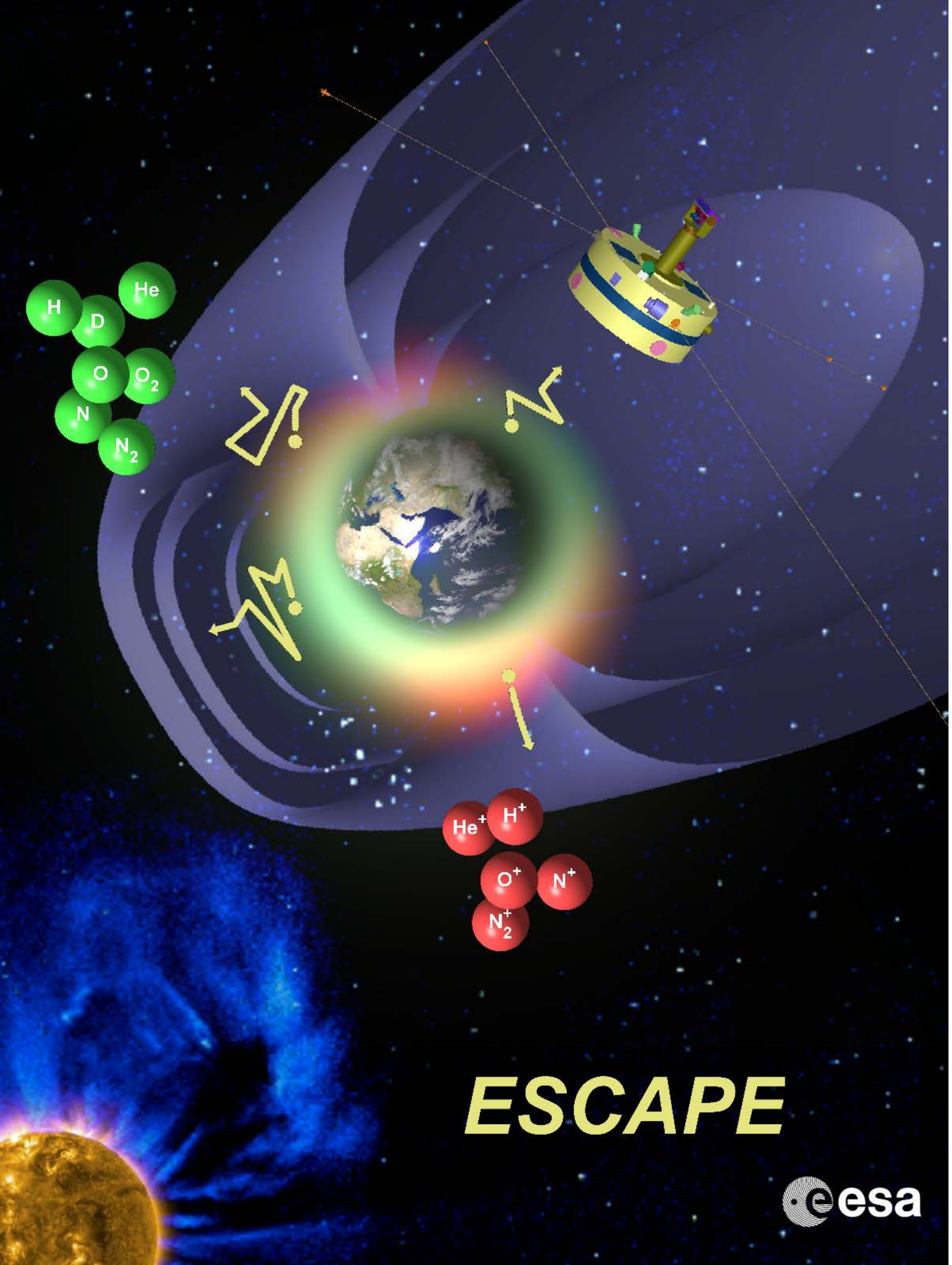


European SpaceCraft for the study of Atmospheric Particle Escape (ESCAPE): a planetary mission to Earth, proposed to ESA in response to the M5-call

Iannis Dandouras,
Masatoshi Yamauchi,
Johan De Keyser,
Henri Rème, Octav Marghitu,
and the ESCAPE Proposal Team

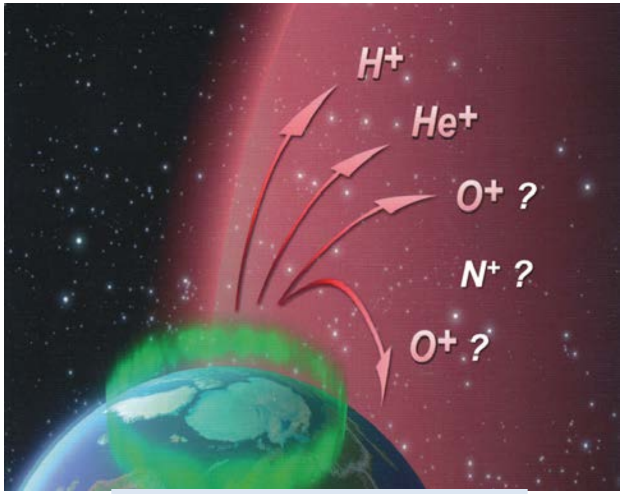
Europlanet Workshop
on Planetary Atmospheric Erosion
Romania, June 2018

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

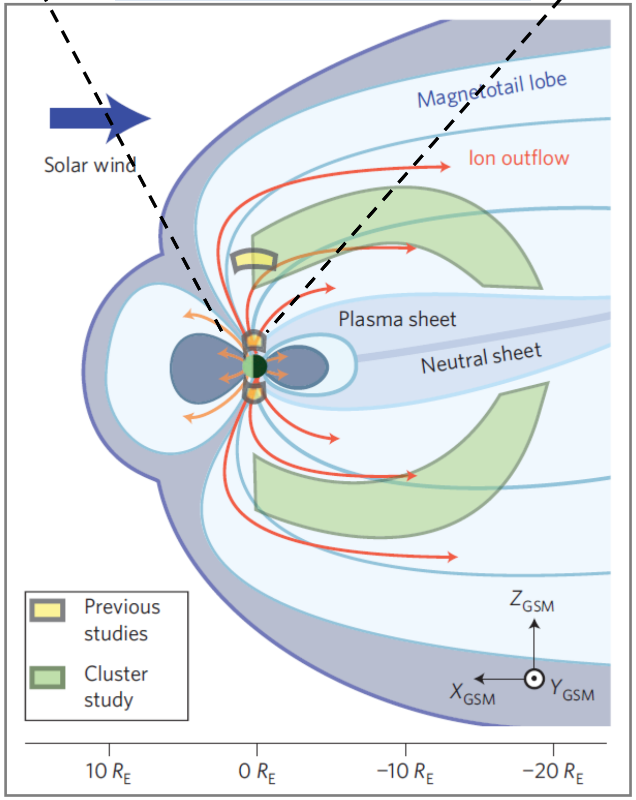
What are the dominant escape mechanisms?

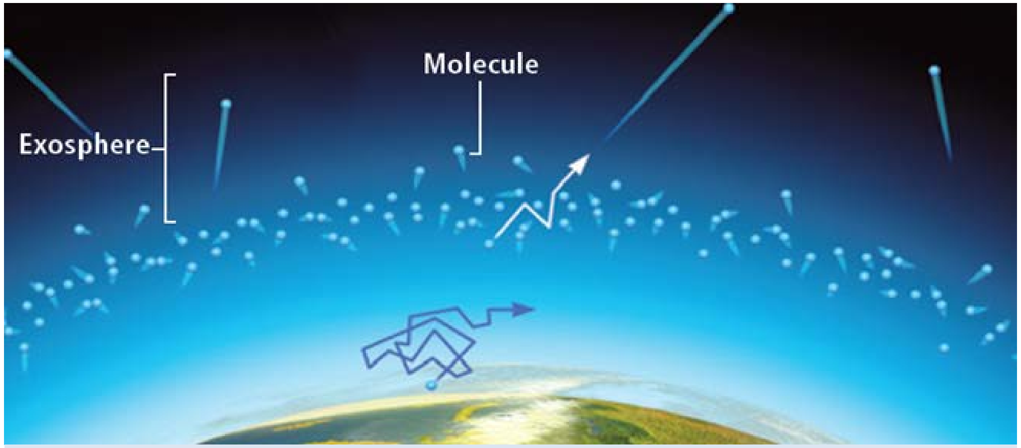
What is their dependence on the solar and geomagnetic activity conditions?

How the atmosphere expands during space weather events?



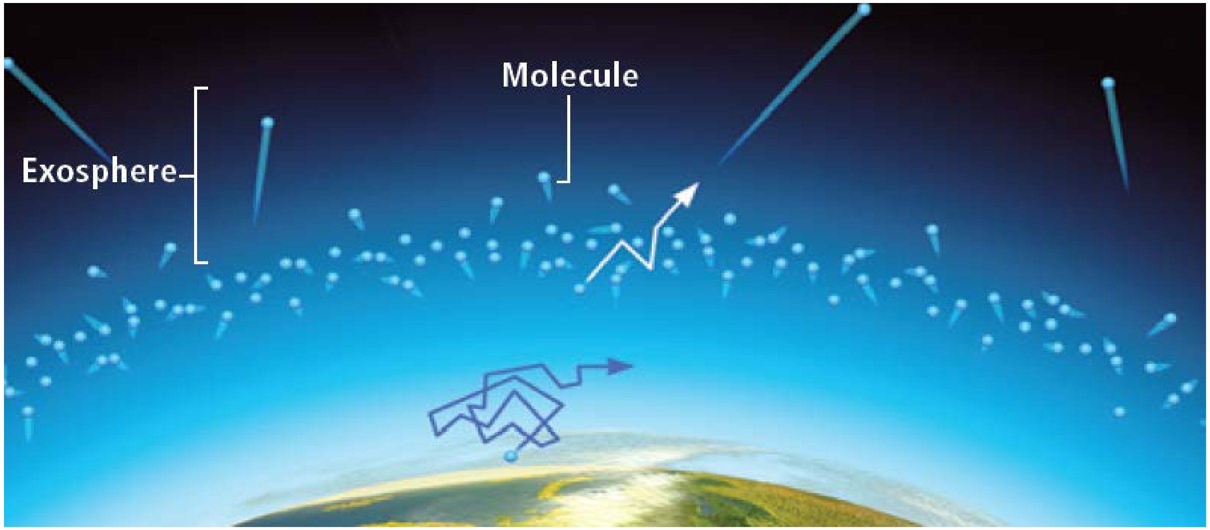
Ion escape



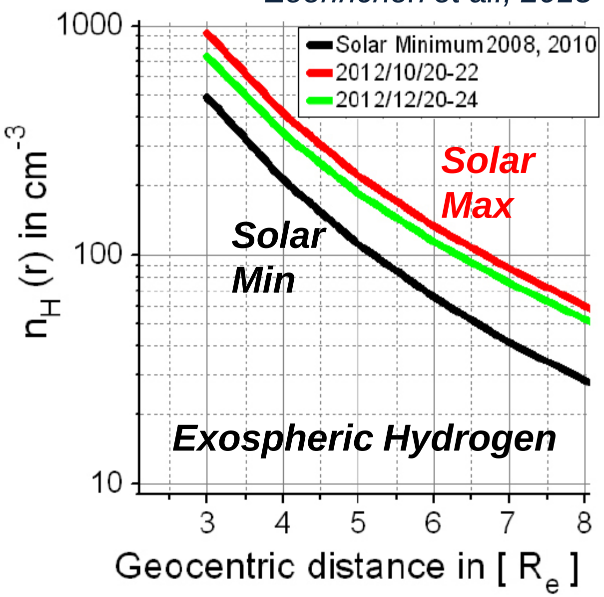


Neutral escape

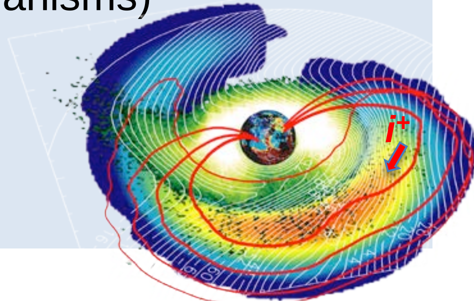
Exosphere:
the « source » of atmospheric escape



