Curvaceous and Flowing: Saturn's Magnetosphere and all of its Charms

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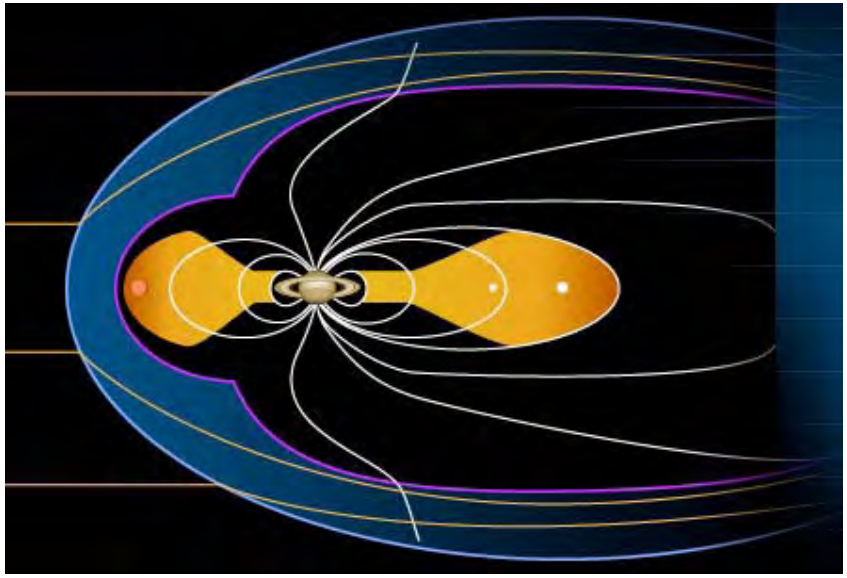
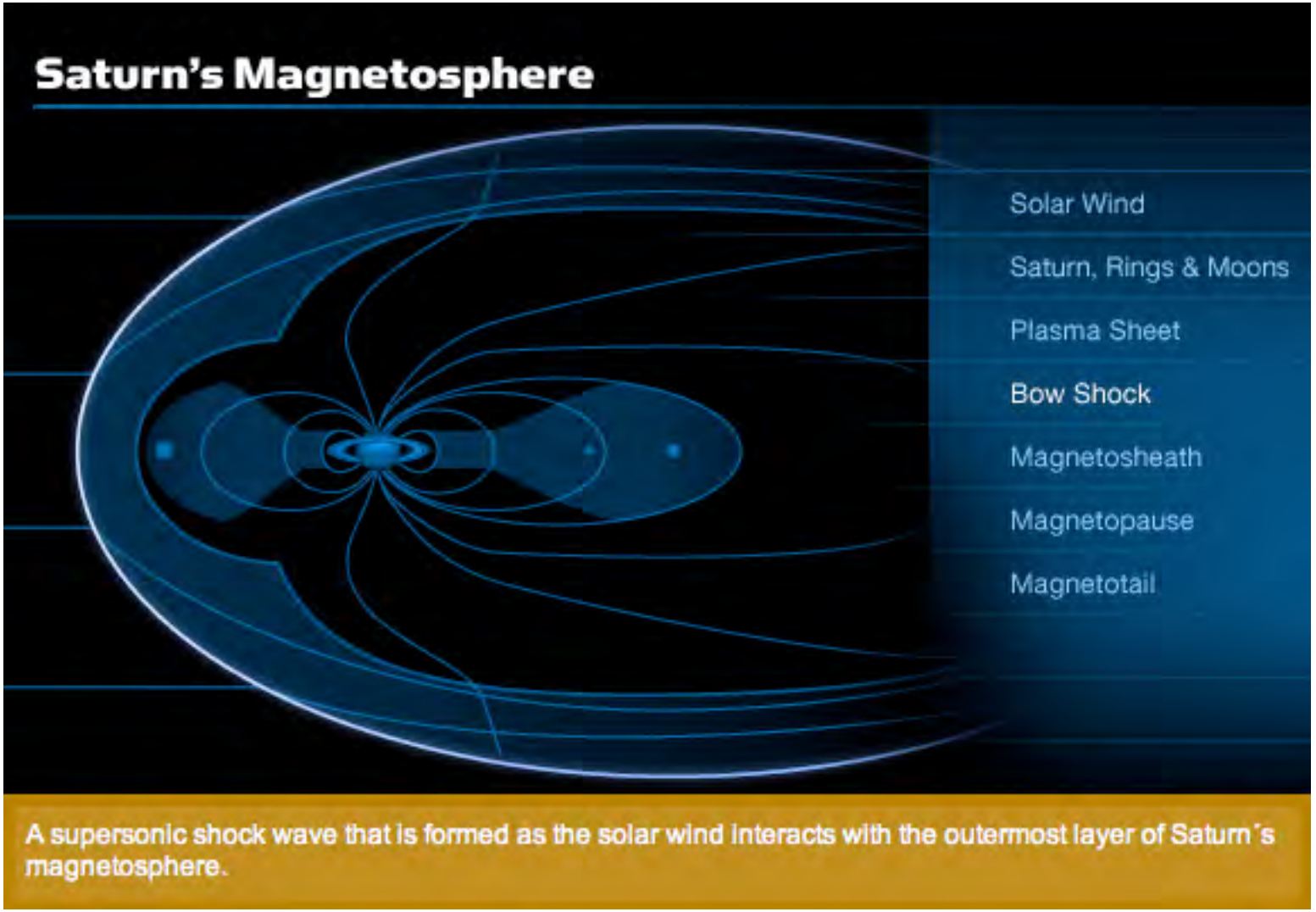
Basic Elements of the Magnetosphere

- Bow Shock
- Magnetosheath
- Magnetopause
- Moons & Rings
- Plasma Sheet/ magneto-disc
- Neutral Cloud
- Magnetotail

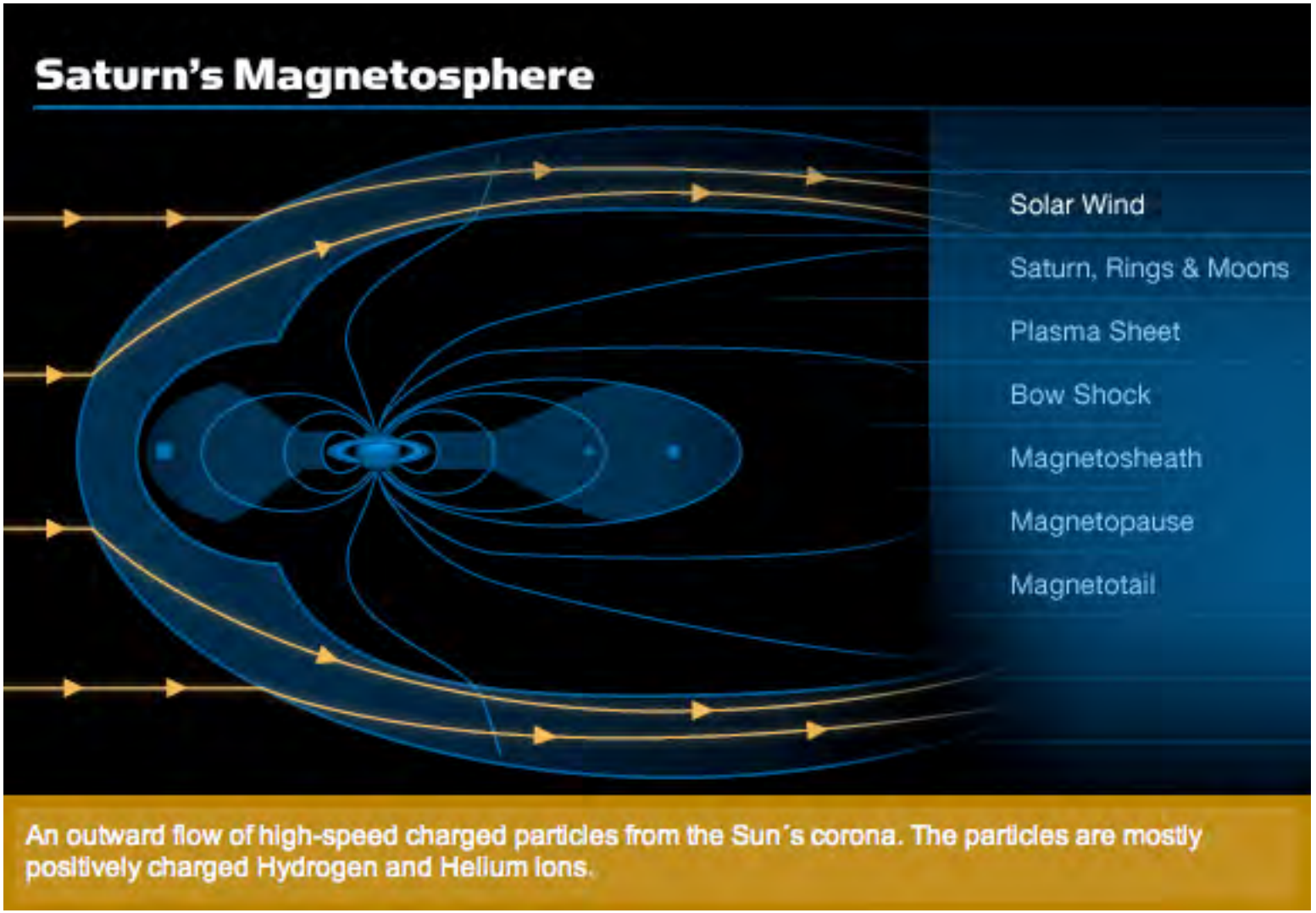


All of these parts ARE IN MOTION!

Bow Shock


Saturn's Magnetosphere
Solar Wind
Saturn, Rings & Moons
Plasma Sheet
Bow Shock
Magnetosheath
Magnetopause
Magnetotail
A supersonic shock wave that is formed as the solar wind interacts with the outermost layer of Saturn's magnetosphere.

Solar Wind


Saturn's Magnetosphere
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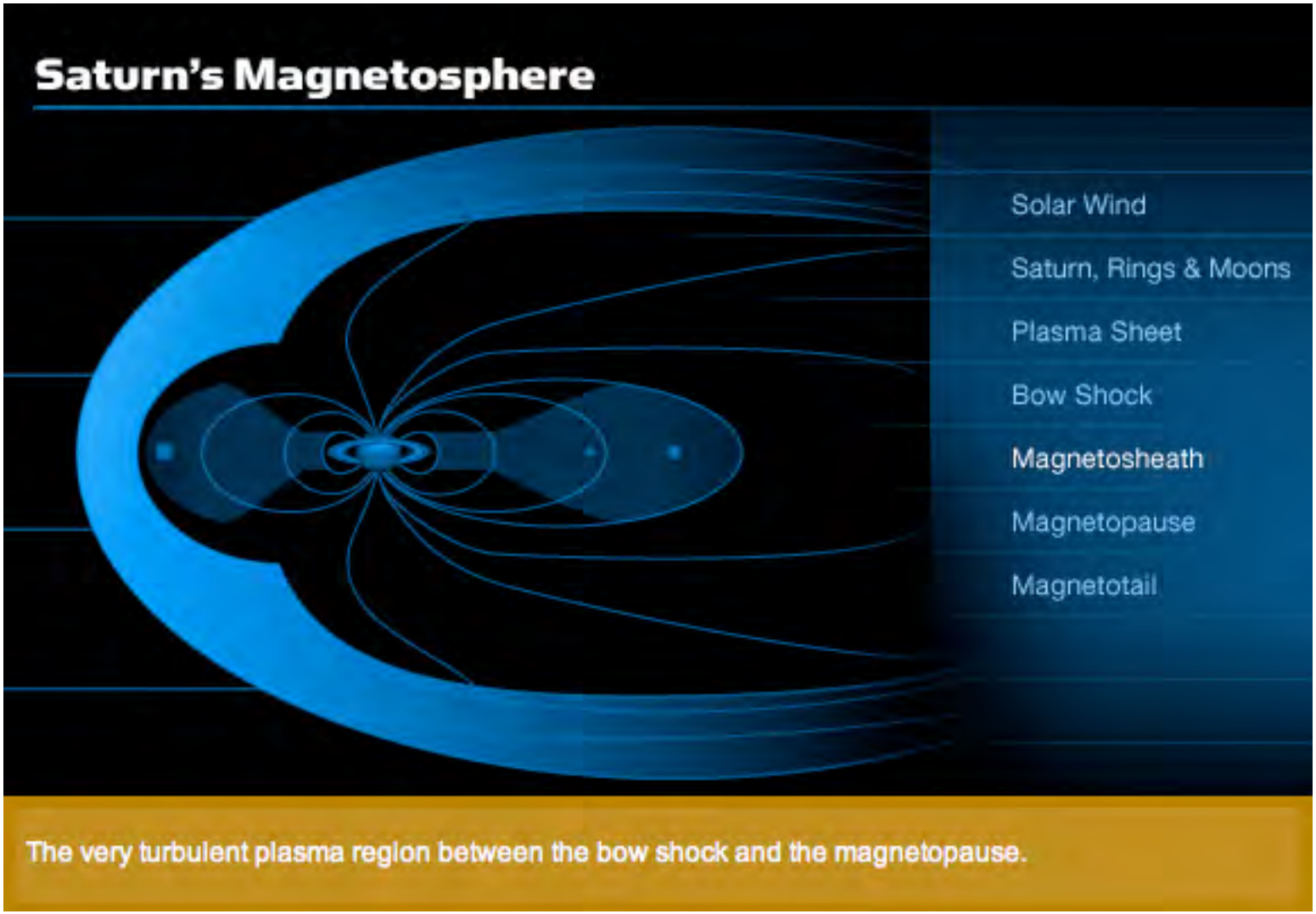
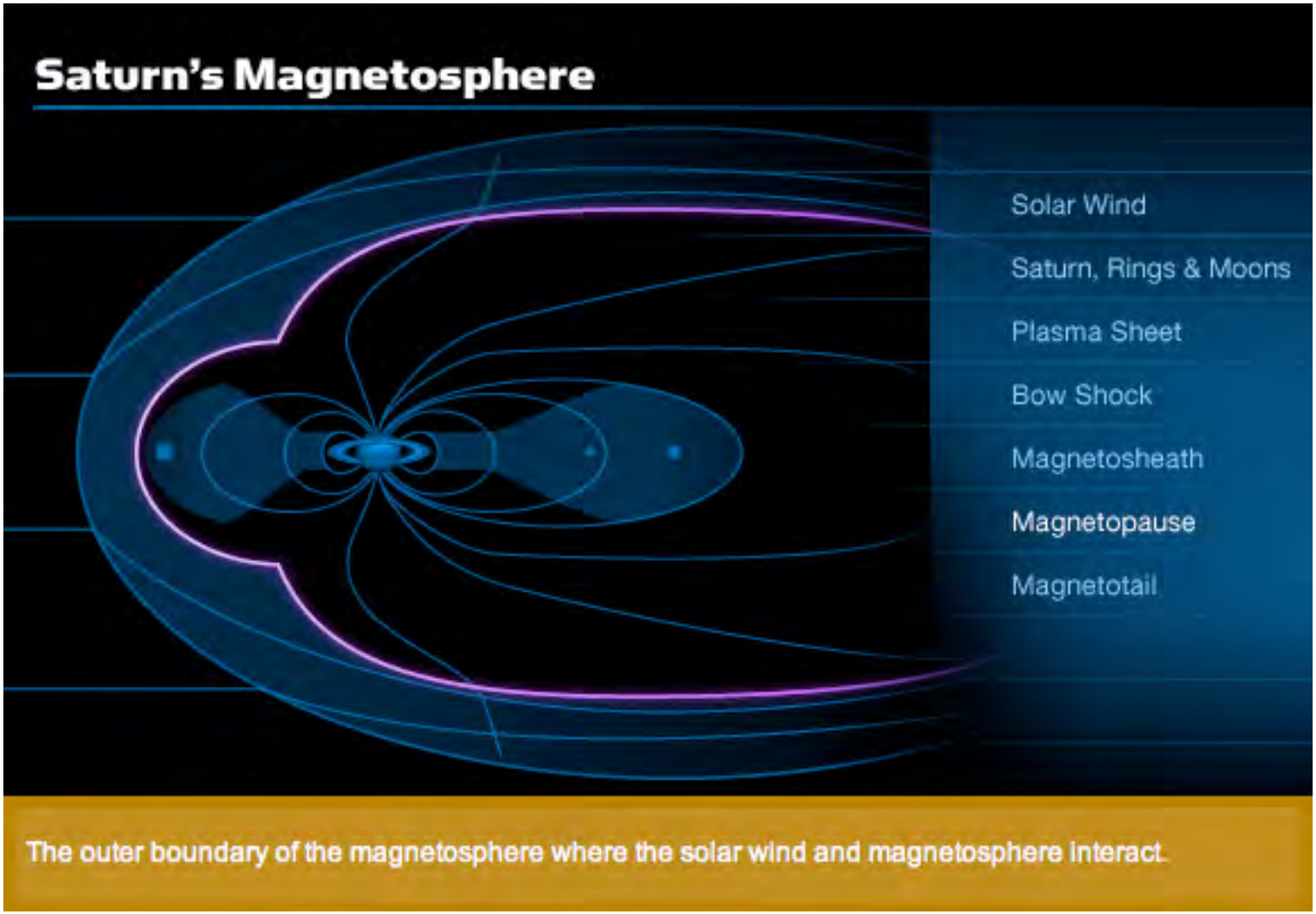
An outward flow of high-speed charged particles from the Sun´s corona. The particles are mostly positively charged Hydrogen and Helium ions.

