

The background of the slide features a composite image. On the left, a portion of the Earth is visible, showing blue oceans and brown/green landmasses. A satellite is shown in orbit around the Earth, with its solar panels and various instruments extended. The right side of the image is dominated by a bright, glowing sun or star, with a large, diffuse, yellowish-white cloud or nebula-like structure extending from it towards the left. The overall scene is set against a dark, starry space background.

Origine des ions magnétosphériques : mesures CLUSTER

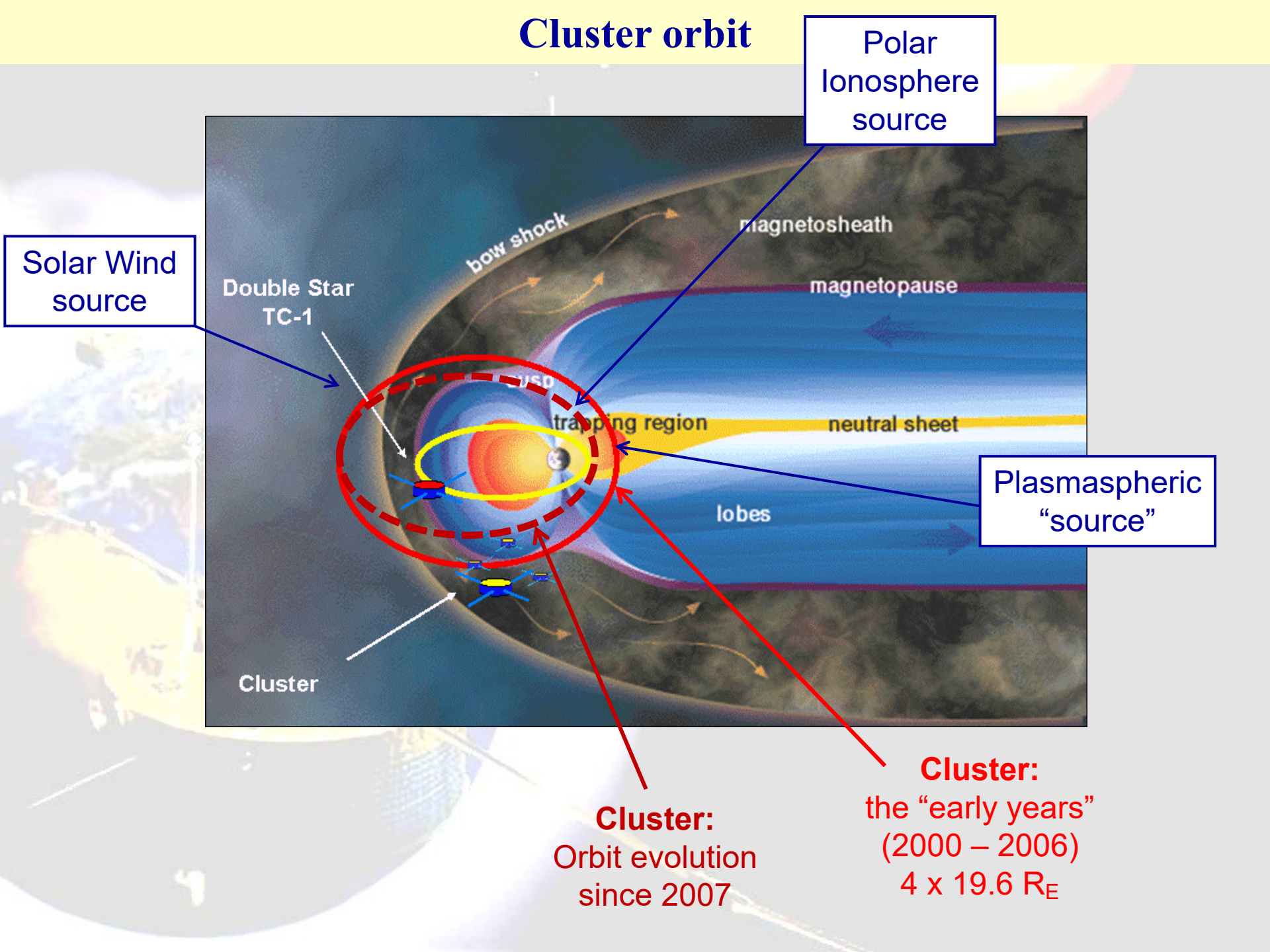
Iannis Dandouras

IRAP, CNRS / Université de Toulouse, Toulouse

et l'équipe CIS

Colloque du PNST, Hendaye, 16 Mars 2016

Cluster orbit



Polar
Ionosphere
source

Solar Wind
source

Double Star
TC-1

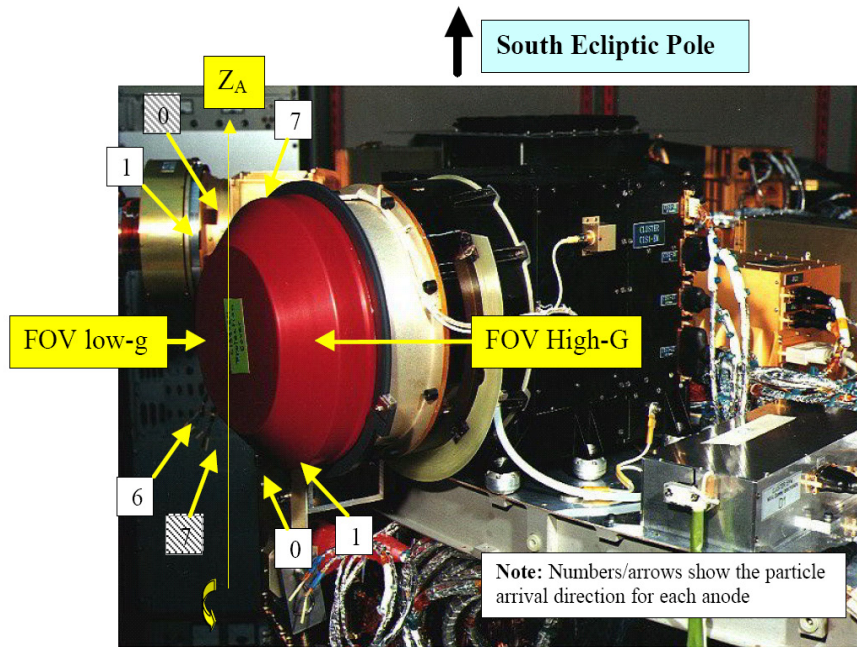
Plasmaspheric
"source"

Cluster

Cluster:
Orbit evolution
since 2007

Cluster:
the "early years"
(2000 - 2006)
4 x 19.6 R_E

The CIS Experiment onboard Cluster



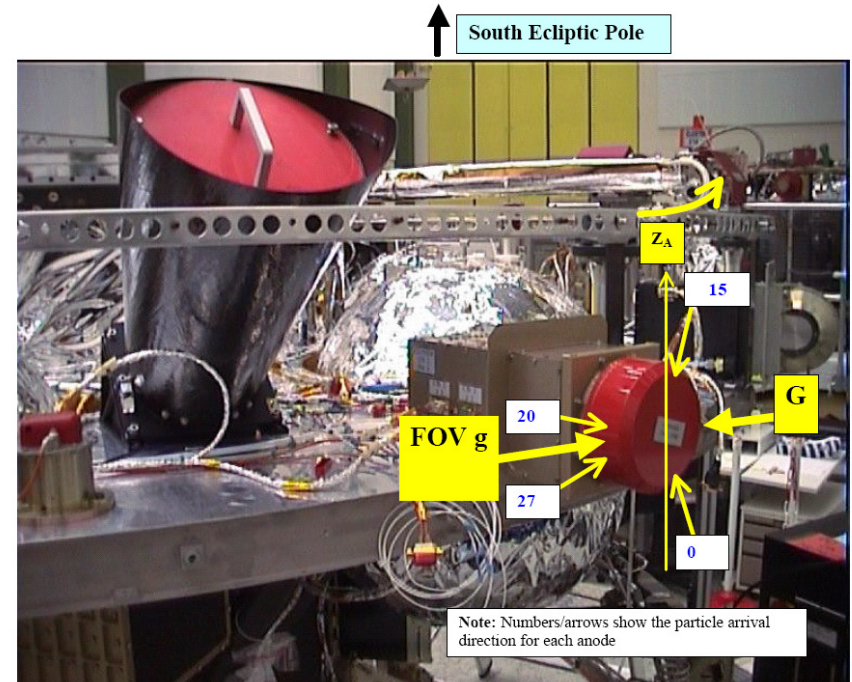
CODIF (CIS-1)

Ion Composition and Distribution Function Analyser

3D ion distributions with mass-per-charge composition determination (Time of Flight)

25 eV/q - 40 keV/q Energy Range

+ RPA : 0.7 – 25 eV/q



HIA (CIS-2)

Hot Ion Analyser

3D ion distributions with high angular resolution

5 eV/q - 32 keV/q Energy Range

Rème et al., 2001

The Solar Wind Source

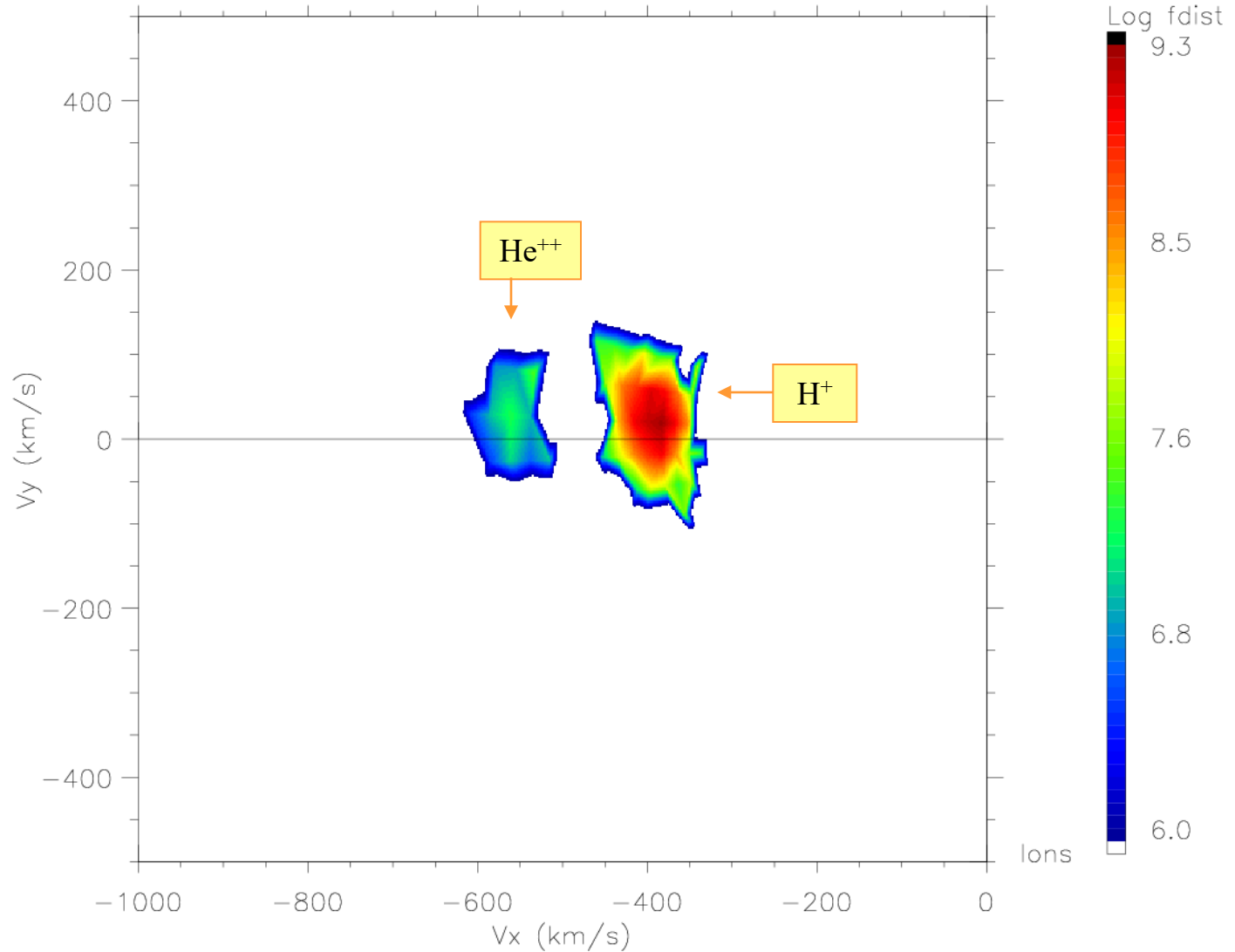


CIS – HIA Ion Distribution Function in the “Quiet” Solar Wind

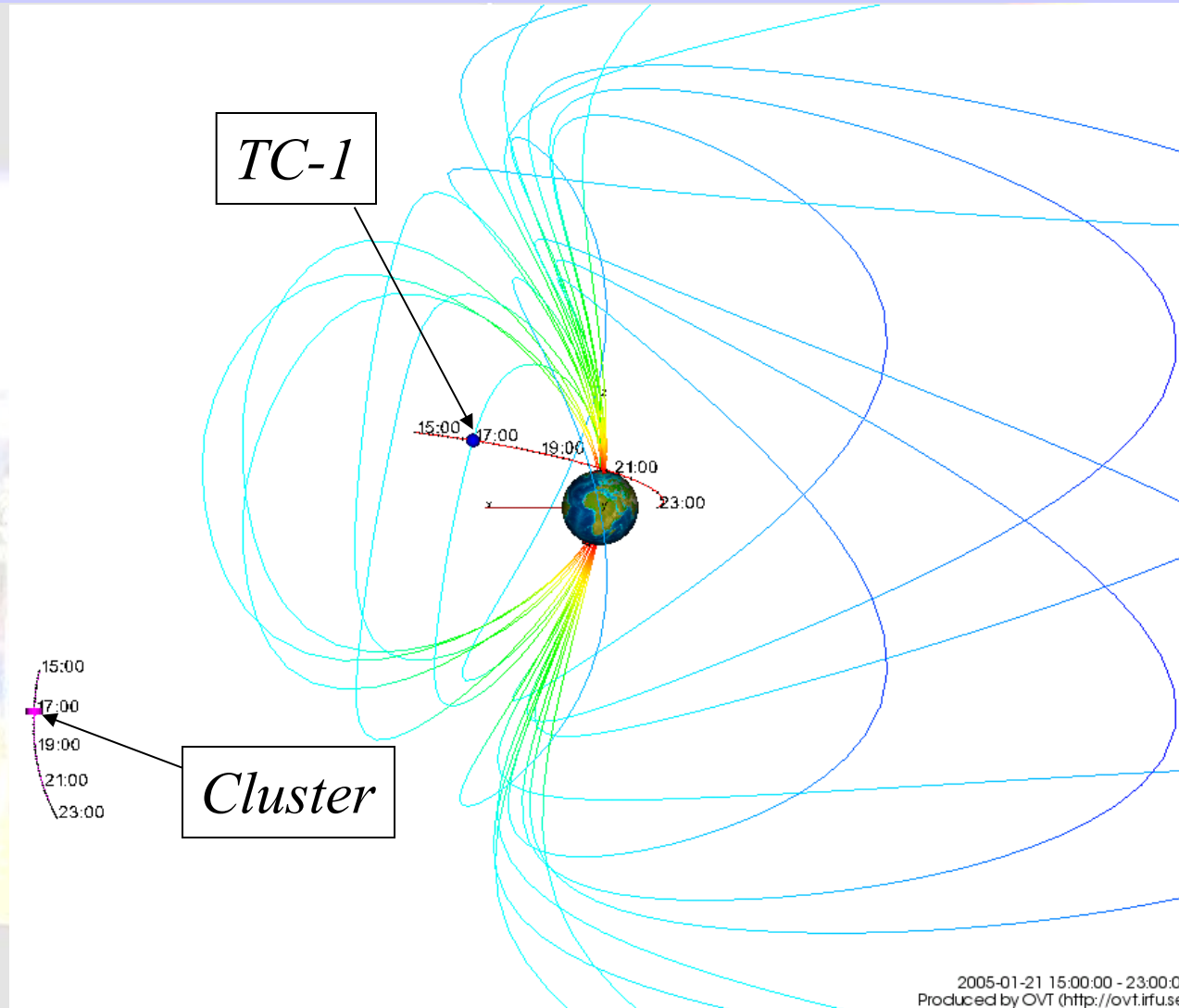
CIS–HIA

SAMBA (SC 3)

