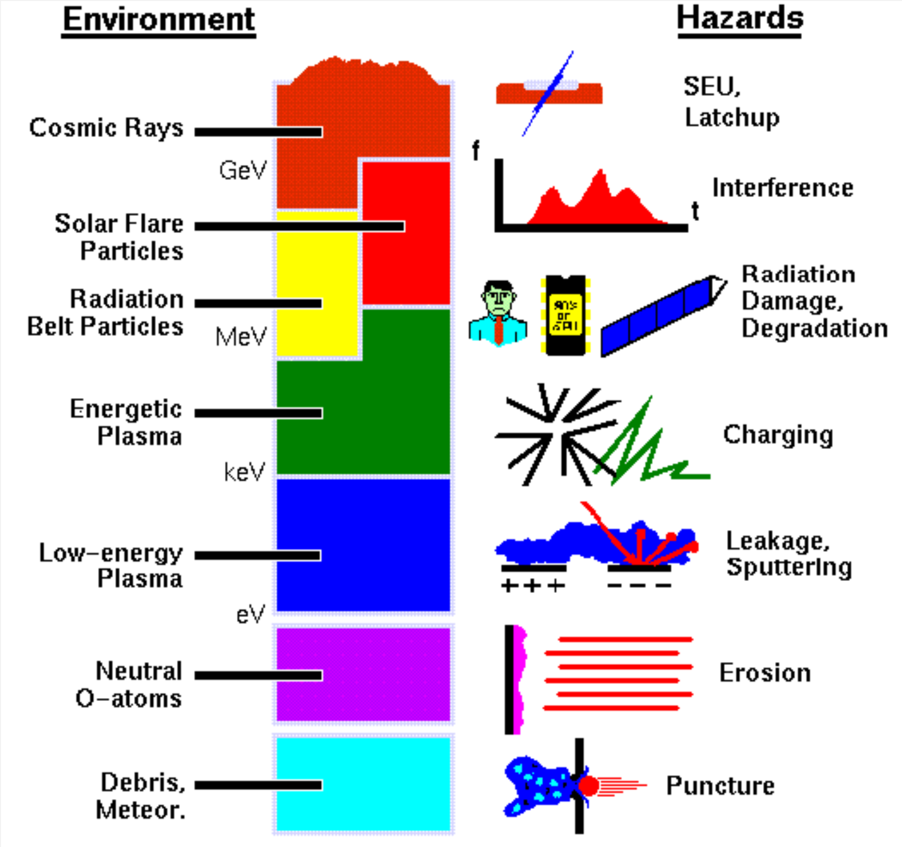
Table 2. Average solar wind parameters at 1 AU, for the time around solar activity minimum.

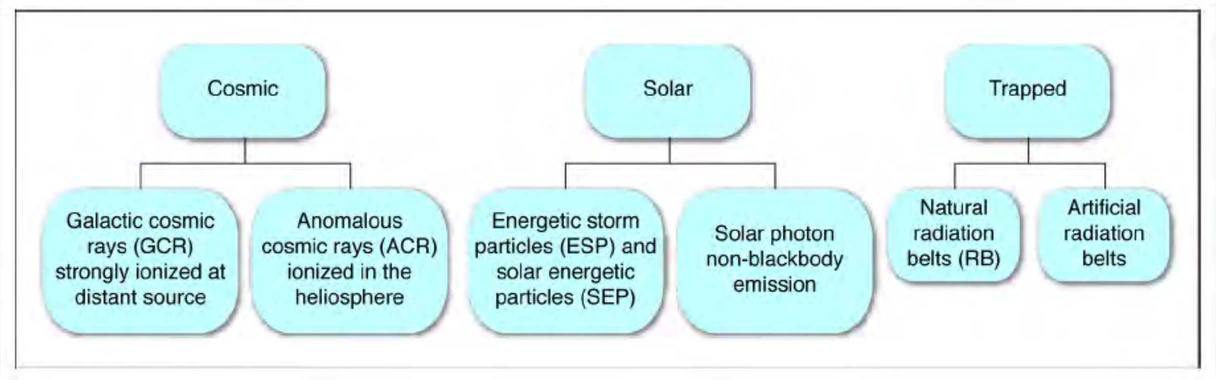
	Slow wind	Fast wind
Flow speed v_P	250–400 km s^{-1}	400–800 km s^{-1}
Proton density n_P	10.7 cm^{-3}	3.0 cm^{-3}
Proton flux density $n_P v_P$	3.7×10^8 cm^{-2} s^{-1}	2.0×10^8 cm^{-2} s^{-1}
Proton temperature T_P	3.4×10^4 K	2.3×10^5 K
Electron temperature T_e	1.3×10^5 K	1×10^5 K
Momentum flux density	2.12×10^8 dyn cm^{-2}	2.26×10^8 dyn cm^{-2}
Total energy flux density	1.55 erg cm^{-2} s^{-1}	1.43 erg cm^{-2} s^{-1}
Helium content	2.5%, variable	3.6%, stationary
Sources	Streamer belt	Coronal holes