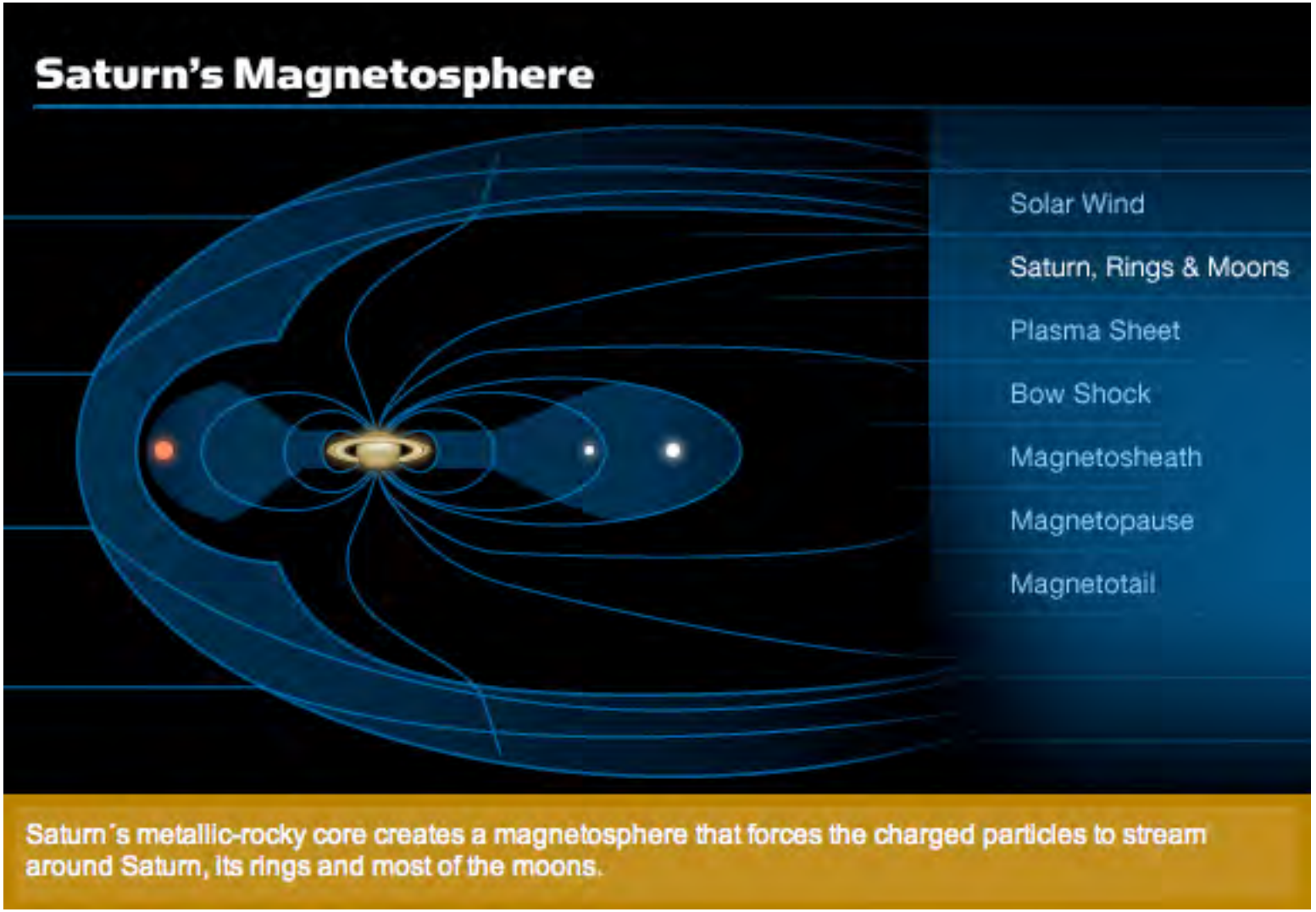
Magnetosheath



Magnetopause



Rings & Moons


Saturn's Magnetosphere
Solar Wind
Saturn, Rings & Moons
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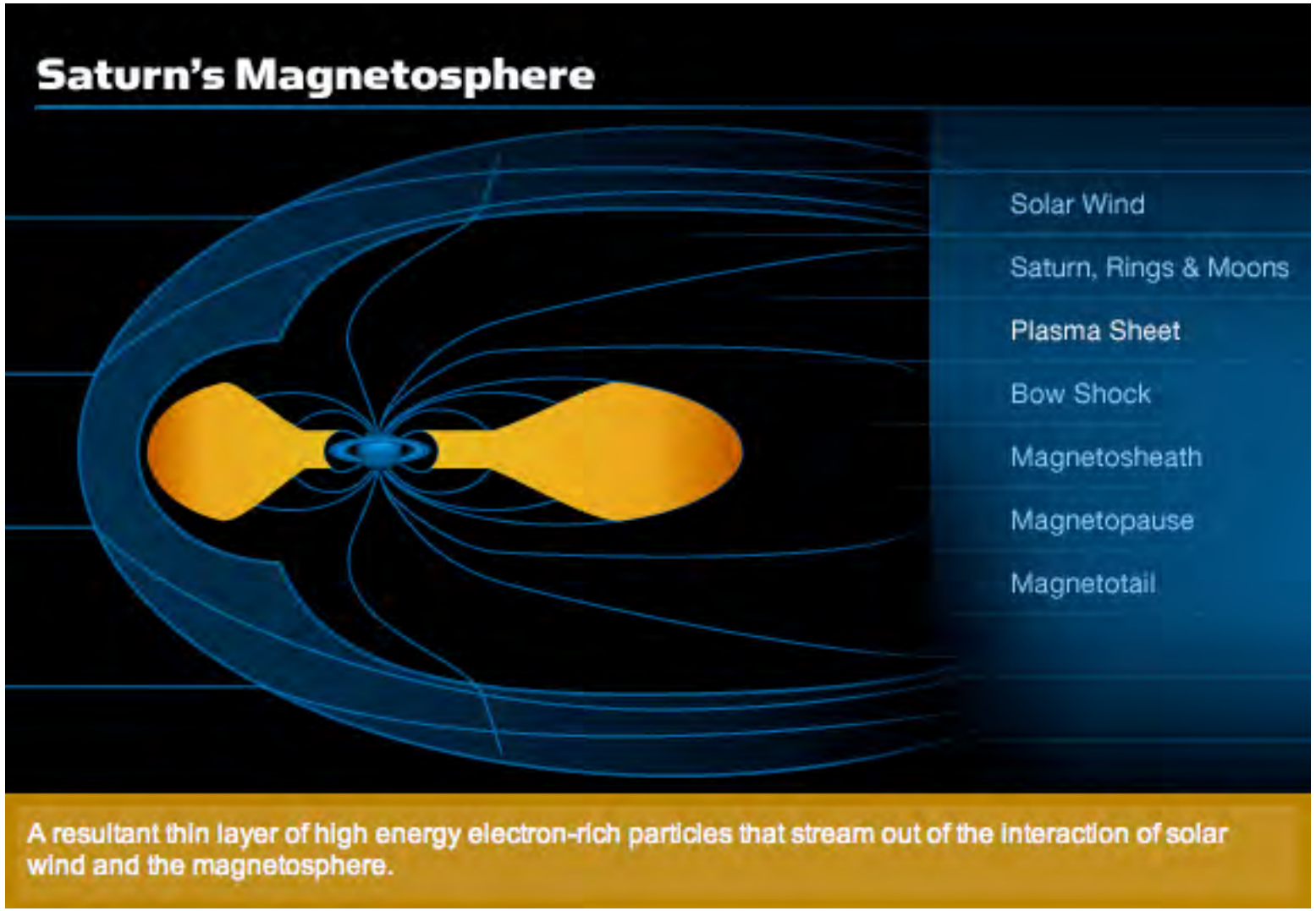
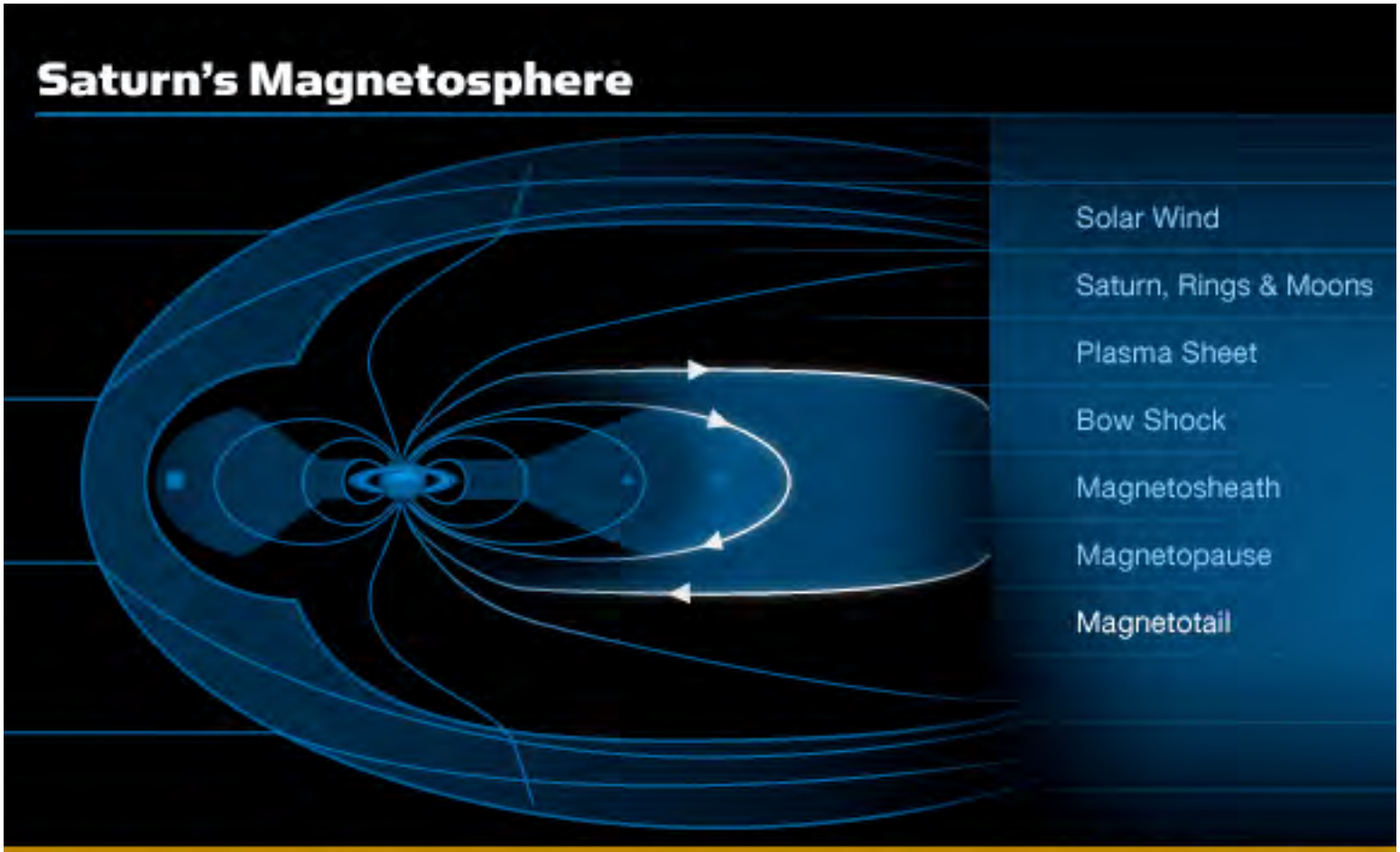
Magnetopause
Magnetotail
Saturn's metallic-rocky core creates a magnetosphere that forces the charged particles to stream around Saturn, its rings and most of the moons.

Plasma Sheet, Magnetodisc,& Neutral Cloud



Magnetotail



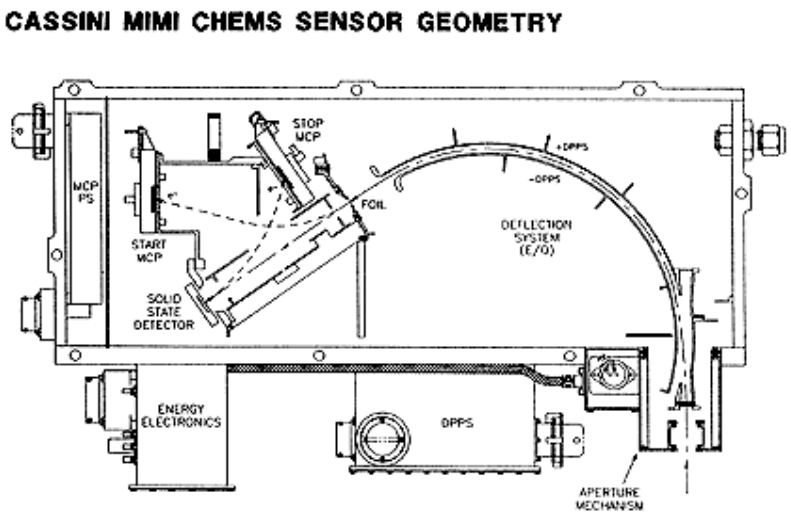
The long, trailing limb of Saturn´s magnetosphere on the side facing away from the sun composed of trapped ionized particles.

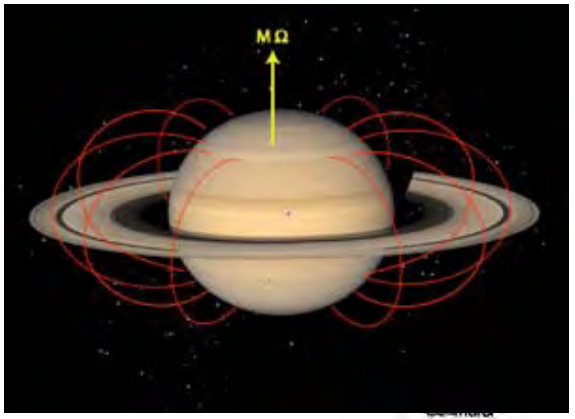
Important to remember that these are just pictures. We will use data to construct a more realistic understanding.

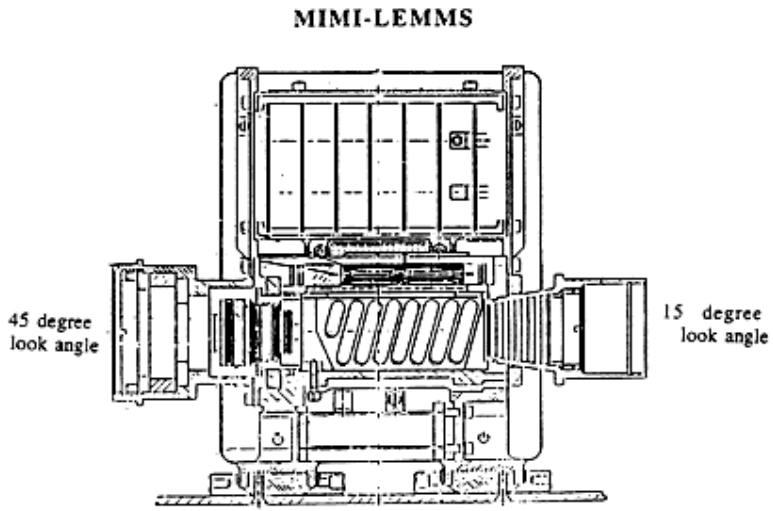
Like a blind man using his tactile senses, we use:

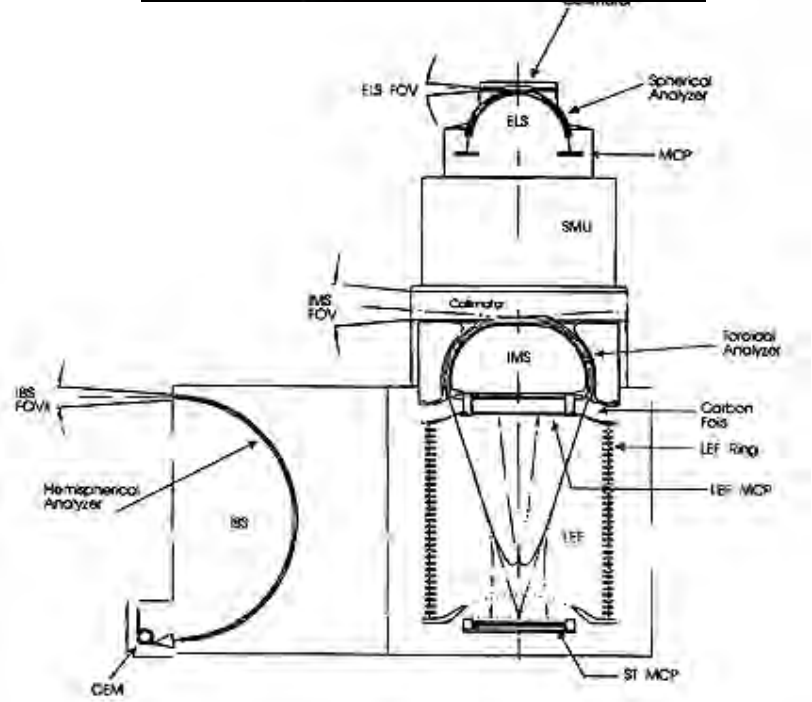
- *Magnetometer - identifying currents and magnetic field*
- *Plasma Wave - identifying (analog to audio) signals*
- *Particle instruments - CAPS, MIMI - identifying flow directions (feel), composition (taste)*

What do the Magnetometer, RPWS, & particle instruments do?