01/Jan/2003 16:48:54.489



21 January 2005 Extreme Solar Event: ICME Arrival

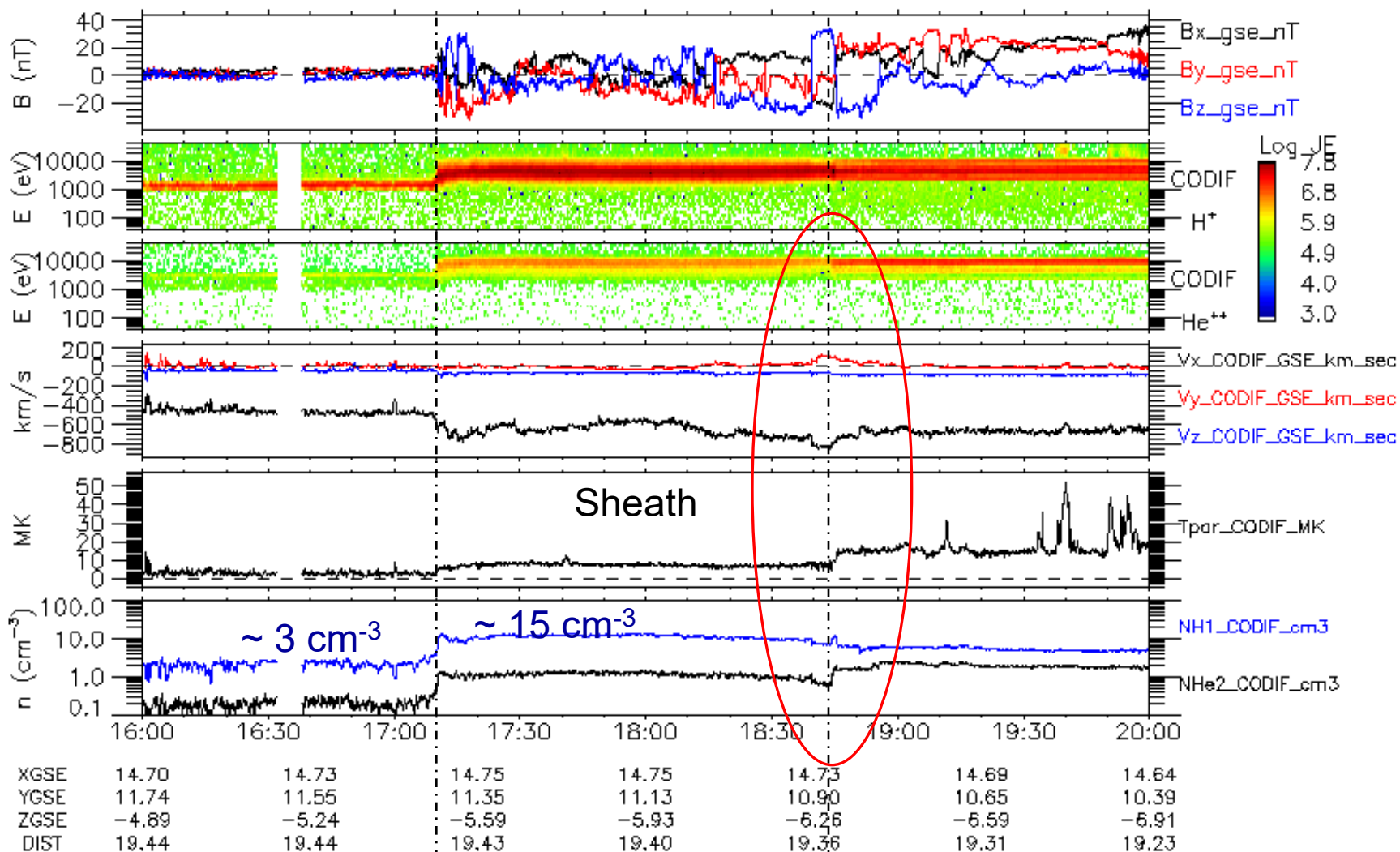


- Cluster SC4 was situated in the **solar wind** region, at MLT ~ 14.5 h.
- TC-1 was in the **Magnetosheath** region, at $R \sim 8 R_E$ and at MLT ~ 17 .

CIS

TANGO (SC 4)

21/Jan/2005



Dandouras et al., 2009

Foullon et al., 2007

17:10 : ICME
shock arrival
(hot pileup)

18:44:
Secondary
front arrival

He⁺⁺ enrichment:
arrival of the
« flare driver gas »

**Calculated position
of the bow shock
subsolar point:**

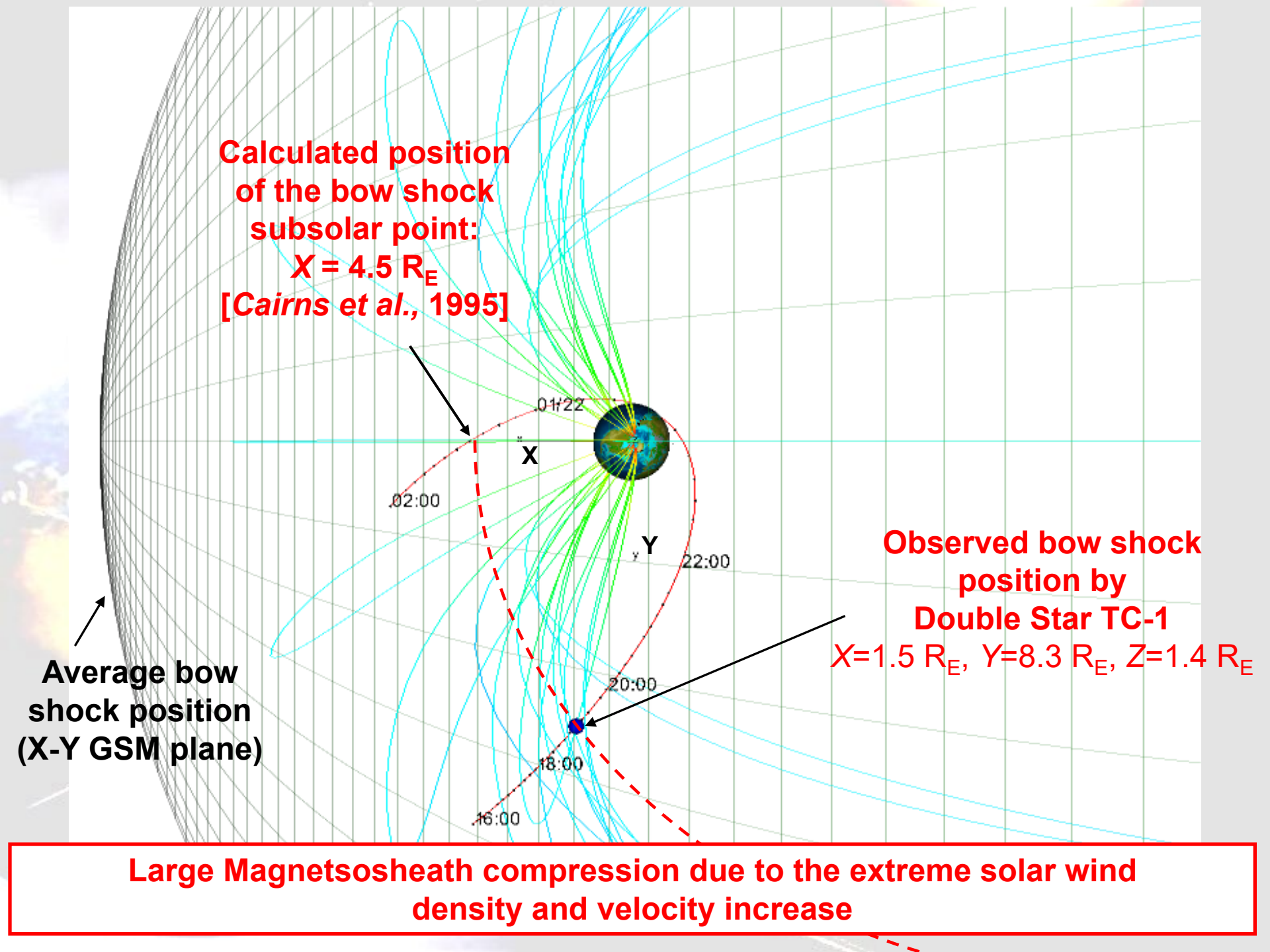
$$X = 4.5 R_E$$

[Cairns et al., 1995]

**Average bow
shock position
(X-Y GSM plane)**

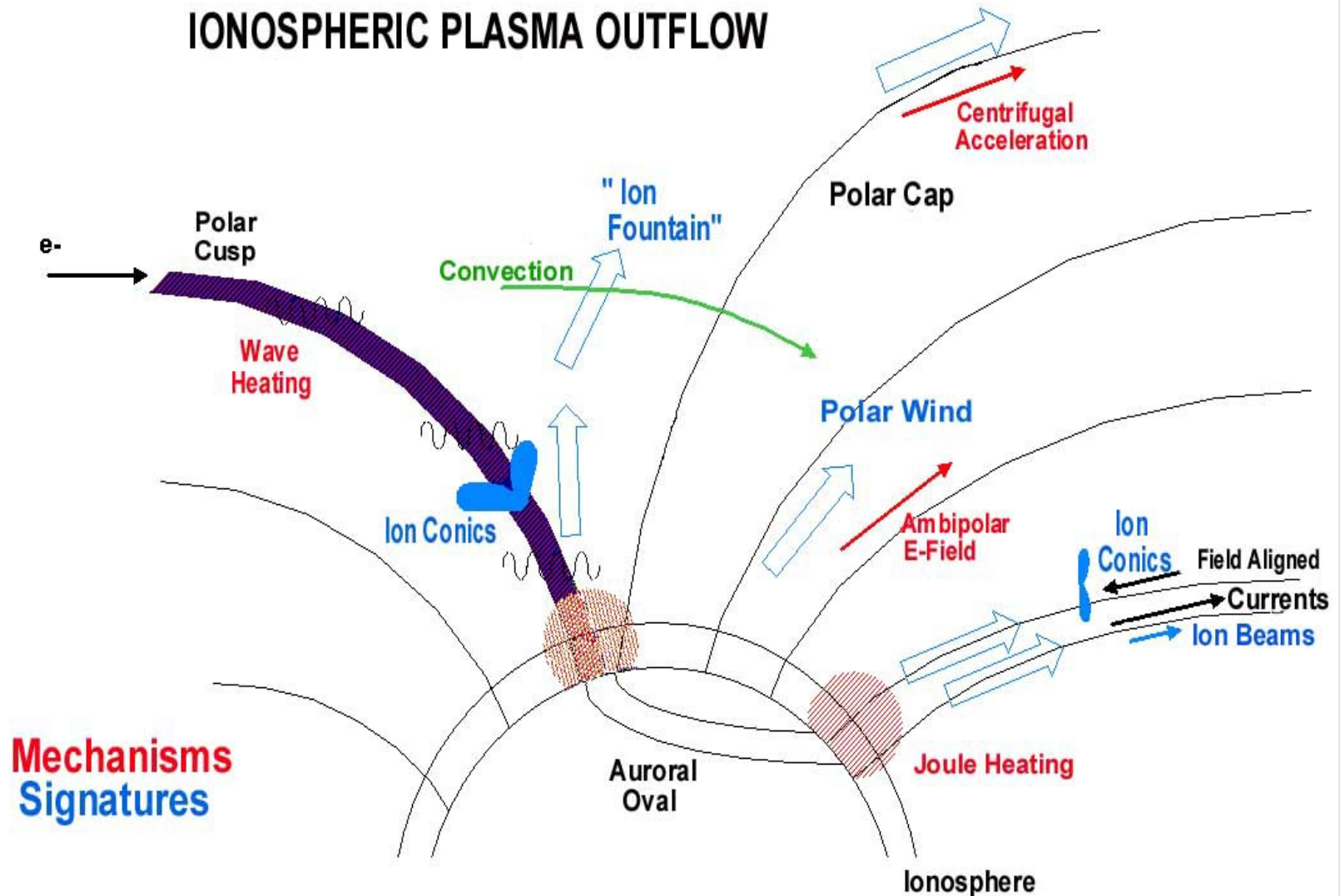
**Observed bow shock
position by
Double Star TC-1
 $X=1.5 R_E, Y=8.3 R_E, Z=1.4 R_E$**

**Large Magnetosheath compression due to the extreme solar wind
density and velocity increase**



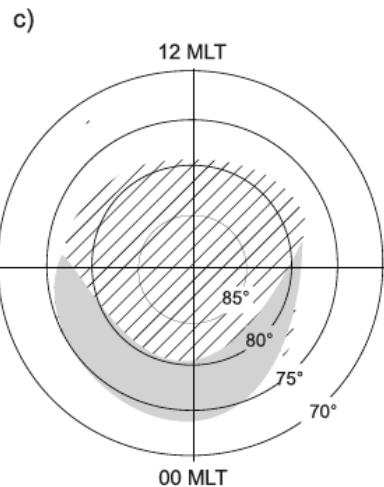
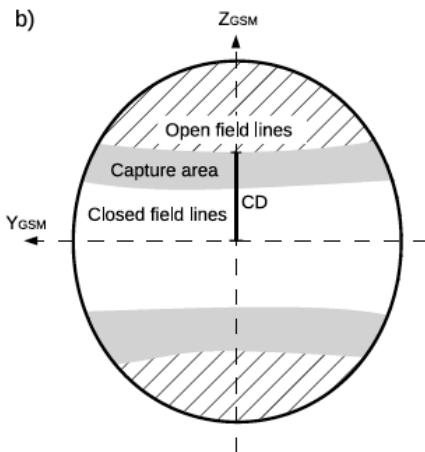
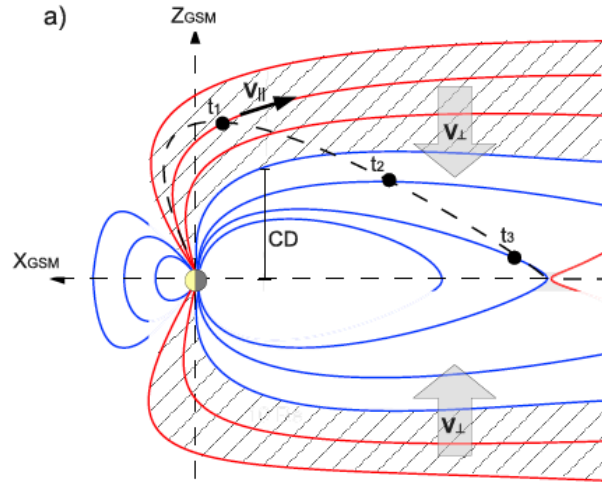
The Polar Ionosphere Source and Outflow Mechanisms

IONOSPHERIC PLASMA OUTFLOW

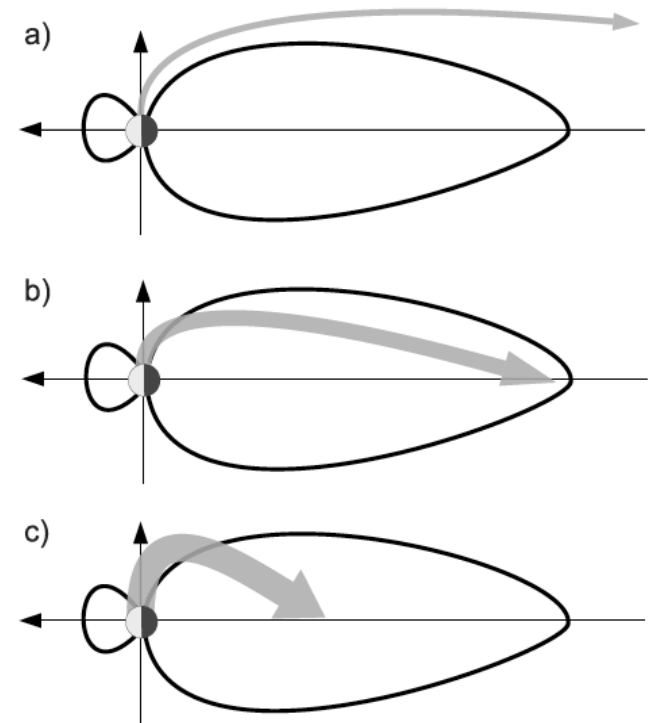


Ion Fate is a Strong Function of the Activity Level

HAALAND ET AL.: CIRCULATION AND LOSS OF COLD PLASMA



a: Quiet conditions, direct loss downtail

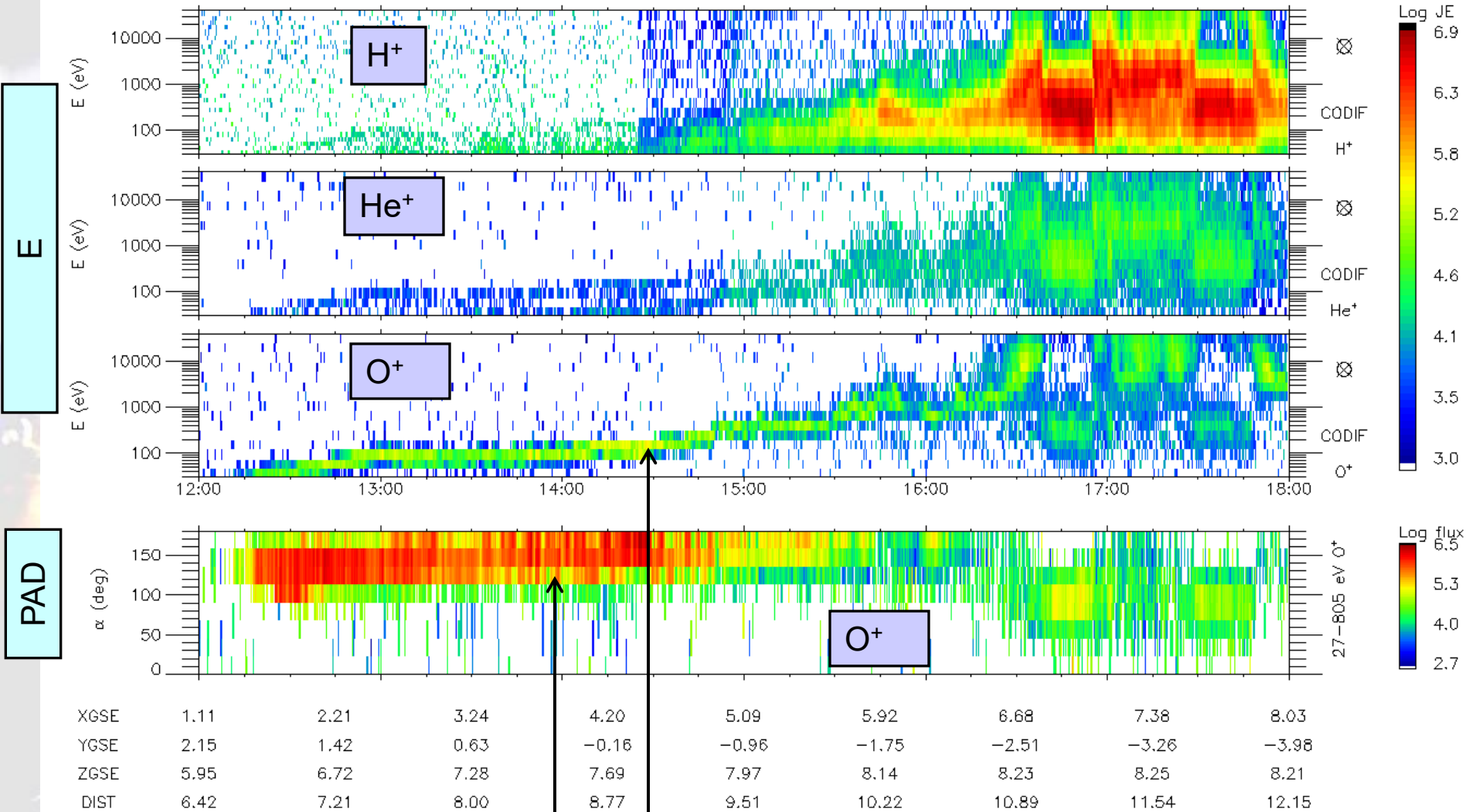


c: Disturbed conditions, supply close to Earth

CIS

RUMBA (SC 1)

