Saturn's magnetosphere after the Cassini

~ Works related to RPWS/LP ~

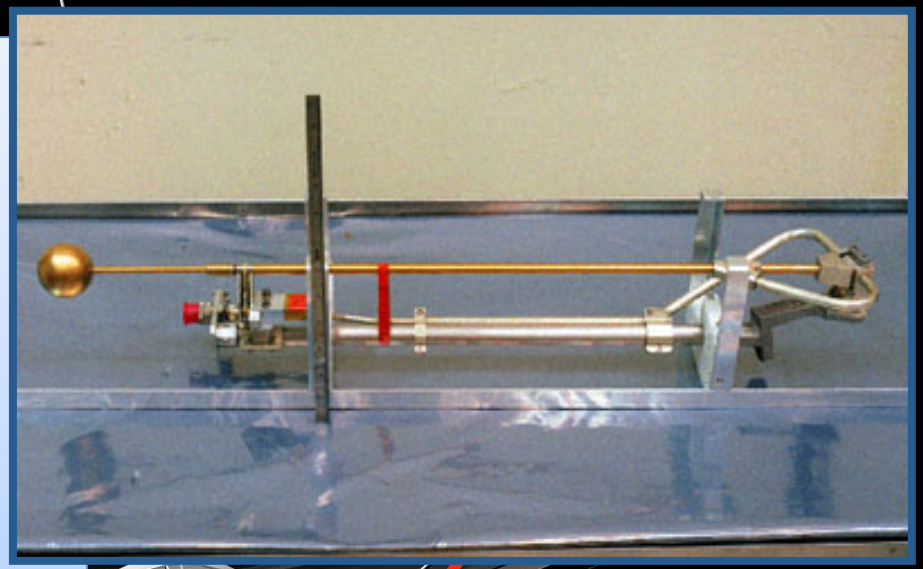
M. W. Morooka[1] , J.-E. Wahlund[2],
M. K. G. Holmberg[2], O. Shebanis[2], and E. Odanaka[1]
(1) PPARC, Tohoku University, (2) IRF Uppsala

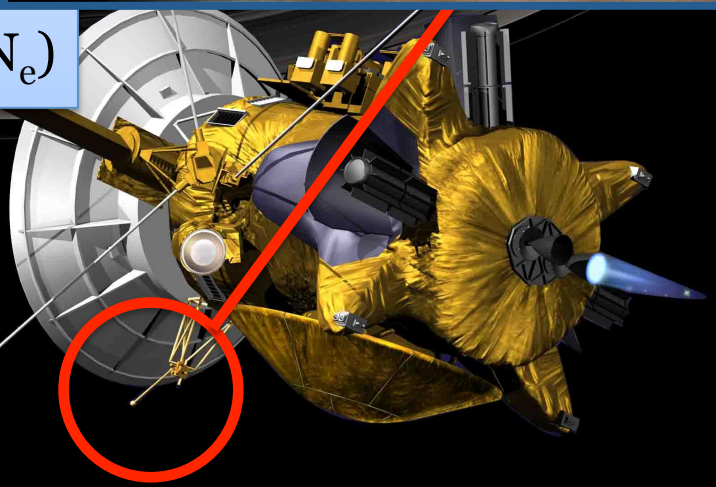
Radio and Plasma Wave Science/Langmuir Probe

Cassini RPWS/LP

Langmuir Probe (LP)

- ✓TiN coated sensor (5 cm)
- ✓Cold Plasma
  - •Number density (N_e, N_i)
  - •Temperature (T_e)
  - •Ion drift speed (V_{di})
  - •Spacecraft (dust) potential (U_{SC})
- ✓Electron density in tenuous plasma (N_e)





Radio and Plasma Wave Science/Langmuir Probe

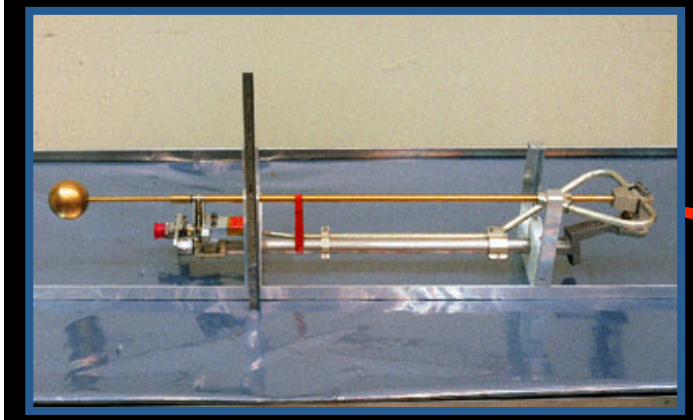
Cassini RPWS/LP

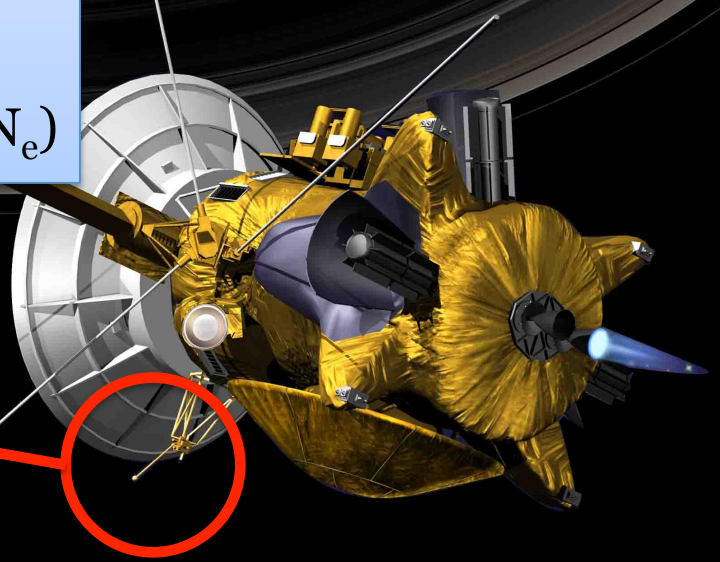
Langmuir Probe (LP)

- ✓TiN coated sensor (5 cm)
- ✓Cold Plasma
  - •Number density (N_e, N_i)
  - •Temperature (T_e)
  - •Ion drift speed (V_{di})
  - •Spacecraft (dust) potential (U_{SC})
- ✓Electron density in tenuous plasma (N_e)

LP Science

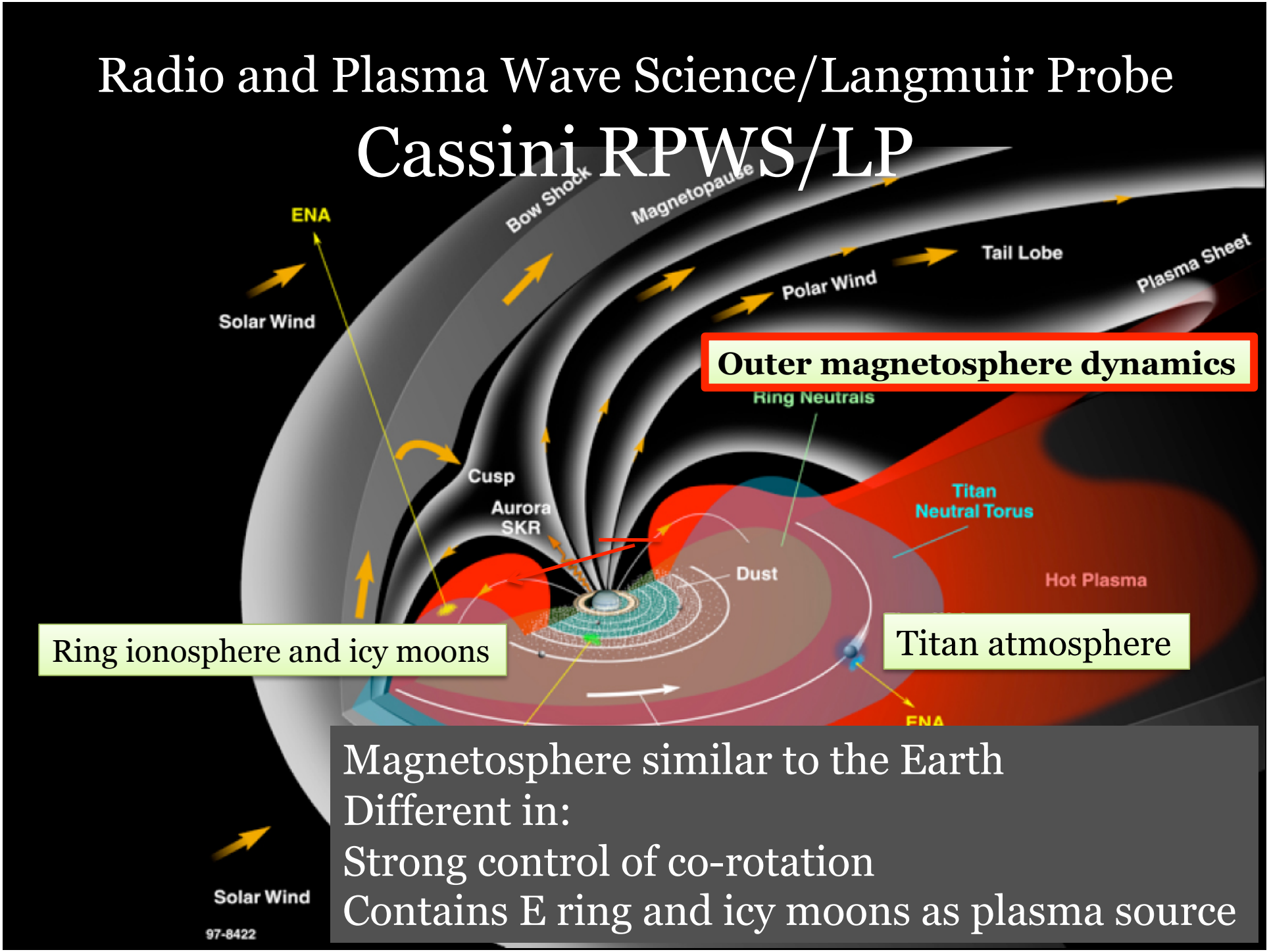
- **Titan atmosphere**
- **Ring ionosphere and icy moons**
- **Outer magnetosphere dynamics**





Radio and Plasma Wave Science/Langmuir Probe

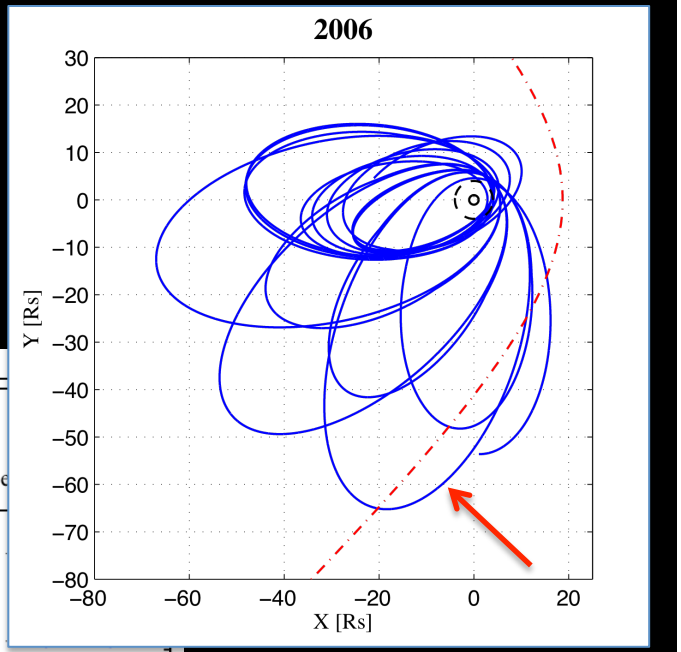
Cassini RPWS/LP

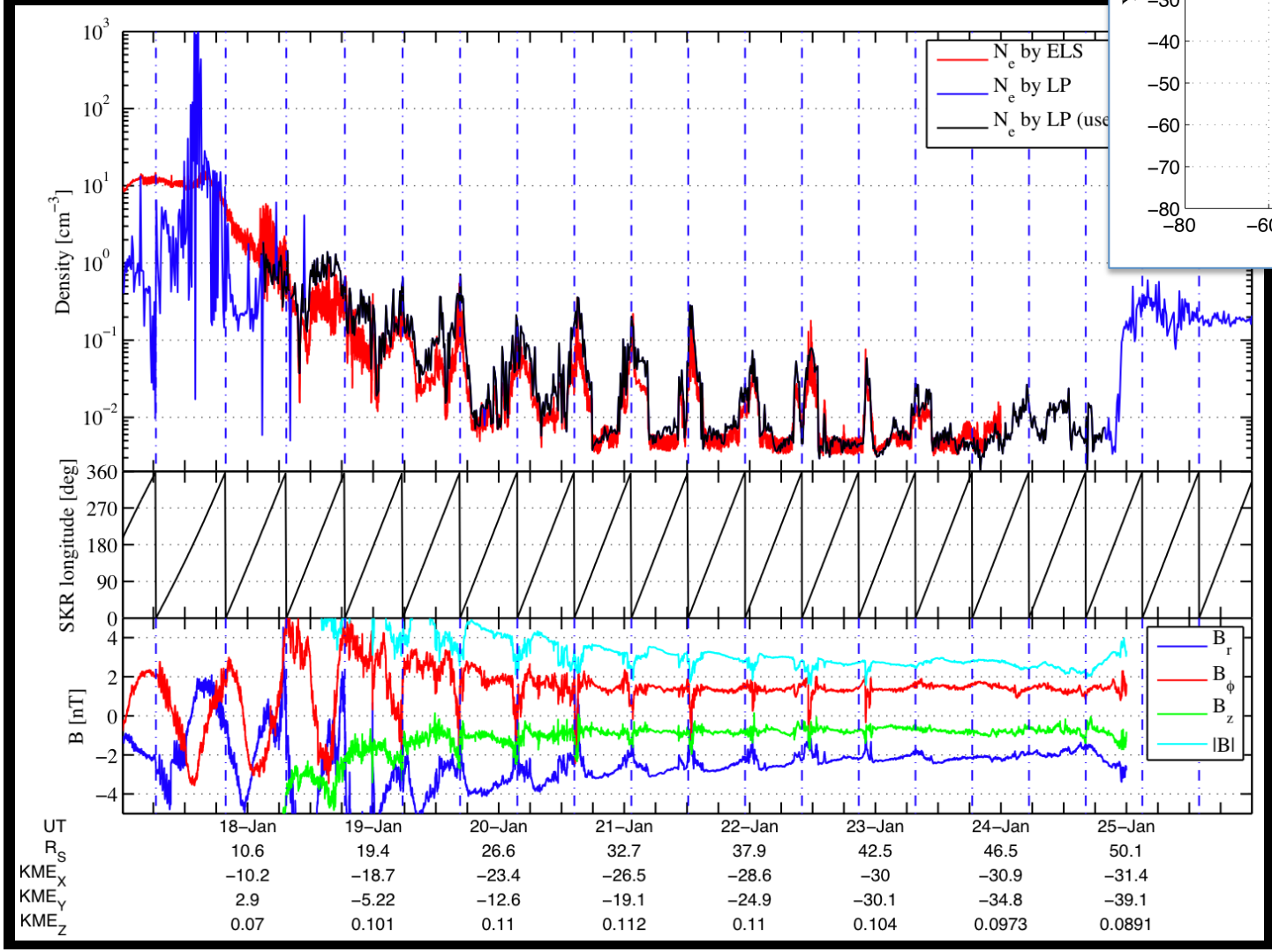


Magnetosphere similar to the Earth
Different in:
Strong control of co-rotation
Contains E ring and icy moons as plasma source

Periodic structure of the magnetosphere

Electron densities by LP in the outer magnetosphere





UT		18–Jan	19–Jan	20–Jan	21–Jan	22–Jan	23–Jan	24–Jan	25–Jan
R_S		10.6	19.4	26.6	32.7	37.9	42.5	46.5	50.1
KME_X		−10.2	−18.7	−23.4	−26.5	−28.6	−30	−30.9	−31.4
KME_Y		2.9	−5.22	−12.6	−19.1	−24.9	−30.1	−34.8	−39.1
KME_Z		0.07	0.101	0.11	0.112	0.11	0.104	0.0973	0.0891

Periodic structure of the magnetosphere (*In-situ*)

- Magnetic field data from Pioneer 11, Voyager 1 and 2, 'cam shaft' model by Espinosa et al., [2000]
- Periodic electrons/ions (few tens to hundred keV) modelation by Voyager 1 and 2 [Carbary and Krimigis, 1982], and Cassini [Krupp et al., 2005]
- Magnetopause oscillation. [Clarke et al., 2006]
- The electron densities near the Enceladus orbit [Gurnett et al., 2007]
- Low energy (few hundreds eV) electron [Arridge et al., 2008]
- Periodicity similar to SKR of Spoke [Porco and Danielson 1982]

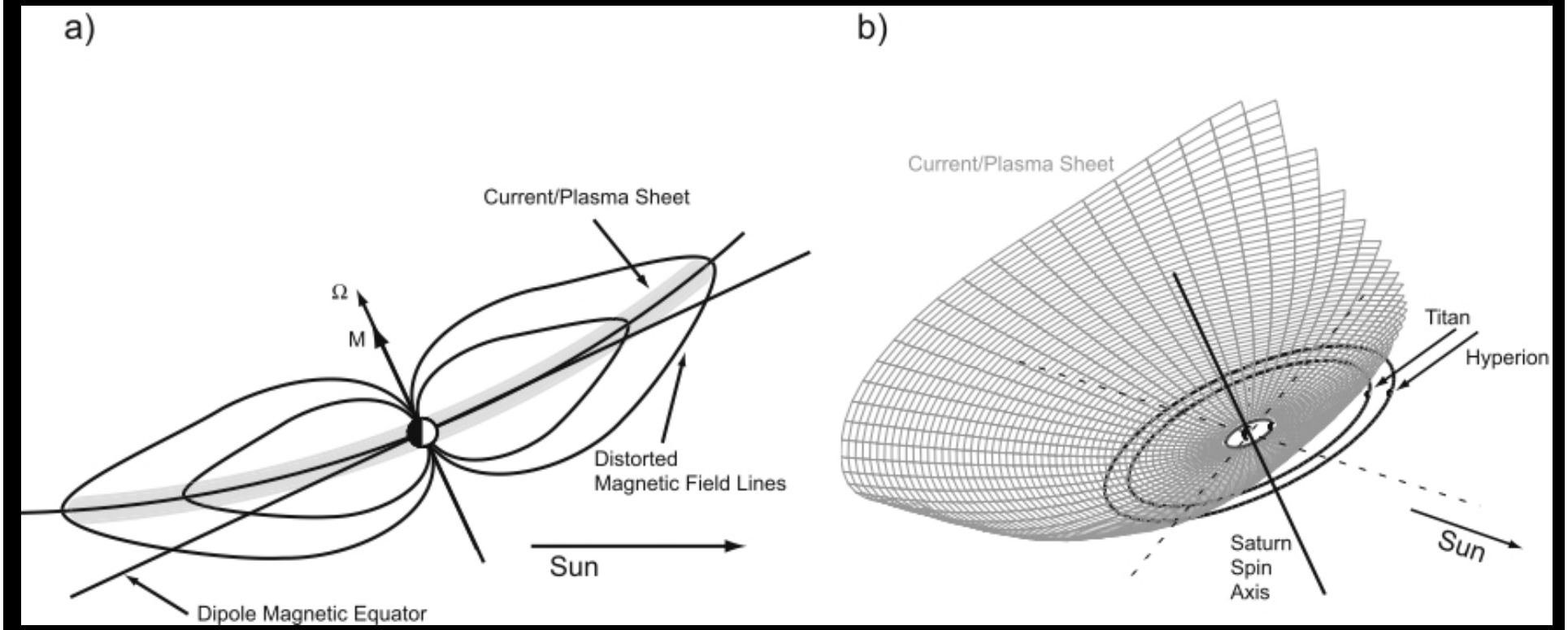
The planetary spin modulation was mystery since magnetic dipole axis of Saturn is almost parallel to the spin axis.