Density scales as $1/r^3$
Flow speed ~ constant
Solar wind B_r α $1/r^2$ B_ϕ α $1/r$
Dynamic pressure ρu^2 drops off with distance
Mach number increases with distance



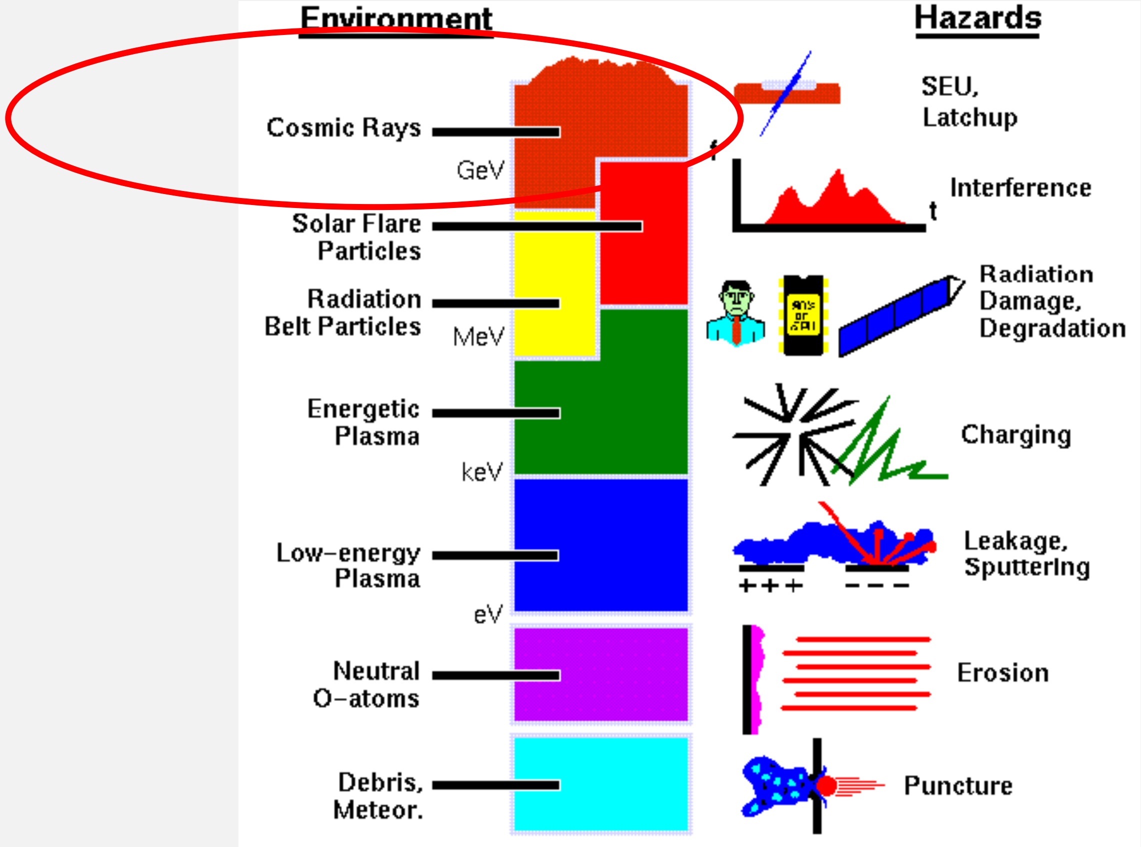
Space Weather – Radiation Sources and Effects