18/Apr/2002



Typical upflowing O⁺ beam

Scaled Upflowing Ionospheric O⁺ Flux

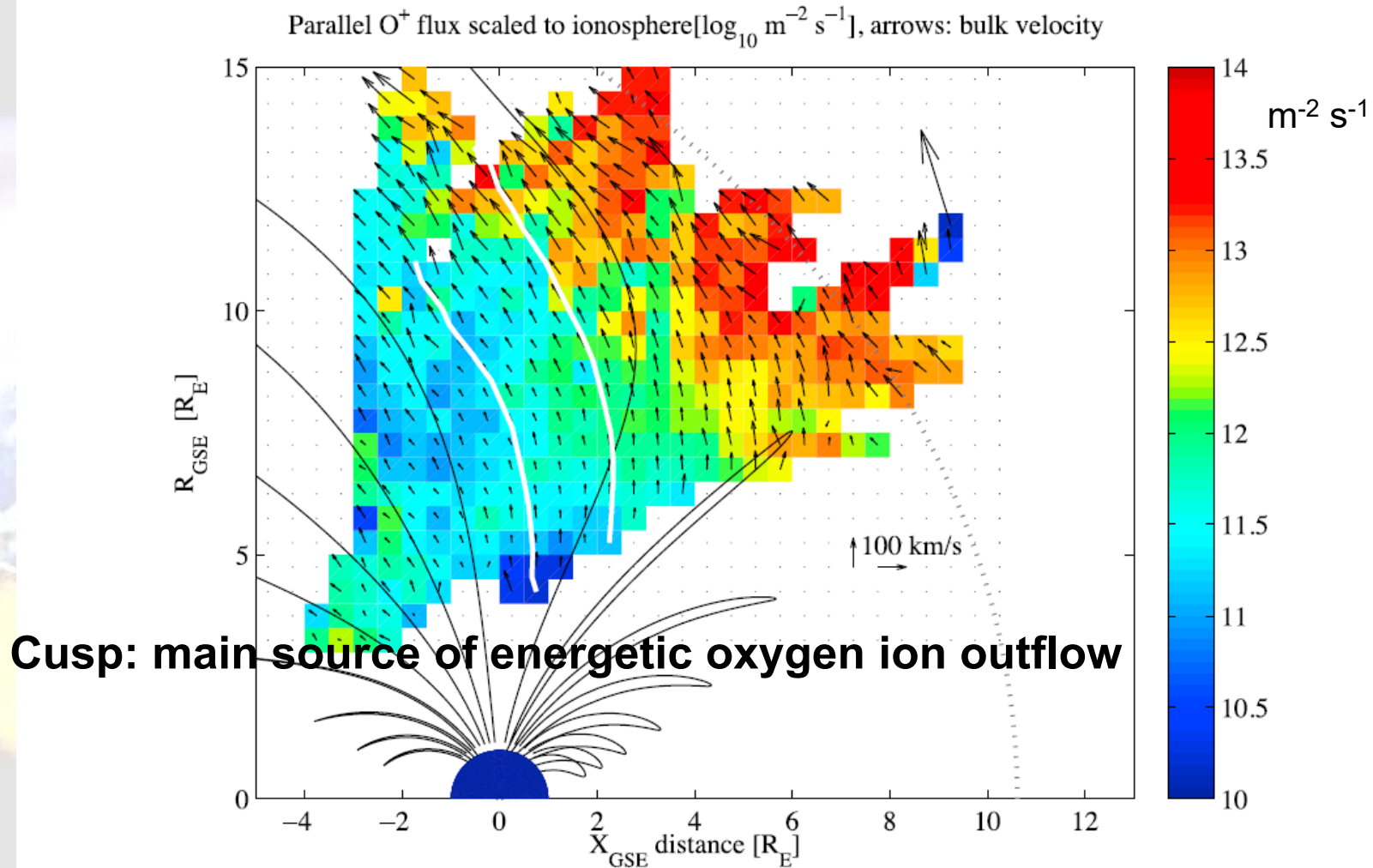
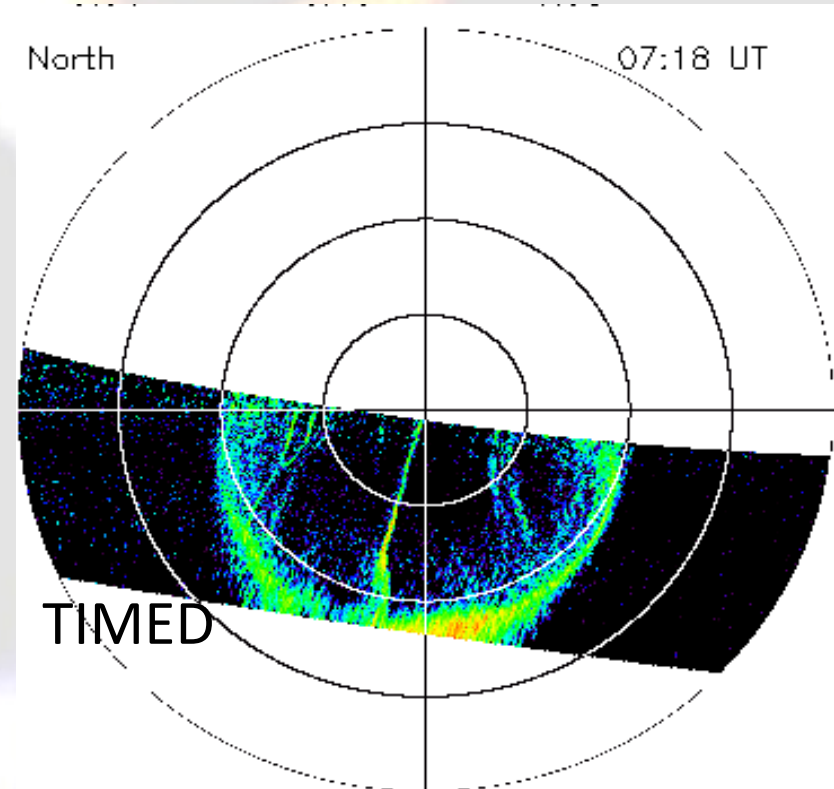
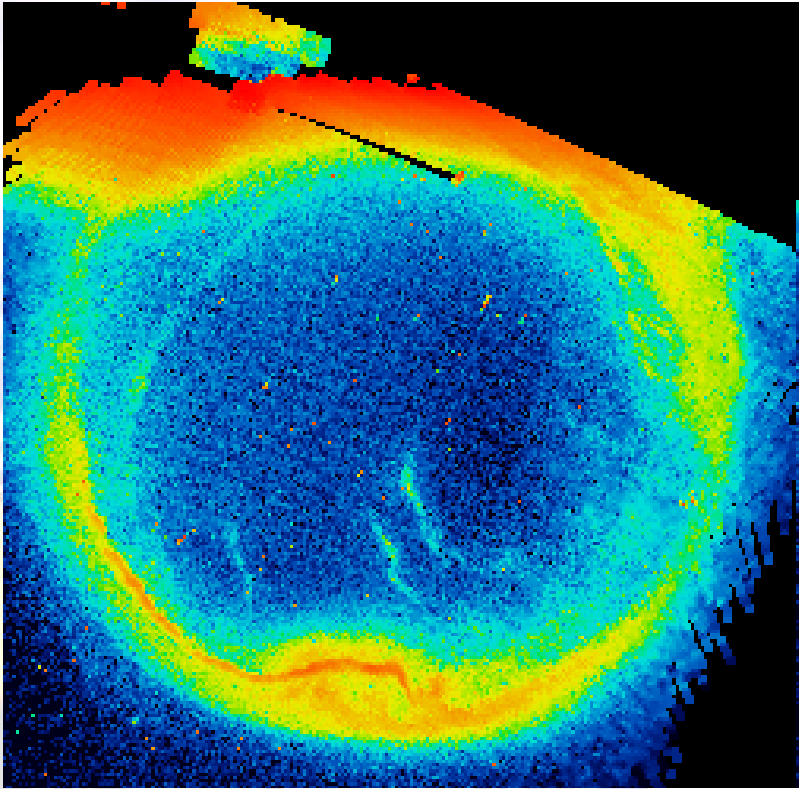


Figure 1. Parallel flux of O⁺ scaled to ionospheric altitude shown in cylindrical GSE coordinates (R_E). The flux is shown with a color scale in units of $\text{m}^{-2} \text{ s}^{-1}$. Black arrows indicate the direction and relative magnitude of the parallel bulk velocity of O⁺. Solid black curves indicate sample field lines from the Tsyganenko T89 model, at $Y_{\text{GSE}} = 0$ and spaced 5° apart. A model magnetopause is indicated by the thick dotted line.

Magnetosphere-ionosphere coupling above the polar caps during periods of northward IMF: Small scale polar cap arcs



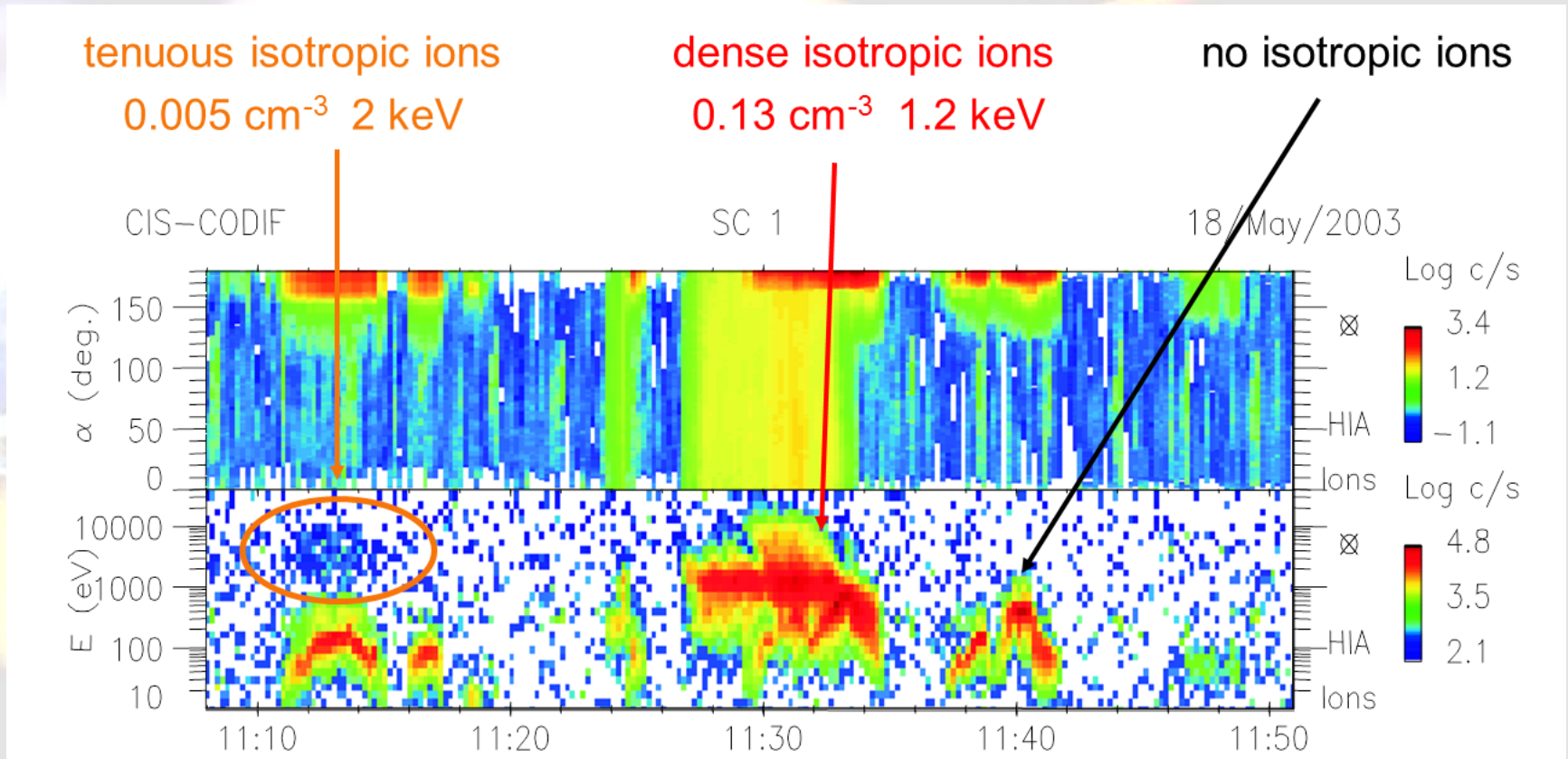
How many classes of small scale PC arcs?

Magnetic Field line topology: open or closed?

Generation of polar cap arcs, magnetospheric configuration?

Statistical properties of Polar Cap Ion Beams

~40 % of PCIB are associated with a warm isotropic ion population



$T \sim 500\text{-}2000 \text{ eV}$

Density highly variable. Not correlated to temperature.

Statistical properties of Polar Cap Ion Beams

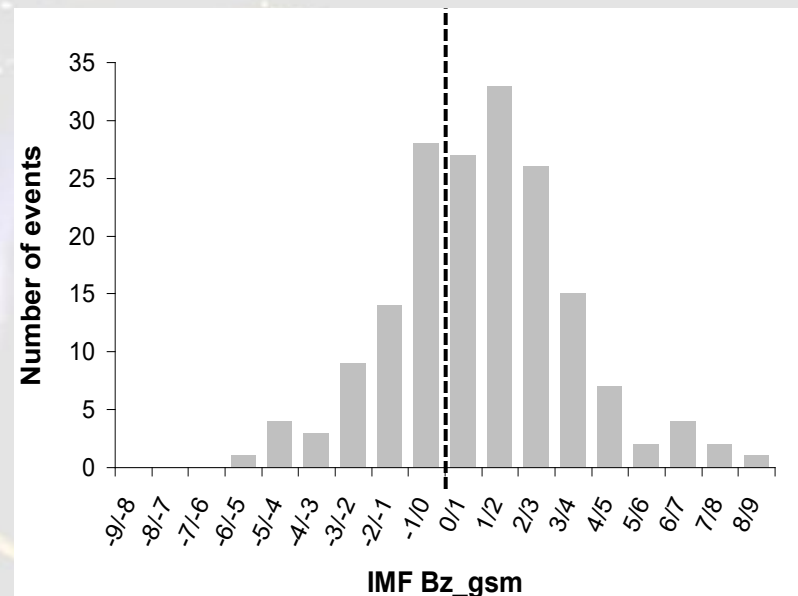
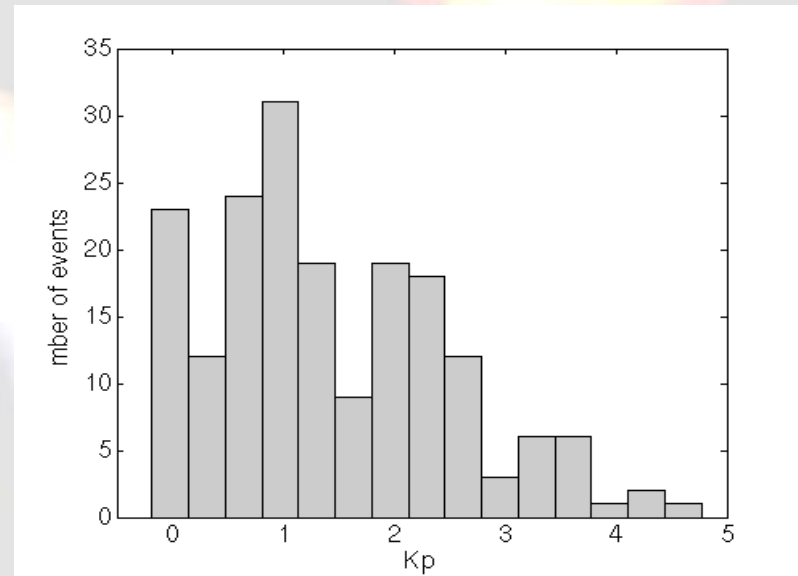
Quiet conditions

