Simultaneous detection of terrestrial ionospheric heavy ions in the Earth’s inner magnetosphere and at the Moon

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Europlanet Workshop on Planetary Atmospheric Erosion, Romania, June 2018

ARTEMIS observations of terrestrial ion outflow in the tail of the magnetosphere

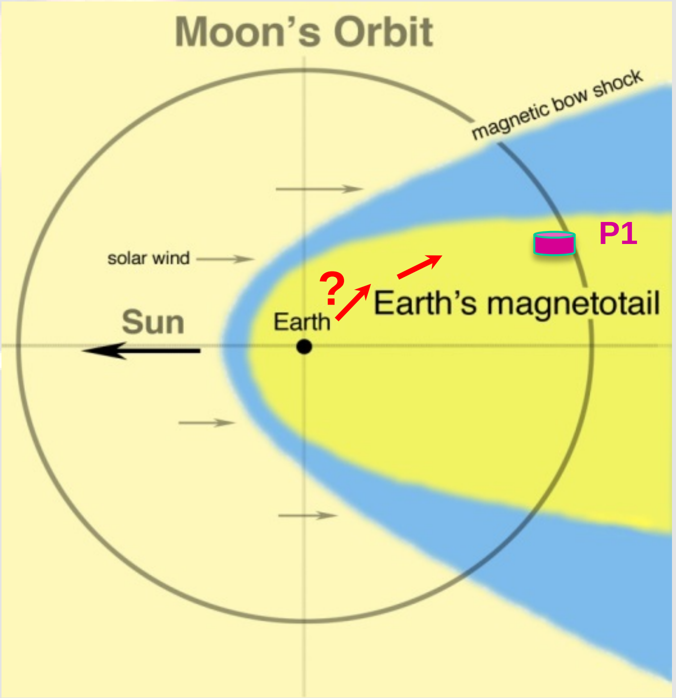
Can we observationally establish the **link** between:

- the heavy ions observed in the magnetotail

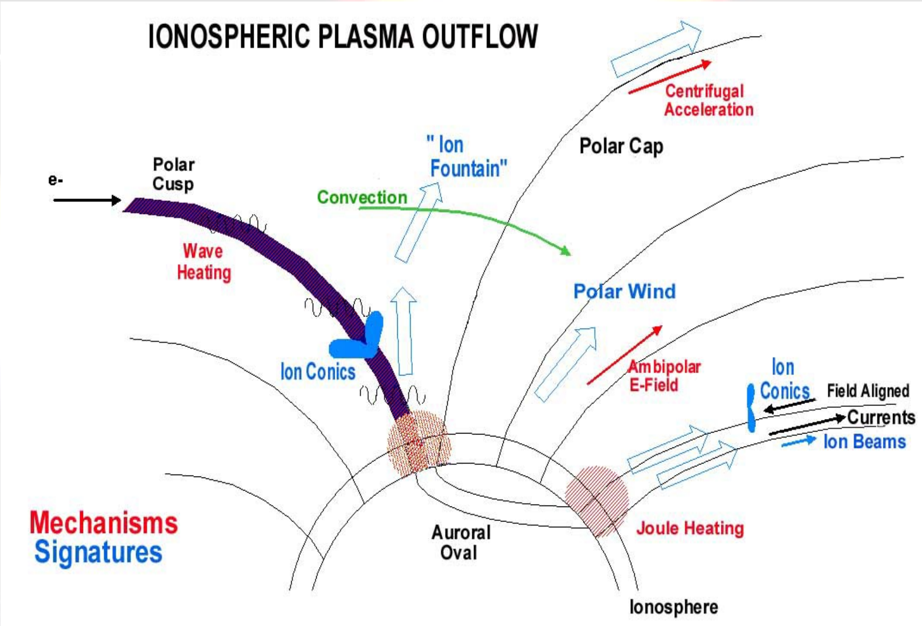
close to the Moon

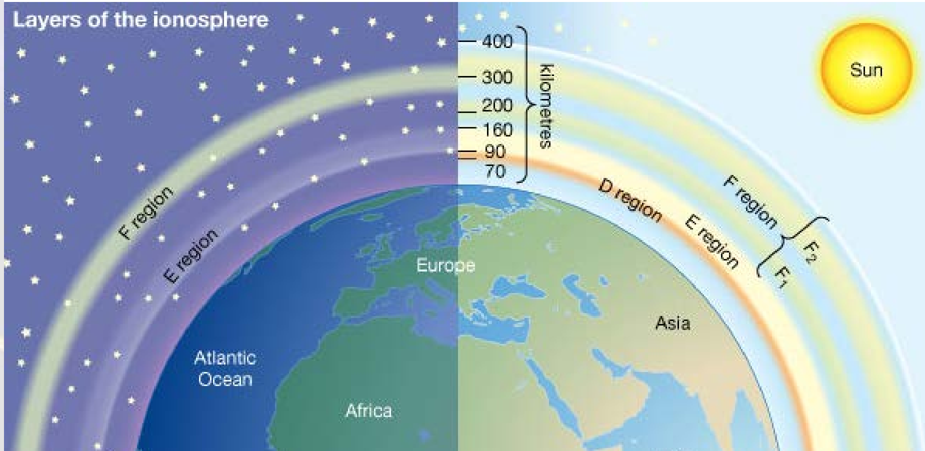
and

- the **inner terrestrial magnetosphere / upper ionosphere**?

