Two cases of atmospheric escape in the Solar System: Titan and Earth

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Thanks for contributions to the Cassini / MIMI Team
and to the Cluster / CIS Team

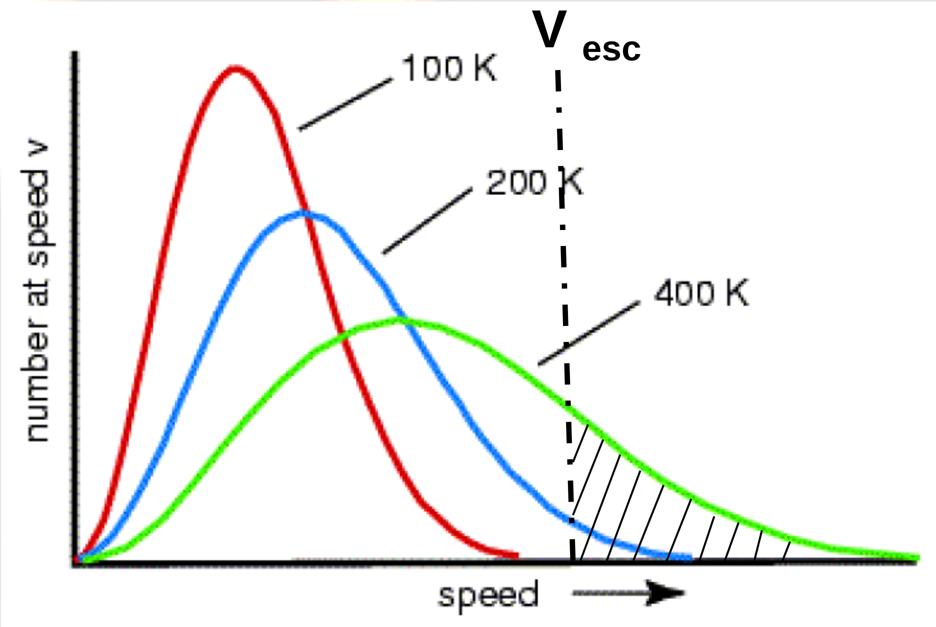
Special thanks to the organisers of the 10th Hellenic Astronomical Conference

OUTLINE

- Introduction on atmospheric escape
  and on the exospheres
- Part 1:   the case of Titan
- Part 2 : the case of the Earth

INTRODUCTION

Escape into space of the constituents of a planetary upper atmosphere can occur :



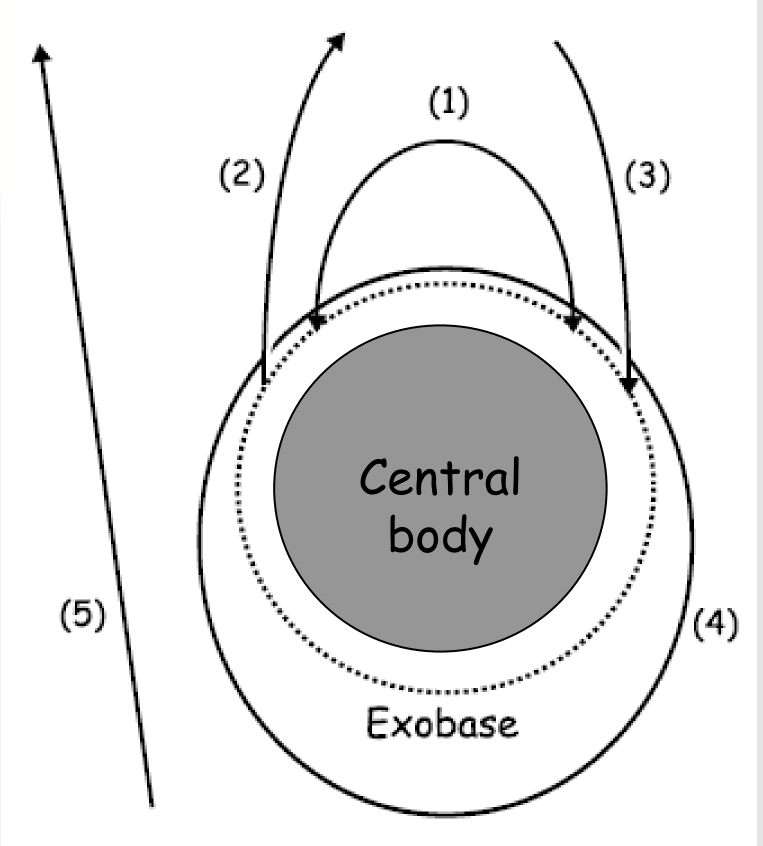
- in the form of **neutral gas :**
  - thermal escape (or Jeans escape)
  - non-thermal escape :
    - sputtering
    - photochemical production of fast neutrals
    - ionisation and pick-up, …
- in the form of **plasma**.

The long-term stability of an atmosphere results from the balance between **source** and **escape rates** (+ eventual sequestration in the ground).

Exosphere (or corona): the uppermost part of an atmosphere, where collisions between particles are negligible

Particle trajectories there can be:

1) ballistic
2) escaping
3) coming from outside
4) satellite orbits
5) in “transit”



Chamberlain [1963] modelling of an exosphere:

- Definition of a distribution function at the exobase: critical level h_c, temperature T_c and densities N_c
- Altitude profile of the distribution function by using the Liouville equation:

$$N(r) = N_C\, e^{-(\lambda_C - \lambda)}\, \zeta(\lambda)$$

$\zeta(\lambda)$: partition function, $\lambda = G\,M\,\mathrm{M} / k\,T_C\,r$

- External limit of an exosphere : limit of the influence of the gravitational field (Hill sphere)

Observation of an Exosphere

Credit : NASA

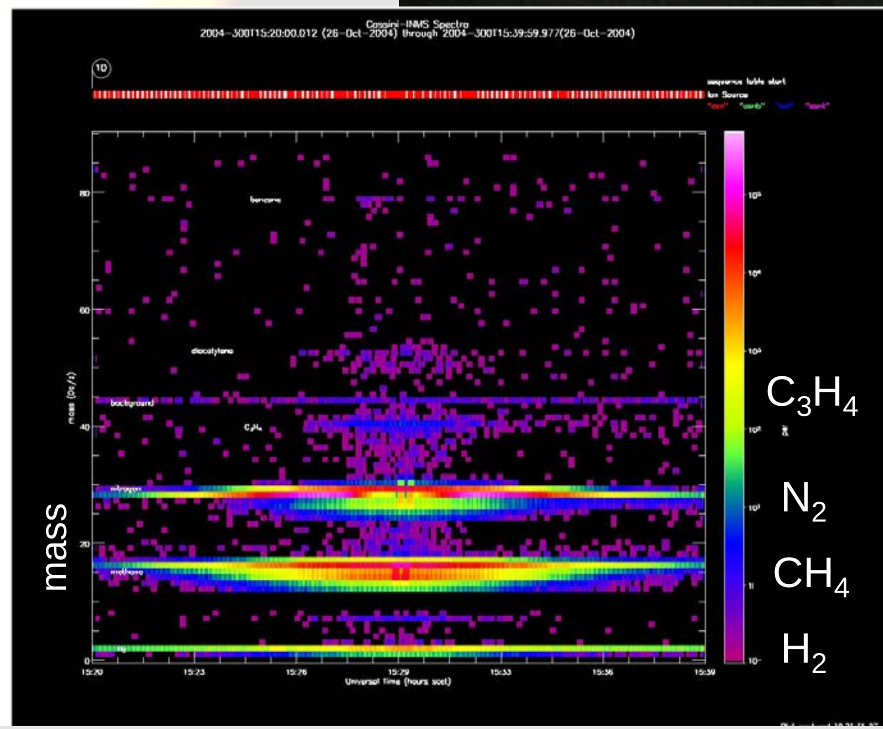
- **By imaging :**

  e.g. Lyman–α imaging of the H component

Observation of an Exosphere

- **By imaging :**
  e.g. Lyman–α imaging of the H component

- **By direct particle detection :**
  Ion and Neutral Mass Spectrometry

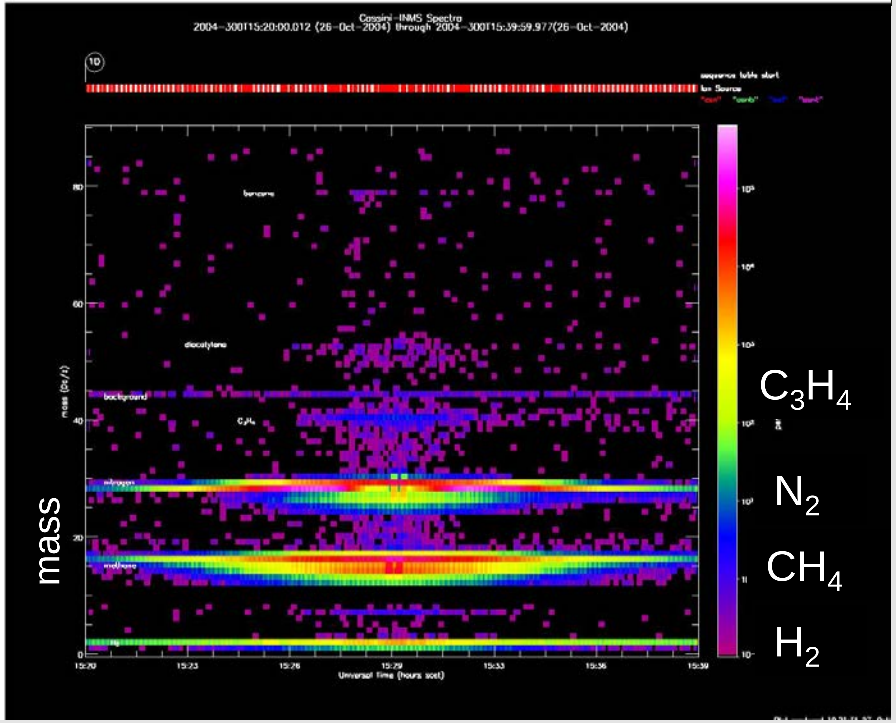


Credit : INMS Team

Observation of an Exosphere

- **By imaging :**
  e.g. Lyman–α imaging of the H component

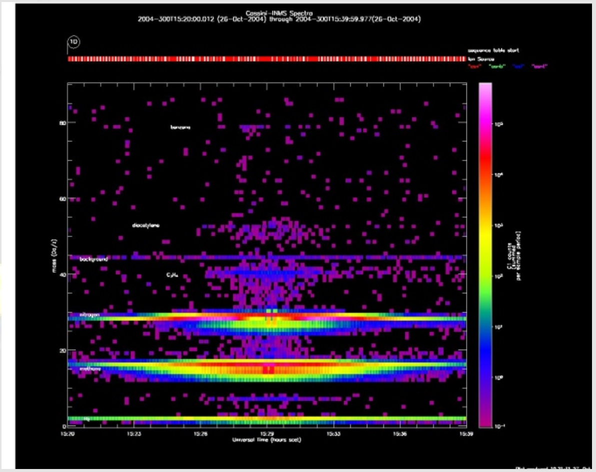
- **By direct particle detection :**
  Ion and Neutral Mass Spectrometry
  Cassini INMS
  BepiColombo STROFIO



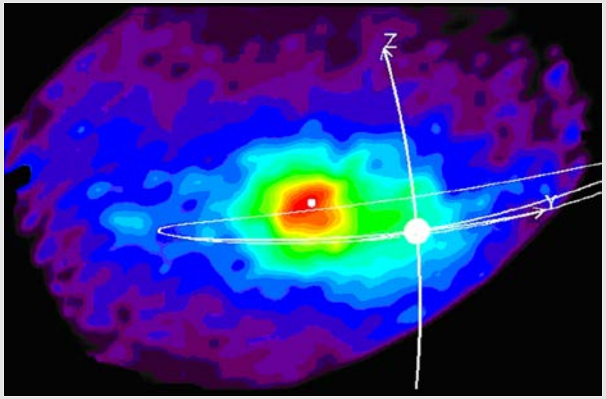
Credit : INMS Team

Observation of an Exosphere

- **By imaging :**
  e.g. Lyman–α imaging of the H component



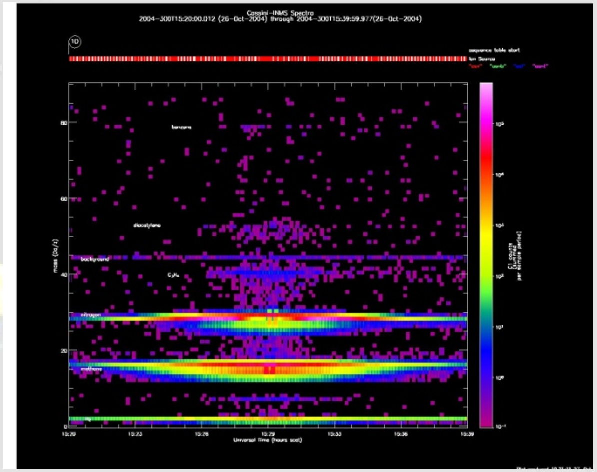
- **By in-situ particle detection :**
  Ion and Neutral Mass Spectrometry



- **Through its interaction with the Magnetosphere :**
  Energetic Neutral Atom imaging

Observation of an Exosphere

- **By imaging :**
  e.g. Lyman–α imaging of the H component



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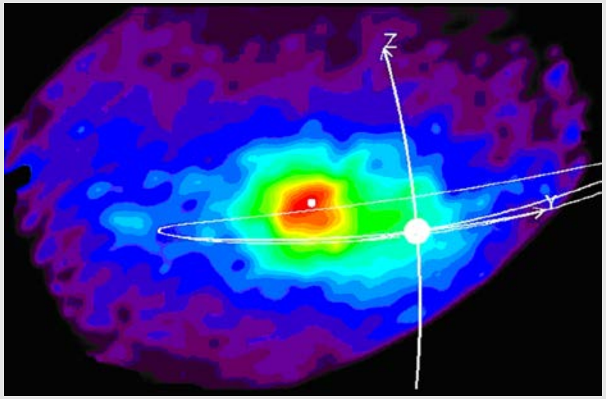


- **Through its interaction with the Magnetosphere :**
  Energetic Neutral Atom imaging
  Cassini MIMI
  BepiColombo ELENA

Exospheric Imaging:
ENA (Energetic Neutral Atoms) production principle

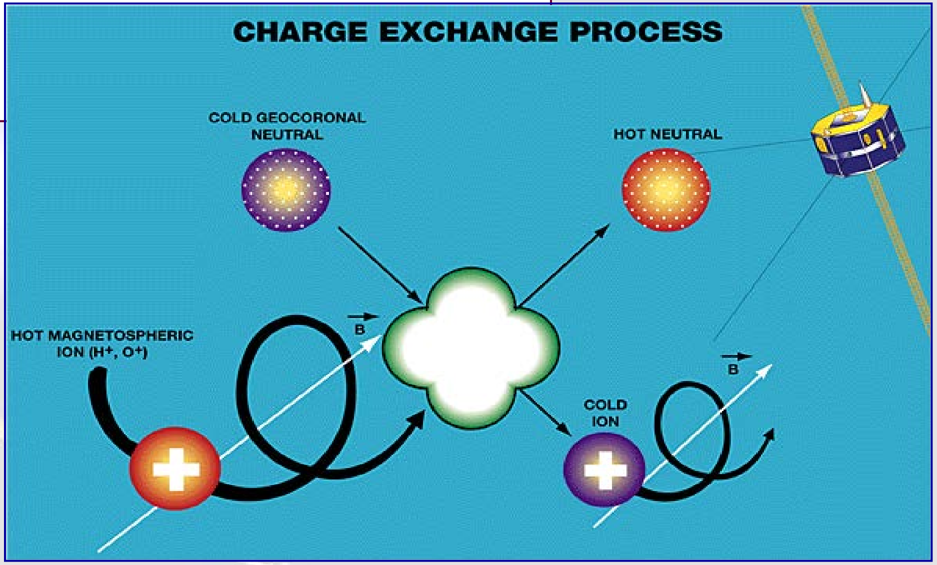
$$j_{ENA}(E) = \Sigma_k\, \sigma_{ik}(E) \int j_i(E)\, n_k(l)\, dl$$

$j_{ENA}(E)$: Energetic Neutral Atoms (ENA) Flux

$j_i(E)$: Ion Flux (i species)

$n_k(l)$: Exospheric Density (k species)

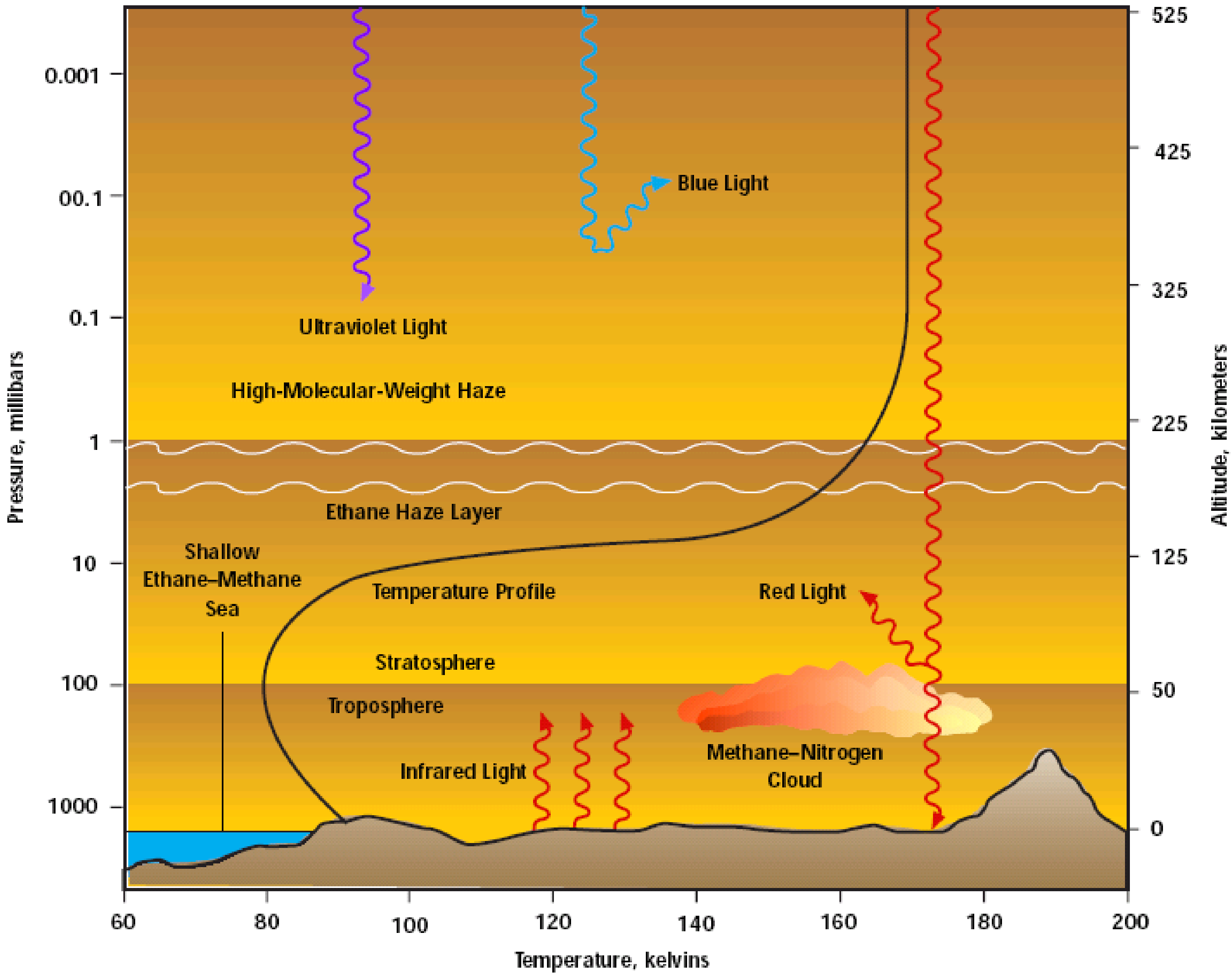
$\sigma_{ik}(E)$: Charge Exchange Cross-Section between Ions i and Exospheric Atoms k