Mainly IMF $B_z > 0$

but

35% for IMF $B_z < 0$

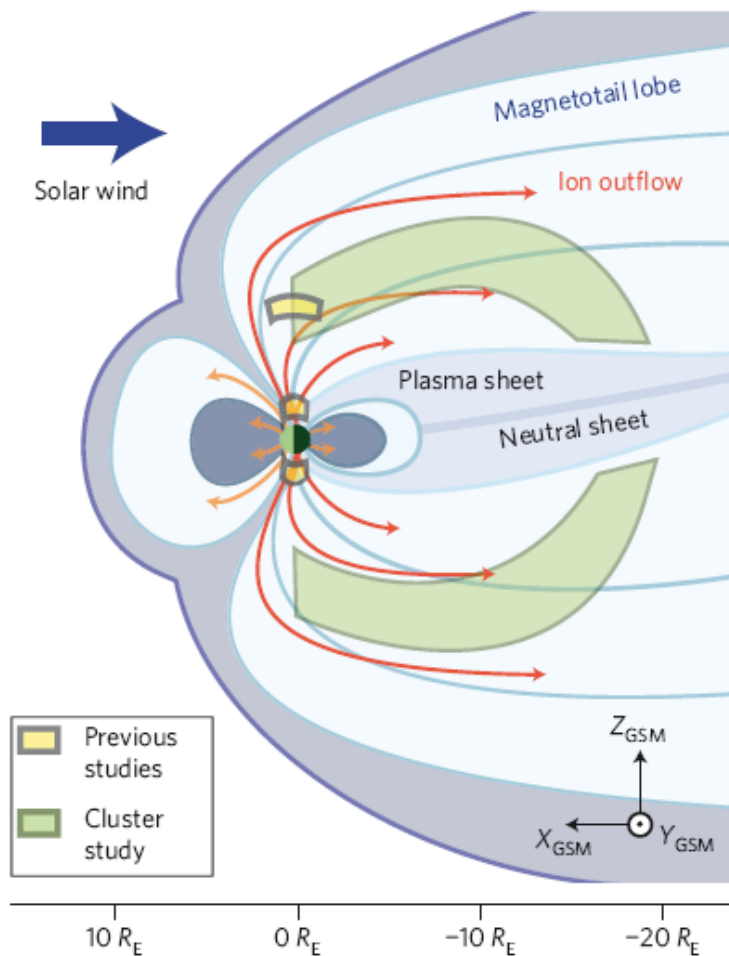
*Maggiolo et al.,
Ann. Geophys. 2011*



The background of the slide is a composite image. On the left, a satellite is shown in orbit around Earth, with its various instruments and antennas visible. The Earth's surface shows continents and oceans. On the right, a bright solar flare or coronal mass ejection is depicted as a glowing, multi-colored (yellow, orange, red) plume of plasma extending from the sun. The overall scene is set against the blackness of space with some stars visible.

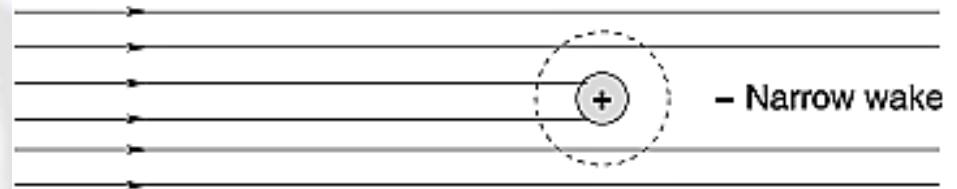
The Ionospheric Source Signatures in the Magnetotail Lobes

Low-energy (order 10 eV) ion flow in the magnetotail lobes: spacecraft wake

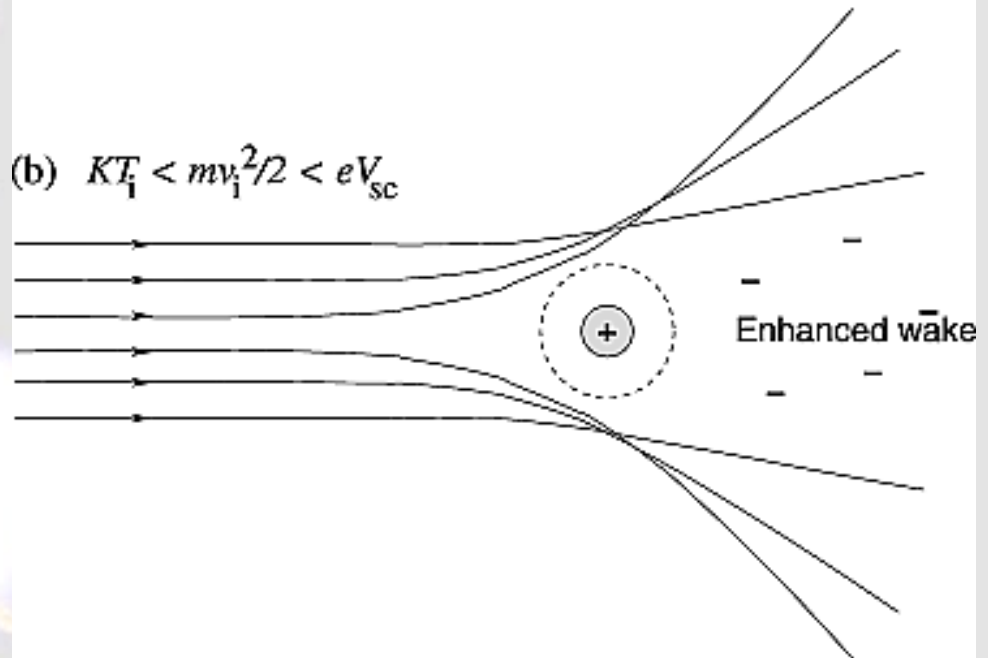


Engwall et al.,
Nat. Geosci., 2008

(a) $mv_i^2/2 > KT_i, mv_i^2/2 > eV_{sc}$

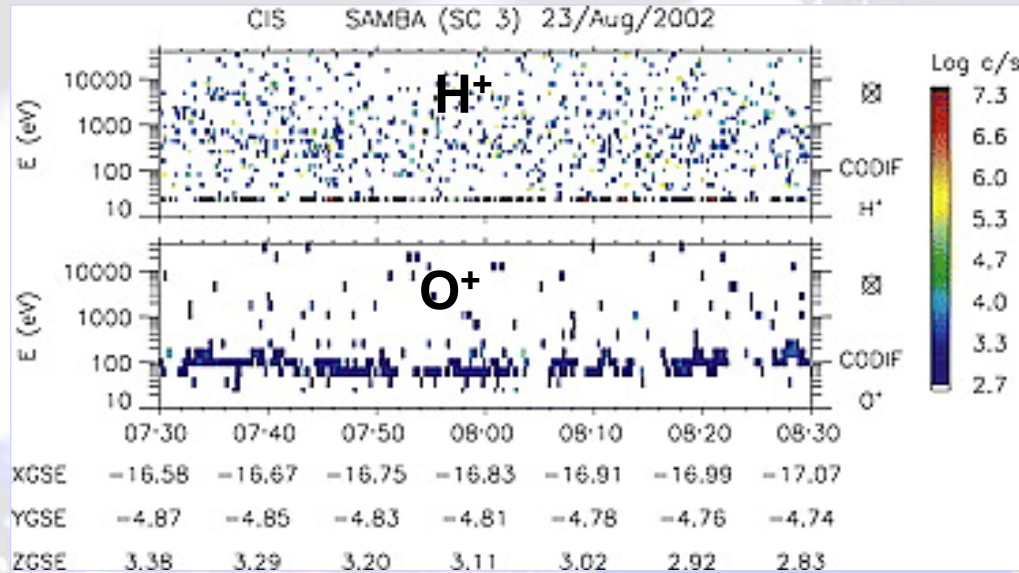


(b) $KT_i < mv_i^2/2 < eV_{sc}$



Engwall et al.,
GRL, 2006

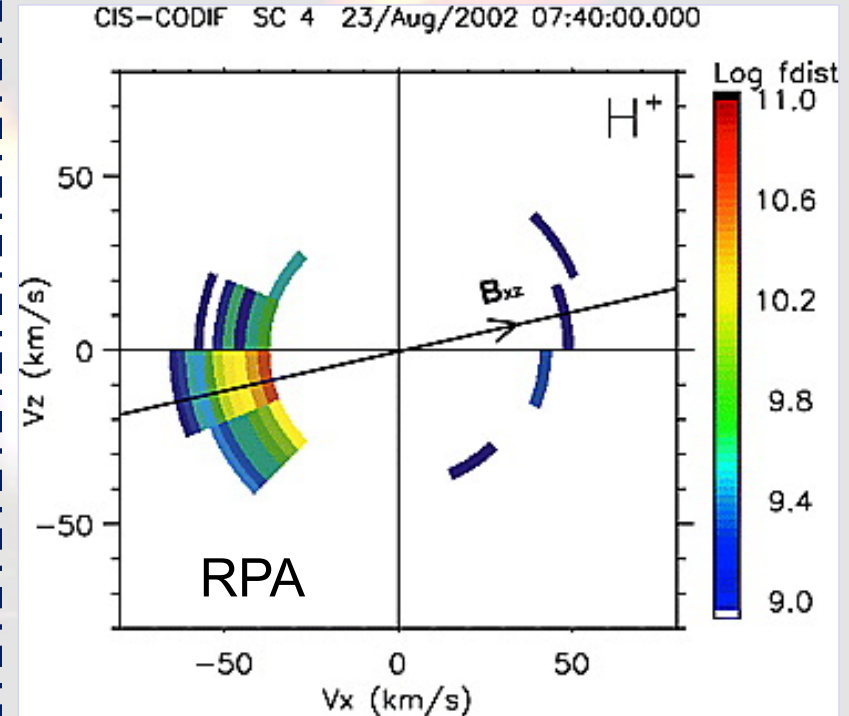
sc3: ASPOC switched off: wake



*Engwall et al.,
GRL, 2006*

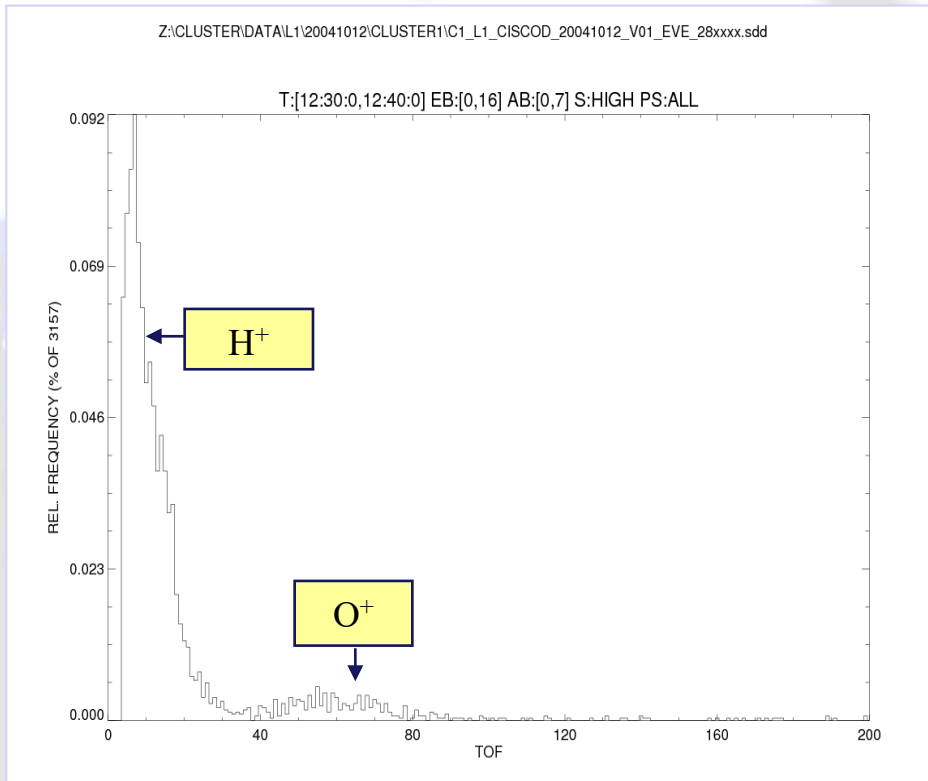
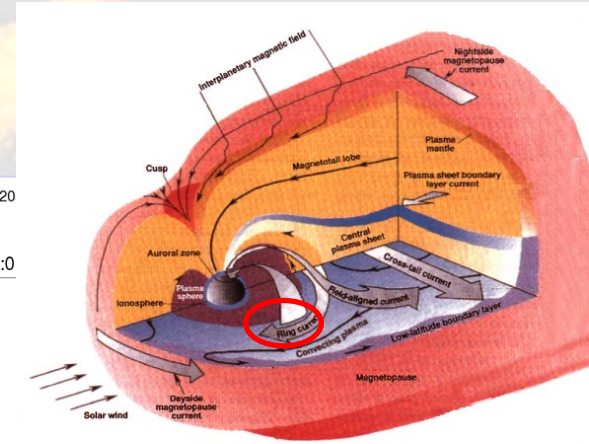
- CODIF has detected an **O⁺ ion beam**, in the **anti-sunward direction**.
- The **spacecraft potential (40 – 60 V)** is **too high for the detection of the H⁺ ions** which have typical energies around 10 eV: ~40 km/s ion outflow.
- The thin stripe around the lowest energy in the proton data is an artifact from onboard data compression.

sc4: ASPOC switched on: no wake

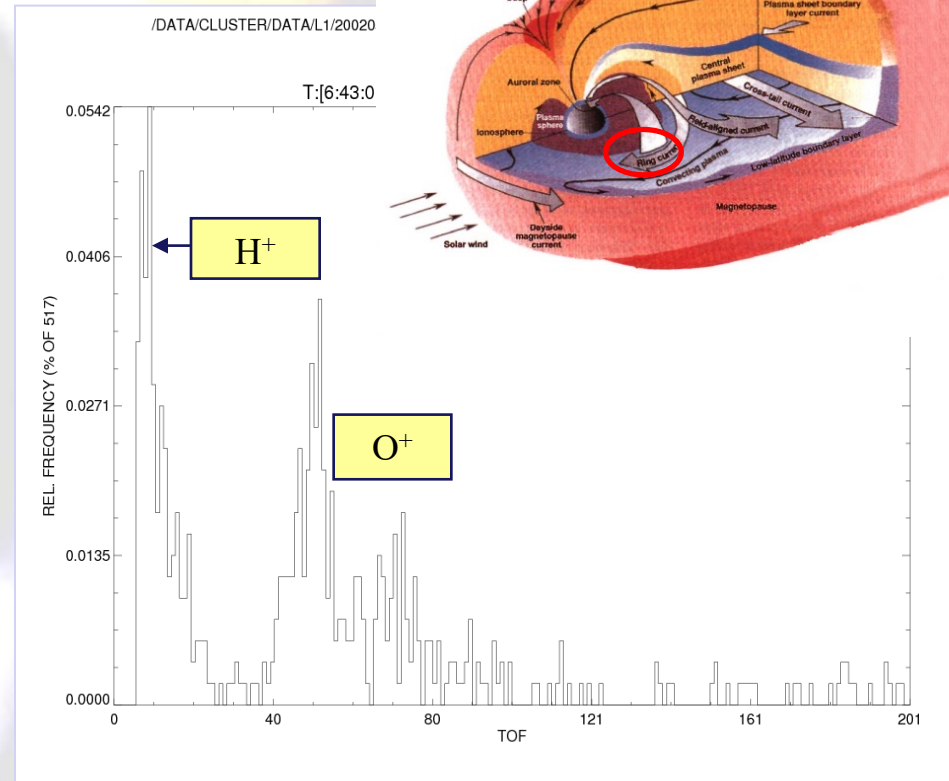


- Distribution function for **H⁺**. Velocities have been **corrected for the spacecraft potential of 7 V**.
- The lowest velocities missing due to the instrument cutoff at 0.7 eV (w.r.t. spacecraft).
- B_{xz} is the magnetic field projected in the x-z-plane.