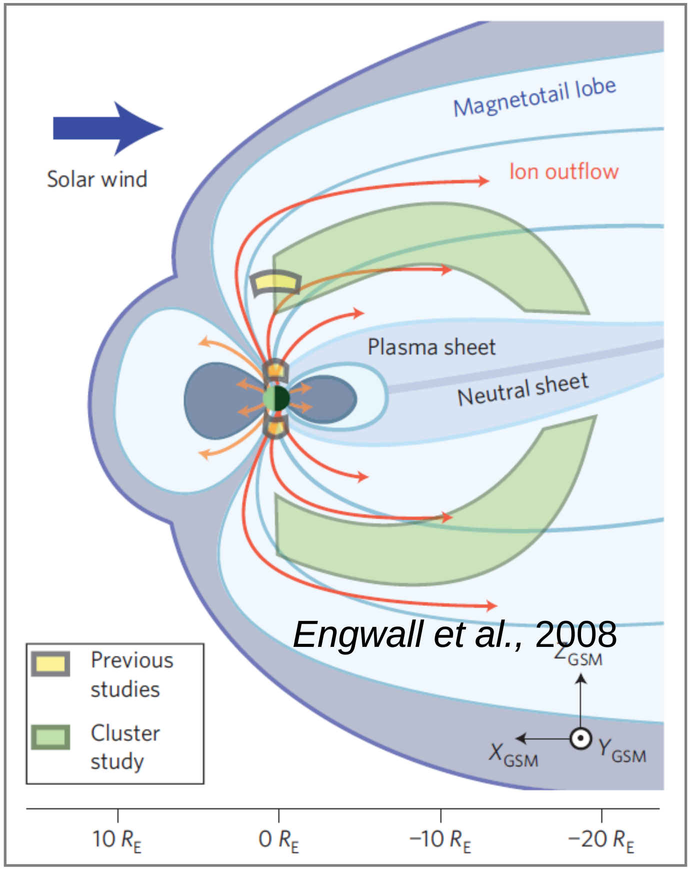
Zoennchen et al., 2015

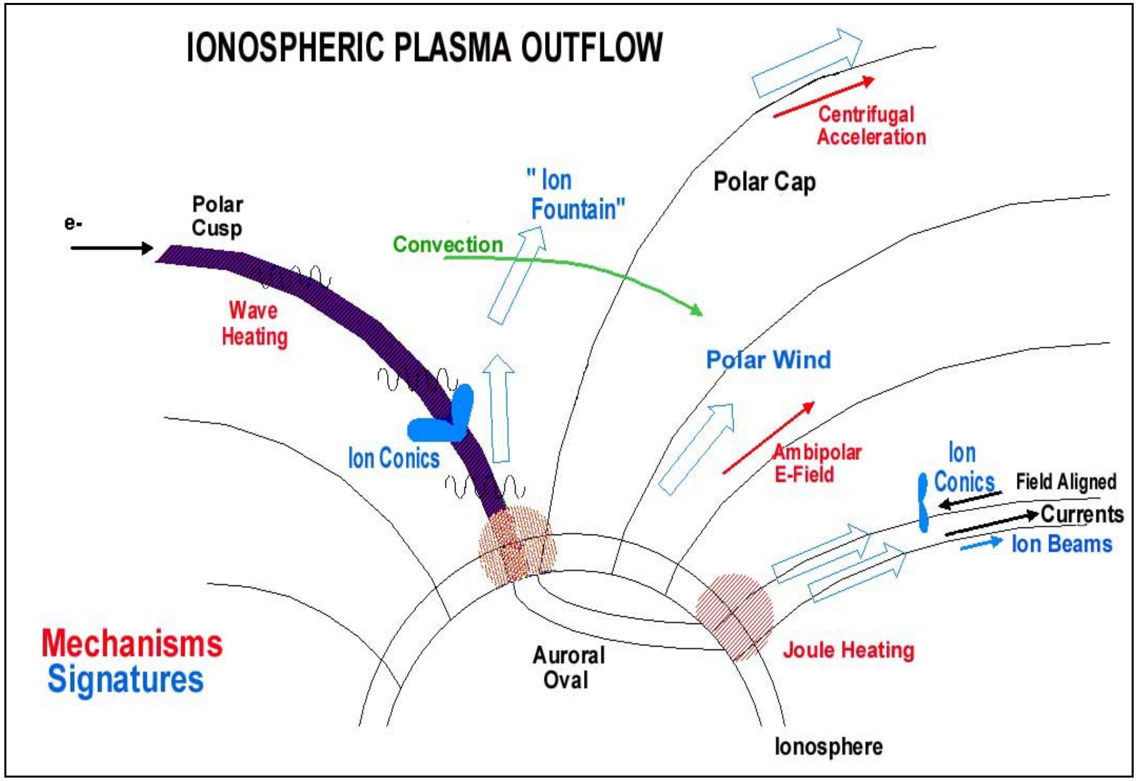


- **Mandatory for escape modelling**
  (thermal and some non-thermal escape mechanisms)
- **Dynamic and structured**: altitude density profile, composition, ionisation
- **Poor observational knowledge for the Earth**:
  no measurements > 600 km for nitrogen, no measurements > 700 km for oxygen;
  quasi-absence of measurements for isotope ratios (indic. escape mechanisms)
- **Ion source** above the ionosphere
- **Magnetospheric storm dynamics**:
  Ring current control and decay through charge exchange interactions



Ion energisation by EM waves and E//





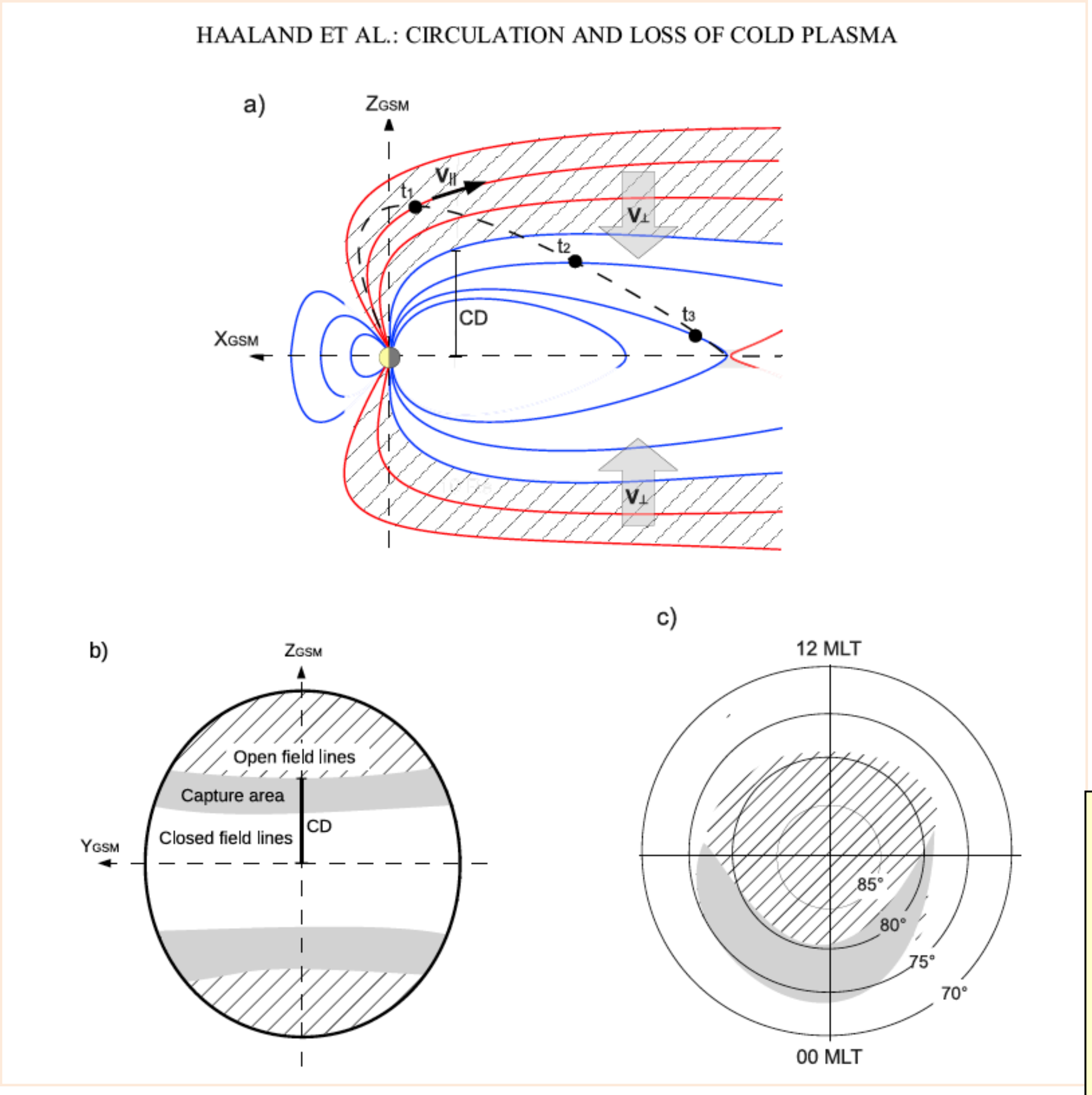
Earth : ~10^{26} ions s^{-1}

varying by a factor of > 10 as a function of **activity level**

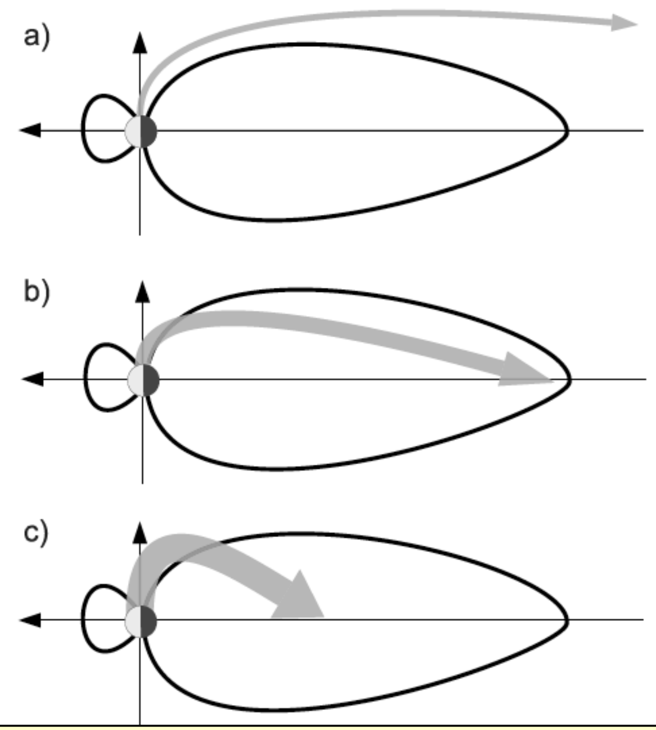
cf. presentations during this workshop

- Dominant heavy ion escape mechanism for Earth
- O^+ escape energy: 10 eV
- Mass-independent (almost)