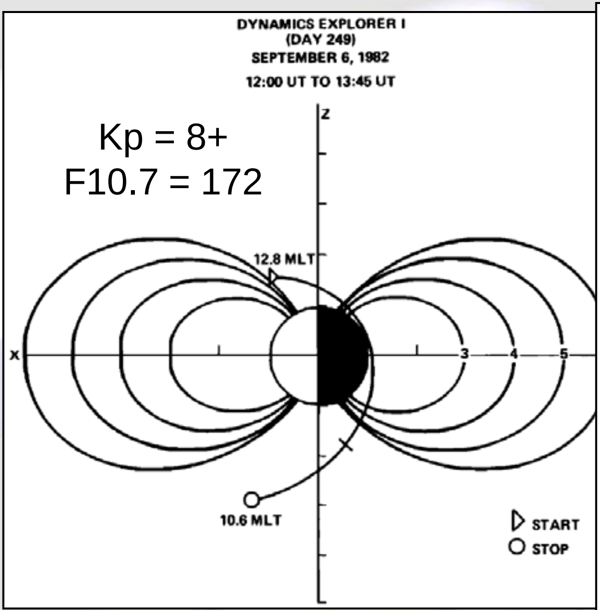


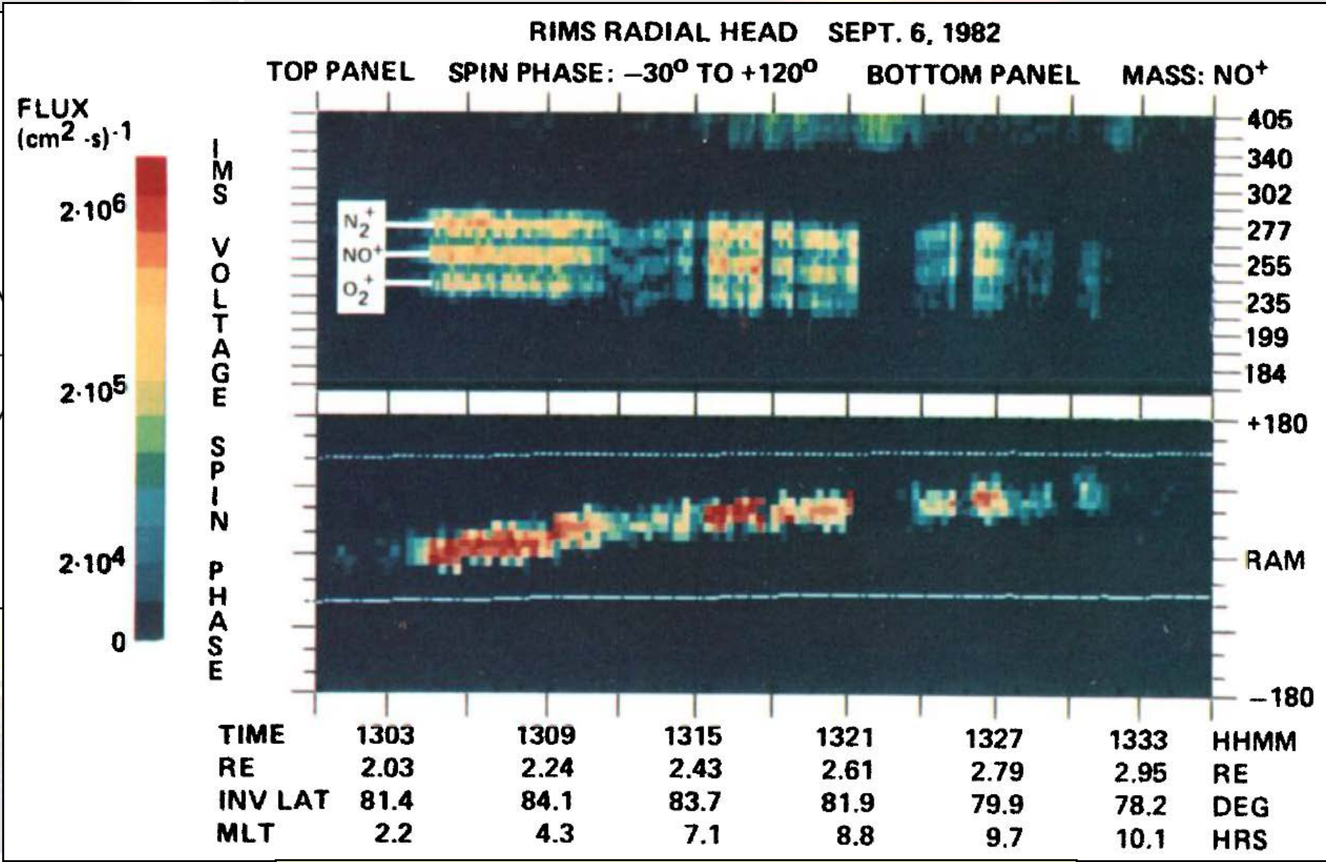
- **N_2^+ , NO^+ and O_2^+**, molecular ions are typical constituents of the **lower E region of the terrestrial ionosphere**.
- During geomagnetically quiet periods they are present in only minor abundances in the F region.
- However, during active periods, **heavy molecular ions** of **terrestrial origin**, including N_2^+ , NO^+, O_2^+, have been observed:
  - ✓ in the near-Earth: e.g. *Klecker et al.,1986; Yau et al., 1993; Wilson and Craven, 1999*
  - ✓ and in the far tail (~146 R_E): *Christon et al., 1994*.





Example of past molecular ion outflow observations over the polar cap during a large magnetic storm



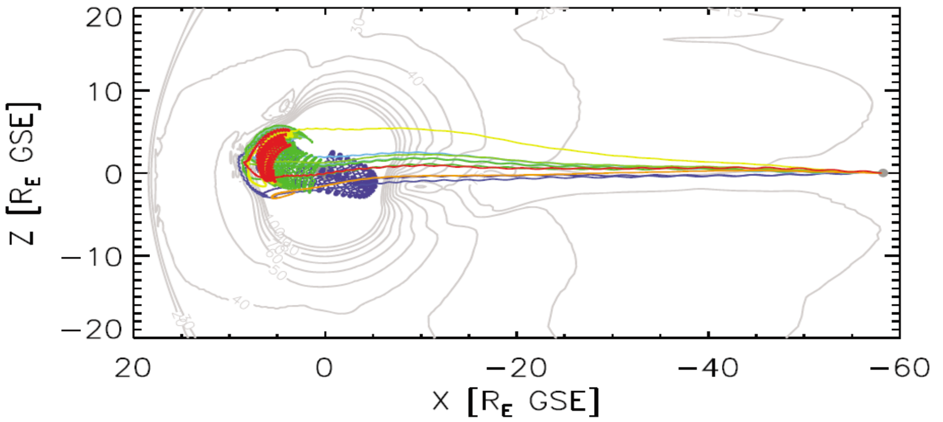


- Maxwellian distri. near perigee
- Field-aligned at higher altitudes
- 5 – 10 km s^{-1} upward flow
- Up to **~10^{10} ions m^{-2} s^{-1}**

Craven et al., JGR, 1985

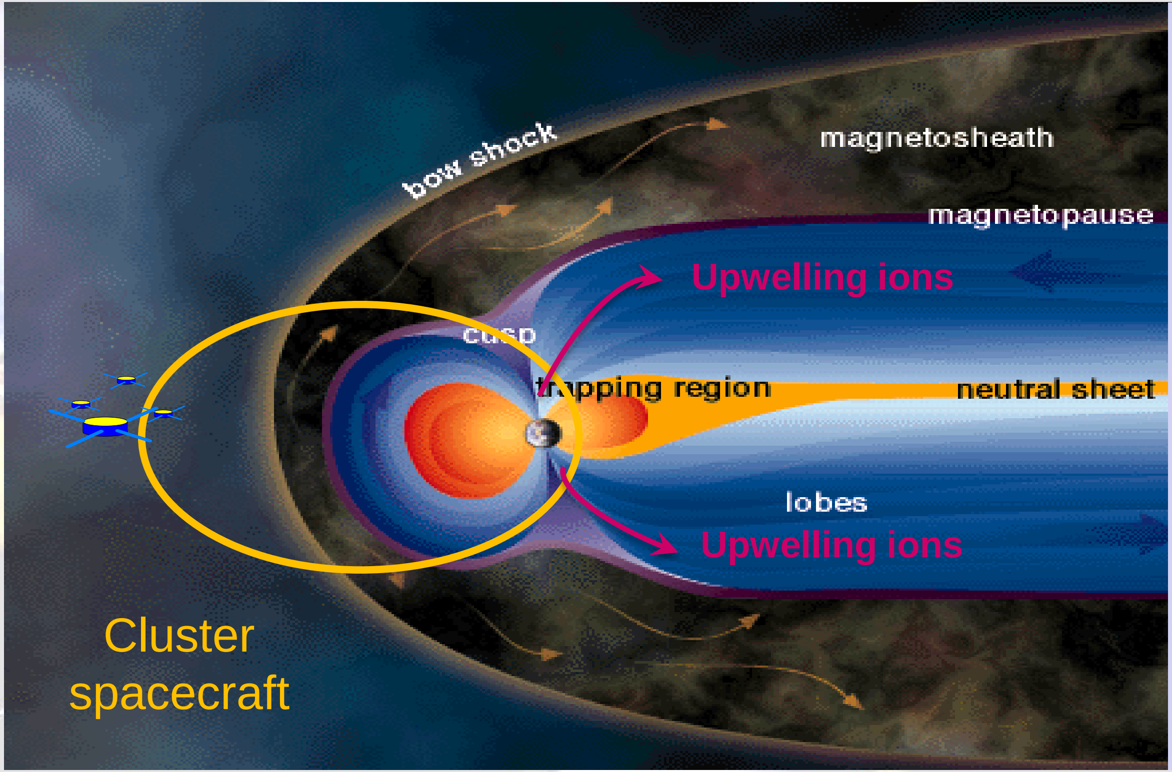
Dynamics Explorer-1 RPA: E ~ 20 eV

- **Heavy ion escape** plays a determinant role in the **long-term evolution of the atmospheric composition**.
- Terrestrial heavy ions, transported to the Moon suggest that the **Earth's atmosphere of billions of years ago** may be **preserved on the lunar regolith** [Terada et al., *2017*].
- Ions that escape from the ionosphere in the polar cap region can be folded into narrow **monoenergetic beams** [e.g., Cladis, *1986*; Seki et al., *1998*; Nilsson et al., *2006, 2008*].
- MHD Open Global Geospace Circulation Model **simulations** (backward particle tracing, Raeder et al., *2001*) **suggest that the molecular ions, observed by ARTEMIS, originated in the inner magnetosphere** (~4 – 7 R_E).