Ionospheric ions effect on the inner magnetosphere composition: Ion Time-of-Flight Spectra in the Ring Current



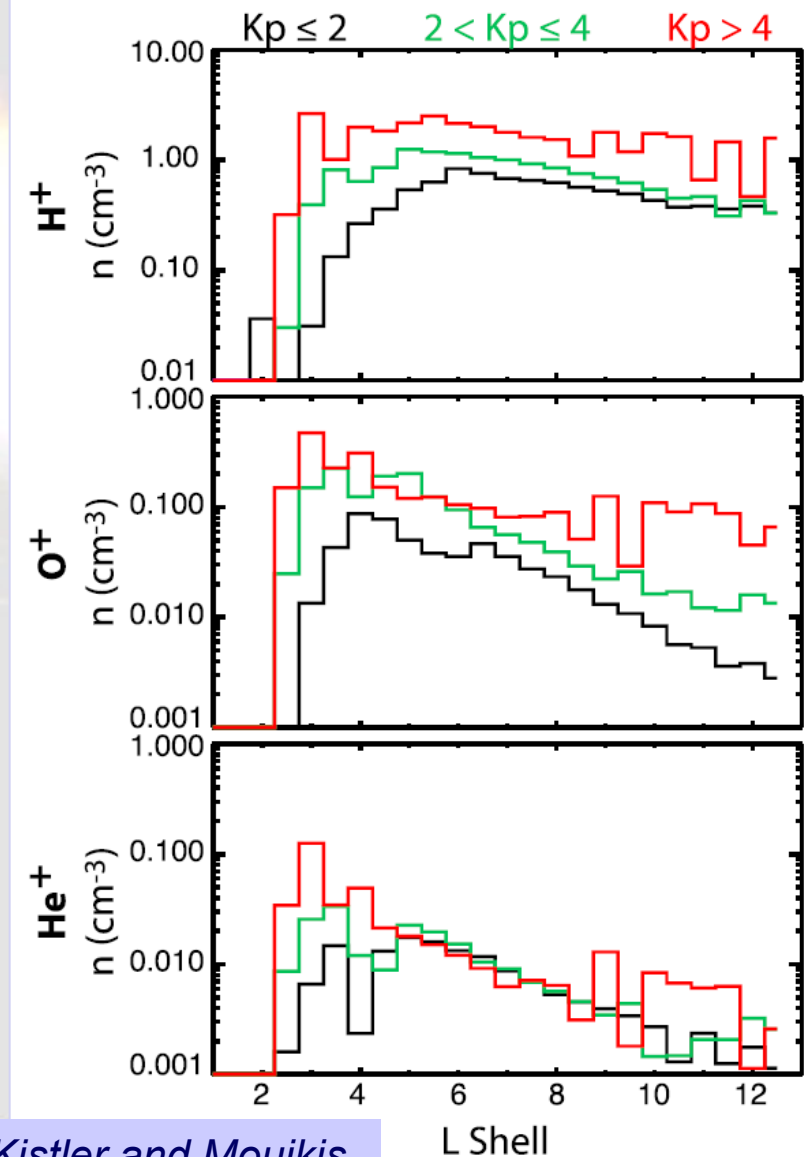
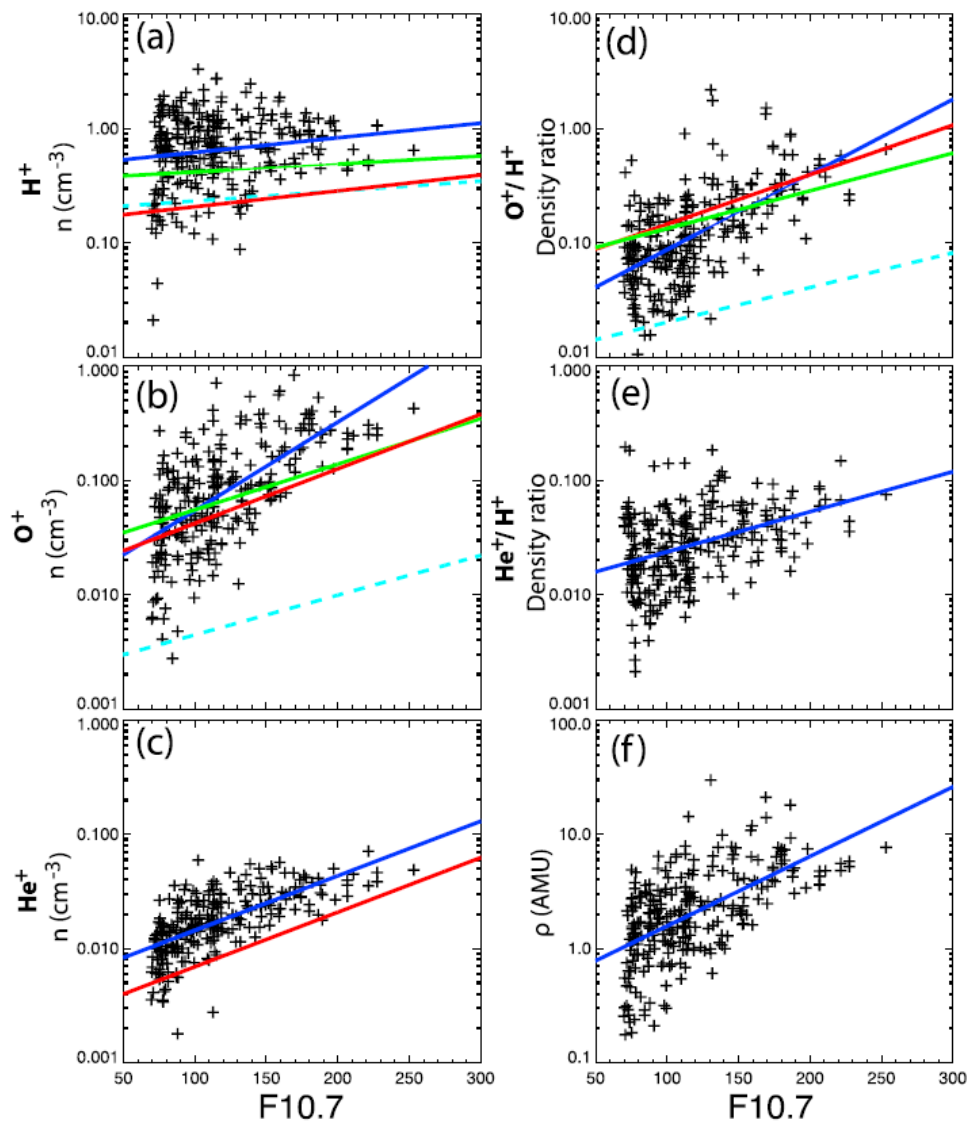
Quiet-time event



Moderate Storm time event

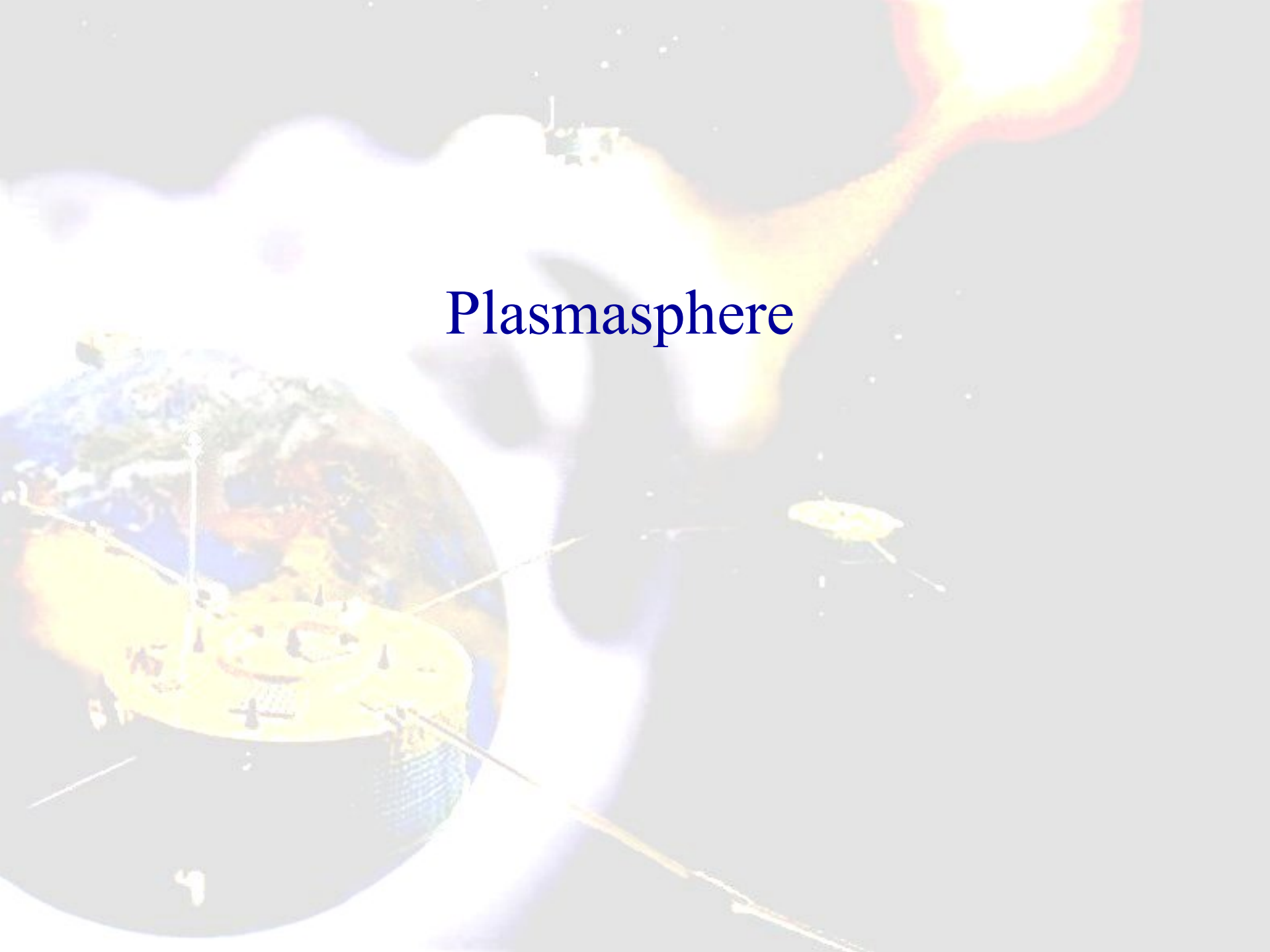
Ionospheric ions effect on the inner magnetosphere composition: Statistics over a solar cycle

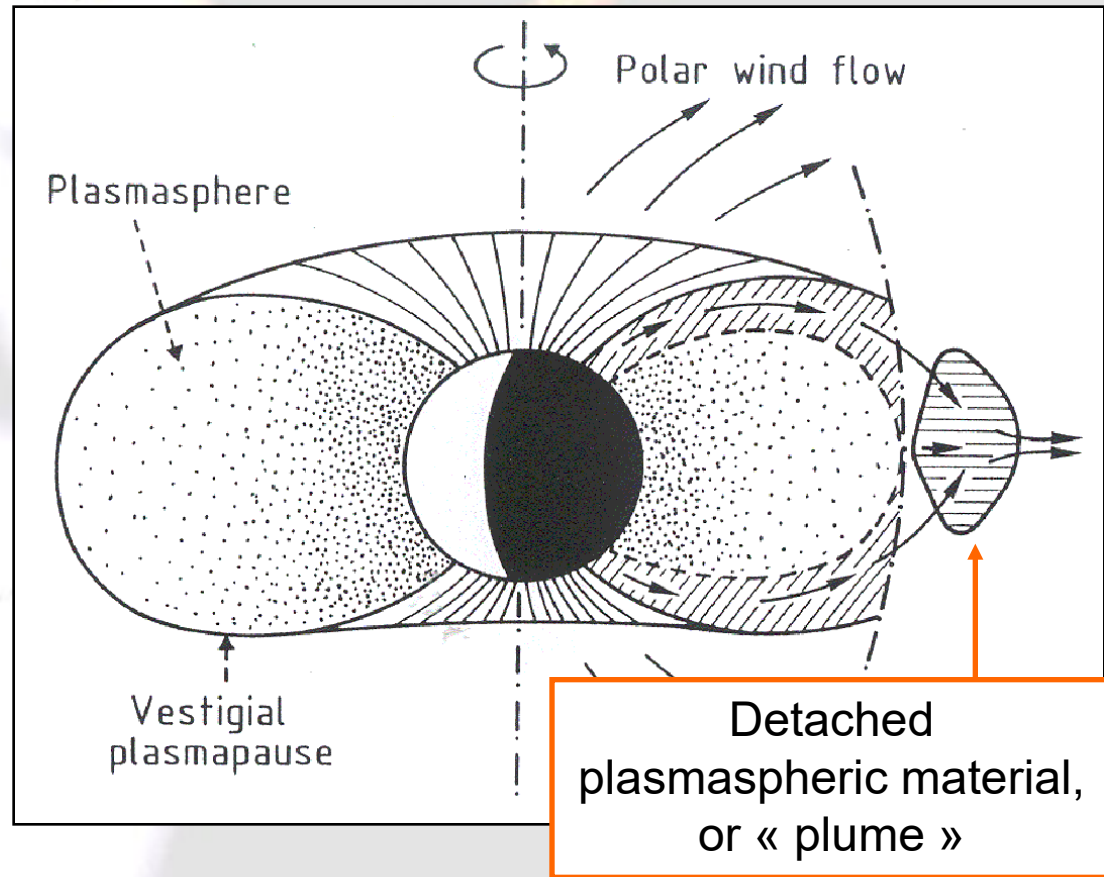
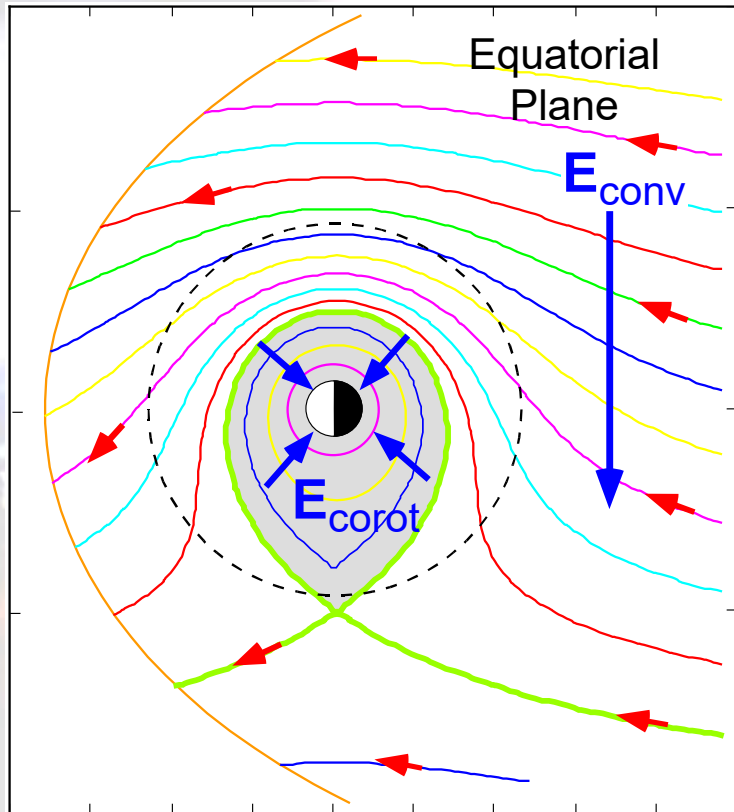
L = 6-7 / Energy = 1-40 keV / MLT = 21-3 / Kp ≤ 2



