On the role of the Ionosphere for the Atmospheric Evolution of Planets – insights from Titan

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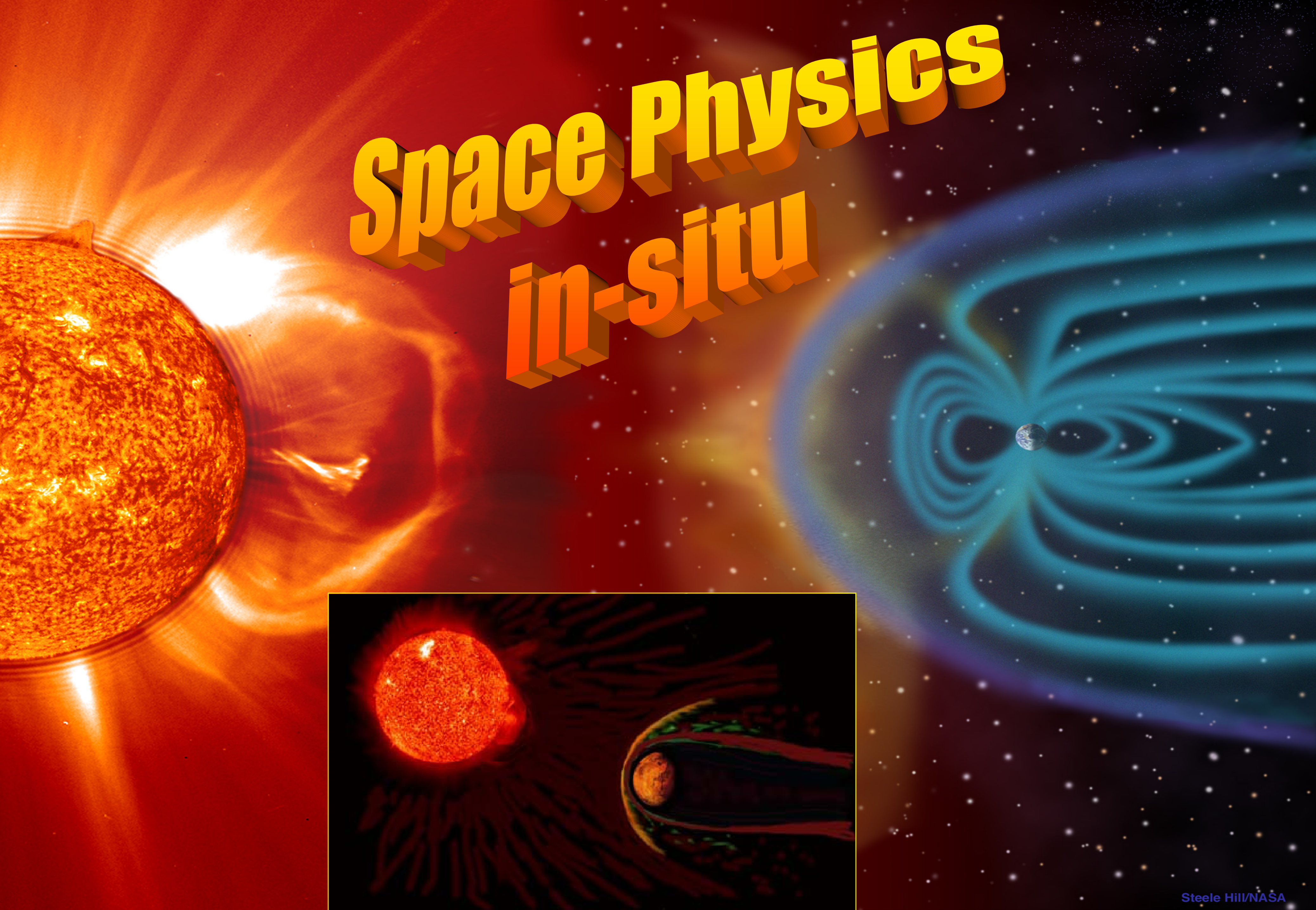
- **Brief overview of understanding**
  - **Ionospheric & Exospheric escape mechanisms**
- **Escape of plasma from the dense & expanded ionosphere of Titan**
  - **Interaction with a dynamic magnetospheric environment**
- **Titan's Ionosphere is a factory for pre-biotic building blocks**
  - **Heavy ions (>100 amu) dominate lower ionosphere**
  - **Negative ions & Aerosol formation**

NORDITA, Stockholm, January 11, 2008

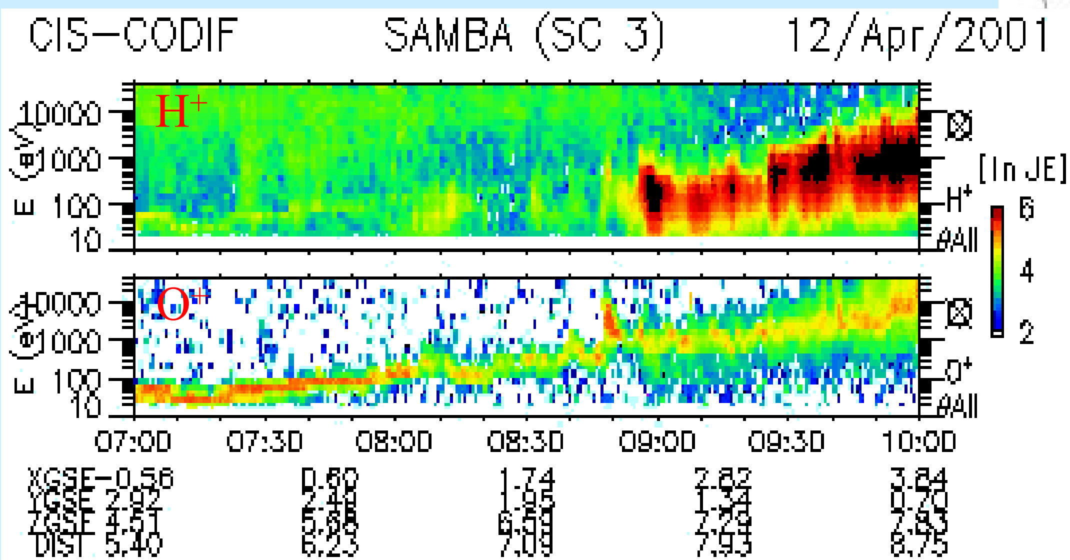

Space Physics
in-situ
Steele Hill/NASA

Brief Overview of Understanding

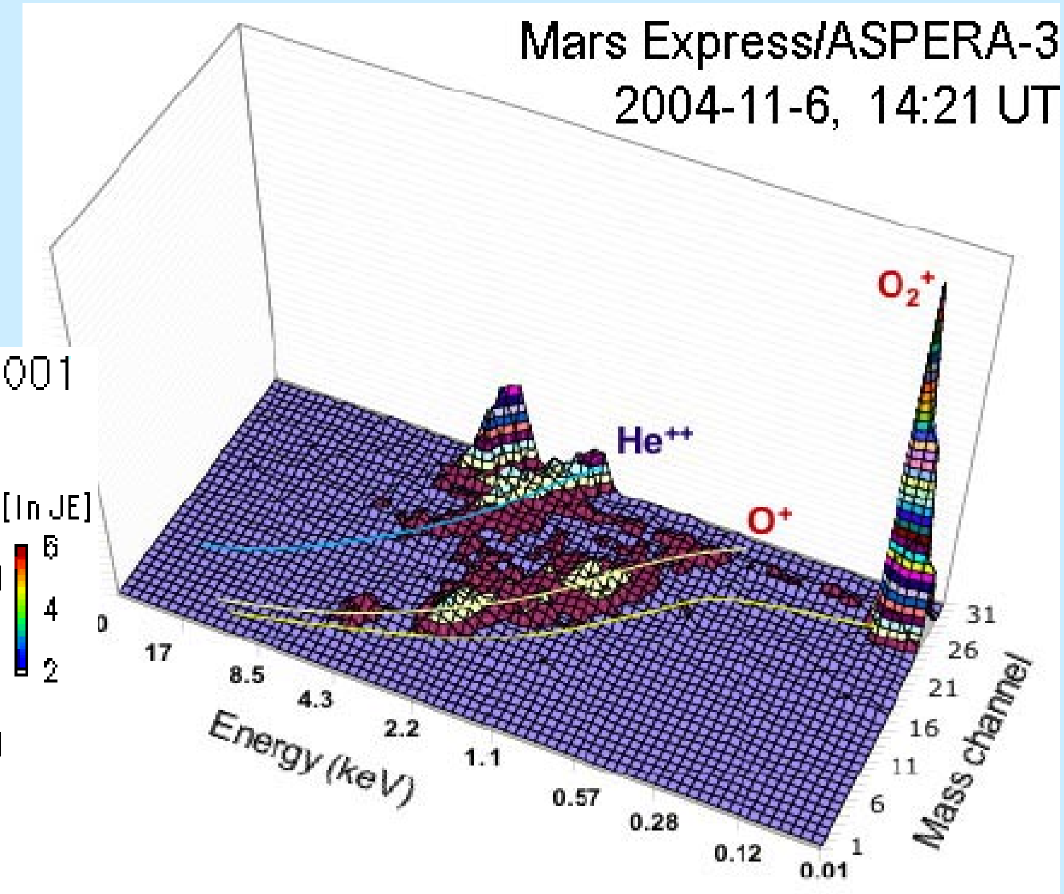
- Jeans escape
  - Thermal tail exceeds escape speed
  - Thermal, affects mostly light neutrals (H, He)
- Hydrodynamic blow-off
  - Extreme EUV condition at early Sun/star
  - Thermal
- Photochemical heating
  - Release of energy in excited states
  - Chemical, light neutrals
- Ion pick-up (subsequent sputtering)
  - Exposed ions in the SW is subject to SW $\mathbf{E}_{DC}$
  - Non-thermal, favours light ions
- Non-thermal ion energization by $\mathbf{E}_{||}$ & plasma waves
  - Local deposit of SW energy to ionosphere cause an electrodynamic coupling that accelerates ions
  - Both heavy and light ions
- Large scale momentum transfer
  - SW $p_{dynamic}$ & EM forces “push” bulk plasma anti-sunward at boundary region
  - Non-thermal, both heavy & light ions

Non-thermal Escape

- Escape rates at Solar Maximum (15000-60000 ton/yr)
  - Mars: 0.5 kg/s (O^+, O_2^+)
  - Venus: 2 kg/s (O^+)
  - Earth: 1 kg/s (O^+)



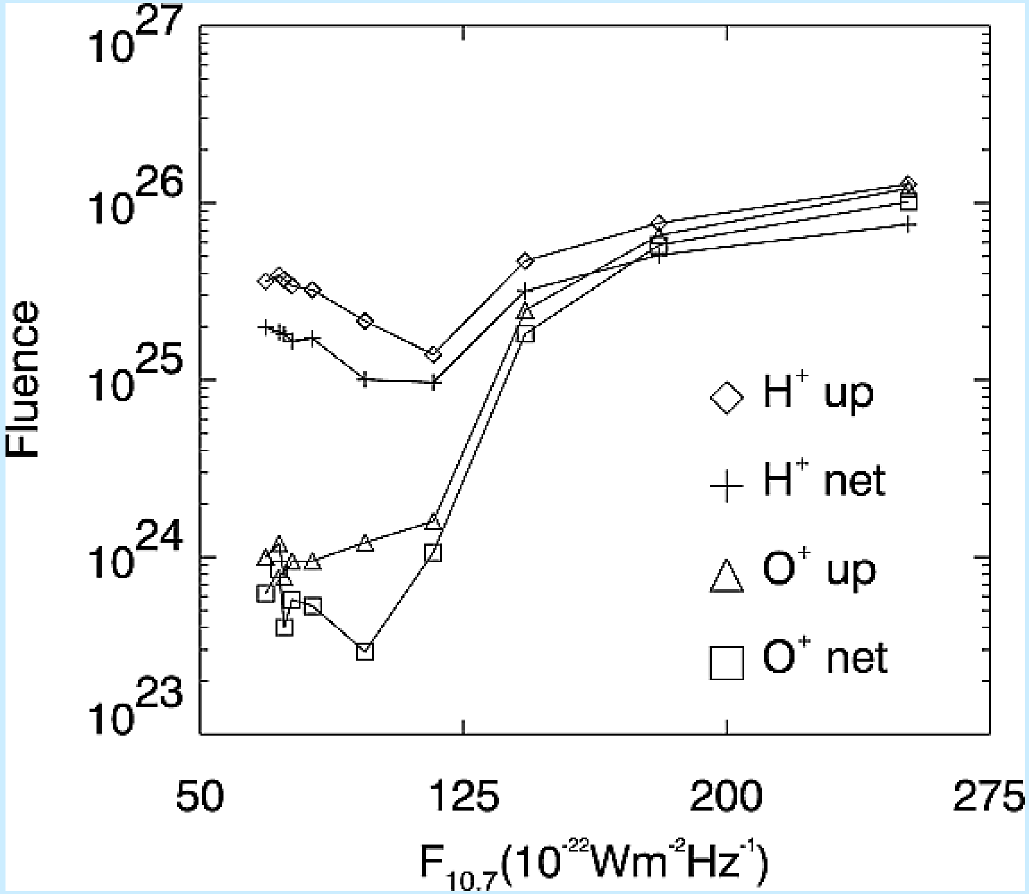
CLUSTER/CIS, [Nilsson et al., 2004]



[Lundin et al., 2004]

Dependence on Solar Activity ($F_{10.7}$)

- Solar activity Max/Min ~ 3
- Earth:
  - O^+ outflow ~ 100 variability
  - H^+ outflow ~ 3 variability
  - Large contribution to O/H-ratio
  - Large O/H at early Earth?
- Venus:
  - Factor 20 change in ionotail density
- Mars:
  - A factor 100 difference between MEX & Phobos-2

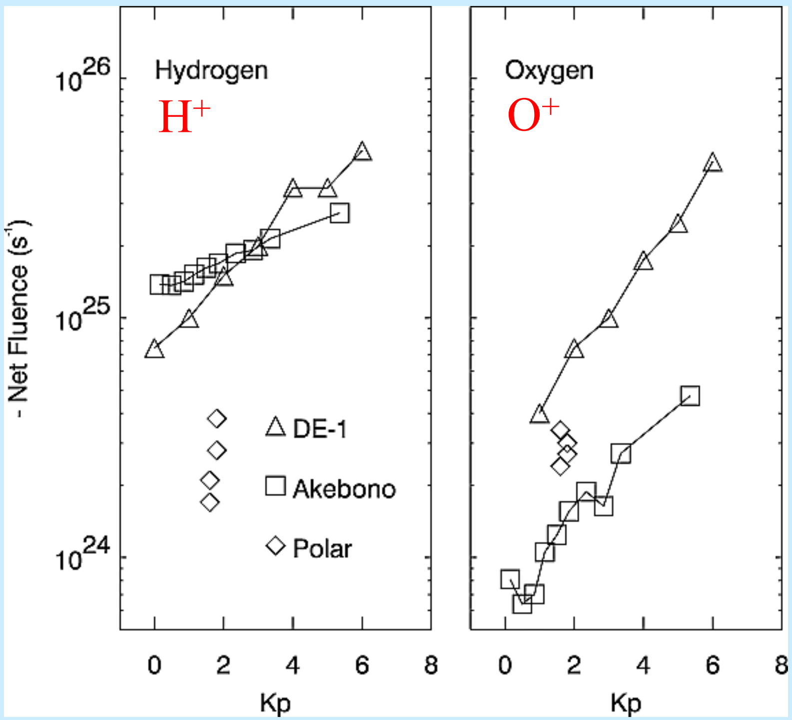


CLUSTER, [Cully et al., 2003]

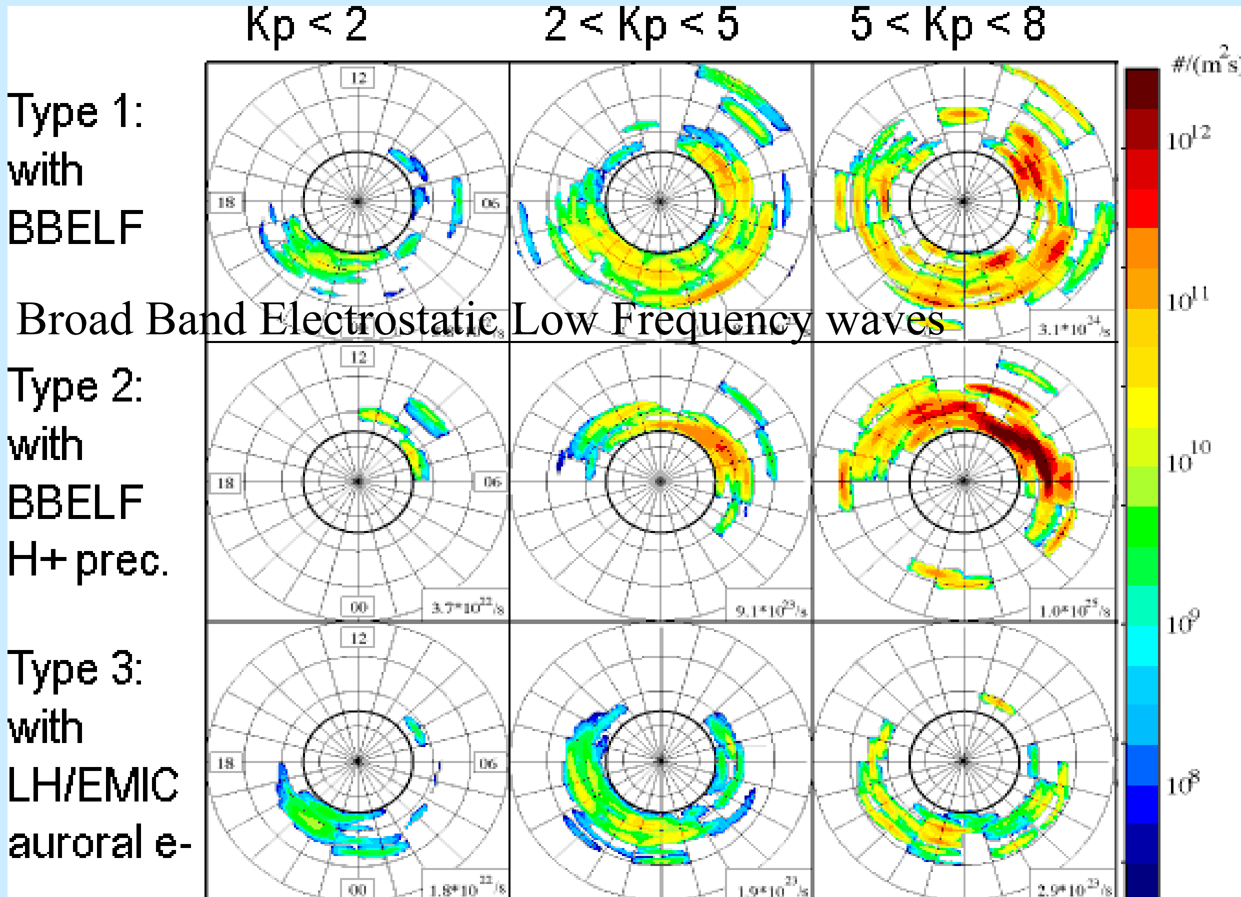
Dependence on Geomagnetic Activity

- Strongly on K_p, SW $p_{dynamic}$, and IMF

Akebono/DE/Polar
[Cully et al., 2003]