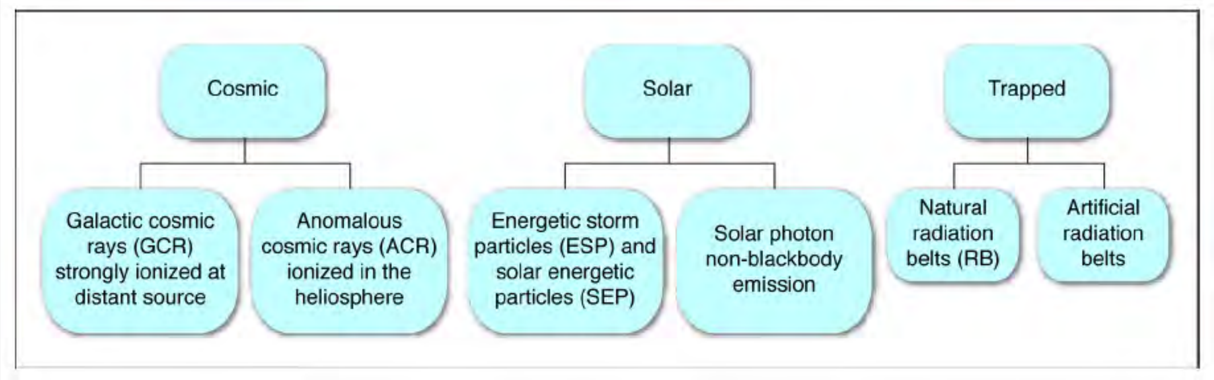




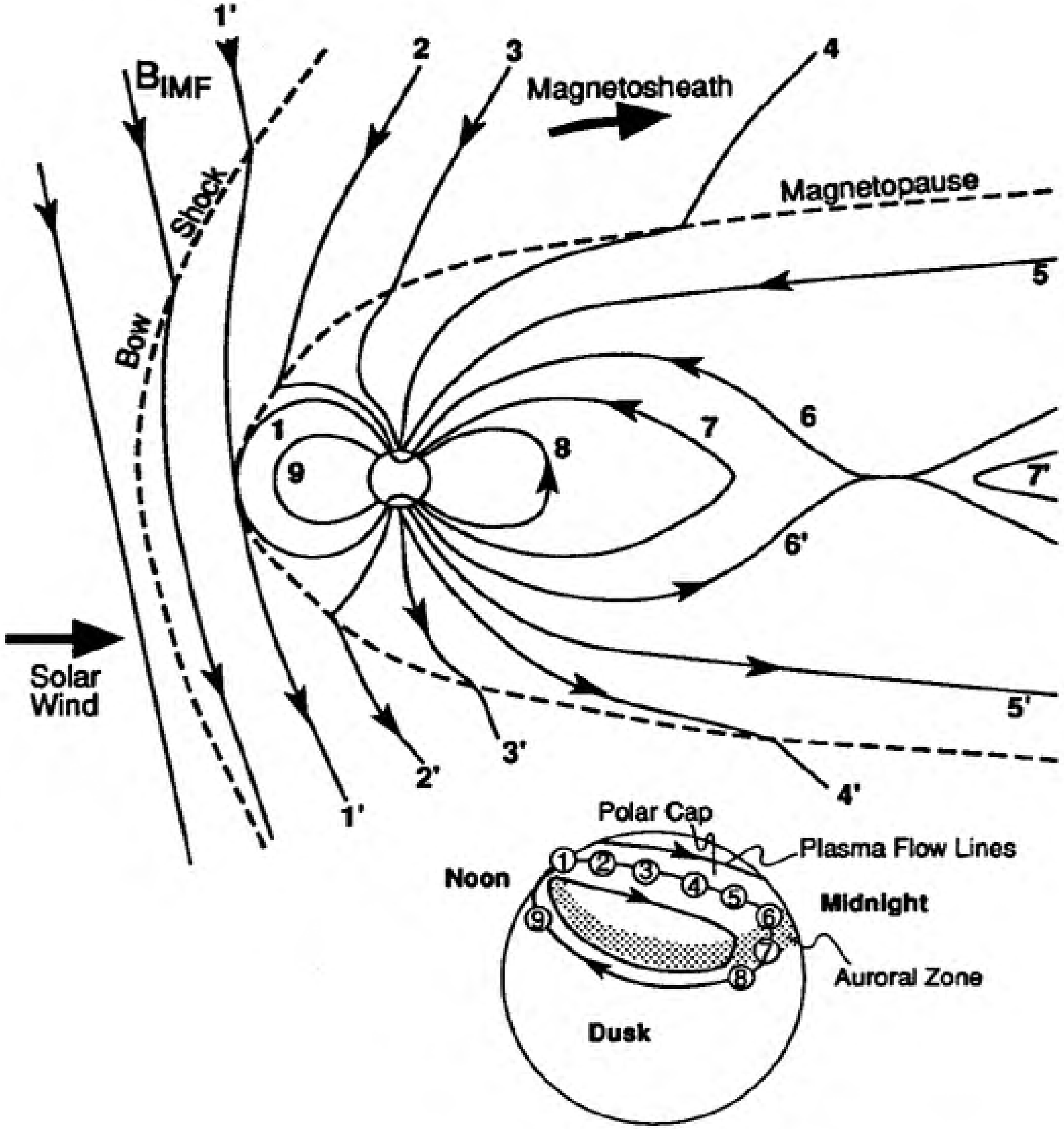
Space Weather – Radiation Sources and Effects