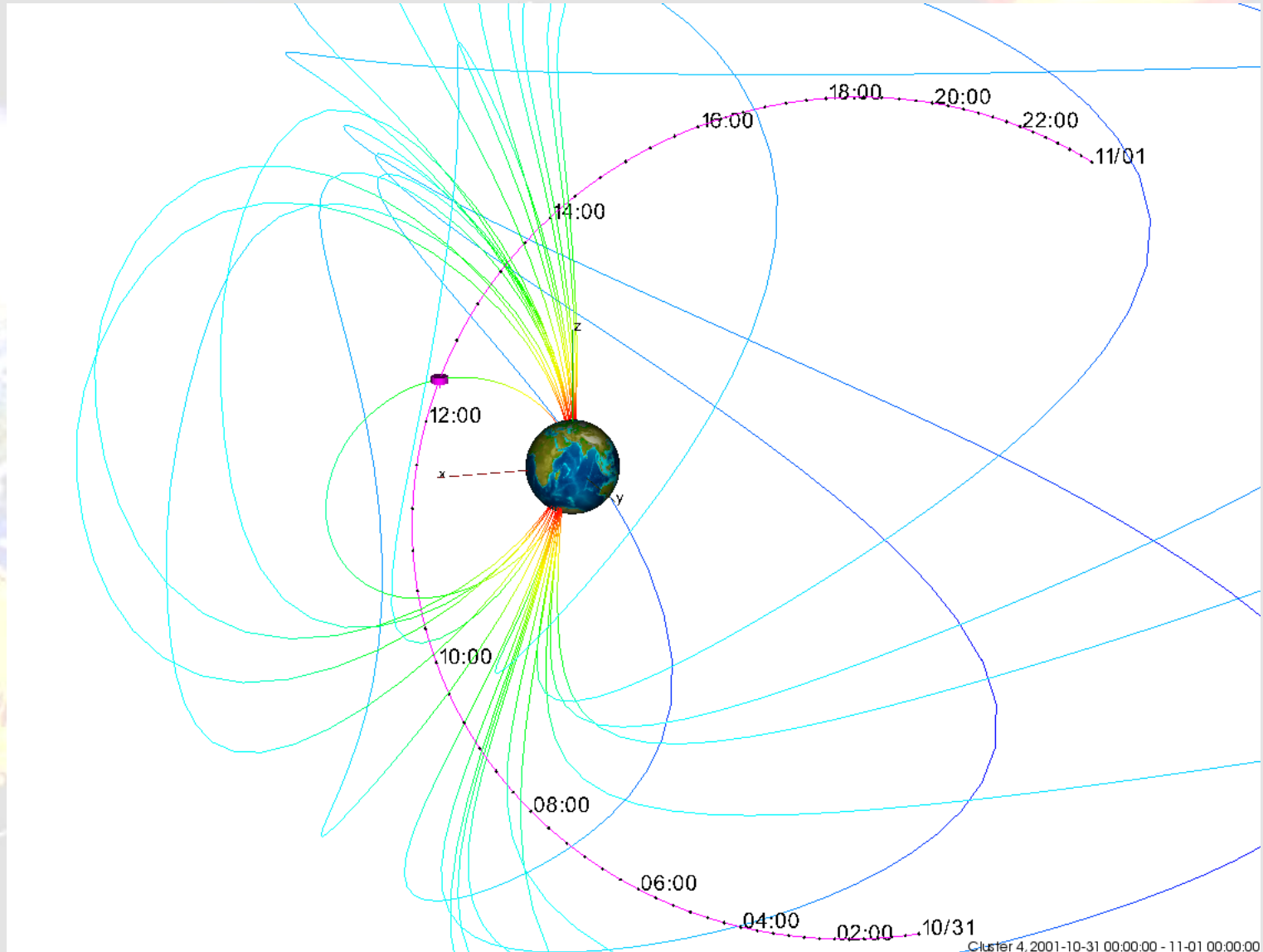
Kistler and Mouikis,
JGR, 2016

Plasmasphere



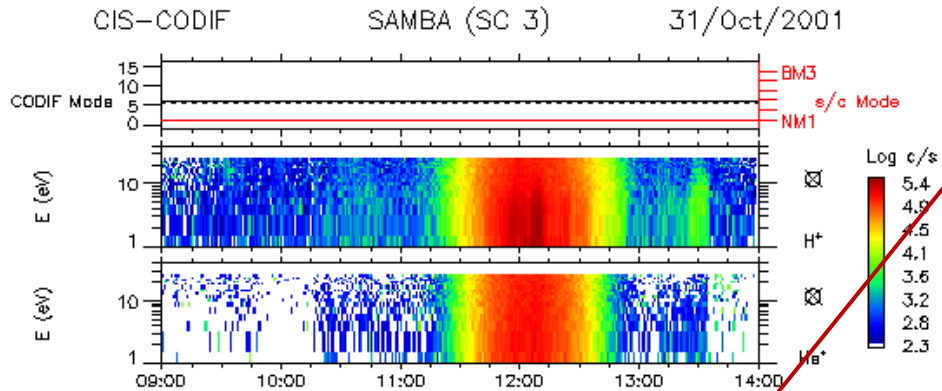
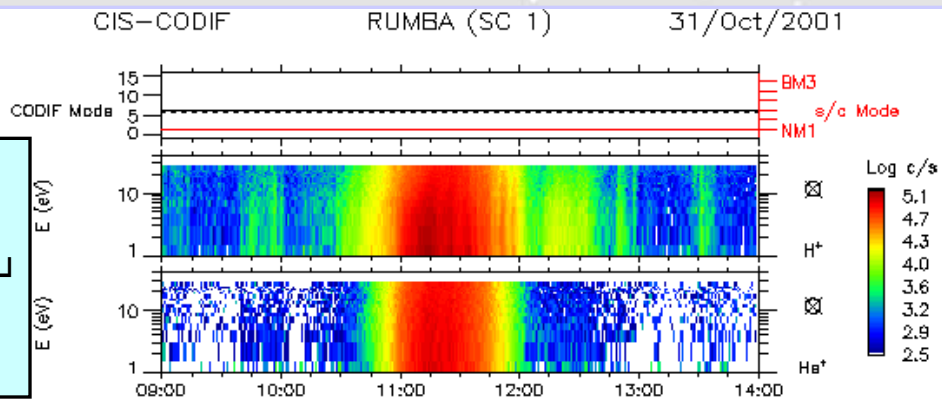


Plasmasphere Cut : Cluster Orbit

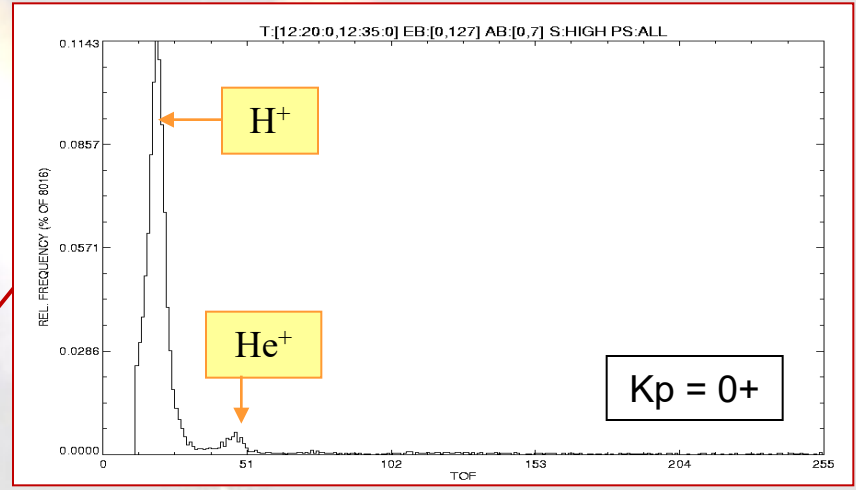
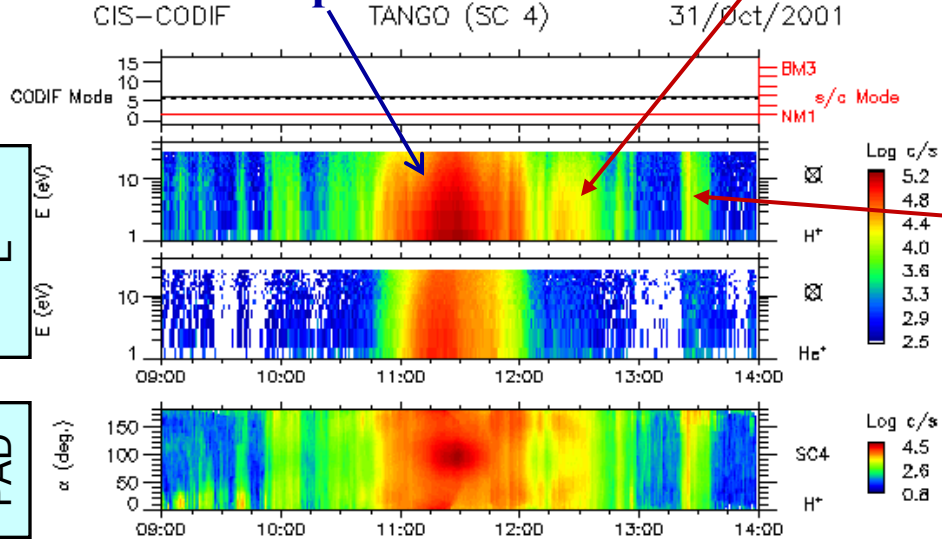


Low-Energy Ions in the Plasmaspheric Plumes

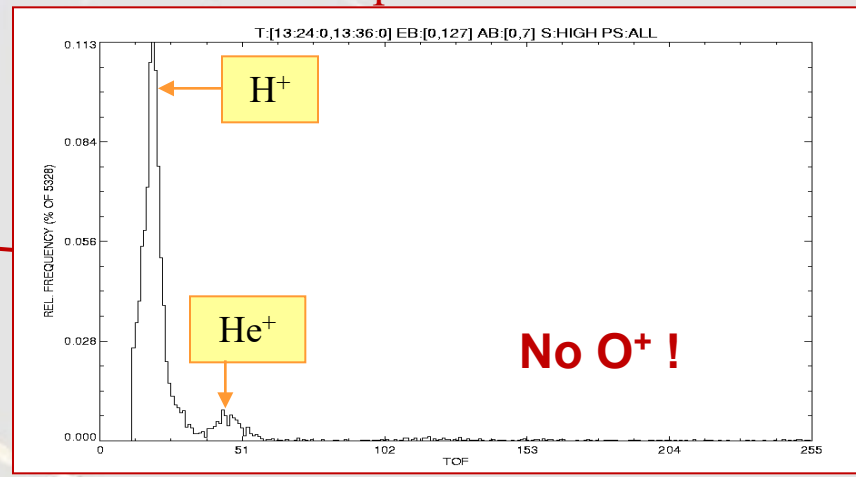
E

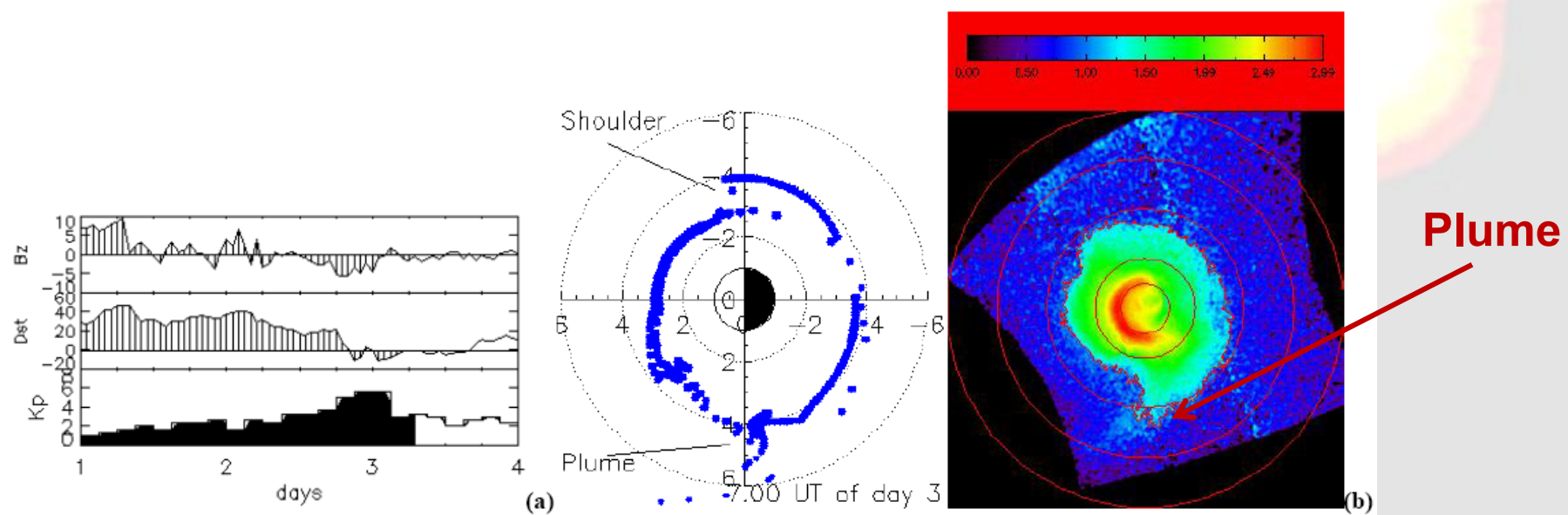


Main Plasmasphere



Ion mass spectra in the Plasmaspheric Plumes





Simulation *EUV / IMAGE*
Pierrard and Cabrera, 2005

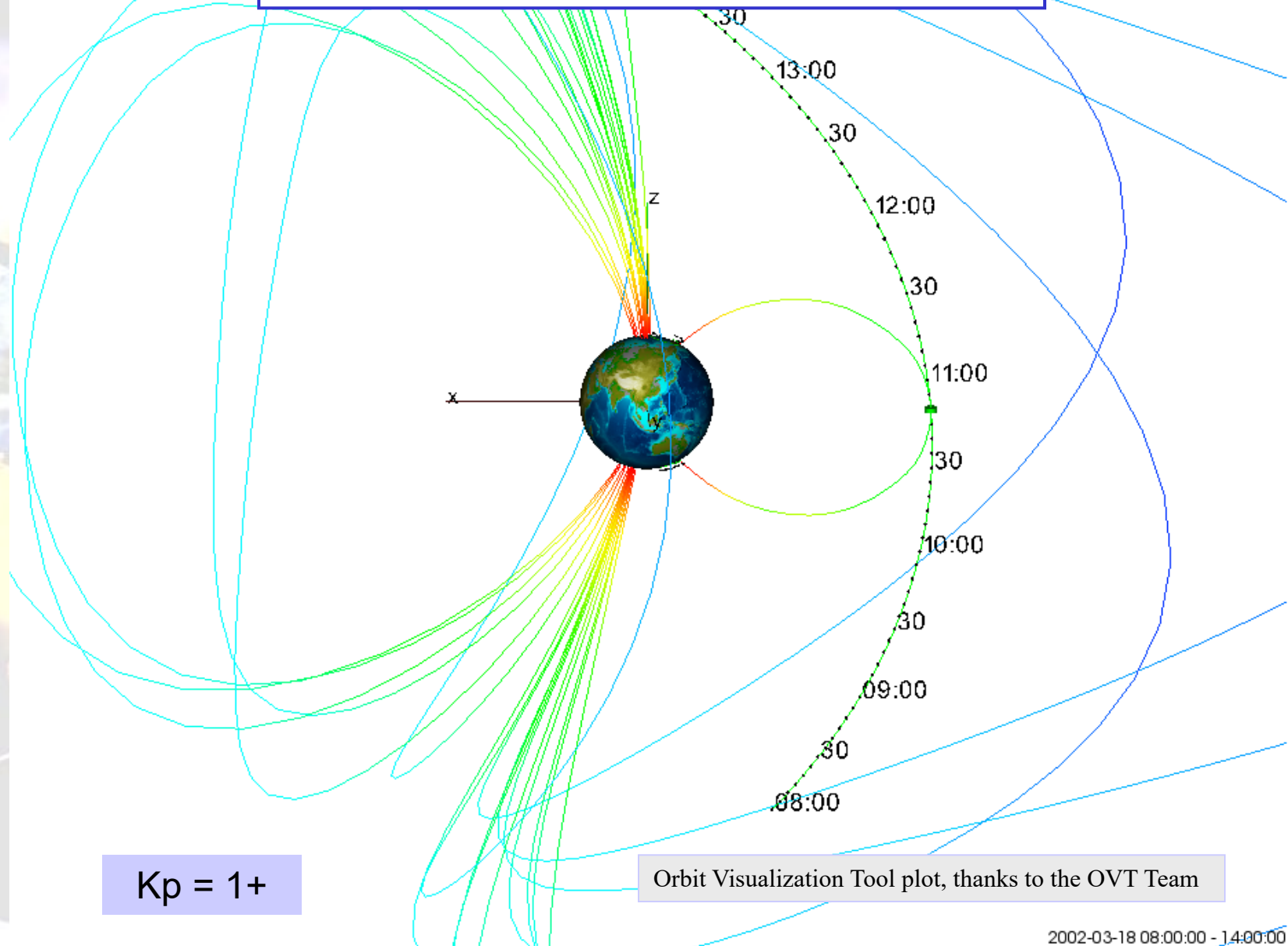
Are plasmaspheric plumes the only mode for plasmaspheric material release to the magnetosphere?

- 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 $L > \sim 2$), 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).
- **Direct detection** of this wind has, however, **eluded observation** in the past.

Plasmasphere cut: night-side quiet-time event



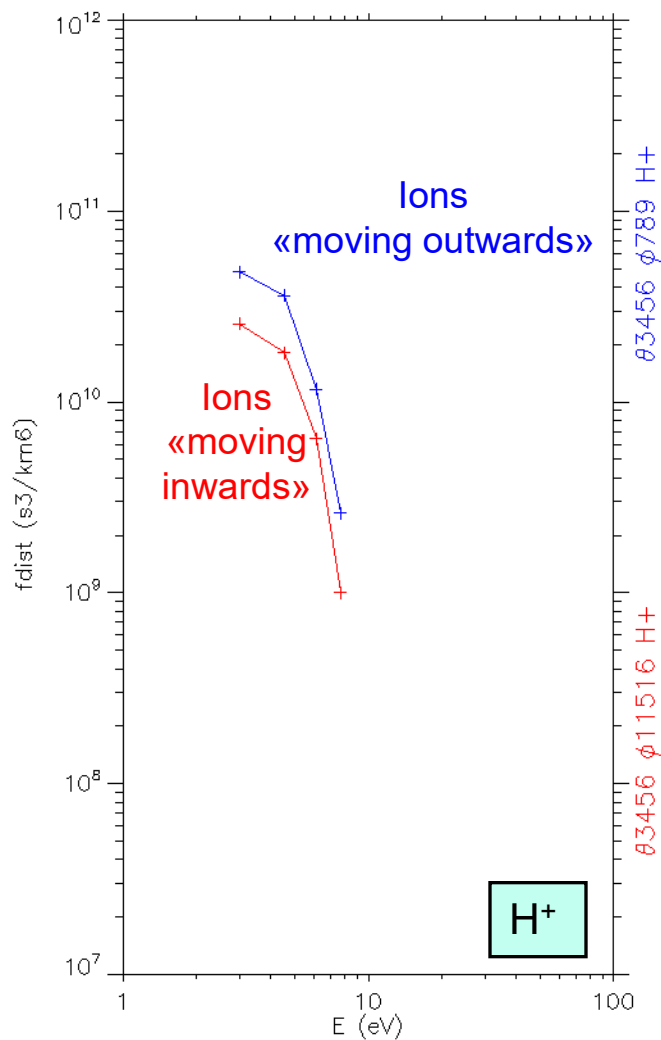
$K_p = 1+$

Orbit Visualization Tool plot, thanks to the OVT Team

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

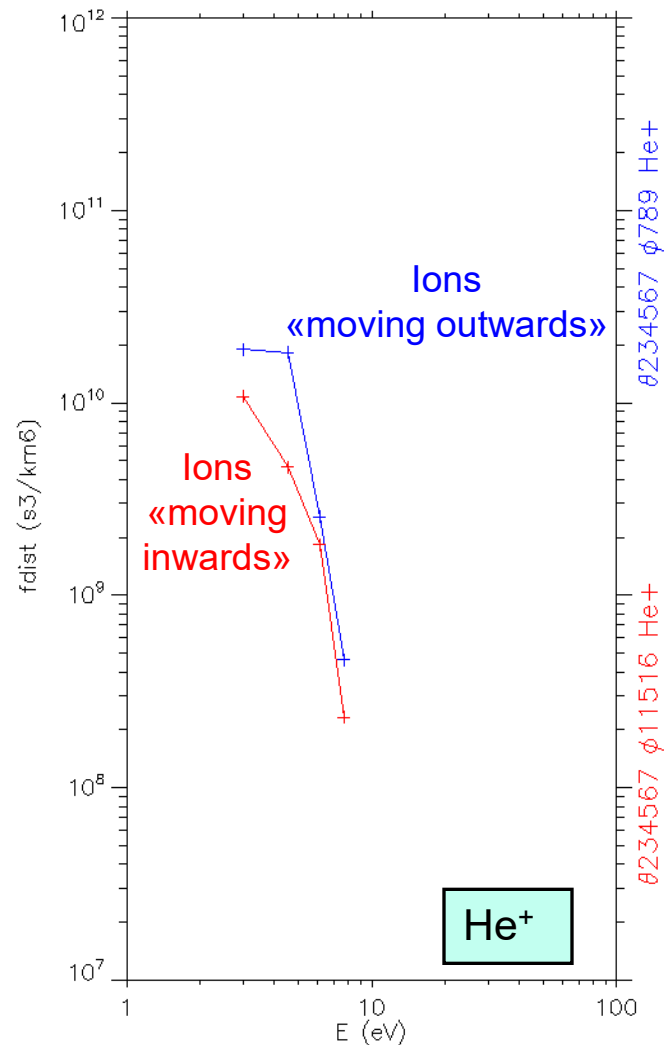
CIS-CODIF

C3 18/Mar/2002 10:52:00.