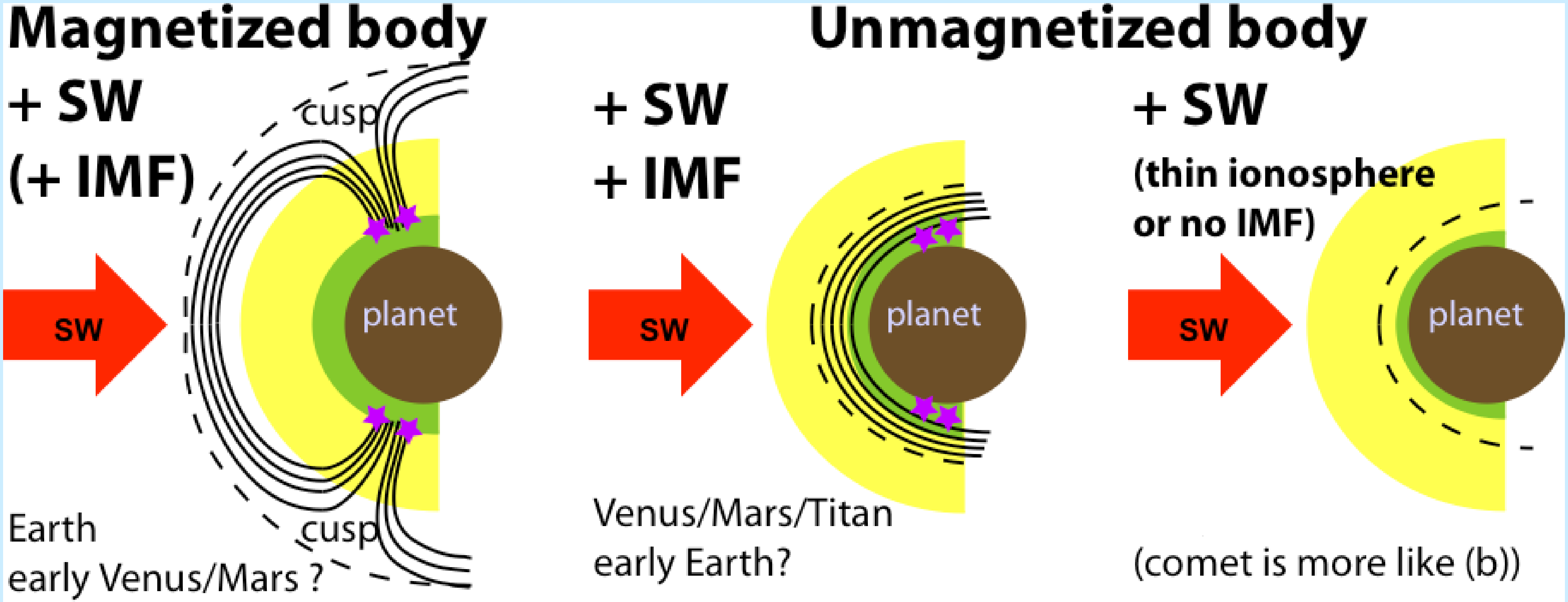
Freja, 1700 km, [Nordqvist et al., 1998]



Broad Band Electrostatic Low Frequency waves

Lower Hybrid & Electromagnetic Ion Cyclotron waves

SW interaction with Atmosphere



- Early Earth?
- SW stopped by the magnetic pressure of the planetary $\mathbf{B}_{\mathrm{Dipole}}$

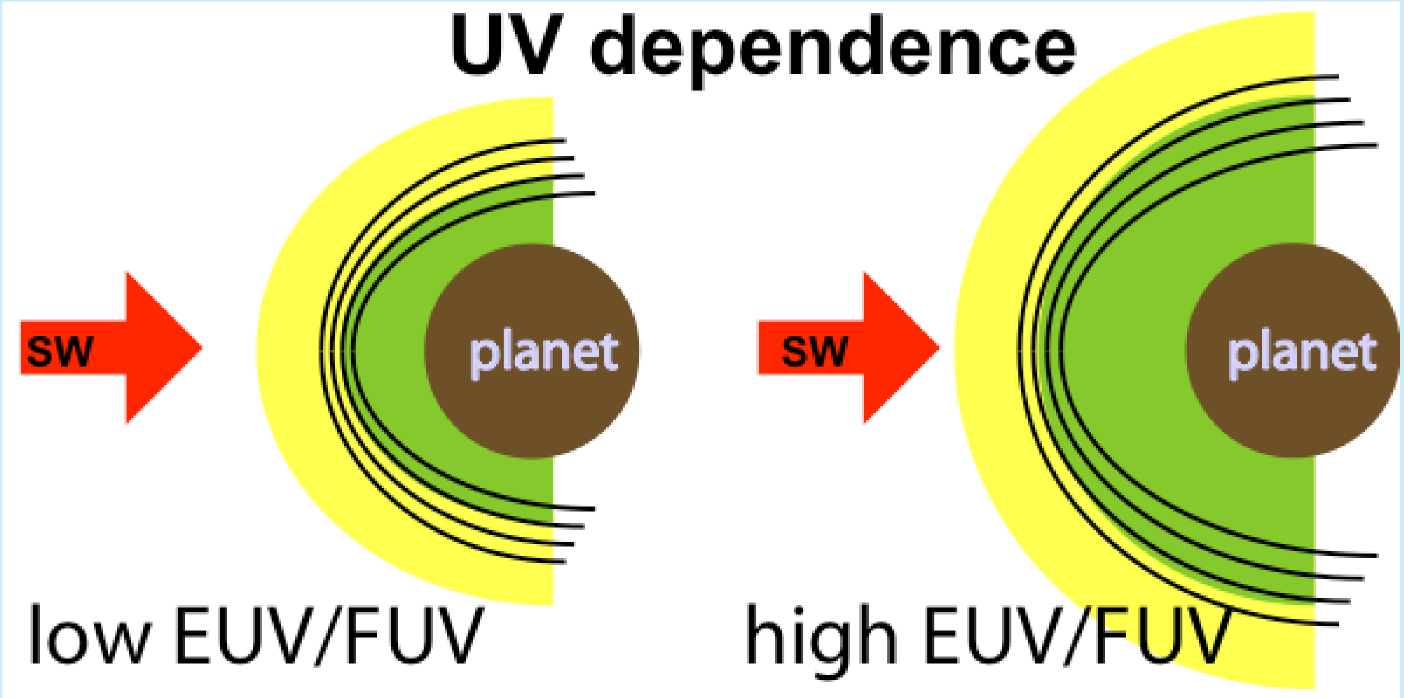
- Early Earth?
- Interplanetary magnetic field (IMF) enhanced around ionosphere due to induction currents (magnetic pile-up)

- Galiean moons: Europa, Callisto, Ganymede

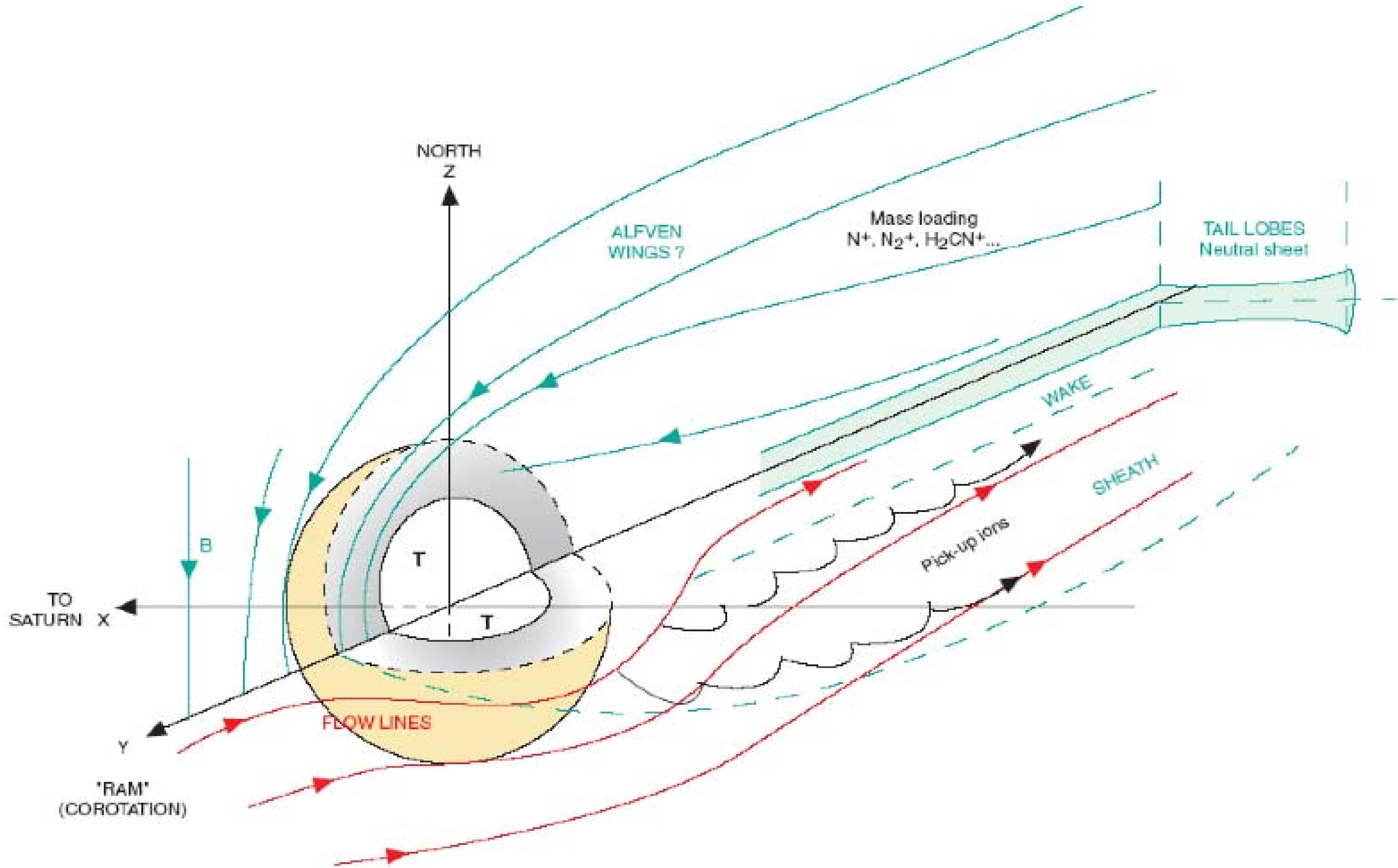
Strong magnetic field between ionosphere & (shocked) SW

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Ionopause is EUV/FUV dependent

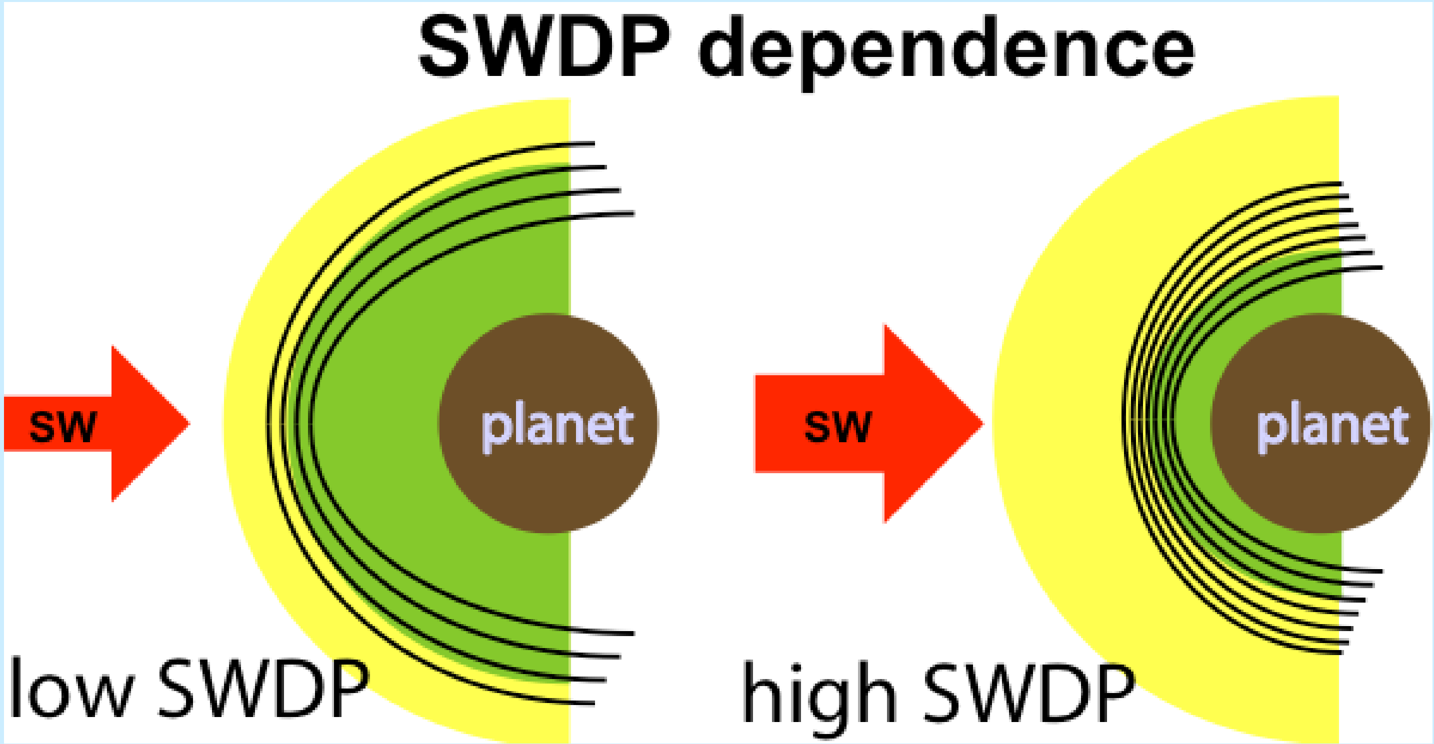


- Solar cycle variation of ionopause altitude
- Venus (& Mars):
  - 1700 km difference [Zhang et al., 2007]
- Extended exosphere/atmosphere => Higher ionization rate (by EUV/energetic particles) => Ionization of otherwise escaping neutrals => trapped by magnetized ionopause/magnetopause =>
- Reduction of Jeans escape (mostly H, He)
- Higher ionopause => less neutrals beyond => Reduction of ion pick-up



NORTH
Z
ALFVEN
WINGS ?
Mass loading
N+, N2+, H2CN+...
TAIL LOBES
Neutral sheet
WAKE
SHEATH
B
T
T
Pick-up ions
TO
SATURN X
FLOW LINES
Y
"RAM"
(COROTATION)

SW dependence of ionopause altitude

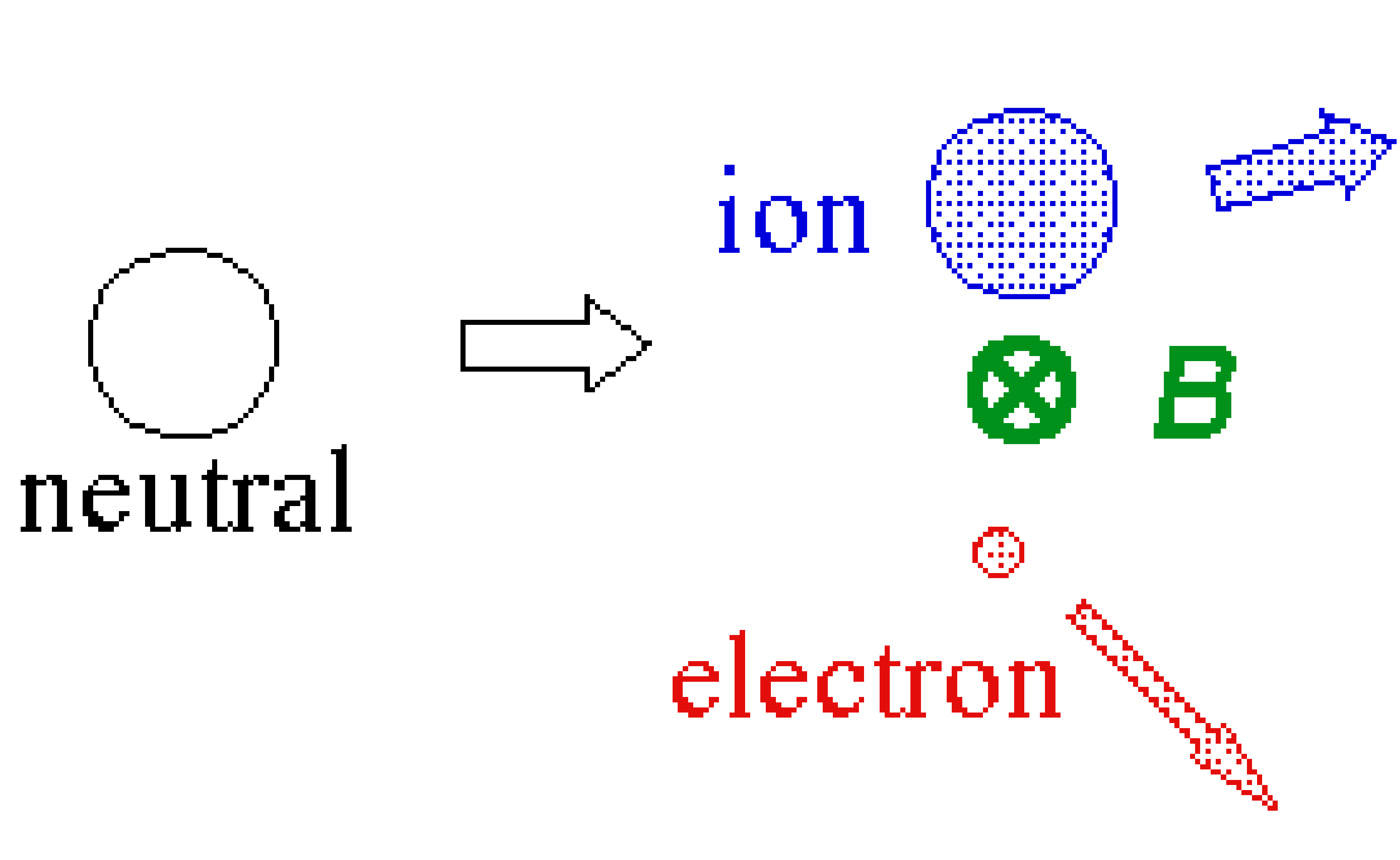


- Expect:

1. Strong & stable IMF => No change
2. Variable IMF => Lower pressure balance altitude (cancel B)
3. Strong SW $p_{dynamic}$ => Lower pressure balance altitude

Exra ionization (hot case)

- Critical Ionization Velocity (CIV)



Early Earth Ionosphere

- Most likely high EUV/FUV
- Most likely high SW $p_{dynamic}$
- Probably strong/active IMF

⇒Larger O escape & larger O/H-ratio escape then present

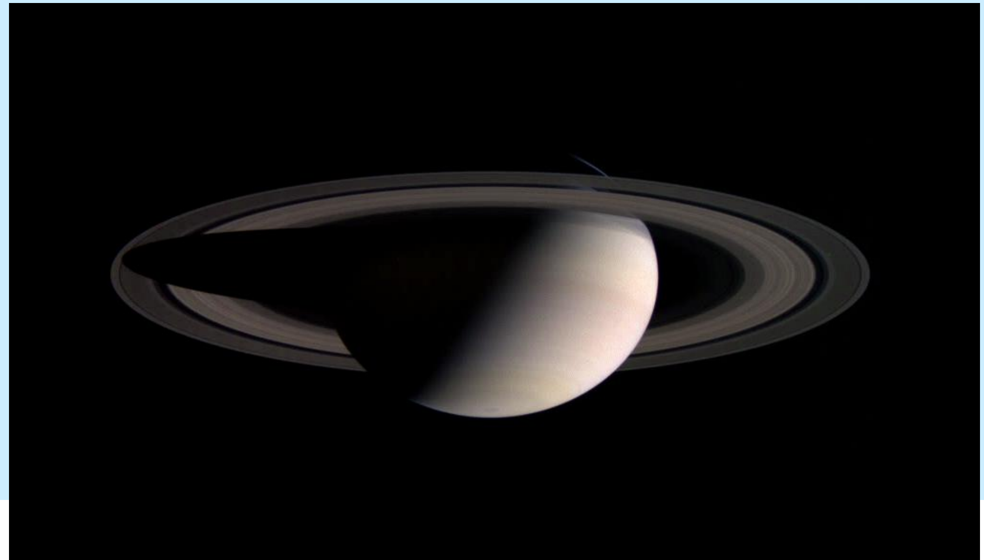
⇒The Early Atmosphere could have been chemically reduced

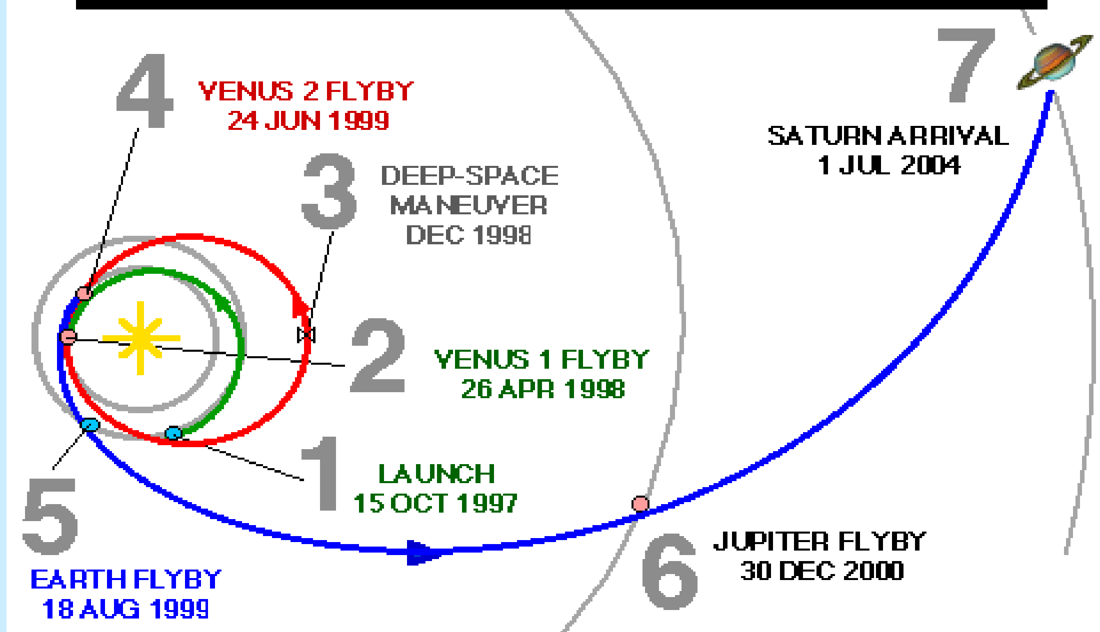
Many unclear parameters!

- Magnetized/Non-magnetized
- Atmospheric composition
- Internal conditions

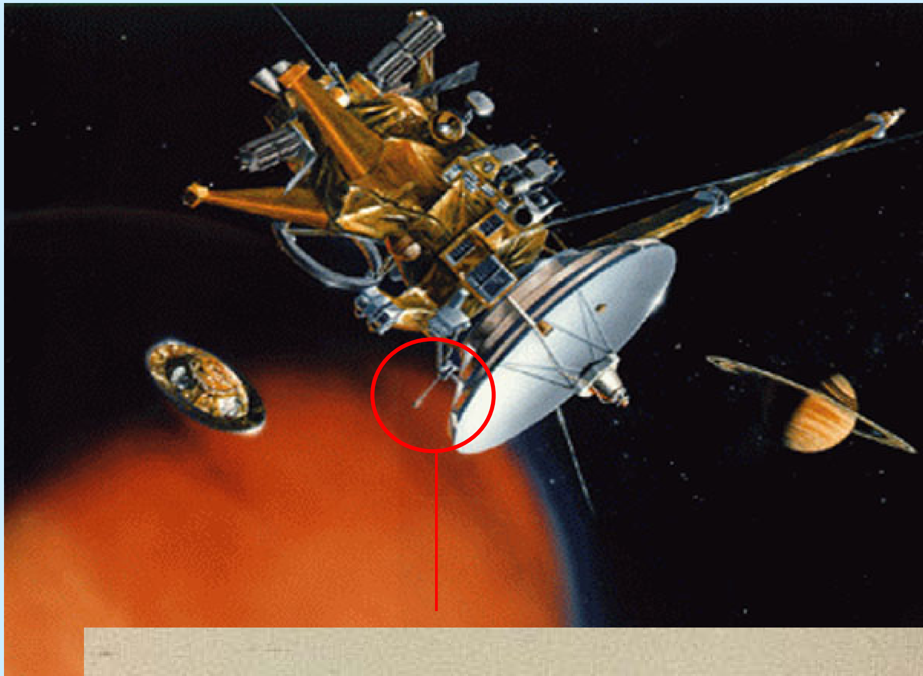
Dense & Expanded Ionosphere of Titan

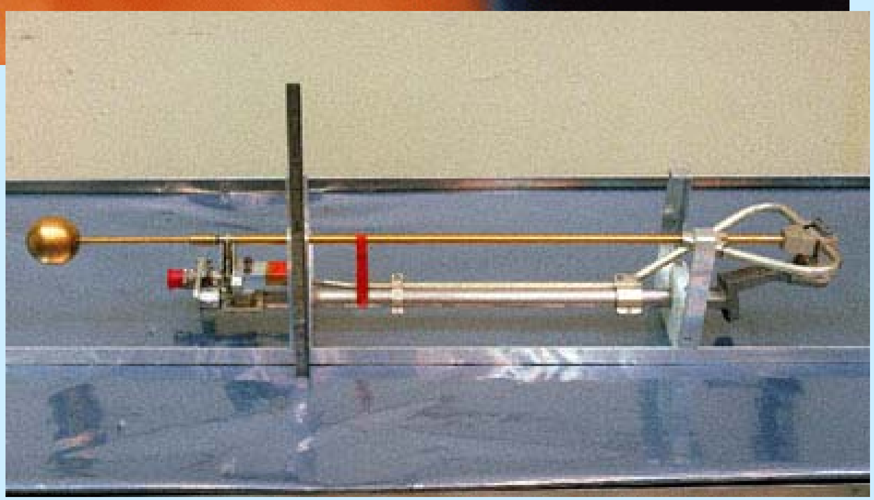
Cassini/Huygens to Saturn





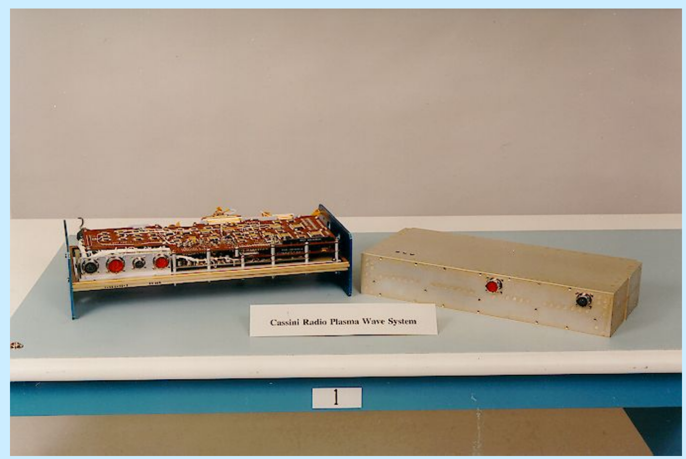
Cassini RPWS LP
Mätningar av plasma





- Langmuirsond (LP)
- ”Väderstation” för elektriskt laddad gas
  - Mycket noggrann Ampere-meter
  - Några pA känslighet

  - Densitet
  - Temperaturer
  - Hastighet
  - Rymdfarkostladdning
  - Sammansättning (grov)



Langmuir Probe theory (brief)

LP measures currents: $$I = I_i + I_e + I_{ph,Ly-\alpha} + I_{e*,i*} + I_{dust}$$

From OML theory (with Maxwellian distribution function, Fahlesson approximation):

U < 0

$$I_e = I_{e0}\exp(-\chi_e) \ll$$

$$I_i = I_{i0}(1-\chi_i)$$

U > 0

$$I_e = I_{e0}(1-\chi_e)$$

$$I_i = I_{i0}\exp(-\chi_i) \ll$$

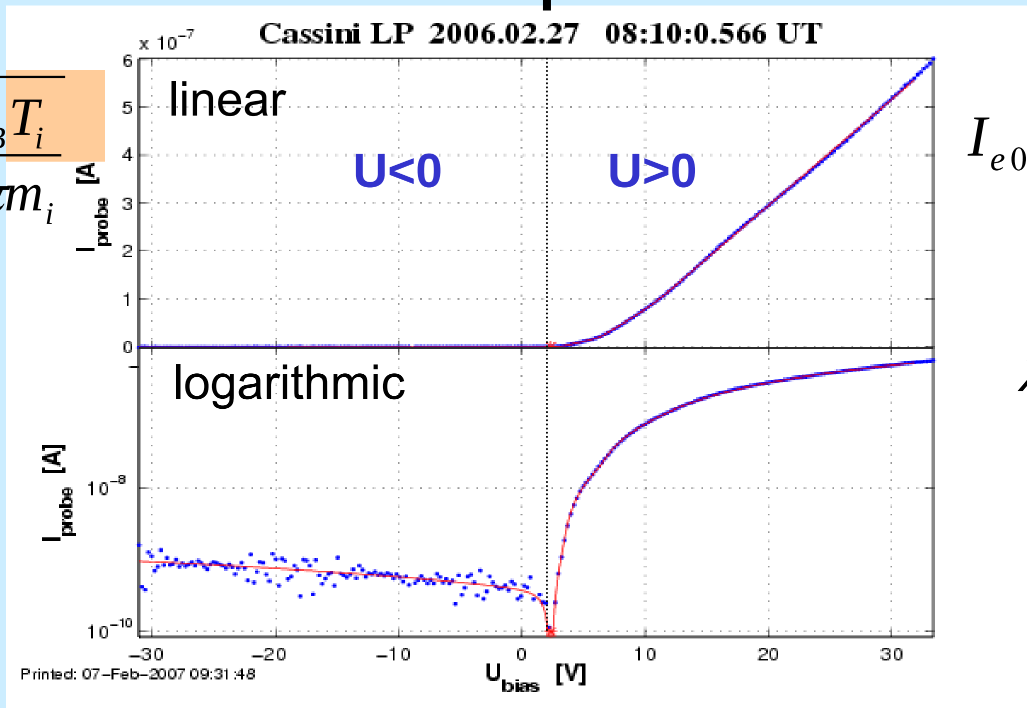
with

$$I_{i0} = A_{LP} n_i q_i \sqrt{\frac{v_i^2}{16} + \frac{k_B T_i}{2\pi m_i}}$$

$$\chi_i = \frac{e(U_{bias}+U_{SC})}{\frac{m_i v_i^2}{2} + k_B T_i}$$

$$I_{e0} = A_{LP} n_e q_e \sqrt{\frac{k_B T_e}{2\pi m_e}}$$

$$\chi_e = \frac{e(U_{bias}+U_{SC})}{k_B T_e}$$

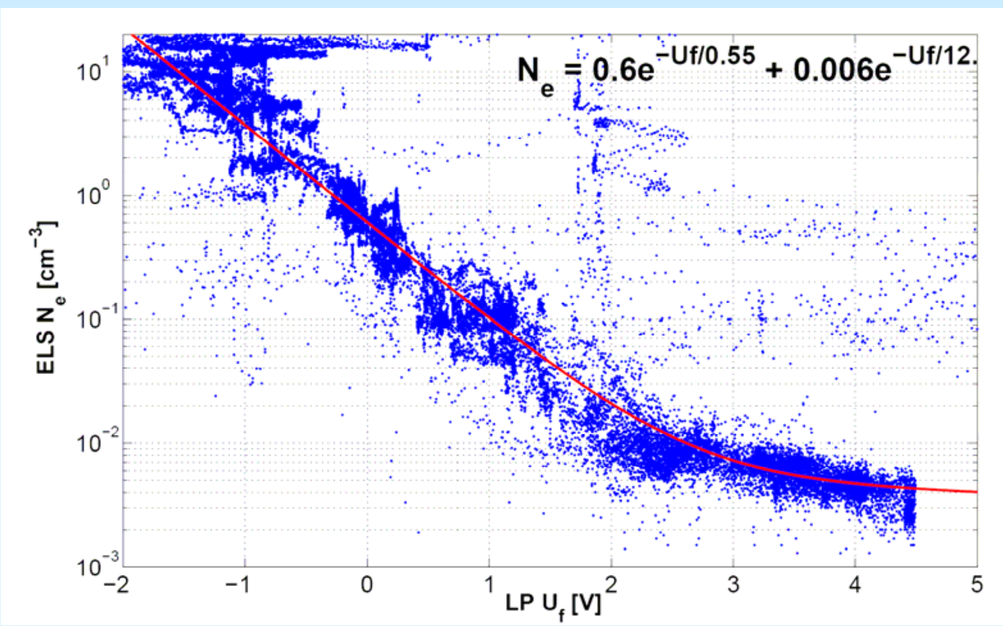


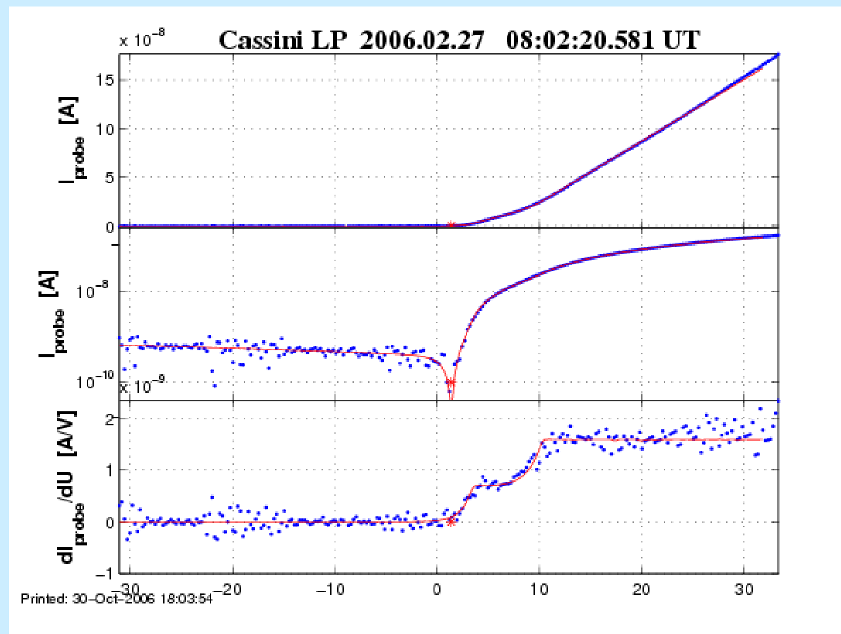
+ *Ly-α intensity fr.* I_{ph}

n_e-Estimation from the LP

- LP well designed for dense/cold plasma
- S/C photo-e^- contaminate for low densities