Physicist Victor Hess on a balloon flight in 1912. Credit: SPL





DUNGEY CYCLE



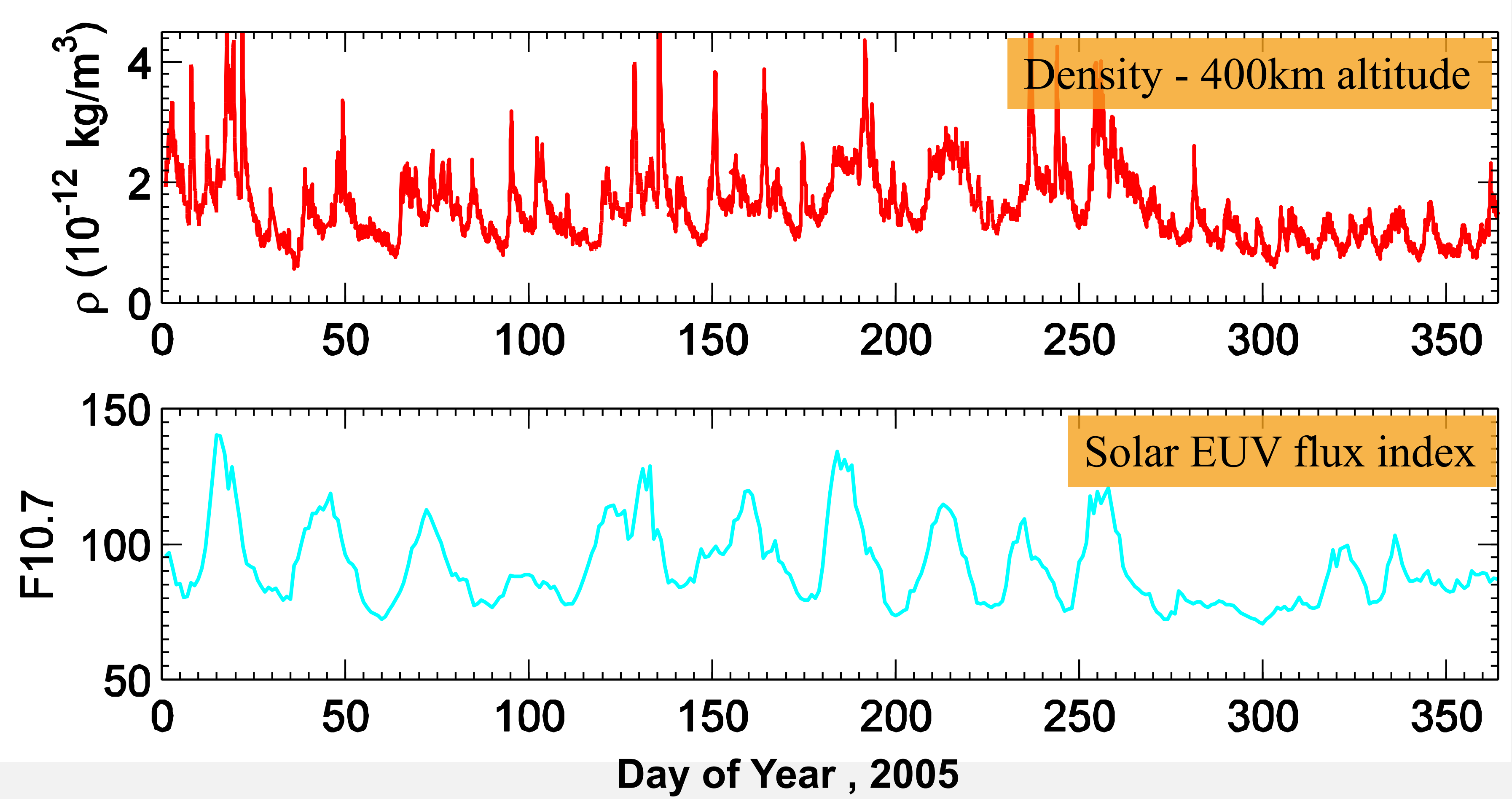
F_{pc} = open magnetic flux in the polar cap