Fate of escaping ions
as a function of magnetospheric activity level



a: Quiet conditions :
direct loss down tail



c: Disturbed conditions :
ion trajectories towards
the inner magnetosphere
(partially re-injected)
& source of ring current

Nitrogen Escape

Molecular dissociation energy:

N_2: 945 kJ/mole (9.79 eV)

O_2: 497 kJ/mole (5.15 eV)

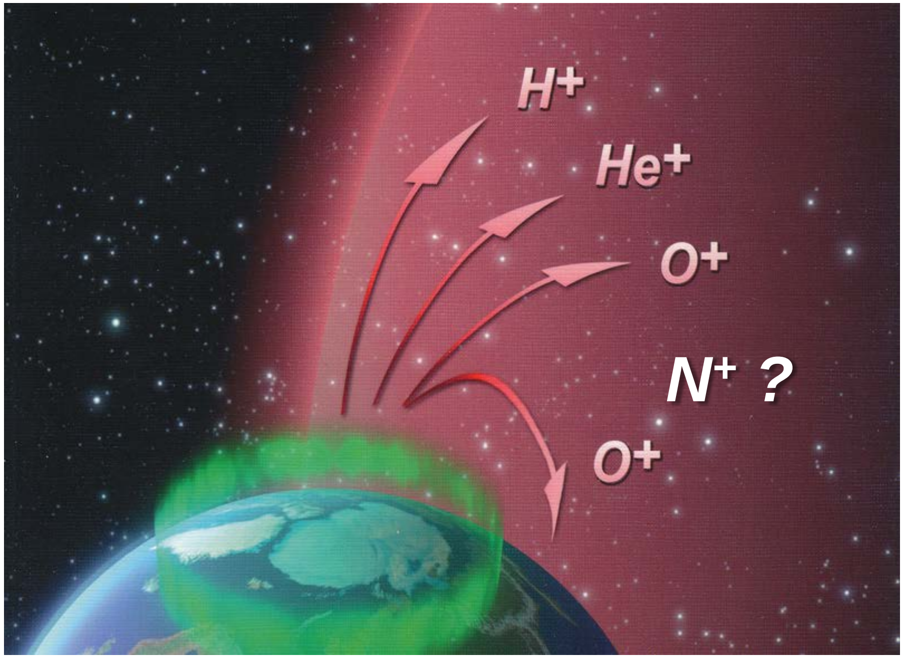
H_2: 436 kJ/mole (4.52 eV)

Ionisation energy:

N: 1402 kJ/mole (14.53 eV)

O: 1314 kJ/mole (13.62 eV)

H: 1312 kJ/mole (13.60 eV)



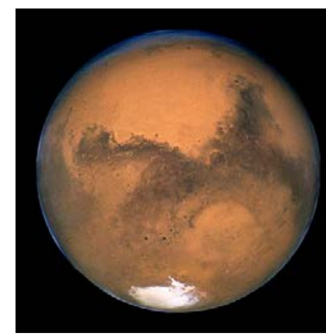
- ❑ **Nitrogen** is **more difficult to dissociate** (triple bond) **and to ionise**
  - ➢ ***Escape is more difficult***
- ❑ **The key:** Study the **N^+ / O^+ escape rate as a function of solar forcing**

For ***E*** **< 50 eV**:

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

At **higher energies** (50 eV - 30 keV) : **absence of measurements**

Atmospheres of the Telluric Planets

Venus	Earth	Mars
96.5 % **CO_2** 3.5 % **N_2** 0.015 % **S_2** 0.007 % **Ar**	78 % **N_2** 21 % **O_2** 0.93 % **Ar** 0.039 **%** **CO_2**	96 % **CO_2** 1.93 % **Ar** 1.89 % **N_2** 0.15 % **O_2**
$P_{atmo.Venus}$ ~ **92 bar**	$P_{atmo.Earth}$ ~ **1 bar**	$P_{atmo.Mars}$ ~ **0.007 bar**
N_2: ~ 4 times as much as on Earth		**N_2: ~ 10^{-4} times** as much as on Earth (M_{Mars} ~10 % of M_{Earth})
		

- The three « sister planets » formed **out of the same protoplanetary nebula**
- It is important to know how the different escape mechanisms made these planets so different. Comparison with these non-magnetised planets will also help to understand how much the magnetosphere “protects”, or not, the terrestrial upper atmosphere.

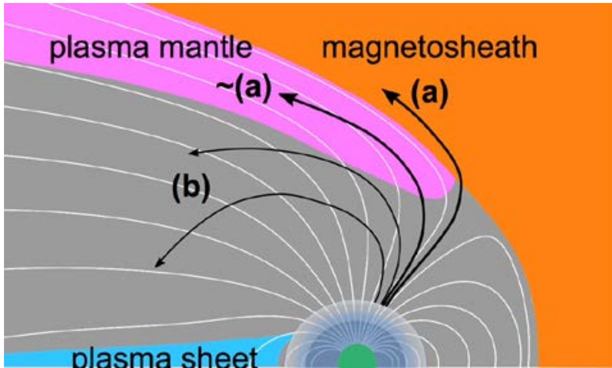
What needs to be measured?

Basic altitude profiles in the exosphere & upper ionosphere (500–2000 km).

- **Temperature** and **densities** of major **neutrals and ions** (H, He, O, N, O_2, N_2, NO, and CO_2).
- **Isotope ratios** ($^{17}O/^{16}O$, $^{18}O/^{16}O$, $^{15}N/^{14}N$, D/H).
- Their **variability** in space and time (+ correlation with drivers)

Differential fluxes (energy-angle distributions) of the hot ions (N^+, N_2^+, O^+, H^+, and He^+) in the lower magnetosphere and upper ionosphere > 800 km.

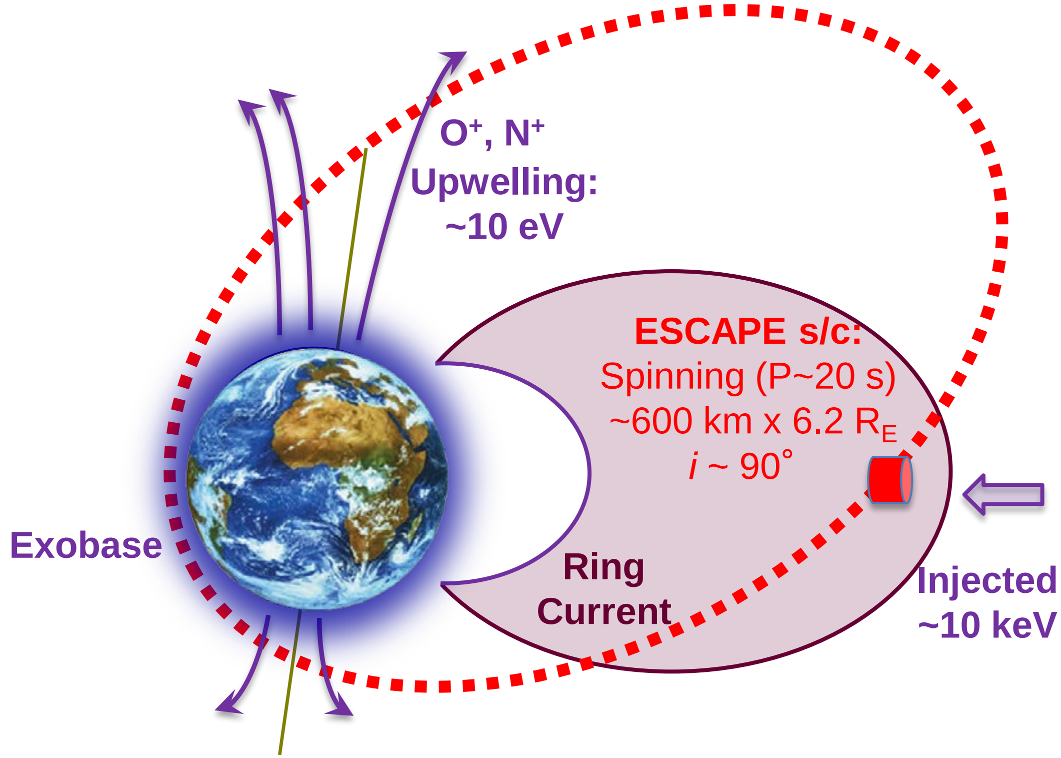
⇒ Correlation with **external drivers**:
solar EUV flux, solar wind,
ionospheric / geomagnetic conditions,
non-linear response during extreme events.