Periodic structure of the magnetosphere (*In-situ*)

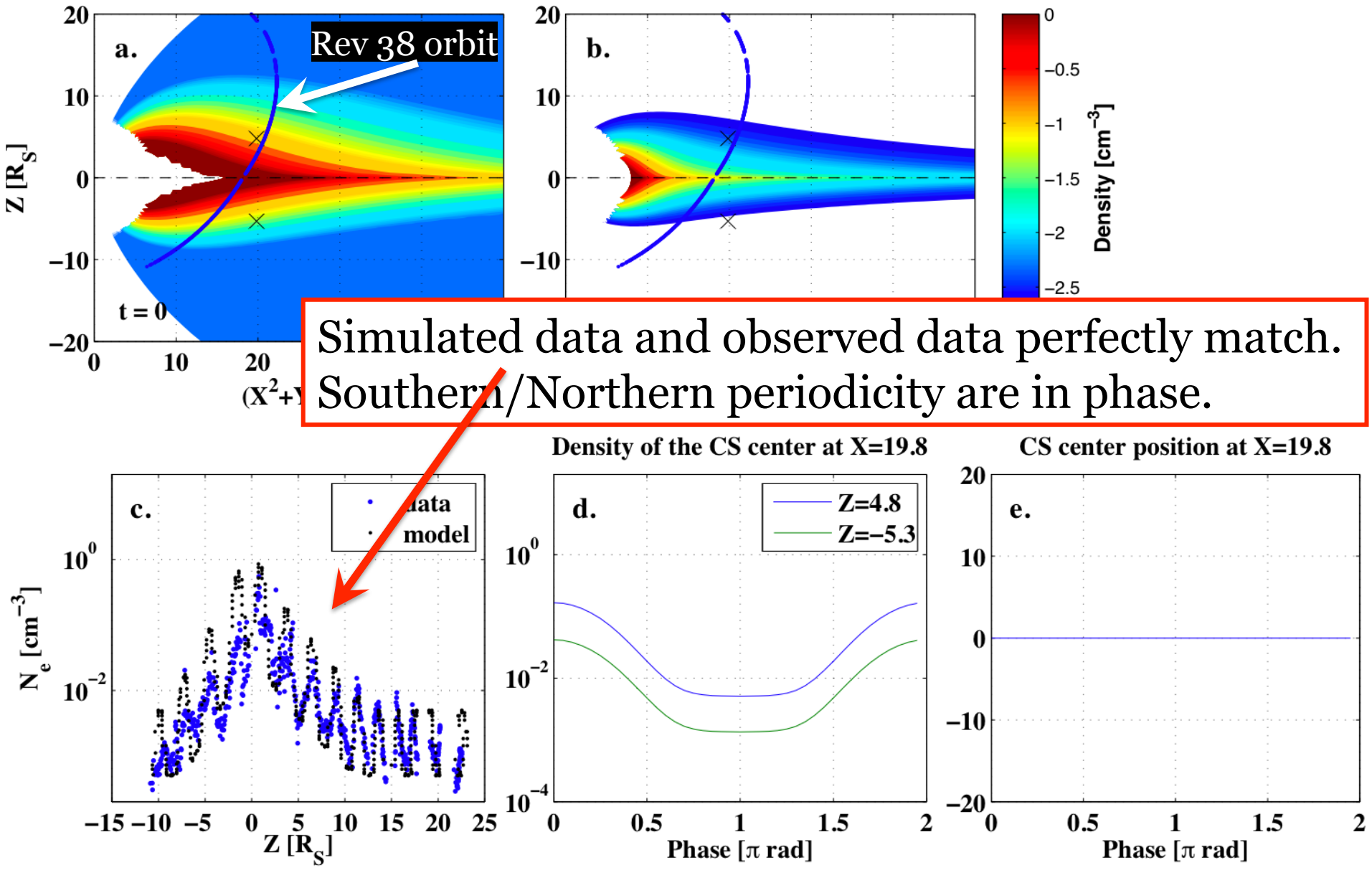
Small magnetic dipole tilt angle can make plasma sheet flapping.

The sun direction was from the southern hemisphere during the first four years.

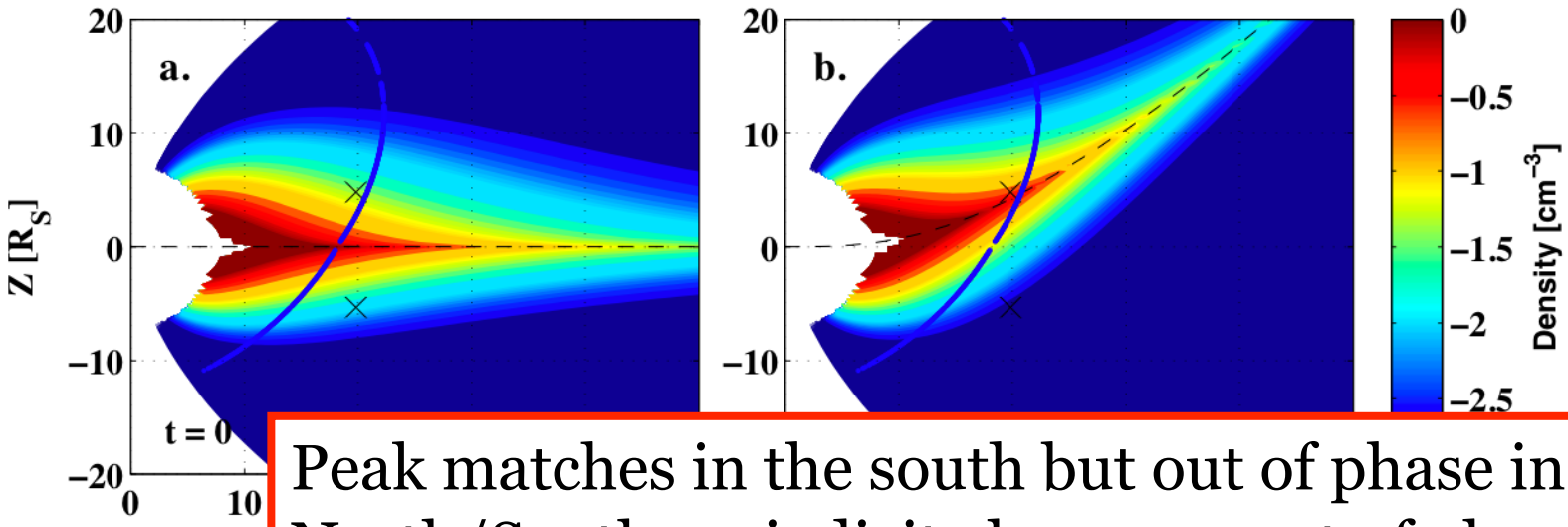
Arridge et al., [2008]



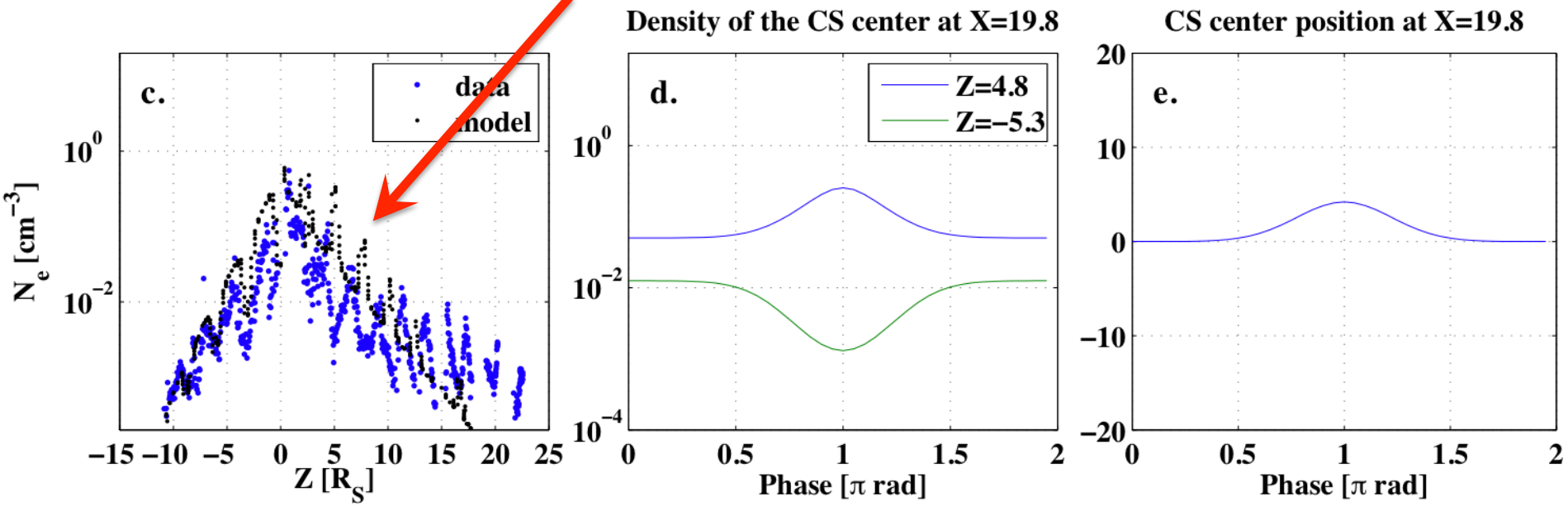
Test 1: longitudinal asymmetry



Test 2: CS flapping in spin period



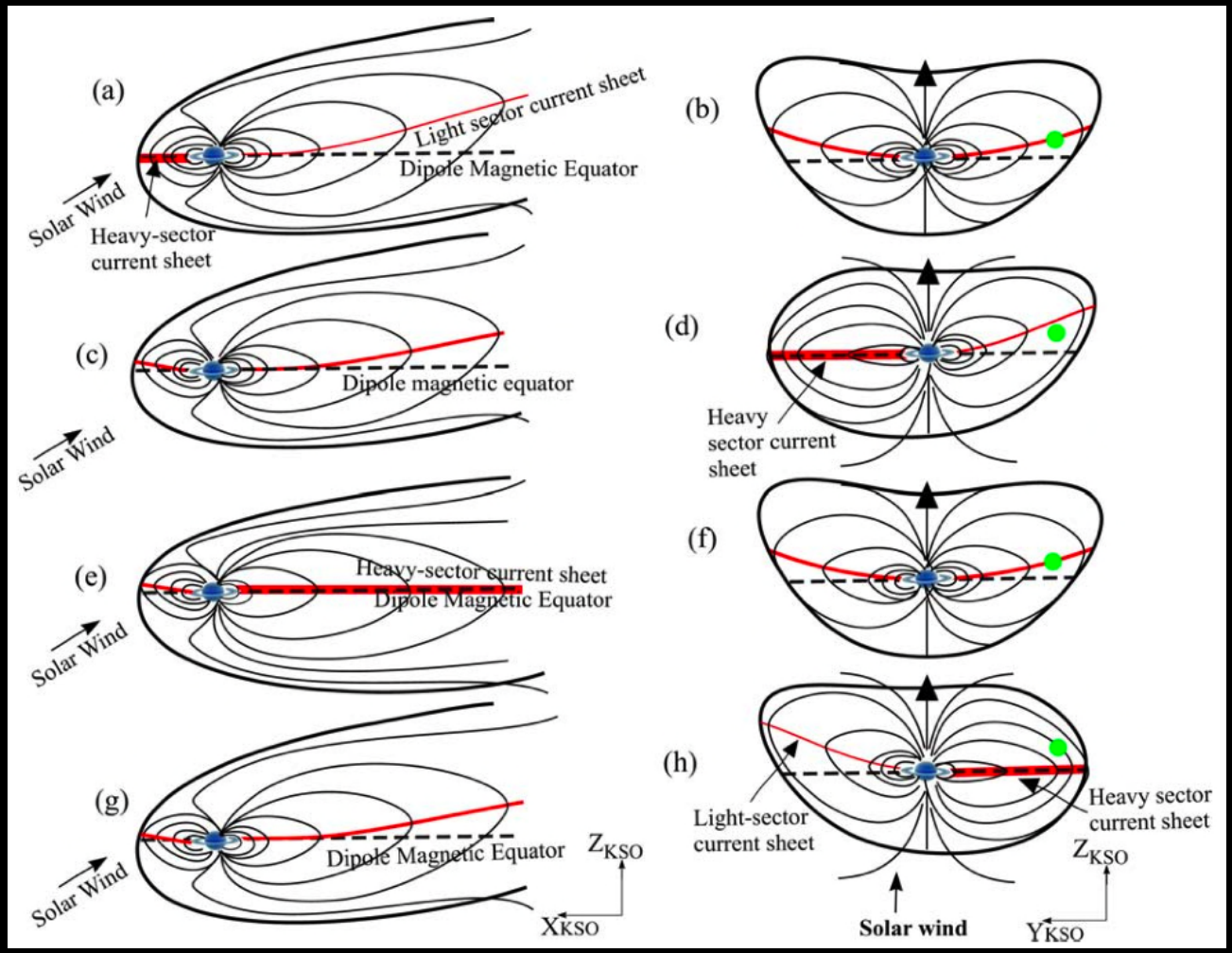
Peak matches in the south but out of phase in the north.
North/South periodicity becomes out of phase.



Periodic structure of magnetosphere (*In-situ*)

Flapping plasma sheet AND longitudinal asymmetry

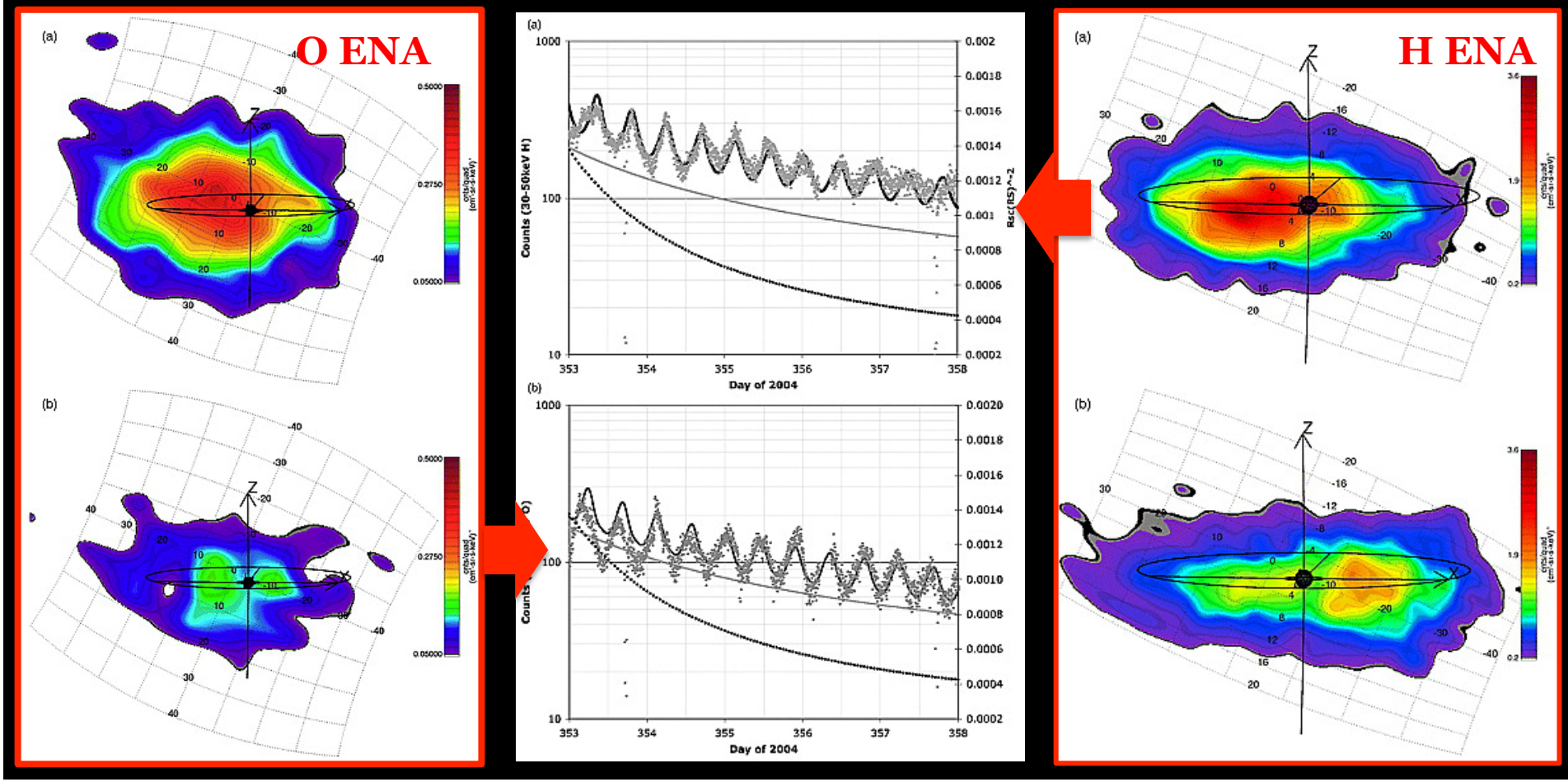
[Khurana et al., 2009]



Periodic modulation of the magnetosphere (*Remote sensing*)

ENA's integrated intensity shows periodicity.