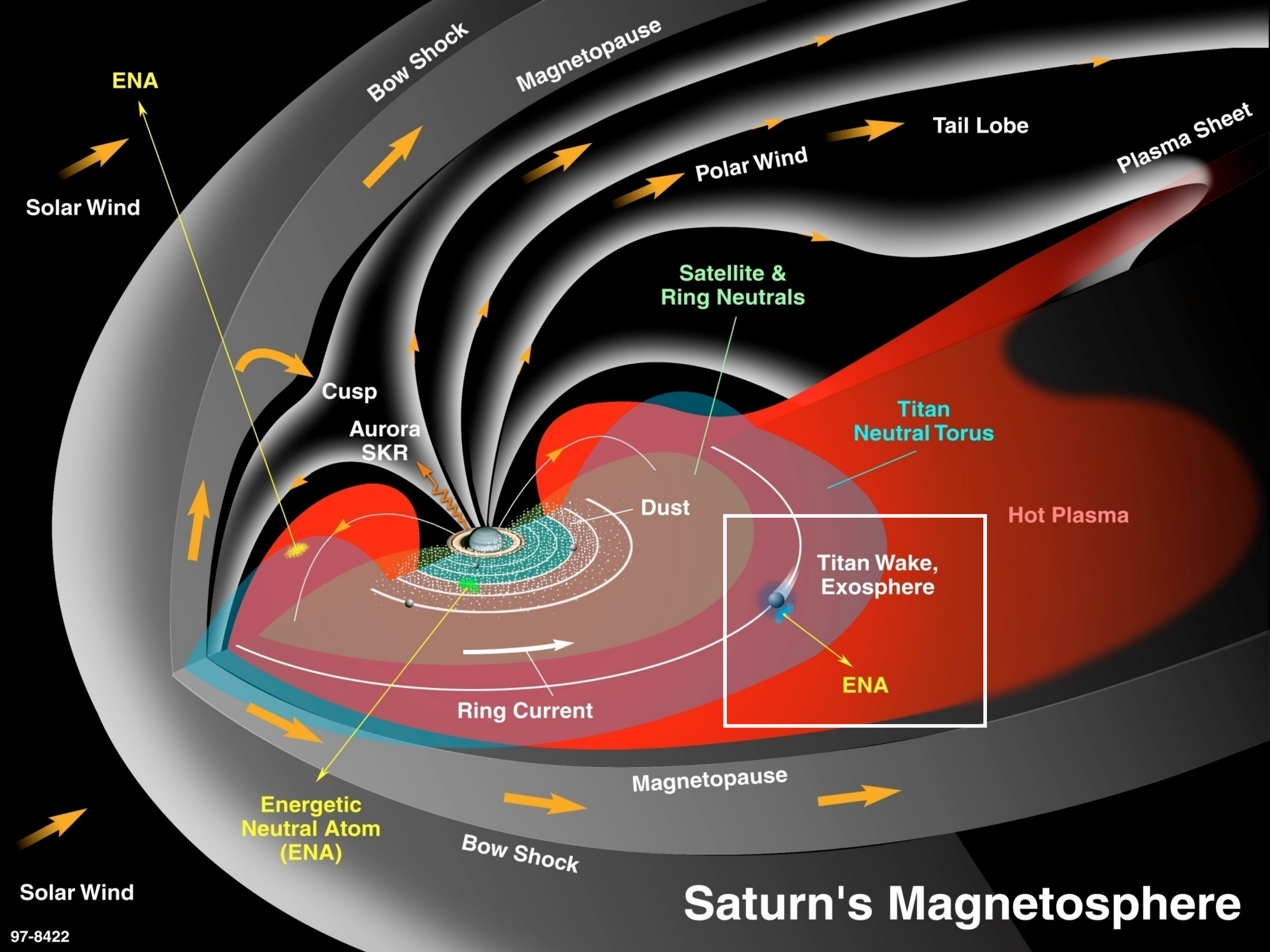


Part 1 :

Titan

Titan atmospheric interactions





Saturn's Magnetosphere

MIMI

(Magnetospheric Imaging Instrument)

onboard Cassini

P.I. : S.M. Krimigis, APL / JHU

- **INCA**

Ion and Neutral Camera, 90°x120° FOV

~3 *keV - 3 MeV ions and neutrals*

- **CHEMS**

Charge-Energy-Mass Spectrometer

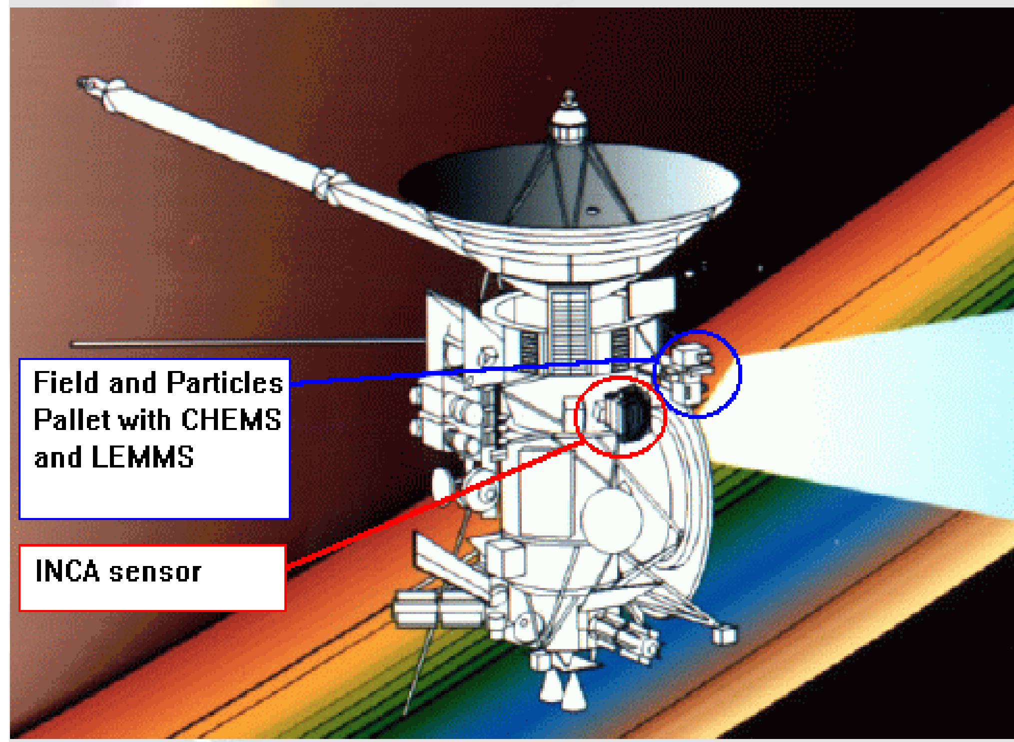
3 - 220 keV ions

- **LEMMS**

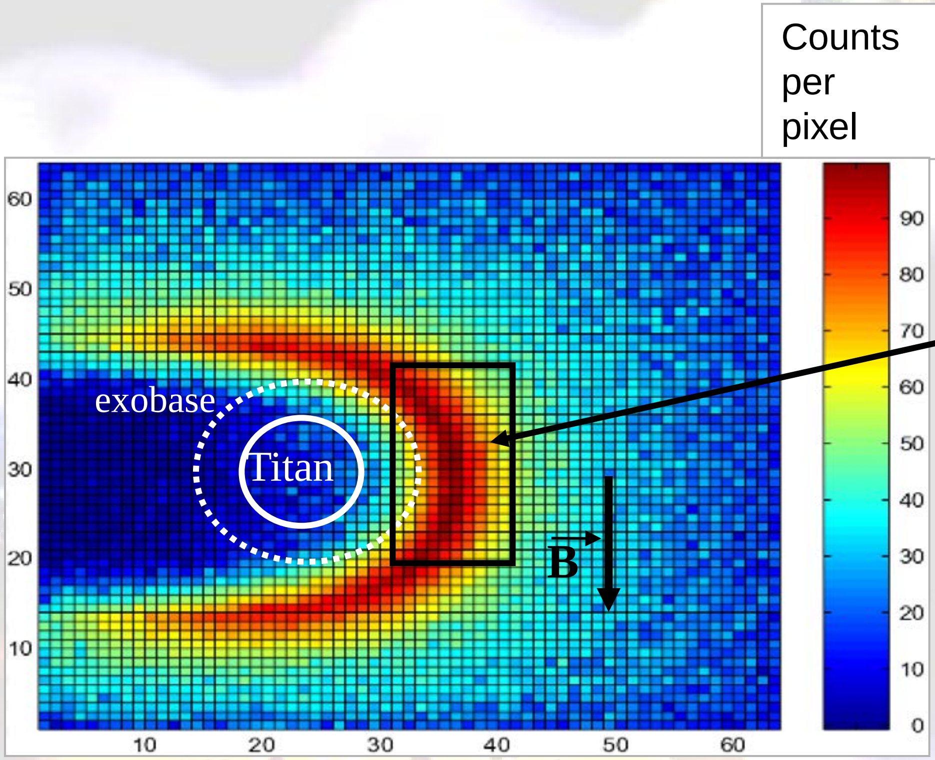
Low Energy Magnetospheric Measurement System

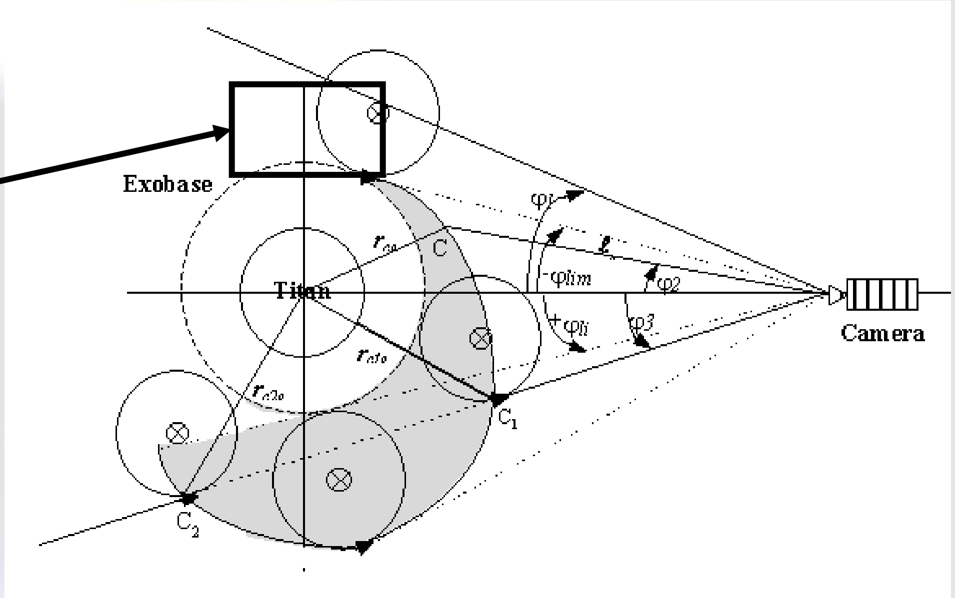
30 keV - 160 MeV ions

15 keV - 5 MeV electrons



Titan Simulations: a few years ago…

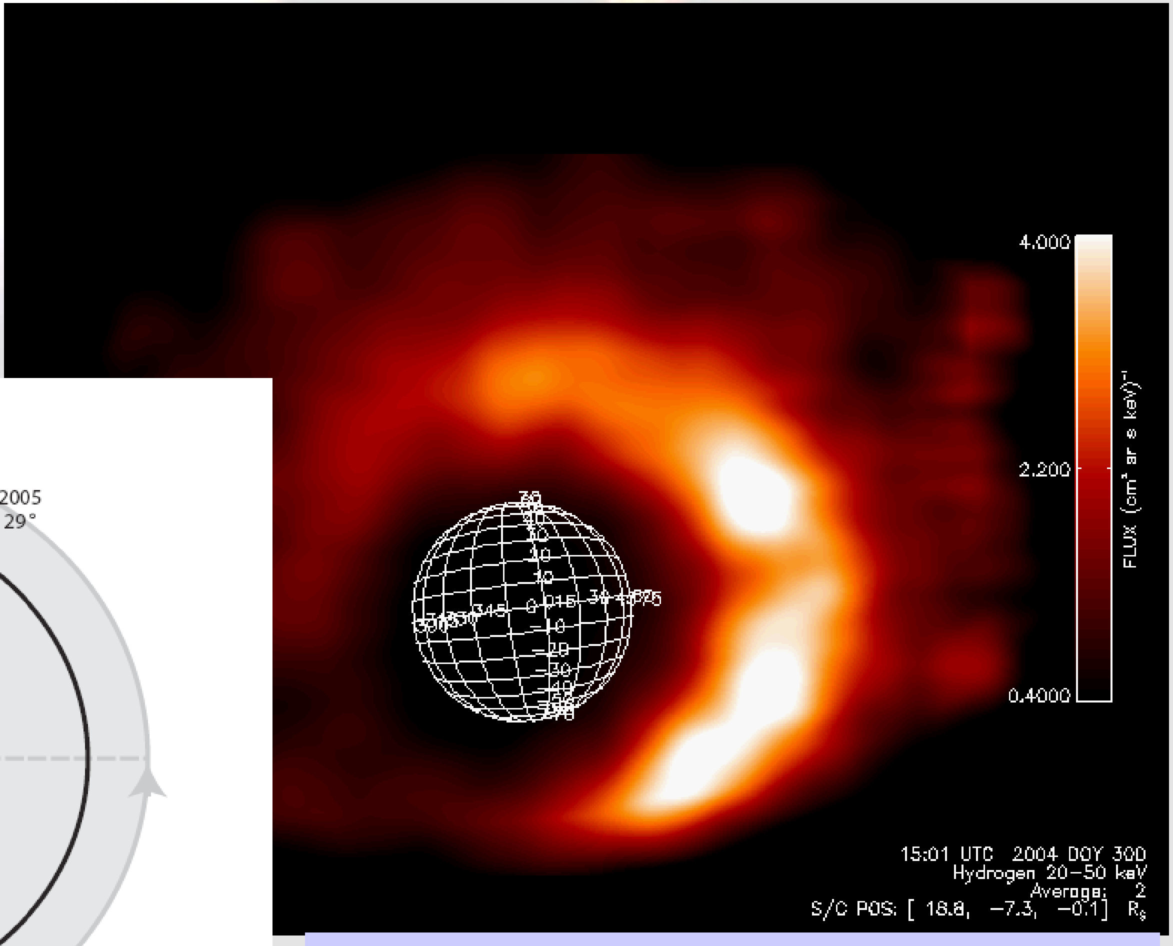


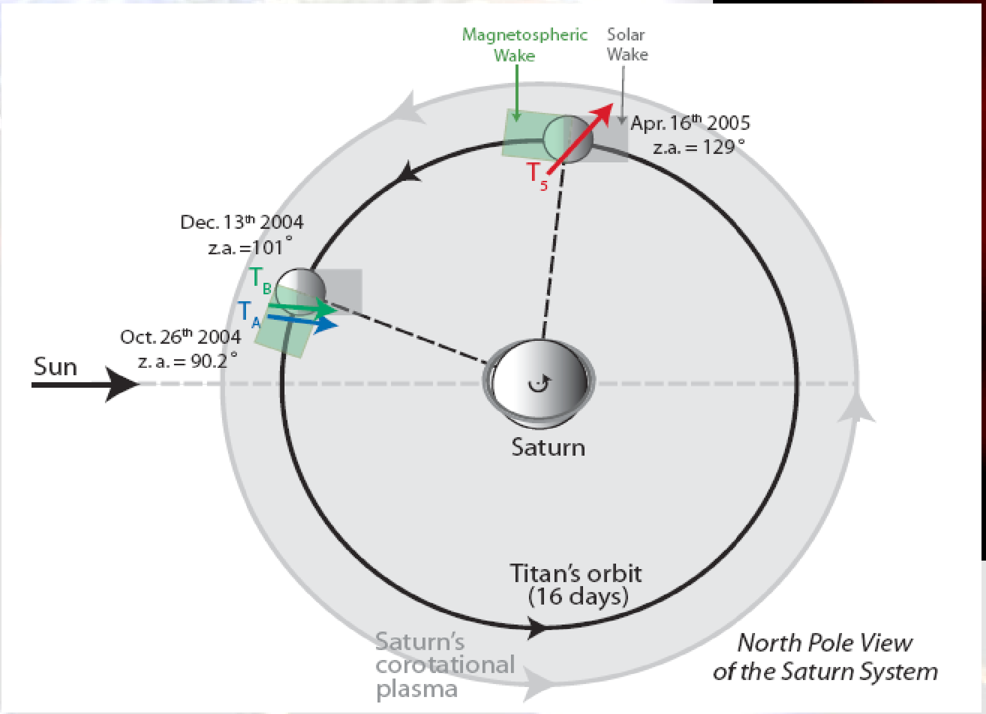


H = 6000 km 10 keV < *E* < 50 keV
t_{expo} = 5.75 minutes
Simulation Monte Carlo

Dandouras and Amsif, Planet. Sp. Sci., 1999

Titan ENA Observation by MIMI-INCA : Ta Flyby (24 OCT 2004)





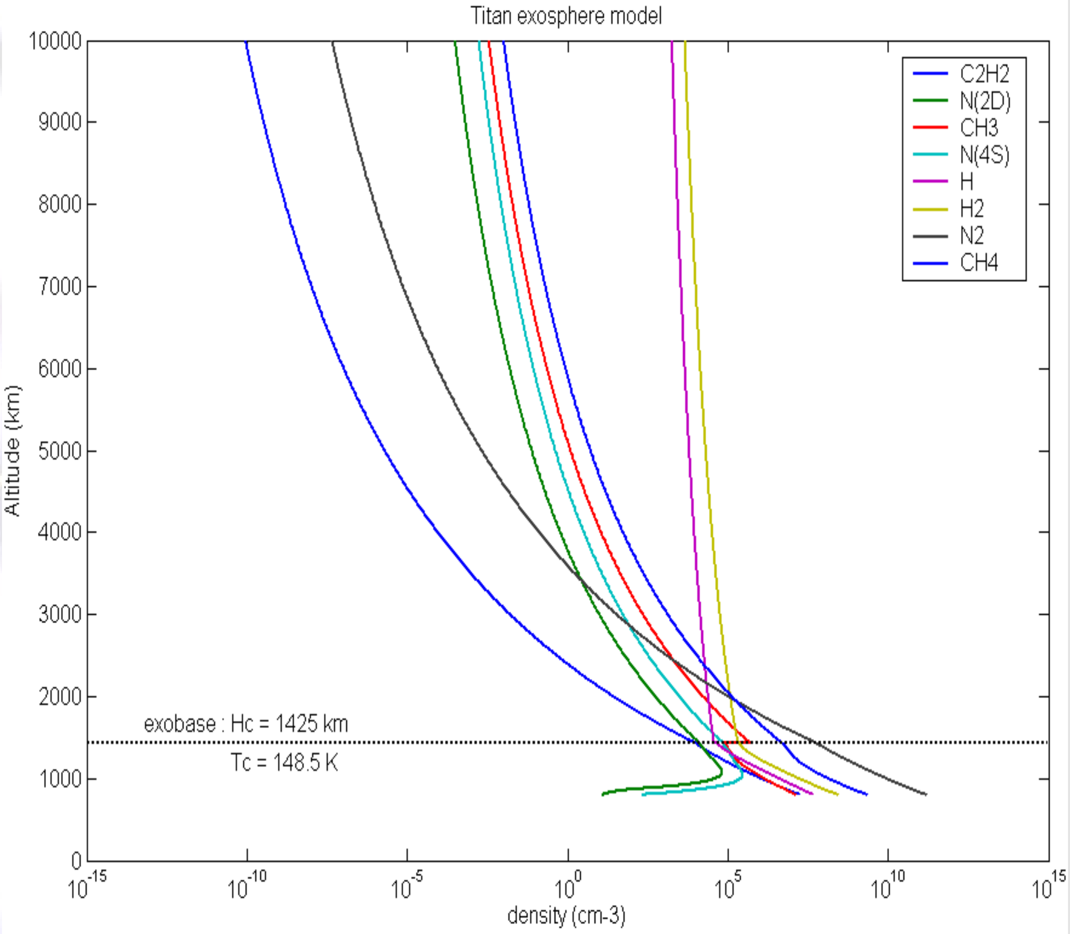
Dandouras et al.,
Philosph. Trans. Royal Soc., 2008

H = 8000 km   20 keV < E < 50 keV t_{expo} = ~ 8 minutes

Titan exosphere model : 1st step

Development of a Titan exosphere model: thermal equilibrium assumed (1st approach)