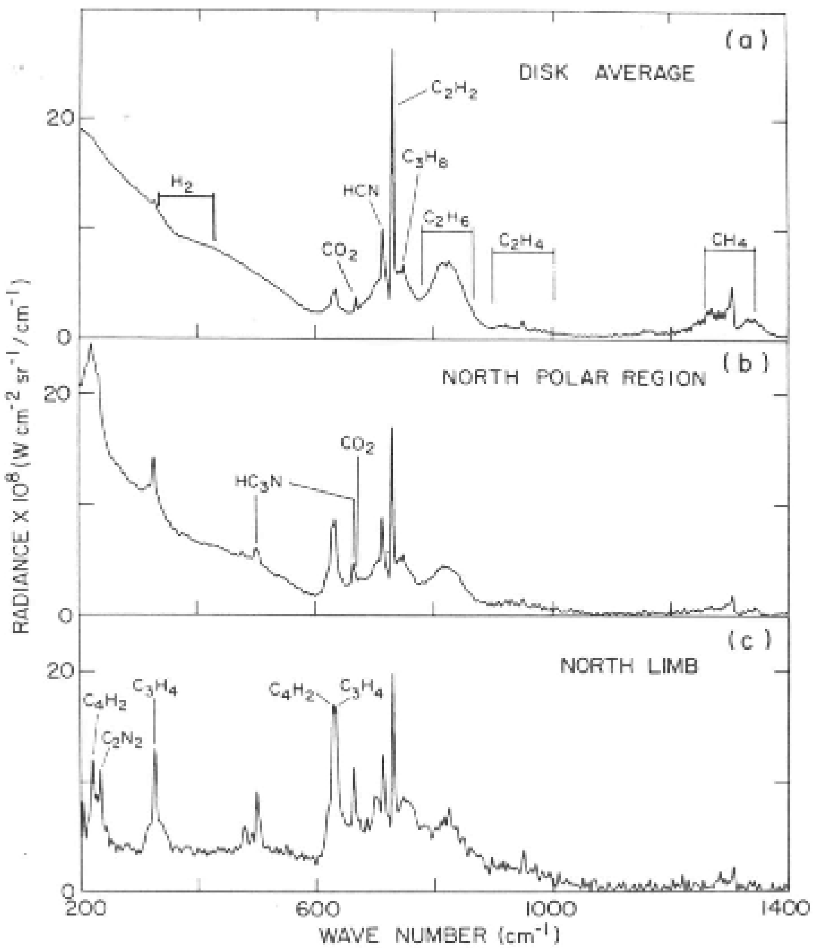
- $n_e < 5\ cm^{-3}$
  - U_{float} derived from sweep analysis
  - N_e deduced from ELS-LP empirical relationship (proxy)
- $n_e > 5\ cm^{-3}$
  - Assume we have at least two e^- populations (photo-e^-, ambient)
  - Can be identified in dI/dU



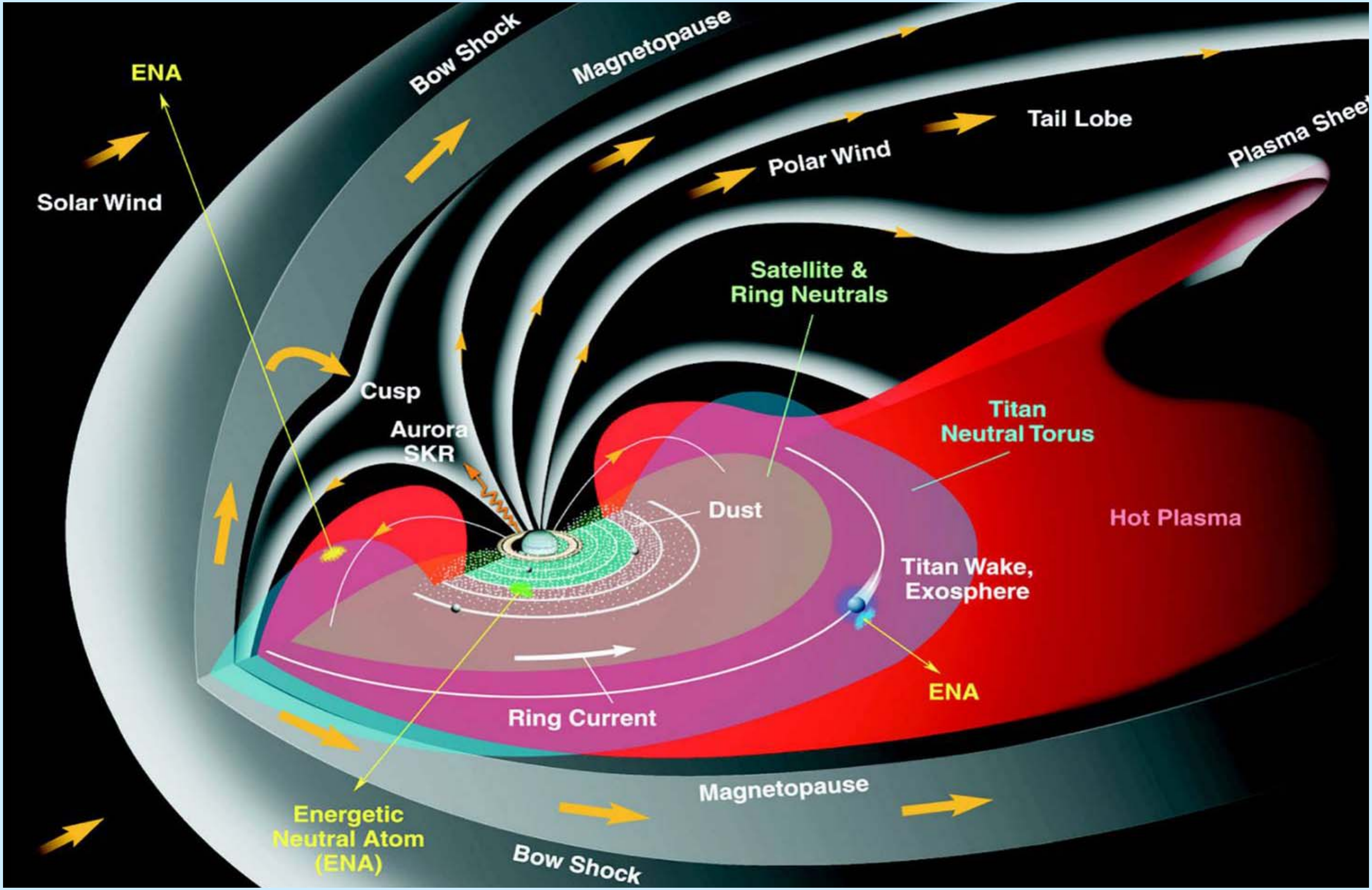


Titan

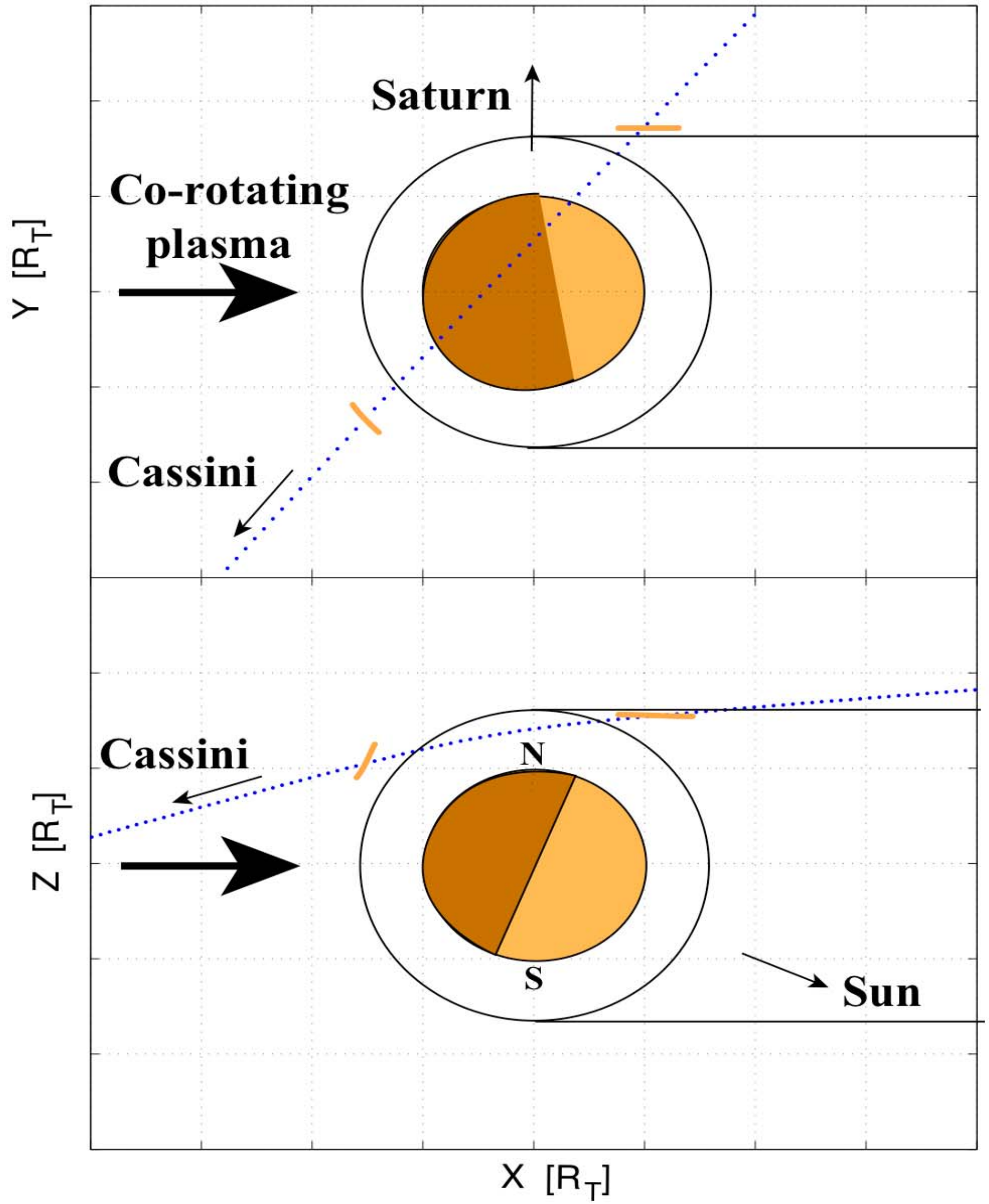
- Voyager-1 (1981)
  - Thick Atmosphere
    - 1.5 bar
    - N_2 82-98%
    - CH_4 2-8%
    - Ar few %?
- Thick Organic Haze

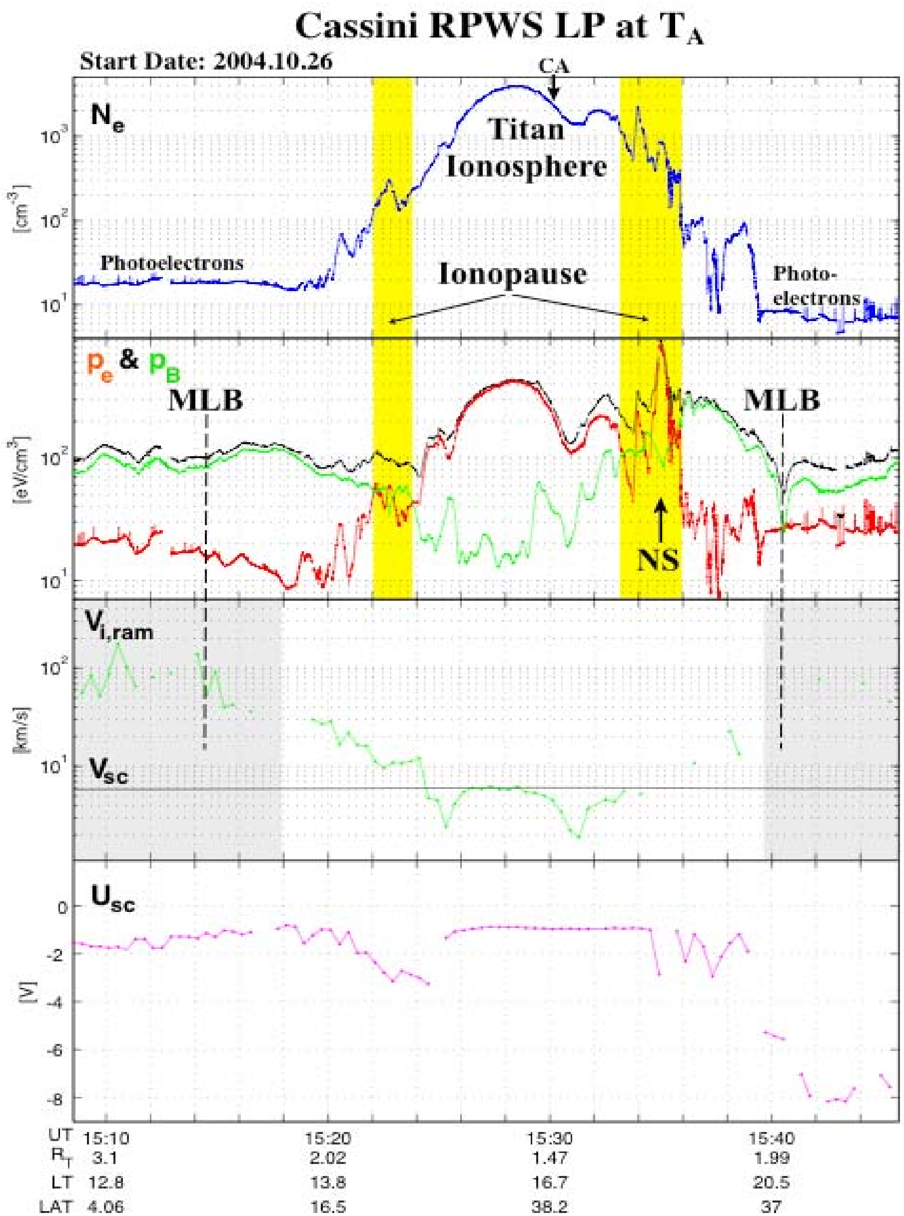


Saturn’s Magnetosphere



T5 Flyby Geometry





Ionosphere of Titan

Max $n_e = 3800\ \mathrm{cm}^{-3}$

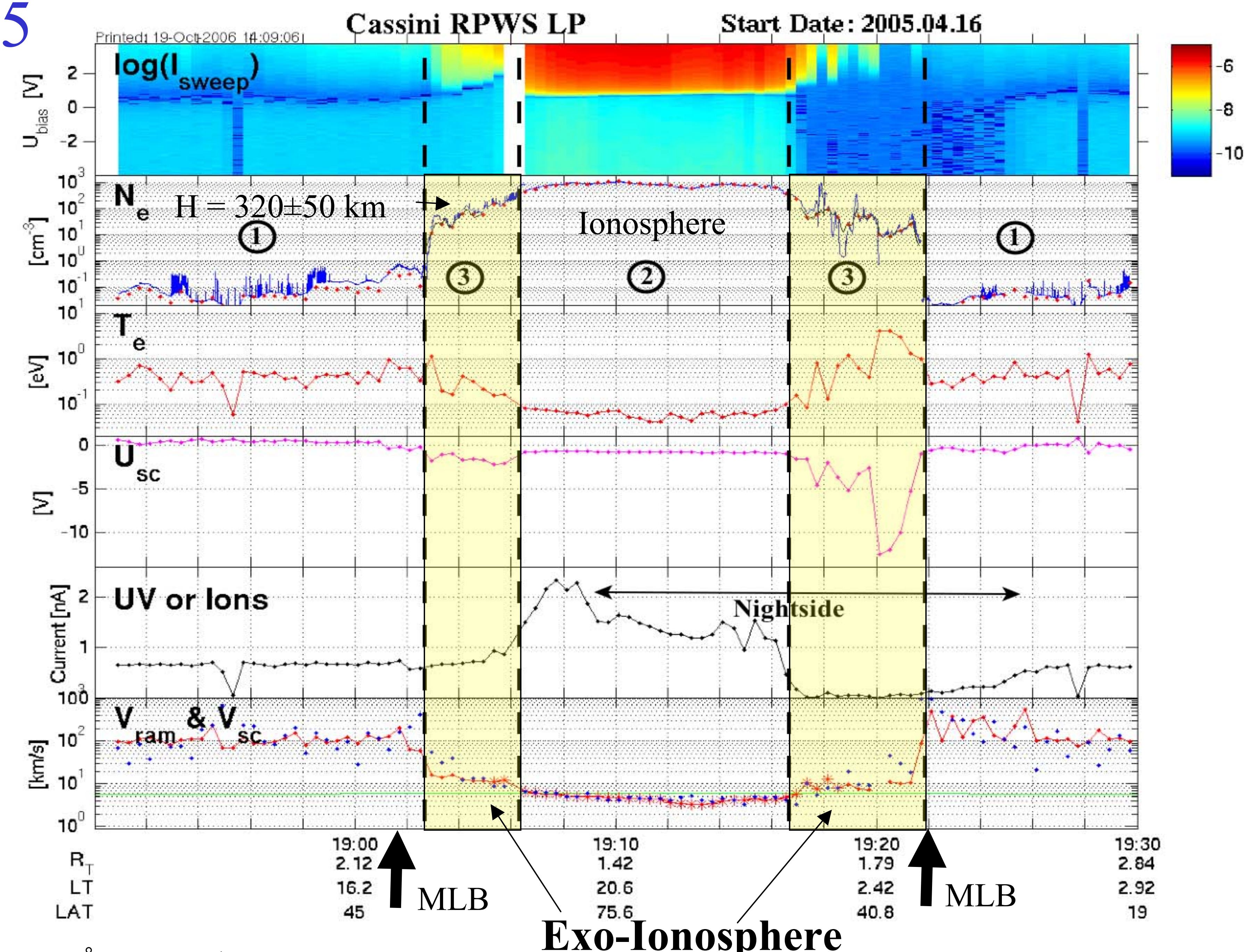
Escape Flux (Cyl.)