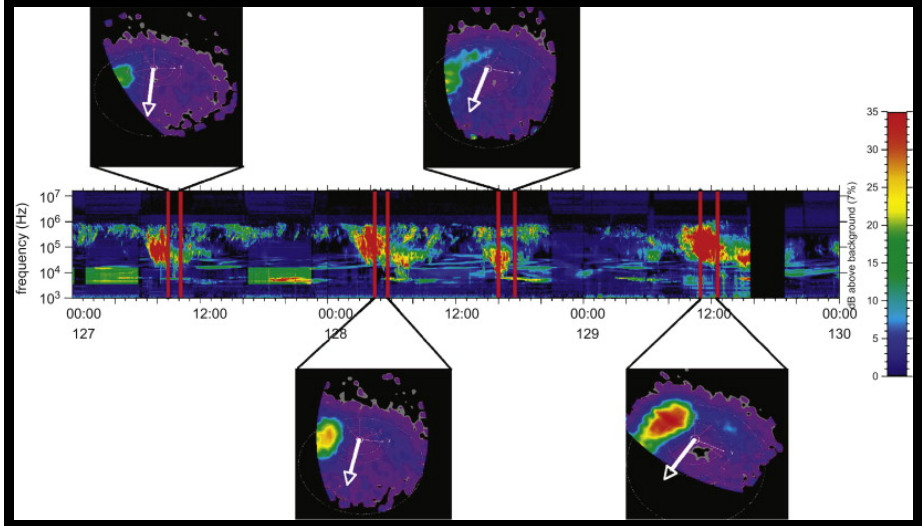
Paranicas et al., [2005]

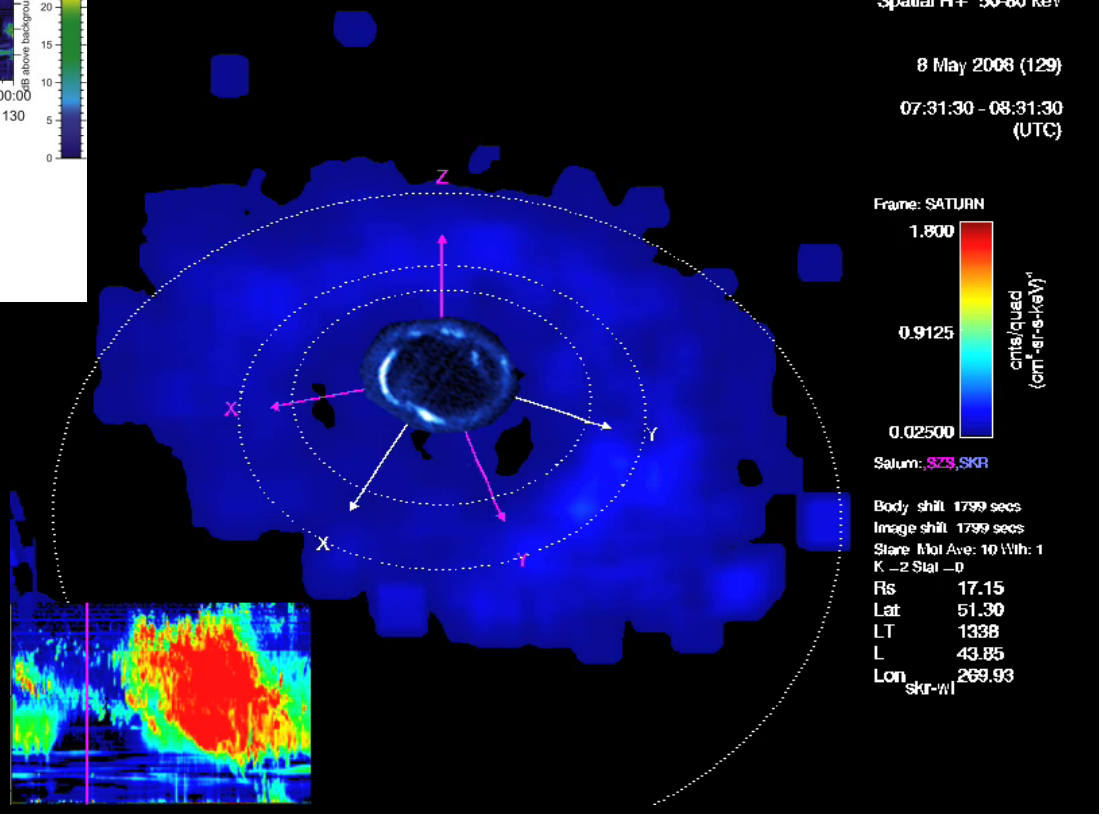


Periodic modulation of the magnetosphere (*Remote sensing*)

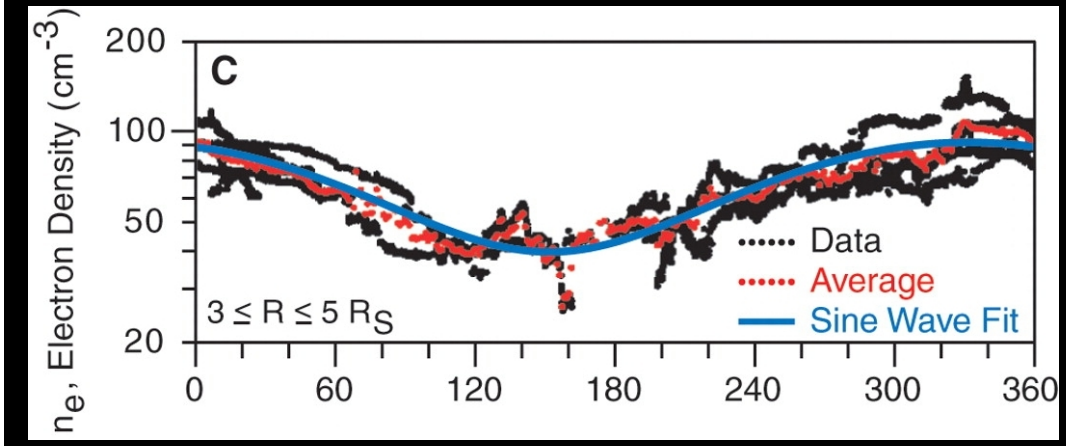
Periodic occurrence of plasma energization and its association to SKR and UV aurora.

Michel et al., [2009]



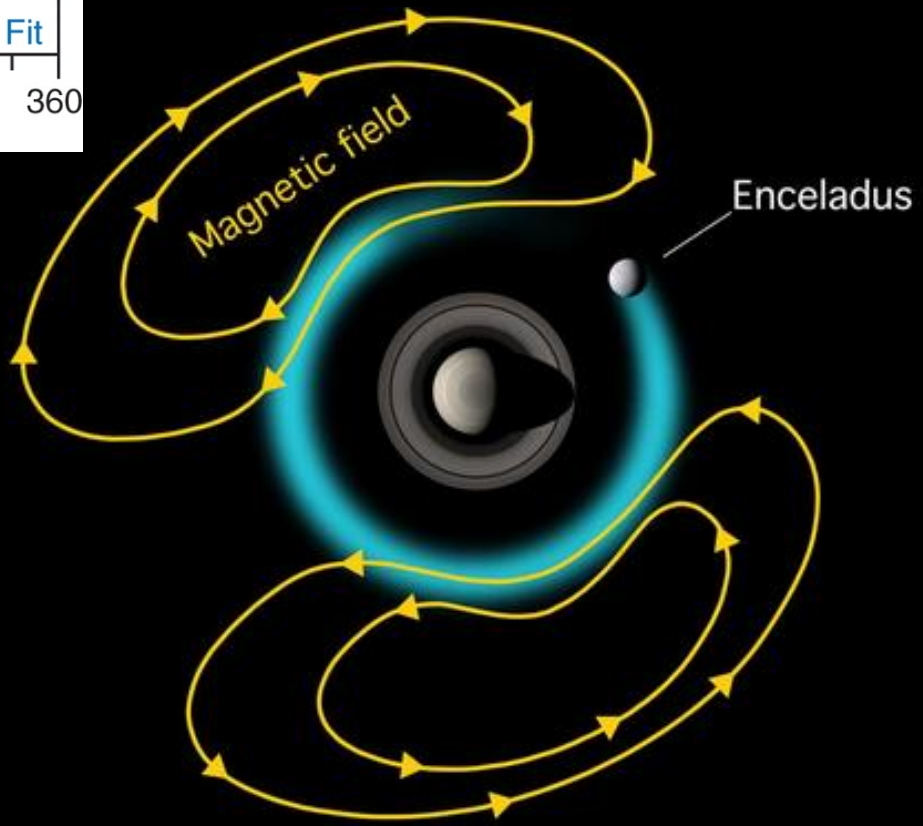


Periodic modulation of the magnetosphere (*Model*)

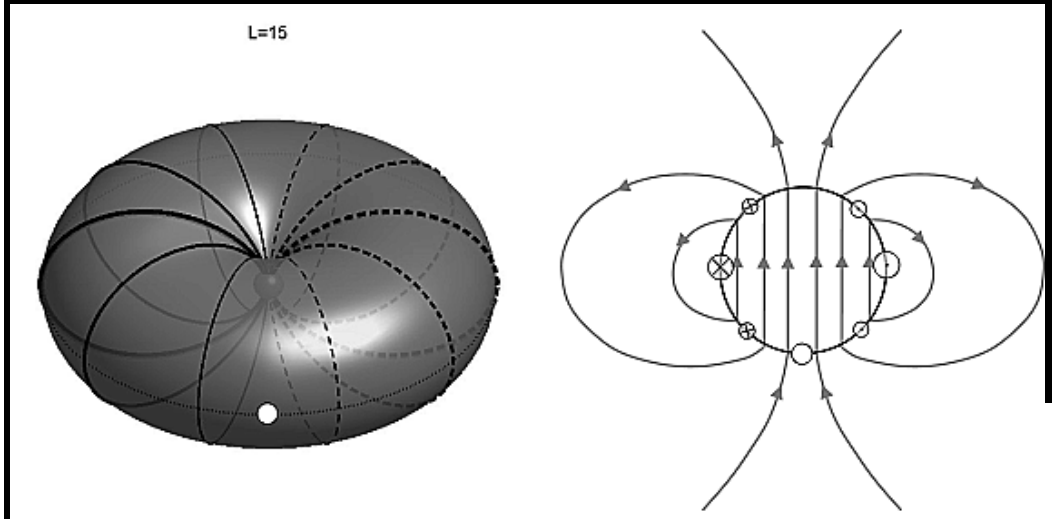


Electron density modulation around Enceladus orbit
Gurnett et al., [2007]

Co-rotating convention system makes plasma outflow from one longitude.



Periodic modulation of the magnetosphere (*Model*)

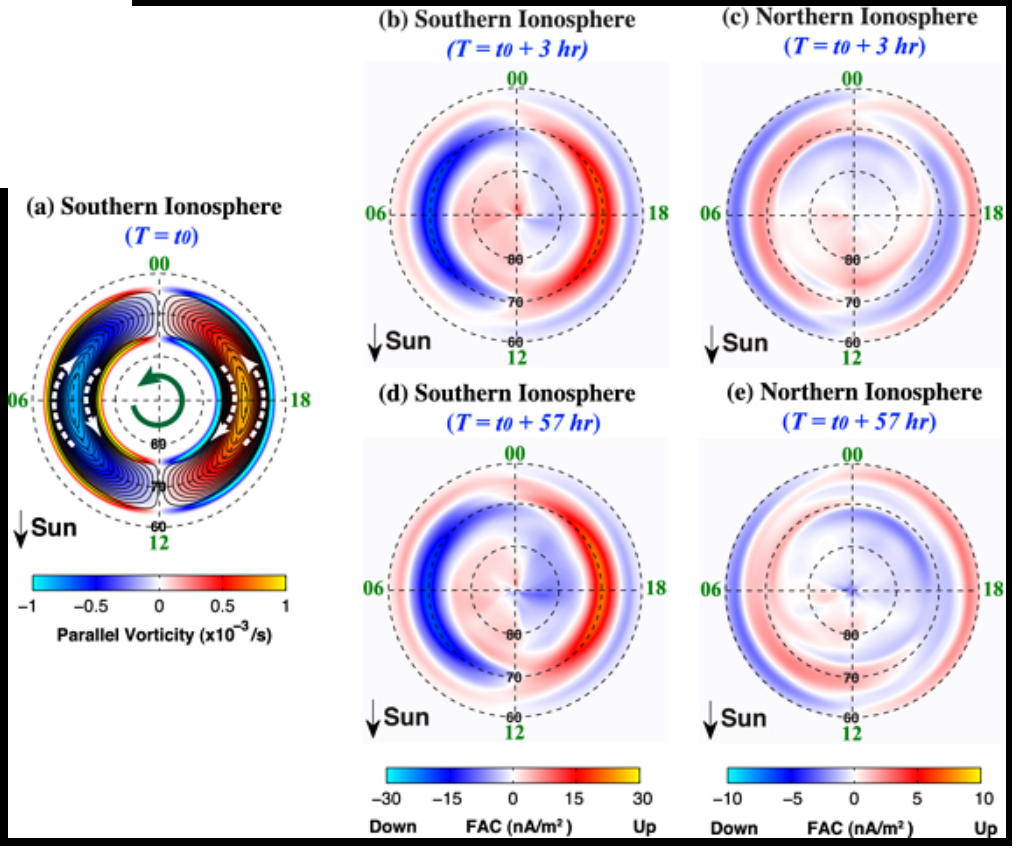


Rotating inhomogeneous FAC system.

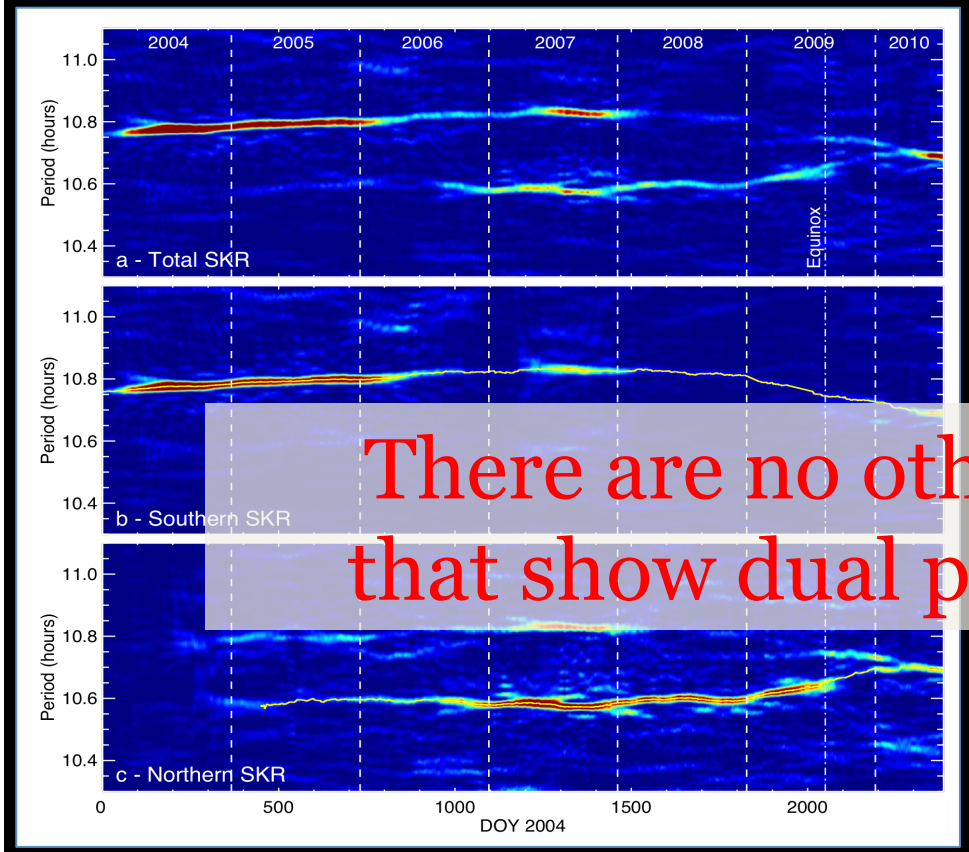
Southwood and Kivelson, [2007]

Localized vortical flow in one hemisphere creates the periodicities in the magnetosphere and on another ionosphere.