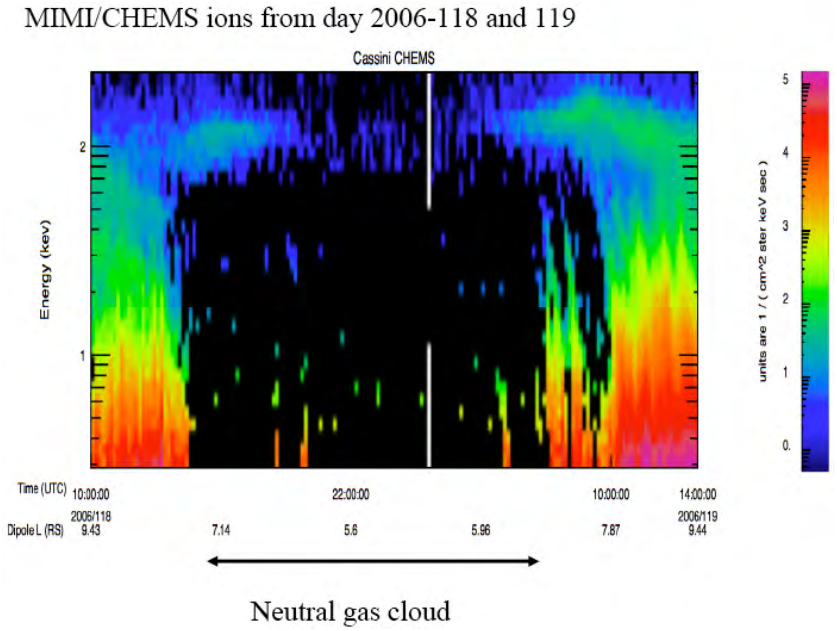


Cassini Plasma Spectrometer (CAPS)

- The Cassini Plasma Spectrometer (CAPS) measures the energy and electrical charge of particles such as electrons and protons that the instrument encounters. The instrument is used to study the composition, density, flow, velocity, and temperature of ions and electrons in Saturn's magnetosphere. Shaped much like a teardrop, Saturn's magnetosphere is huge. It spreads out almost a million miles, engulfing the orbits of Titan and most of the ringed planet's icy moons, as well as the famous rings.
- The instrument consists of three sensors: an electron spectrometer, an ion beam spectrometer, and an ion mass spectrometer. A motor-driven actuator rotates the sensor package to provide 208-degree scanning in the azimuth of the spacecraft. The electron spectrometer makes measurements of the energy of incoming electrons; its energy range is 0.7 to 30,000 electron volts. The ion beam spectrometer determines the energy to charge ratio of an ion; its energy range is 1 electron volt to 50 kilo-electron volts. The ion mass spectrometer's energy range is 1 electron volt to 50 kilo-electron volts.

MIMI

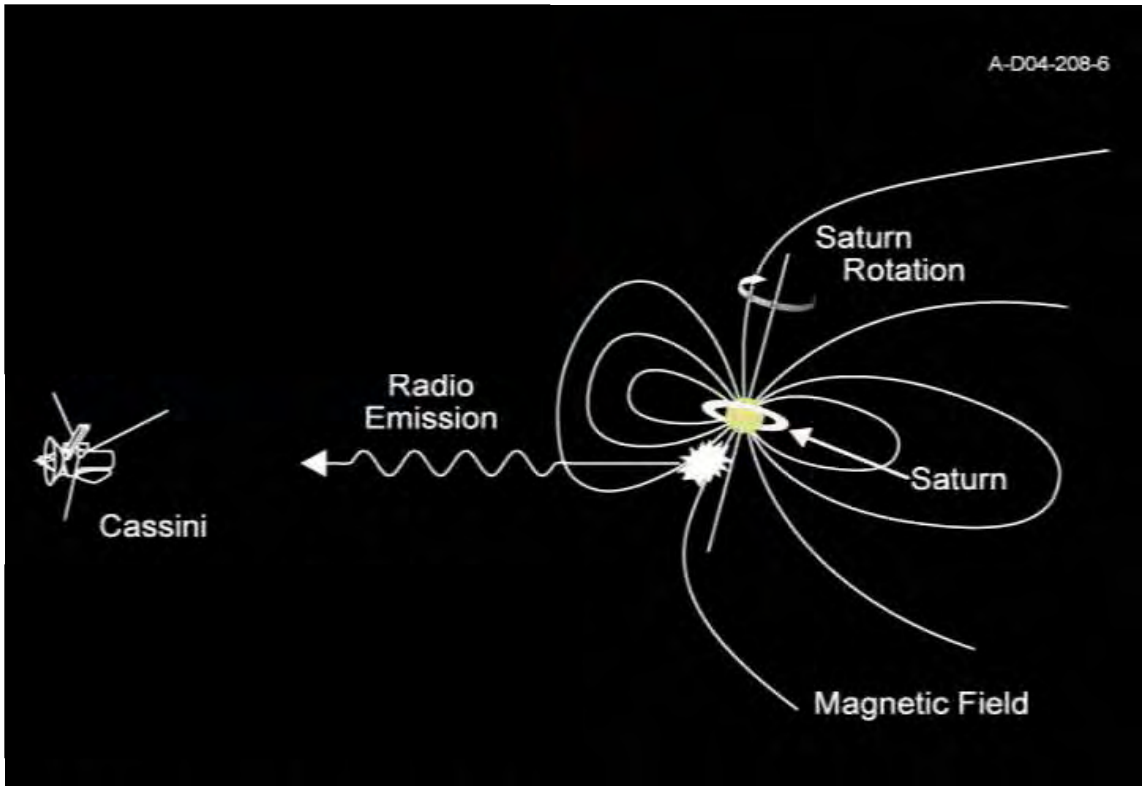
- 3 separate sensors: CHEMS, LEMMS, and INCA
- CHEMS and LEMMS detect energetic charged particles



- INCA images energetic charged particles and neutrals (like IMAGE @ Earth)
- Nominal Energy Ranges:
  - CHEMS: 3<E< 220 keV/q
  - LEMMS front: Ions: 0.3<E< 18 MeV; electrons: 0.015<E<0.884MeV
  - LEMMS back: Ions: 1.6<E< 160 MeV; electrons: 0.1<E<5 MeV
  - INCA: 7 keV/nuc <E< 3 MeV/nuc

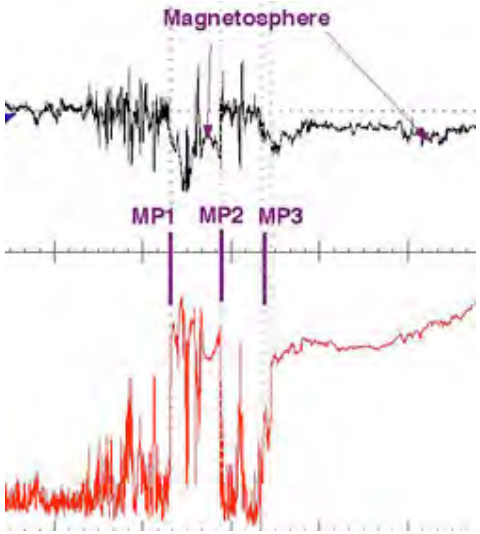
RPWS

Like other remote sensing instruments, RPWS senses signals from a distance.



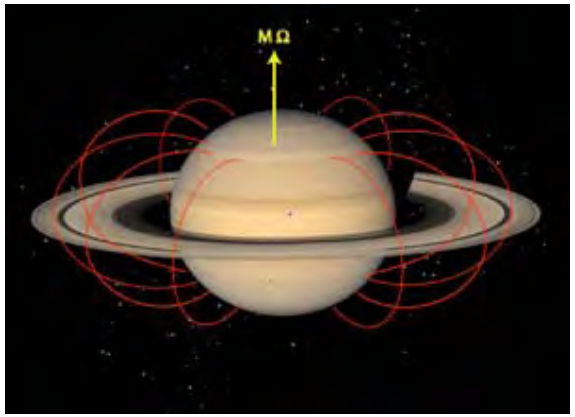
Sound does not travel in space, however since space is filled with an electro-magnetic medium, perturbations of that medium, in the form of radio waves are detected by RPWS.

MAG

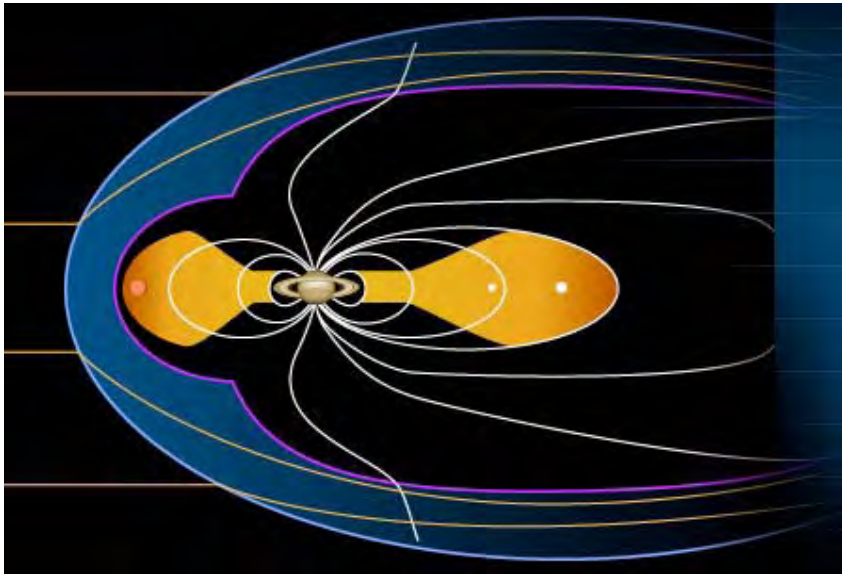


- MAG includes both a flux gate magnetometer and a vector/scalar helium magnetometer. Because magnetometers are sensitive to electric currents and ferrous metal components, they are generally placed on an extended boom, as far from the spacecraft as possible.
- On Cassini, the flux gate magnetometer is located midway out on the 11-meter (36-foot) magnetometer boom extending out from the spacecraft, and the vector/scalar helium magnetometer is located at the end of the boom. The magnetometer electronics are located in a bay in the Cassini orbiter's spacecraft body..
- Samples different wavelengths (frequencies) than RPWS.
  - Like a base instrument compared to a flute - samples different frequencies.

Part 1: Global Morphology



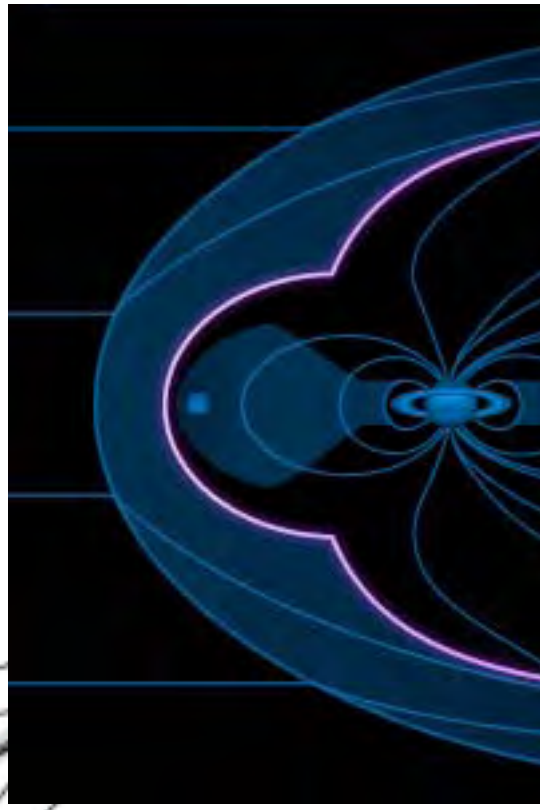
Very simple view



A more complex view, but what do the measurements tell us?

Question #1: Is there a current disc on the dayside?

- Magnetopause crossings, and plasma measurements were used to estimate shape, then to derive the pressure and centrifugal balance as Saturn's magnetosphere holds off the solar wind. [Arridge, et al., 2006a]
- The balance of forces proves that the dayside of Saturn's magnetosphere, indeed, possesses a 'current disc' or 'sheet'
- Centrifugal forces suggest that the current sheet is 'bowed' - like a bowl. [Arridge, et al., 2006b]



S/c rarely sees the PS, as if it is bending away.

Part 1: Global Morphology - Bowl Shape [Arridge, et al., 2006]

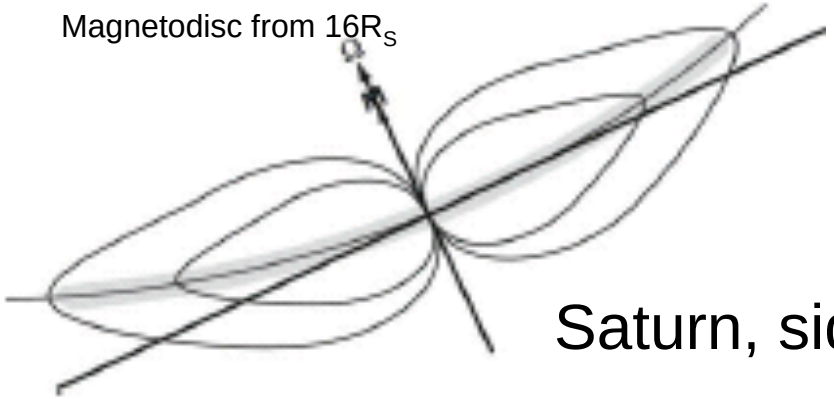
Saturn Result + background

•The thin current sheets observed by CASS have been described as magnetodisc current sheets + magneto-tail currents.
•One tenth the current of the mighty Jovian current disc, where centrifugal stresses are dominant
•The Jovian magneto-disc is the site of plasma storage, transport, and magnetic reconnection (we'll discuss these things starting on page X). What of Saturn?