A. R. Poppe, M. O. Fillingim, et al., 2016

Cluster



- Cluster : 4 spacecraft launched in 2000 in a tetrahedral configuration.
- Each equipped with 11 instruments.
- High inclination orbit.
- 4 x 19.6 R_E initial orbit.
- Still operating.
- All data available at the Cluster Science Archive: www.cosmos.esa.int/web/csa

Cluster: CIS / CODIF:

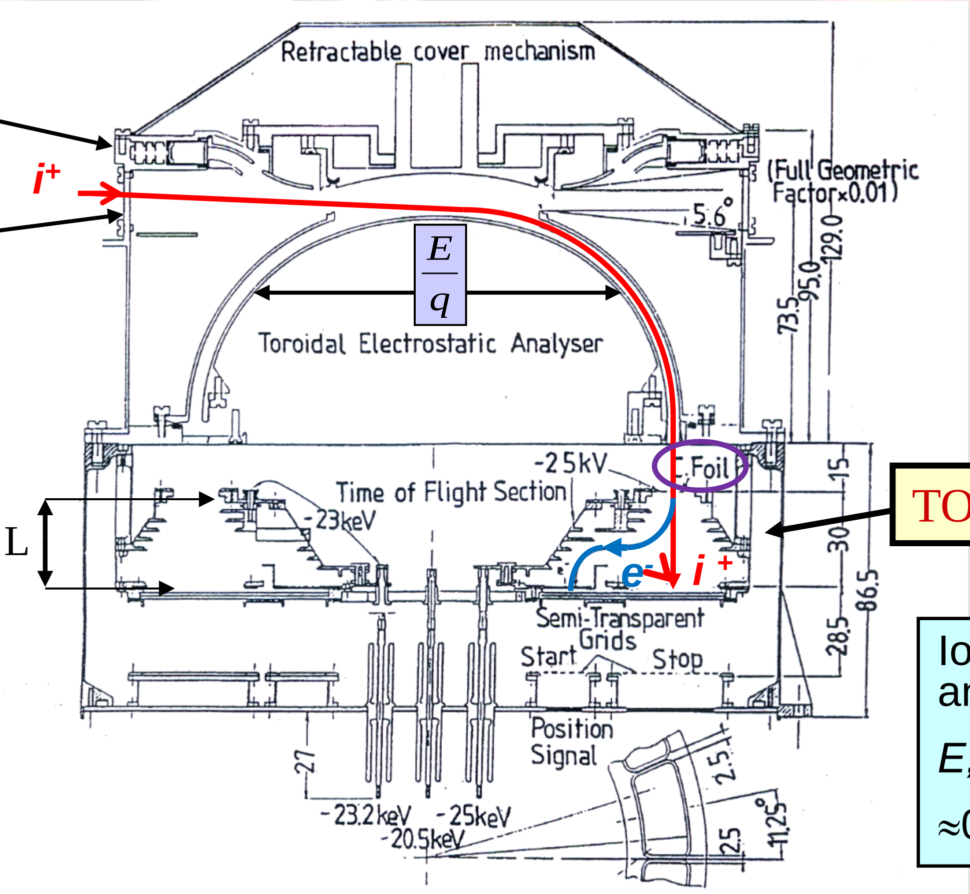
Ion Composition and Distribution Function Analyser

RPA entrance

Main entrance

$$\frac{m}{q} = \frac{2\times\left(\frac{E + E_{pacc} - E_{loss}}{q}\right)}{\left(\frac{L}{TOF}\right)^2}$$

$m / \Delta m \sim 5 - 7$



TOF system

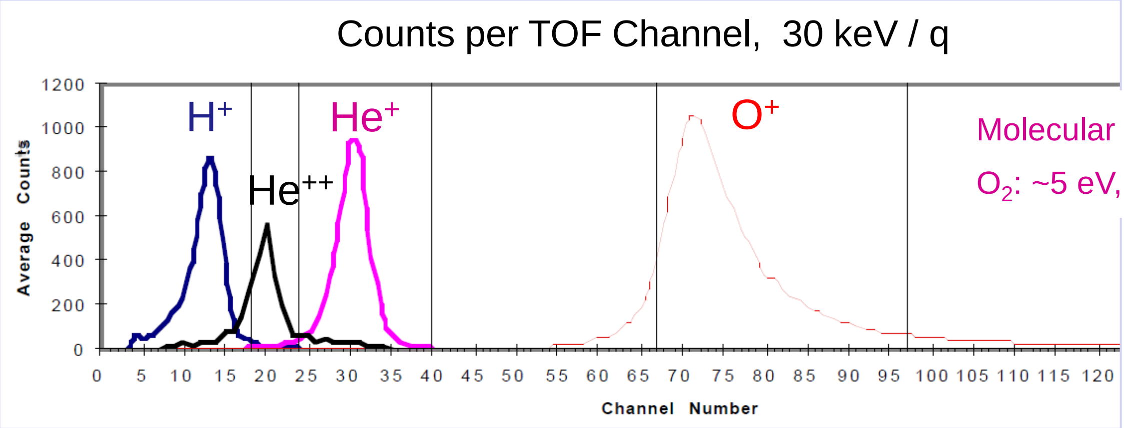
Ion 3-D distributions and mass analysis:

E, m, ϕ, θ, t

≈0 eV/q - 40 keV/q

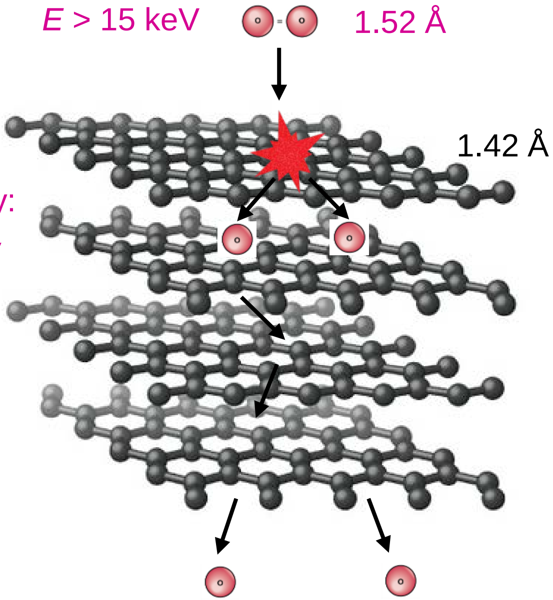
Can CODIF detect molecular ions?

CODIF has been fully calibrated on-ground for atomic ions detection



CODIF time-of-flight (TOF) spectra for the four major ion species

Molecular ions traversing thin carbon foils



Molecular bond energy:

O_2: ~5 eV, N_2: ~10 eV

20% energy lost due to the fragmentation process

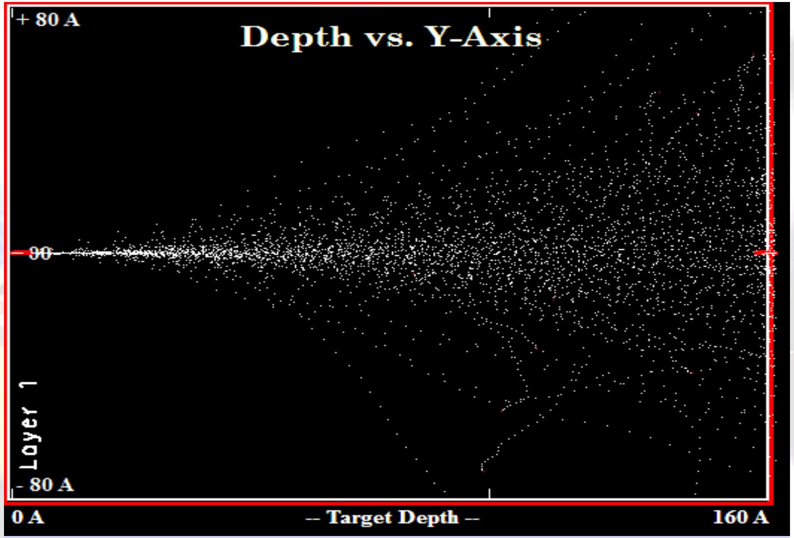
Tape et al., 1976

Heredia-Avalos & Garcia-Molina, 2000

Can CODIF detect molecular ions?