Jia et al., [2012]



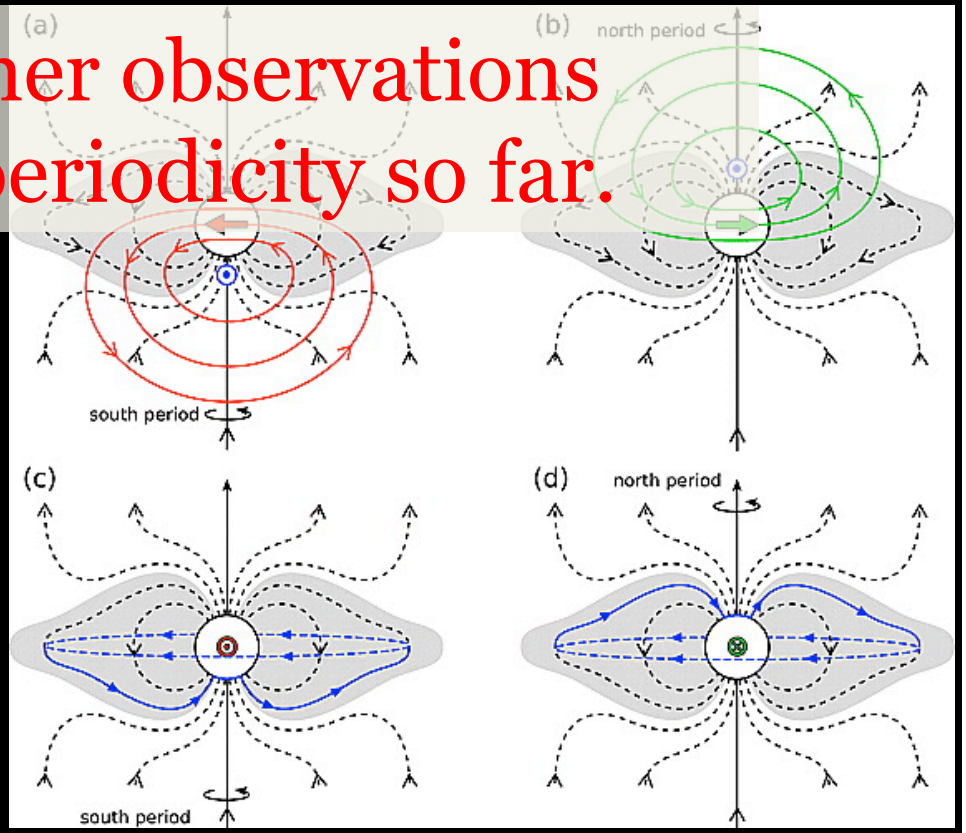
Dual periodicities



Spectrograms of SKR signals shows two periodicities:
One from north (left hand polarization) and another from south.

Lamy et al., [2008]

There are no other observations that show dual periodicity so far.

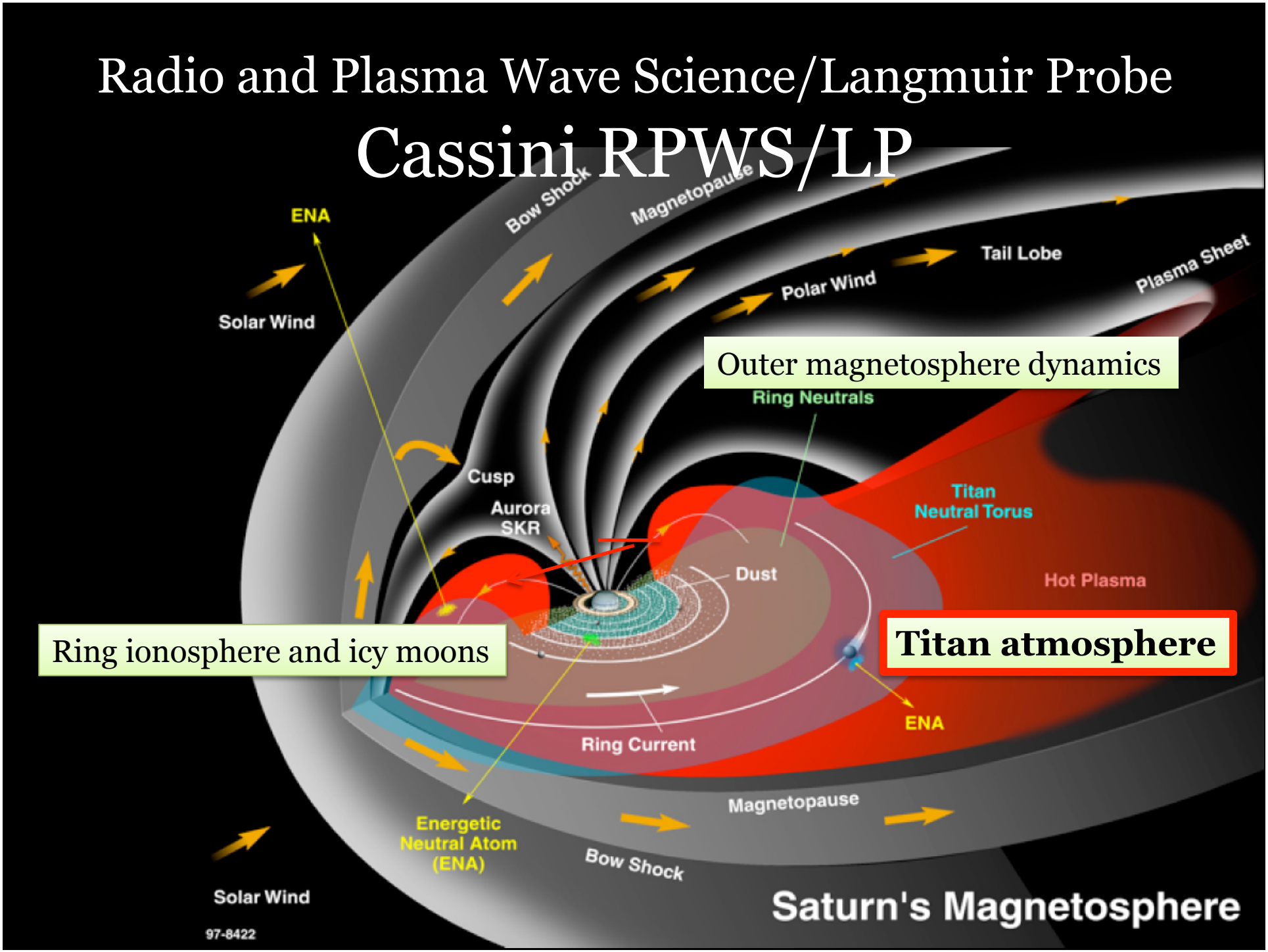


Magnetic field also shows different periodic FAC system in north and south.

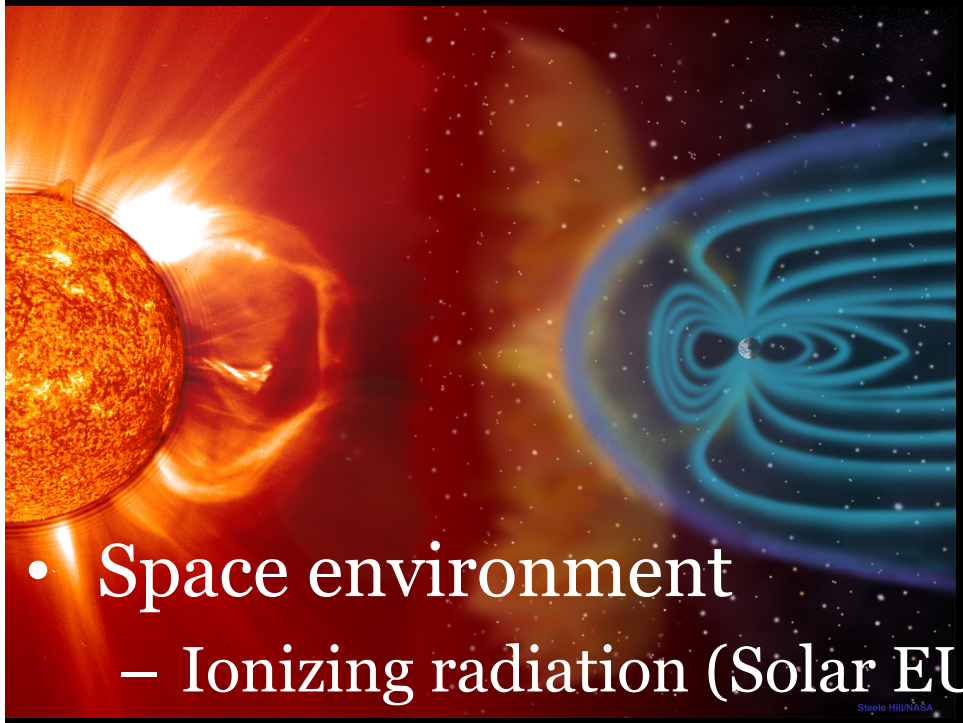
Provan et al., [2009, 2011, 2012]
Andrews et al., [2010, 2011, 2012]

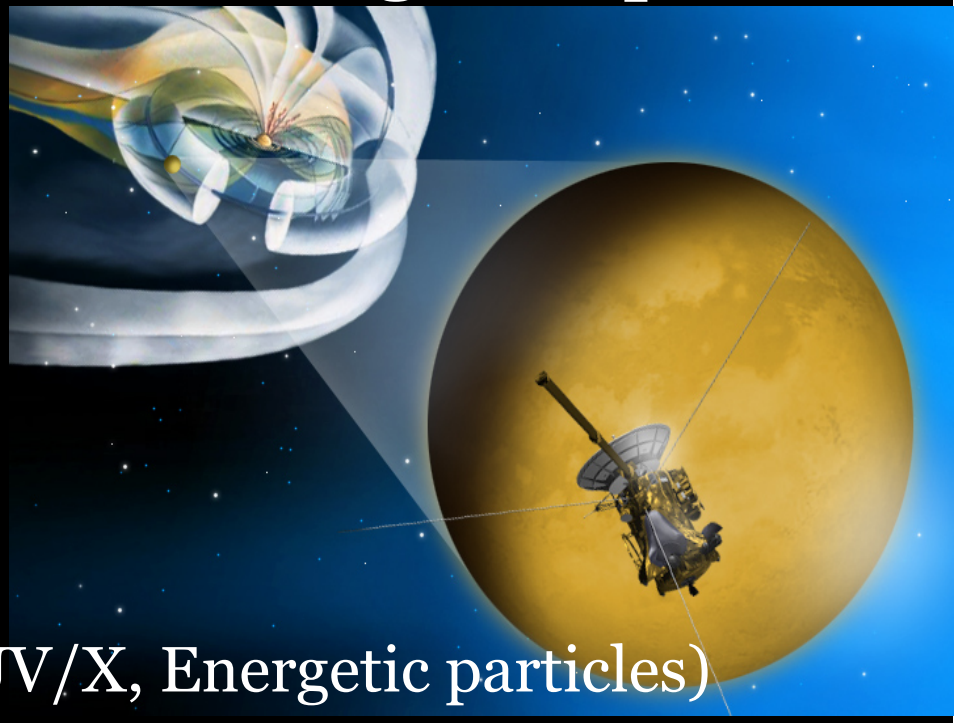
Radio and Plasma Wave Science/Langmuir Probe

Cassini RPWS/LP



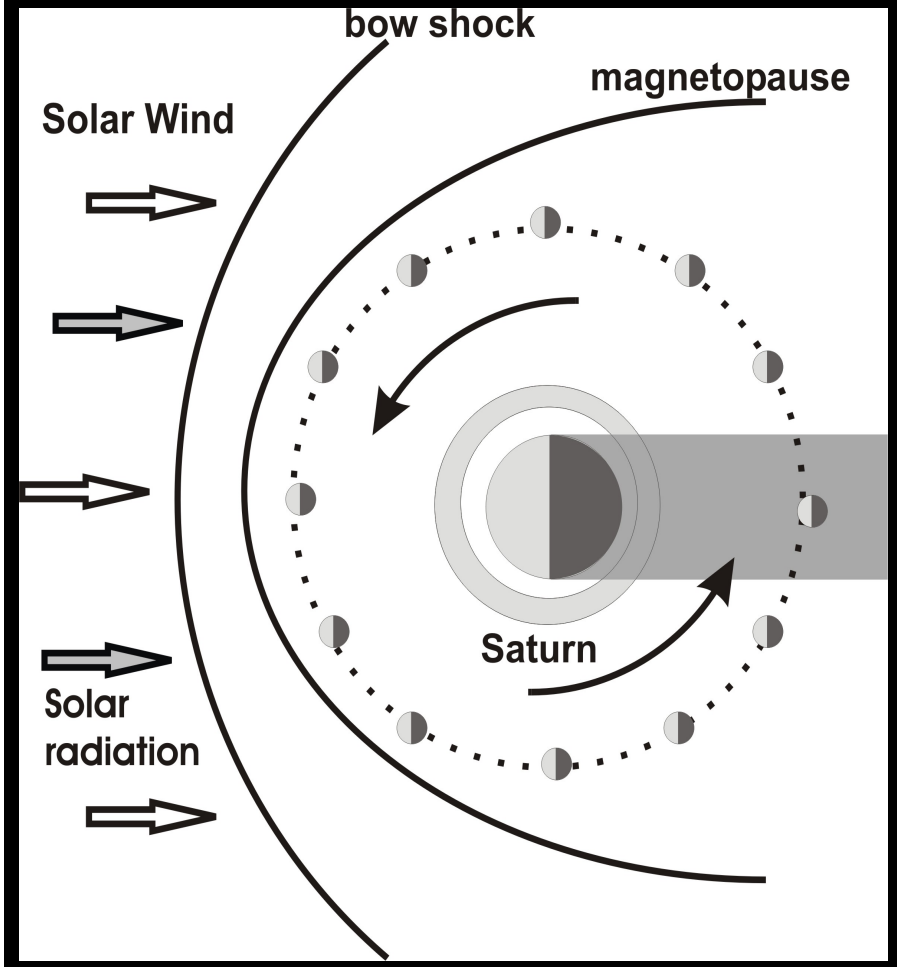
Titan atmosphere and its interaction with Saturn's magnetosphere





- Space environment
  - Ionizing radiation (Solar EUV/X, Energetic particles)
  - Triggers upper atmospheric chemistry
    - in a N_2-CH_4 atmosphere
    - Produce complex organic molecules (via N_2^+, N^+)
    - Leads to formation of organic aerosol ("haze")
    - Deposition on surface (+H_2O => Hydrolysis)
- Ex: Titan, Early Earth?

Titan atmosphere and its interaction with Saturn's magnetosphere

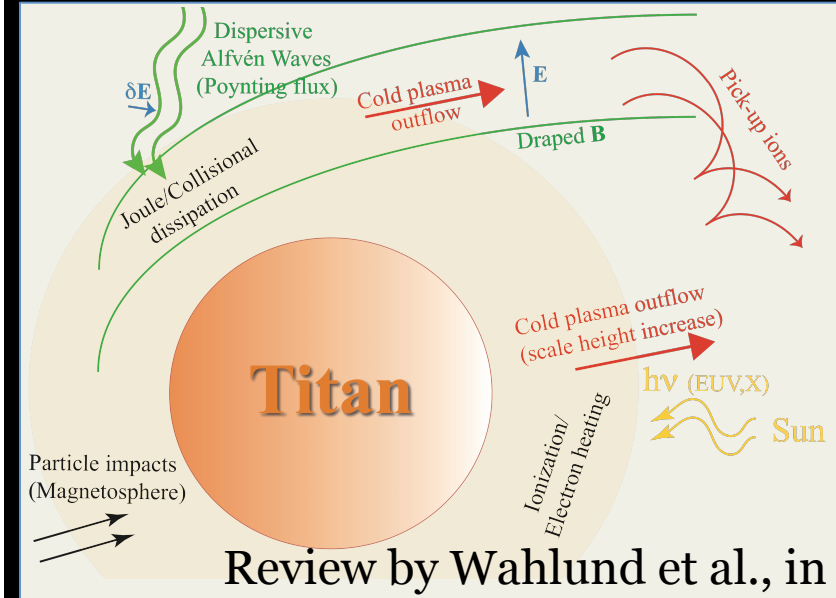


Ionization sources depends on orbit position.

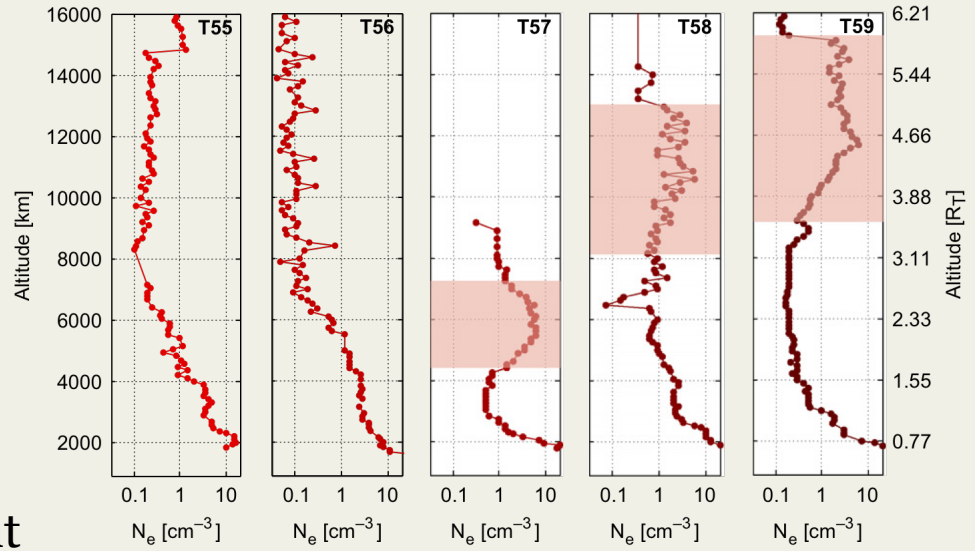
Ionosphere influence

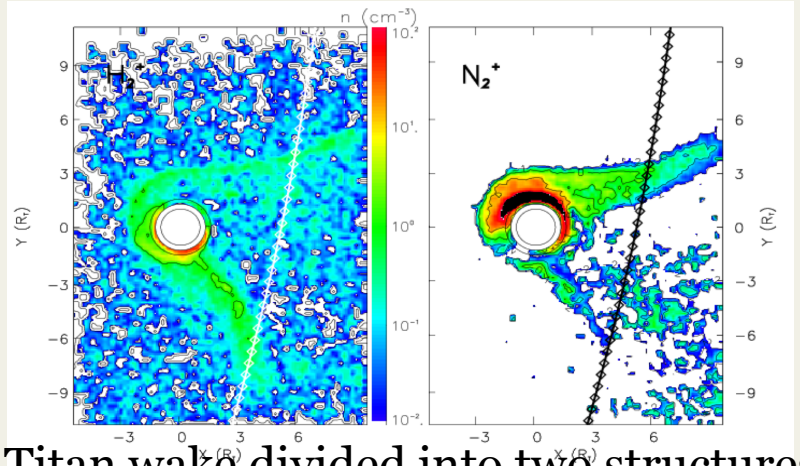
- Solar EUV/X
- Magnetospheric particle impacts
- Magnetospheric electrodynamics
- Dayside to nightside transport
- ...