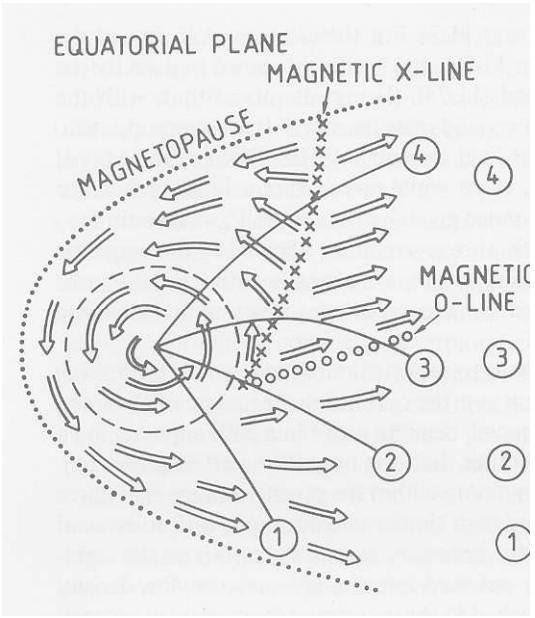
Dipolar to $4R_S$

Quasi- Dipolar from $4R_S$ to $16R_S$

Magnetodisc from $16R_S$



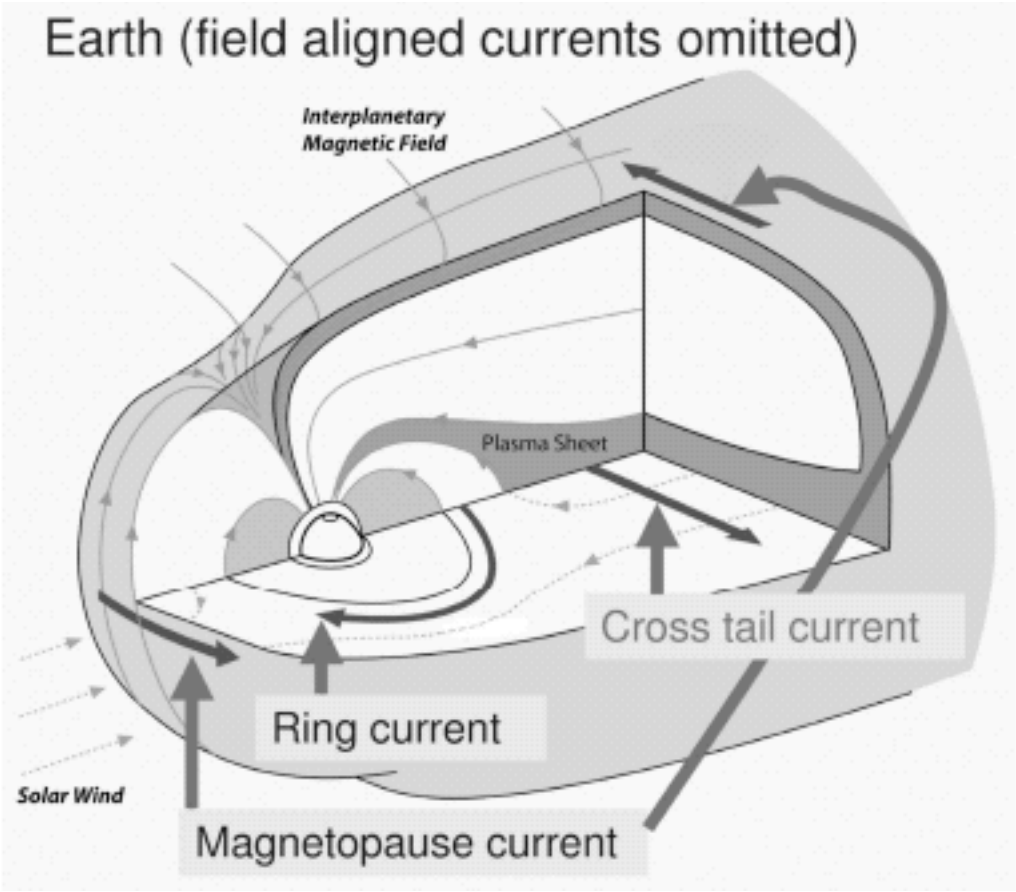
Saturn, side view



Jupiter, top view

Earth Global Magnetospheric Current System

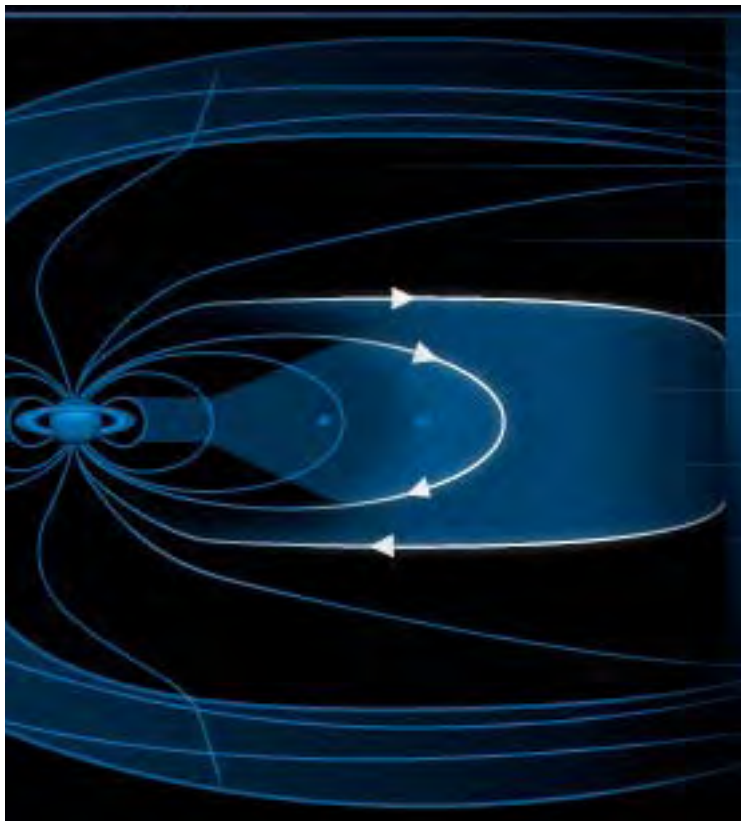
- Earth does not have a current ‘disc’, but a cute little ‘ring current’ (very pastoral).
- Note: Centrifugal forces are minimal- particles drift, frozen onto magnetic field lines
- Note: The ring current, carried by energetic particles, has no direct analog at Jupiter.



Currents in the terrestrial magnetosphere, Khurana, 2004.

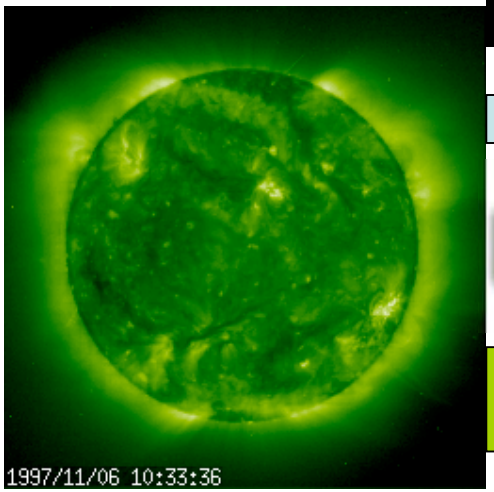
Part 2: Global Morphology, tail

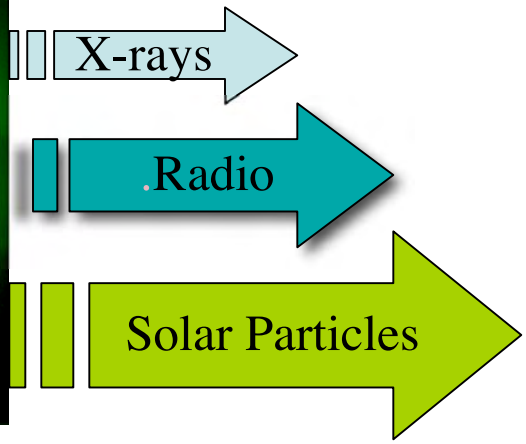
Question #2:
How is the Tail formed?
Via solar wind interaction, or planetary wind?



Terrestrial Space Weather

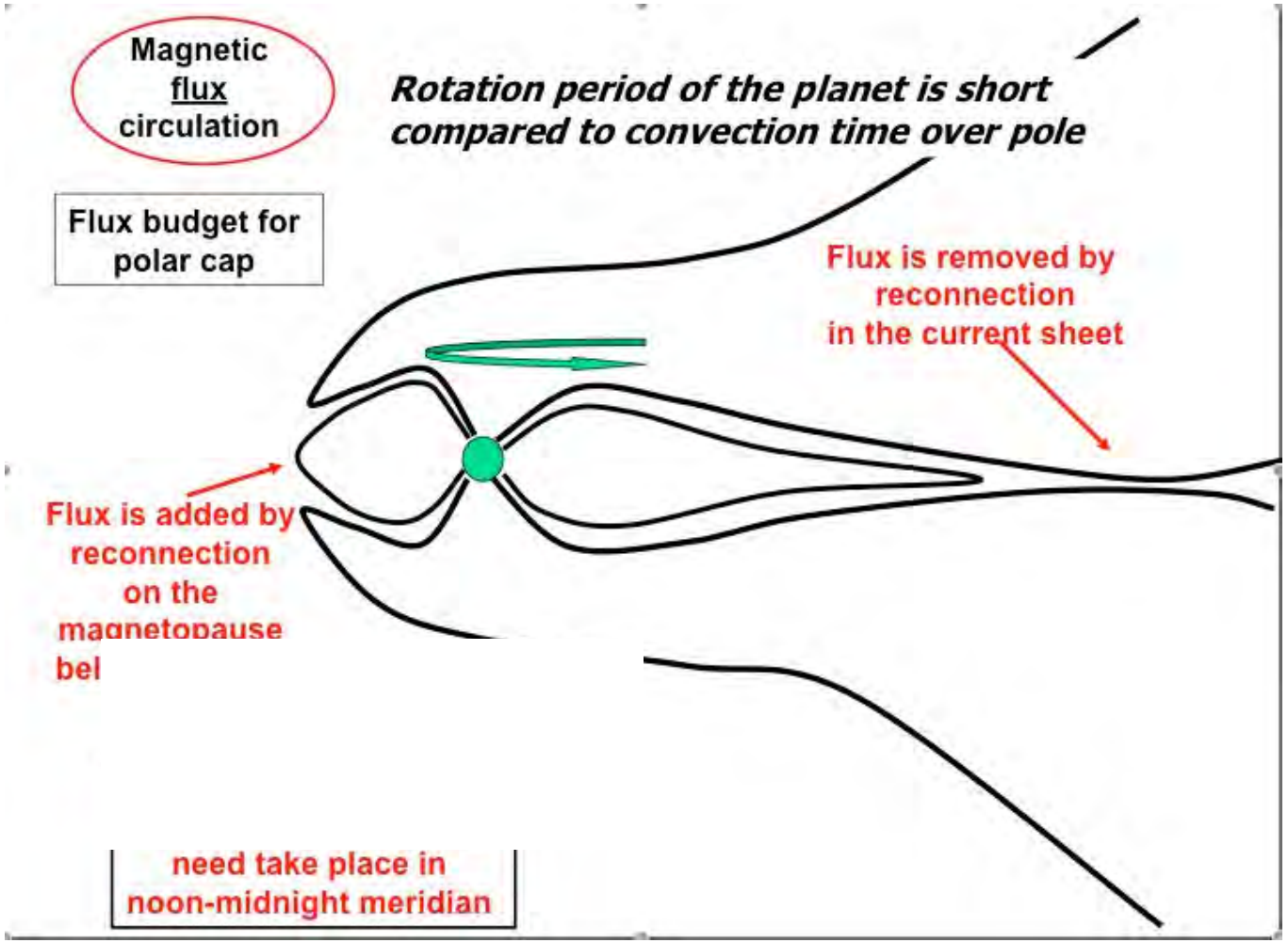
- **Signal light reflects the general level of space weather disturbance (measured near Earth.)**





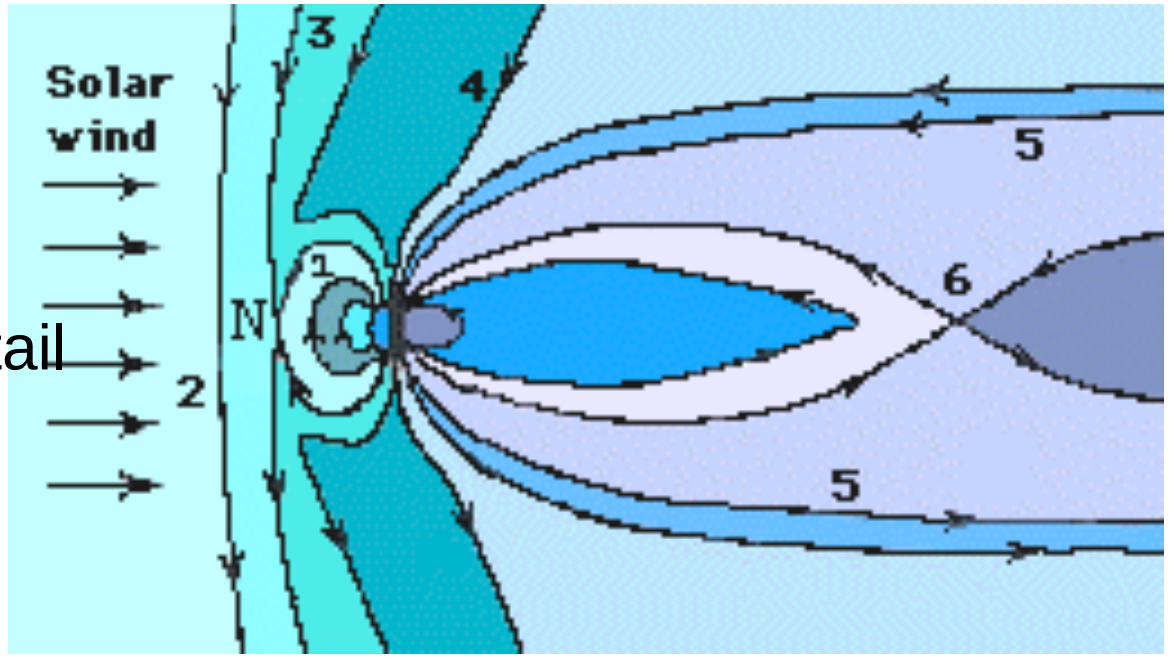
Earth: Basic Plasma Convection & Magneto-tail formation

note: an empty tail cavity does not mean a magnetotail is present



Earth tail formation driven by: Sun/Earth interaction

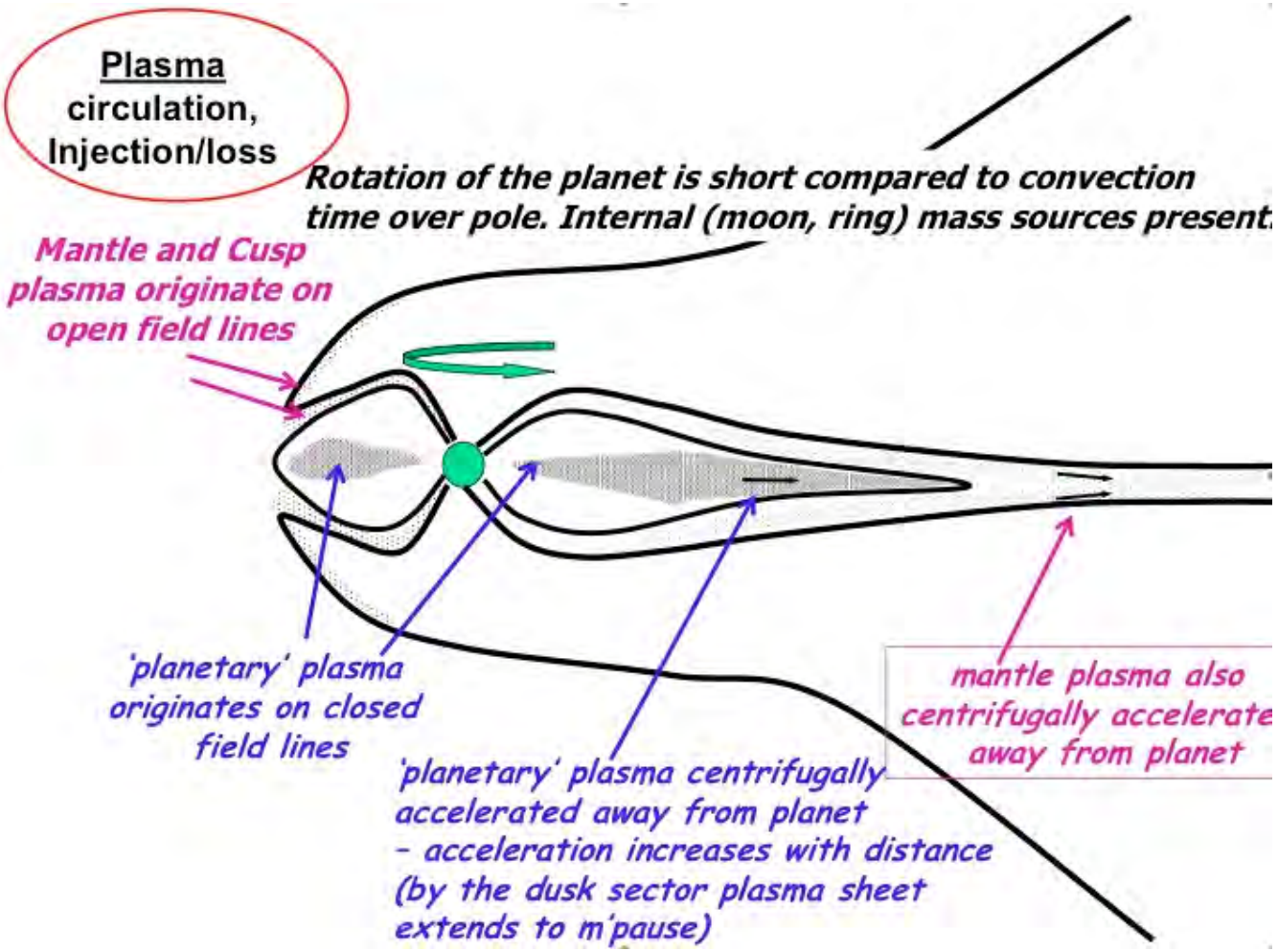
- This is the 'Dungey' model of the Earth's magnetosphere
- In which the magnetotail stretches out and an 'X'-line is formed deep into the tail [range = 50 R_E?]; Earth's moon is at 60 R_E
- The X-line moves in response to the solar wind pressure on any given day.



Dungey model

Other planet convection: Saturn?

(Magneto-tail formation & circulation for giant planets where centrifugal forces are important)



What constitutes a Magnetotail?