ESCAPE M5 Mission Proposal

ESCAPE Orbit

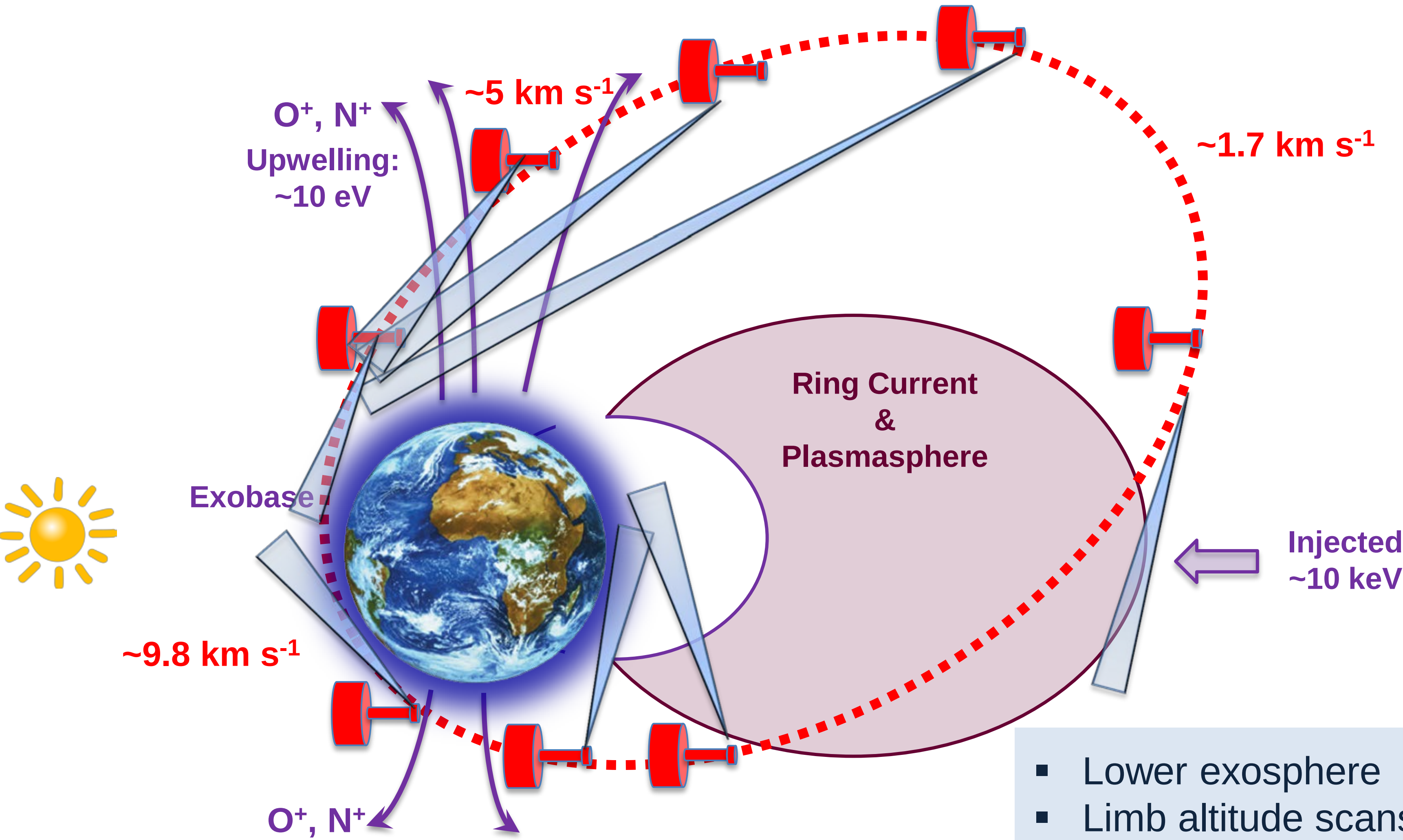
- **Perigee**: ~500 to 700 km altitude
  ***exobase**:*
  source of escaping populations
- **Apogee**: ~33 000 km altitude
  ***inner magnetosphere**:*
  transport and injected ions
- **Inclination**: ~90˚
  polar cap:
  upwelling ions;
  EISCAT-3D conjunctions



ESCAPE Spacecraft

- **Instrumentation**: **in-situ** & **remote sensing** measurements
- **Stabilisation**: **spinning**, P ~20 sec: *in-situ measurements 3D distributions*
- **Equipment**: **despun platform**; *remote sensing instruments*
- **Launch:** *Ariane 6.2*

Remote sensing of a selected exosphere region, while acquiring in-situ measurements in the upwelling region



Imagers provide both: **remote sensing observations** of escaping populations and **visual support for outreach to the public**

- Lower exosphere
- Limb altitude scans
- Ion upwelling regions
- Middle exosphere
- Plasmasphere

Altitude resolution~100km

ESCAPE: Instrumentation

	In-situ measurements	TRL
Particles	**INMS: Cold ion and neutral mass spectrometer** (*M/ΔM* > 1000): Univ. Bern	7 - 8
	WCIMS: Cold ions f_{dist}, neutrals *(dens. & T)*: NASA-GSFC	7
	MIMS: Light hot ions (*M* < 20, ~5 eV/q – 40 keV/q): IRAP	5
	NOIA: Heavy hot ions (*M* > 10, 10 eV/q – 30 keV/q): IRF, Kiruna	$\geq$ 6
	EMS: Energetic ions (20 – 200 keV): Univ. New Hampshire, USA	$\geq$ 6
	ESMIE: Electrons (~5 eV – 20 keV): UCL/MSSL, London, UK	$\geq$ 6
Fields & Waves	**Waves** (5 Hz – 20 kHz): ASCR, Prague **Search Coil**: LPC2E, Orléans	$\geq$ 5
	SLP: Sweeping Langmuir probe: e-density, E-field, spacecraft potential BIRA-IASB, Brussels	4 - 5
	MAG: Magnetic field: IWF, Graz, Austria	8

Remote sensing measur.	TRL
UVIS: UV imaging spectrometer (85 – 140 nm; 391 nm and 428 nm): Tokyo University, Japan	6 - 7
AMC: Aurora and airglow camera (670 nm and 762 nm): Tohoku Univ.	7 - 8
ENAI: ENA imager (2 – 200 keV): INAF/IAPS, Rome	> 5

Ground conjugate measurements

EISCAT-3D:

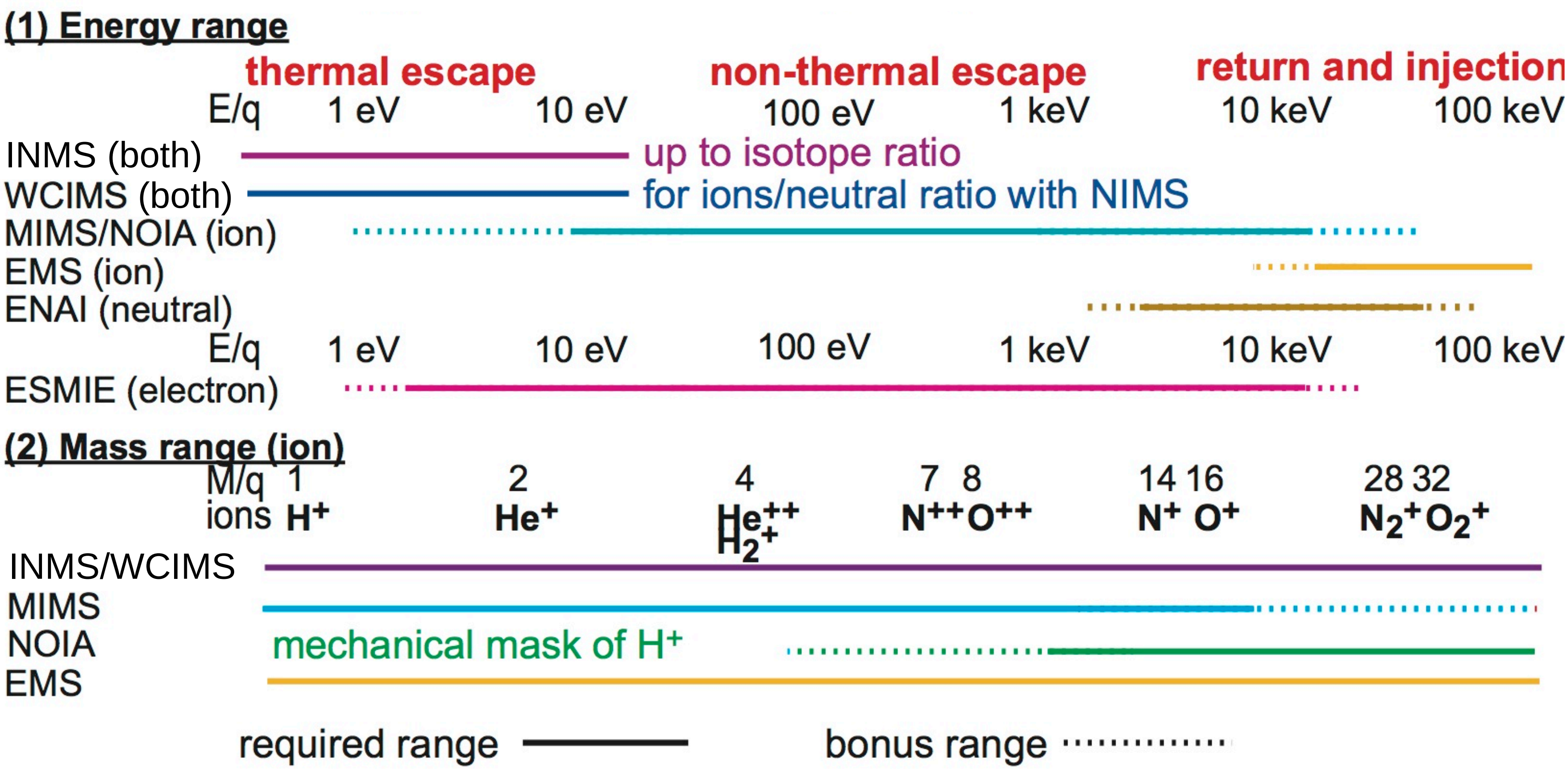
Conjugate ground-based 3-D radar ionospheric observations (ions and electrons at *H* > 500 km)

Optical Observations:

IMAGE Network

+ International Modelling Team

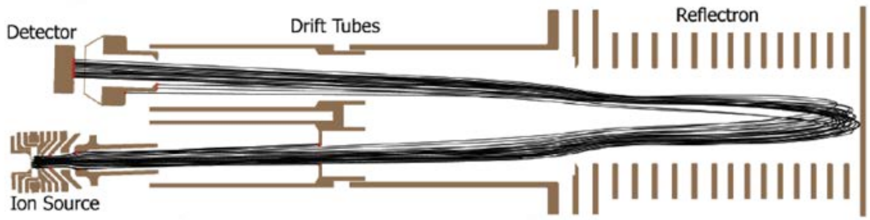
Energy and mass coverage of the particle instruments



Unlike past missions, the instrument sensitivity range of **ESCAPE** is tuned for the exobase and lower exosphere, while the in-situ measurement instruments will be capable of performing measurements even in the magnetosphere.

ESCAPE will measure **isotope fractionation**, not studied by prior missions.