Titan cold plasma outflow



Review by Wahlund et al., in print



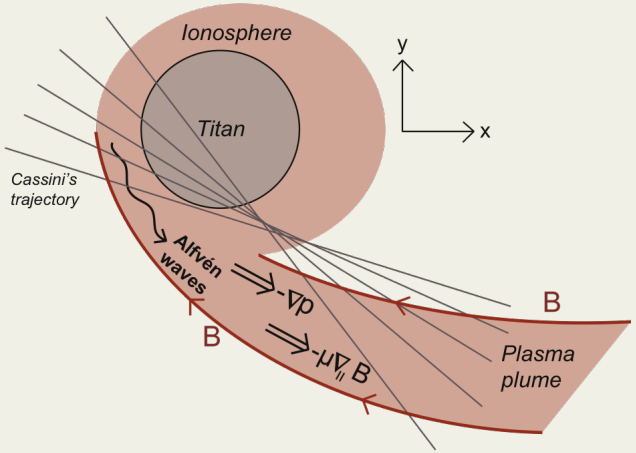


Titan wake divided into two structures:

Heavy ions on Saturn side

Light ions on ant-Saturn side

Modolo et al., [2007]



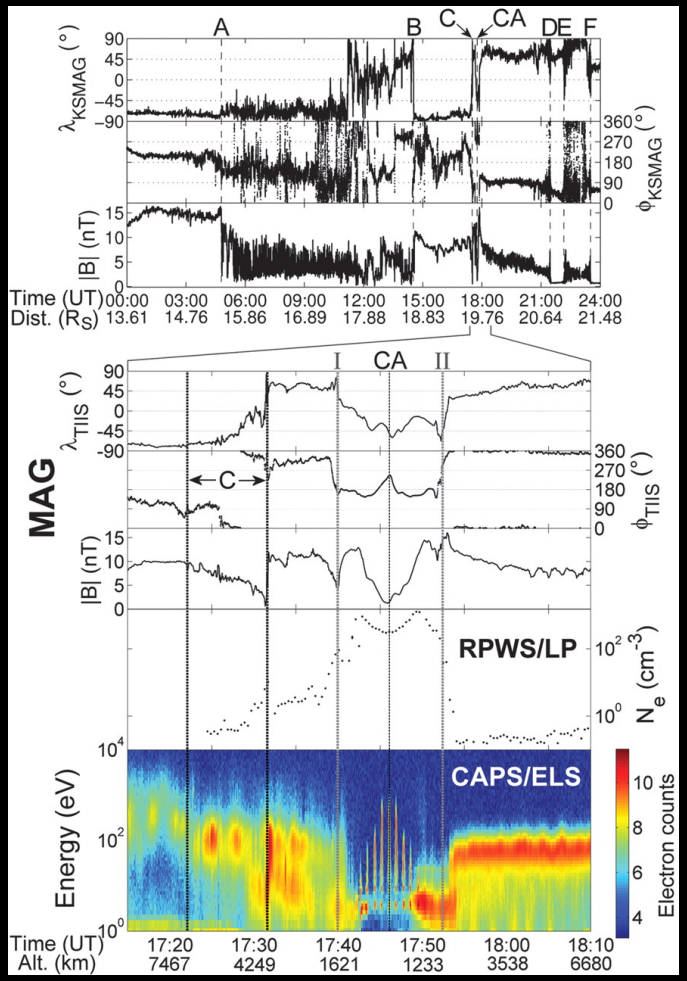
Plume of escaping Titan ionosphere assoc. with magnetic field perturbation.

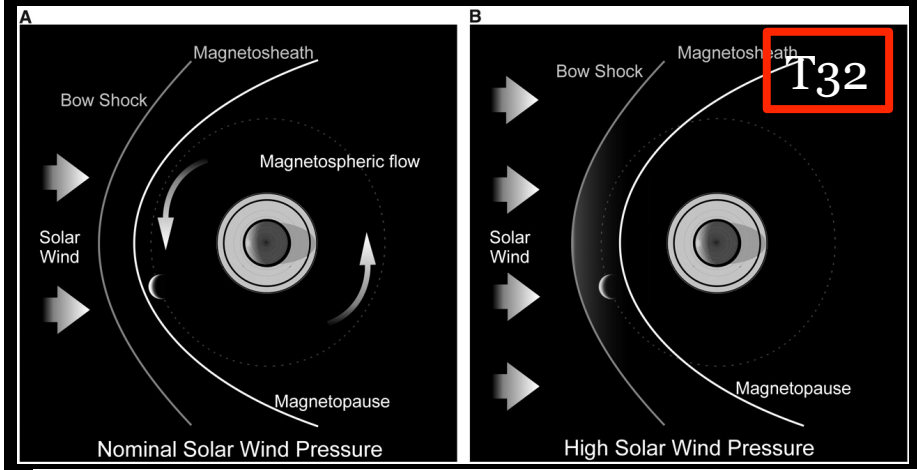
Edberg et al., [2011]

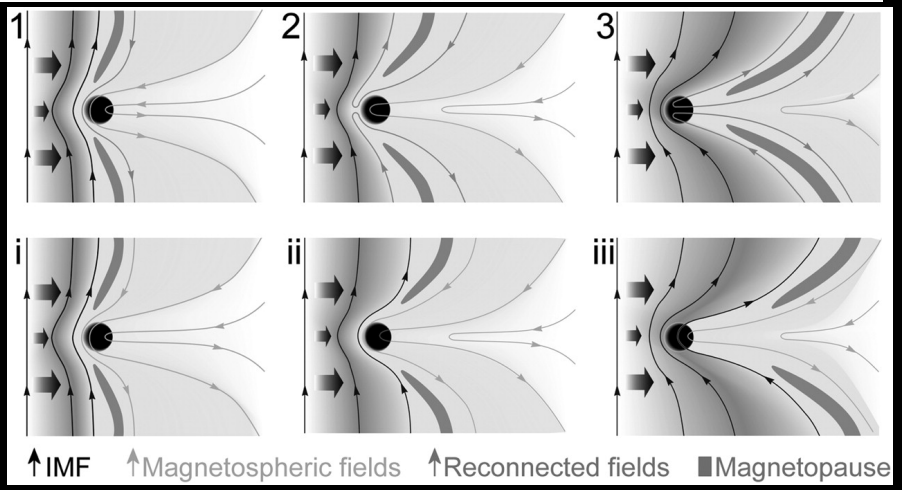
Titan meats the solar wind shock region

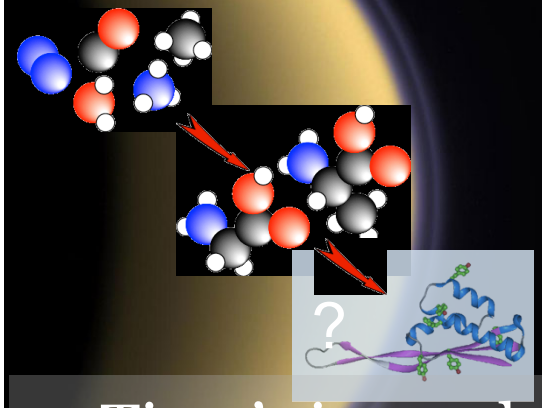
• Titan's flow-induced magnetosphere was populated by "fossil" fields originating from Saturn.
• Reconnection may have been involved in the replacement of the fossil fields by the interplanetary magnetic field.

Bertucci et al., [2008]

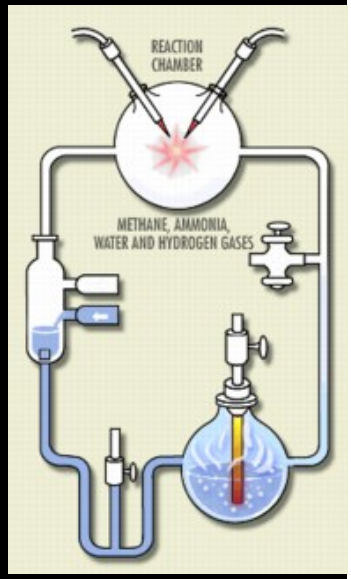




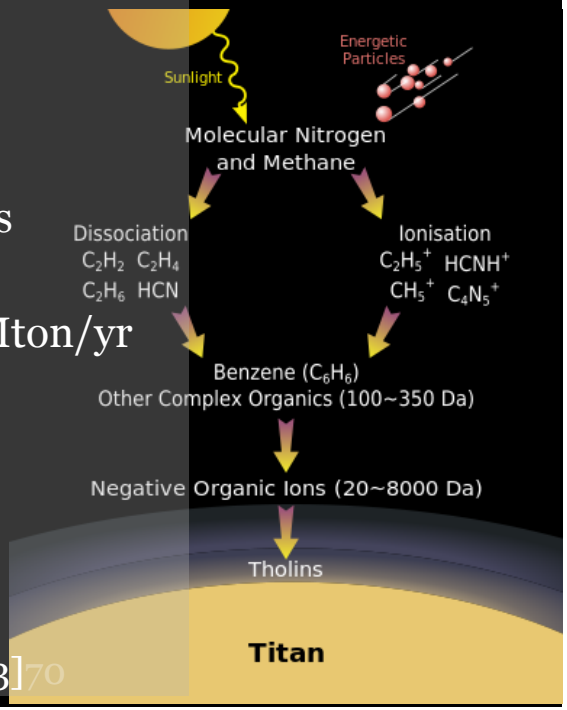




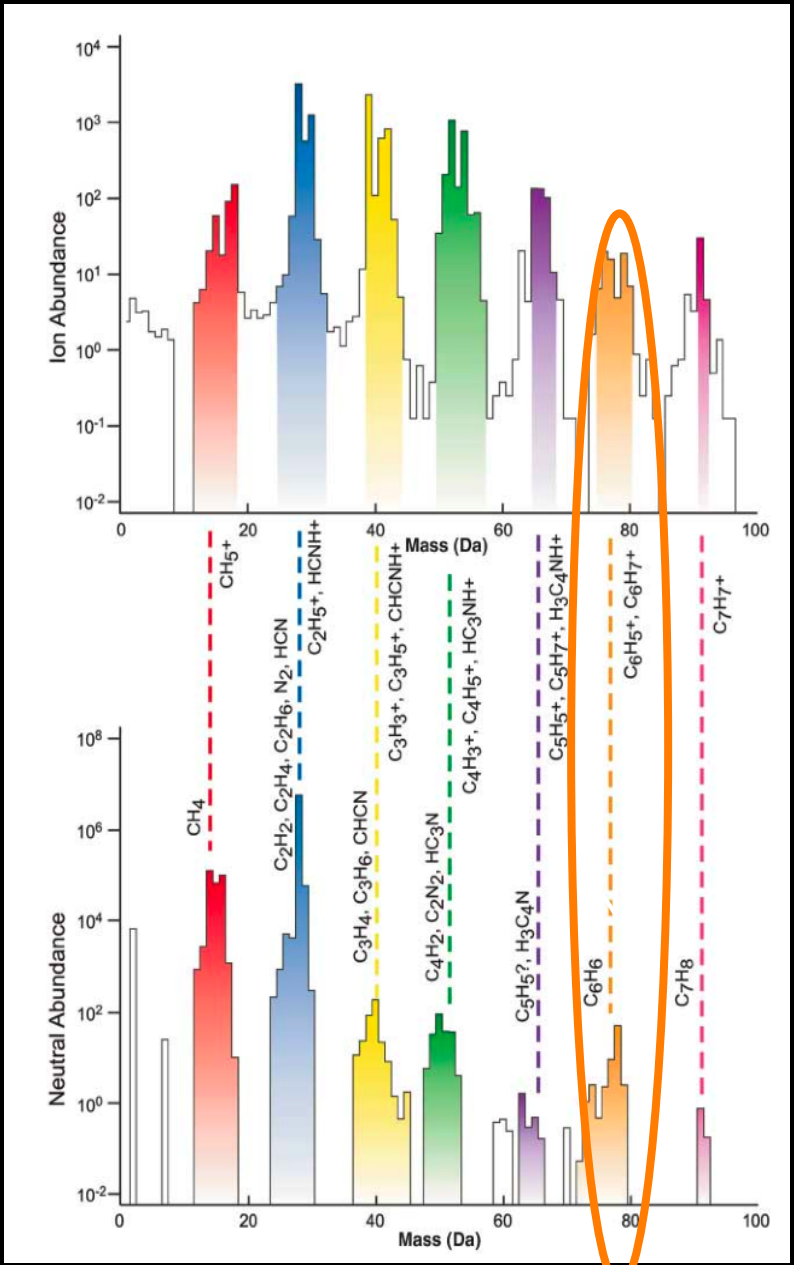
Titan

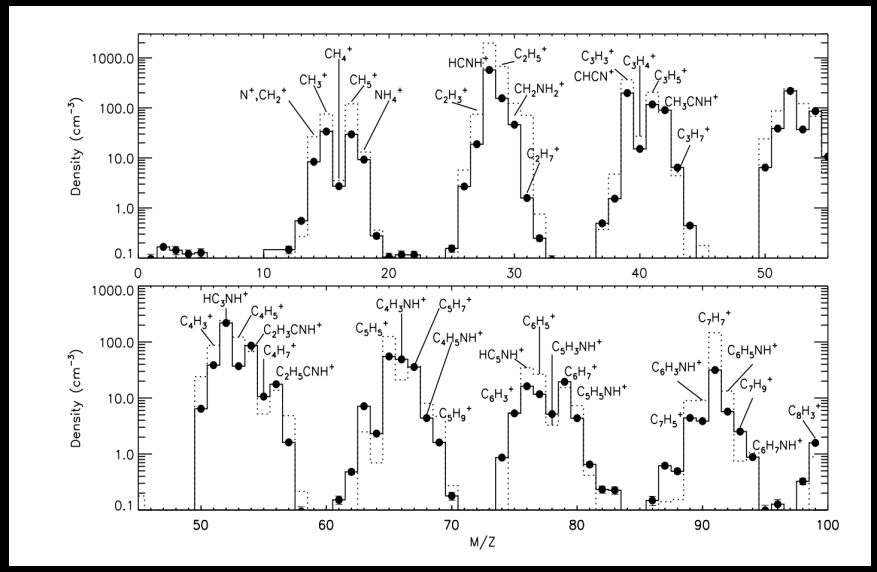


- Titan's ionosphere is a substantial source for aerosol formation & other complex organic chemistry
  - Ionization sources and formation of ionosphere (mostly $HCNH^+$, $C_2H_5^+$)
    - [*Wahlund et al.*, 2005; *Cravens et al.*, 2005; *Ågren et al.*, 2009]
  - Presence of heavy (up to 40000 amu) negative organic ions
    - [*Coates et al.*, 2007; 2010]
  - Presence of heavy (up to at least 350 amu) positive organic ions
    - [*Waite et al.*, 2007]
  - Heavy positive ions (>100 amu) recombine and deposit 0.1-1 Mton/yr
    - [*Wahlund et al.*, 2009; *Crary et al.*, 2009; *Sittler et al.*, 2009]
  - Large amount (dominant part) of heavy negative ions in lower ionosphere
    - [*Ågren et al.*, 2012]
  - Can explain Aerosol growth
    - [*Lavvas et al.*, accepted, 2012; Shebanits et al., in preparation 2013]

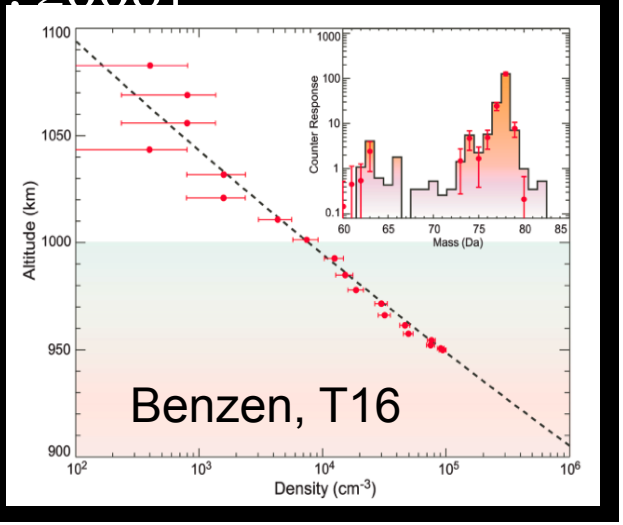


Detection of Complex Chemistry

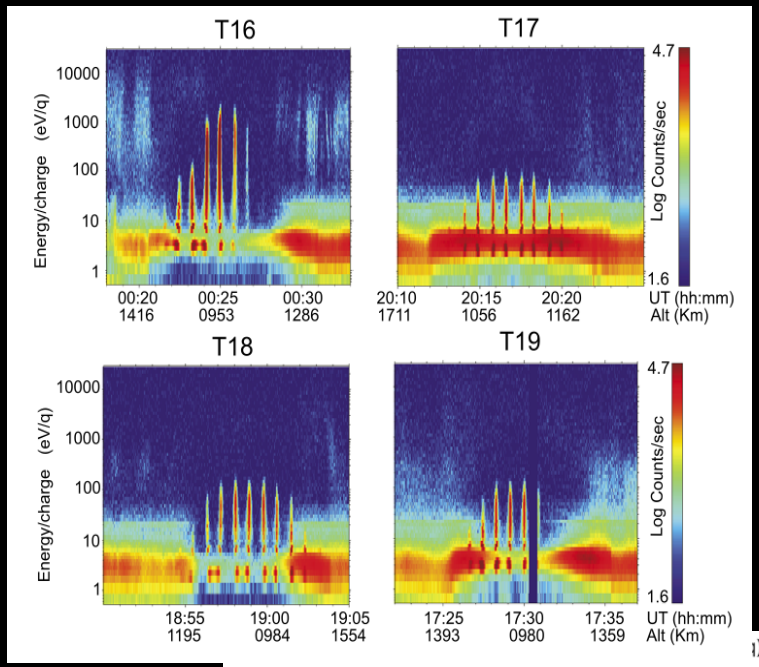


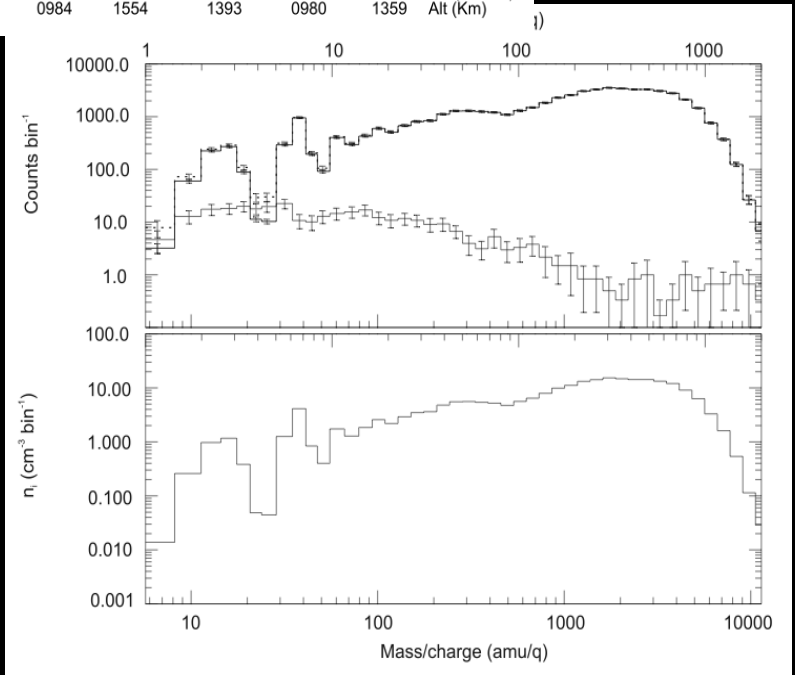


Tholin formation? *Waite et al.*, [2007]
Compare with laboratory measurements.
Vuitton et al., [2007, 2008]