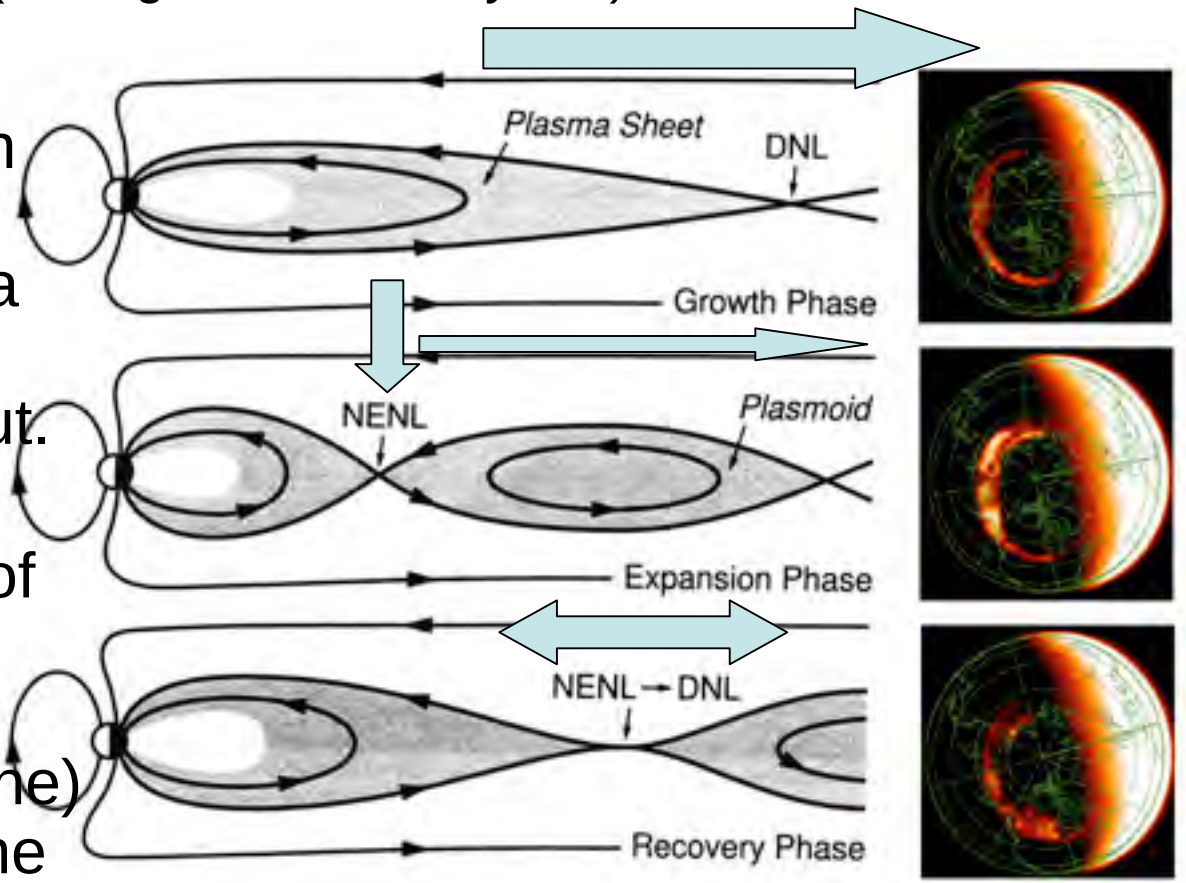
An asymmetrical cavity is not a magnetotail.

- A magnetotail carries a current in the middle
- Earth: formed via solar wind interaction (Dungey-style circulation)
- Jupiter: formed via planetary wind

Active Sun/Earth interaction *Background*

(adding flux to the dayside)

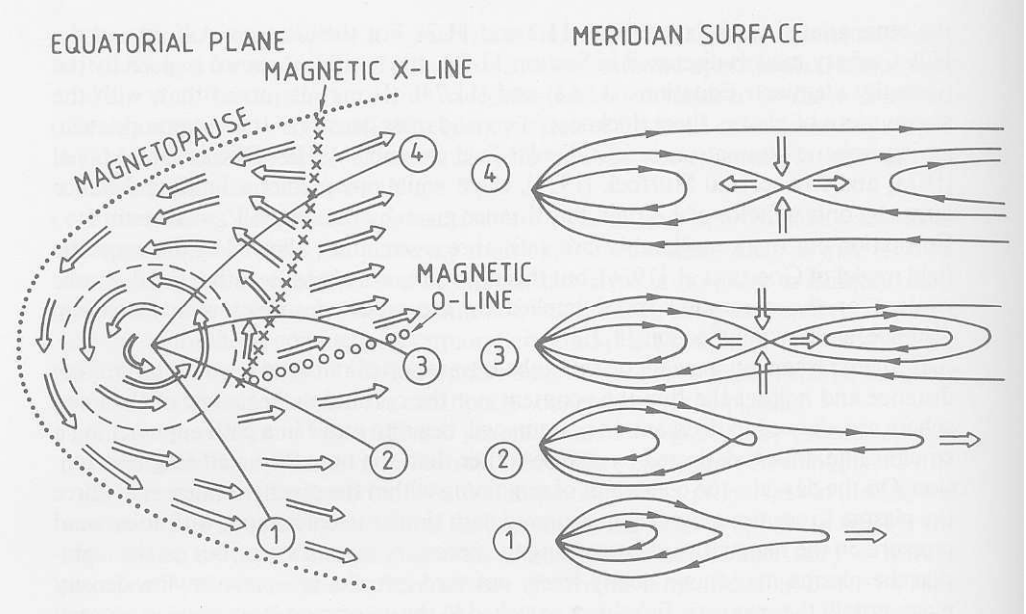
- Panel 1: the 'Growth Phase' of the magnetotail during a geomagnetic storm. The tail stretches out.
- Panel 2: the 'Expansion'' phase of the storm activity. A NENL - Near Earth Neutral Line (or X-line) is formed close to the earth. It them moves deeper into the magnetotail.



- Panel 3: the 'Recovery Phase'. Here the NENL moves to where the DNL was before it all started. (Which means that 'stuff' is moving down the tail, toward the moon).

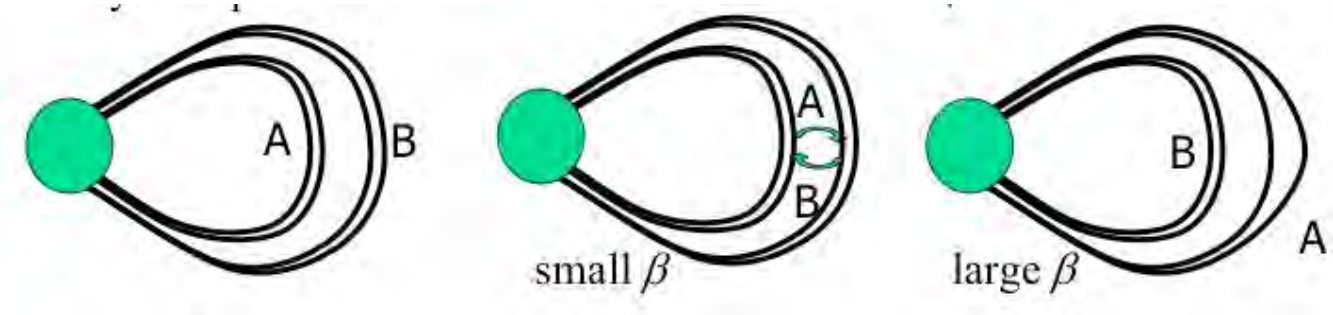
Jupiter: Where Corotation Dominates

- Rather than a ‘Dungey’-type interaction, Jupiter exhibits a complicated morphology, with shredding of the magnetodisc on the dusk side. [Vasyliunas]



Interchange Instability

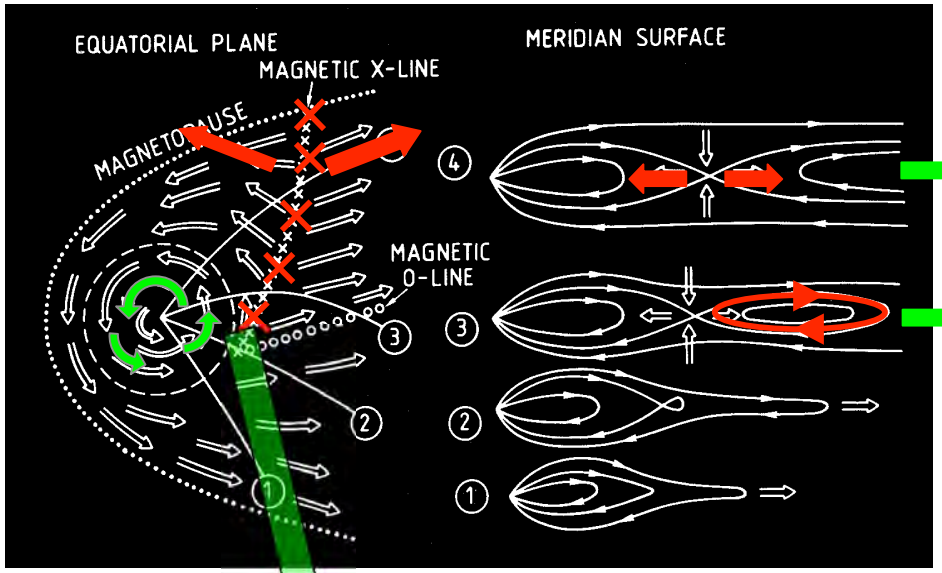
- 'Flux tubes' serve as a physical mechanism for transporting plasma.

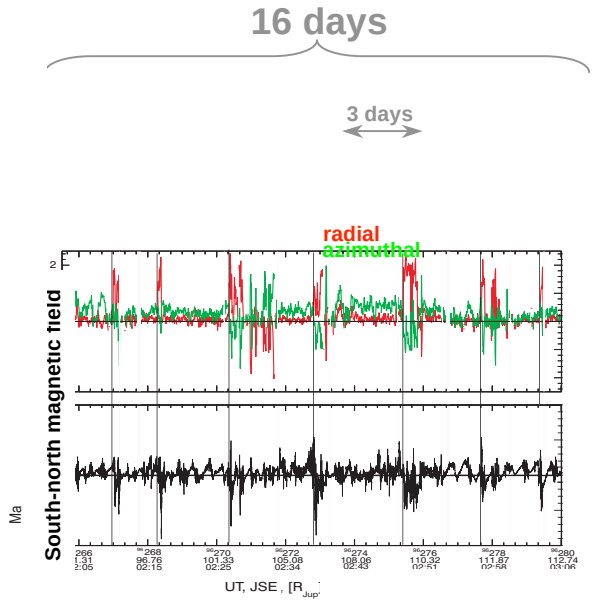


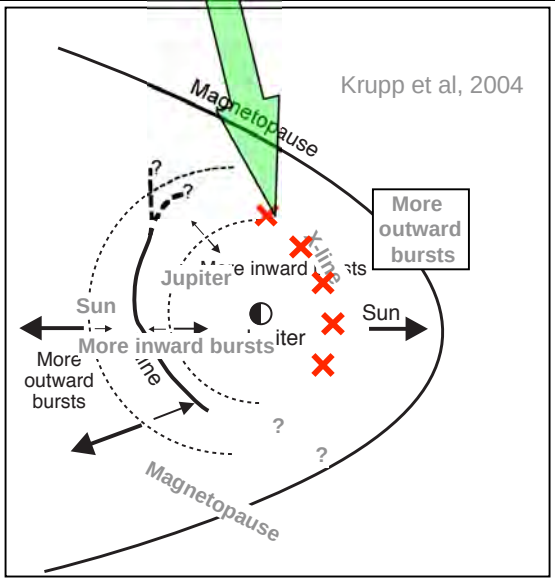
Schematic of currents flowing radially in the equatorial plane and closing in the ionosphere. Hill, 1979.

- Jupiter: flux tube interchange mechanism is an important way to carry plasma generated at Io downstream.
- Saturn: Saw similar phenomena near Dione.

Energetic particle flow & the Jovian magnetotail







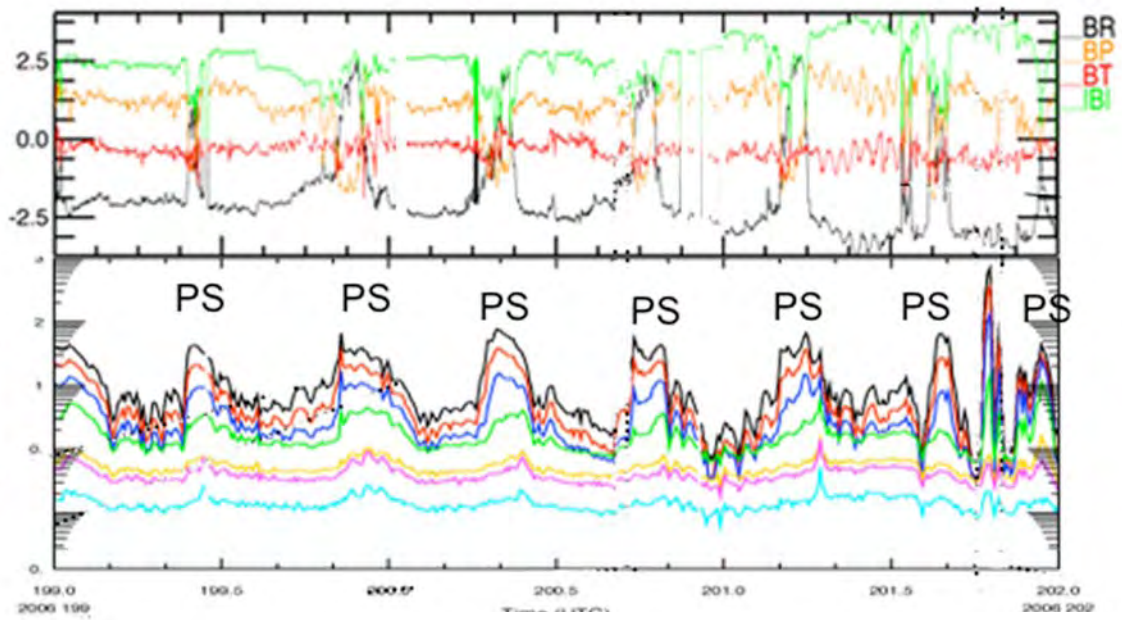
1.) Energetic particle flow bursts were instrumental in diagnosing the dynamics of the Jovian magnetotail with the GLL MIMI analog instrument

2.) Transient *periodical disturbances with repetition period of several days* (the most characteristic 2-3 days) were observed in the Jovian magnetotail.

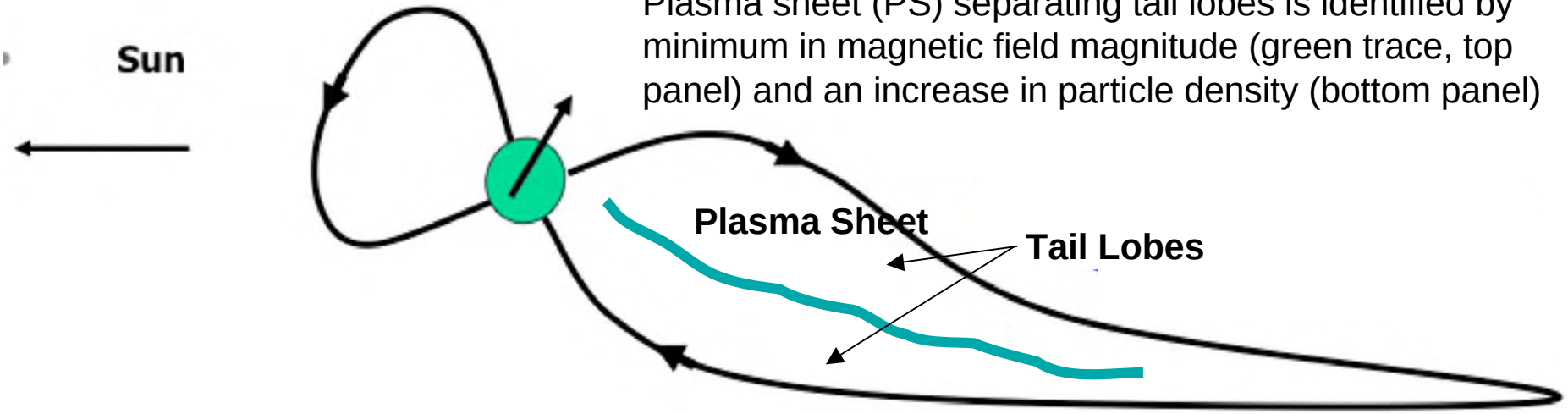
implies plasma is being released down the tail on those timescales.

Saturn Conundrum

- Though the rotational axis and the dipole axis are aligned, Saturn's rotational axis is tiled with respect to the ecliptic.
- Figure shows an example of MAG and MIMI data from a recent tail pass
- Spacecraft (s/c) will be above then below the plasma sheet (PS). So the plasma sheet will 'beat' past the s/c.