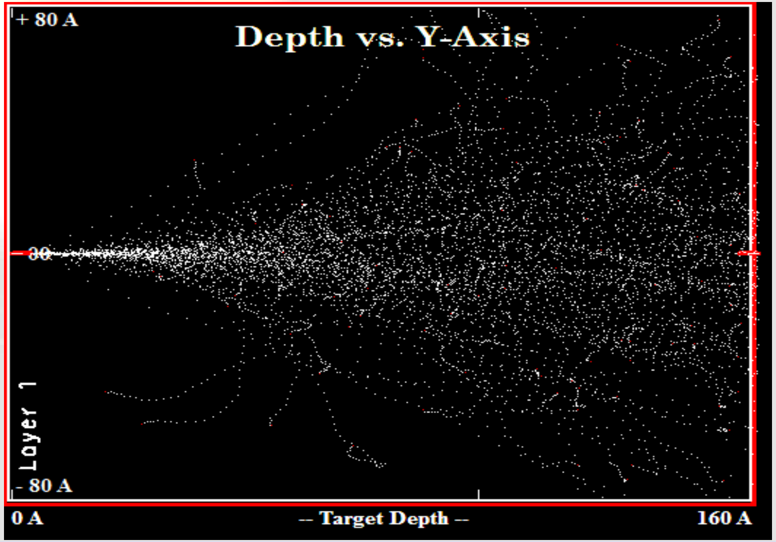
Simulated Oxygen ions transmission through the CODIF carbon foil (~3 µg cm^{-2})

Atomic Ions



- **O^+** <u>entering</u> ions: **15 keV** (including post-acceleration)
- O^+ <u>transmitted</u> ions: **~10.33 keV**

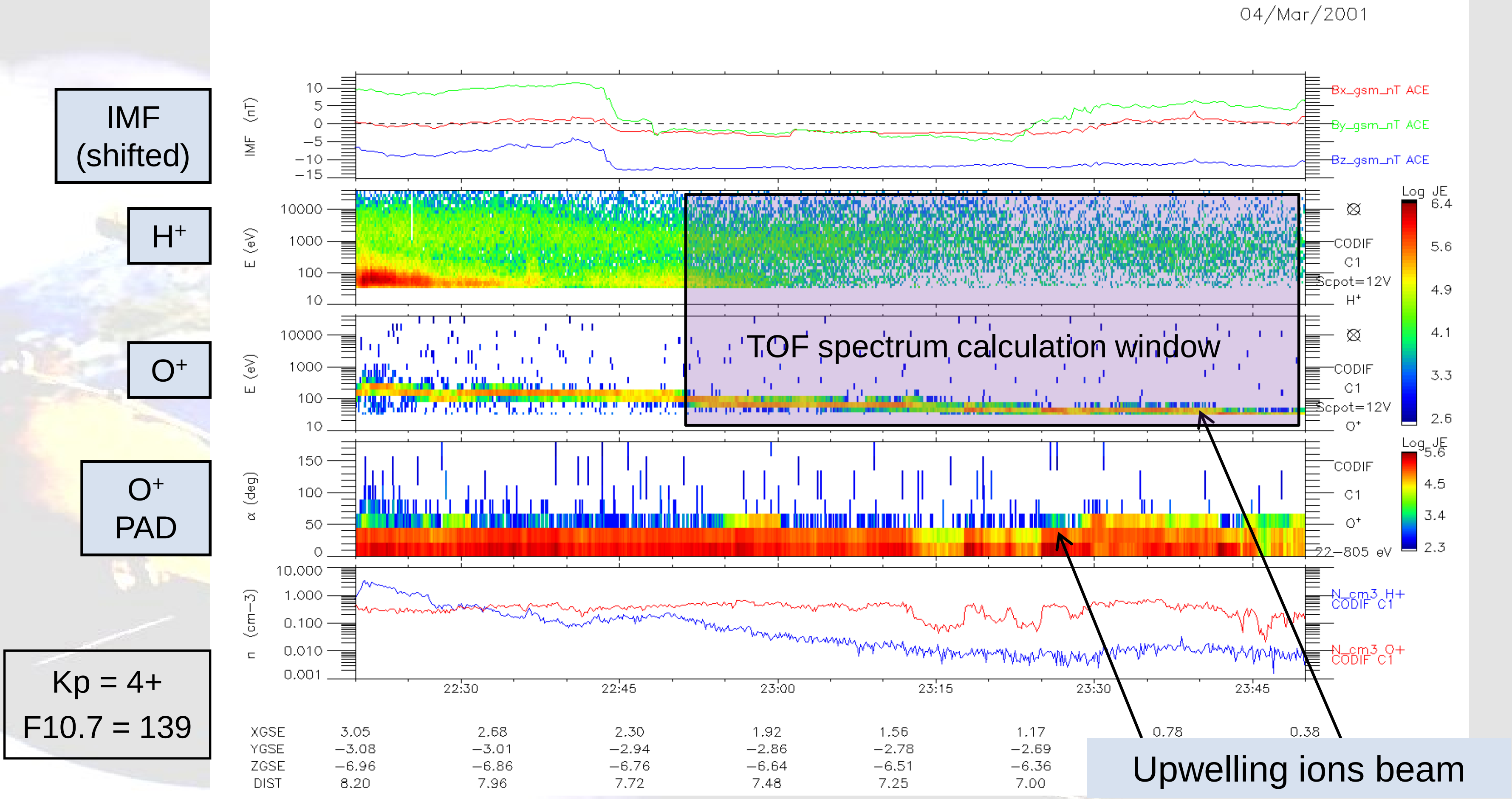
Molecular Ions



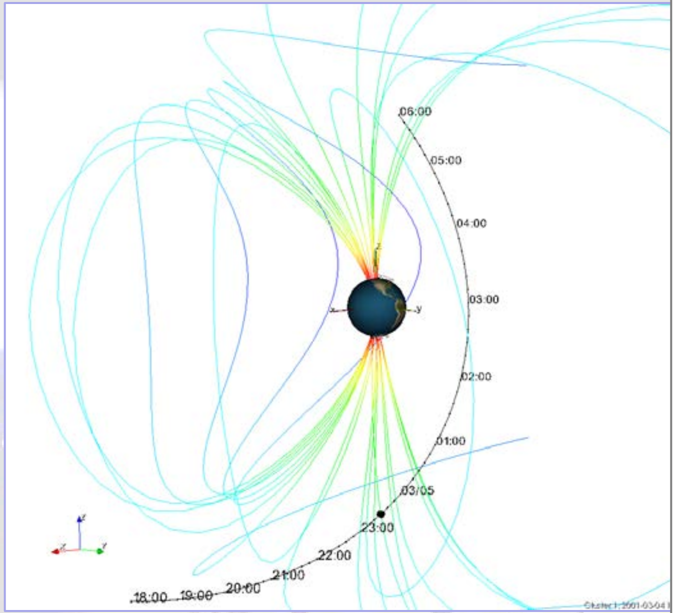
- O atoms resulting from fragmentation of **15 keV** <u>entering</u> **O_2^+ ions**
- O <u>transmitted</u> atoms/ions: **~2.66 keV** (including 20% additional energy loss due to the fragmentation process: *Tape et al., 1976*)