Detection of Negative Ions >10000 amu/q



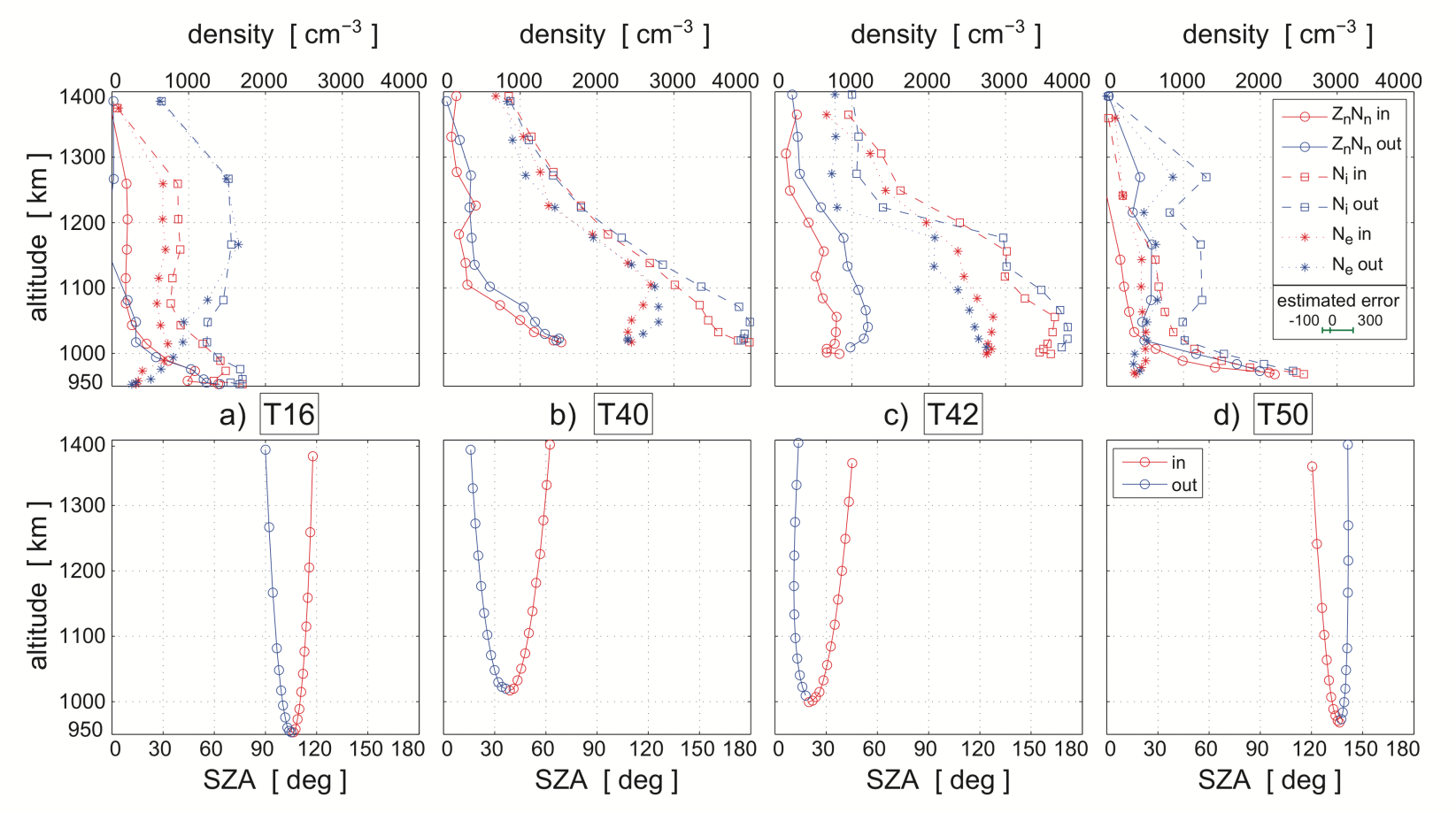


- [*Coates et al.*, 2007; 2010]
- Dissociative e^--attachment?
  - Darkness => No photo-detachment
- Up to 200 cm^{-3}
  - Large fraction of N_e
- Charge
  - $U \approx k_B T_e \sim -0.25$ V
  - Ca 5e/ion
  - 50000 amu
  - 10-30 nm!
- Initial stages for aerosol (tholin) formation?

- Catalytic polymerization
  - CN^-, NH_2^-, (O^-)
  - NCN^-, $HNCN^-$, C_3H^-
  - $C_5H_5^-$, C_6H^-, $C_6H_5^-$
  - Polyenes, Nitriles
  - PAH
  - Cyano-aromatics

LP observations of Heavy organic ions in Titan's Lower Ionosphere

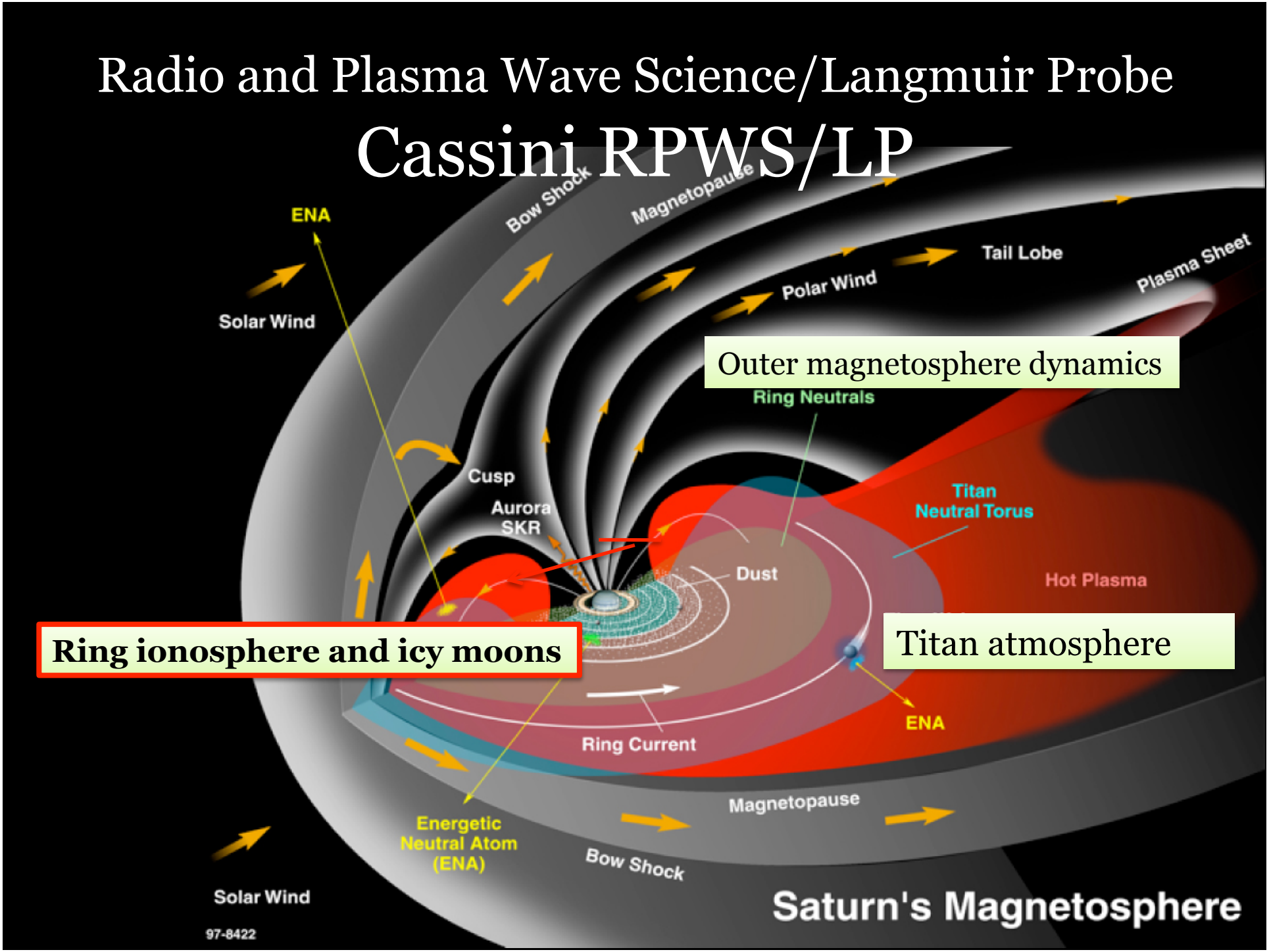
More heavy negative ions detected on the nightside.

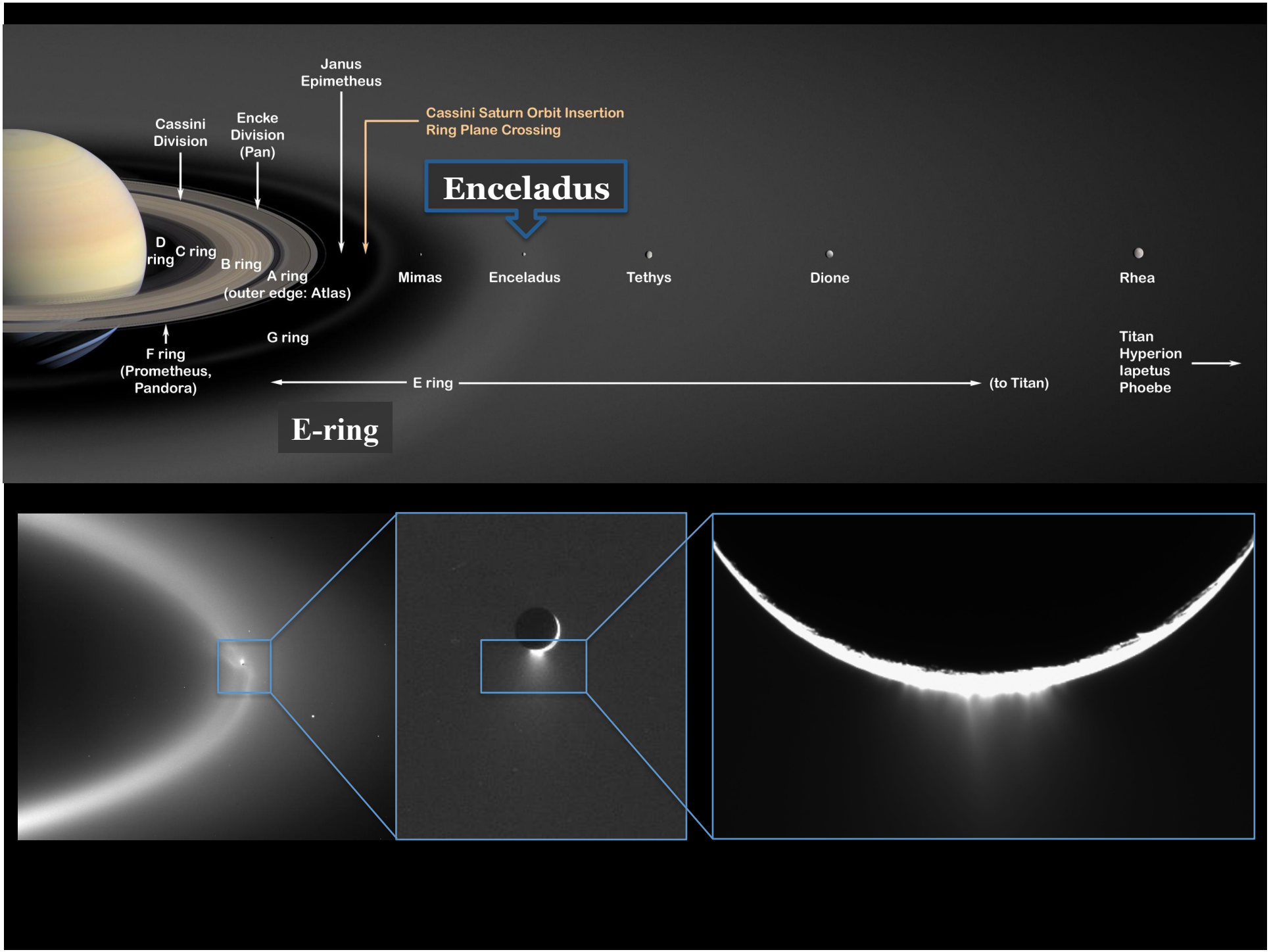


Shebanits et al, submitted

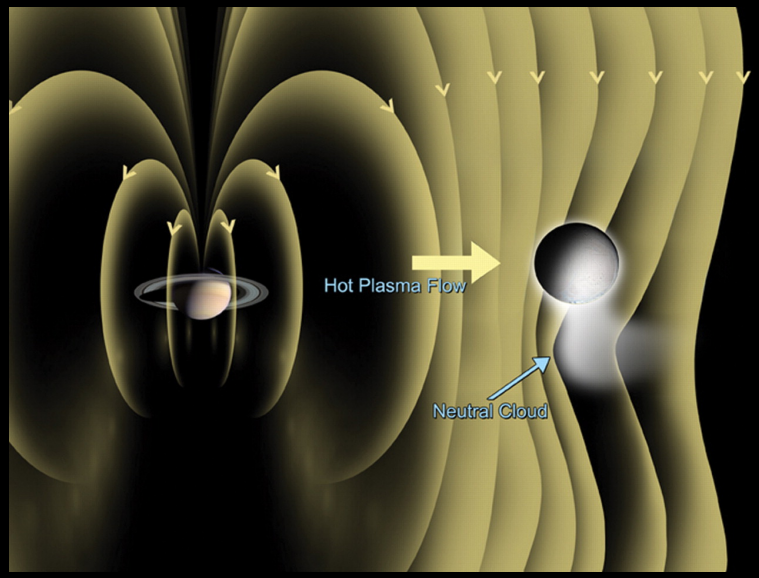
Radio and Plasma Wave Science/Langmuir Probe

Cassini RPWS/LP




Janus
Epimetheus
Cassini Division
Encke Division (Pan)
Cassini Saturn Orbit Insertion
Ring Plane Crossing
Enceladus
D ring
C ring
B ring
A ring
(outer edge: Atlas)
Mimas
Enceladus
Tethys
Dione
Rhea
G ring
F ring
(Prometheus, Pandora)
E ring
(to Titan)
Titan
Hyperion
Iapetus
Phoebe
E-ring

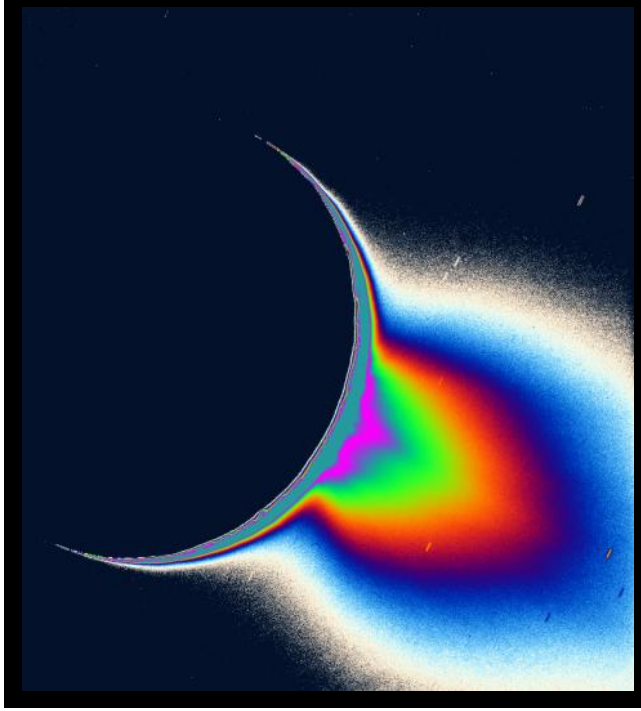
Enceladus plume detected by MAG

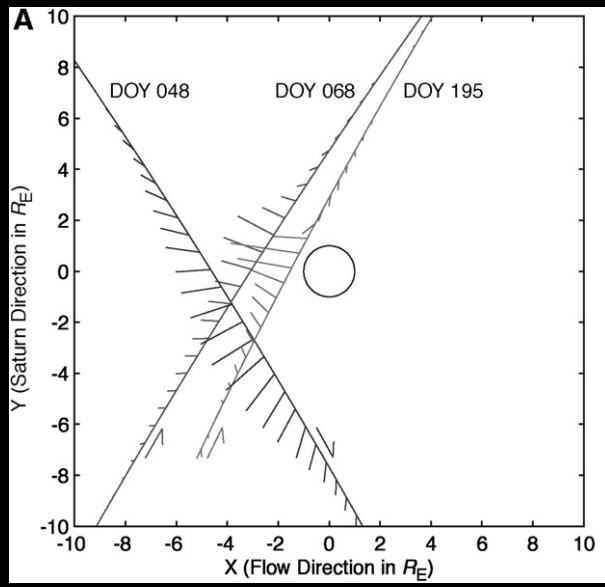


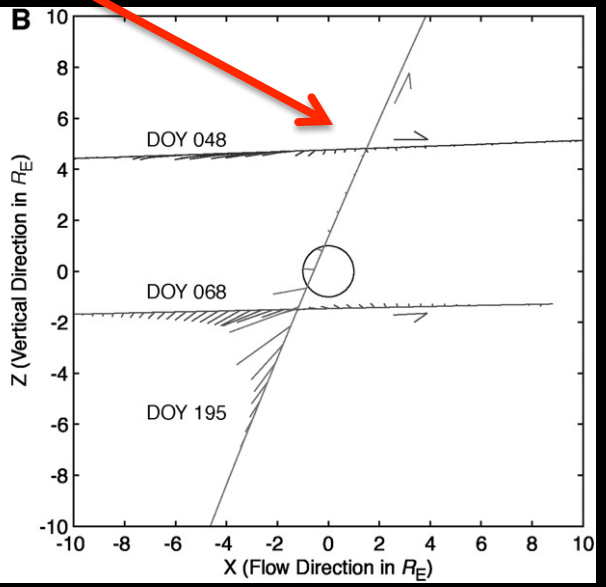
- Bx shows the expected Alfvén wing of the southern plume.
- By are rather difficult to interpret.