$\int n_e v_i \sim \text{few} \times 10^{25}$ ions/s

$\approx$1-2 kg/s

Wahlund et al., *Science*, 2005

T5

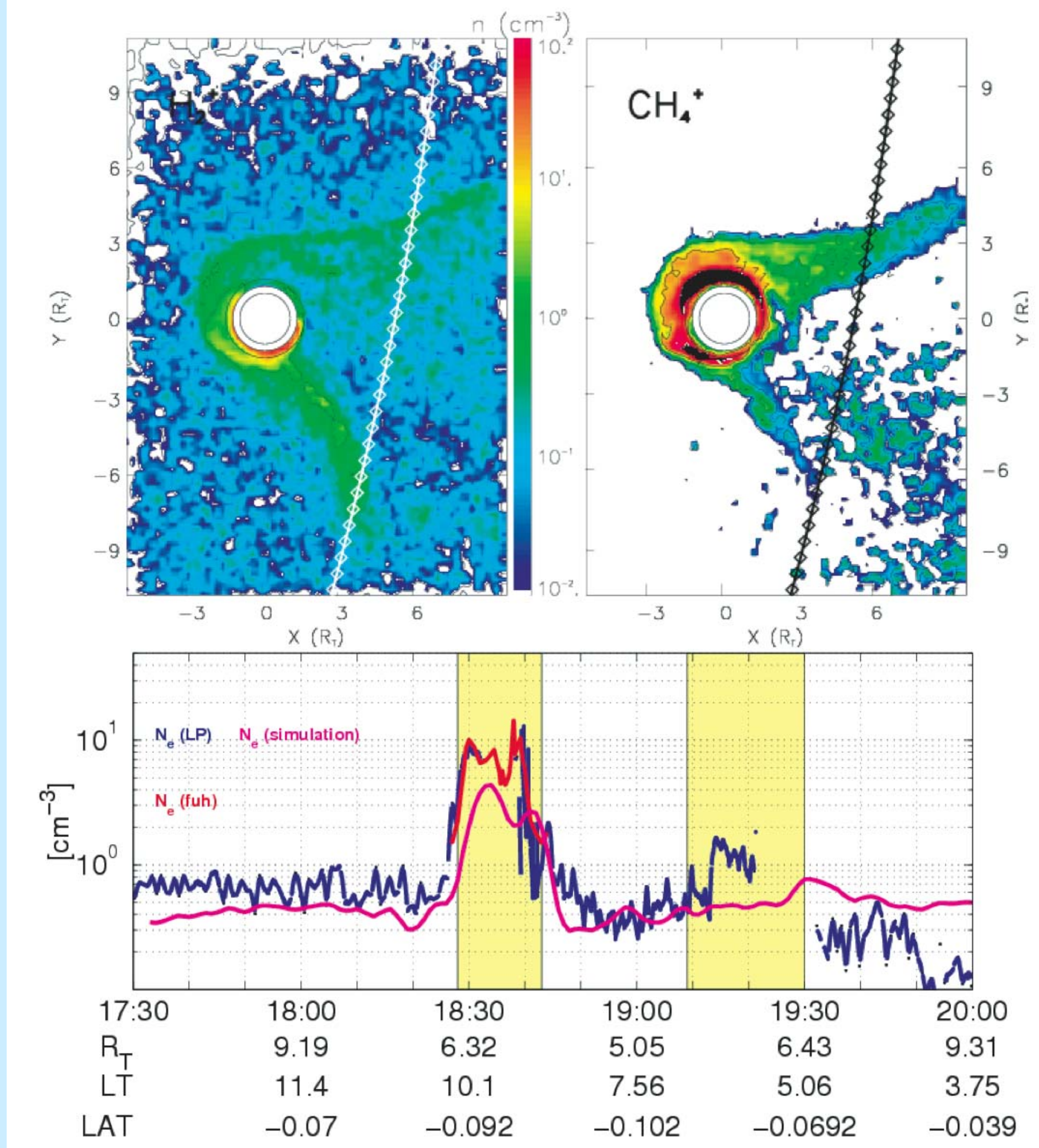


[Ågrén et al., 2008]

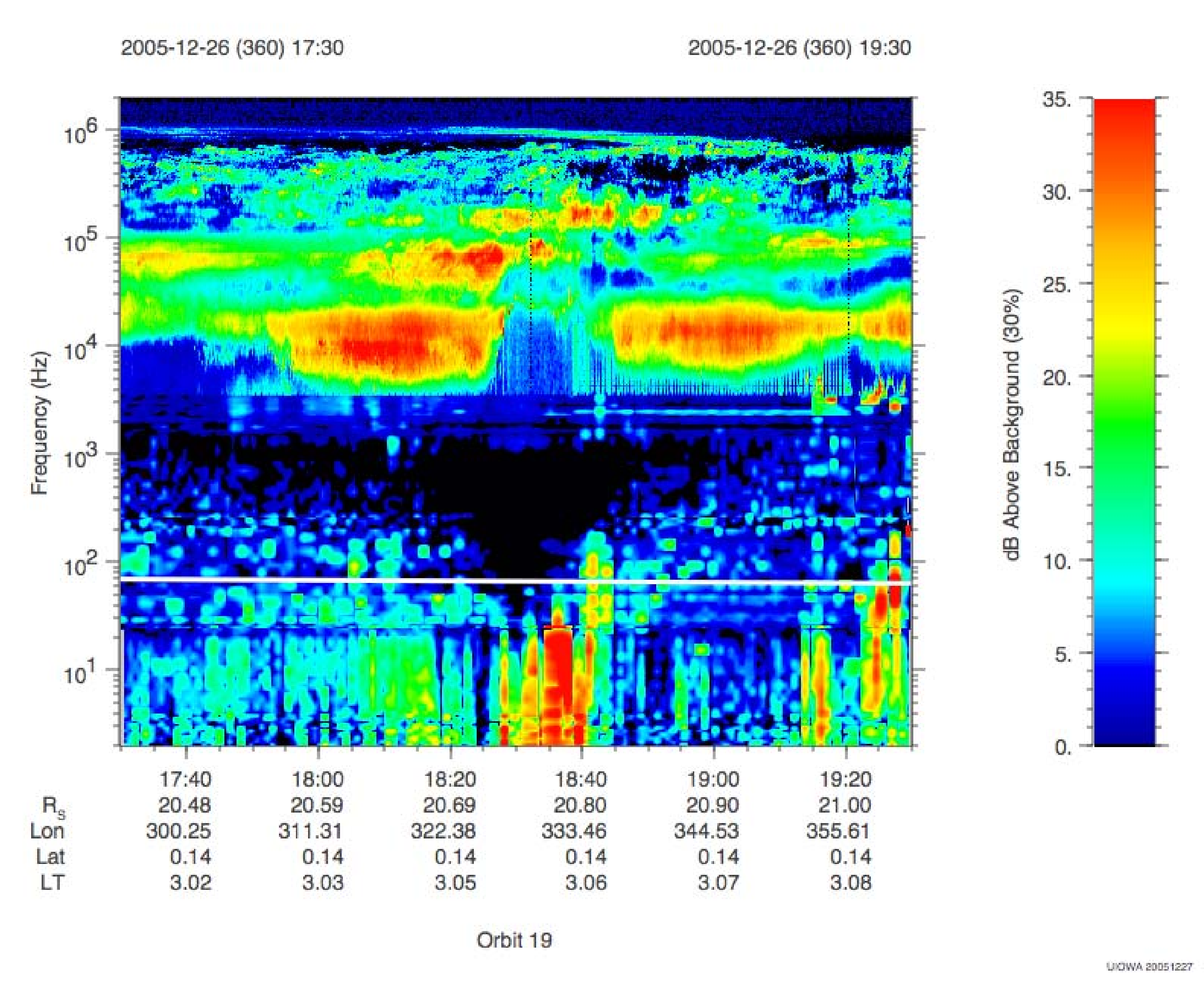
Ionospheric Plasma Escape from Titan (T9)

[Modolo et al., GRL, 2007a & b]

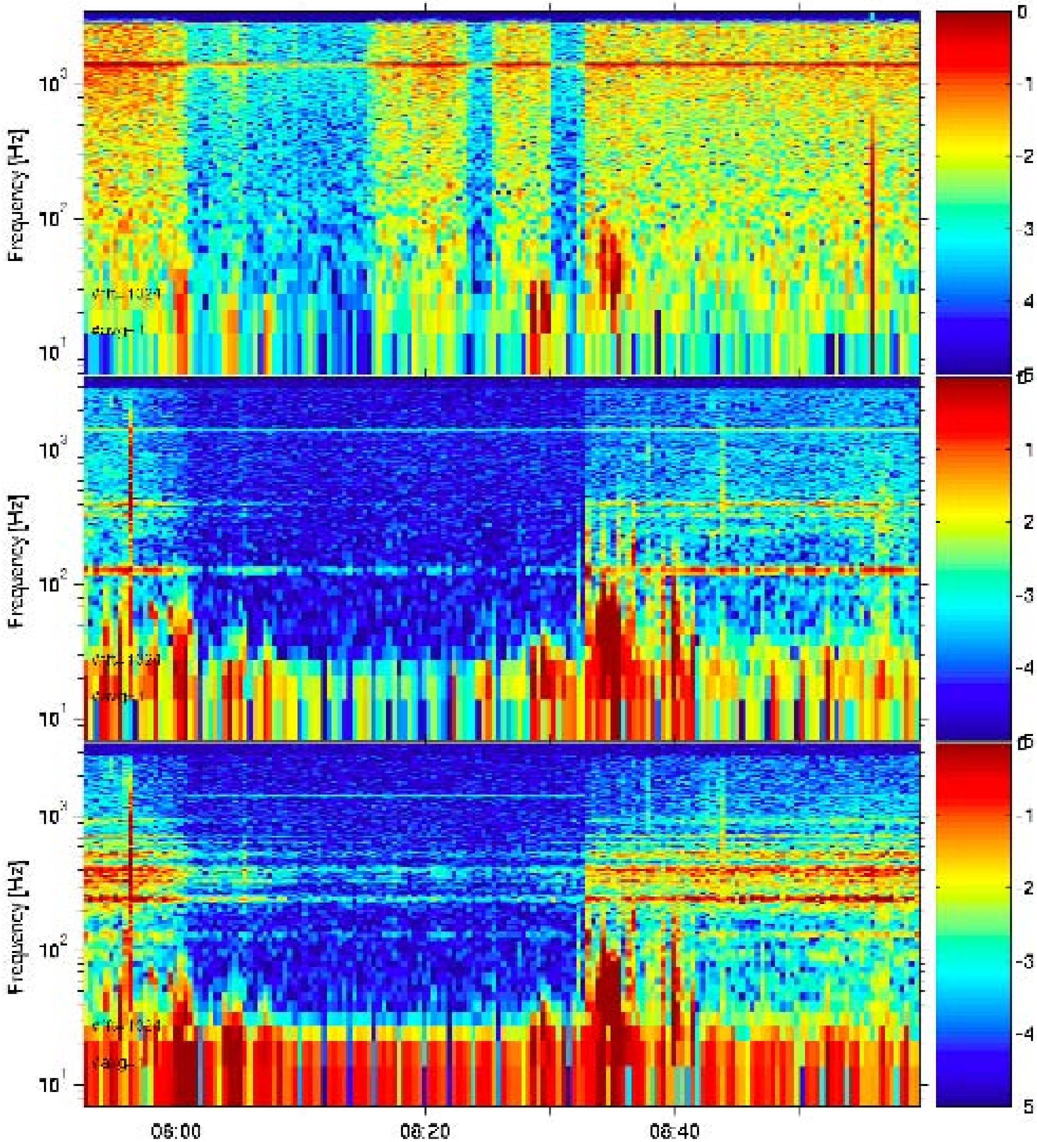
- Differential outflow processes
  - Light ions
    - Magn. ionization side
    - charge-exchange
  - Heavies
    - Solar ionization side
    - Convection **E**-fields
    - Alfvén wings?
- Occurs during enhanced magnetospheric plasma outflow event
- Plasma erosion:
  - Heavies: ~4×10^{25} ions/s
  - Light ions: ~2×10^{25} ions/s



T9 Plasma waves

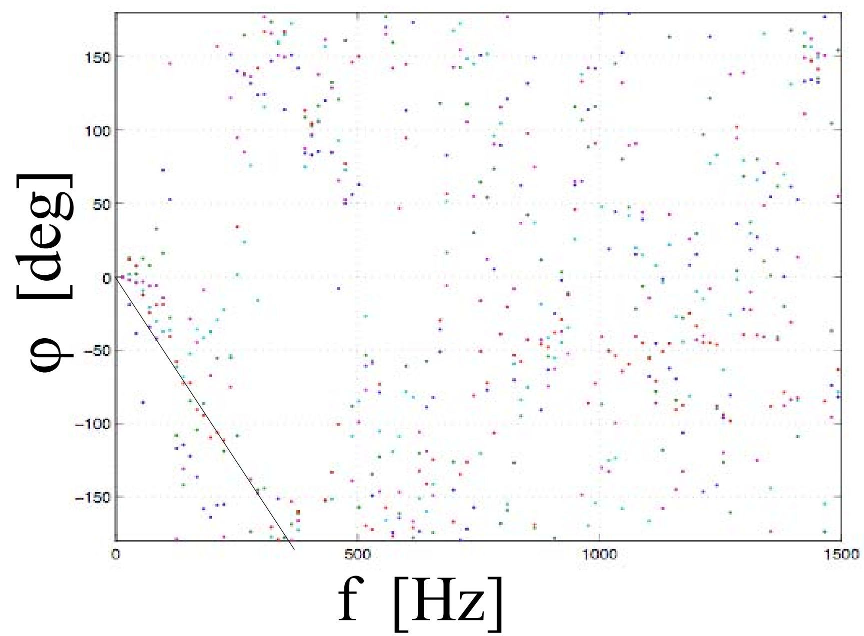


T11



- Possible ion acoustic like emissions below 100 Hz
- $C_s \sim 7$ km/s
  - Beam driven/ion-ion instab?