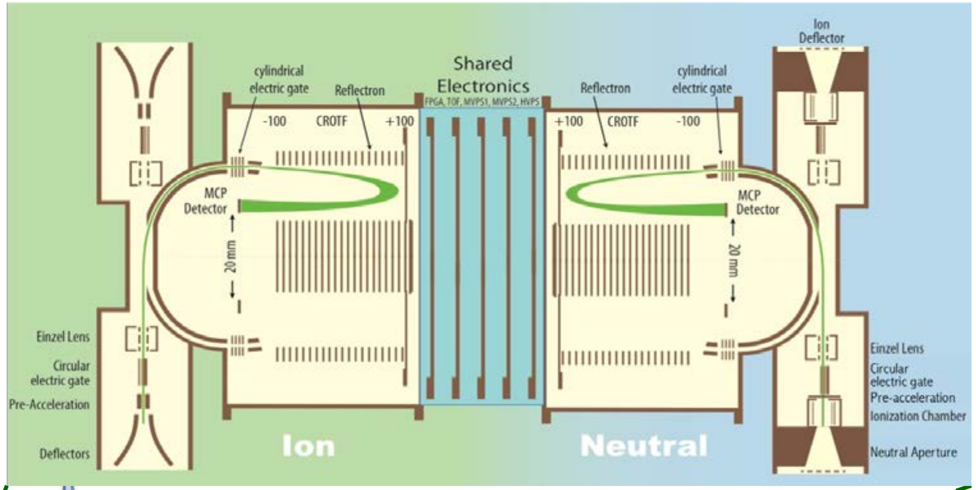
Cold Ions & Neutrals:
INMS & WCIMS
are complementary



INMS

Ion Head FOV
180° x 1° aperture
looking outward radially

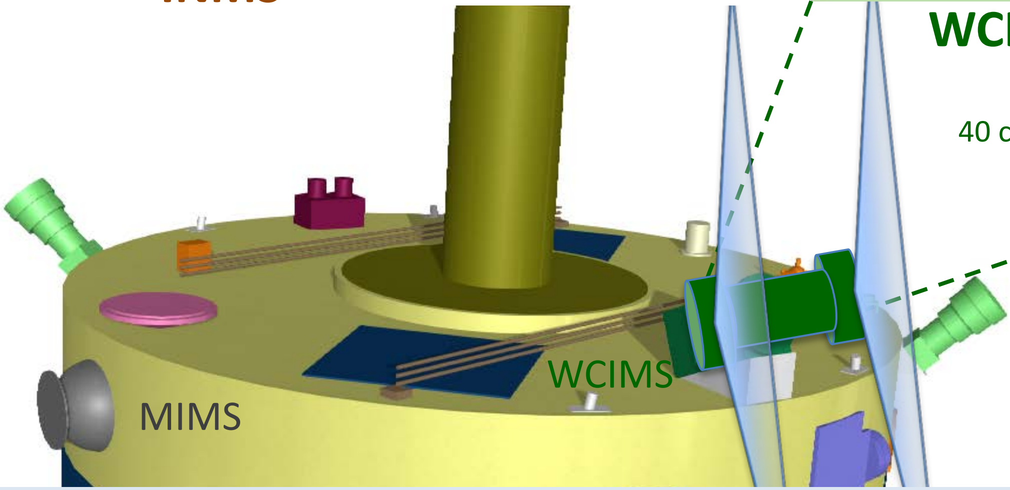
Neutral Head FOV
180° x 1° aperture
looking outward radially



WCIMS detectors head

(new design)

40 cm x 20 cm approximate cylinder



INMS (University of Bern):
Provides a higher mass resolution (***M/ΔM* >1000**), <u>isotope analysis</u>, but does not provide distribution functions (ions) and temperatures (neutrals), which are essential for escape modelling.

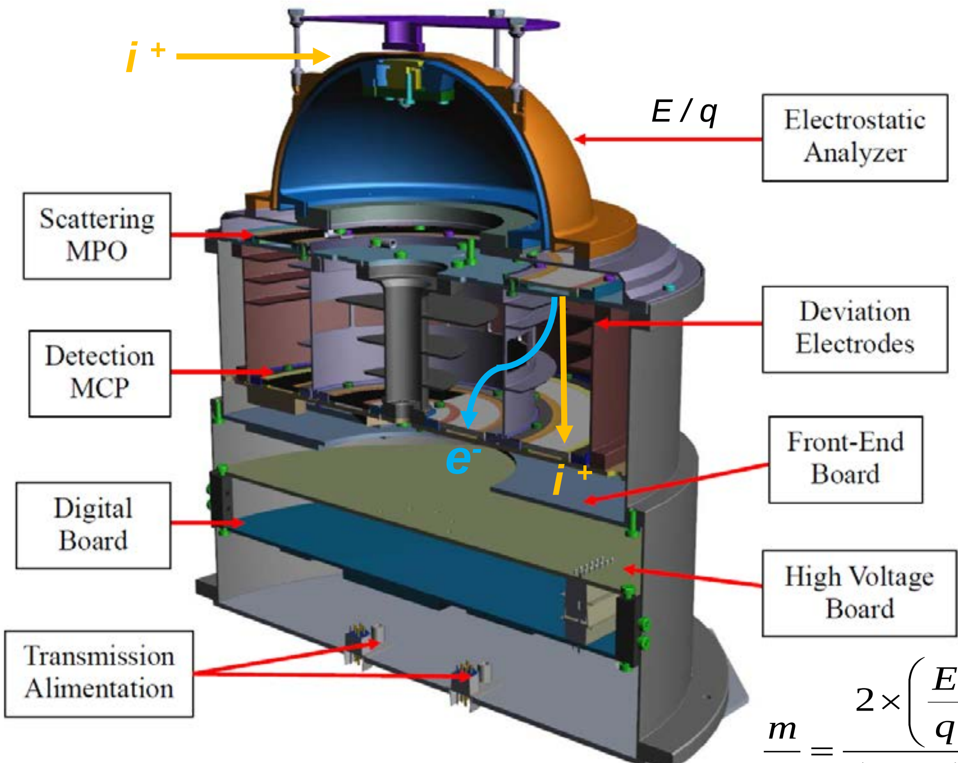
WCIMS (NASA / GSFC):

Ions: E ~0-40 eV, <u>distri. functions</u>, mass range up to 40 amu, mass resolution ***M/ΔM* ~60**.

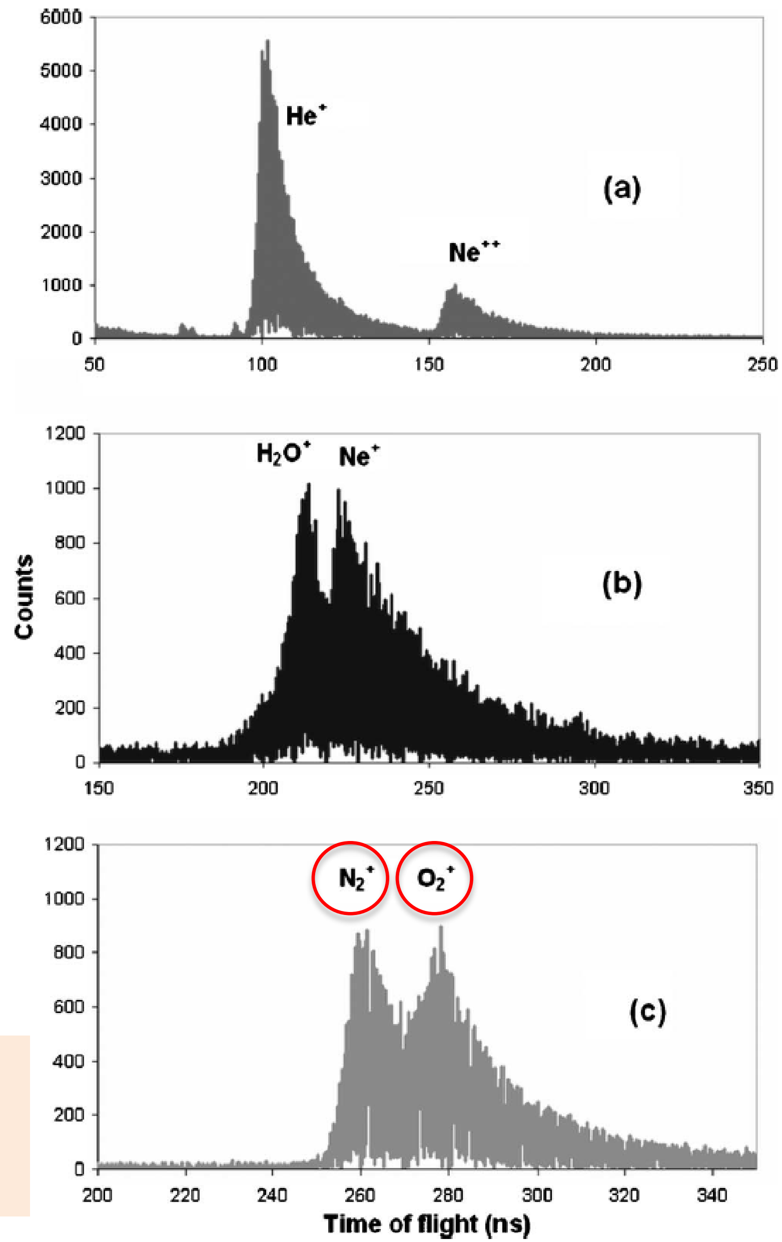
Neutrals: No energy distribution but <u>densities, temperatures & bulk velocities</u> with spin resolution, up to 40 amu, ***M/ΔM* ~60**.

MIMS Hot Ions Mass Spectrometer

Grazing incidence MCP as "start foil" for the time-of-flight



$$\frac{m}{q} = \frac{2 \times \left(\frac{E}{q}\right)}{\left(\frac{L}{TOF}\right)^2}$$



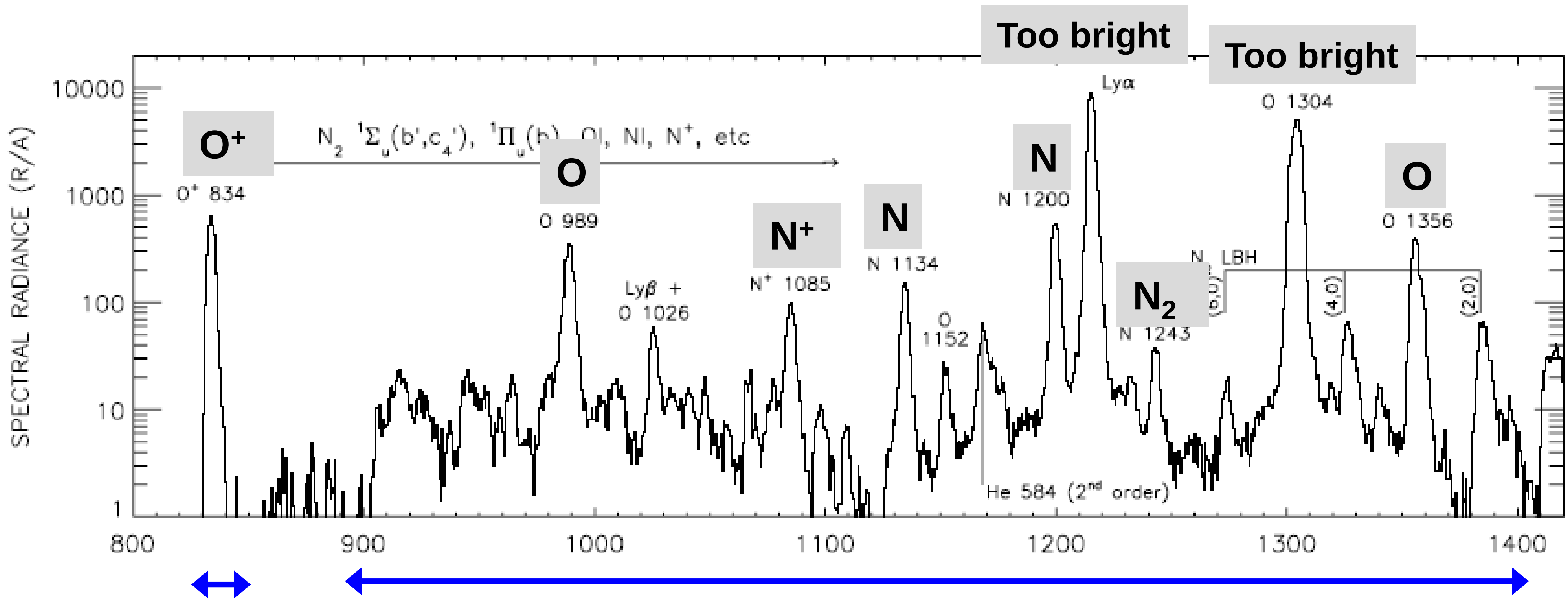
E: ~5 eV/q – 40 keV/q

m / Δm : 15 - 18

Devoto, Médale and Sauvaud, Rev. Sci. Instr., 2008;