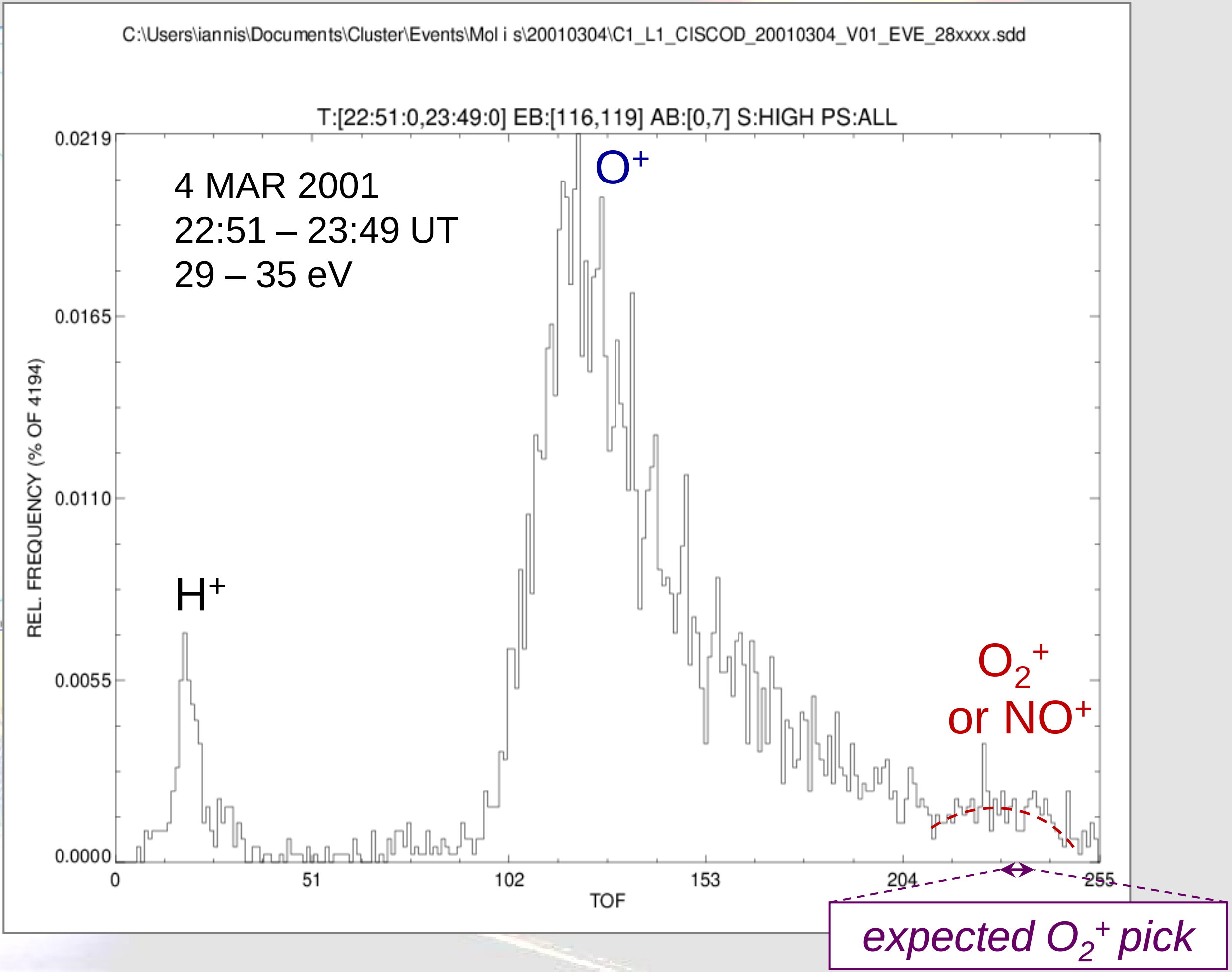
SRIM simulations

Search first, for molecular ions detection, in the early years of Cluster: higher heavy ion detection efficiency by a factor of ~20