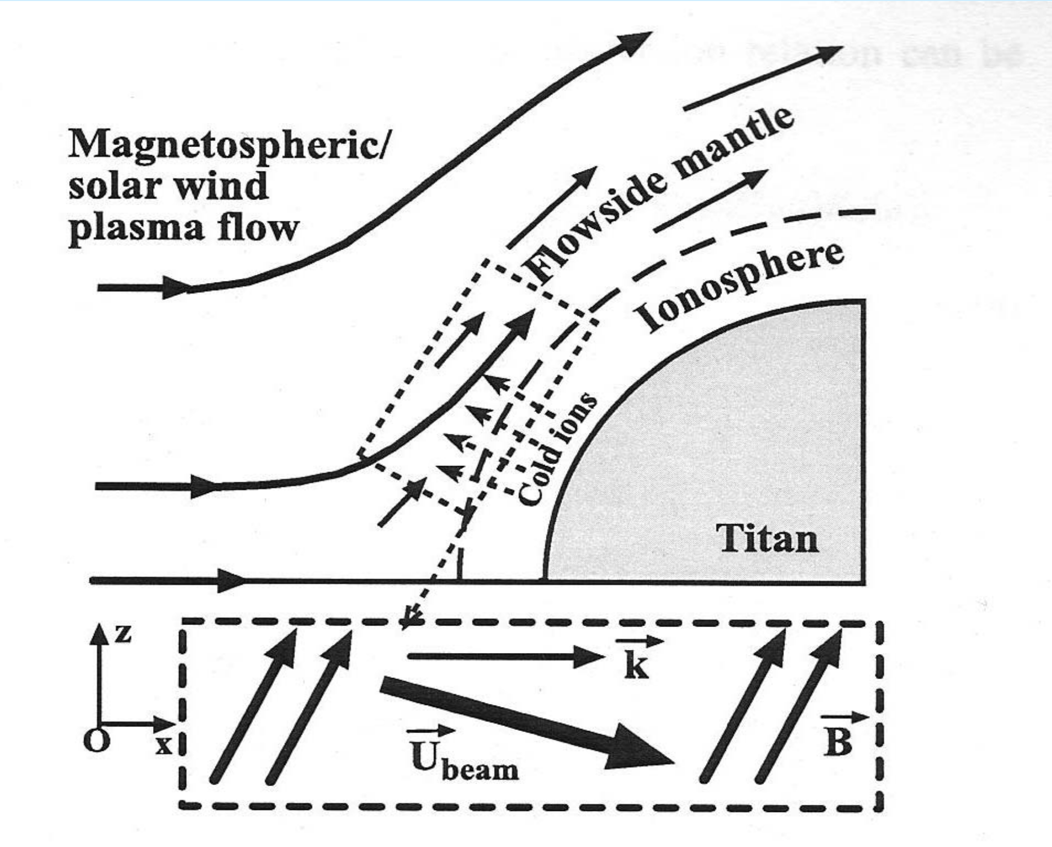
E- vs E+

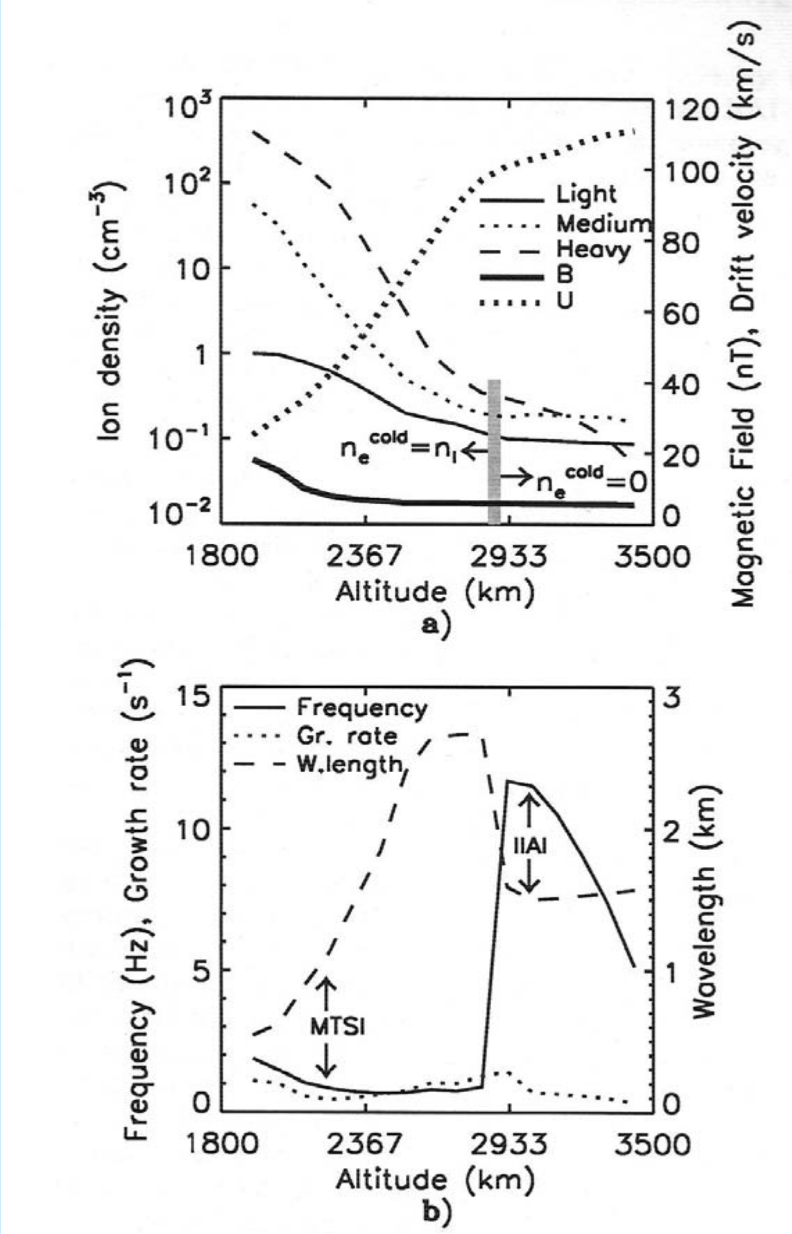


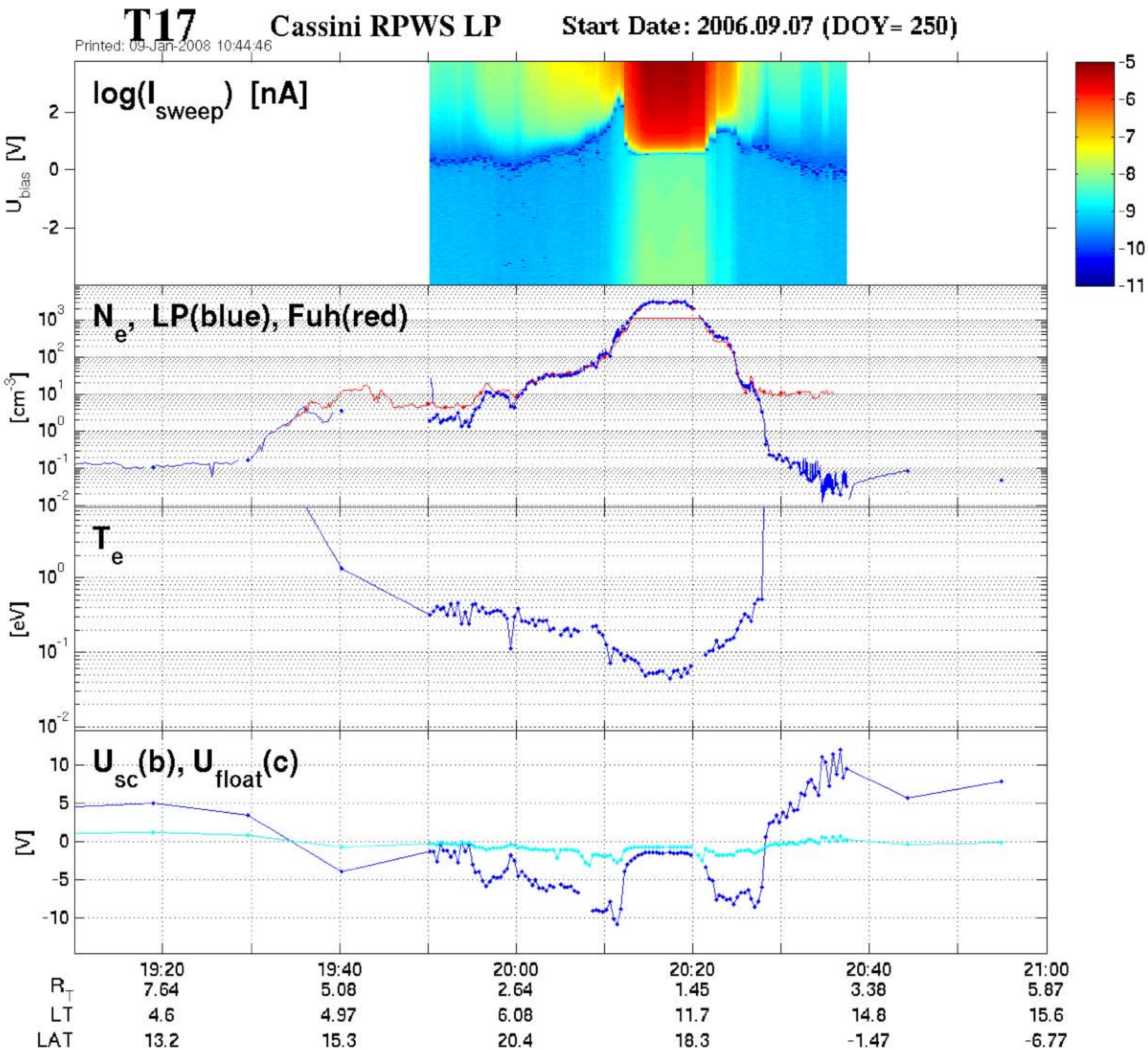
Wave induced Plasma Escape

[Dobe & Szego, JGR, 2005]

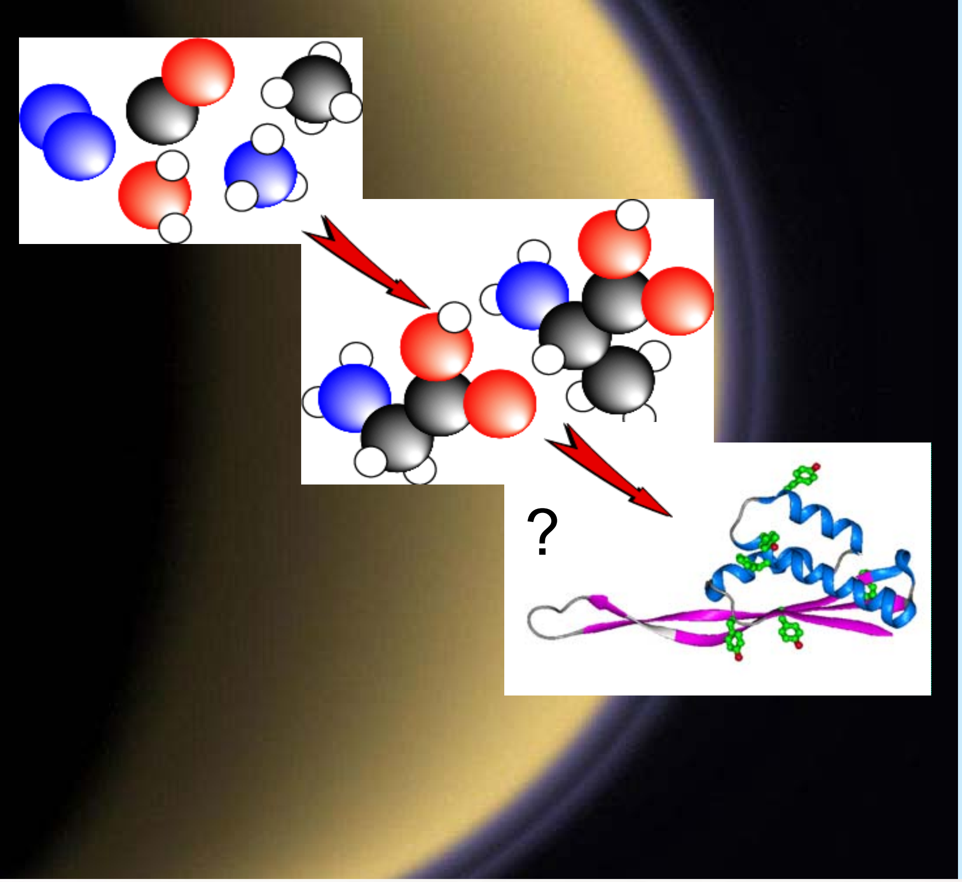
- Solar wind driven ion acoustic (lower hybrid) wave generation cause “enhanced drag” of cold ionospheric ions





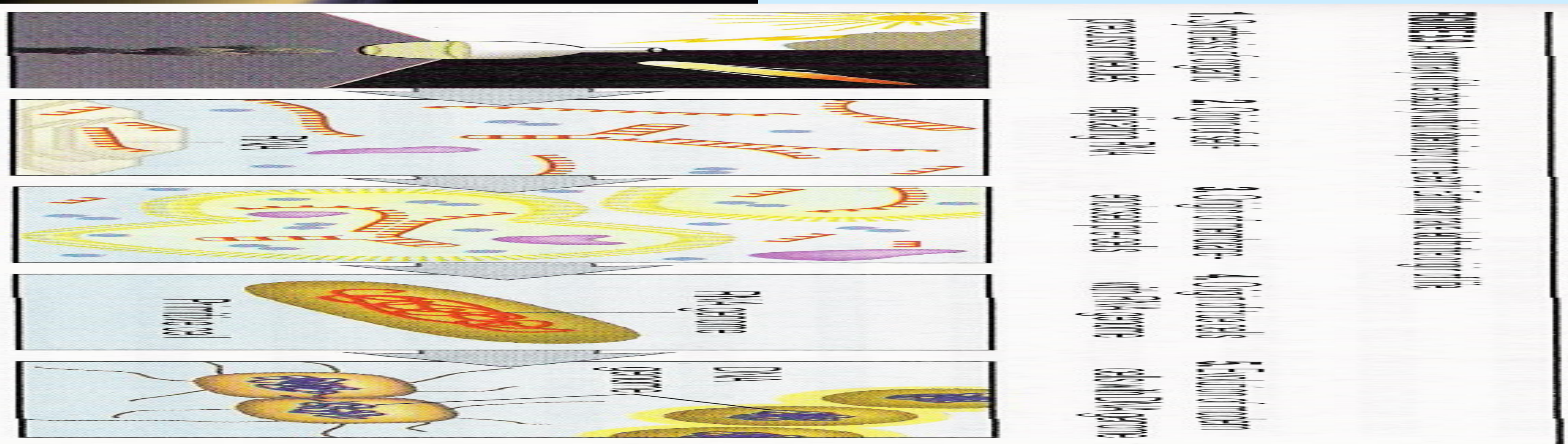

T17
Cassini RPWS LP
Start Date: 2006.09.07 (DOY= 250)
Printed: 09-Jan-2008 10:44:46
log(I_sweep) [nA]
U_bias [V]
N_e, LP(blue), Fuh(red)
[cm^-3]
T_e
[eV]
U_sc(b), U_float(c)
[V]
19:20
19:40
20:00
20:20
20:40
21:00
R_T
7.64
5.08
2.64
1.45
3.38
5.87
LT
4.6
4.97
6.08
11.7
14.8
15.6
LAT
13.2
15.3
20.4
18.3
-1.47
-6.77

Production of Heavy Organics in Titan's Ionosphere

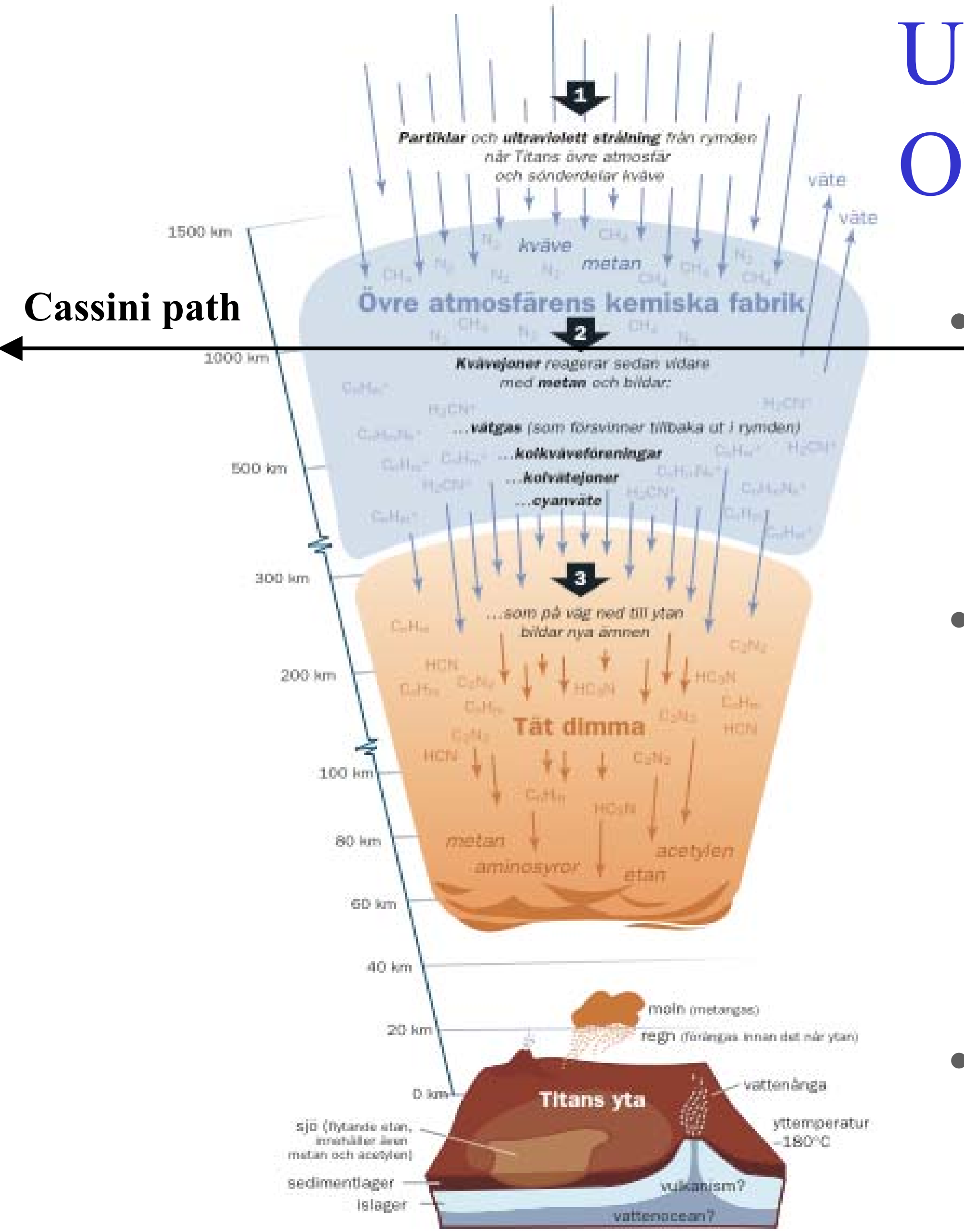


From Simple to Complex

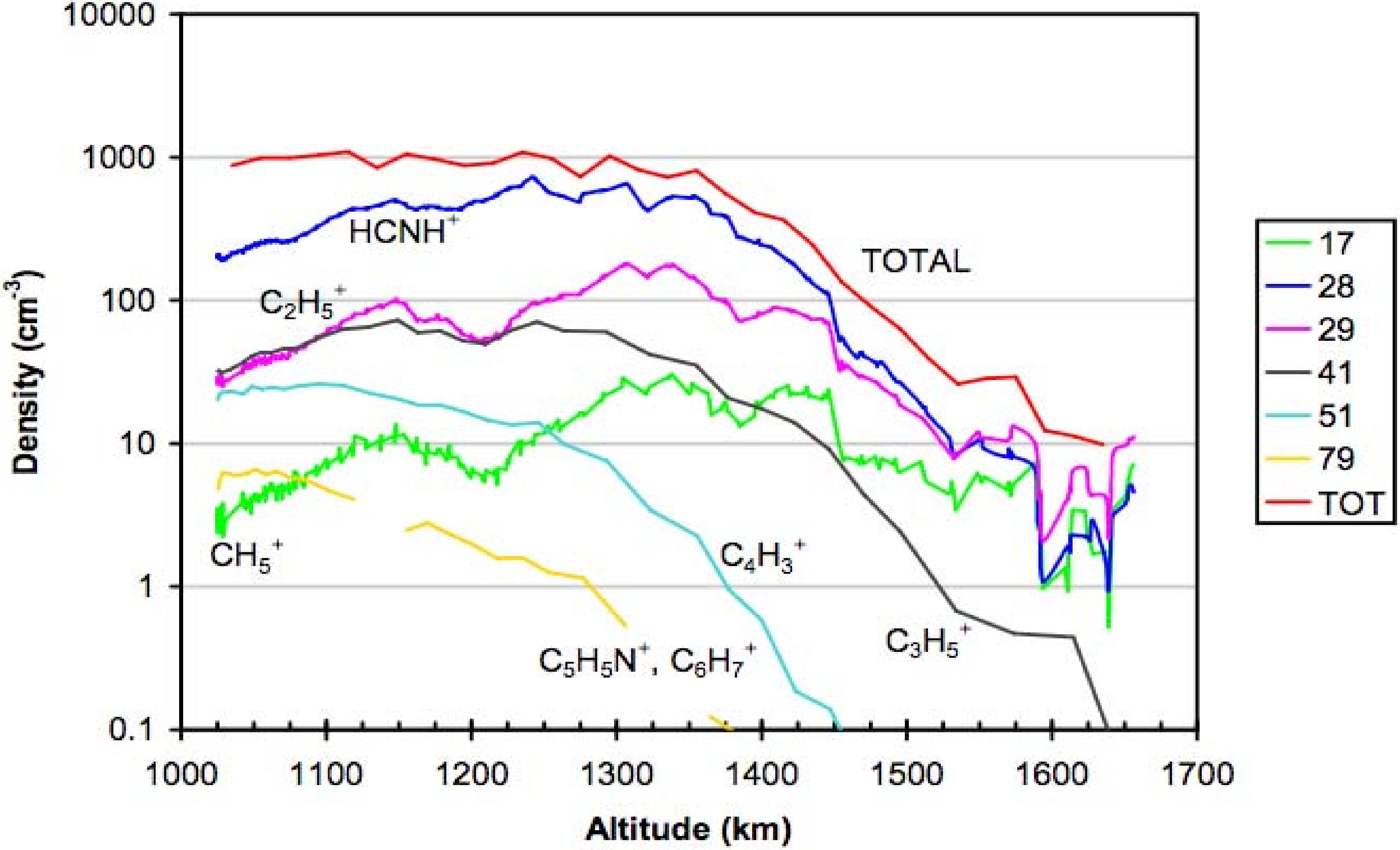
- The origin of Life!?
  - Atoms ⇒ **Pre-biotic** molecules ⇒ **Self-replicating** bio-molecules
  - Short RNA-strands that undergoes **Molecular Evolution** through **Autocatalysis**