- Profiles in thermal equilibrium : Chamberlain approach (Maxwellian distribution at the exobase)
- Exobase altitude (Z_c = 1425 km) and temperature (T_c = 149 K) from INMS results
  courtesy INMS team
  (see next slide)
- Exobase densities from D. Toublanc atmospheric model for the major species (new version consistent with latest data and Vervack model)



Garnier, Dandouras, et al., Planet. Space Sci., 2007

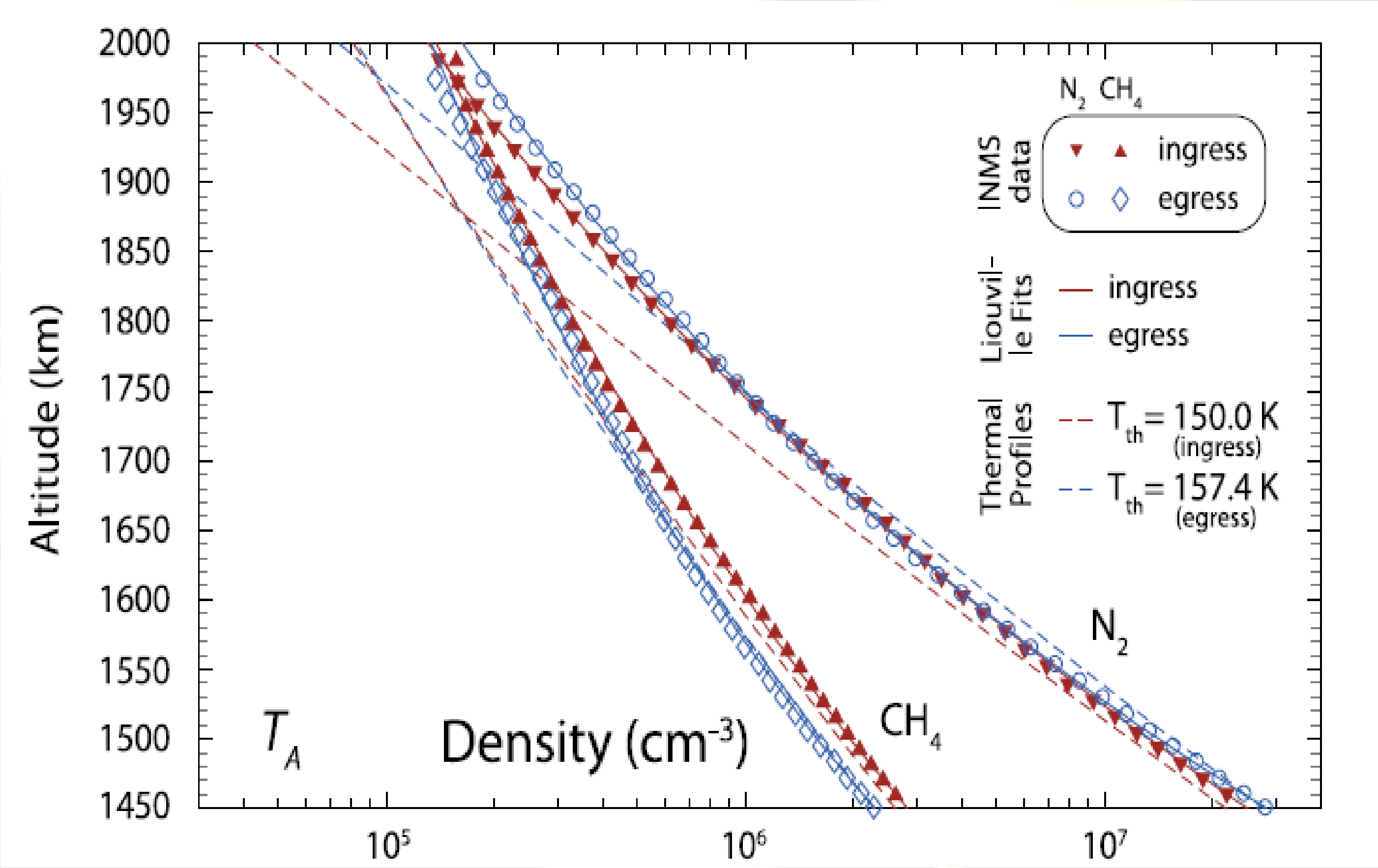
However: evidence for non thermal escape

- Energy input from Saturn's magnetosphere and from Solar UV radiation can drive several non-thermal mechanisms in Titan's upper atmosphere.

- Non thermal escape anticipated by *:*
  - *Ip* [1992] : anticipated nitrogen torus (but never observed later);
  - *Lammer and Bauer* [1991] and *Shematovitch et al.* [2003] : dissociative mechanisms for N_2; production of pick-up ions;
  - *Lammer and Bauer* [1993] : sputtering;
  - *Lammer et al.* [1998] and *Cravens et al.* [1997] : chemical and photochemical production of fast neutrals (N and N_2), …

INMS data evidence of non thermal escape

The best fit of INMS data, below 2000 km altitude for N_2/CH_4 : $Ta/Tb/T_5$, is not by thermal profiles, but for kappa distributions: *De la Haye et al.*, 2007



De la Haye et al., J. Geophys. Res., 2007

Exosphere fit with a Kappa distribution

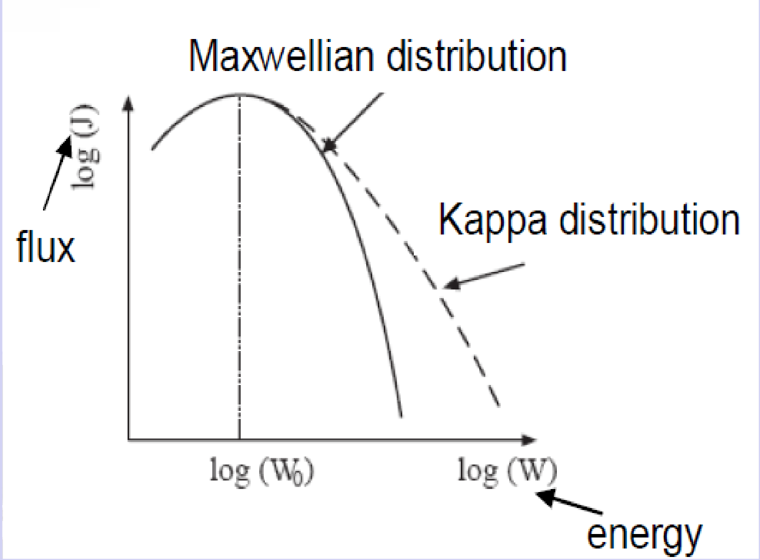
- Kappa distributions are commonly used for plasmas, to take into account non thermal populations.
- Introduced by Vasyliunas (1968) for the Earth's plasma sheet.
- Why not use them for exospheres, which interact with such plasmas and where there is no thermalisation ?

$$f_\kappa(r,v) = \frac{n(r)\Gamma(\kappa+1)}{\kappa^{3/2}\pi^{3/2}\omega_0^3\Gamma(\kappa-1/2)}\left(1+\frac{v^2}{\kappa\omega_0^2}\right)^{-\kappa-1}$$

$$\omega_0^2 = \frac{2kT}{m}\frac{\kappa-3/2}{\kappa}$$

$$\Gamma(\kappa) = \int_0^\infty e^{-t}t^{\kappa-1}dt$$

~ Maxwellian when $\kappa \Rightarrow \infty$



Titan exosphere model : 2nd step
a non thermal model

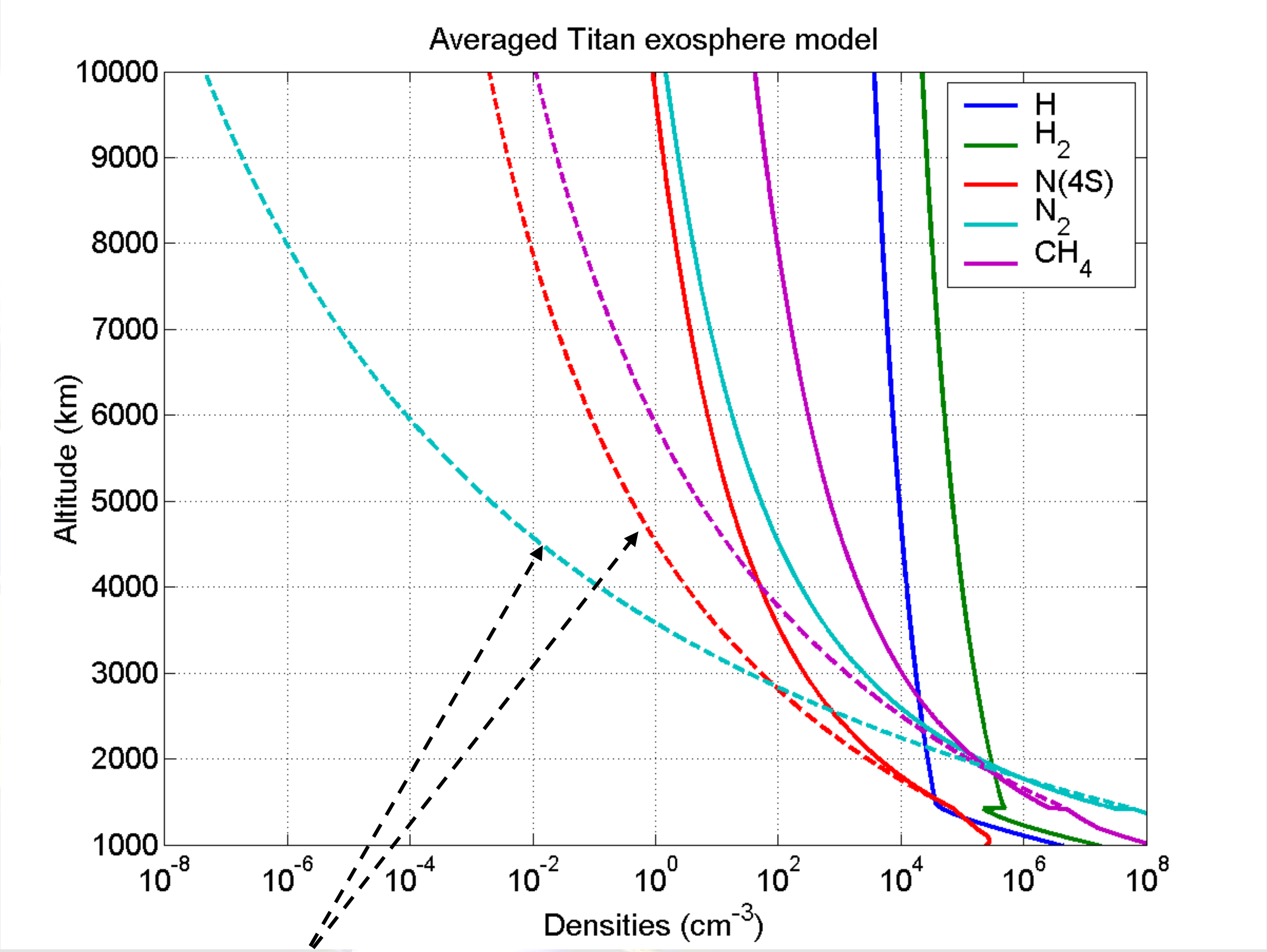
- Use of the best fit parameters determined by INMS for the lower exosphere to develop non thermal profiles for the extended exosphere
- Use of the *Kim* [1991] formalism for propagating upwards the distribution function
- Large variability between flybys (even between ingress/egress)

➢ **Calculation of an averaged exosphere model (over Ta/Tb/T5) and fitted with a kappa distribution at exobase for N, N_2, CH_4**

⇨ kappa ≈ 12 - 13

➢ **Maxwellian distribution at exobase for H, H_2**

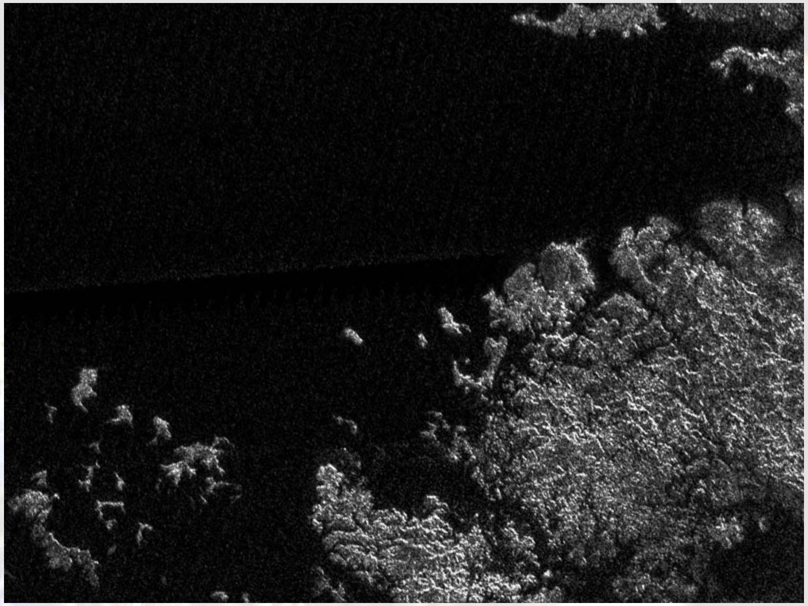
Average non-thermal Titan exosphere model: Ta, Tb, T5

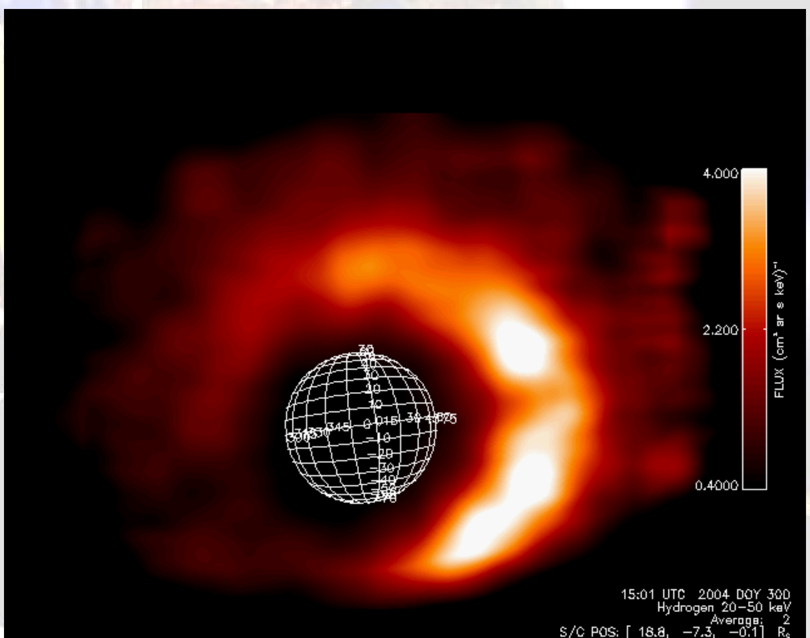


Thermal :
Garnier et al., Planet. Space Sci., 2007

Non-thermal:
Garnier, PhD Thesis, 2007

Non thermal exosphere : escape rates





Titan atmosphere

Non thermal exosphere : escape rates

$$F_c = \frac{1}{4}\int_{E_{esc}}^{\infty} \phi_{exo}(E)\sqrt{\frac{2E}{m}}dE$$

For $\mathbf{N_2}$ and $\mathbf{CH_4}$, non-thermal escape rates:

10^4 cm^{-2} s^{-1}

which for the total spherical shell gives **2×10^{22} s^{-1}**

→ emptying the Titan atmosphere in ~10^{12} years

For **H** and $\mathbf{H_2}$, thermal (Jeans) escape rates:

1.9 and **3.9×10^{27} s^{-1}**

Note: Johnson (2006): 4×10^{25} N s^{-1} , equivalent for CH_4

Titan upper atmosphere energy sources

Energy Source	Energy Flux (erg/cm^2/s)	Global Input (Watts)[4]	Comments
Plasma Protons	1.6e-4	3.4e7	Magnetized
Plasma Electrons	1.6e-4	3.4e7	Magnetized
Plasma Heavy Ions	1.5e-3	3.2e8	Unmagnetized
Energetic Ions	5.0e-4 to 1.0e-2	1.05e8 to 2.0e9	$27 < E_P < 255$ keV[1]
Energetic Electrons	2.0e-4	4.0e7	$28 < E_e < 533$ keV[1,2]
UV airglow	1.6e-3	3.5e8	Altitude ~ 1300 km[3]
UV ionization	1.6e-4	3.4e7	Altitude ~ 1300 km[3]
Ohmic Heating			Not yet known
GCR	1.6e-4 to 2.7e-3	3.2e7 to 5.4e8	Integrated Flux
Dust	1.8e-3	1.8e8	Interplanetary Dust

Sittler et al.,
"Titan from Cassini-Huygens" book., *2009*

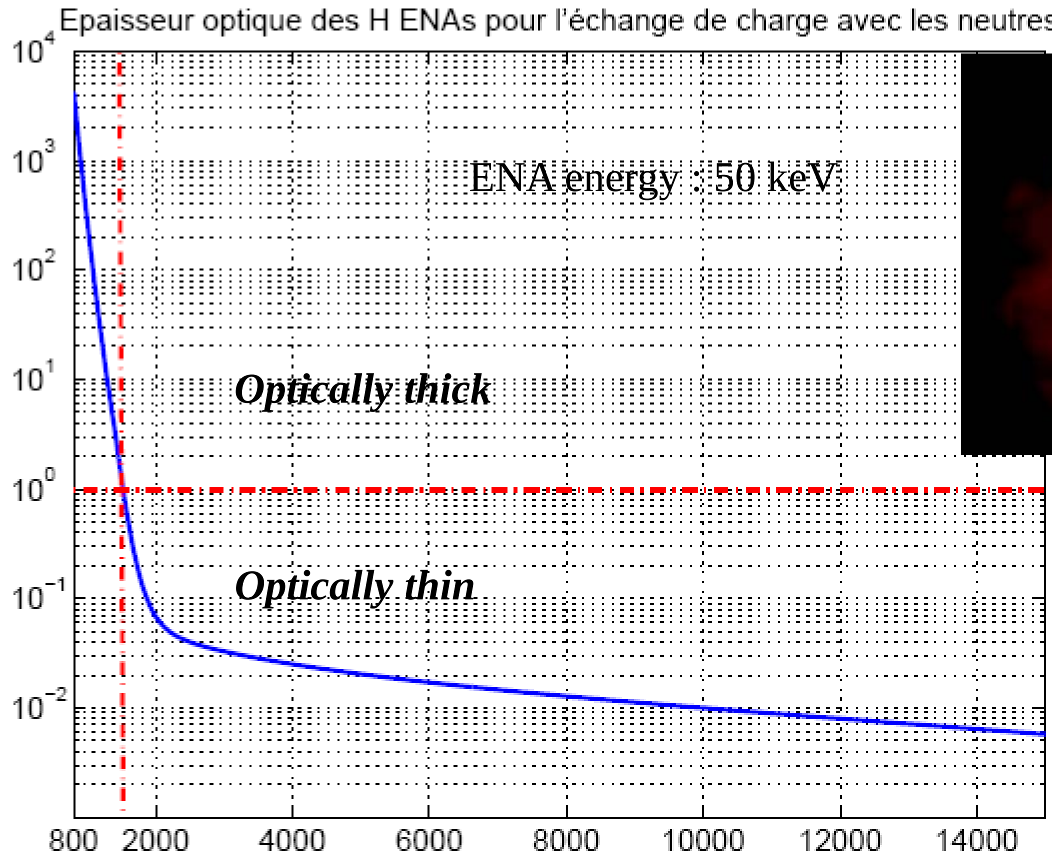
Energetic proton and oxygen ion precipitation, from Saturn's magnetosphere, can be the most important energy source for Titan's upper atmosphere:

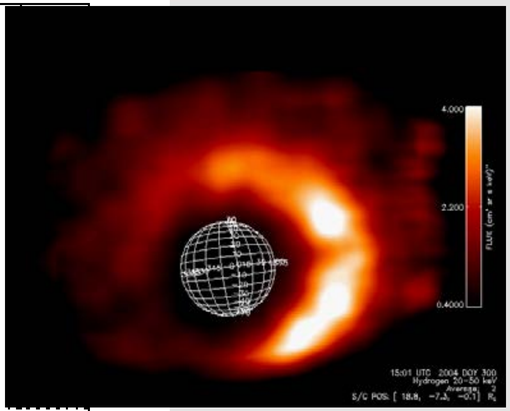
- Energy deposition, sputtering
- Ionisation
- Charge exchange with exosphere and ENA production
- Ionospheric chemistry