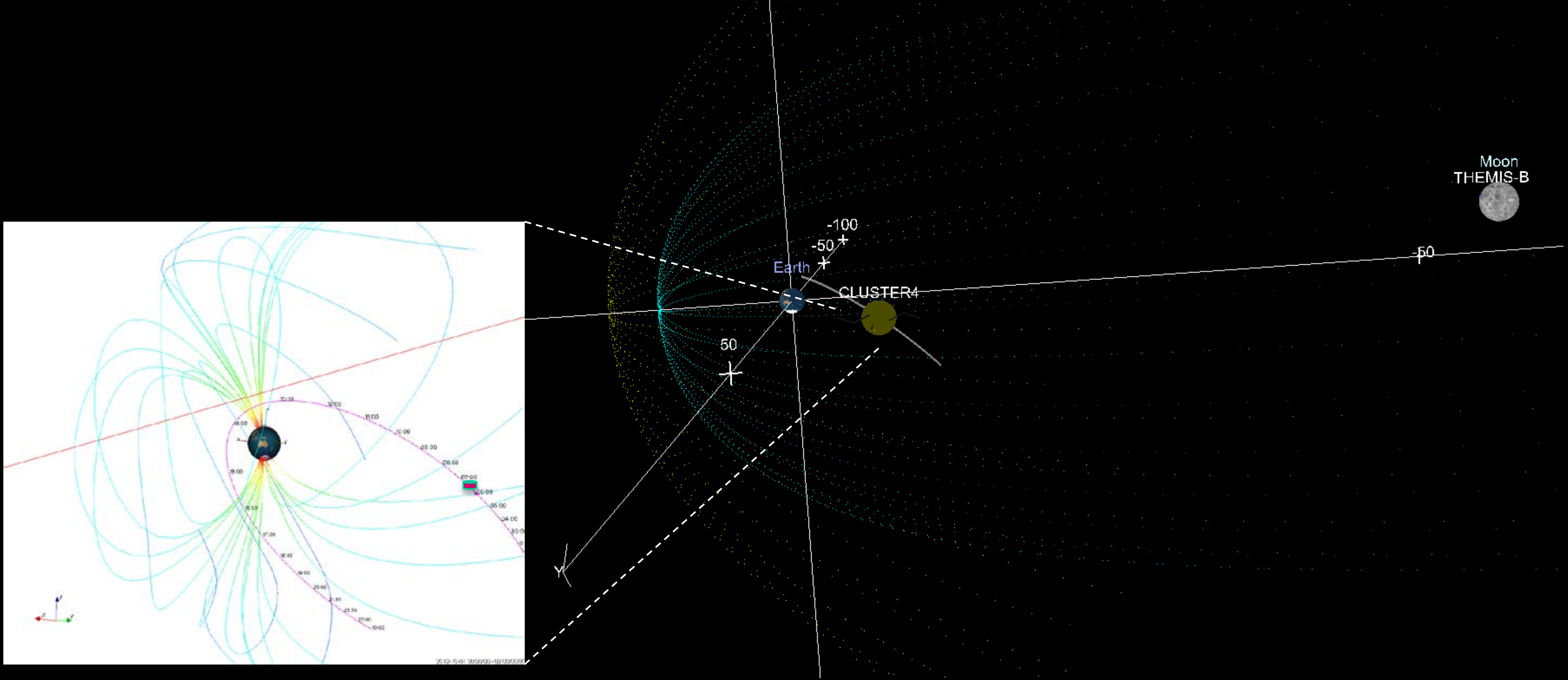


CODIF time-of-flight spectrum in the upwelling ions beam





ARTEMIS 1 OCT 2012 heavy ion observation:
Cluster location in the Southern Lobe

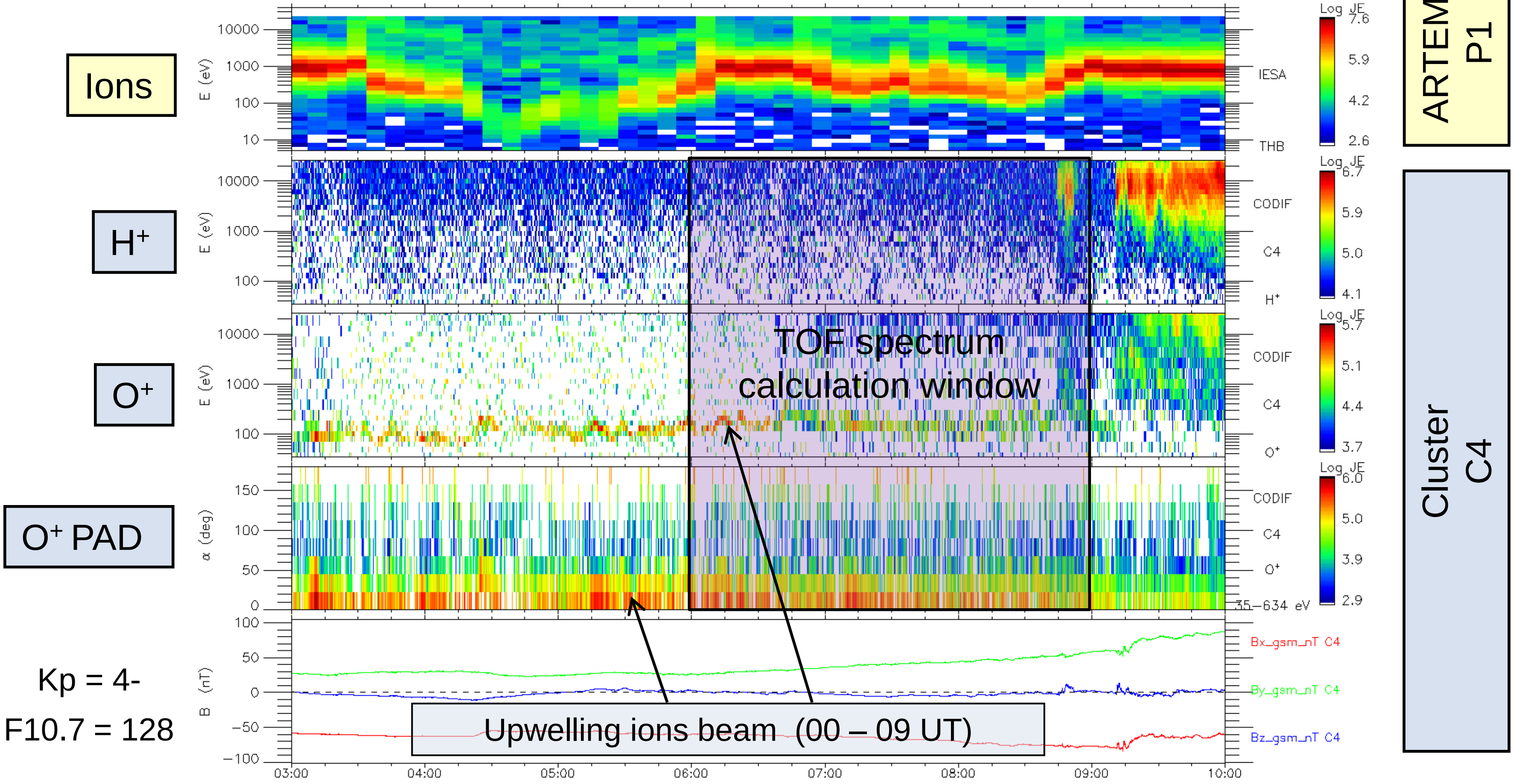


Time: 2012/10/01 07:30:00

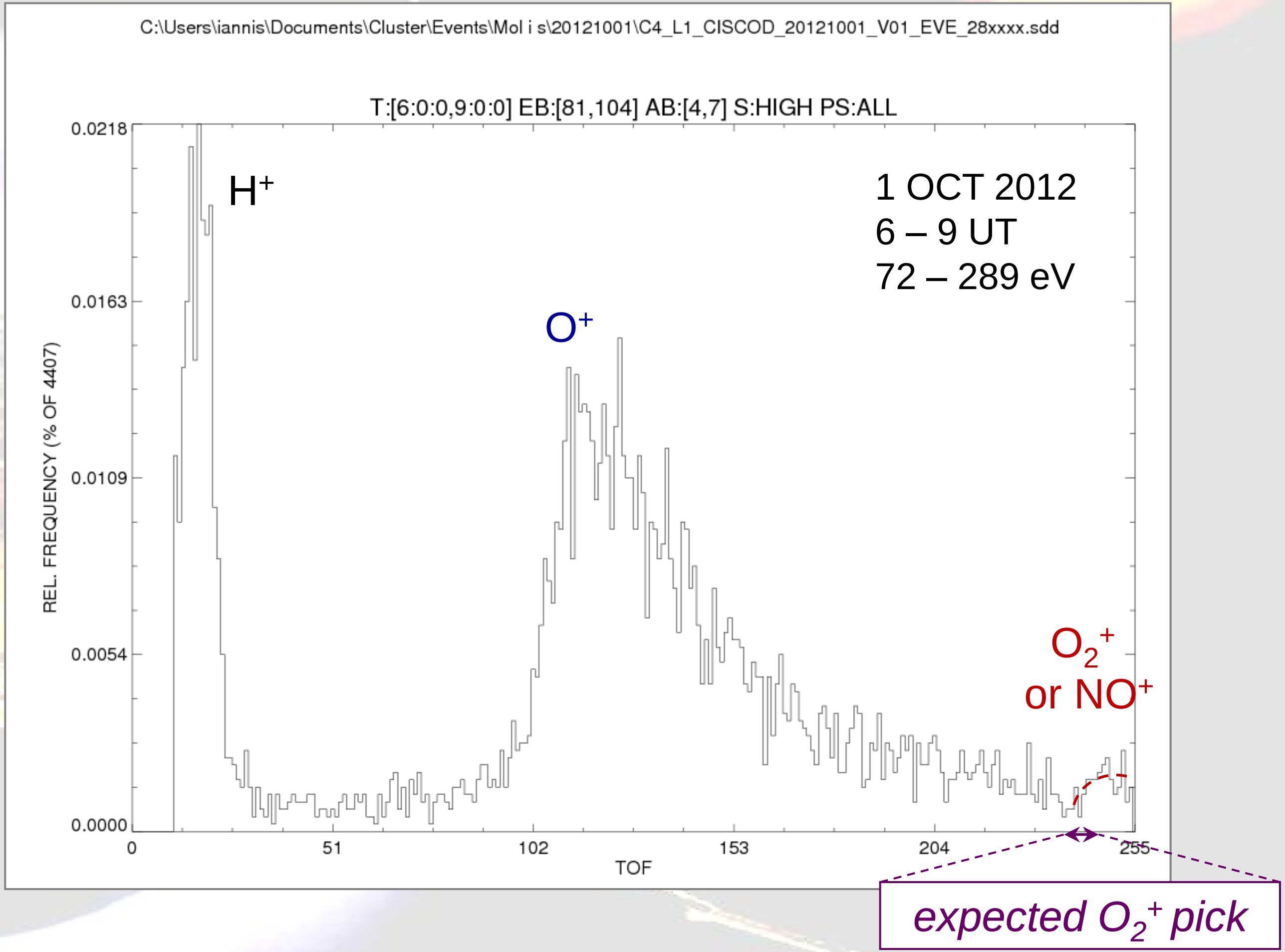
Distances (Re = Earth radius = 6371.010km)

Frame = GSE
Center = Earth
Start = 2012/10/01 02:00:00
Stop = 2012/10/01 12:00:00

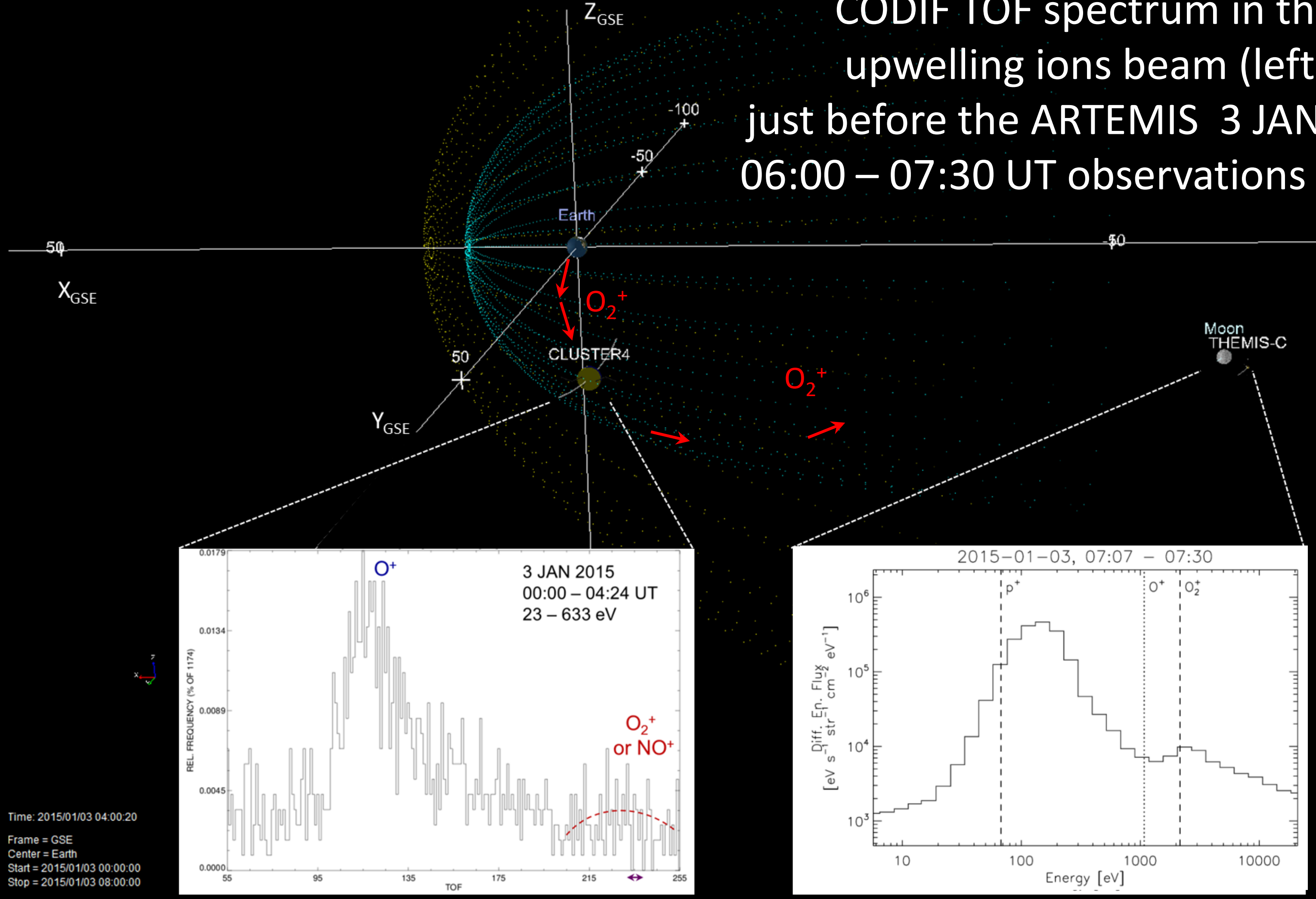
Cluster - CODIF ion spectrograms during the ARTEMIS 1 OCT 2012 heavy ion observation