Upper Atmospheric Organic Factory

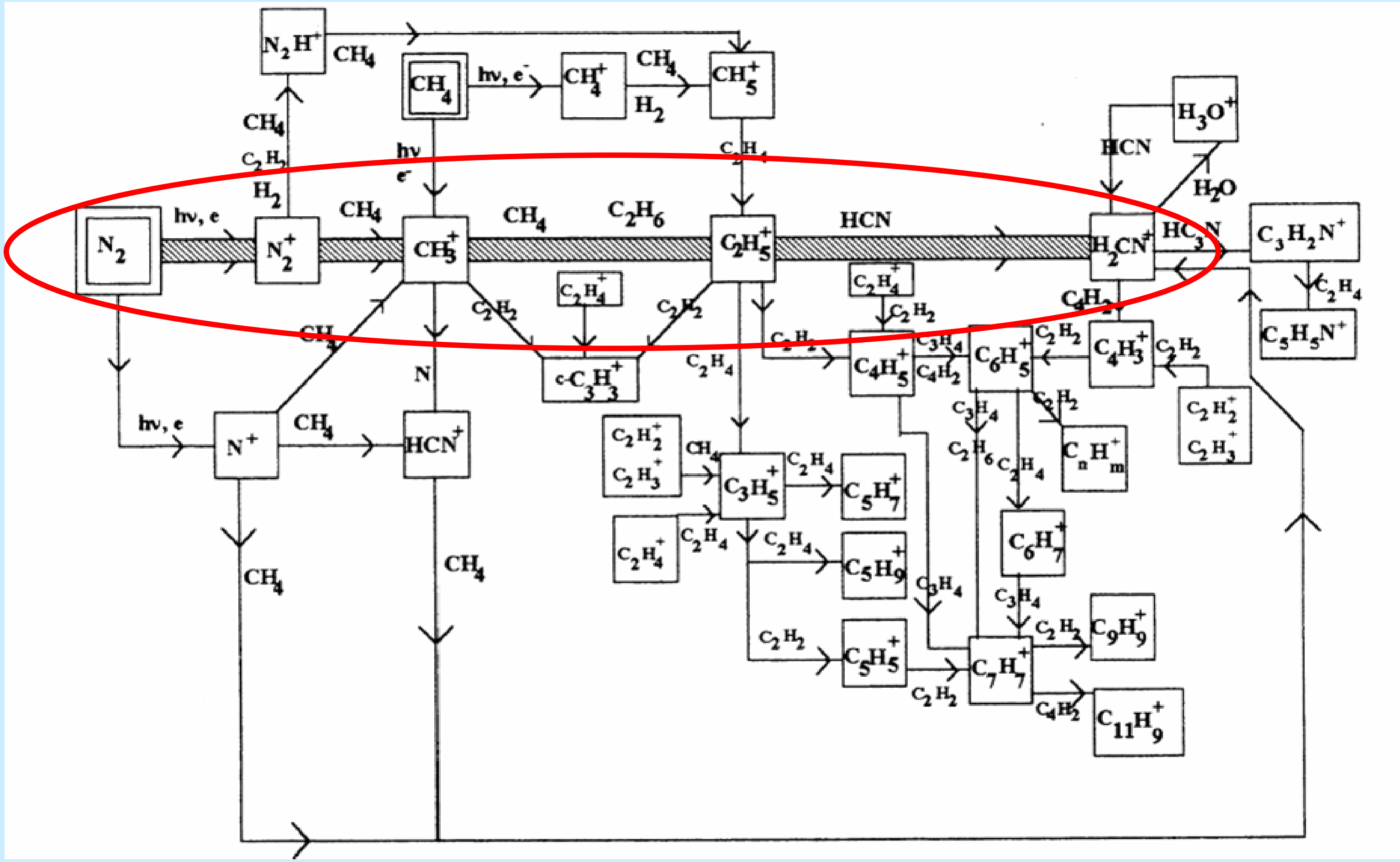


- Driven by Energetic Radiation
  - Solar UV
  - Magnetospheric electrons
  - Break N_2 (covalent bond) & ionize
- N-radicals react with CH_4
  - Hydrocarbons (Ethane, Acetylene)
  - Nitriles (HCN-polymers, Adenine)
  - Diffuse downward, H escape
  - Organic Haze protect from UV
- No Oxygen!
  - Few amino acids expected



10000
1000
100
10
1
0.1
Density (cm-3)
1000
1100
1200
1300
1400
1500
1600
1700
Altitude (km)
HCNH+
TOTAL
C2H5+
CH5+
C4H3+
C3H5+
C5H5N+, C6H7+
17
28
29
41
51
79
TOT

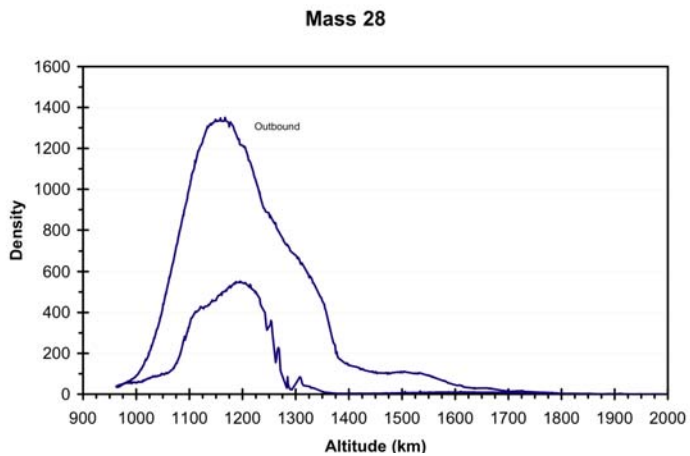
Chemistry in Titan's ionosphere

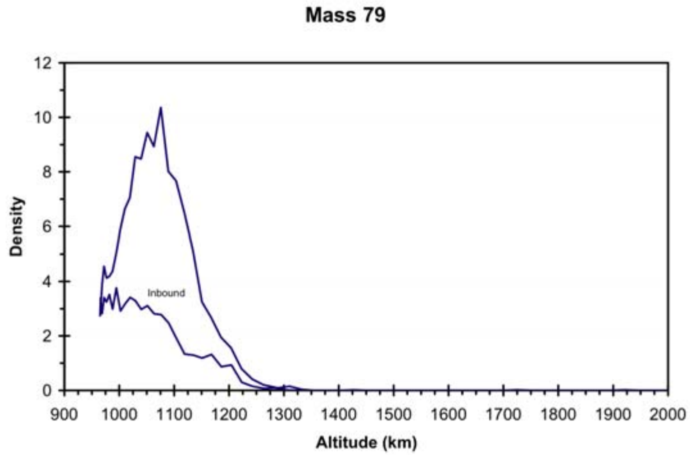


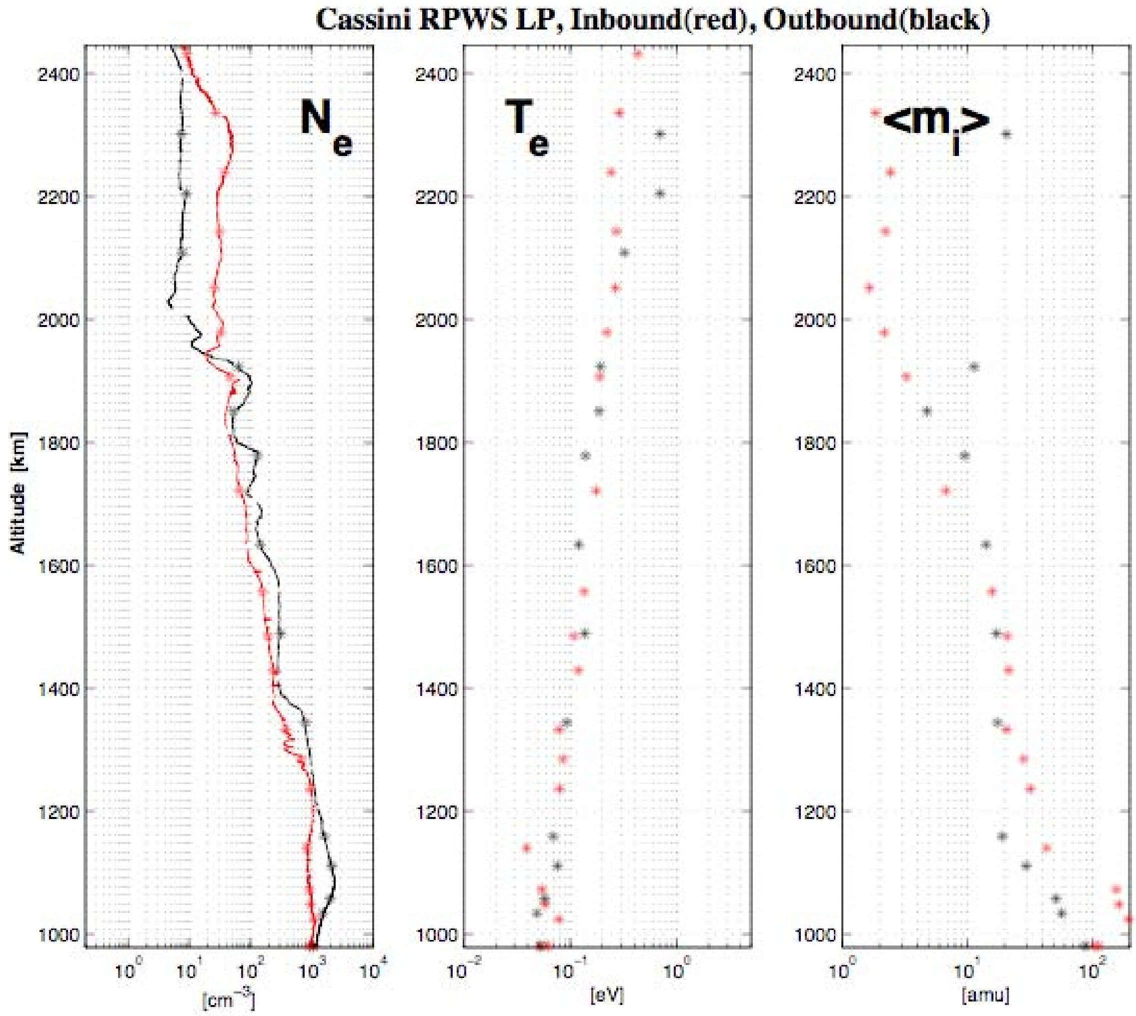
Keller et al. 1998

T18, RPWS & INMS density profiles don't agree in the deep Titan's ionosphere…

[Courtesy of H. Waite, T. Cravens, I. Robertson, R. Yelle]







Lower Ionosphere dominated by >100 amu heavies

n_e(LP)

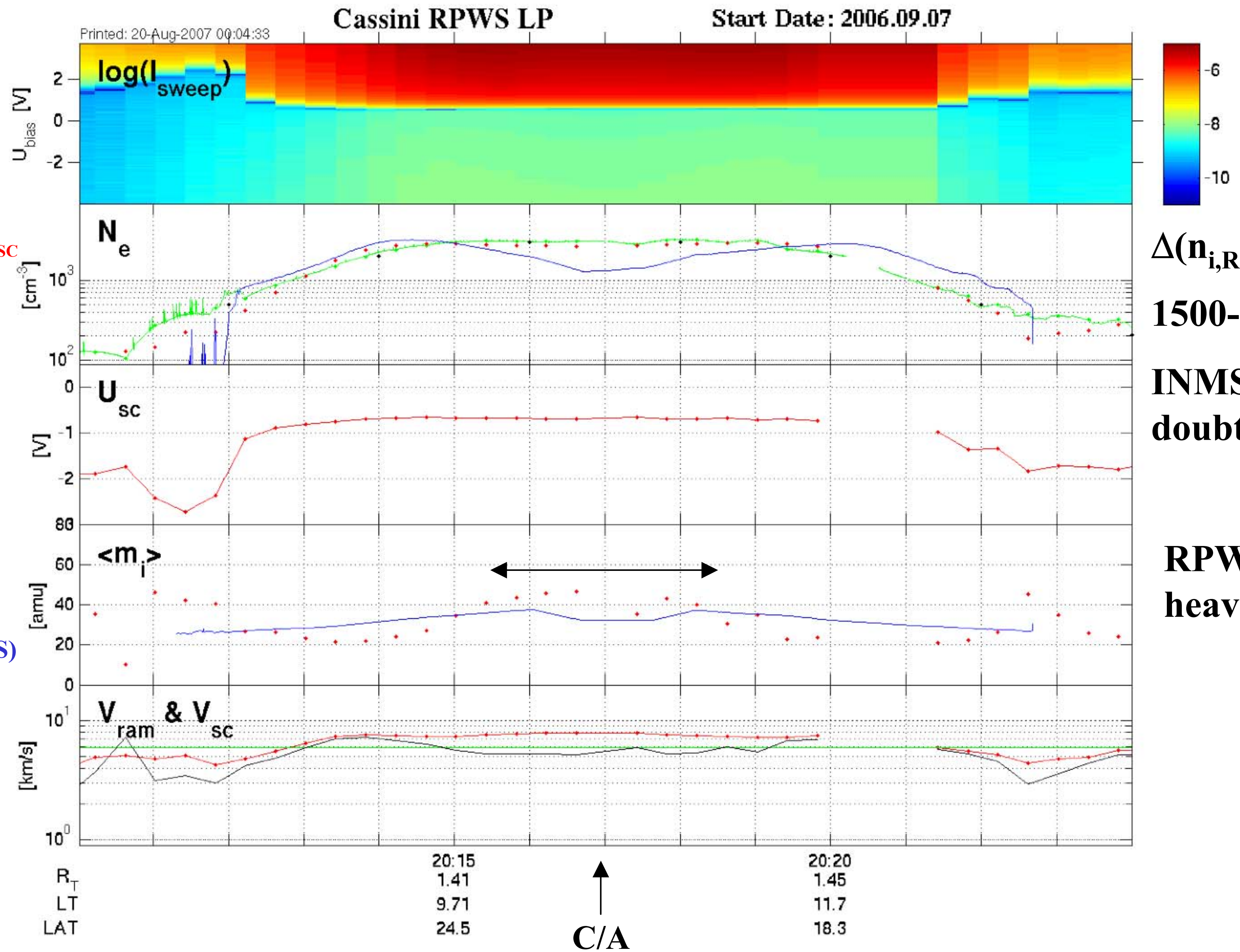
n_i(LP) at V_{SC}

$n_e(f_{uh})$

n_i(INMS)

$\langle m_i \rangle$ (LP)

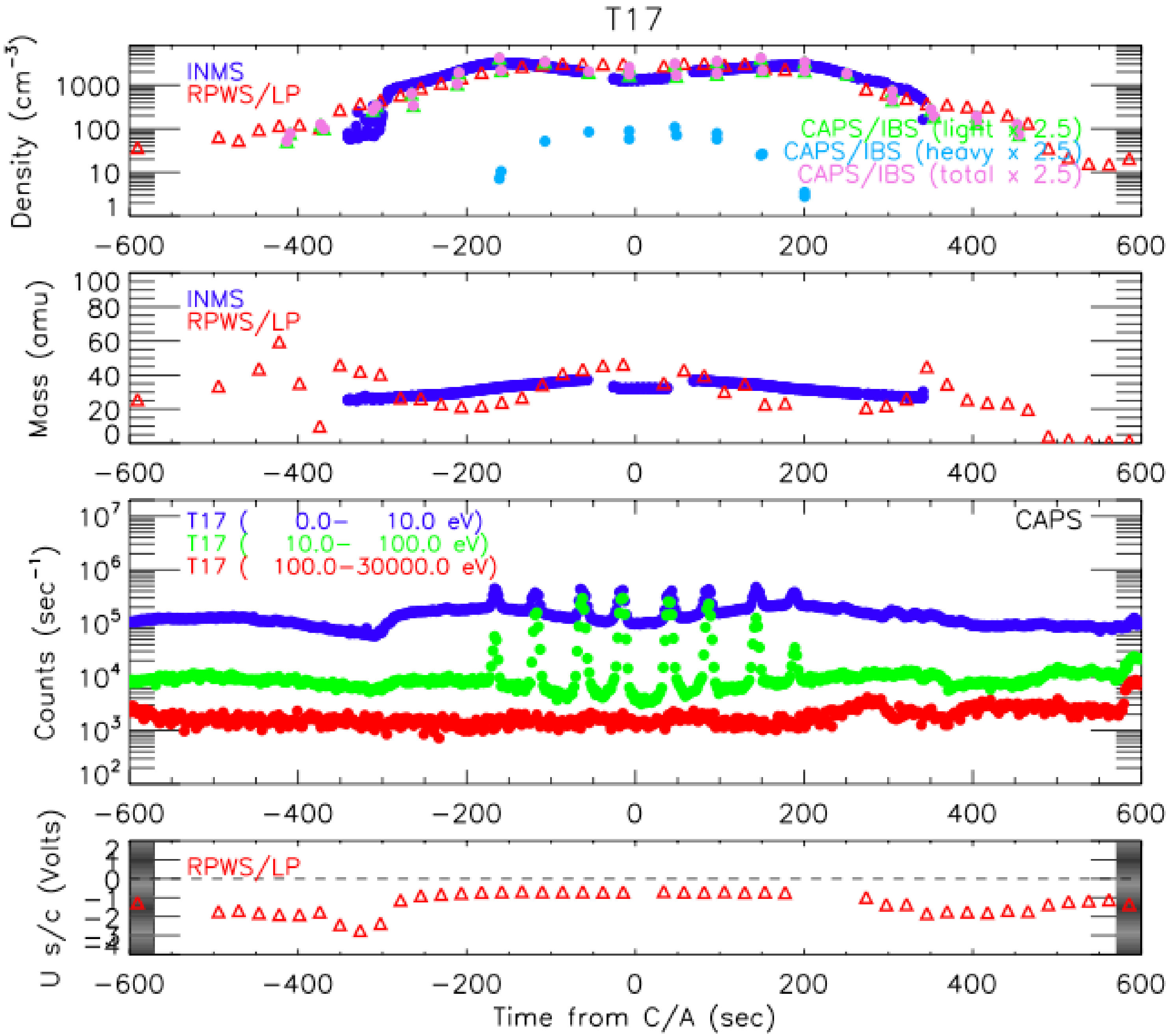
$\langle m_i \rangle$ (INMS)