Φ_D = dayside reconnection rate

Φ_N = nightside reconnection rate

$$\frac{dF_{PC}}{dt} = \Phi_D(t) - \Phi_N(t)$$

PERIODIC THERMOSPHERE MASS DENSITY PERTURBATIONS

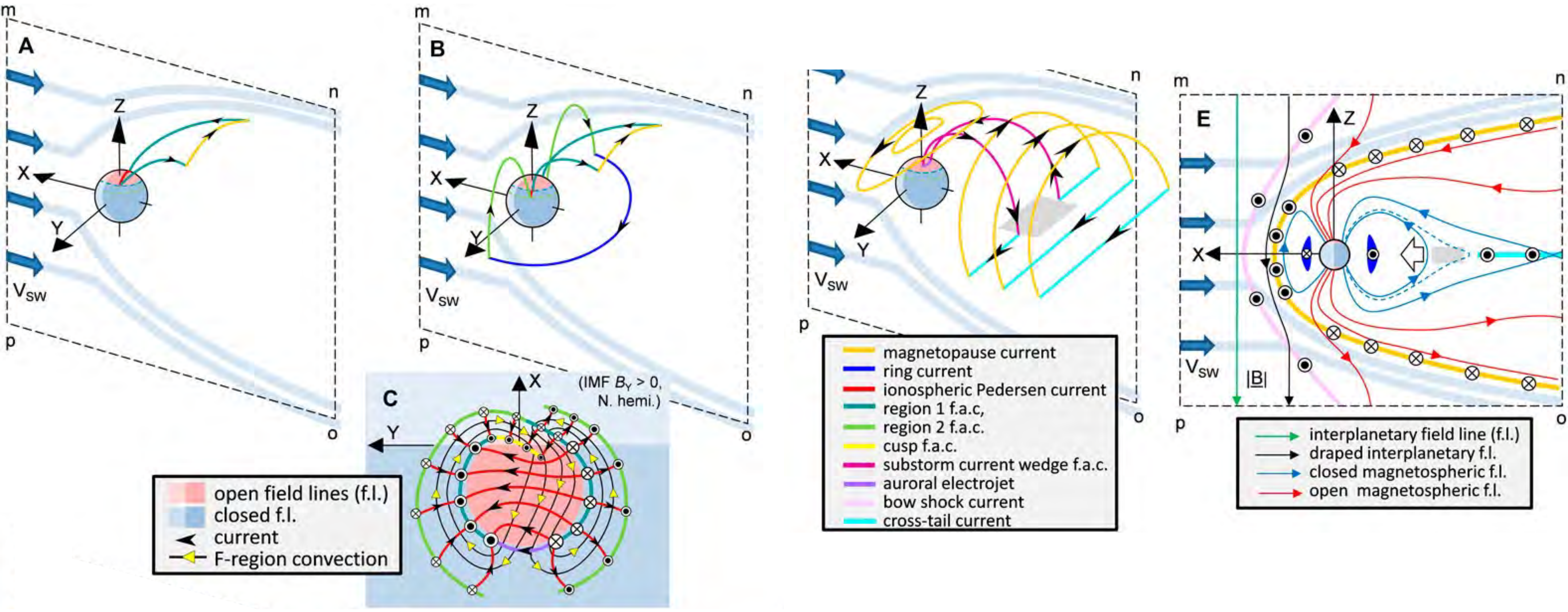


Note: Orbit-averaged density with an overall estimated error (systematic and statistical) of less than 10%