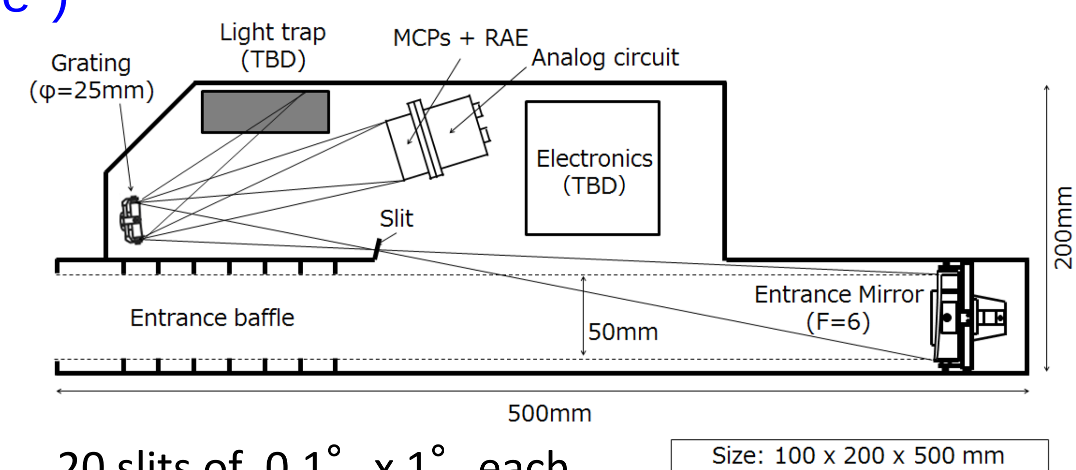
Cadu et al., IWIPM, 2012;

UVIS (UV Imaging Spectrometer): coverage



and : 58 nm (He), 30 nm (He+)

University of Tokyo



20 slits of 0.1° x 1° each

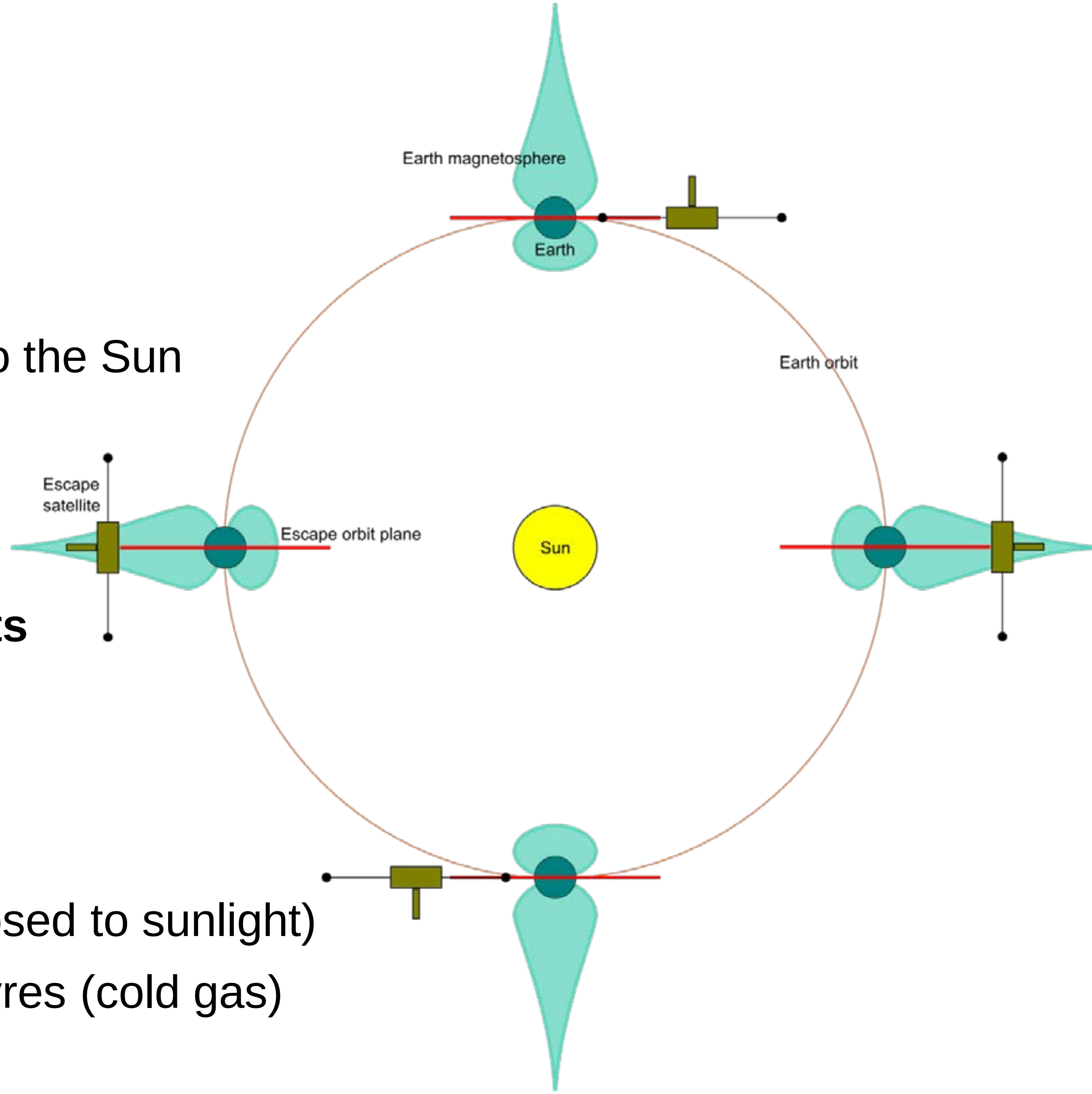
ESCAPE attitude

Requirements:

- 3 rotations / minute
- Constant attitude with respect to the Sun
- No shadows on the SLP probes
- Allow auroral zone view for the inbound/outbound orbit legs
- **No nitrogen or CH_4 propellants**

Resulting Design:

- Sun-pointing spin axis
- Despun platform in the shadow (UVIS & AMC FOVs never exposed to sunlight)
- 10° / 10 days attitude manoeuvres (cold gas)

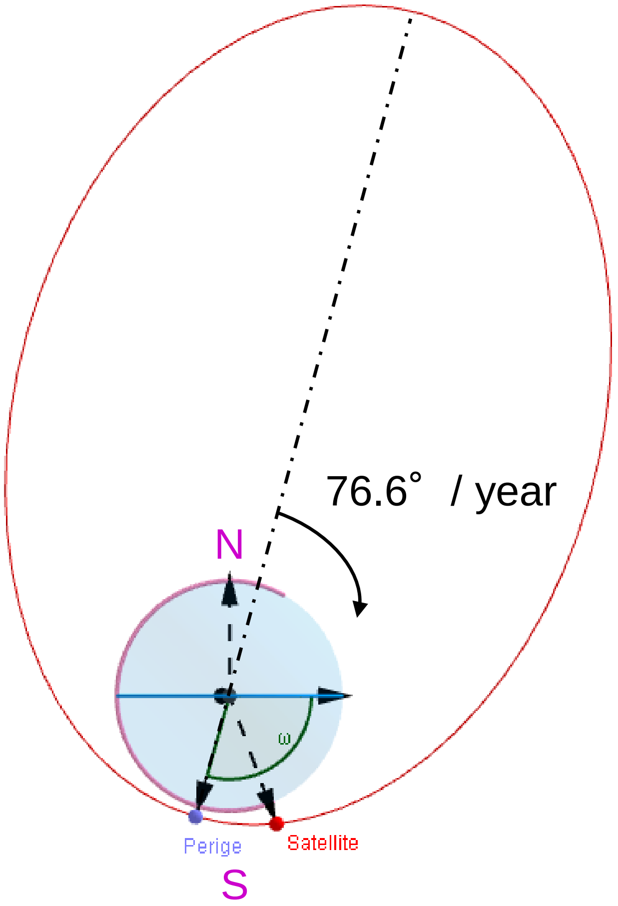


ESCAPE Orbit

- Initial perigee altitude : **800 km**
- Apogee altitude : **33 000 km**
  (6.2 R_E geocentric distance)
- Orbital plane inclination : **90°**
- Initial latitude of the line of apsides: **85° N**
- Argument of perigee: 255°

It results:

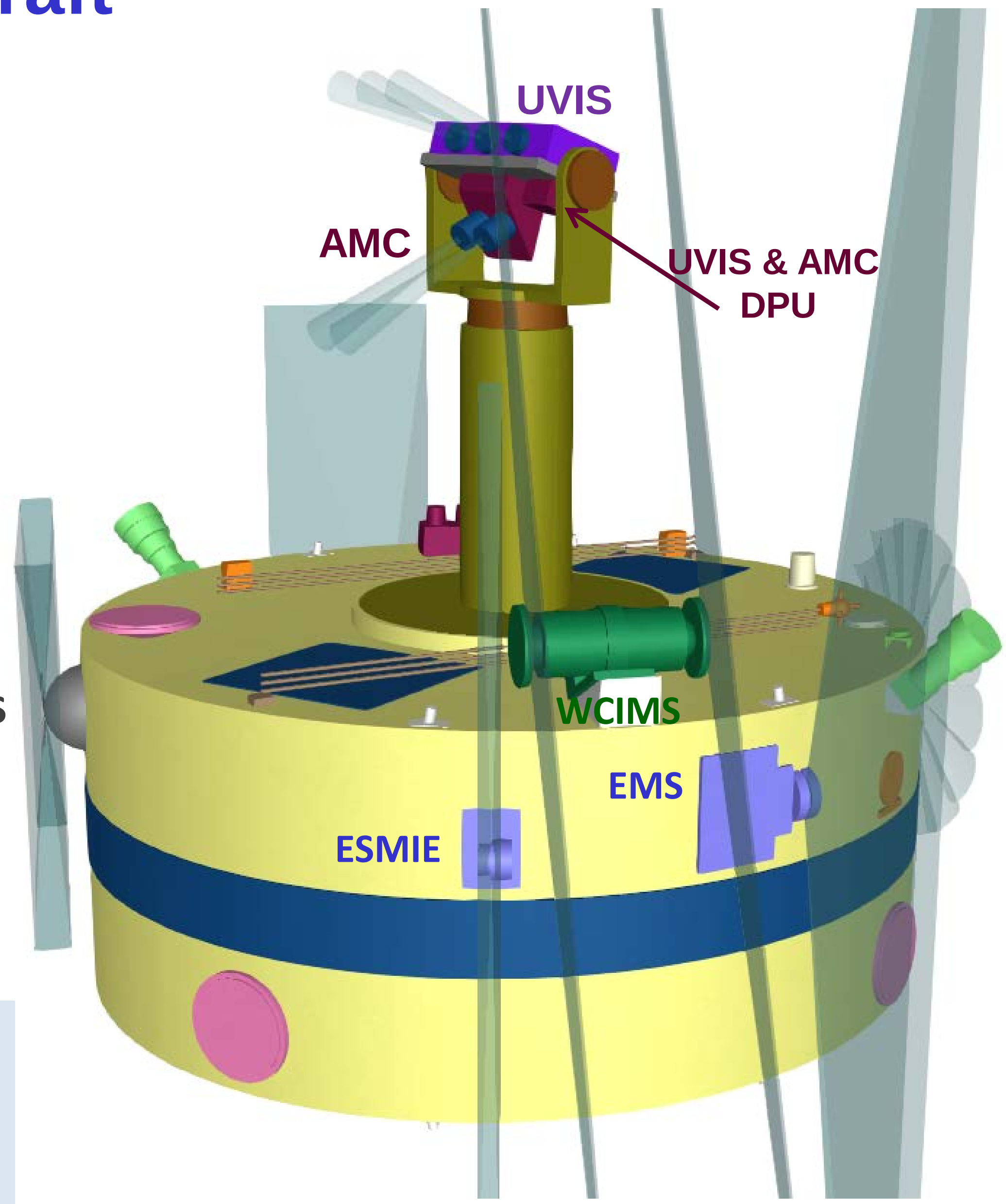
- Almost "inertial" orbital plane (wrt the Sun-Earth line)
- **9 h 45** orbital period
- 2697 orbits in 3 years
- No need for orbit maintenance manoeuvres
  (unless we want to gradually change the orbit characteristics)
- **-0.21° / day rotation** of the line of apsides in this plane (230° in 3 years)
- This latitudinal drift is in // with the longitudinal drift (wrt the magnetosphere, but fixed in inertial space)
- Slow oscillation of the perigee altitude,
  between 800 and 480 km
- Need for deorbiting at the end of mission