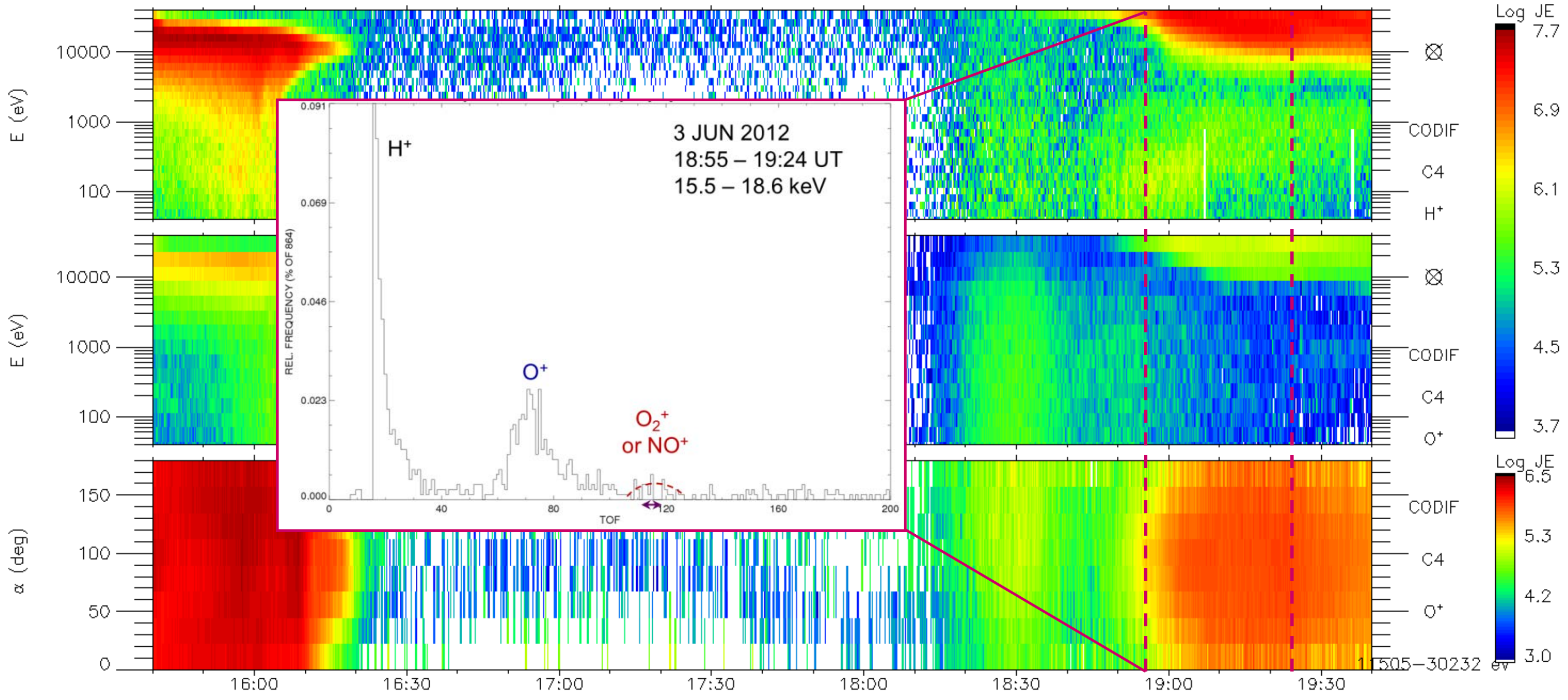
CODIF time-of-flight spectrum in the upwelling ions beam



CODIF TOF spectrum in the upwelling ions beam (left) just before the ARTEMIS 3 JAN 2015 06:00 – 07:30 UT observations (right)

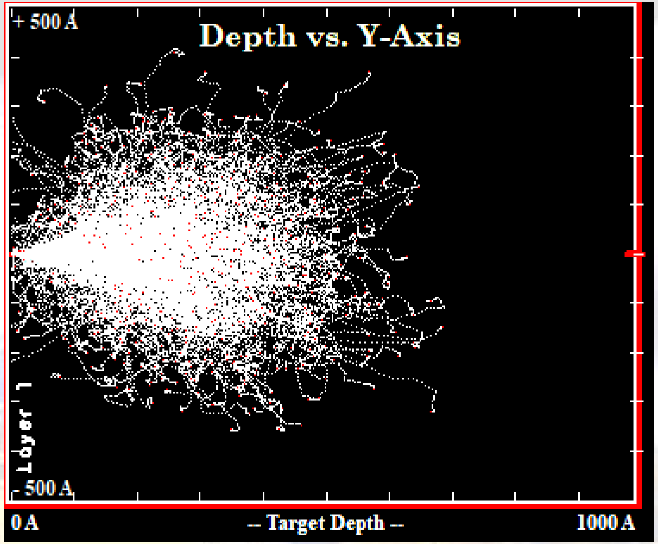


Cluster - CODIF ion spectrograms in the ring current region just before the ARTEMIS 4 JUN 2012 08:00 – 08:30 observation



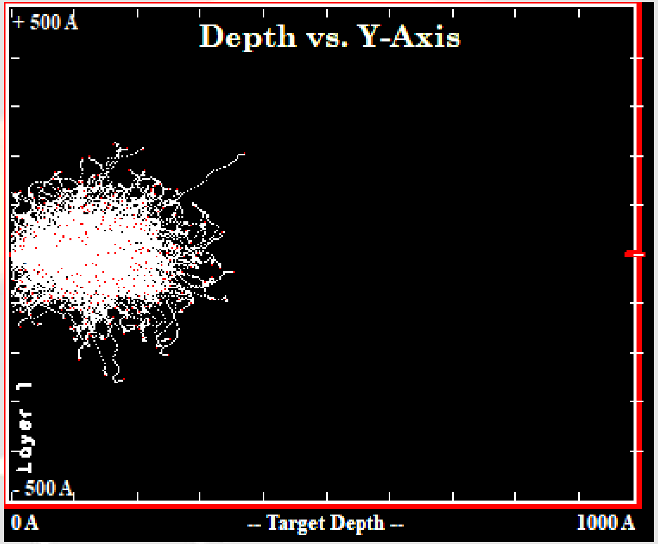
XGSE	−3.41	−2.71	−1.57	0.20	1.84	2.81	3.42	3.82
YGSE	−2.82	−1.41	0.23	1.57	1.62	0.96	0.12	−0.71
ZGSE	1.47	1.77	1.77	0.92	−0.72	−2.20	−3.43	−4.42
DIST	4.66	3.53	2.38	1.83	2.55	3.69	4.84	5.88

Terrestrial heavy ion implantation in the near-side Lunar regolith



Simulation of the trajectories of **10 keV O^+** ions impinging on the lunar regolith.

<u>Deposition depth</u>: 300 – 500 Å
i.e. within the first ~100 atomic layers



Simulation of the trajectories of O^+ ions of 4 keV each, resulting from the fragmentation of **10 keV O_2^+** molecular ions, impinging on the lunar regolith.