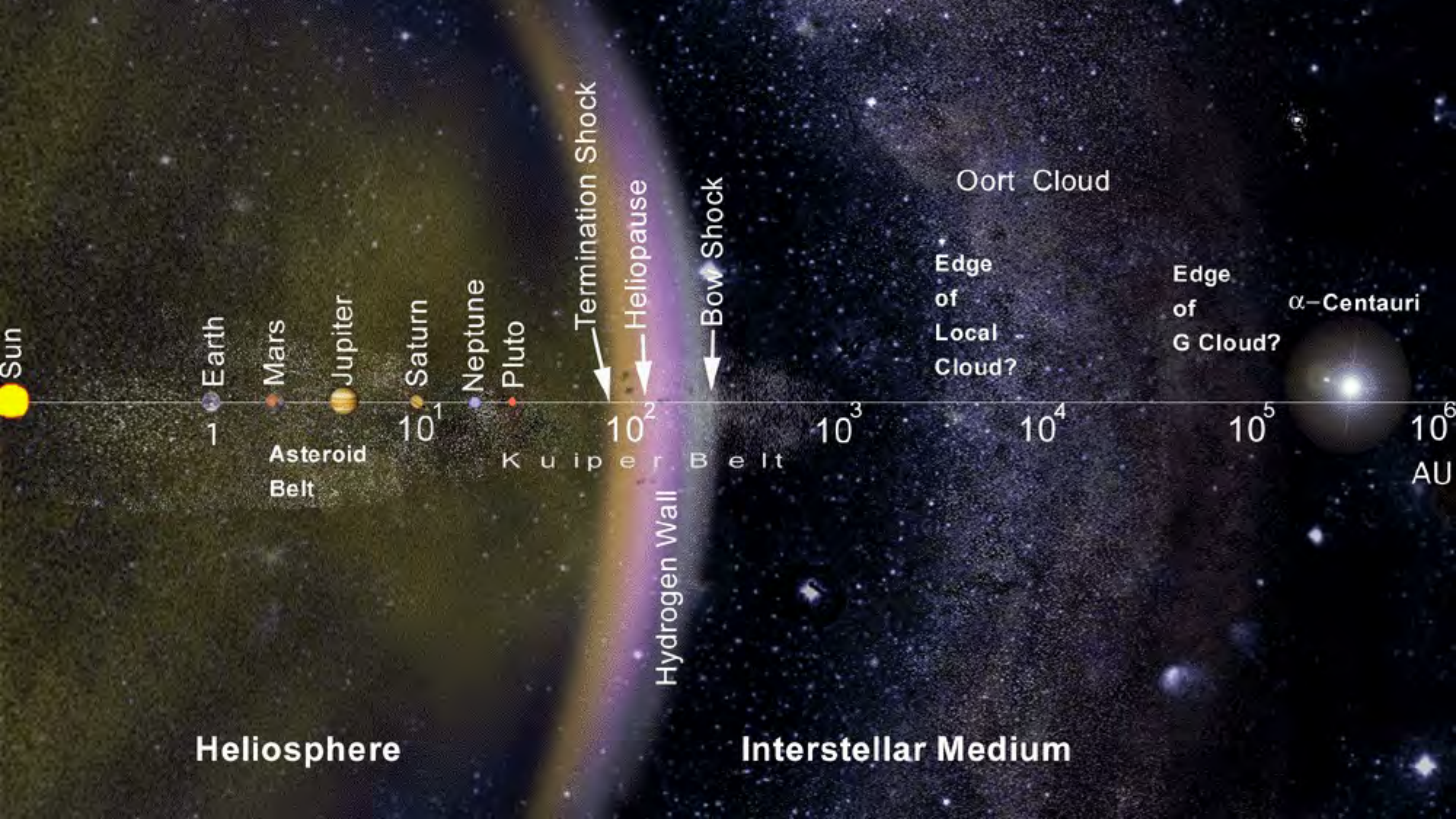
$$R_{MP}/R_{planet} \sim 1.2 \{B_o^2 / 2 \mu_o \rho_{sw} V^2_{sw}\}^{1/6}$$

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



Lockwood (2022) Frontiers
"The Joined-up Magnetosphere"


Sun
Earth
Mars
Jupiter
Saturn
Neptune
Pluto
Termination Shock
Heliopause
Bow Shock
Oort Cloud
Edge of Local Cloud?
Edge of G Cloud?
α−Centauri
1
10^1
10^2
10^3
10^4
10^5
10^6
AU
Asteroid Belt
Kuiper Belt
Hydrogen Wall
Heliosphere
Interstellar Medium