Ion / ENA absorption mechanisms: Collisions with neutrals

Optical thickness

(Statistical number of collisions cumulated along a trajectory)

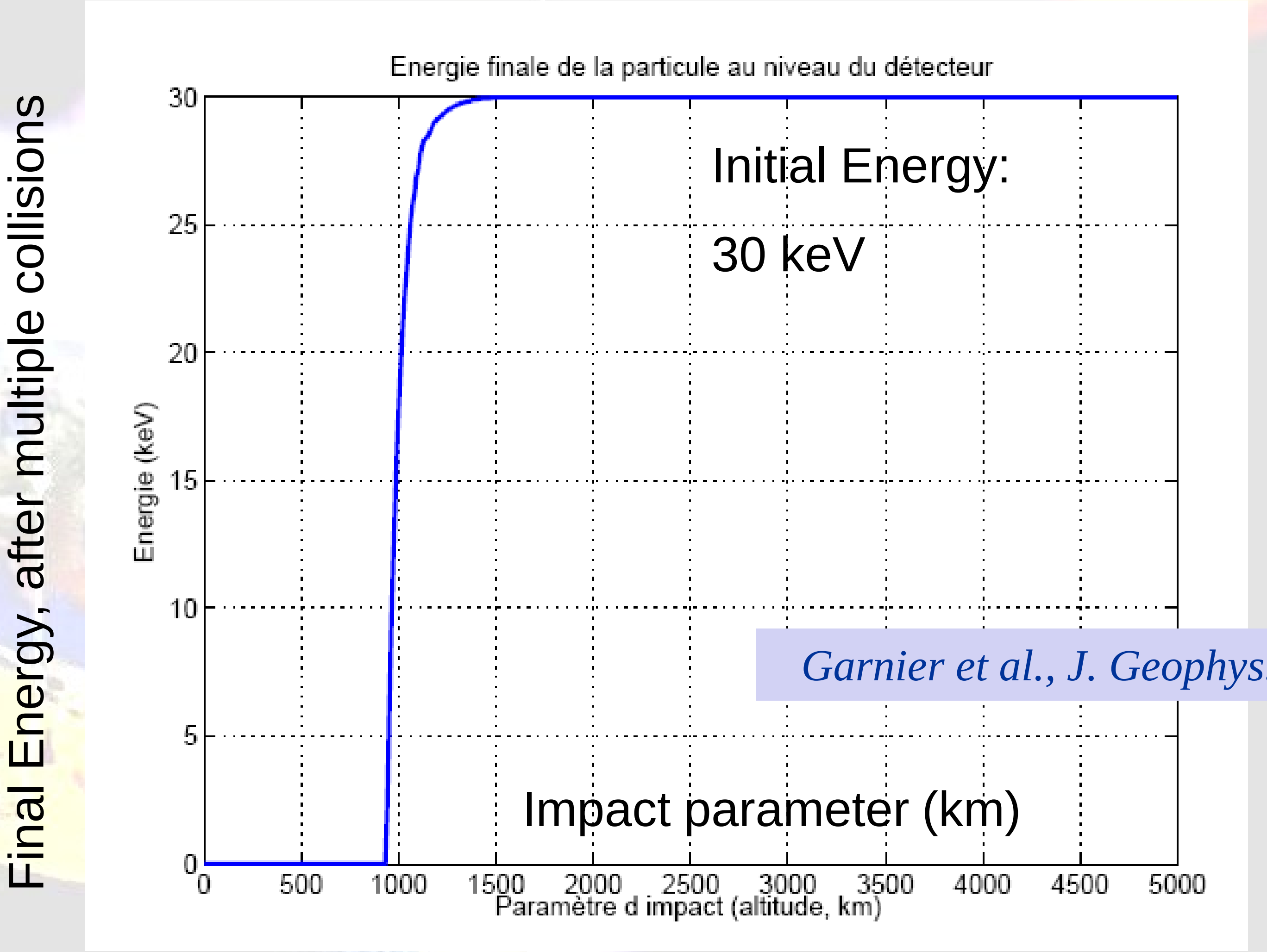




- Limit between optically thick and optically thin ~1500-1550 km altitude (depends on energy, from 20 to 50 keV, and on cross sections used)

=> The collisions with neutrals are the main loss for H ENAs, implying a lower limit for ENA emission below 1550 km altitude

Thermalisation of ENAs



Garnier et al., J. Geophys. Res., 2008

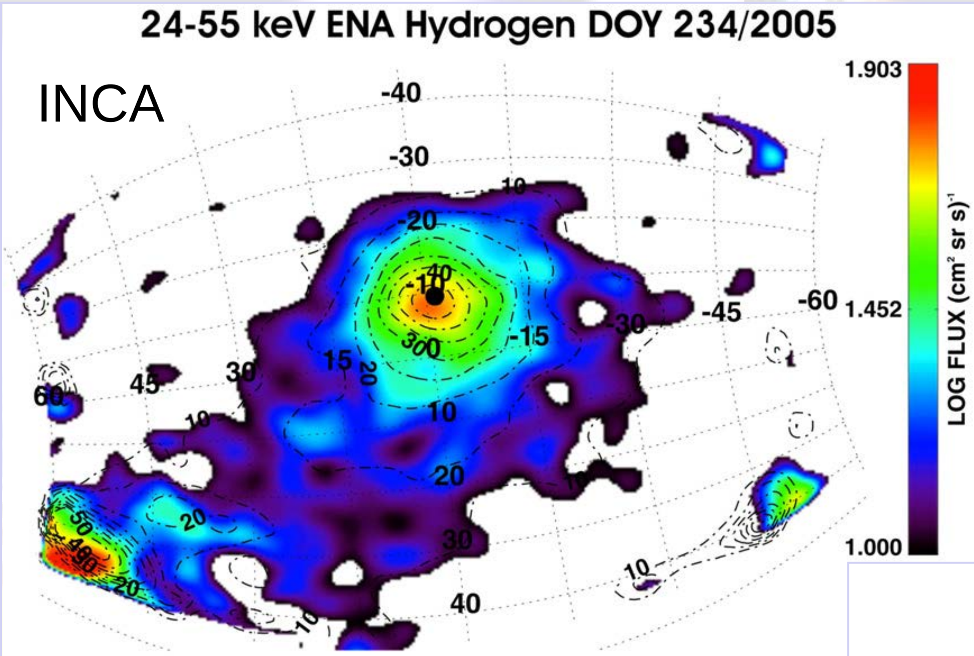
- ~30 eV “lost” in each charge-exchange collision.
  - ➢**Limit of ENA emissions: ~1000 km**

Titan ENA absorption in the lower exosphere / thermosphere

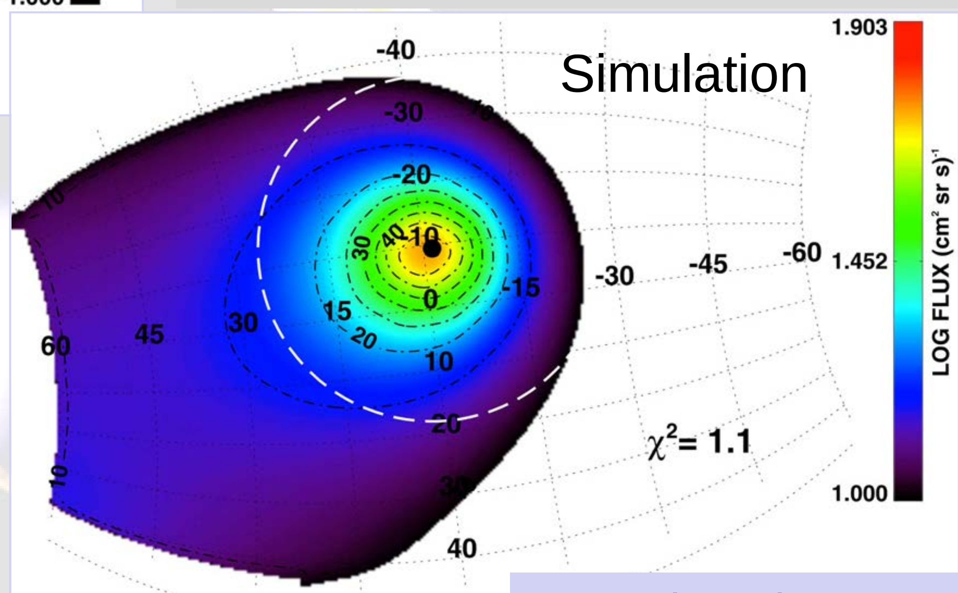
- **Collisions with neutrals** is the **dominant mechanism**.
- Exosphere **optically thin** to ENAs **above ~1500 km**.
- **Strong absorption** of ENAs / limit of emissions **below 1000 km altitude**.
- It is at these altitudes also, below ~1000 km, that **energetic protons and oxygen ions from Saturn's magnetosphere precipitating into Titan's atmosphere deposit their energy, ionise and drive ionospheric chemistry** [*Cravens et al.*, 2008].

Titan's extended exosphere: H_2

Max detectable extent: ~50 000 km (Hill sphere)



- IONS
  - 24-55 keV protons
  - Parametric model
  - Homogenous around Titan [*Dialynas et al., 2009*]
- NEUTRAL GAS
  - TITAN: H_2 $1/r^2$
  - T_{exo}=152.5, n_{exo}=1.302 x 10^6 cm^{-3}



Brandt et al., 2011

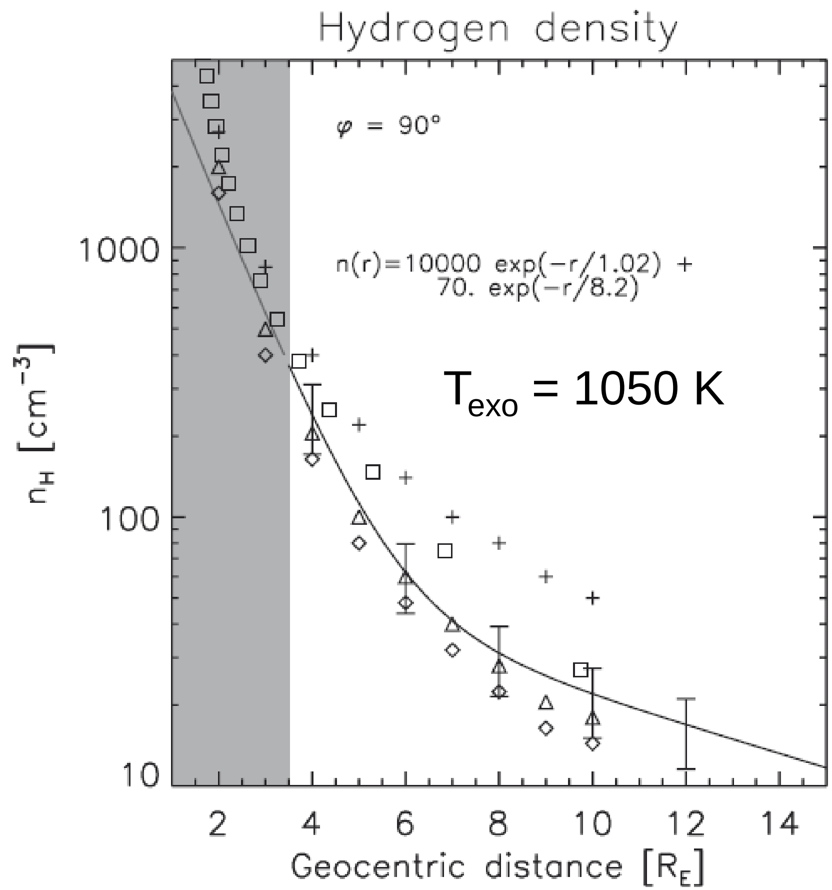
1 / *r* ^{2} law characterises:

- either an escaping population
- or a satellite population
- whereas a ballistic population would follow an 1 / *r* $^{5/2}$ law

Part 2 :

The Earth

Atmospheric escape from Earth:

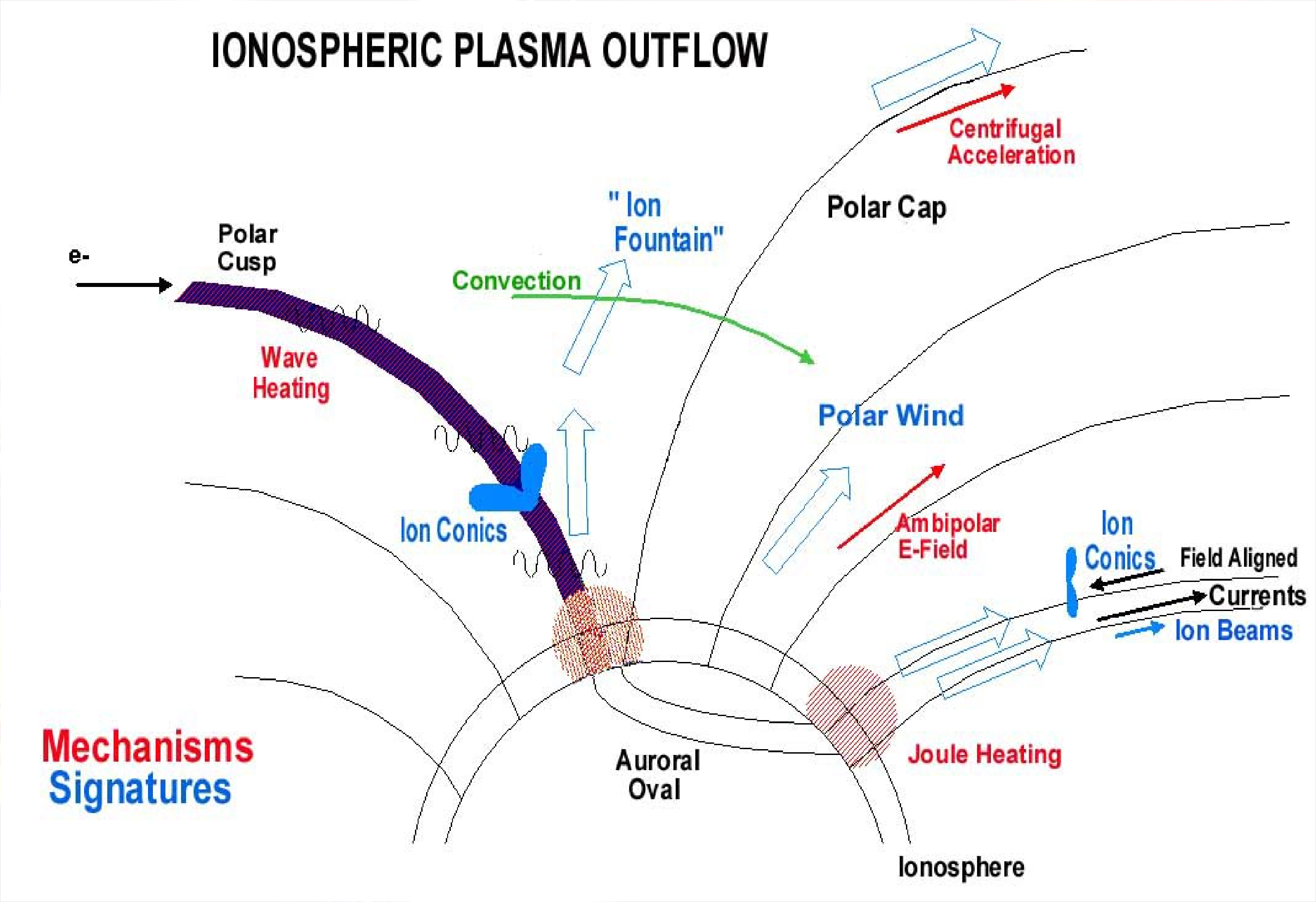


Ostgaard et al., 2003

A: The ***exosphere***

Extremely slow escape

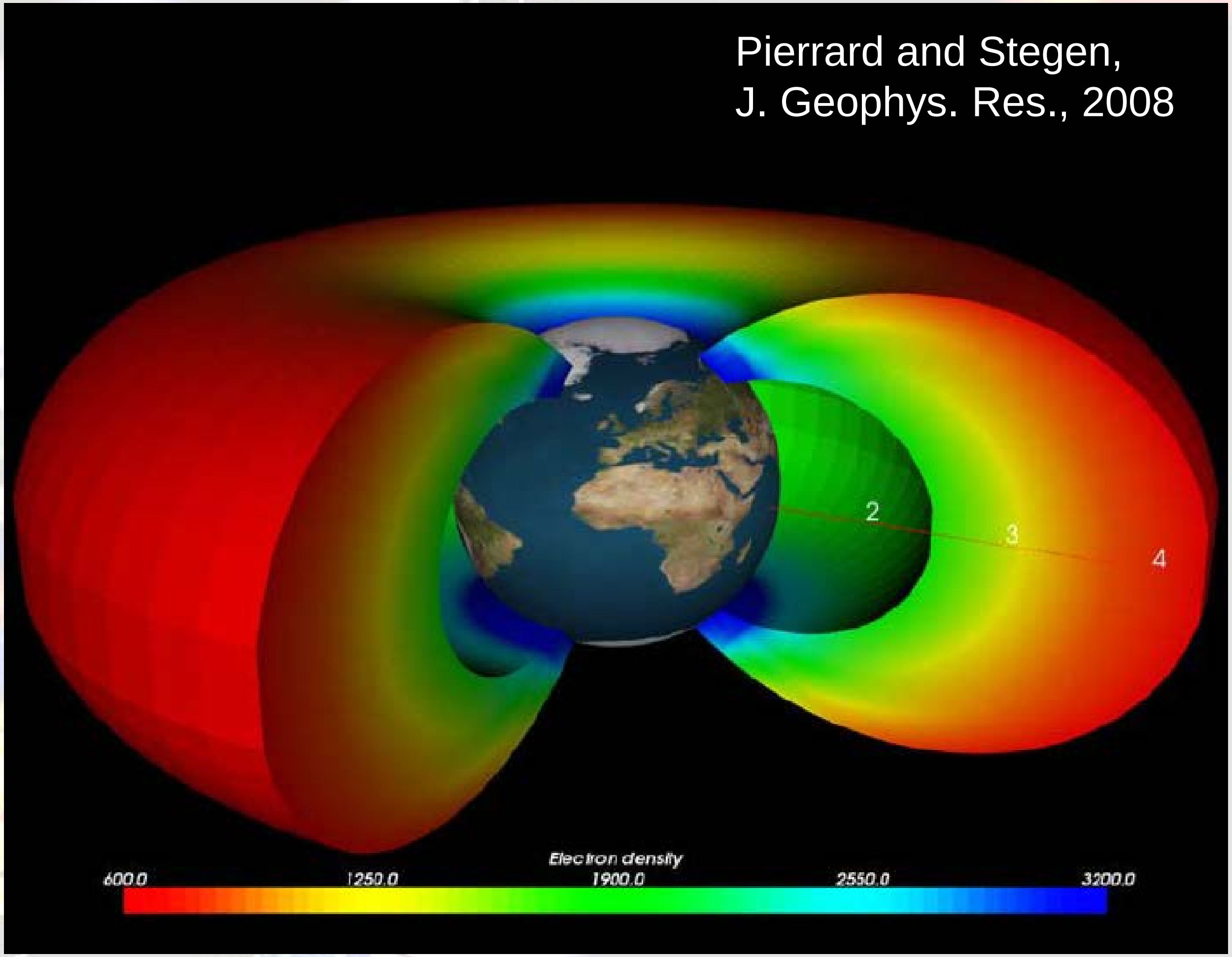
Atmospheric escape from Earth:



B: The ***high-latitude ionosphere***

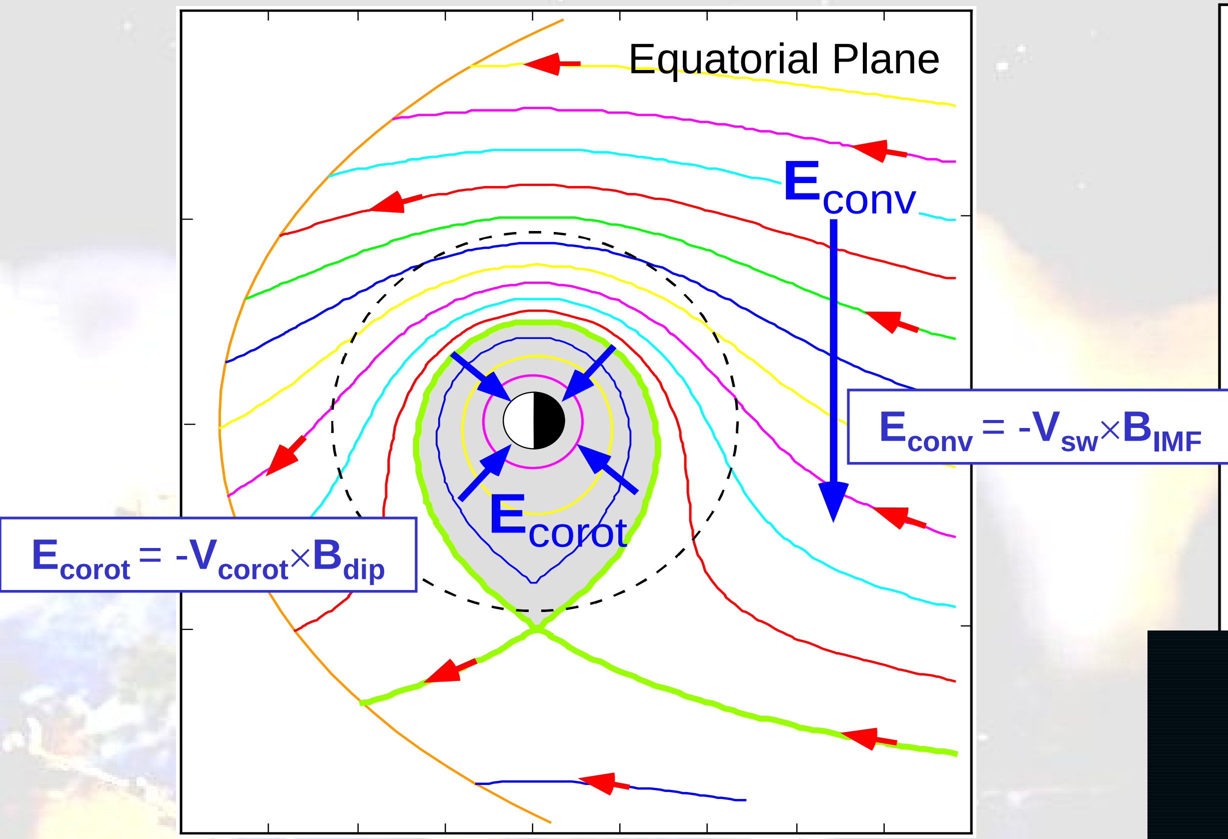
~10^{26} ions s^{-1}

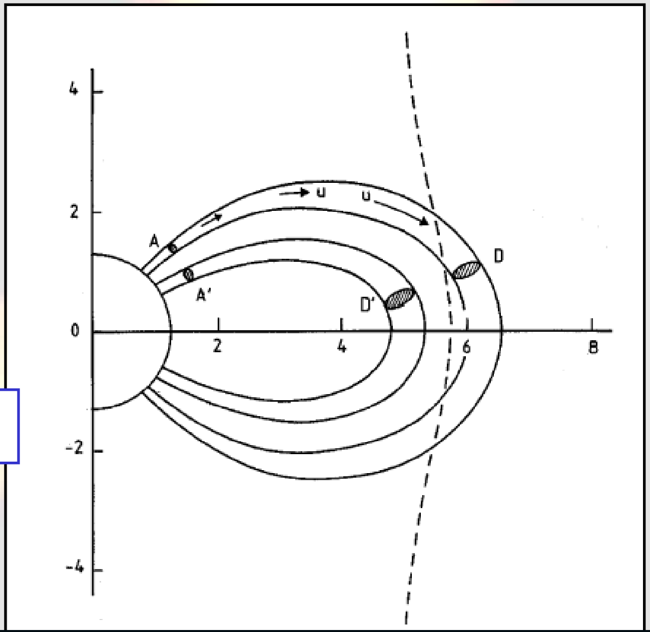
Atmospheric escape from Earth:

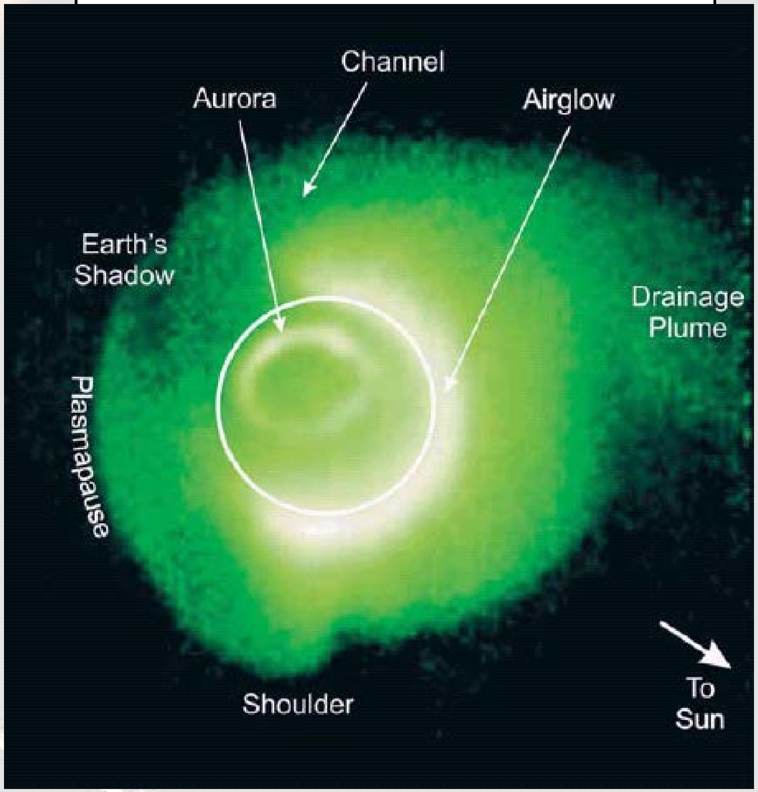


C: The ***Plasmasphere***

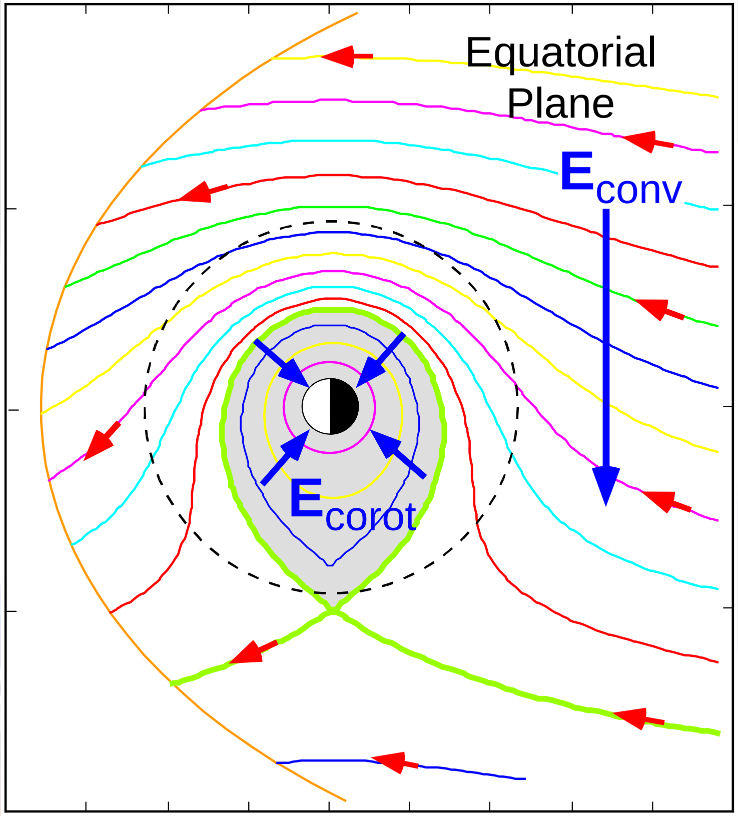
Torus of cold and dense plasma (~1 eV)

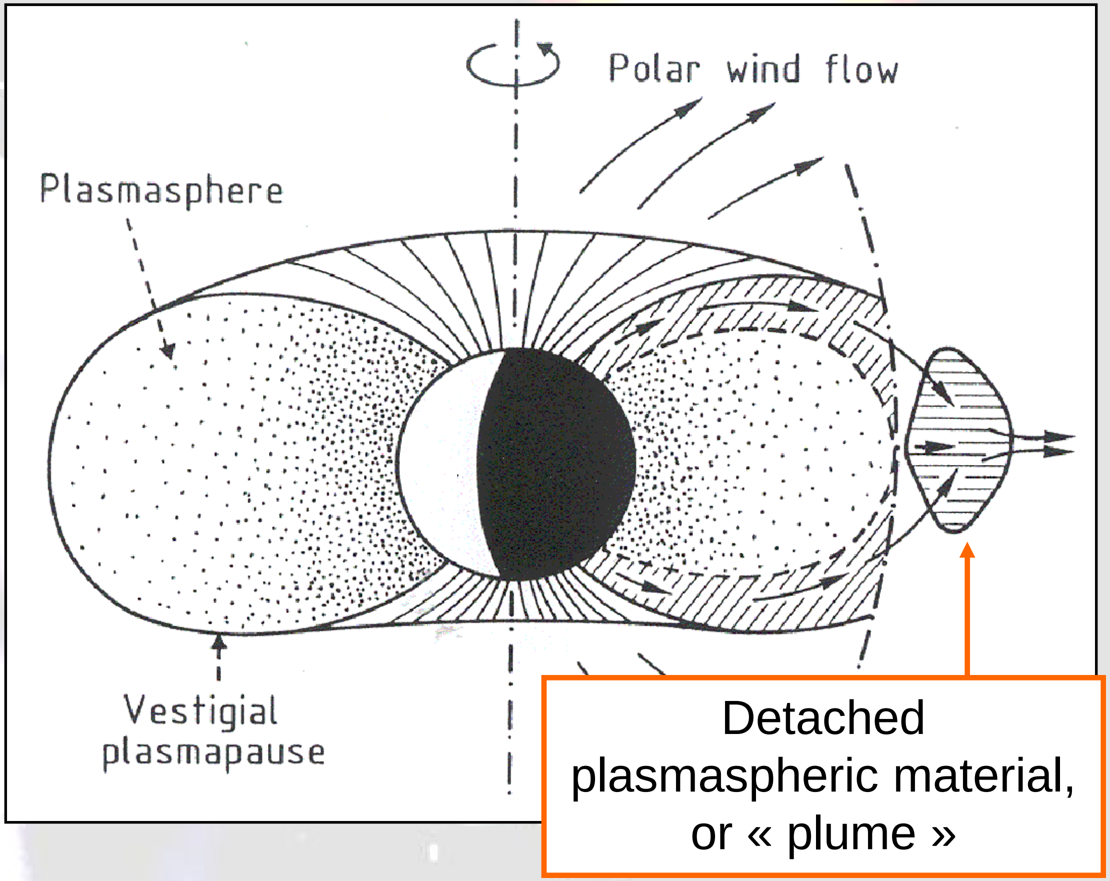






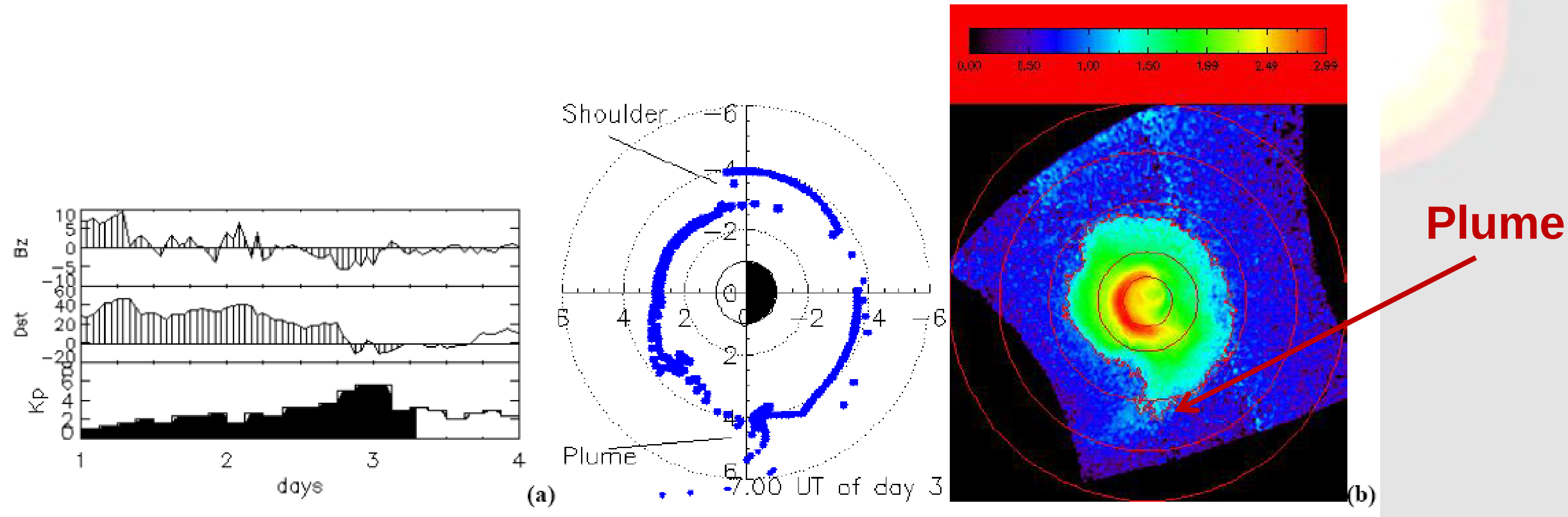
The plasma in the inner magnetosphere **co-rotates** with the Earth. As a consequence, the **ionospheric plasma at mid-latitudes** can expand upward along the magnetic field lines and fill them until the plasma gas pressure is equalized along the entire field line. The plasma region above the ionosphere on such closed magnetic field lines is the **plasmasphere**.





- **Plasmapause** corresponds to the Zero-parallel force surface (gravitational + centrifugal force)
- **Enhancements of the convection electric field** move inward this corotation / convection boundary ("last closed equipotential"), causing **erosion of the outer plasmasphere**
- Formerly corotating outer flux tubes are carried away in the newly strengthened convection field
- The plasmapause becomes closer to the Earth

Lemaire, 1974, 1999, 2001



Simulation *EUV / IMAGE*

Pierrard and Cabrera, 2005

Are plasmaspheric plumes the only mode for plasmaspheric material release to the magnetosphere?

- Plasmaspheric plumes are associated to active periods: change of the electric field.
- In 1992 Lemaire and Schunk **proposed the existence of a plasmaspheric wind**, steadily transporting cold plasmaspheric plasma outwards **across the geomagnetic field lines**, even during prolonged periods of quiet geomagnetic conditions [*J. Atmos. Sol.-Terr. Phys.* 54, 467-477, 1992].

Plasmaspheric Wind: background

- This wind is expected to be a slow radial flow pattern, providing a **continual loss of plasma** from the plasmasphere, (for all local times and for *L* > ~2), similar to that of the subsonic expansion of the equatorial solar corona
- The existence of this wind has been proposed on a **theoretical basis**: it is considered as the **result from a plasma interchange motion** driven by an imbalance between gravitational, centrifugal and pressure gradient forces:

  André and Lemaire, *J. Atmos. Sol.-Terr. Phys.* 68, 213-227 (2006).

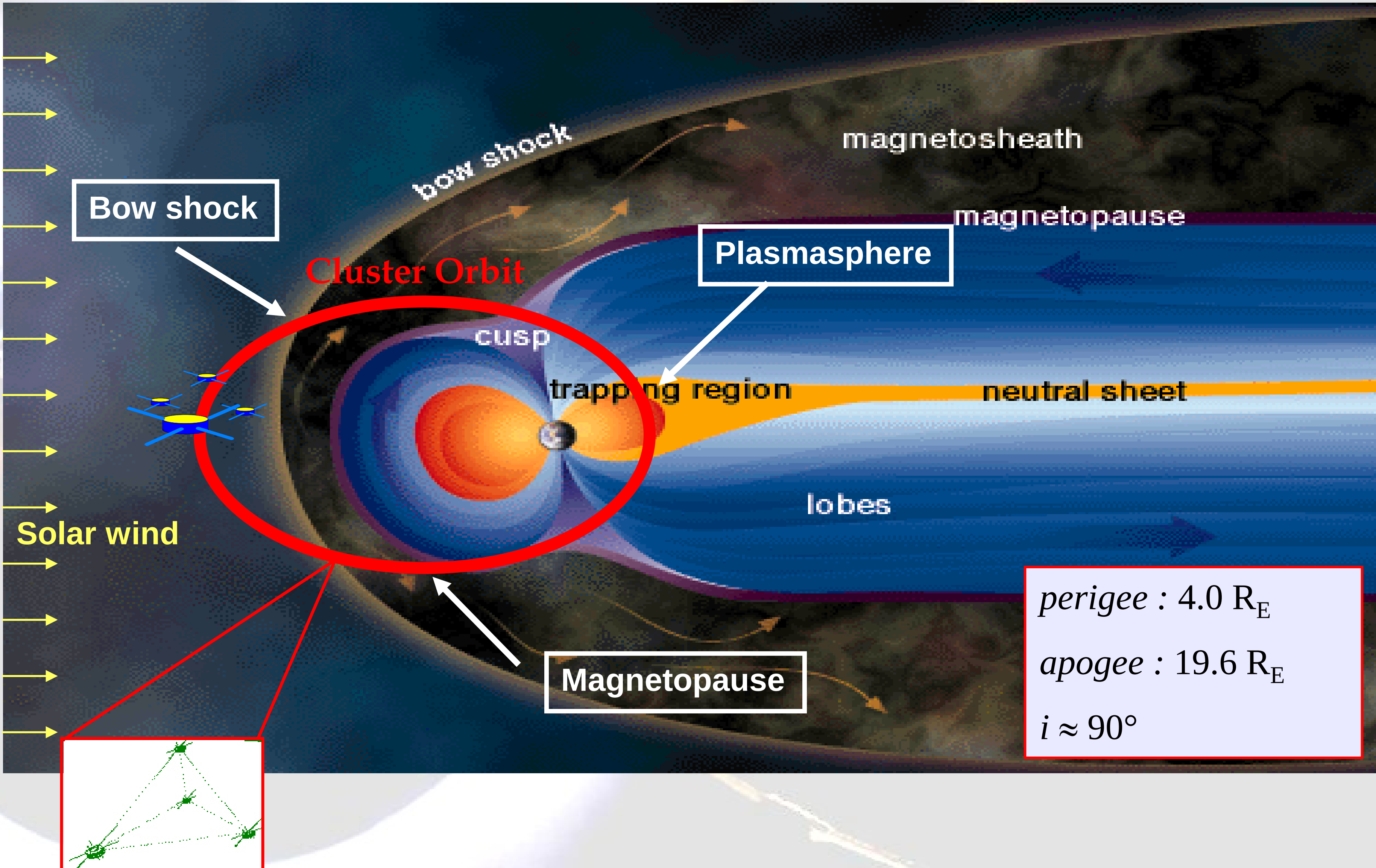
Plasmaspheric Wind: background

- **Indirect evidence** suggesting the presence of a plasmaspheric wind has been provided in the past from :
  - the plasmasphere refilling timing, indicating a a continuous plasma leak from the plasmasphere [Lemaire and Shunk, 1992; Yoshikawa et al., 2003]
  - the smooth density transitions from the plasmasphere to the subauroral region, observed during quiet conditions and at various magnetic local times [Tu et al., 2007].