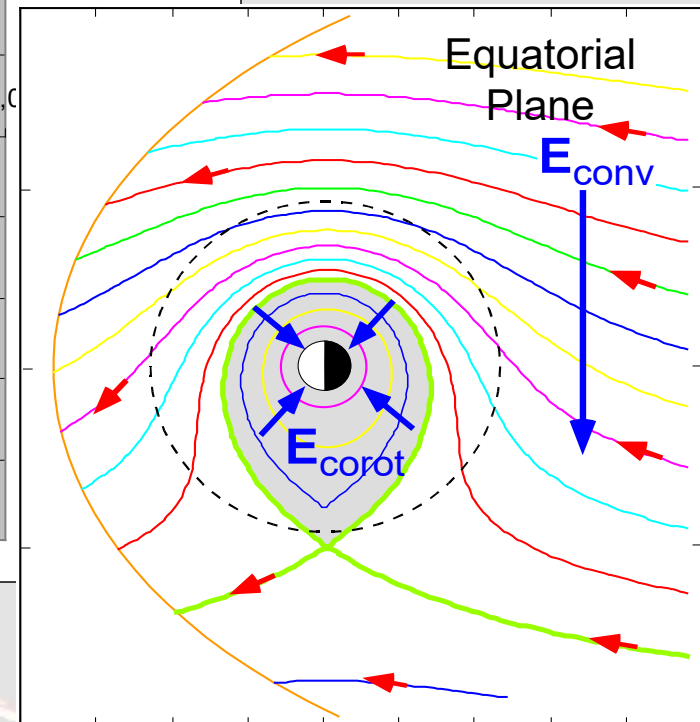
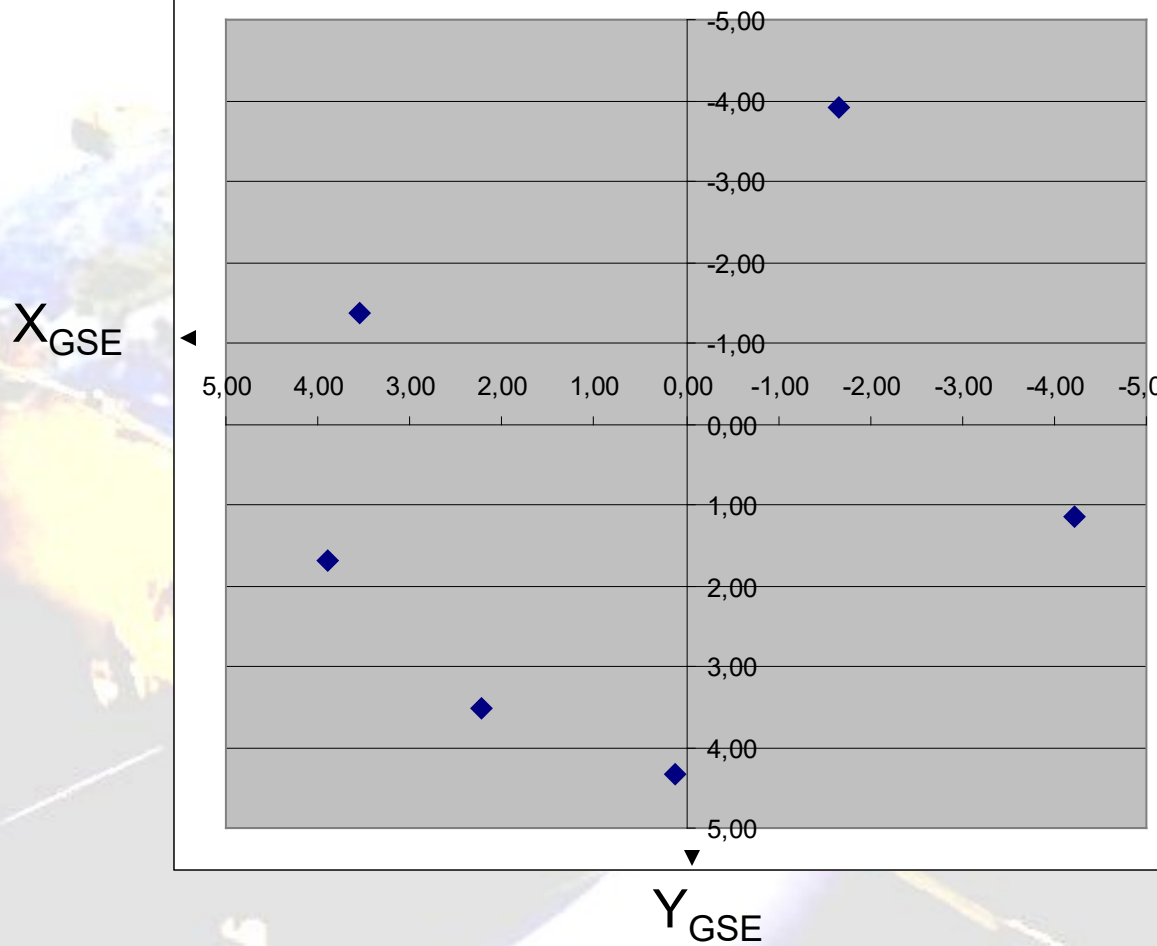


CIS-CODIF

C3 18/Mar/2002 10:52:00.



Analysed Plasmaspheric Wind observation events: Distribution in the equatorial plane



Plasmaspheric Wind: Contribution to the Magnetosphere

Considering:

- $V_{\text{plasmaspheric-wind}} \approx 1.4 \text{ km s}^{-1}$
(at $4 R_E$, from the ion distribution functions)
- Plasmaspheric density $\approx 100 \text{ cm}^{-3}$
(at $4 R_E$, typical values from WHISPER: *Darrouzet et al.*, 2008)
- Escape over half a sphere (in latitude)

We get :

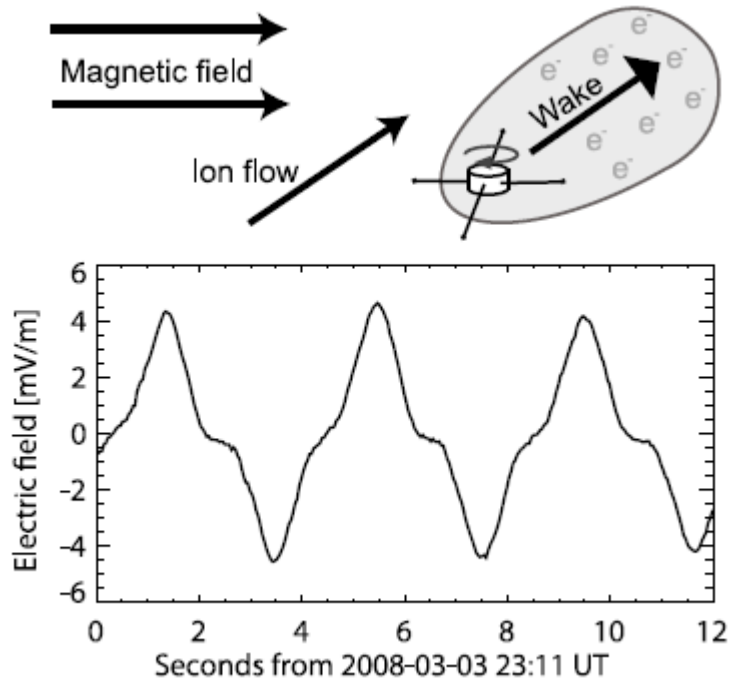
**$\sim 5 \times 10^{26} \text{ ions s}^{-1}$ continuously escaping from the
Plasmasphere and contributing to the Magnetosphere**

For comparison :

Dandouras, Annal. Geophys., 2013

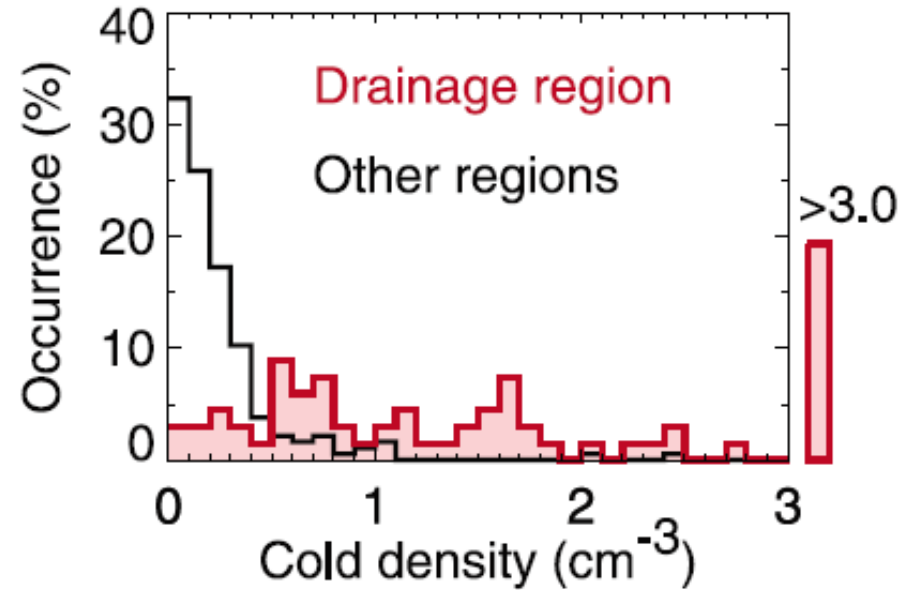
- the solar wind source is $\sim 10^{27} \text{ ions s}^{-1}$
- the high-latitude ionospheric source is $\sim 10^{26} \text{ ions s}^{-1}$
[*Moore et al.*, 2005; *Haaland et al.*, 2009; *Li et al.*, 2012]
- the plumes source is up to $\sim 2 \times 10^{26} \text{ ions s}^{-1}$ (active periods)
[*Borovsky and Denton*, 2008]

Plasmaspheric Wind Contribution to the Magnetosphere: Where does it go?



Using a Spacecraft Wake to Detect Low-Energy Ions:

- Wake behind a positively charged Cluster spacecraft, caused by a supersonic flow of cold ions
- Non-sinusoidal electric field measured with a spin period of 4 s, in a cold plasma



Statistics of low-energy ions inside the magnetopause:

Histogram of density in drainage region and other regions

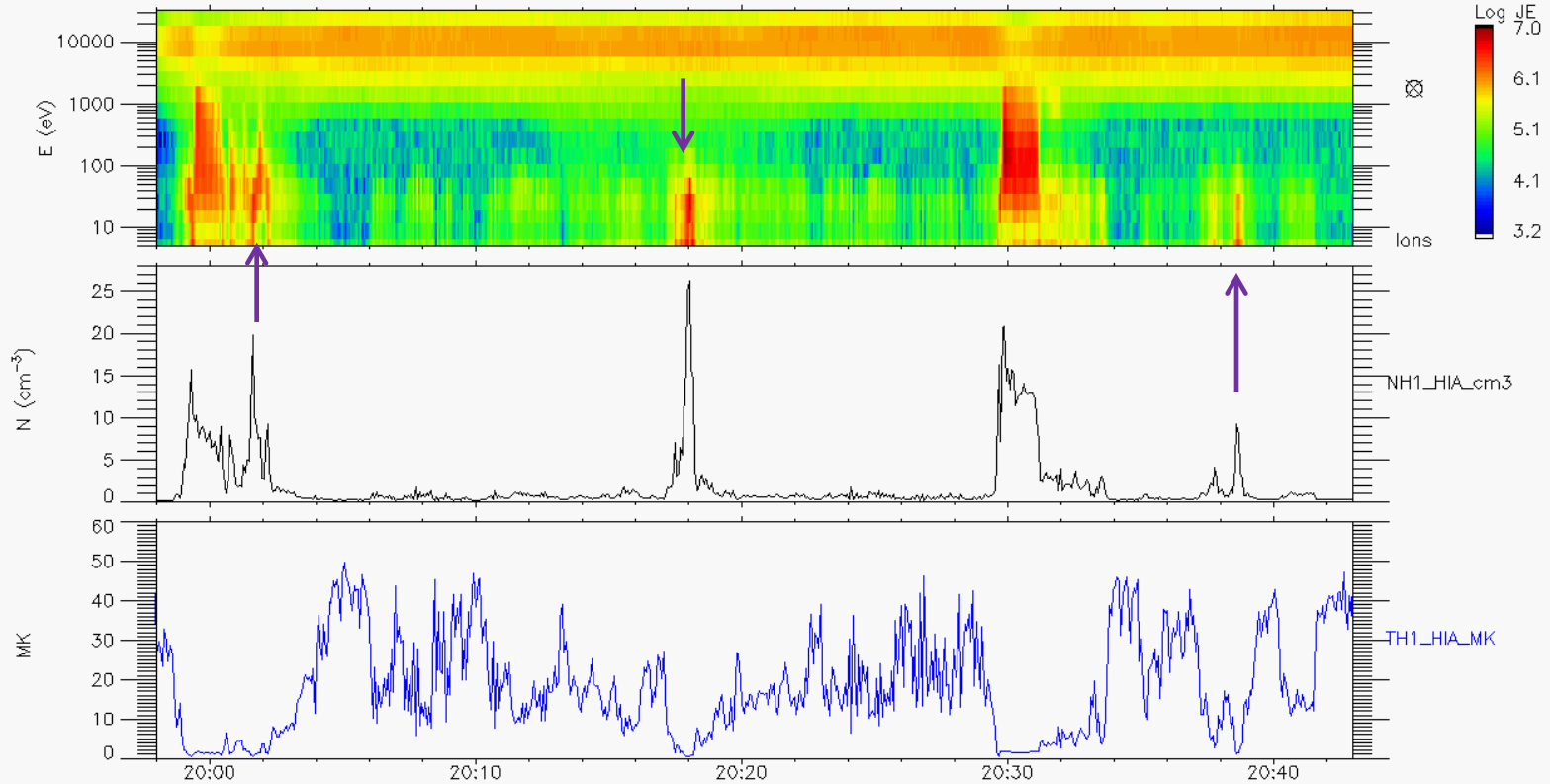
M. André and C. M. Cully,
Geophys. Res. Lett., 2012

Plasmaspheric Wind Contribution to the Magnetosphere: Where does it go?

CIS-HIA

RUMBA (SC 1)

08/Jan/2013



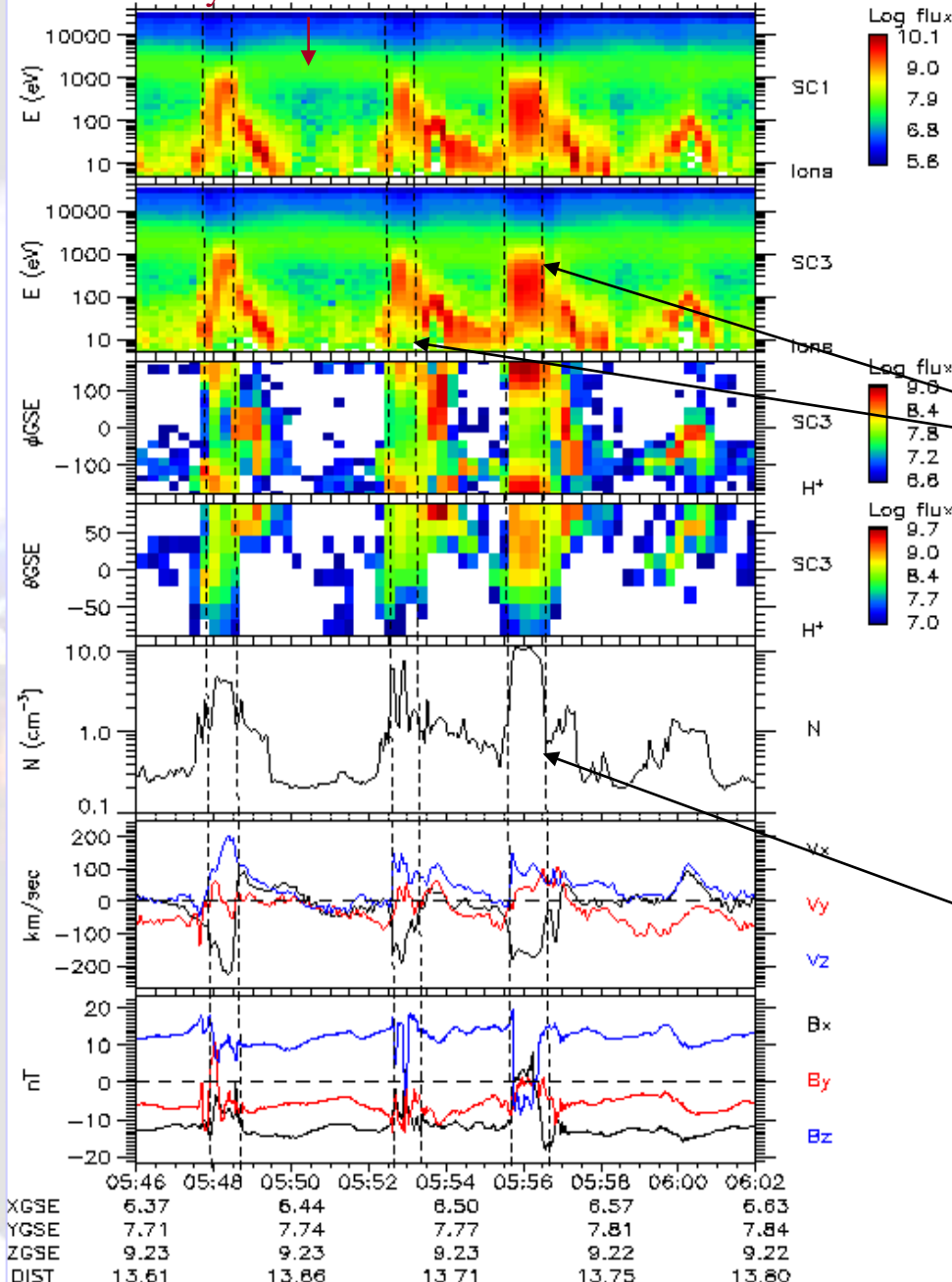
XGSE	9.32	9.17	9.02
YGSE	4.72	4.53	4.35
ZGSE	0.08	0.21	0.33
DIST	10.44	10.23	10.02

After several days of K_p
between 0 and 1

Intermittently accelerated cold plasma, adjacent to the magnetopause and on its magnetospheric side

Dayside Plasma Sheet

31/Jan/2001



- First observations with Cluster of a very dense population of locally accelerated thermal ionospheric ions (H^+ , He^+ , O^+) in a region just adjacent to the magnetopause and on its magnetospheric side.