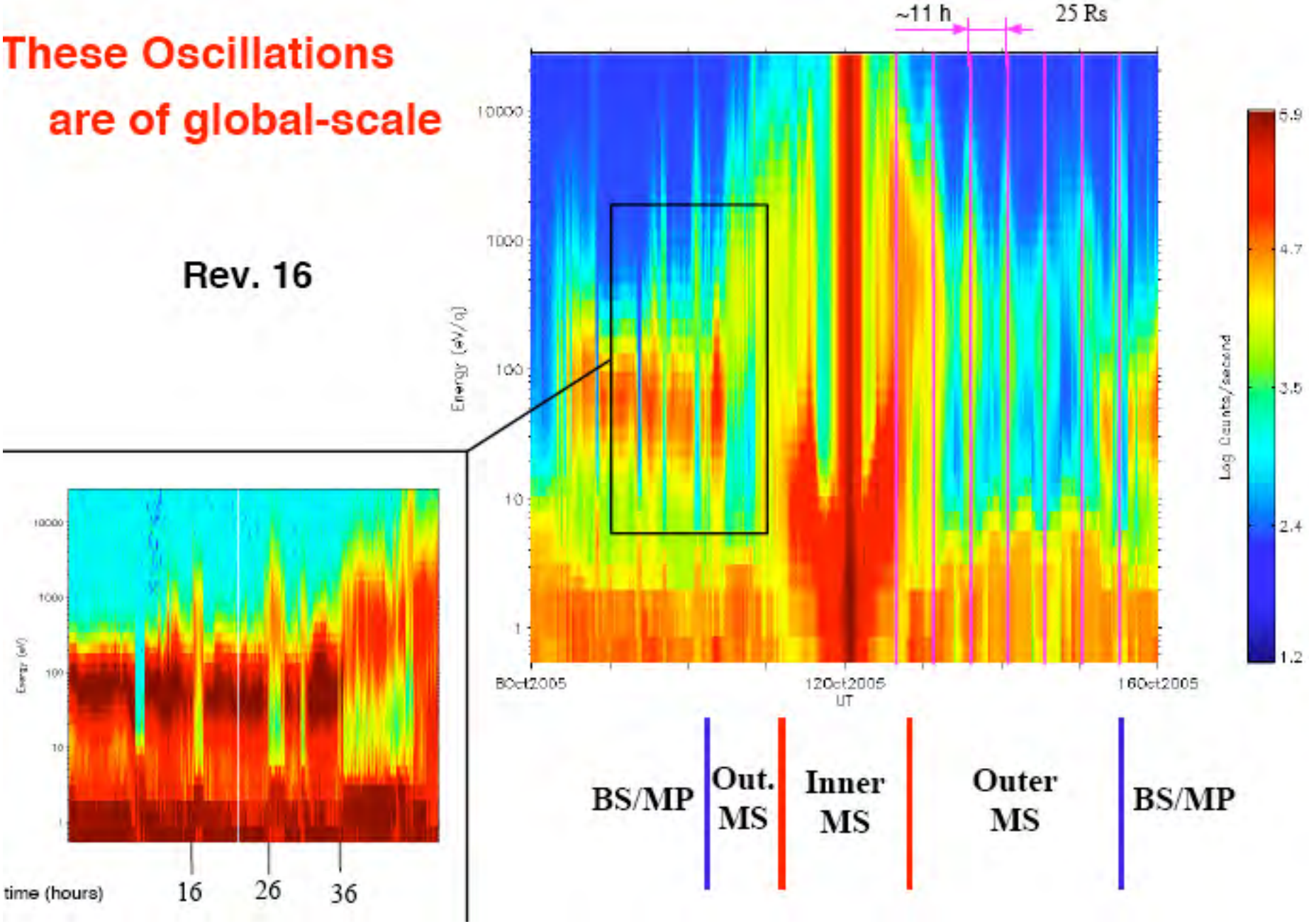
Plasma sheet (PS) separating tail lobes is identified by minimum in magnetic field magnitude (green trace, top panel) and an increase in particle density (bottom panel)



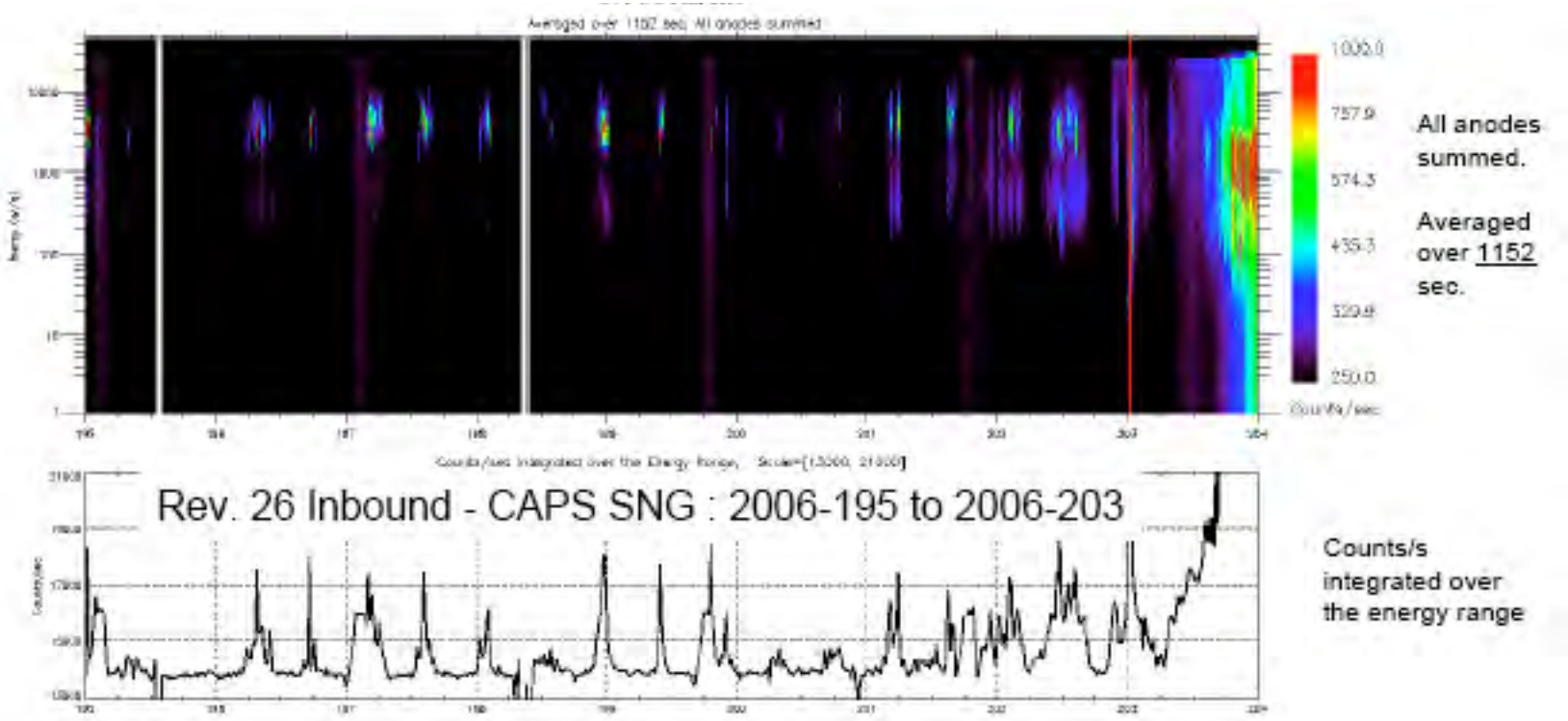
Planetary Period Oscillations in Saturn's Magnetosphere (MIMI)

Saturn Result

Clarke. et al.. GRL. in press



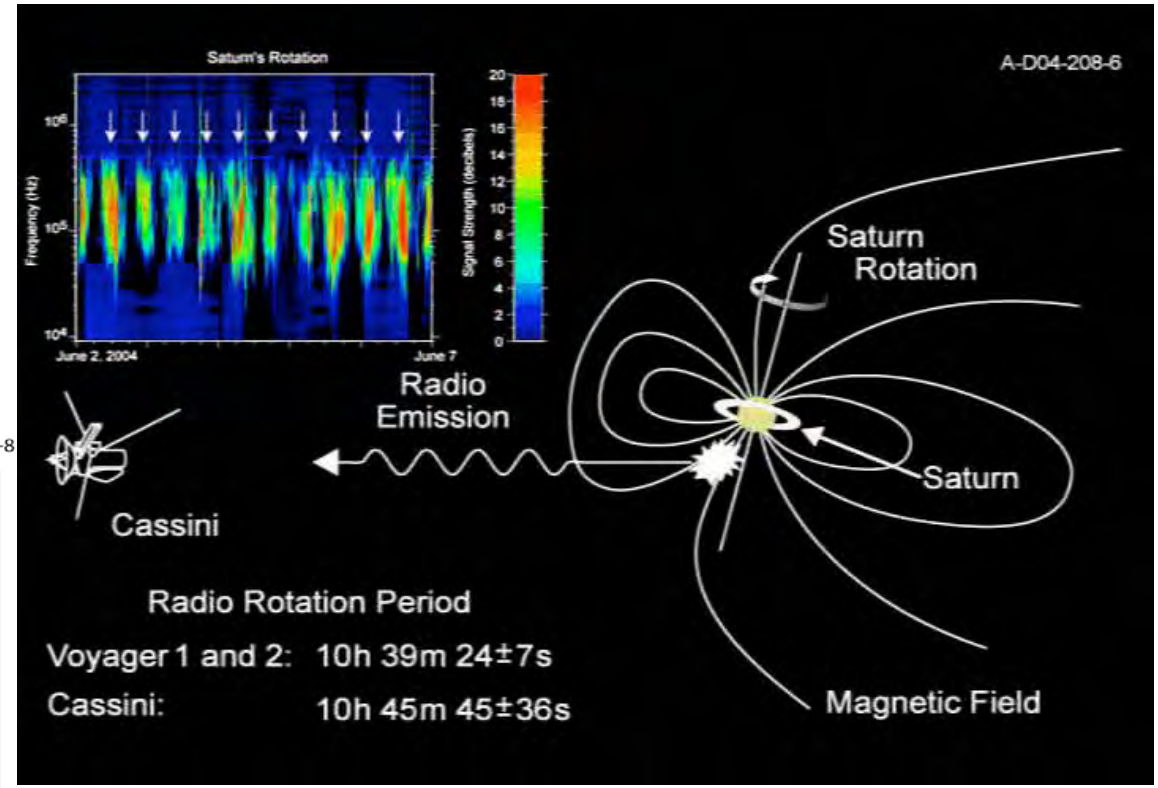
CAPS - Rotational Modulation of Ion Fluxes

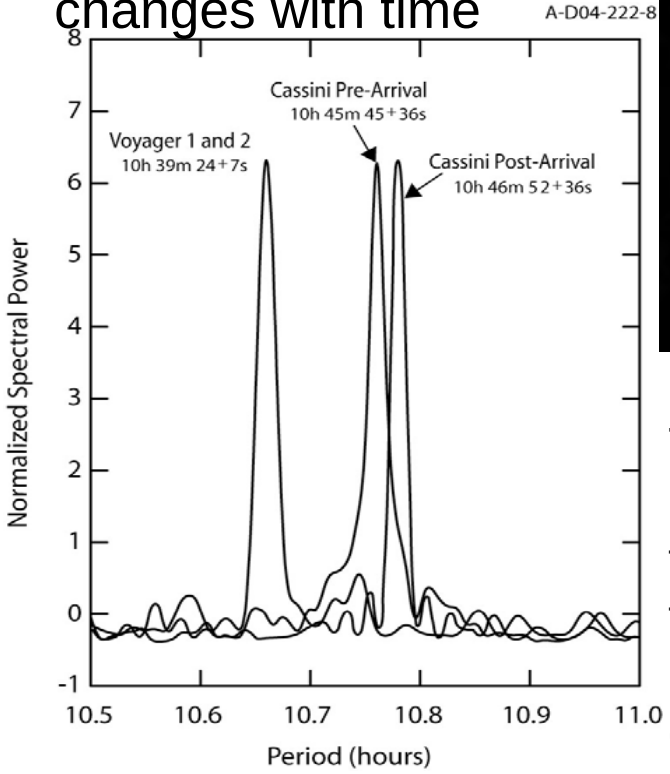


- Spectrograms (upper panet) show the modulation in ion fluxes in the magnetosphere at Saturn's rotational period of 10h 40m. Summation of ion energies (lower panel) also show the periodicity. Radial distance in the figure ranges from 48 Rs to 12 Rs

These modulations are not explained by the periodicity that RPWS measures

- IAU longitude system cannot be used to organize the data
- SKR drifts in longitude and time and the rate of drift changes with time





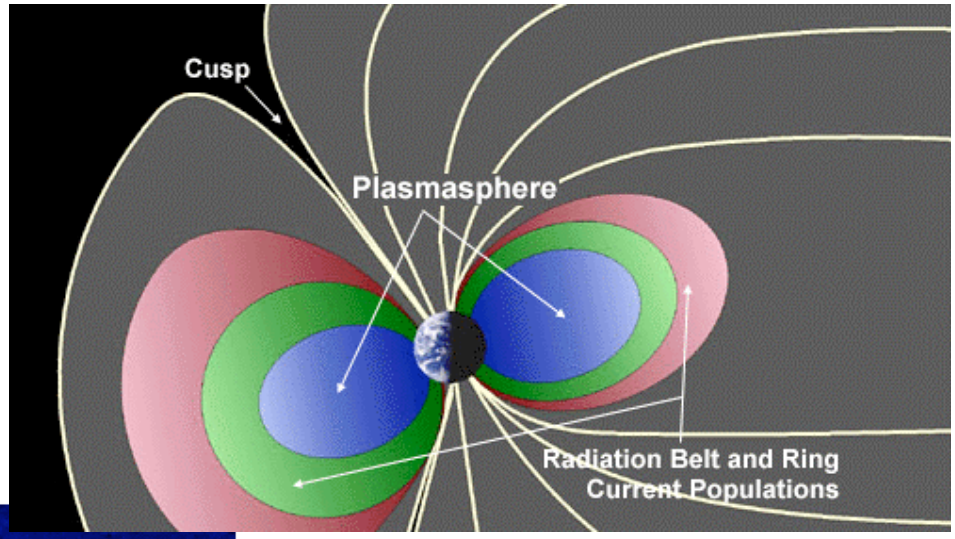
Cassini has found a different radio period than Voyager. The radio period is usually used to determine the rotation period of gas giant planets. A major mystery for Cassini to solve is the reason for the variation of the radio period. Once this mystery is solved, it will be possible to accurately determine the rotation period of the deep interior of Saturn.

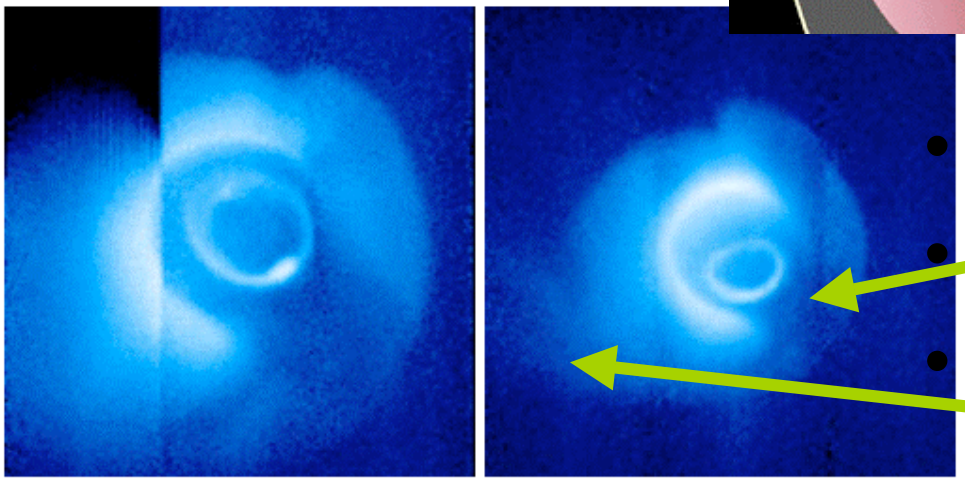
Question # 4: How do we reconstruct the basic pattern of flow within Saturn's magnetosphere? Looking for injections

- *Magnetometer - magnetic field perturbations indicating current*
- *Particle instruments - CAPS, MIMI - particle distribution functions: pancake, butterfly, & others*
- *Plasma wave signatures: SKR, etc.*

EUV “Images” of the Earth’s Plasmasphere

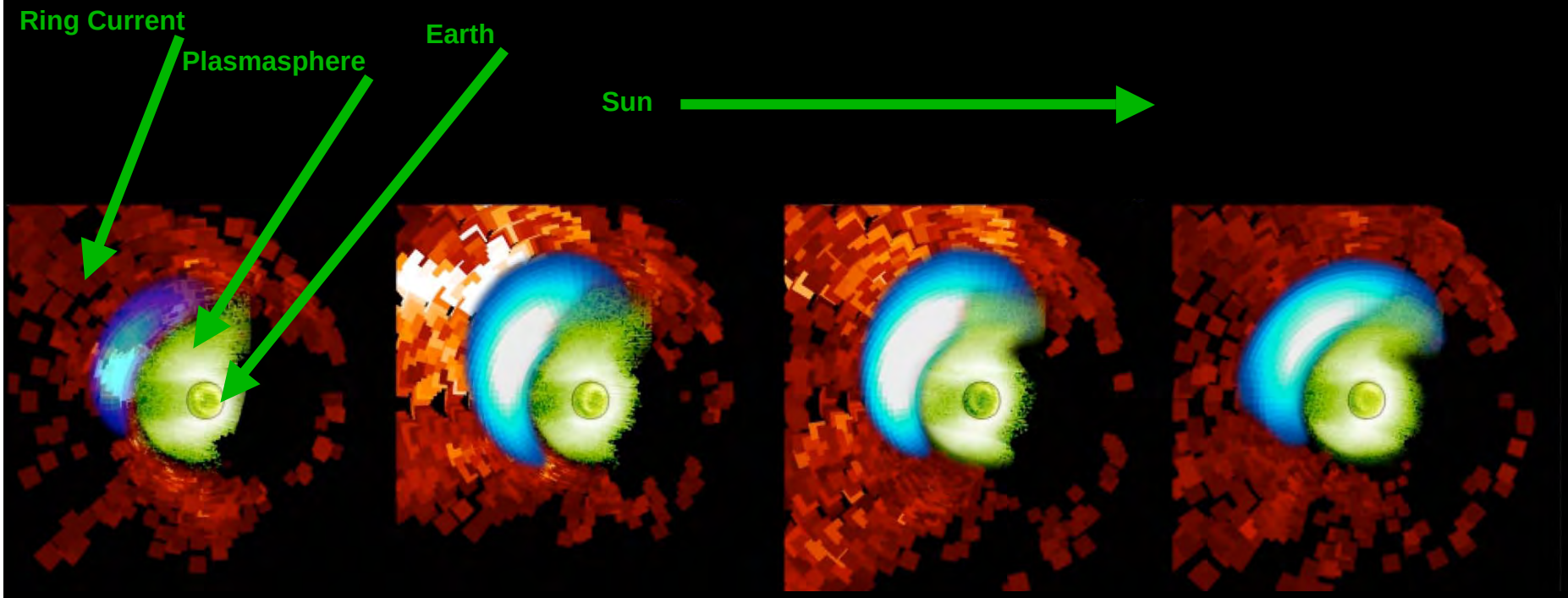
- Right: a schematic
- Left: actual images of the Earth; the surrounding particles; aurora at the pole.