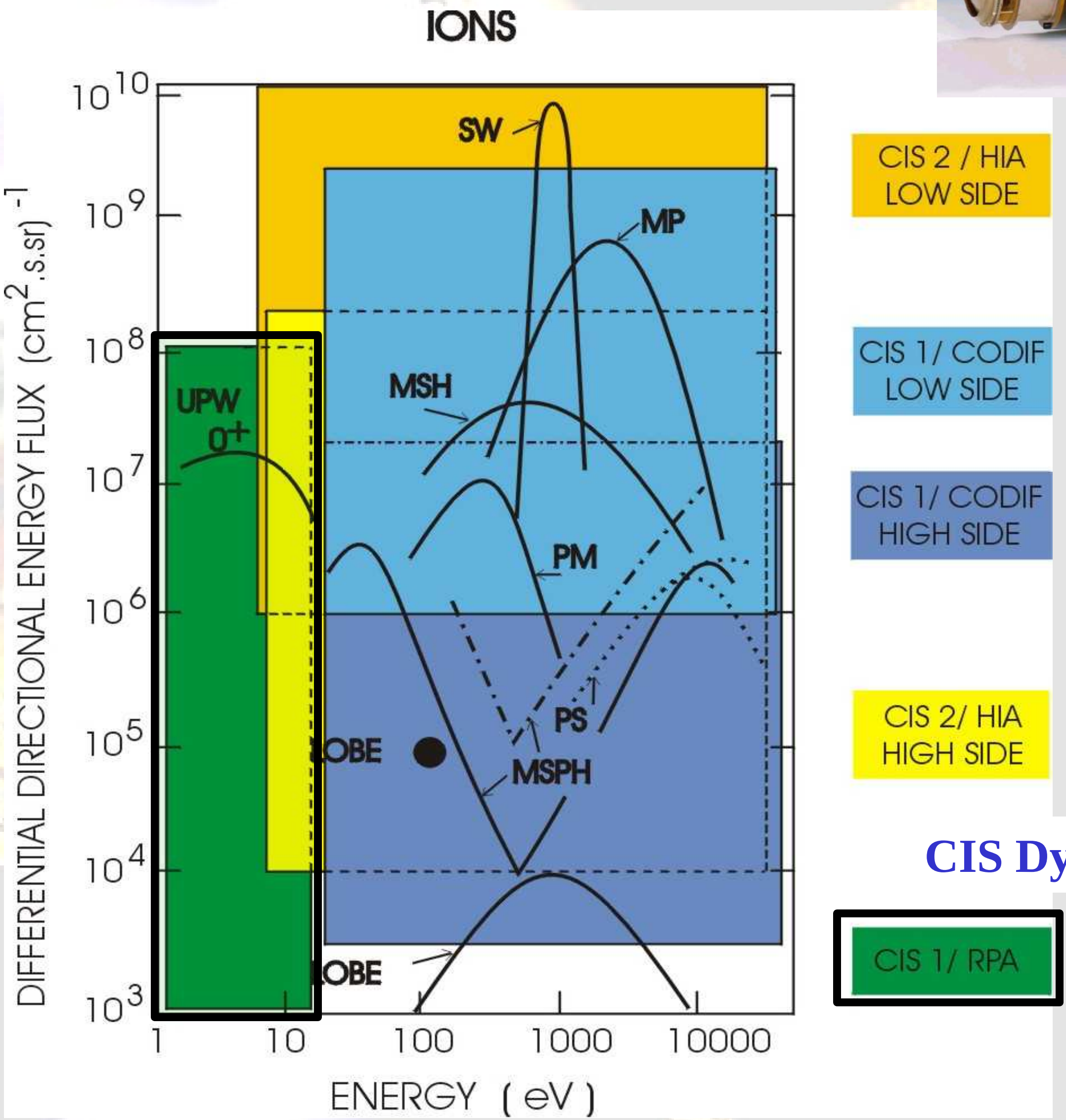
- **Direct detection** of this wind has, however, **eluded observation** in the past.

Existence of a Plasmaspheric Wind:

What Cluster Ion Observations can tell us?

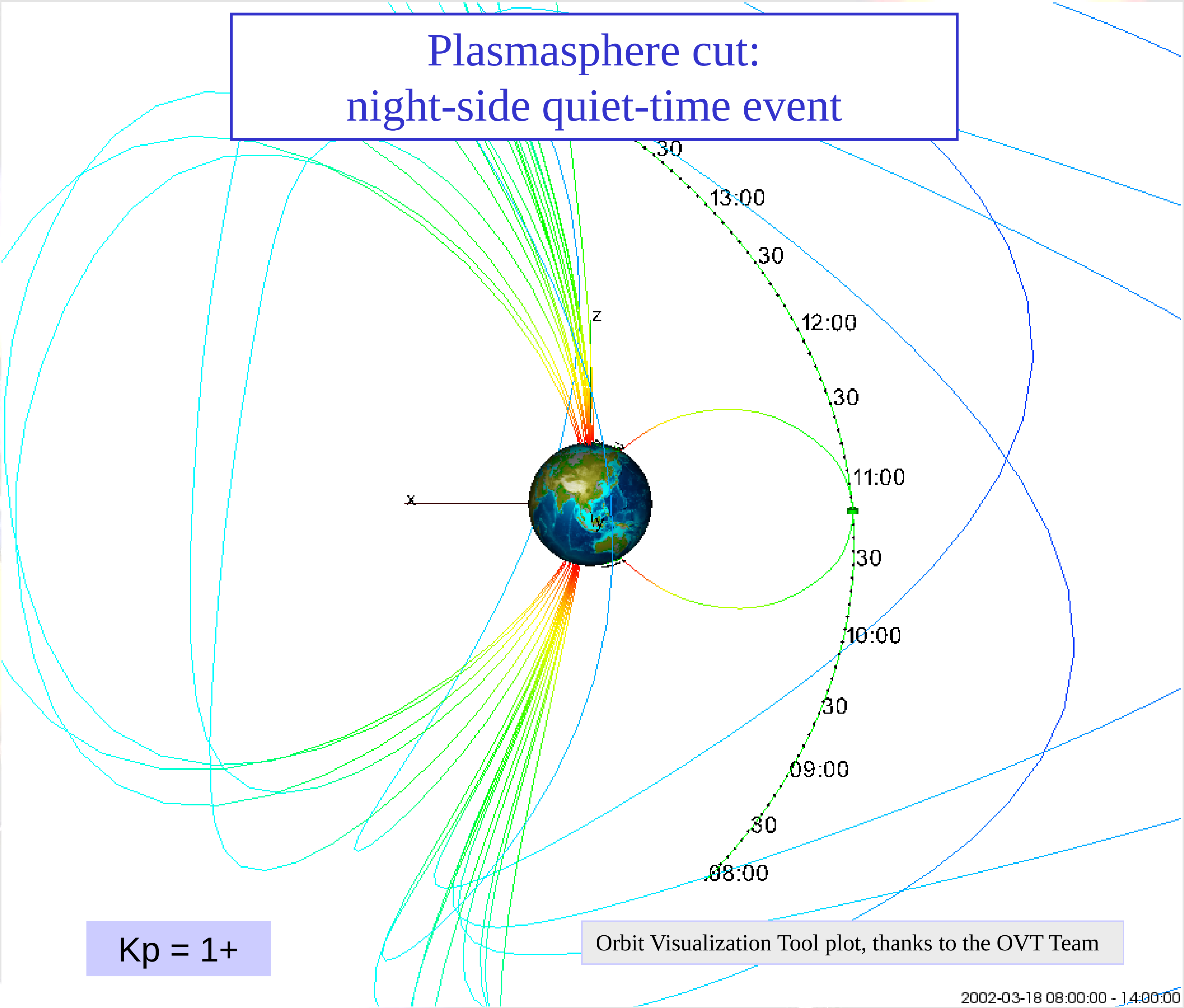


CIS
Cluster Ion Spectrometry



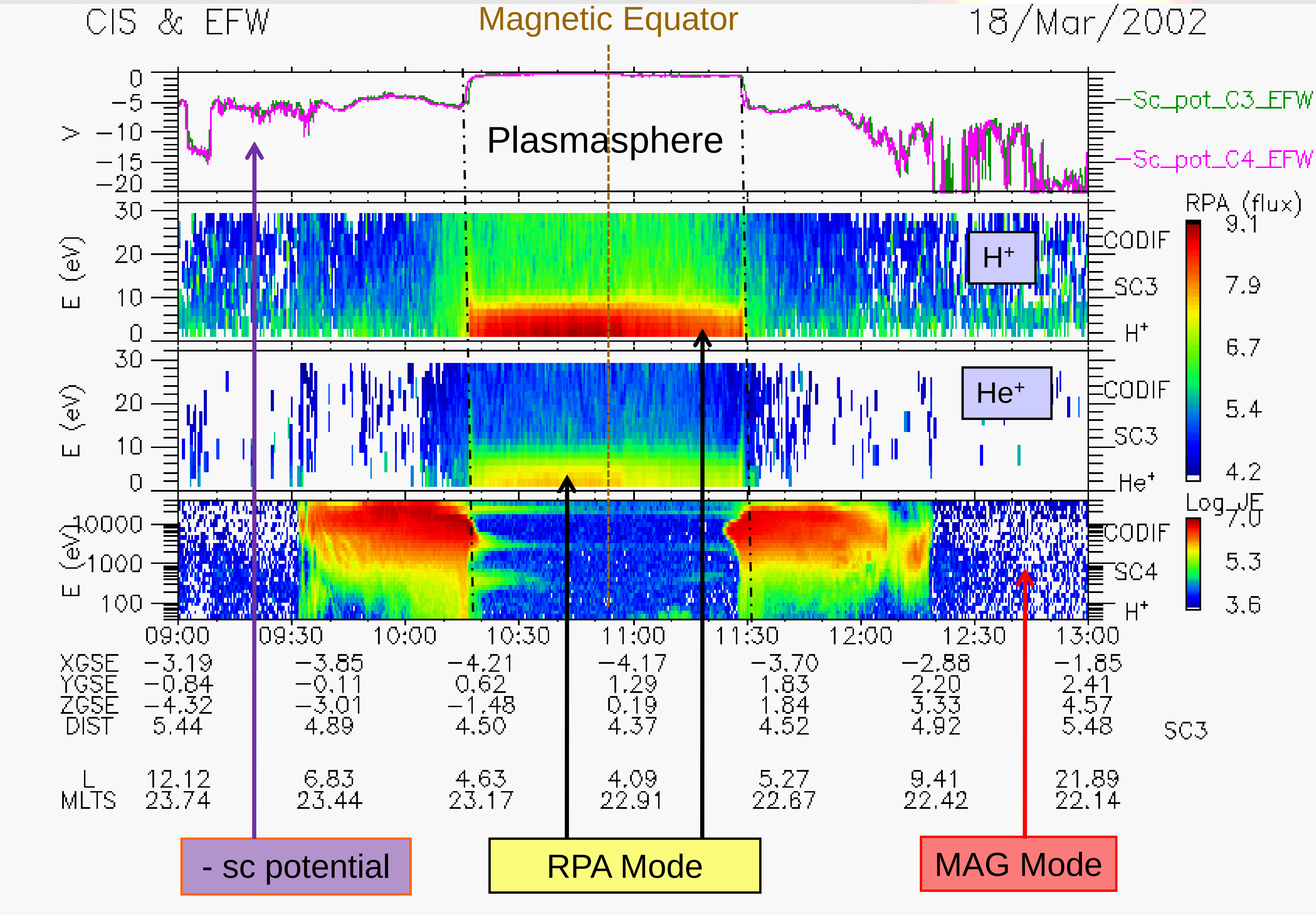
CIS Dynamic Range

Plasmasphere cut: night-side quiet-time event



Kp = 1+

Orbit Visualization Tool plot, thanks to the OVT Team



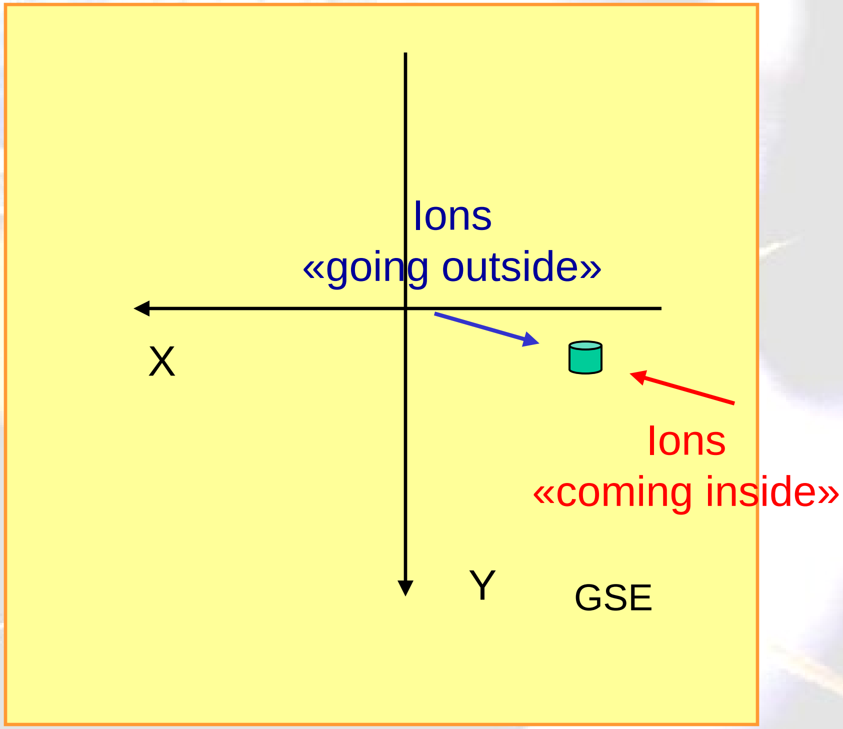
spacecraft potential EFW data thanks to the EFW team and the CAA

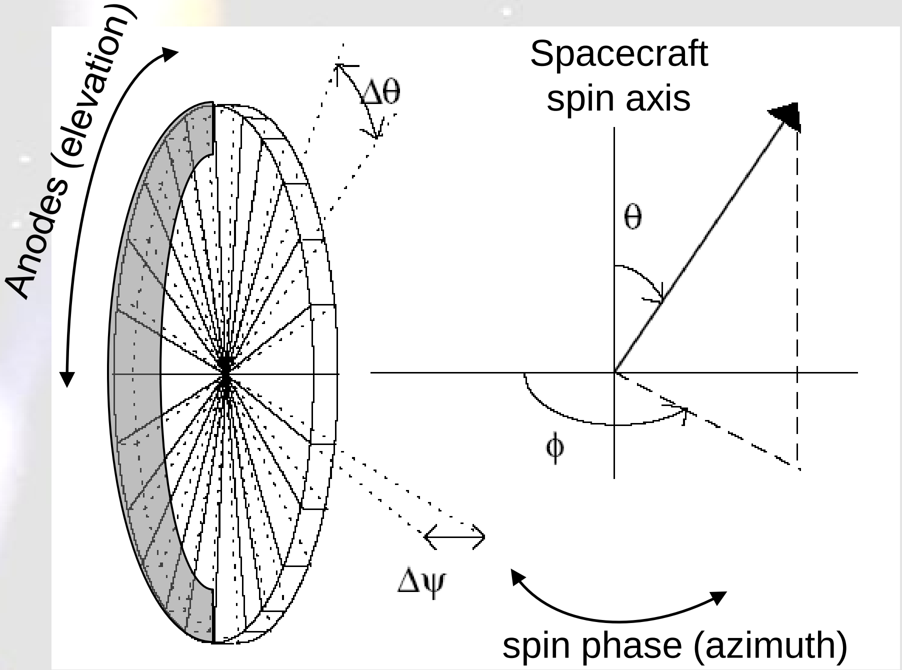
CIS / CODIF data : CIS team

Search for a Plasmaspheric Wind:
Selection of angular portions of the ion distribution function

Spacecraft position on the ecliptic plane
when close to magnetic equator
(18 March 2002 event)

CIS-CODIF
rotating field-of-view

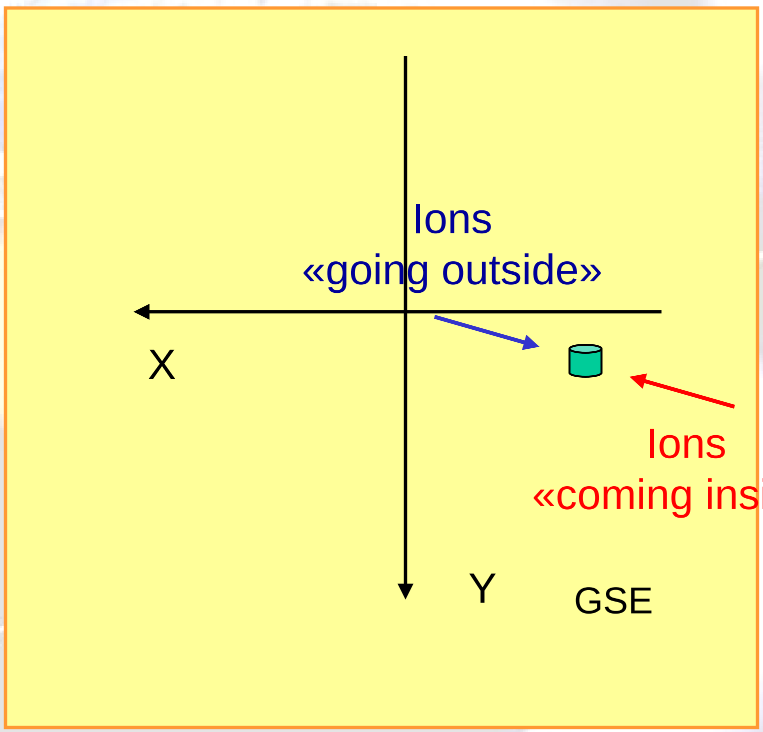


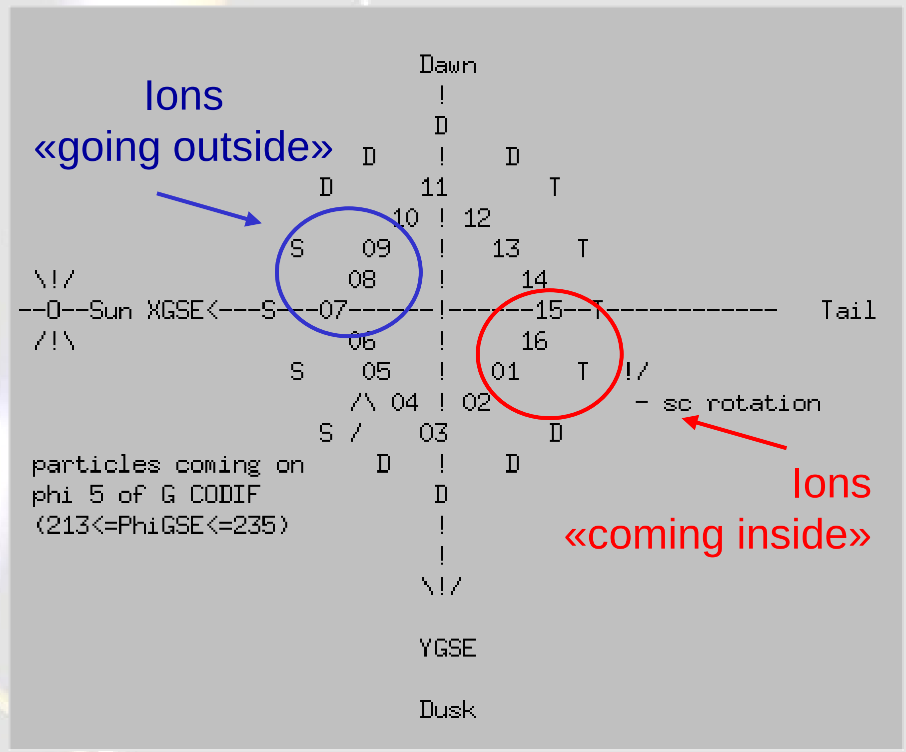


Selection of angular portions of the ion distribution function to search for a Plasmaspheric Wind