Initial ESCAPE orbit (red) and 1000 km altitude projection (magenta)

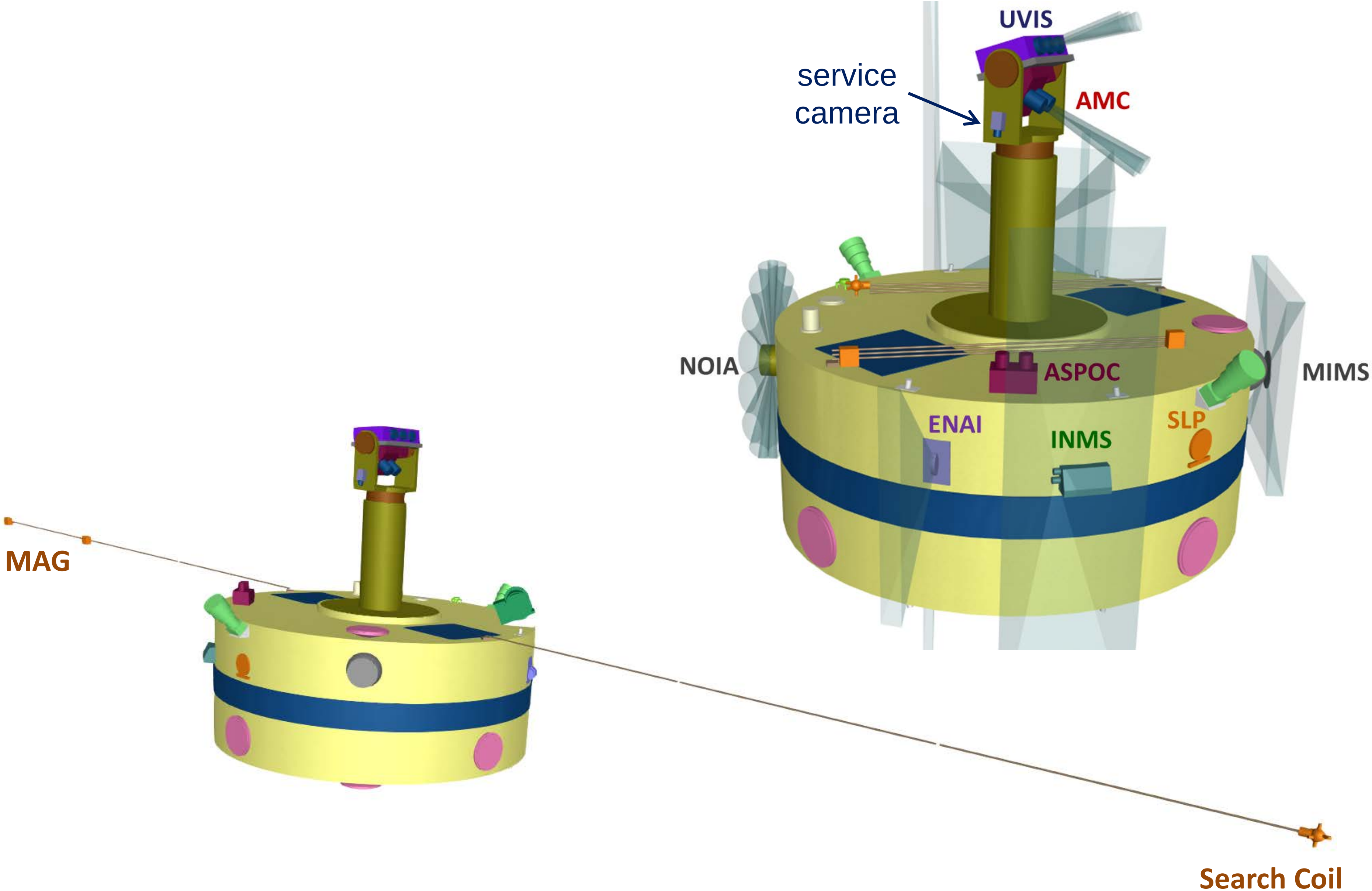
Due to the natural orbit evolution the **orbit covers successively** the <u>northern polar cap escape route</u>, the <u>equatorial ring current</u>, and then the <u>southern polar cap escape route</u>.

ESCAPE spacecraft



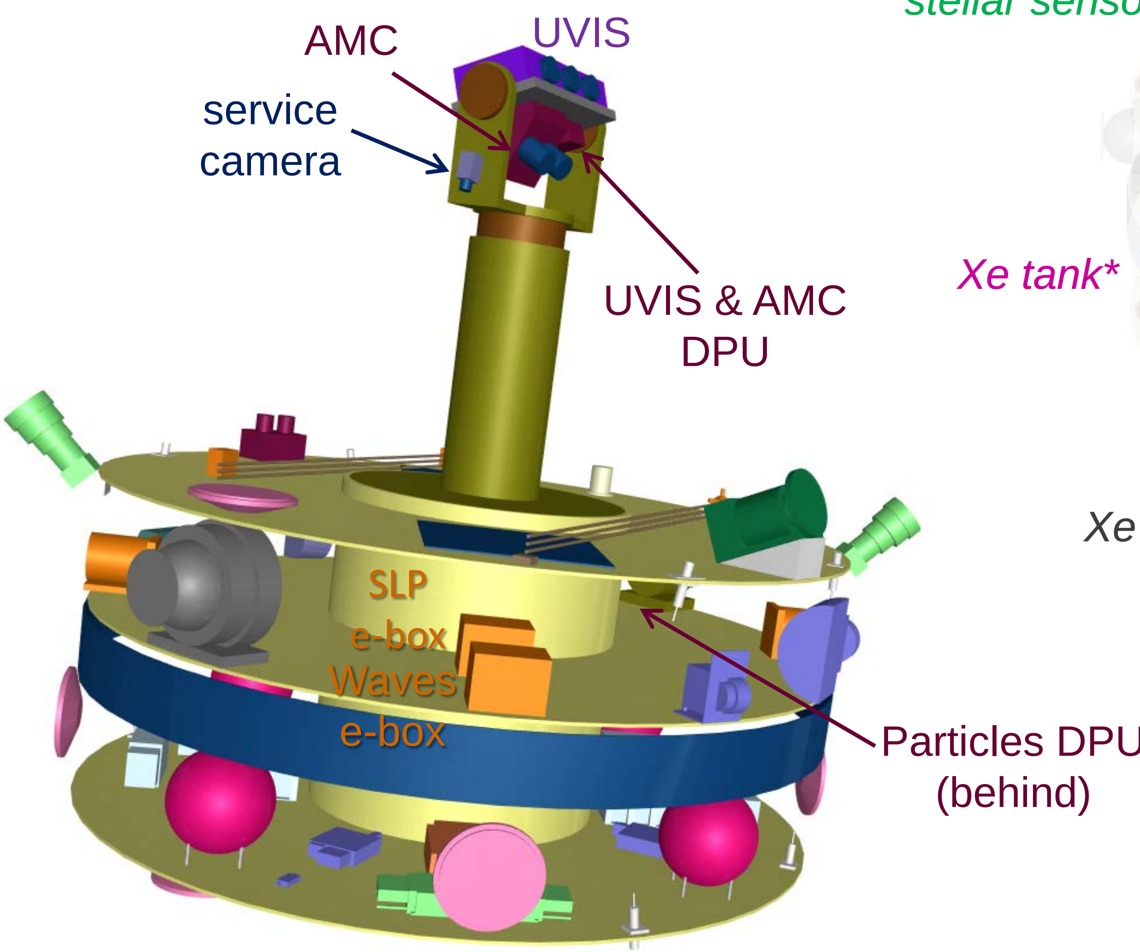
- Main spacecraft:
  2.40 m diameter x 1 m height
- Despun platform mast:
  0.35 m diameter x 1.5 m height