- The observation follows a long period of very weak activity. Recurrent motions of the magnetopause (>100 km/s) are associated with the appearance, inside closed field lines, of recurrent energy structures of ionospheric ions.

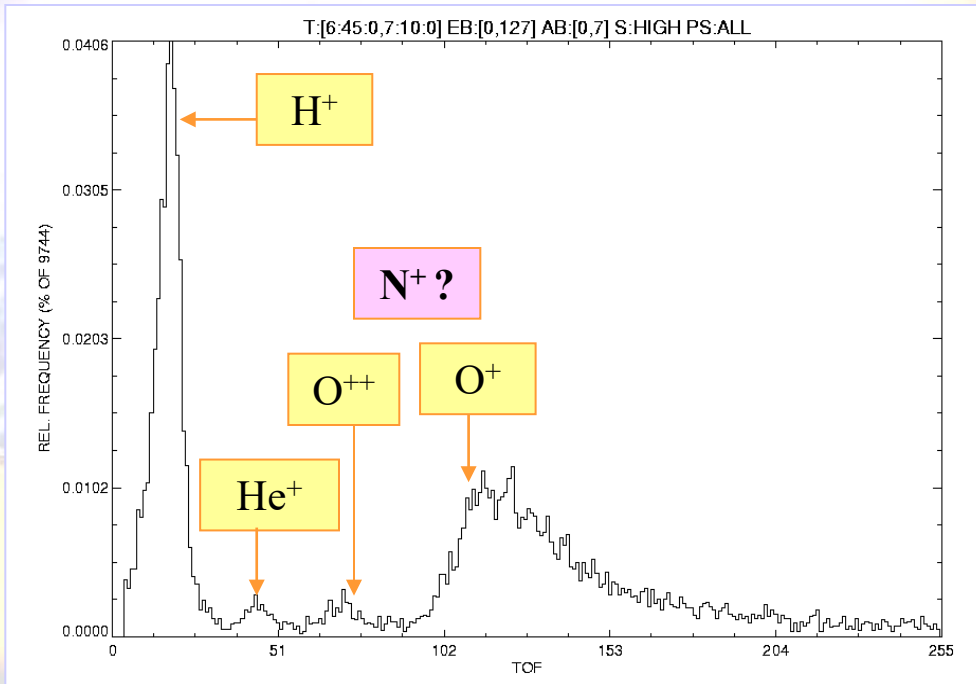
- The heaviest ions are detected with the highest energies.

- The ion behavior is interpreted as resulting from local electric field enhancements / decreases which adiabatically enhance / lower the bulk energy of a local dense thermal ion population.

- When fast flowing, i.e. when detectable, the density (~ 1 cm $^{-3}$) of these ions from terrestrial origin is largely higher than the density of ions from magnetospheric/plasma sheet origin, which poses again the question of the relative importance of solar and ionospheric sources for the magnetospheric plasma during very quiet magnetic conditions.

Sauvaud et al., Ann. Geophys., 2001

What Cluster-CIS Cannot Answer?



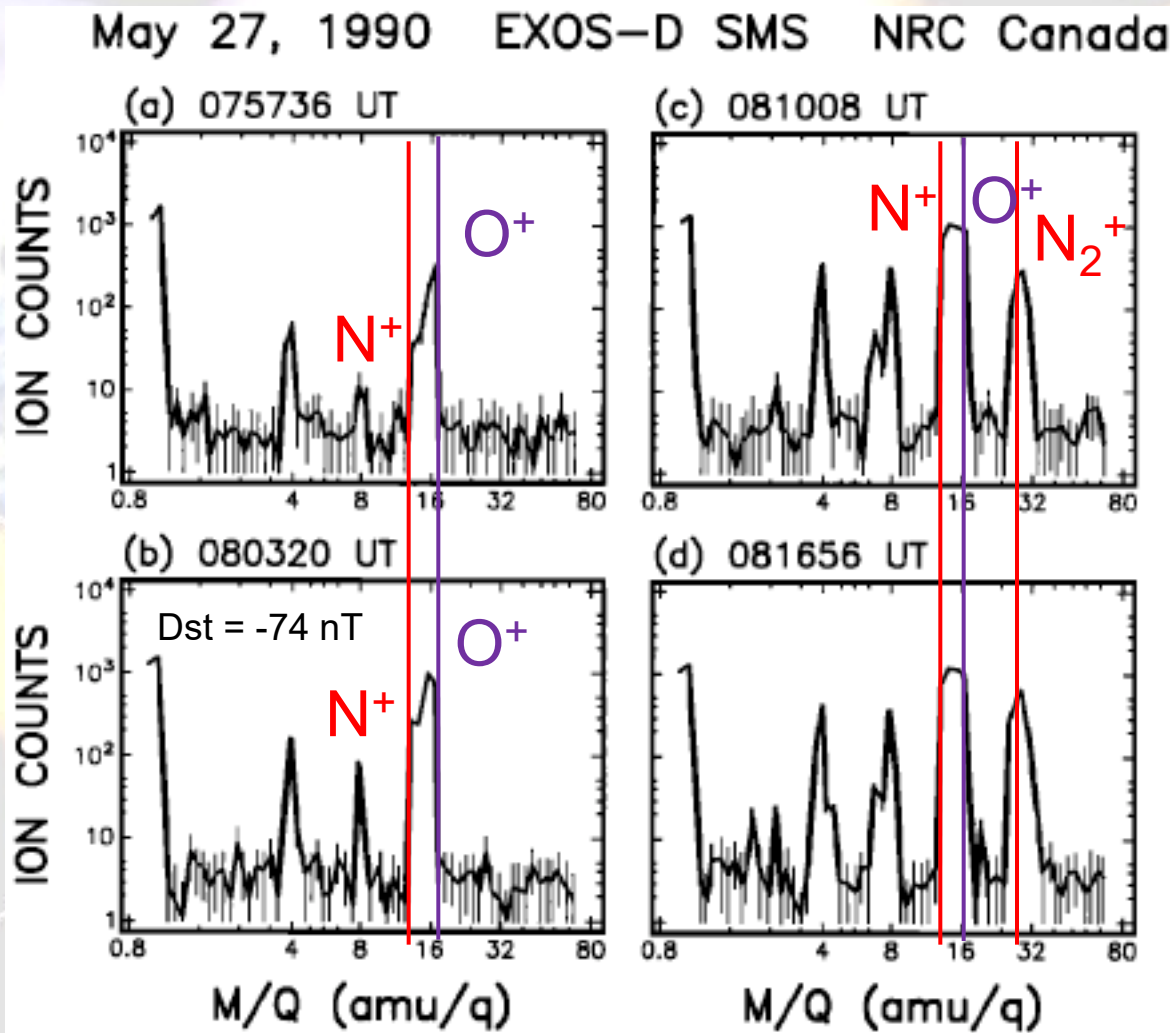
CIS: $M / \Delta M \sim 4 - 6$

To separate N^+ and O^+ :

$M / \Delta M > 7$ needed

Present knowledge on N^+ escape

More drastic changes for N^+ than for O^+ , $E < 50$ eV



N^+ / O^+ escape ratio
Varies from:
< 0.1 (quiet conditions)
to **~1 (intense storms)**

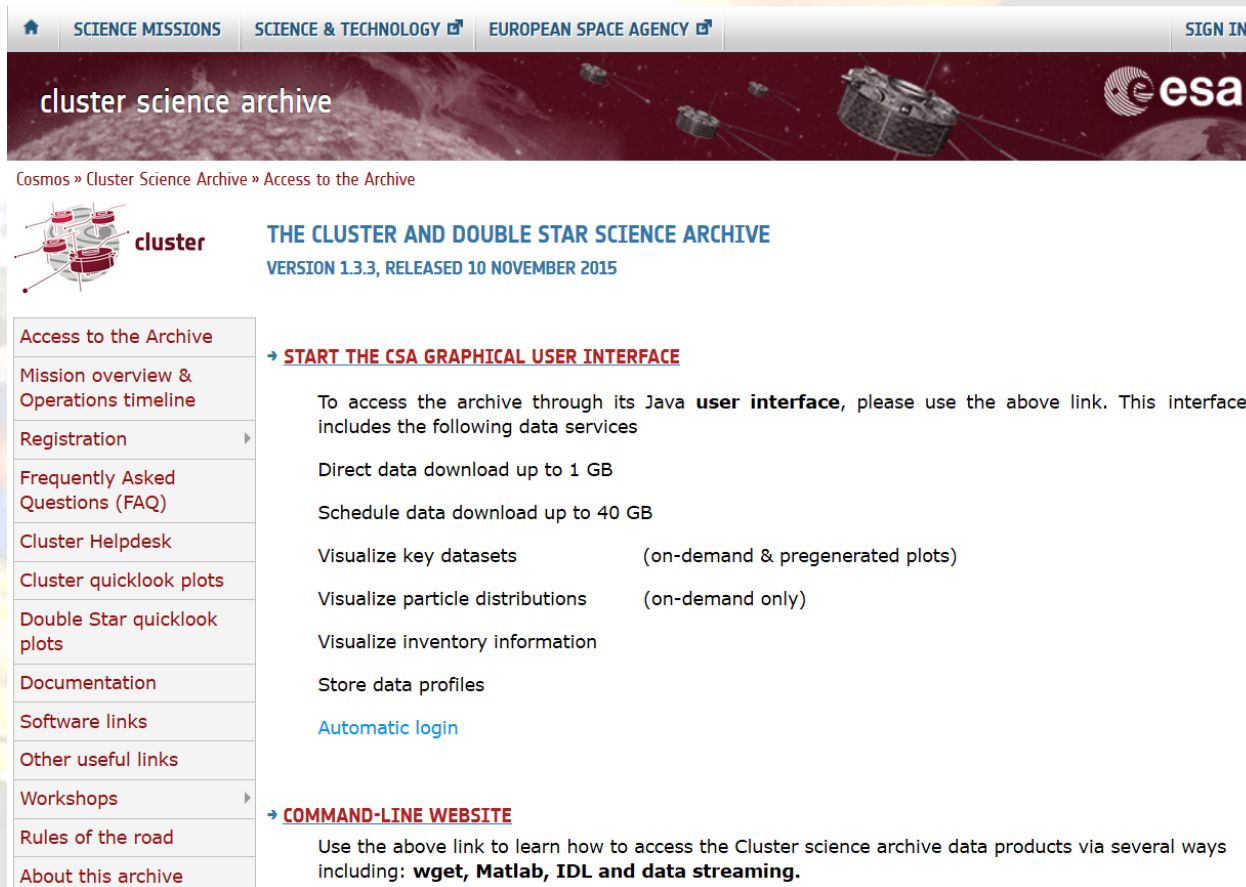
But destination and acceleration is not clear

Cluster - CIS Data Availability

The background of the slide is a composite image. On the left, a portion of the Earth is visible, showing blue oceans and brown/green landmasses. A satellite is in orbit above the Earth, with several long, thin antennas extending from its surface. In the upper right, a bright, glowing solar flare or sunspot is visible, with a large, bright yellow and orange sun in the background. The overall scene is set against a dark, starry space background.

Cluster Data Archiving at the CSA *Cluster Science Archive*

<http://www.cosmos.esa.int/web/csa>
and at the CDPP



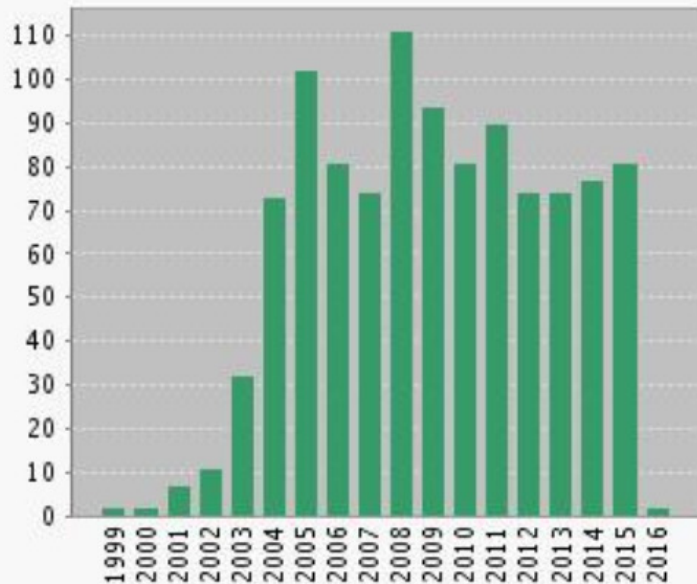
The screenshot shows the Cluster Science Archive website. At the top, there is a navigation bar with links for 'SCIENCE MISSIONS', 'SCIENCE & TECHNOLOGY', 'EUROPEAN SPACE AGENCY', and 'SIGN IN'. Below this is a header with the text 'cluster science archive' and the ESA logo. A breadcrumb trail reads 'Cosmos » Cluster Science Archive » Access to the Archive'. The main content area features a 'cluster' logo and the title 'THE CLUSTER AND DOUBLE STAR SCIENCE ARCHIVE VERSION 1.3.3, RELEASED 10 NOVEMBER 2015'. On the left is a vertical menu with items like 'Access to the Archive', 'Mission overview & Operations timeline', 'Registration', 'Frequently Asked Questions (FAQ)', 'Cluster Helpdesk', 'Cluster quicklook plots', 'Double Star quicklook plots', 'Documentation', 'Software links', 'Other useful links', 'Workshops', 'Rules of the road', and 'About this archive'. The main text area contains a link to 'START THE CSA GRAPHICAL USER INTERFACE' and a list of data services: 'Direct data download up to 1 GB', 'Schedule data download up to 40 GB', 'Visualize key datasets (on-demand & pregenerated plots)', 'Visualize particle distributions (on-demand only)', 'Visualize inventory information', and 'Store data profiles'. There is also a link for 'Automatic login'. At the bottom, there is a link to 'COMMAND-LINE WEBSITE' with a brief description of how to access data products via 'wget', 'Matlab', 'IDL' and 'data streaming'.

All calibrated, high resolution data, together with associated documentation and data caveats. Publicly available data.

CIS Publications

- ~1100 science papers published in refereed journals, based on the analysis of CIS (Cluster) and HIA (Double Star) data.
- List of representative CIS publications at :
http://cluster.irap.omp.eu/public/publications/CIS_publications_list.htm

Citations in Each Year



The latest 20 years are displayed.

References to:

Rème et al., 1997, 2001, 2005

Results found: 3

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Recent review paper:

Welling et al., The Earth: Plasma Sources, Losses, and Transport Processes, Sp. Sci Rev., 2015

CONCLUSIONS

Two main plasma sources for the Earth's magnetosphere:

- ❖ The **solar wind**, which provides mostly hydrogen ($\sim 10^{27}$ ions s^{-1})
- ❖ The Earth's **ionosphere** (and **plasmasphere**), which in addition to hydrogen is capable of delivering considerable amounts of **heavier ions**
- The **Polar ionosphere source** ($\sim 10^{26}$ ions s^{-1} varying by a factor of ~ 3 as a function of the activity level and dependent on the IMF orientation) :
 - **Cusp**: main source of energetic oxygen ion outflow
 - **Polar caps**: substantial contribution of upwelling ions, with solar, IMF and magnetospheric activity dependence
 - **“Hidden” cold ion populations** revealed streaming in the **lobes** and also present inside the **magnetopause**
- The **Plasmaspheric source**:
 - **Plumes**: mainly during active periods ($\sim 2 \times 10^{26}$ ions)
 - **Plasmaspheric Wind**: steadily transporting cold plasma outwards and contributing to the Magnetospheric populations ($\sim 5 \times 10^{26}$ ions s^{-1})
- **Cluster** calibrated high-resolution data available at the **CSA** and at the **CDPP**