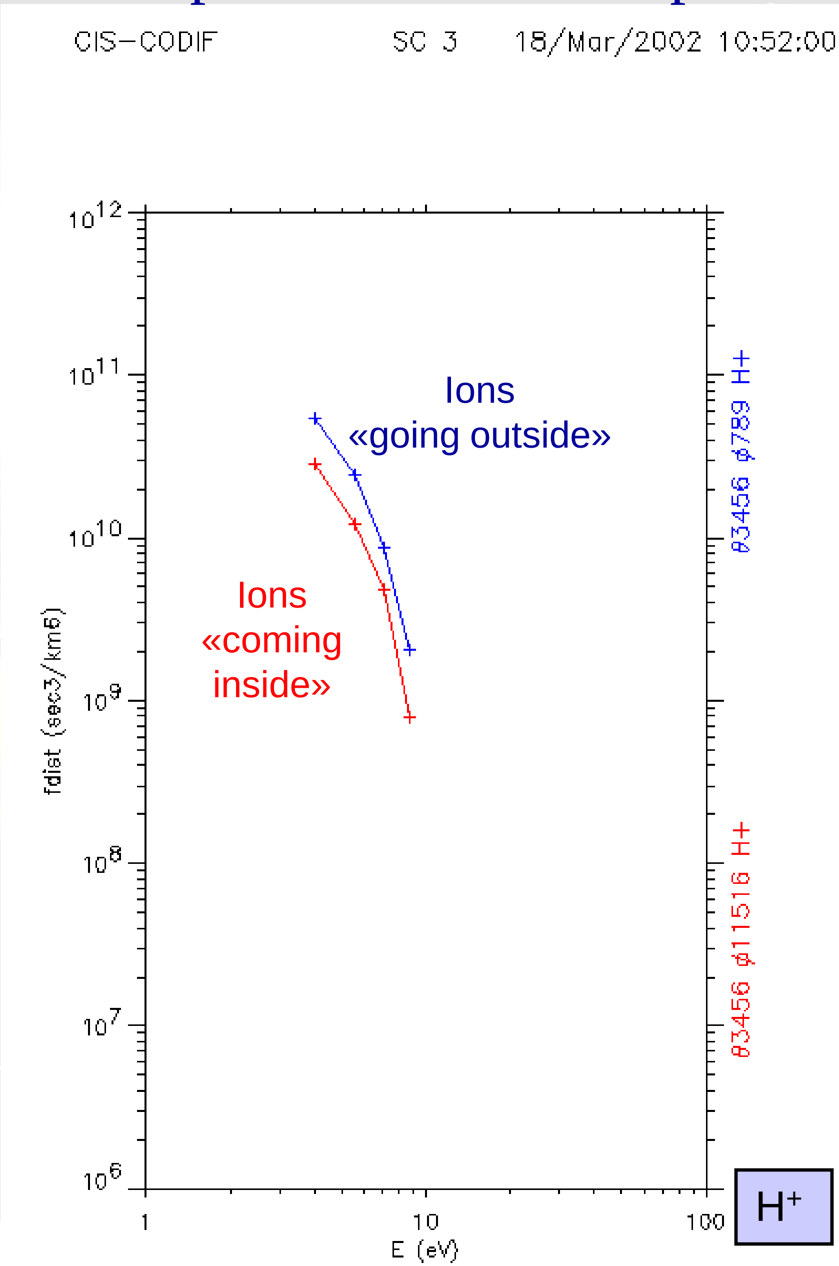
Spacecraft position on the ecliptic plane when close to magnetic equator (18 March 2002 event)

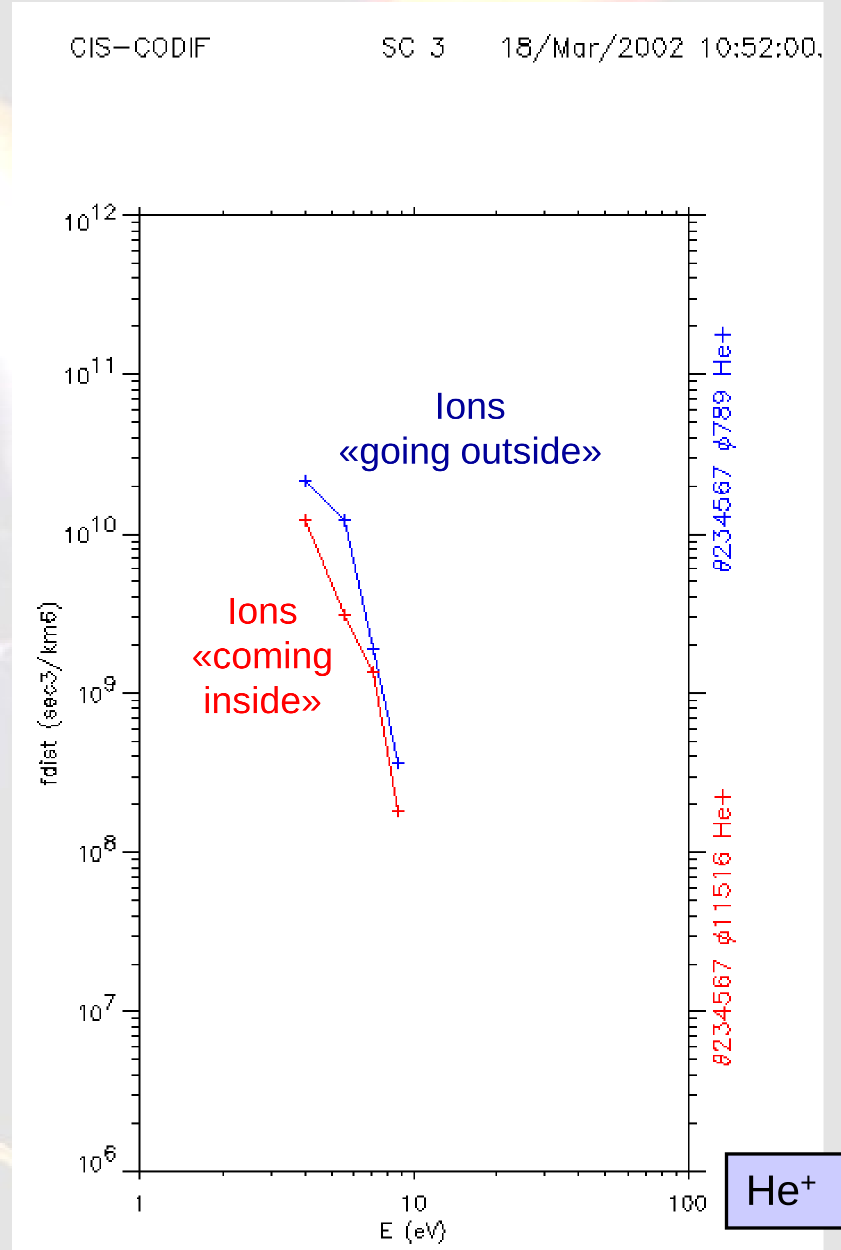
CIS-CODIF azimuthal sectors for an ion distribution function acquisition



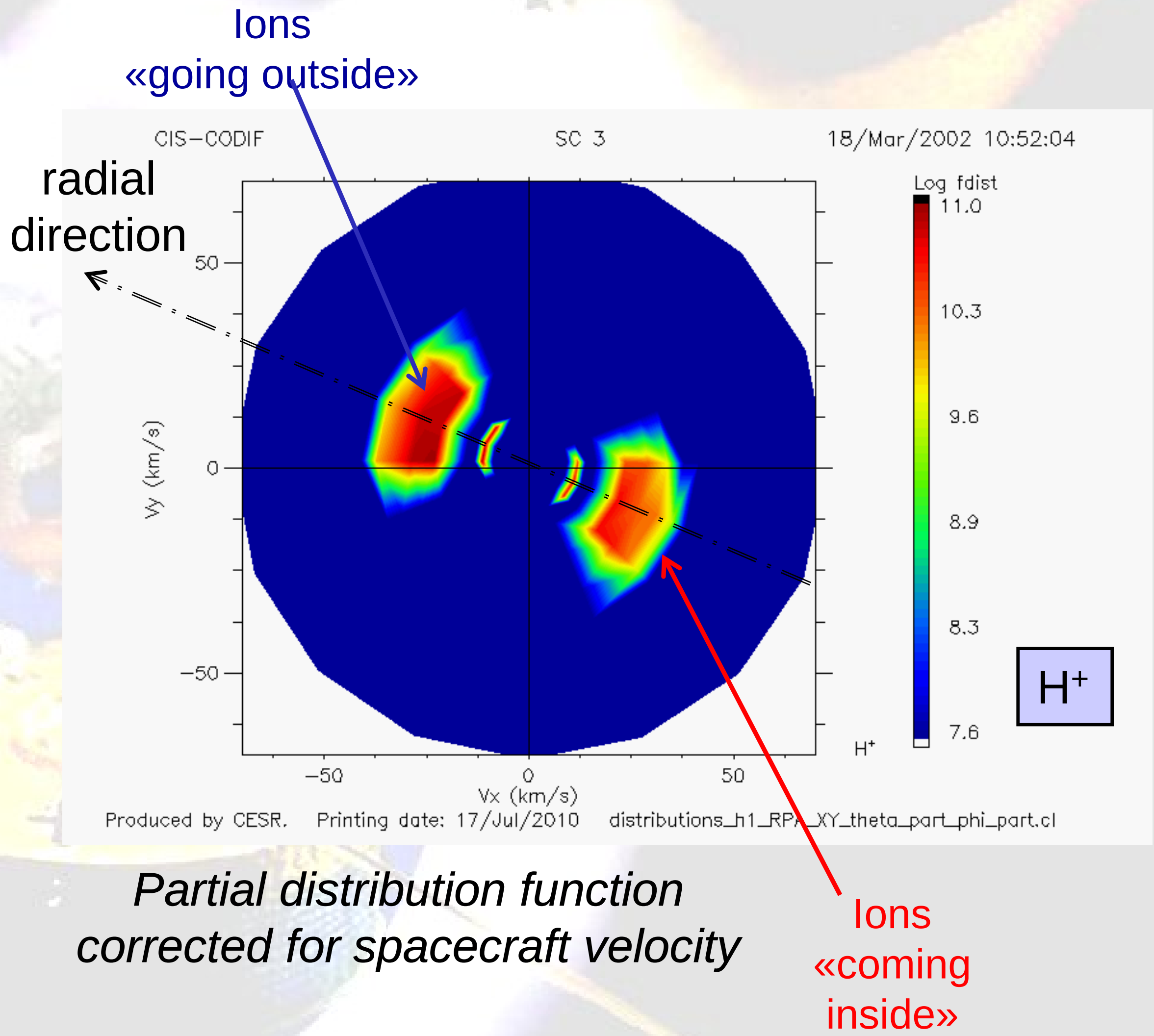


Search for Plasmaspheric Wind:
comparison of the two partial (in azimuth) distribution functions





Search for Plasmaspheric Wind:
comparison of the two partial (in azimuth) distribution functions

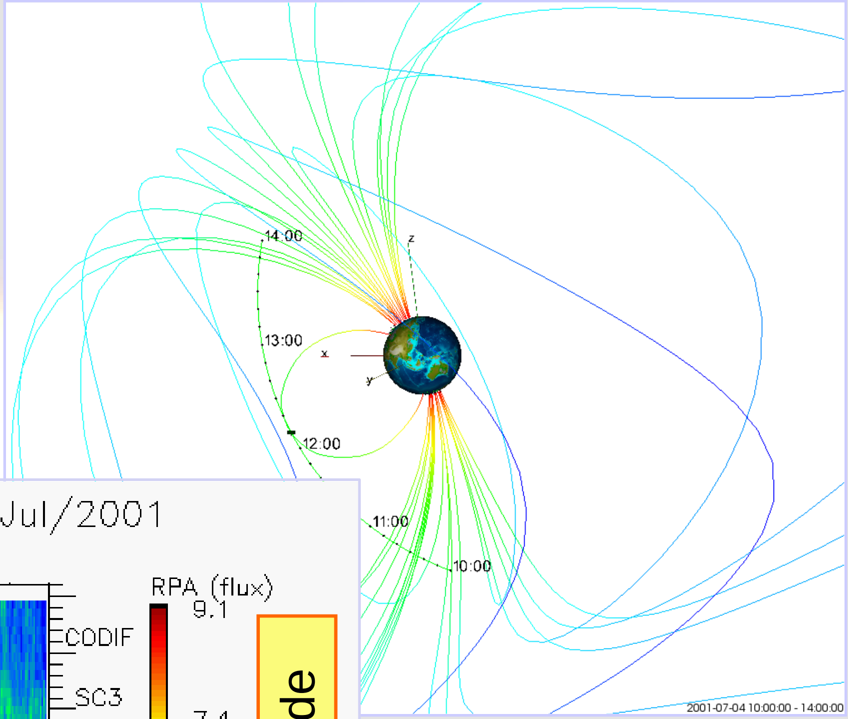


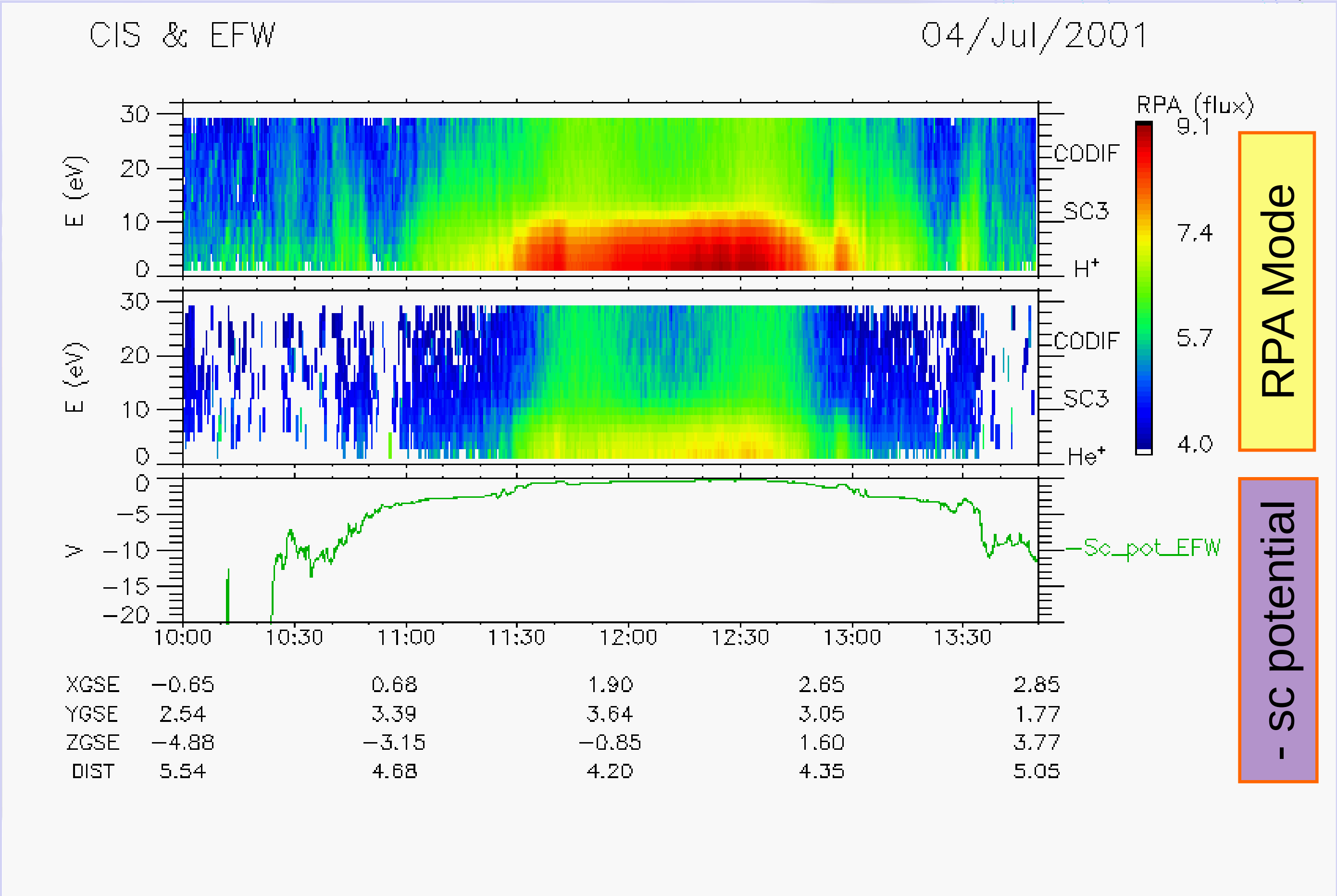
Partial distribution function
corrected for spacecraft velocity

Dandouras, COSPAR, 2010

Plasmasphere Cut :