<u>Deposition depth</u>: 100 – 300 Å
i.e. within the first ~60 atomic layers

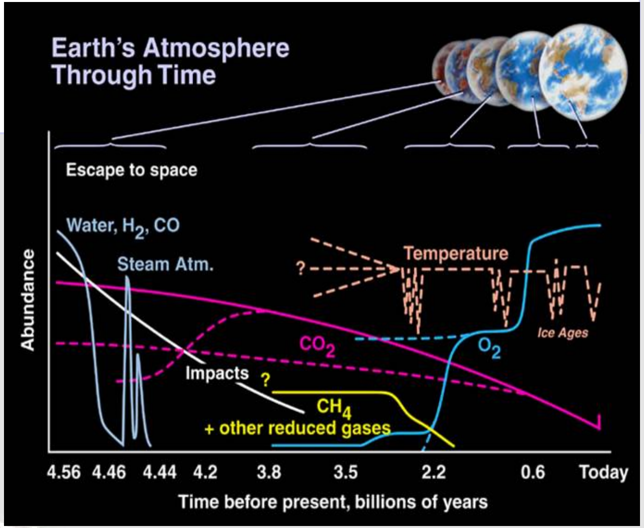
CONCLUSIONS & PERSPECTIVES (1)

- **First simultaneous detection of terrestrial heavy ions** in the **Earth's inner magnetosphere** and at the **Moon**.
- **Heavy ion fluxes, measured by ARTEMIS** at lunar distances, are **consistent with the upwelling atomic O^+ (and / or N^+) ion fluxes**, **measured by Cluster** in the inner magnetosphere.
- Observations consistent with Earth-to-Moon ion transport times and with MHD Open Global Geospace Circulation Model particle tracing simulations.
- They show the existence of a **direct pathway of plasma**, upwelling **from the ionosphere** and then transported and lost **into the deep magnetotail**.
- **~ 1 – 5 × 10^{25} s^{-1} heavy atoms** (O and / or N), i.e. ~ 0.27 – 1.3 kg s^{-1}, **escaping through the distant tail**, when activity conditions are favourable
- **Ionospheric molecular ions** observed by Cluster both **in upwelling ion beams** (escaping distribution, few 10 eV – few 100 eV) and **in the ring current region** (trapped distribution, ~10 – 20 keV).
- **Molecular ion escape**, during **active periods**, is an **additional escape mechanism.**

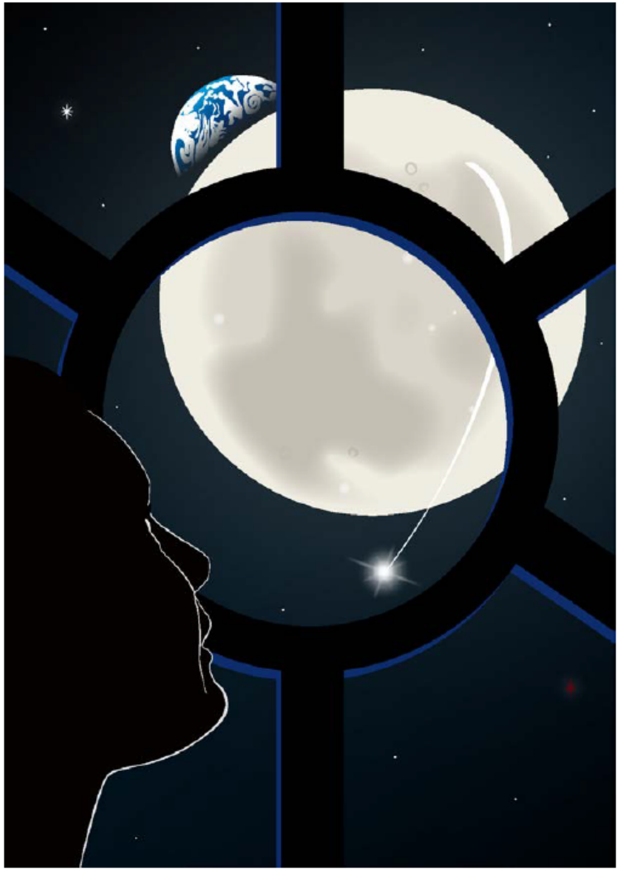
CONCLUSIONS & PERSPECTIVES (2)

- Important in order to understand the long-term (billion years scale) **evolution of the atmospheric composition**, and in particular of the **N / O ratio** (essential for habitability).
- Important to determine the **composition of the escaping atomic** (O^+ and / or N^+ ?) **and molecular ions** (N_2^+ , NO^+, and / or O_2^+ ?) in order to assess their role in the evolution of the atmospheric composition.
- Terrestrial heavy ions, transported to the Moon, suggest that **the Earth's atmosphere of billions of years ago may be preserved on the present-day near-side lunar regolith**.

➢ **Need for high-mass resolution mission to study the atmospheric particle escape.**



ESA Workshop: Research Opportunities on the Deep Space Gateway



ION AND NEUTRAL ESCAPE FROM MOON AND EARTH

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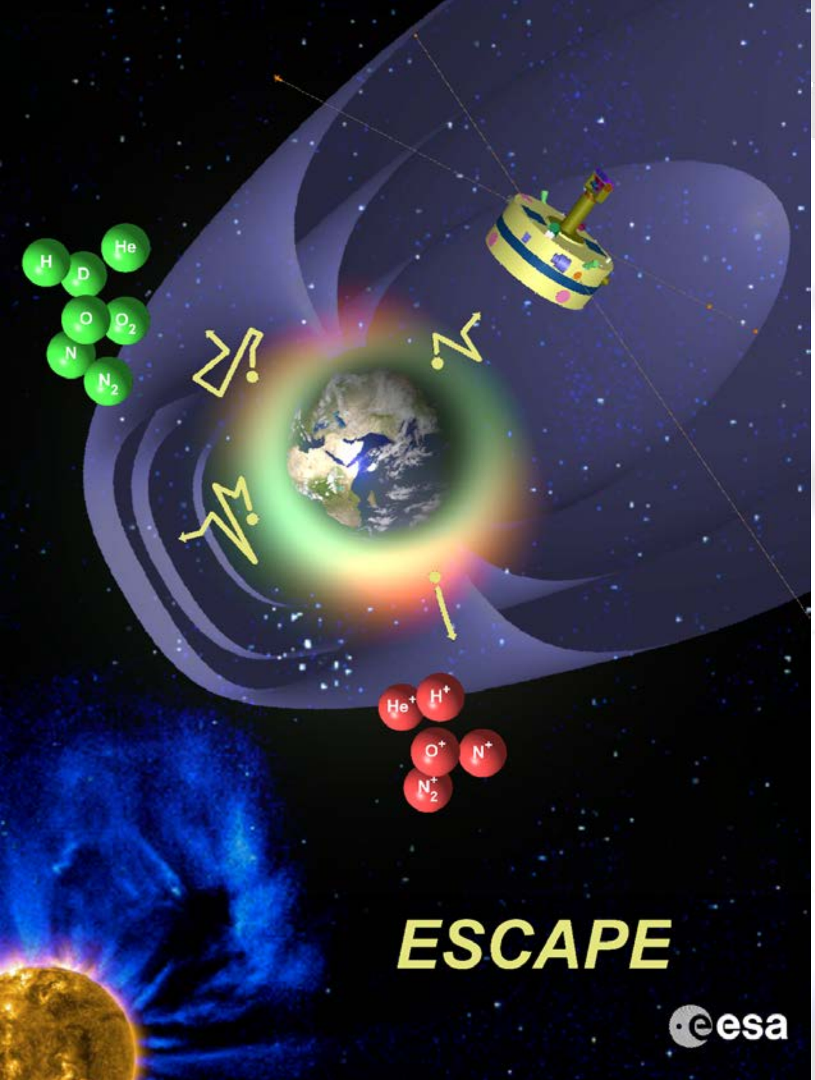
Scientific Domain:
Solar System Sciences

Idea Description:
Moon orbit is a good platform to study the atmospheric escape, both from the Moon surface-bounded exosphere and from the Earth, when the Moon gets into the Earth's magnetotail. We propose to measure the different ions/neutrals with dedicated measurements in order to quantify the ion escape rate and to identify the different escape mechanisms from Earth and moon and their variability due to different solar activity. Such knowledge is important to understand the long-term (billion years scale) evolution of the atmosphere and essential to the history of the moon and Earth as well as their interaction processes with the early Sun. We propose to install dedicated instruments: plasma, magnetic field measurements, energetic neutral imager, and neutral particle detectors outside the spaceship to continuously monitor the environment plasma/particles. These are all passive measurements and do not require any extra operation except for health check of the instruments.



ESCAPE

European SpaceCraft for the study of Atmospheric Particle Escape

A mission proposed in response
to the ESA-M5 call

Iannis Dandouras, Masatoshi Yamauchi,
and the ESCAPE proposal team

How and at what rate is Earth
slowly losing its atmosphere to space?

What are the dominant escape mechanisms?

What is their dependence on the solar and
geomagnetic activity conditions?

See presentation tomorrow

Thank you !