Dougherty et al. (2006)

Magnetic perturbation even in the north!

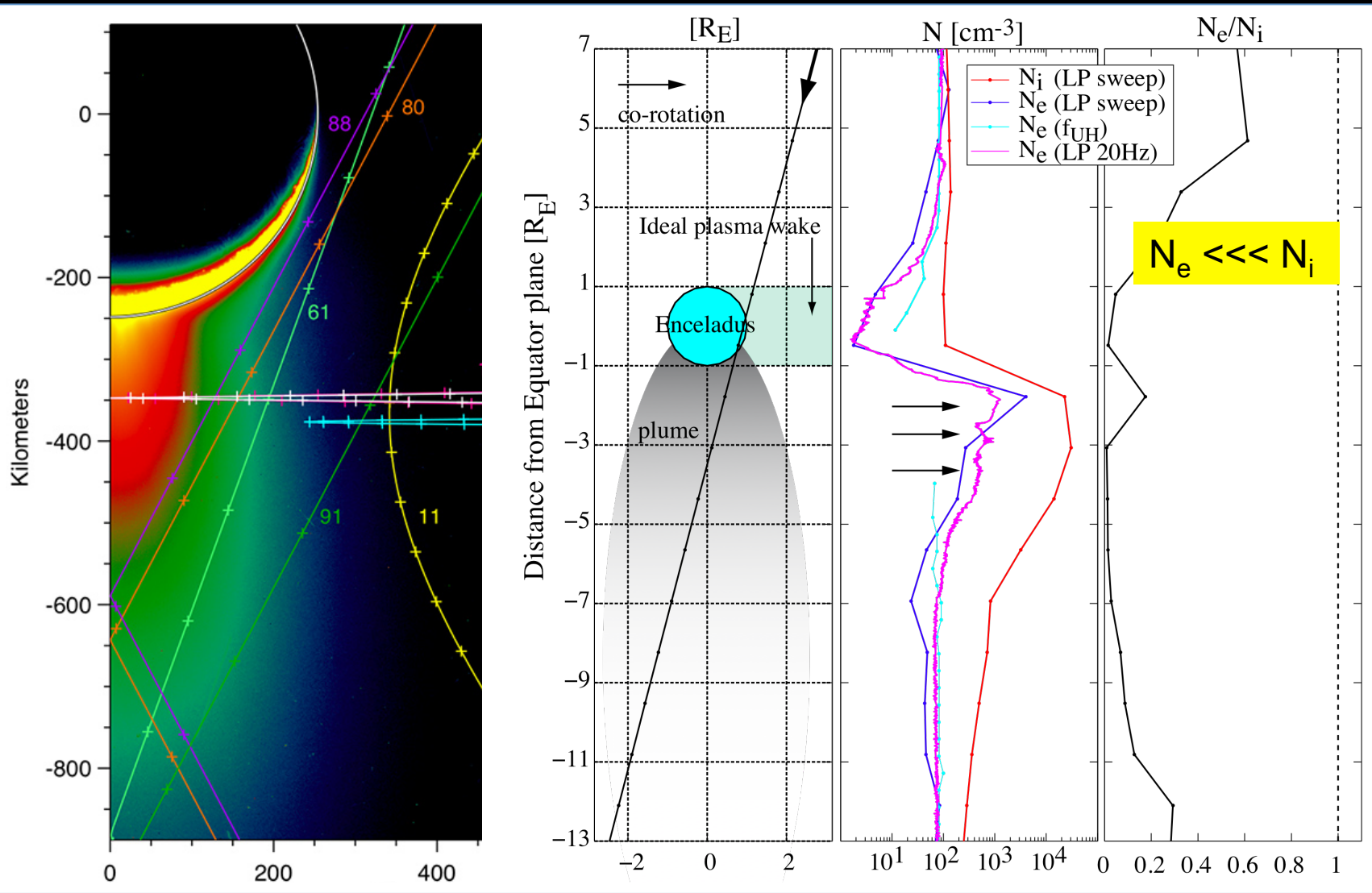






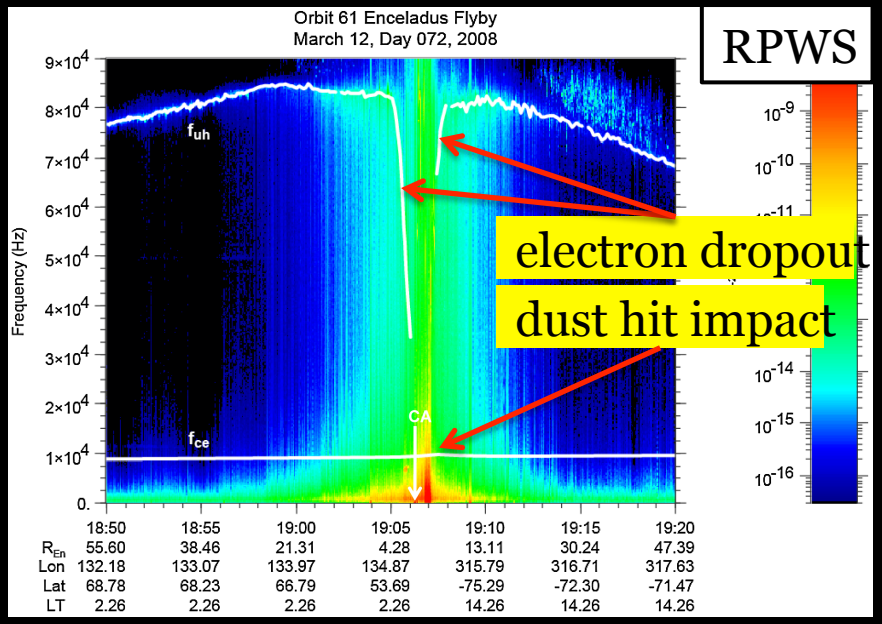
Dusty Plasma evidence at the Enceladus

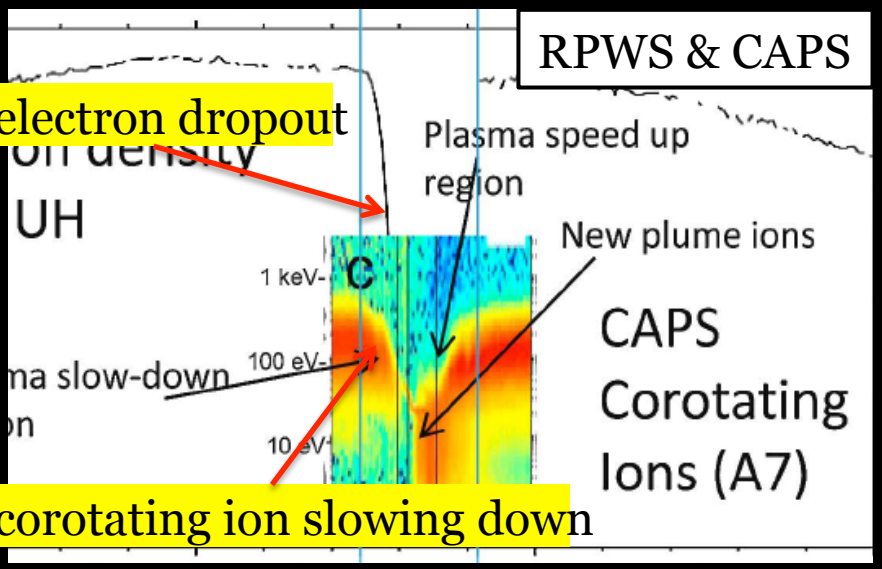
The electron density is very small (1% of ions!) because they are sucked up by the dust.

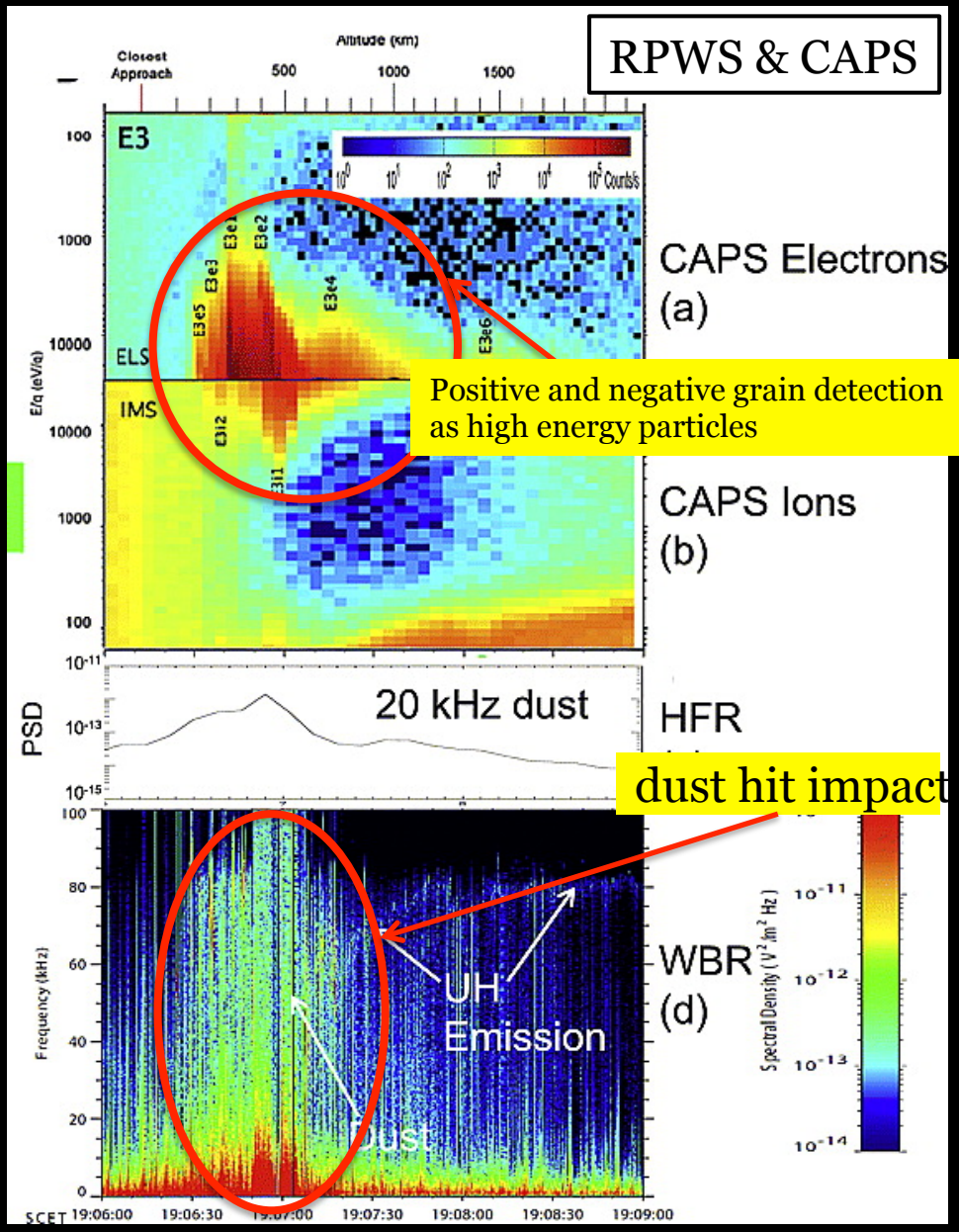


Morooka et al., [2011]

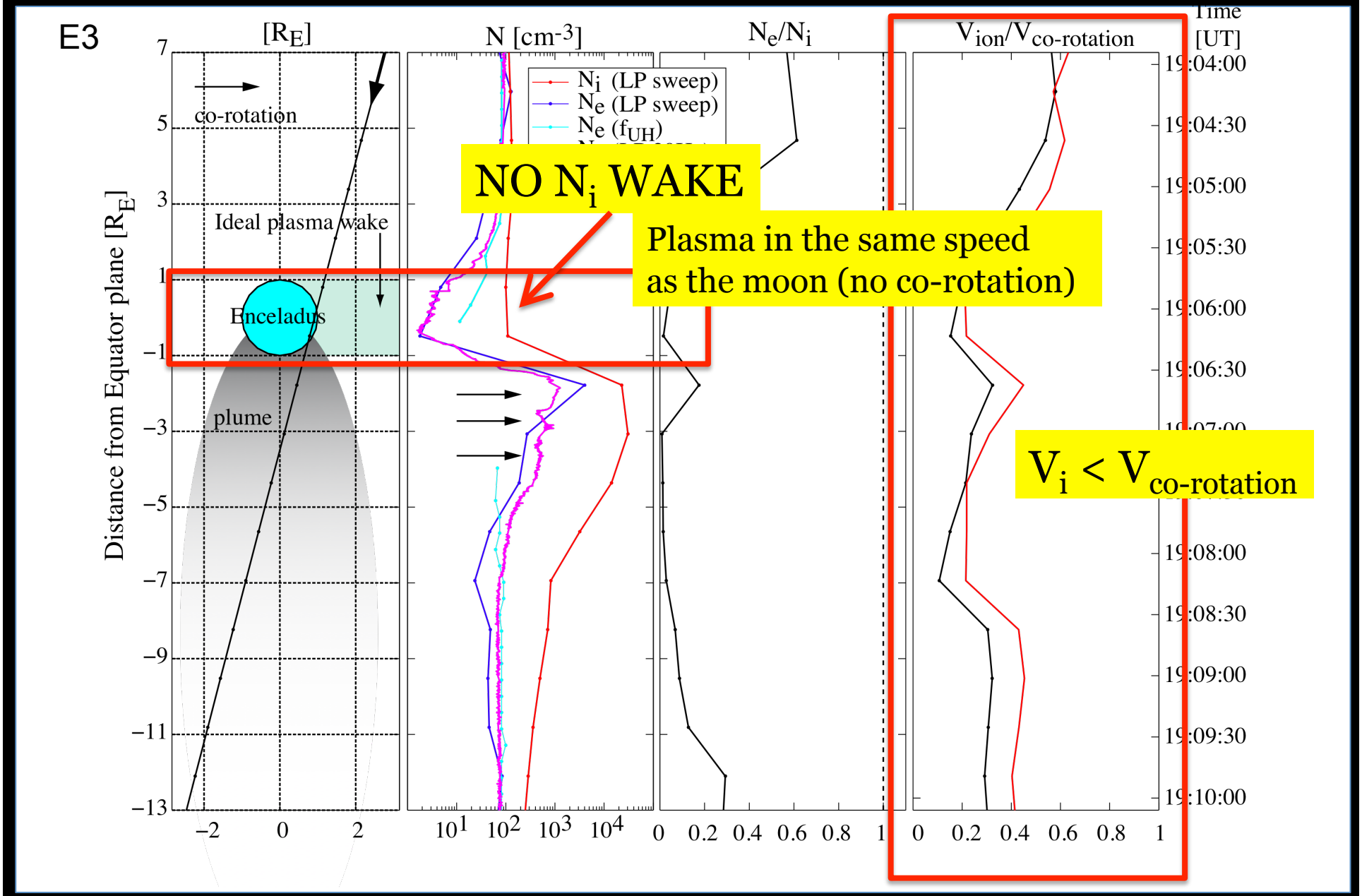
Farrell et al. [2009, 2010]







Charged dust and plasma collective effect



Dusty Plasma?

Plasma = electrons + ions

Dusty Plasma = electrons + ions + small body

↓

absorbs electron/ion and get charged

- Dust are a significant element of the Universe.
- Gravity force is usually focused for the dust dynamics.

$m_e \sim 9 \cdot 10^{-31}$ kg $m_{i\,(water)} \sim 10^{-26}$ kg

$m_d \sim 10^{-24}$ kg *(1 nm size)* 10^{-15} kg *(1 μm size)*

- Dust are affected by the electro-magnetic force when they get charged and interact with plasma.