- Sun at upper left.
- Earth’s shadow
- Plasmaspheric particles middle left.

From the IMAGE s/c



Panel 1:
nominal plasmasphere

Panel 2:
Ring current brightening as energetic particles from the tail impinge on the nightside of the Earth.

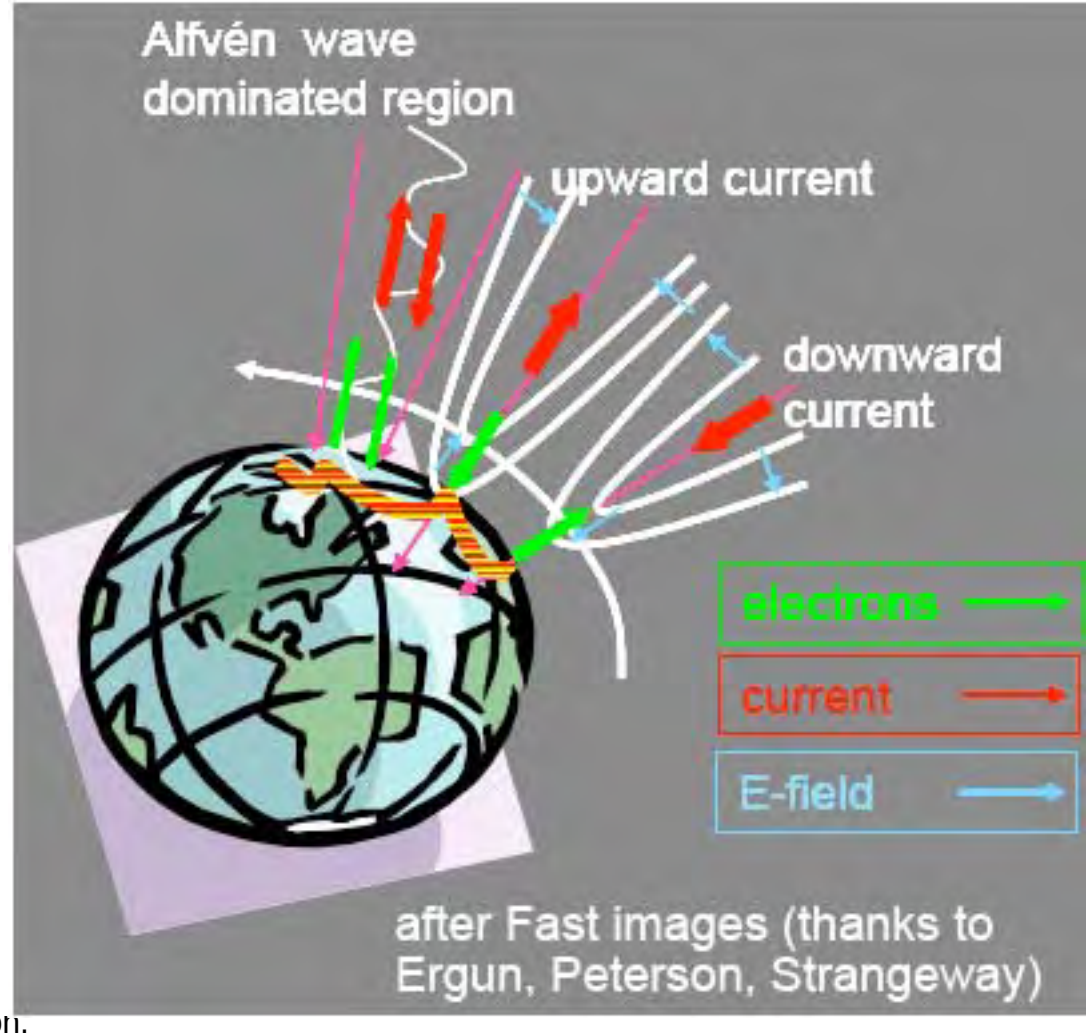
Panel 3:
Plasmasphere grows as the ring current particles are injected into it

Panel 4:
Plasmaspheric loss occurs as particles precipitate and rain out through the auroral zone.

Particle injection results in Aurora (at Earth)

seen on the nightside, particles are coming from the tail

- Typical Geo-magnetic sub-storm, as pictured on last page = 150 G Watts
- Los Angeles municipal burden = 280 M Watts
- So, a substorm is the equivalent of 100 large cities
  - Assuming the municipal ‘burden’ is 10% of the total population



Structure of currents and fields in the auroral region. Pink represents magnetic field direction.

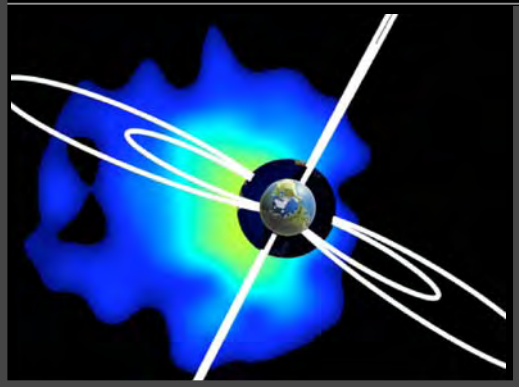
Universal processes of transport and loss of plasma

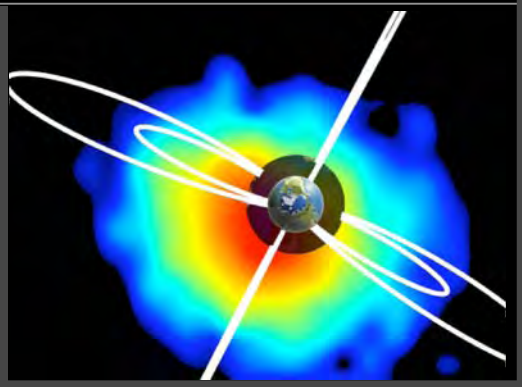
- IMAGE HENA: Energization and injection of oxygen by substorm
- Cassini INCA: Similar global behavior observed at Saturn.
- Identification facilitated by experience with terrestrial ENA observations.

SUBSTORMS

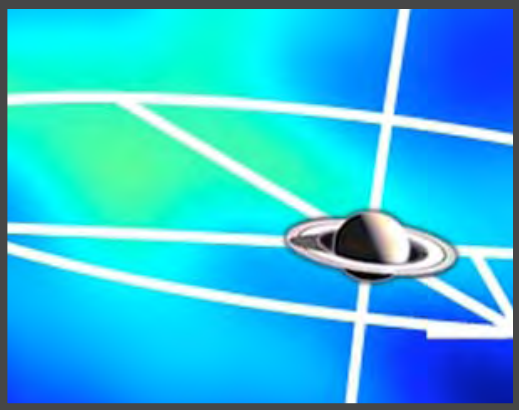
Sudden brightening of oxygen ENAs (Energetic Neutral Atoms) indicates substorm energization