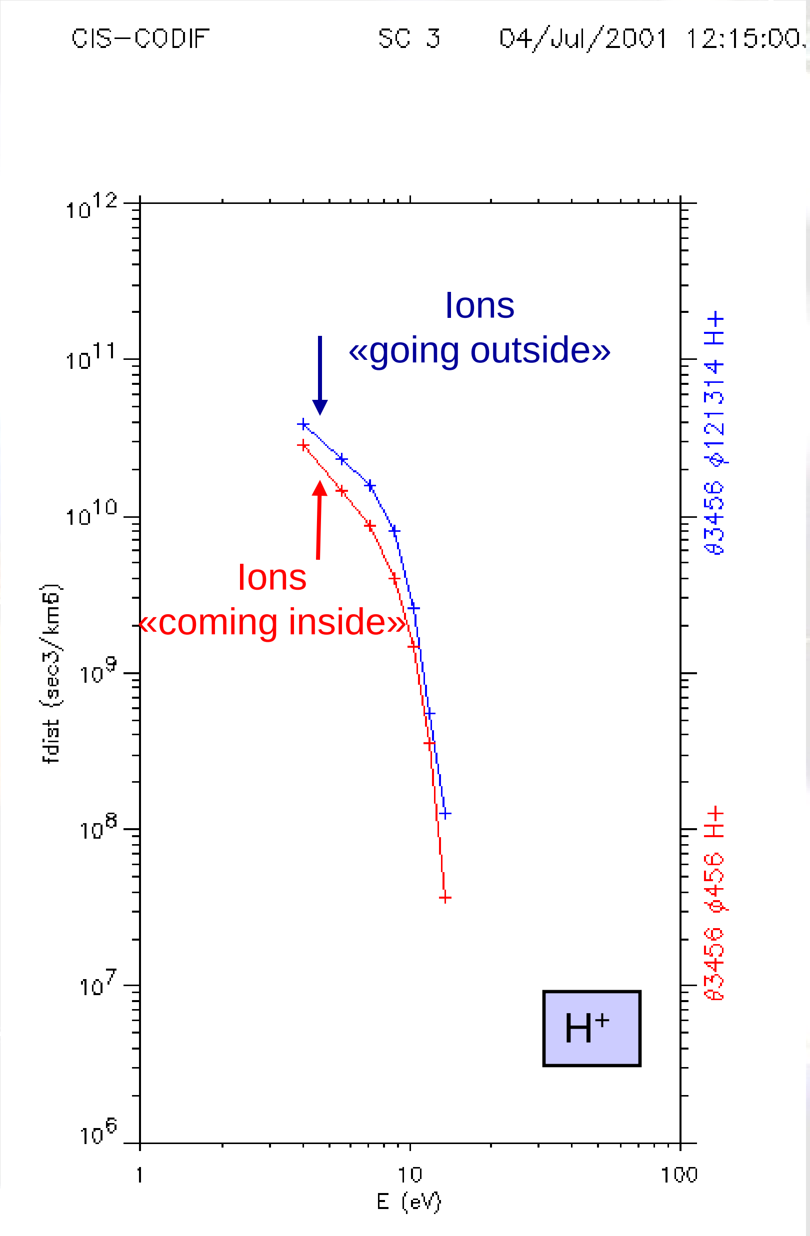
Afternoon-side quiet-time event

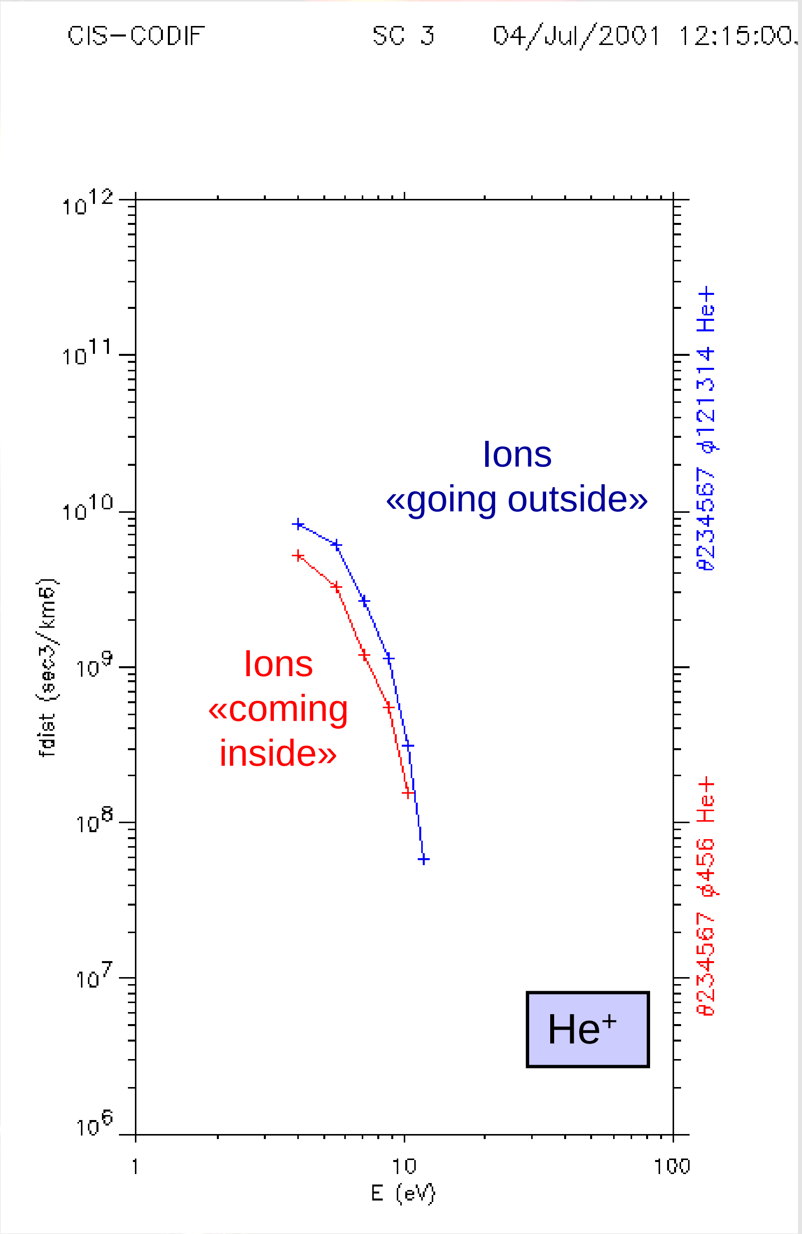




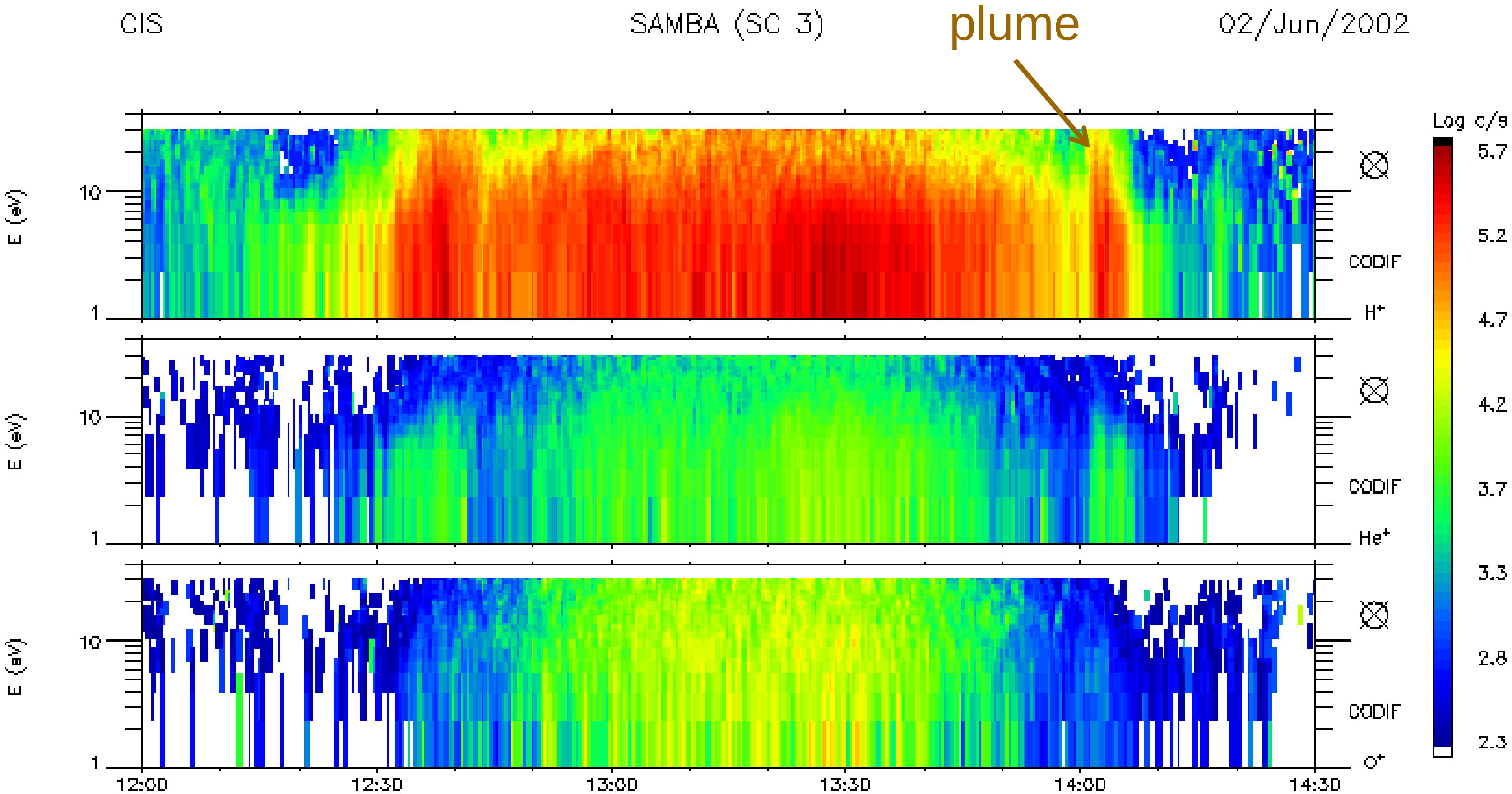
Kp = 1+

Search for Plasmaspheric Wind: comparison of the two partial (in azimuth) distribution functions





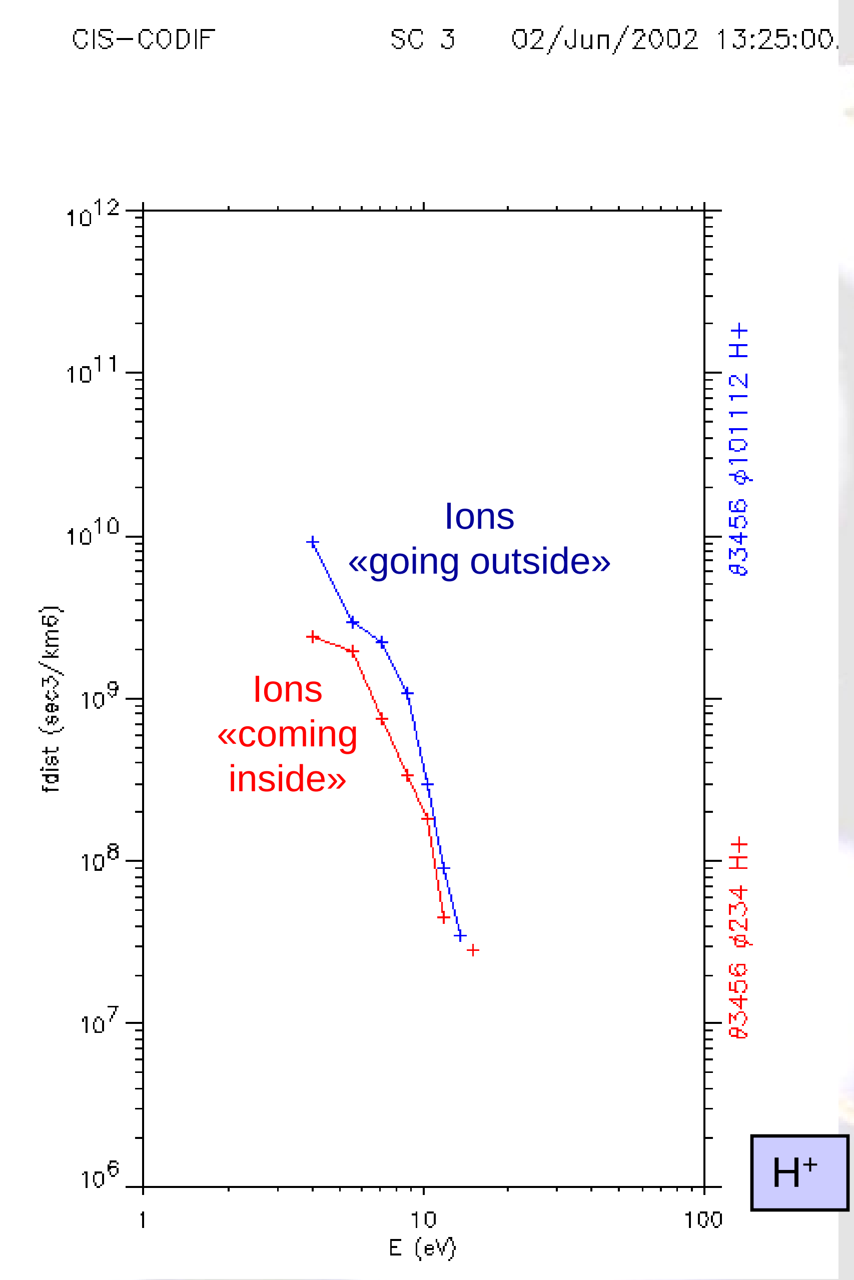
Dusk-side moderately disturbed-time event

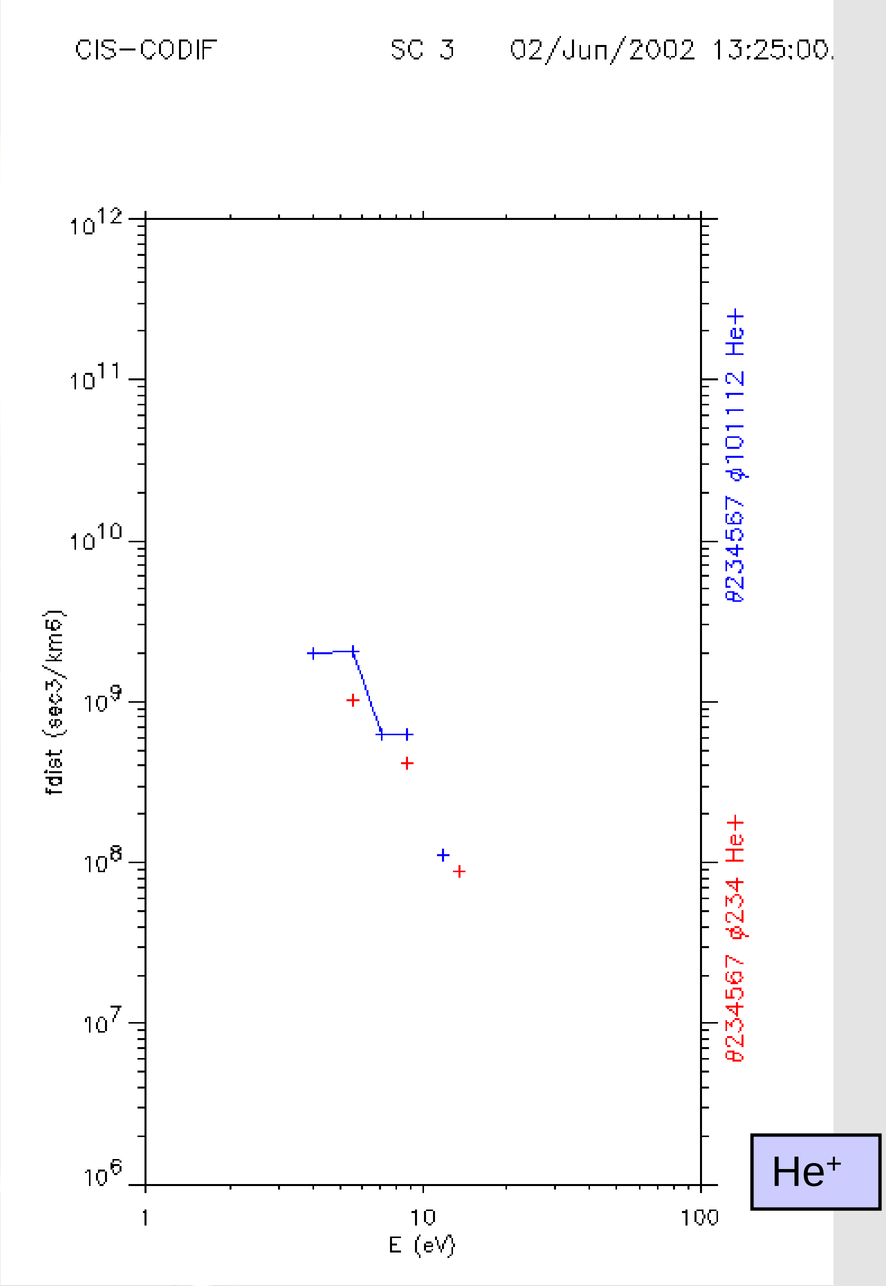


XGSE	−1.19	−0.93	−0.66	−0.36	−0.05	0.25	0.54	0.83	1.10
YGSE	3.60	3.91	4.14	4.29	4.35	4.30	4.15	3.91	3.58
ZGSE	−3.15	−2.45	−1.75	−0.96	−0.16	0.65	1.40	2.16	2.88
DIST	4.93	4.71	4.54	4.42	4.35	4.35	4.42	4.54	4.72

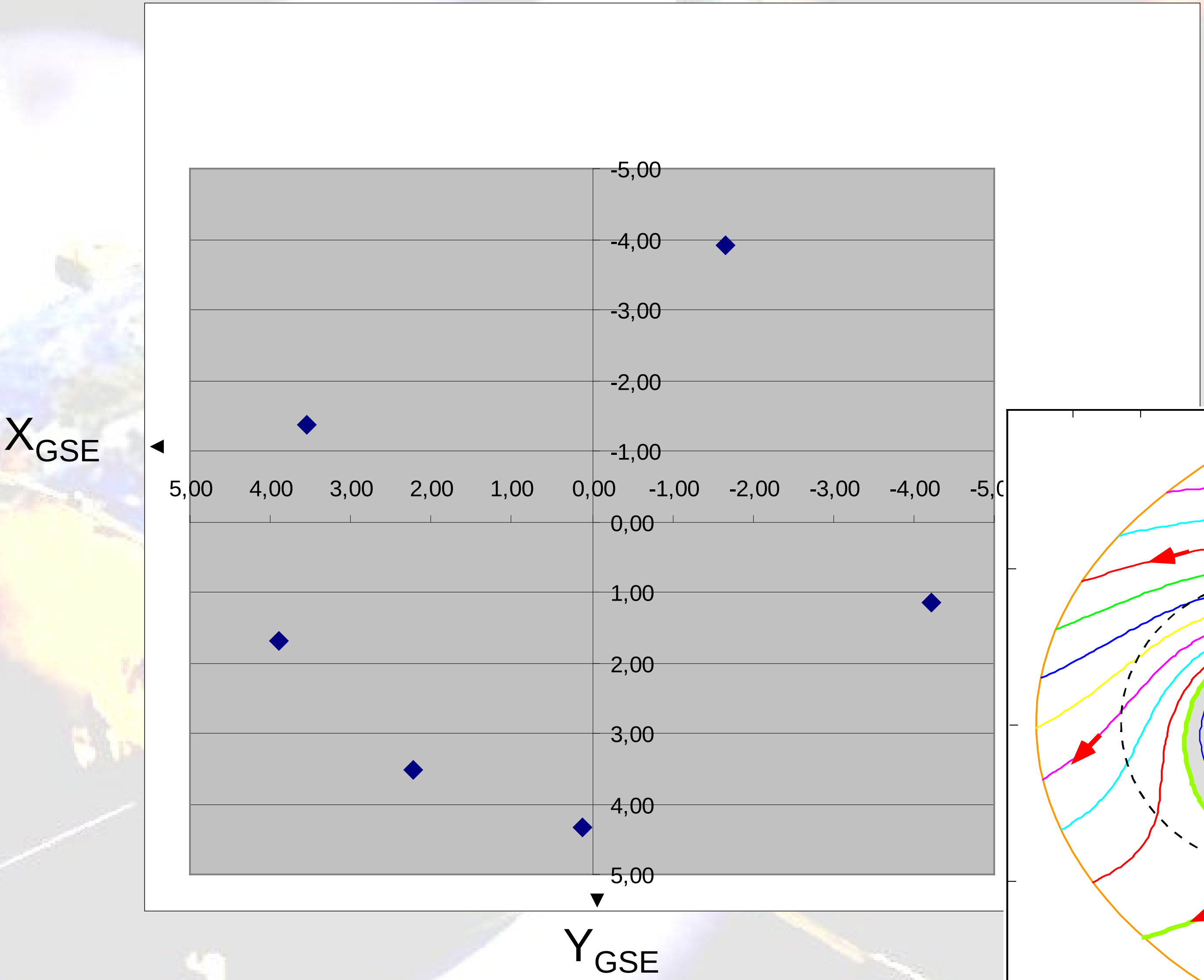
Kp = 3-

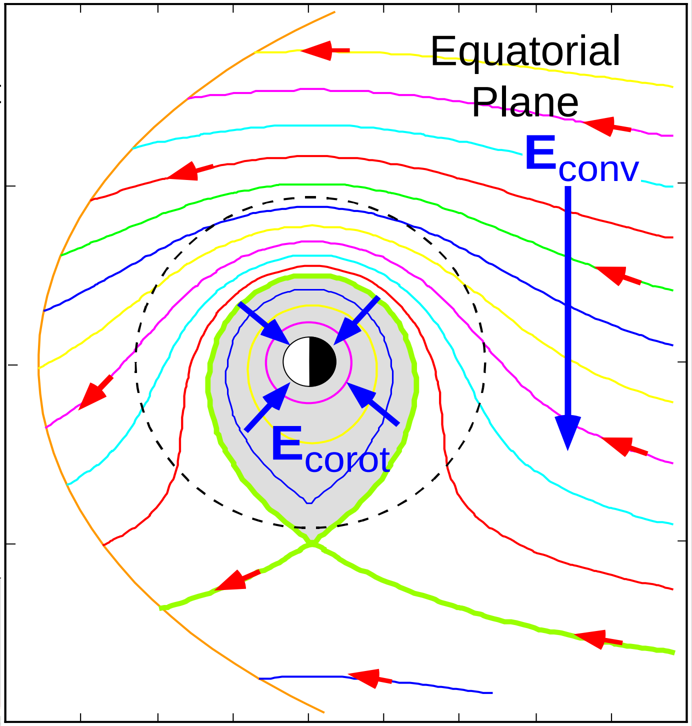
Comparison of the two partial (in azimuth) distribution functions





Analysed Plasmaspheric Wind observation events: Distribution in the equatorial plane





Plasmaspheric Wind: Contribution to the Magnetosphere

Considering:

- V_plasmaspheric-wind ≈ 1.4 km s^{-1} (from the distribution functions, at 4 R_E)
- Plasmasmaspheric density ≈ 100 cm^{-3} (at 4 R_E, typical values from WHISPER)
- Escape over half a sphere

We get :

~5.6 x 10^{26} ions s^{-1} continuously escaping from the Plasmasphere and contributing to the Magnetosphere

For comparison :

- the solar wind source is ~10^{27} ions s^{-1}
- the high-latitude ionospheric source is ~10^{26} ions s^{-1} [*Moore et al.*, 2005]

Dandouras, COSPAR, 2010

Earth's Plasmasphere: Conclusions

- The distribution functions of the H^+ and He^+ populations, close to the equatorial plane and within the main plasmasphere, at the Cluster perigee altitudes ($R \approx 4\ R_E$), clearly show:
  - The **existence of a Plasmaspheric Wind**, steadily transporting cold plasma outwards, across the geomagnetic field lines.
- This Plasmaspheric Wind has been systematically observed:
  - For all the examined quiet-conditions or moderately active conditions events.
  - In all MLT sectors.
  - From $L \approx 2.7$ to the outer plasmasphere ($L \approx 4.0 – 4.5$)
- The Plasmaspheric Wind **can provide a substantial contribution to the Magnetospheric populations**.
- Similar winds should be observed also on other planets, or astrophysical objects, quickly rotating and having a magnetic field.

Ευχαριστω !