$q_d \sim$ *few (1 nm size)* 10^3 charge (μm)

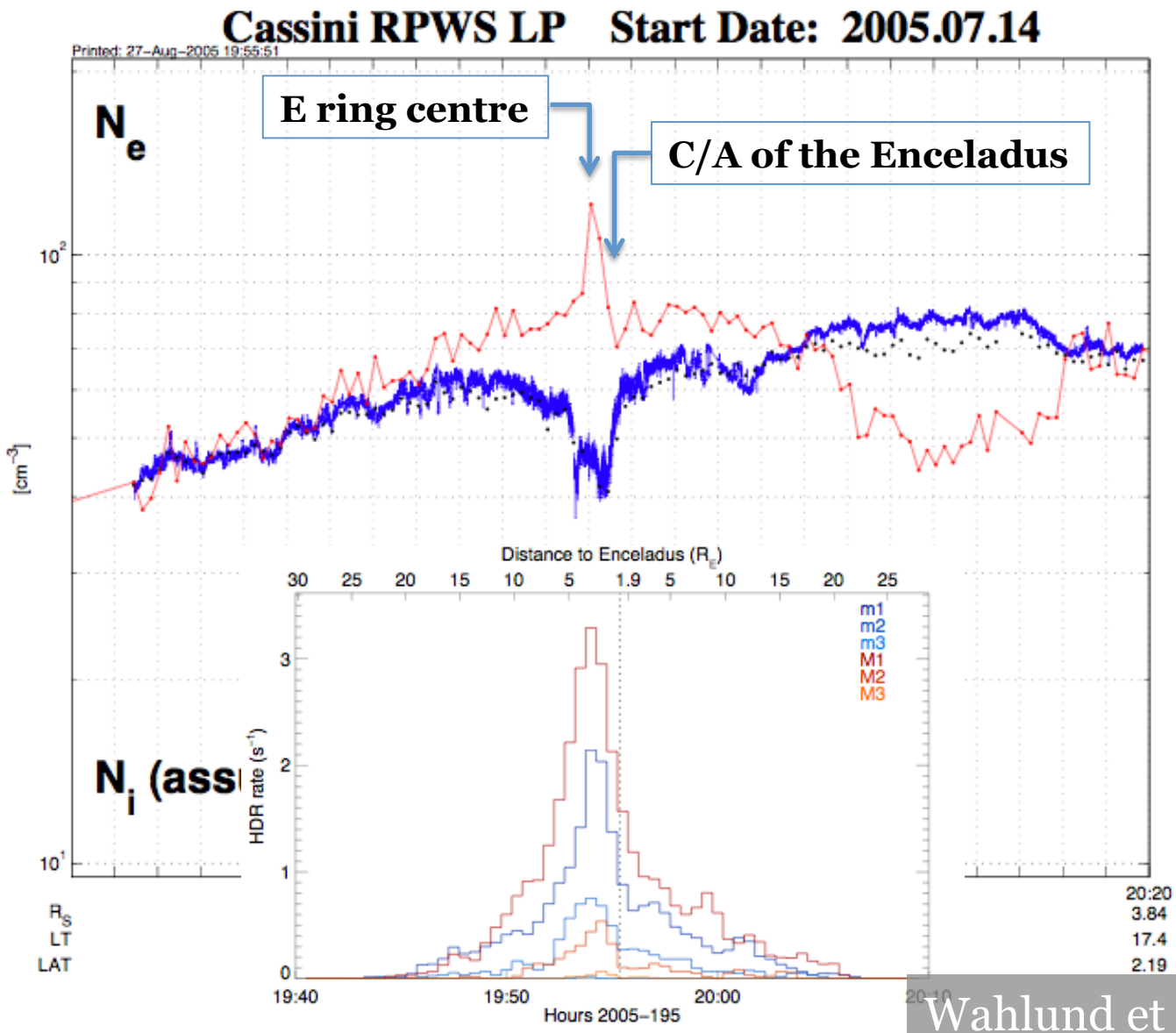
$(M/Q)_d = 10^2 \sim 10^8\,(M/Q)_{ion}$ $(m_i/m_e) \sim 10^4$

This results very low gyro-frequencies are expected:

$\Omega_d \sim 10^{-2} \sim 10^{-6}$ [Hz] at the Enceladus (B=328[nT])

r_{gd} to be $20 \sim 10^5$ [km] (r_{gi} to be 20 [km])

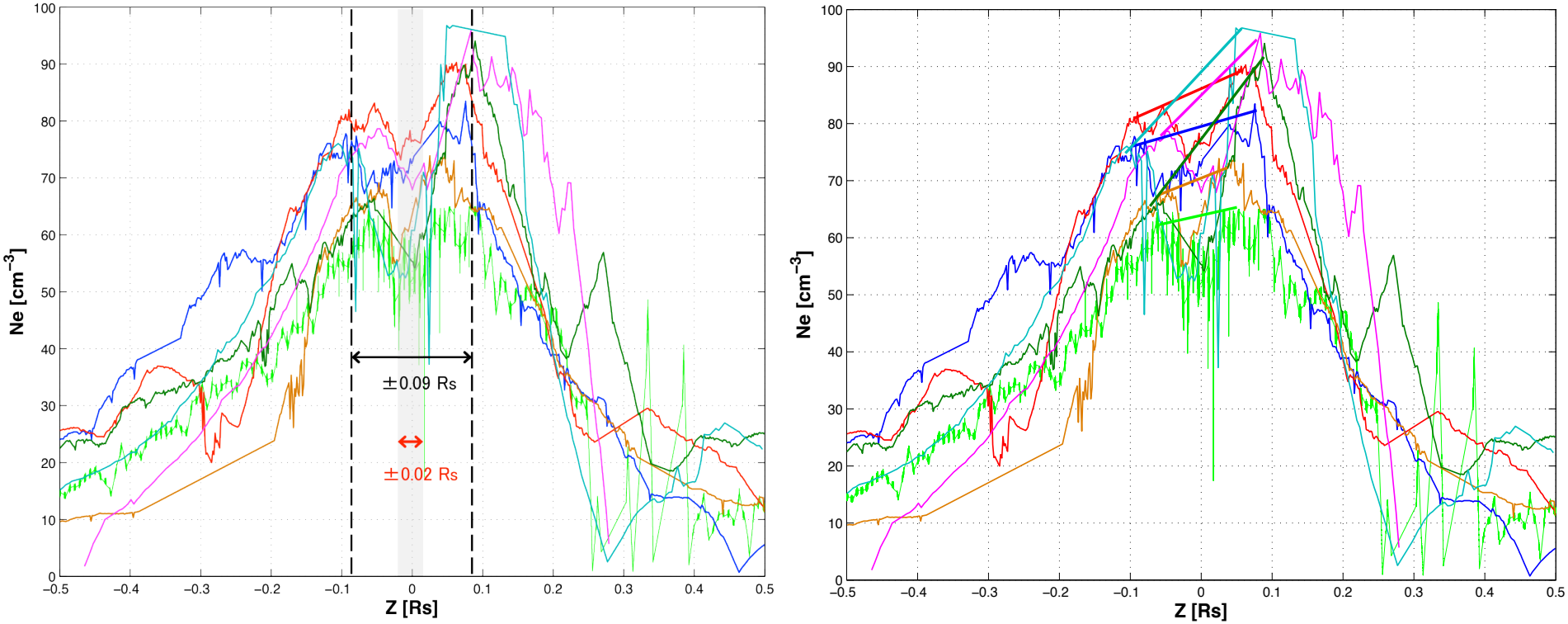
Electrons are attached to the dust near the E ring



Wahlund et al., [2009]

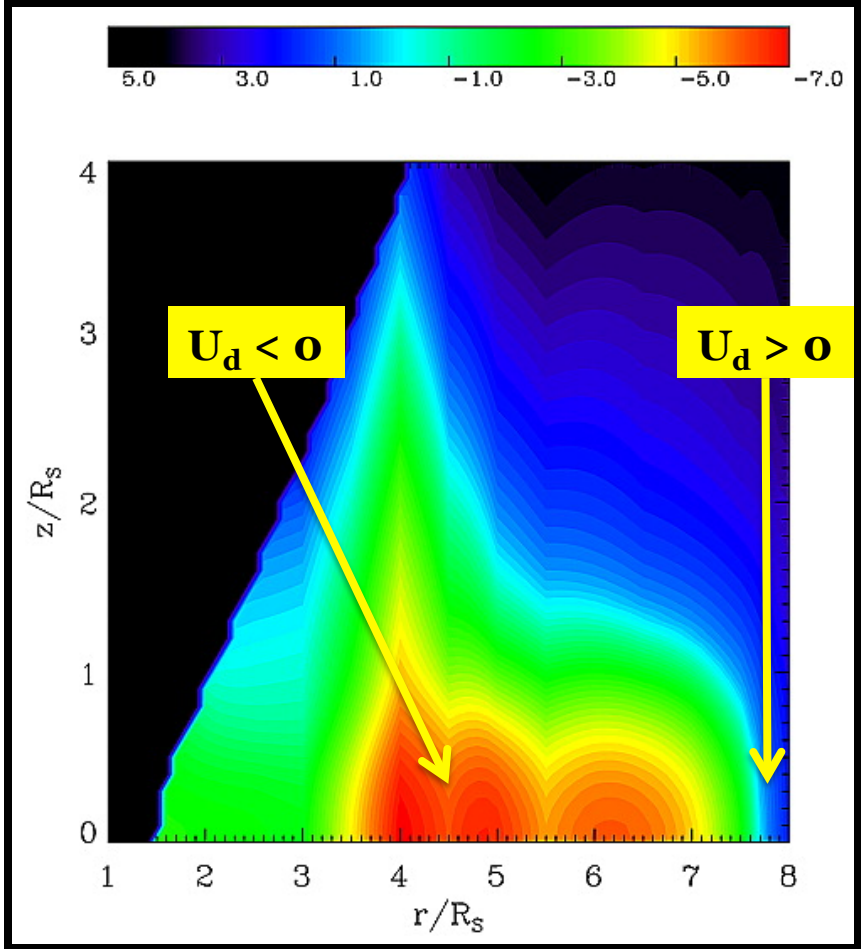
LP Statistical survey of the electron density of E ring

Odanaka et al.

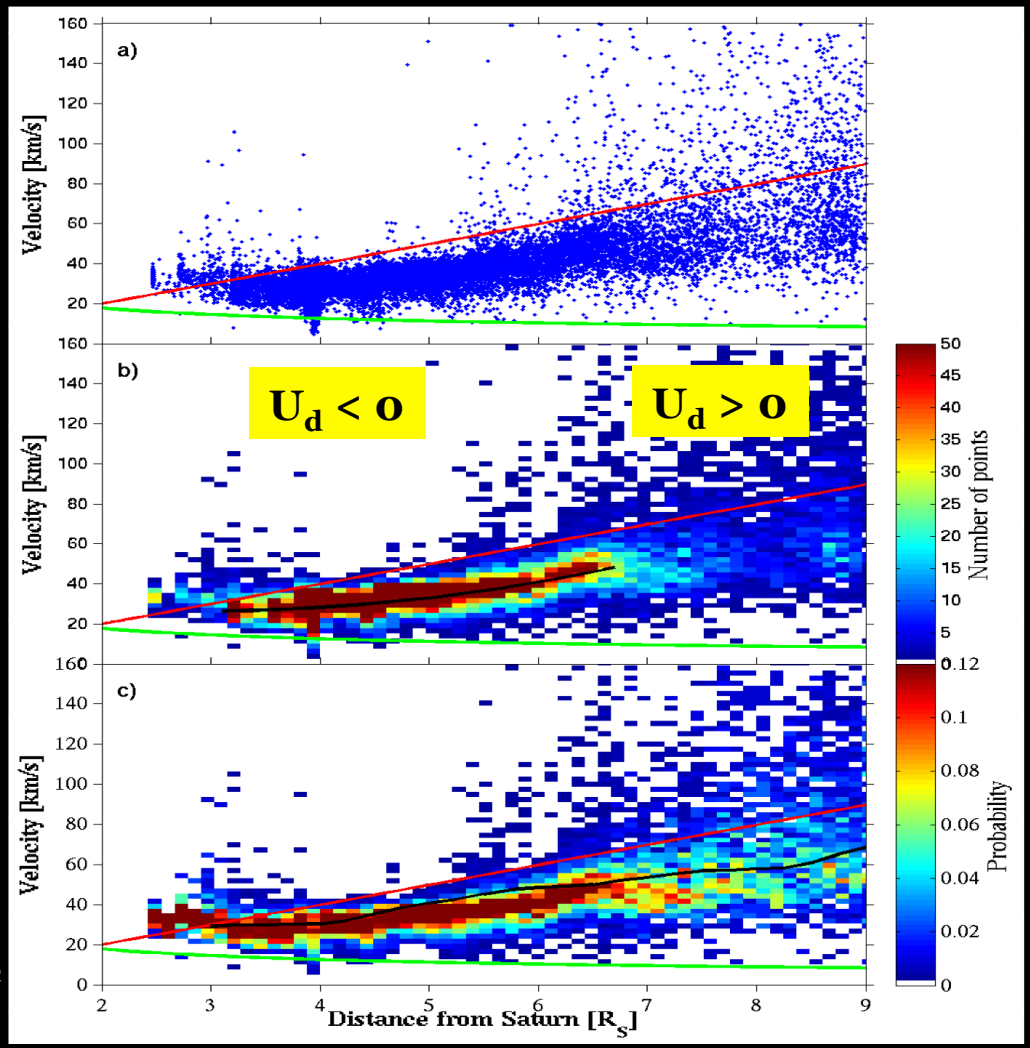


- Electron density dip is found in ~50 % of all the orbit around the Enceladus.
- Density dip centered at Z = ± 0.02 Rs
- Density dip width is about ± 0.09 Rs. … ~ E ring width.
- The north/south asymmetry of electron density.

Ion speed lower than co-rotation in a large region (dust effect?)



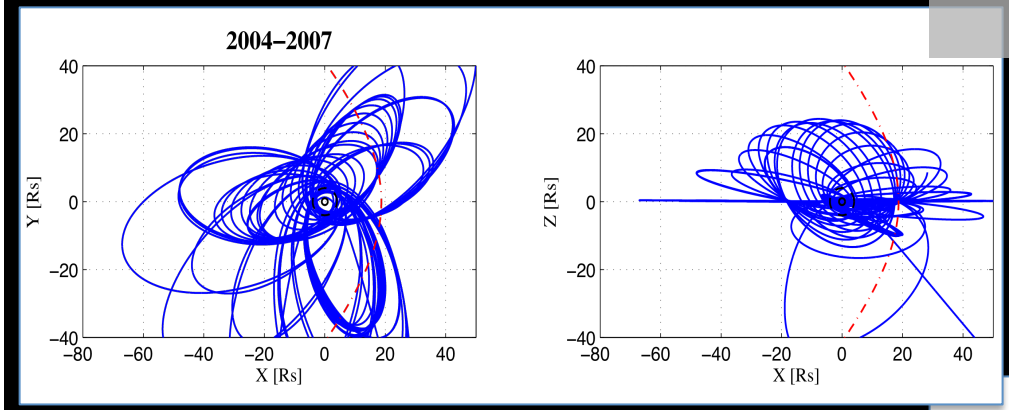
Dust potential in the Saturn's magnetosphere
Juhász and Horányi, [2002 JGR]



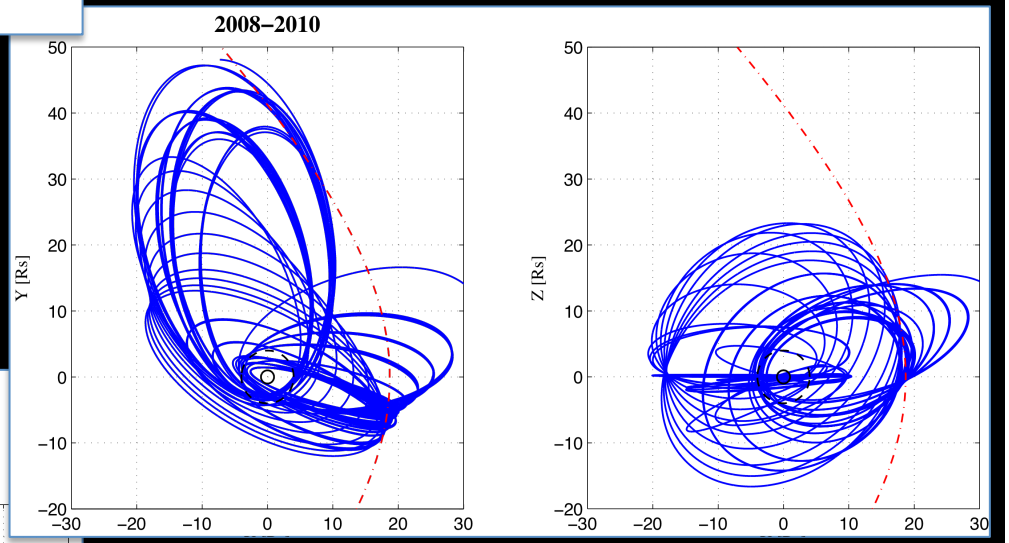
V_i in the equatorial plane ($R_Z \pm 0.5$) [Holmberg et al., 2012]

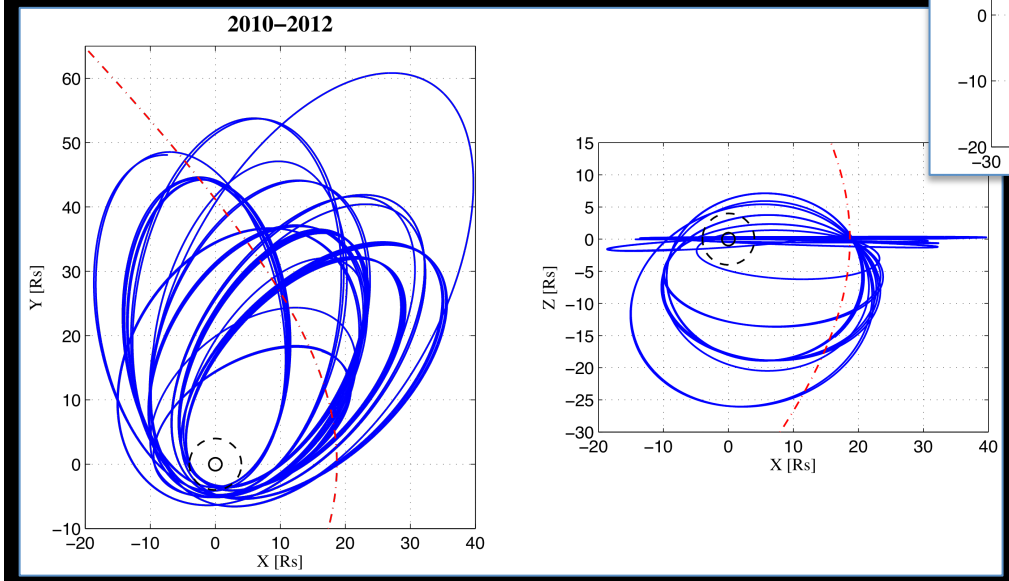
Ion outflow starts when U_d becomes positive ?

Cassini orbits around Saturn



Equinox season





Solstice season