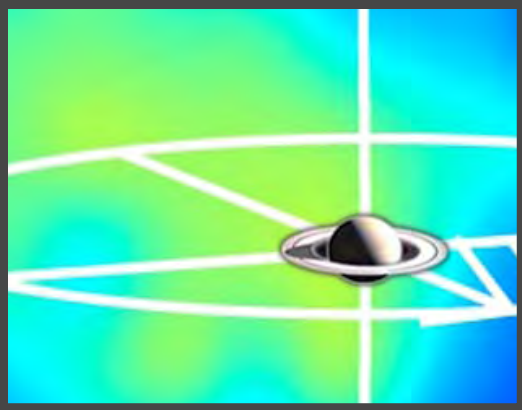
EARTH



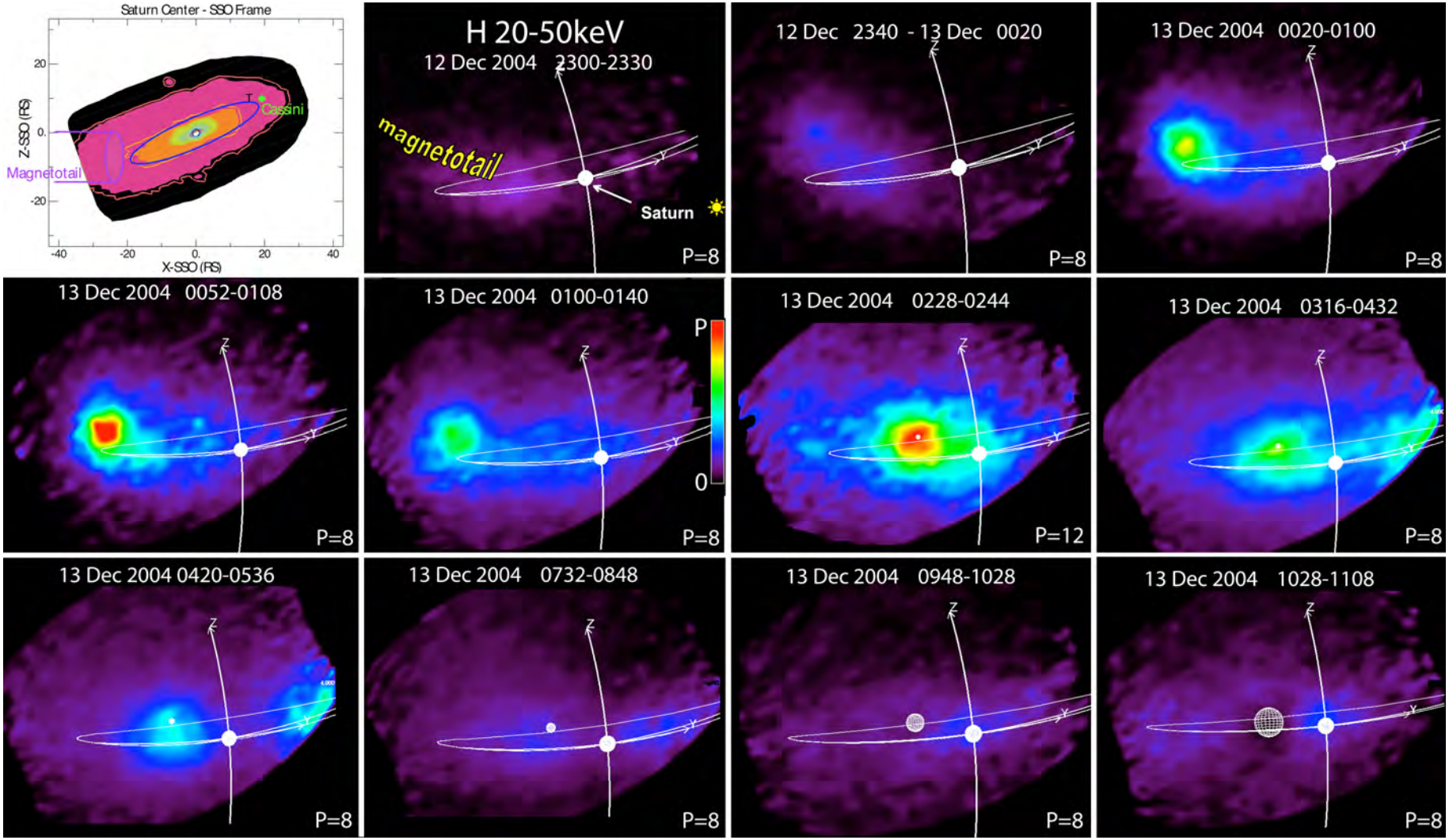


SATURN

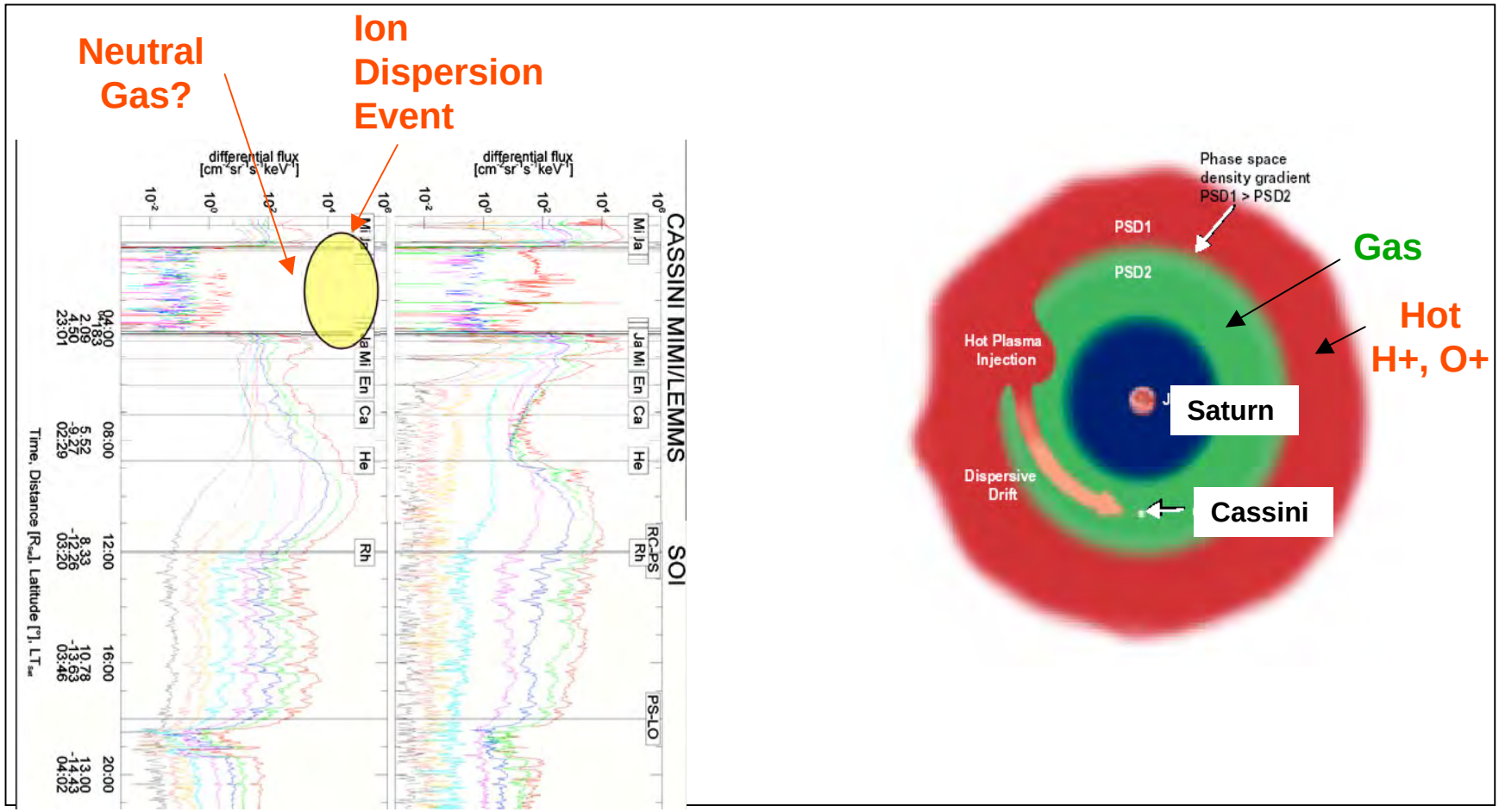




MIMI data show evidence of plasma injection from the tail



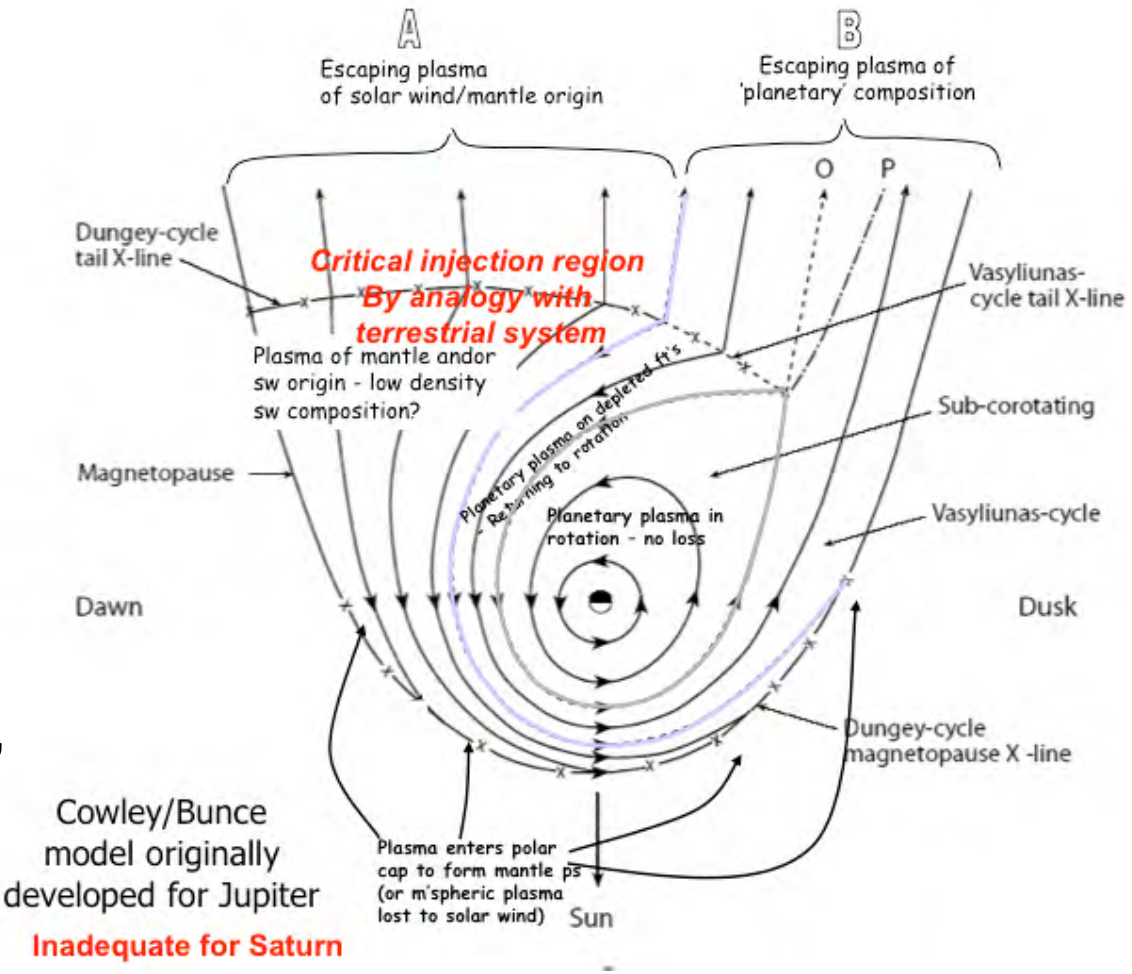
Saturn‘s Ion Injection Events



- **Plasma is injected into neutral gas,**
- **charged particles drift around the planet and reach the spacecraft at at different times**

Plasma Injection & Saturn

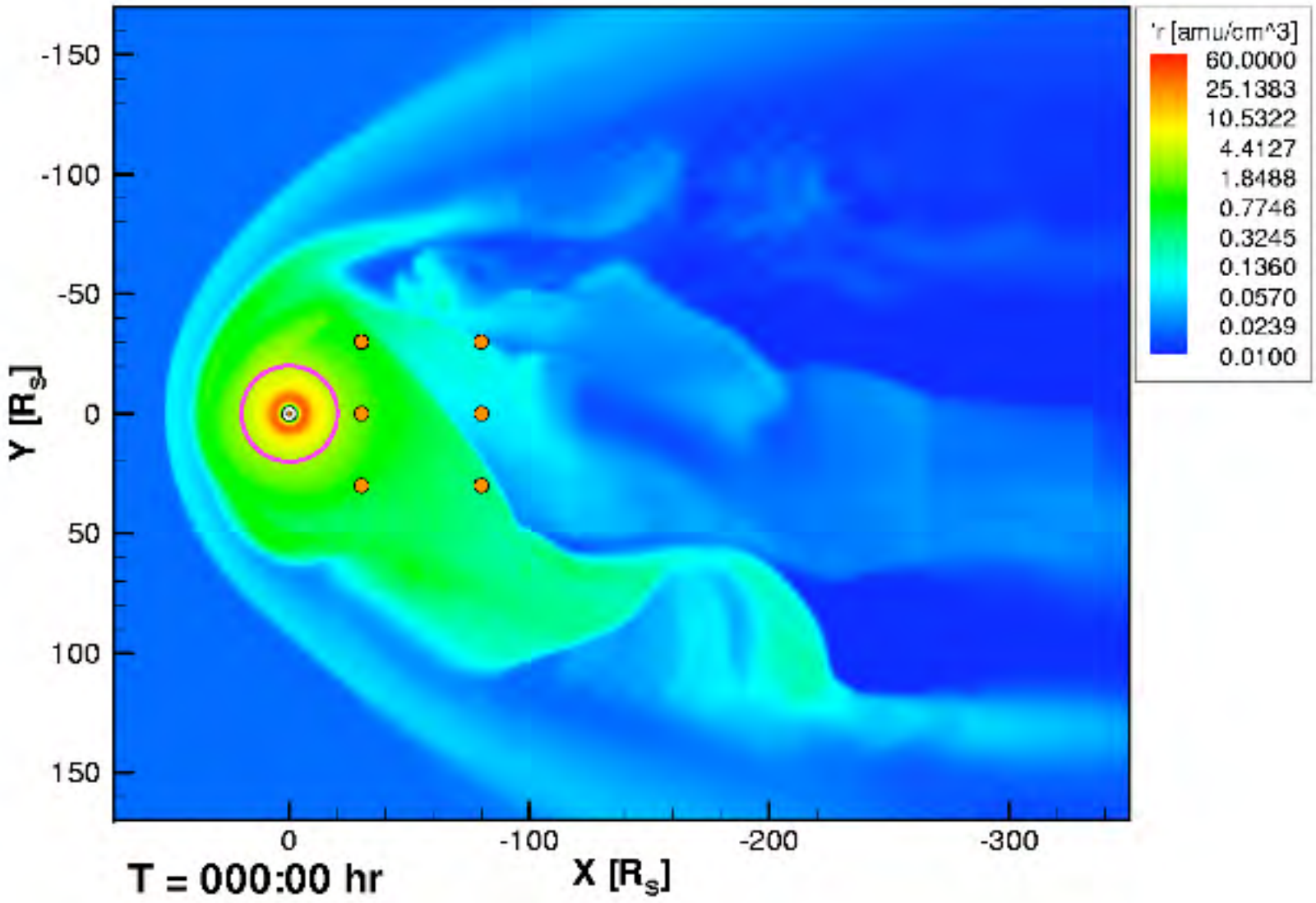
- This figure shows the derived injection for Jupiter
- Doesn't work for Saturn
  - There have been three 'dipolarization events'
    - Aug 4, 2006
    - July 12, 2006
    - March 4, 2006
  - Two of these corresponded with northward turning of IMF
- Implies that, like Jupiter, angular momentum seems to play a role, but, like Earth, there may be significant changes introduced by field lines open to the solar wind.



This simulation shows that Saturn (may) shed on the dawn side

Background

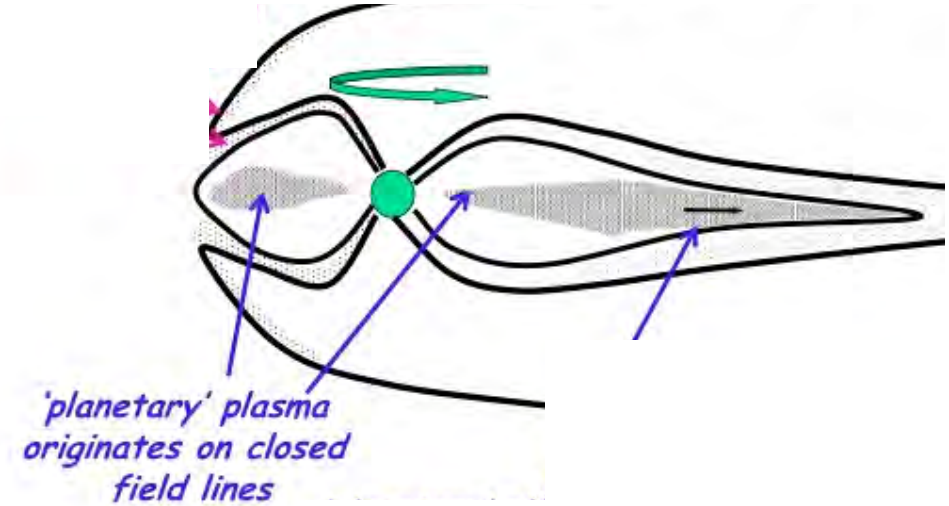
(looking down from the top)



Plasma injection & circulation for Saturn

Summary

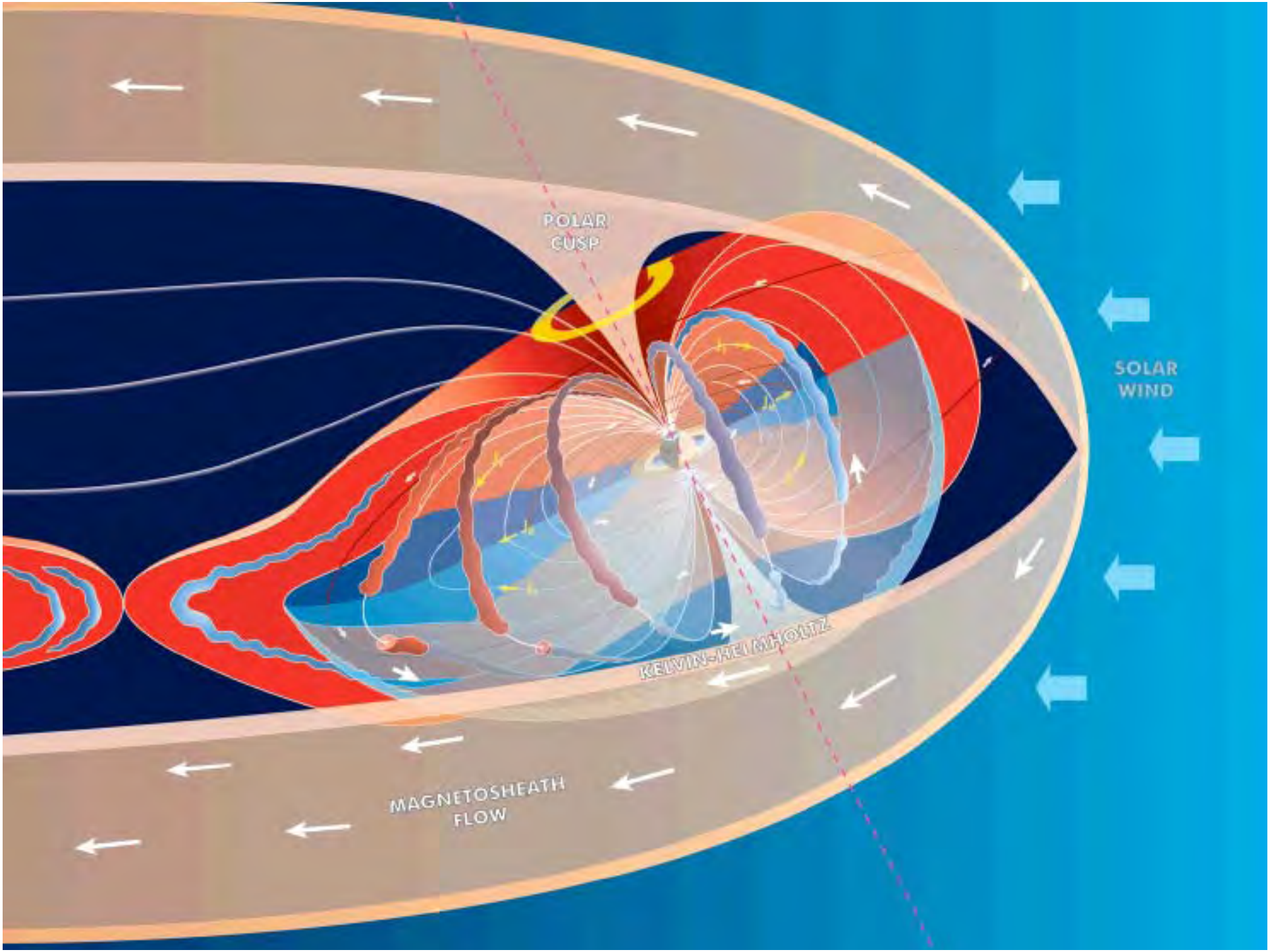
- Is there a tail?
  - Jury out
- Substorms
  - Jury out
- Dayside current sheet that interacts with the aurora?
  - Yes
- Hinged tail current sheet?
  - Yes
- Are we seeing X-lines?
  - Jury out

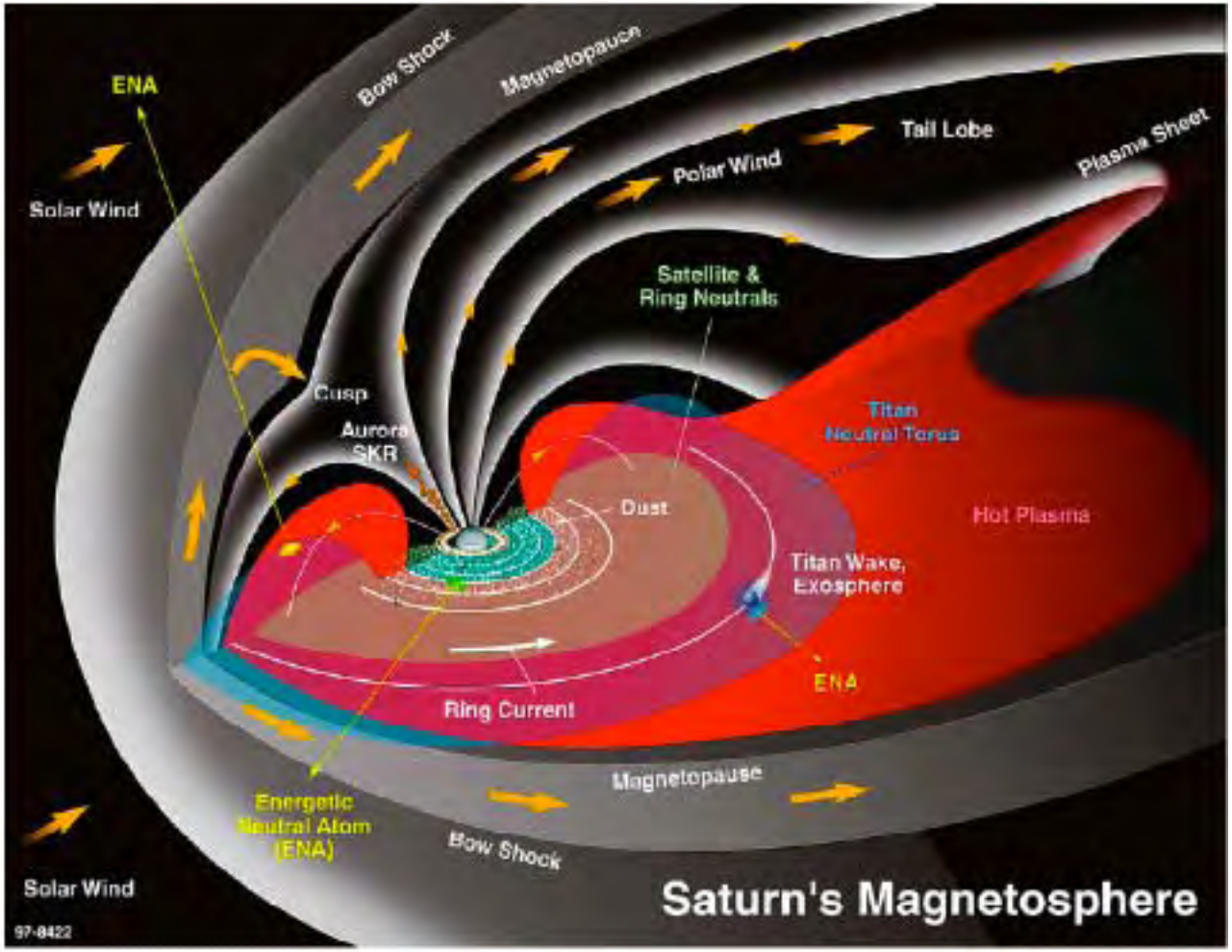


What constitutes a Magnetotail?

An asymmetrical cavity is not a magnetotail.

- A magnetotail carries a current in the middle
- Earth: formed via solar wind interaction (Dungey-style circulation)
- Jupiter: formed via planetary wind
- Saturn: ? No concensus yet, through a central current sheet is quite clearly present. It depends, in part, upon the amount of flux going over the poles.


POLAR
CUSP
SOLAR
WIND
KELVIN-HELMHOLTZ
MAGNETOSHEATH
FLOW


ENA
Bow Shock
Magnetopause
Solar Wind
Polar Wind
Tail Lobe
Plasma Sheet
Satellite &
Ring Neutrals
Cusp
Aurora
SKR
Titan
Neutral Torus
Dust
Hot Plasma
Titan Wake,
Exosphere
ENA
Ring Current
Magnetopause
Energetic
Neutral Atom
(ENA)
Bow Shock
Solar Wind
Saturn's Magnetosphere
97-8422