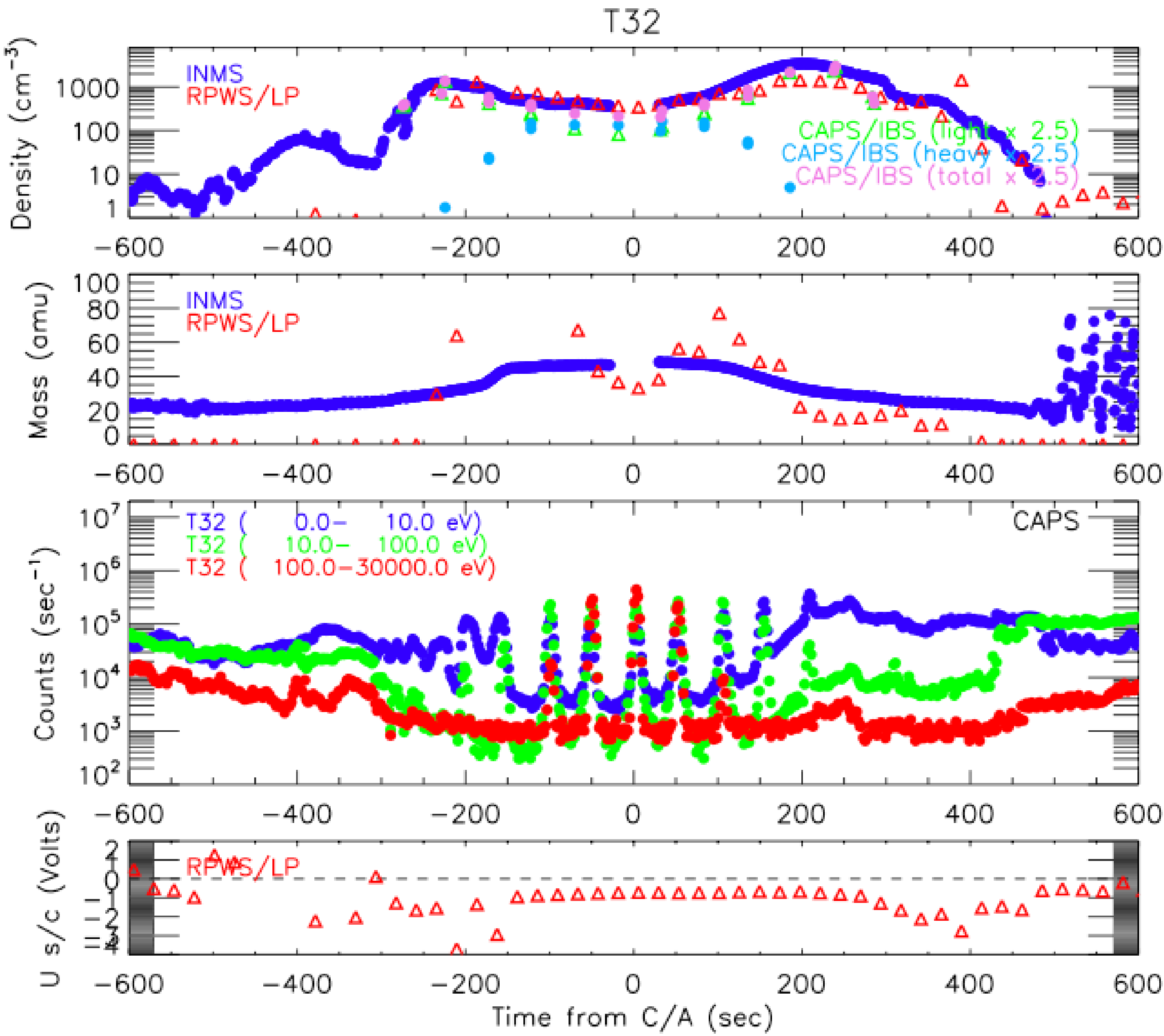


$\Delta(n_{i,RPWS}-n_{i,INMS}) \approx$ 1500-2000 cm^{-3}

INMS total density doubtful

RPWS see heavier ions


T17
Density (cm^{-3})
INMS
RPWS/LP
CAPS/IBS (light x 2.5)
CAPS/IBS (heavy x 2.5)
CAPS/IBS (total x 2.5)
Mass (amu)
INMS
RPWS/LP
Counts (sec^{-1})
T17 (0.0– 10.0 eV)
T17 (10.0– 100.0 eV)
T17 (100.0–30000.0 eV)
CAPS
U s/c (Volts)
RPWS/LP
Time from C/A (sec)

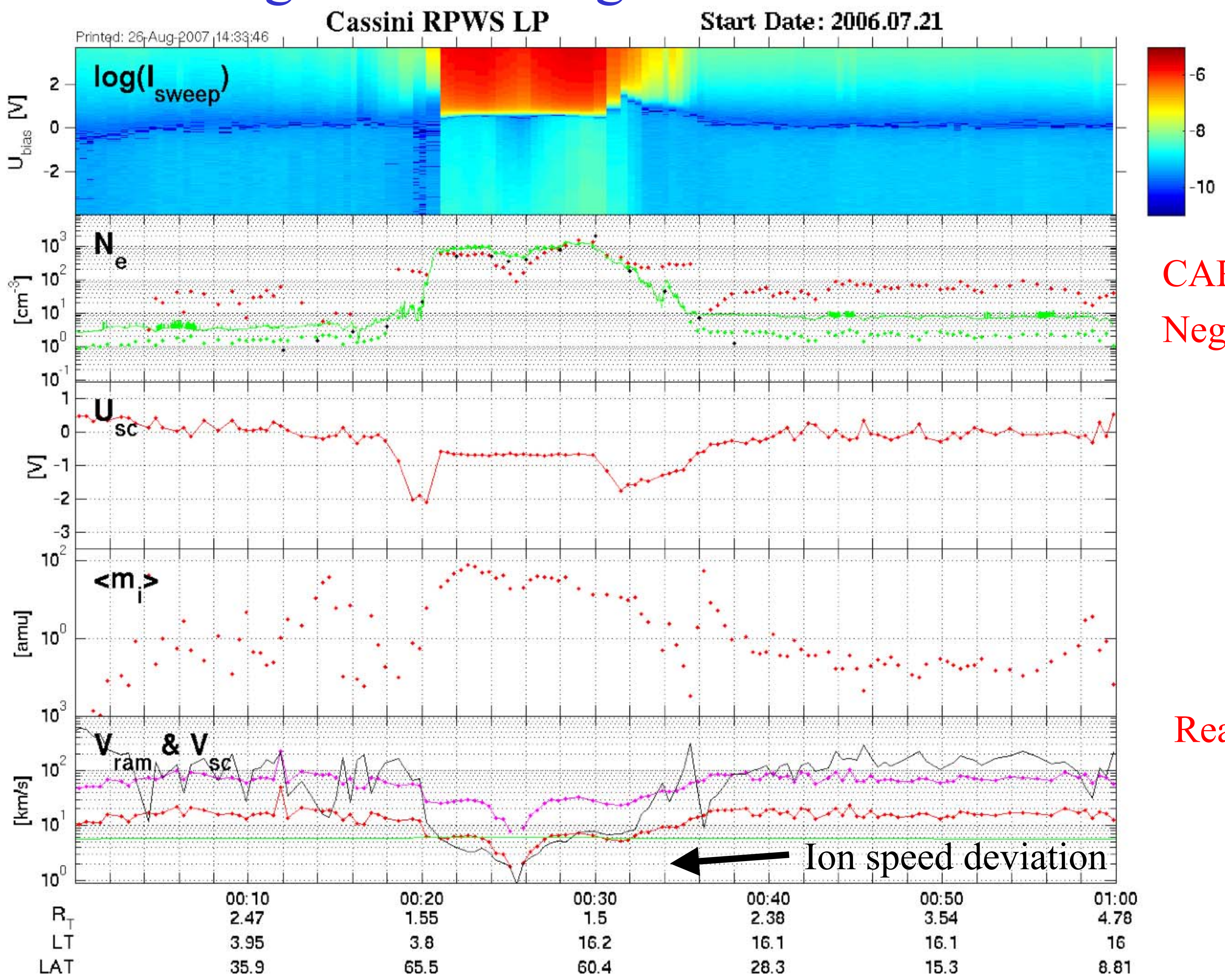

T32
Density (cm^-3)
INMS
RPWS/LP
CAPS/IBS (light x 2.5)
CAPS/IBS (heavy x 2.5)
CAPS/IBS (total x 2.5)
Mass (amu)
INMS
RPWS/LP
Counts (sec^-1)
T32 (0.0- 10.0 eV)
T32 (10.0- 100.0 eV)
T32 (100.0-30000.0 eV)
CAPS
U s/c (Volts)
RPWS/LP
Time from C/A (sec)

Conclusions:

- Lower ionosphere (<1050 km)
  - At times dominated by >100 amu positive ions!
  - At times there exist also substantial amounts of negative ions!
- The deep Ionosphere of Titan is the main producer of heavy organic compounds for the aerosol haze and deposits on the surface
  - Key is the energetic EUV/particle precipitation together with a N_2 and CH_4 atmosphere.
  - We can learn early Earth chemistry from Titan studies
  - Add water and hydrolysis leads to pre-biotic building blocks
  - H_2CN^+ is dominant ionospheric species

END

T16: Negative Ions Signature in RPWS/LP?



CAPS/ELS (A. Coates)

Negative Ion Densities

T16: ~1000 cm^{-3}

T18: ~200 cm^{-3}

T17, T21: somewhat less

T5 none (?)

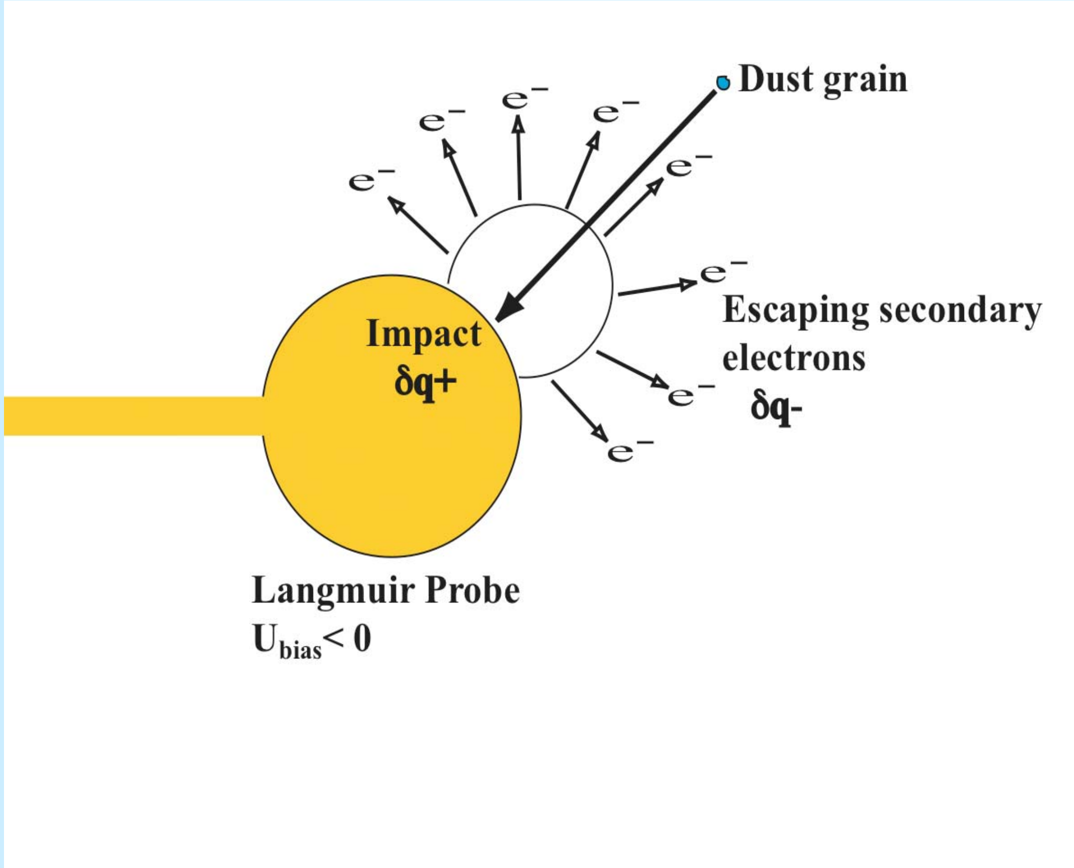
Really need

DC **E**-field

Ion drift meter

… but we don't

I_{dust} Contribution



Any negatively charged component contributes

$$I = I_0(1-\chi) \quad \text{for} \quad U = U_{bias} + U_{SC} \geq 0$$

$$I = I_0 \exp(-\chi) \quad \text{for} \quad U = U_{bias} + U_{SC} < 0$$

where for charged dust $\quad (T_{dust} << \frac{1}{2} m_{dust} v_{dust}^2)$

$$I_0 = A_{LP} q_{dust} n_{dust} \frac{|v_{dust}|}{4}$$

$$\chi = 2e(U_{bias} + U_{SC})/m_{dust} v_{dust}^2 \quad << 1$$

also

$$\exp(-\chi_{dust}) \approx 1$$

i.e., charged dust don't affect the gradient, but give a constant ram flux

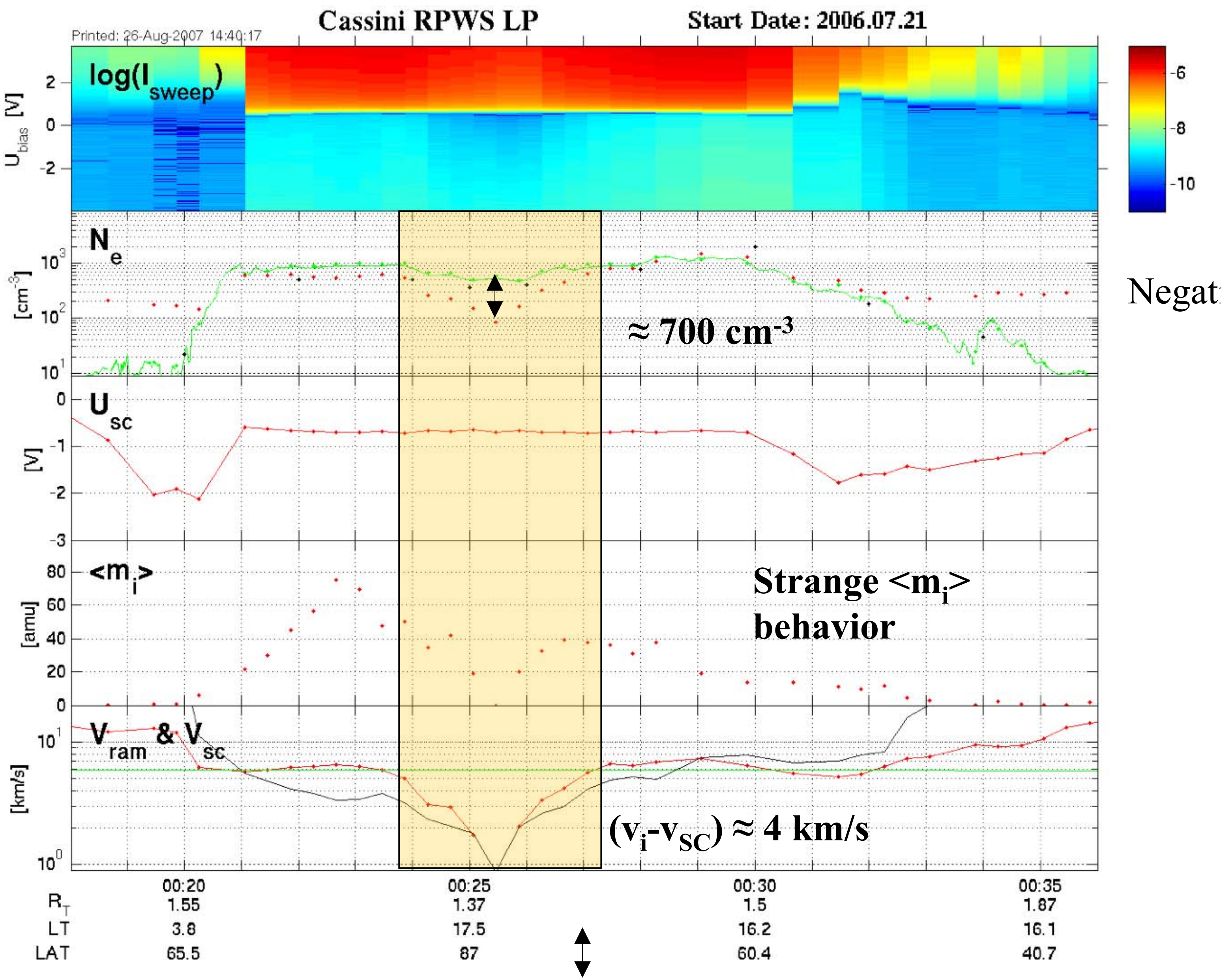
$$I_{dust} = A_{LP} q_{dust} n_{dust} \frac{|v_{dust}|}{4} \quad \text{for all } U$$

(positive)

This gives normaly a neglible contribution. However, the secondary electron yield from each dust hit is not:

$$I_{dust,sec} = Y_{yield} \bullet I_{dust}$$

≈ 0.1– 0.3 nA observed in E-ring (negative)



Negative ion density!?