Thanks to PASO-CNES

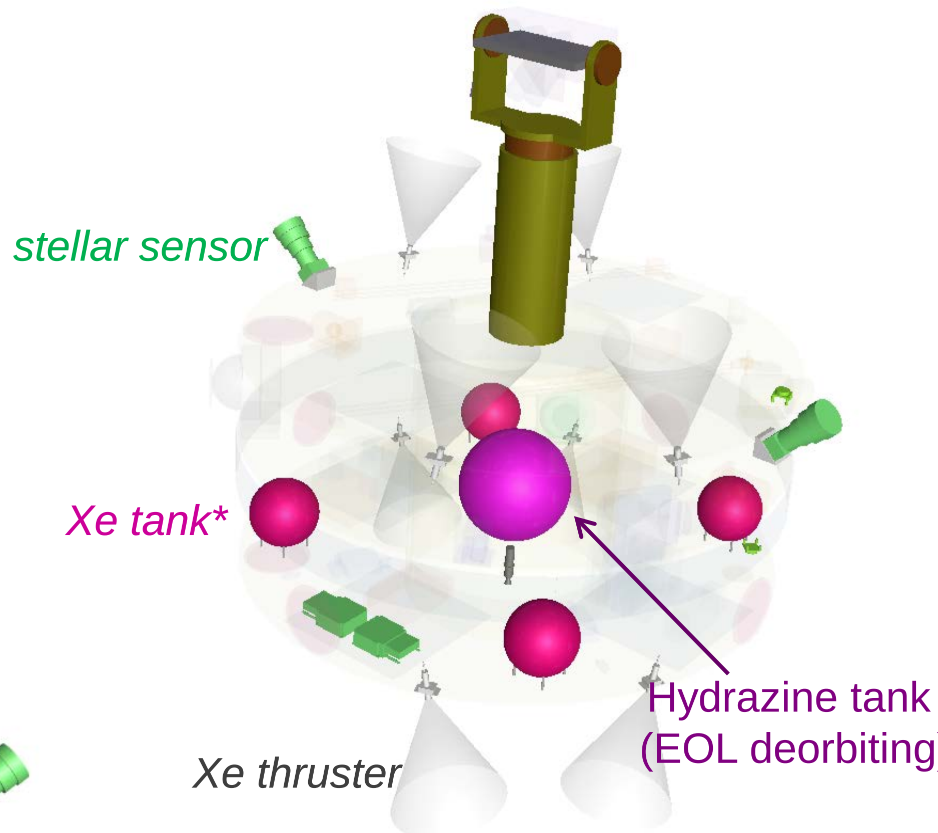


Thanks to PASO-CNES

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES



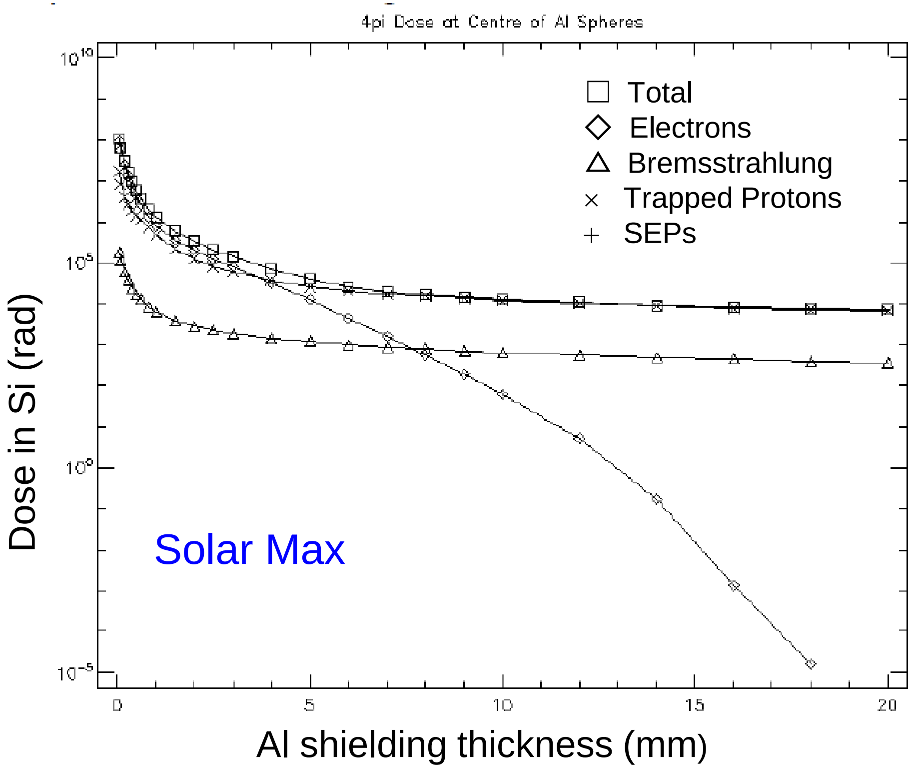
ESCAPE satellite internal view

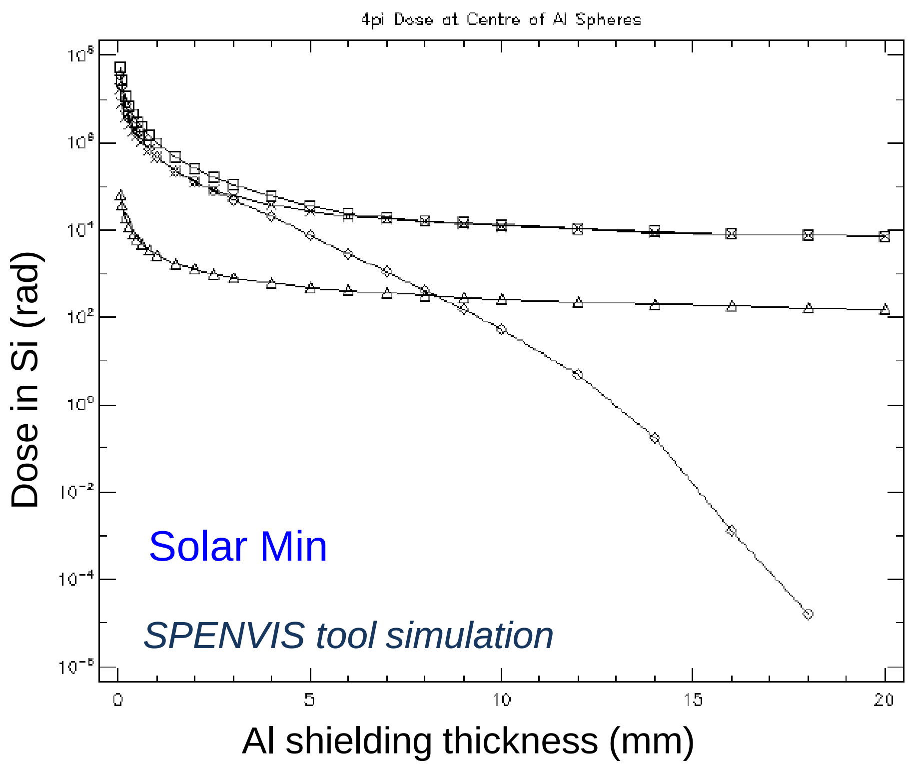


ESCAPE attitude and orbit control system

** Could be Kr, Xe, or a mixture of noble gases*

ESCAPE Orbit Total Ionising Dose





Total ionising dose in silicon (rad) as a function of the aluminium shielding thickness (mm) for: solar maximum (left panel) and for solar minimum (right panel)

ESCAPE will experience total ionising doses, after 3 years, of maximum ~35 – 40 krad behind 5 mm of aluminium shielding

Single events (SEUs, latch-ups) need to be considered.
During high penetrating particle rates, particle instruments DPU issues a flag.

ESCAPE spacecraft bus and payload mass budget

BUS Subsystem	Without margin [Kg]	Margin [%]	Margin [Kg]	Including margin [Kg]
Subsystem STRUCTURE	74,55	20,00%	14,91	89,46
Subsystem POWER	51,42	20,00%	10,28	61,70
Subsystem AOCS	5,47	9,88%	0,54	6,01
Subsystem COMS	21,70	14,52%	3,15	24,85
Subsystem OBDH	19,00	20,00%	3,80	22,80
Subsystem PROPULSION	29,91	6,50%	1,95	31,86
Subsystem Despun Platform	38,02	19,87%	7,55	45,57
Total dry mass without system margin	240,07	17,57%	42,18	282,26
System margin		20,00%	56,45	338,71
Propellant mass	170,00	20,00%	34,00	204,00
Total wet mass including all margins				542,71

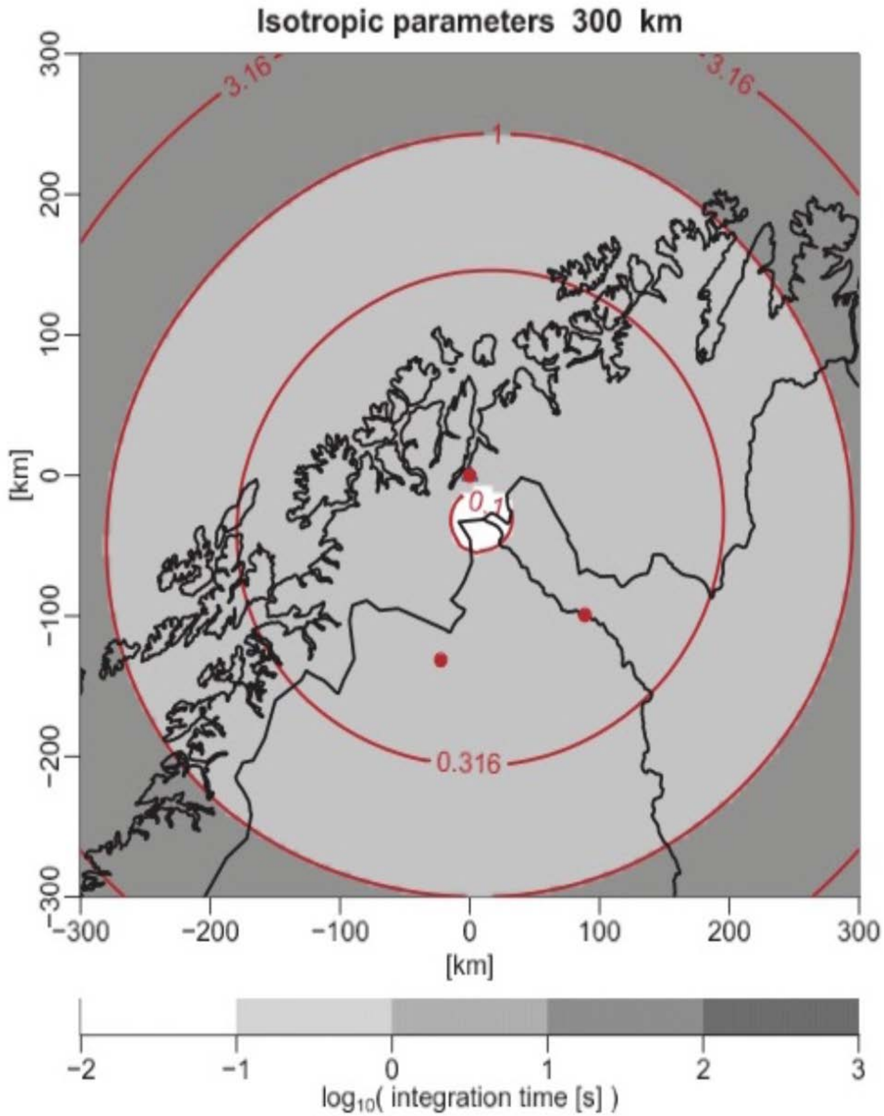
PAYLOAD Subsystem	Target wet mass [Kg] : Unit Name	Quantity	Mass [Kg]	Margin [%]	Without margin [Kg]	Margin [%]	Margin [Kg]	Including margin [Kg]
Subsystem Ion and Neutral Mass Spectrometer					5,50	20,00%	1,10	6,60
Subsystem MCP Ion Mass Spectrometer					7,50	20,00%	1,50	9,00
Subsystem Nitrogen Oxygen Ion Analyser					8,00	10,00%	0,80	8,80
Subsystem Plasma Electron And Current Experiment					7,00	20,00%	1,40	8,40
Subsystem MAG					3,40	12,35%	0,42	3,82
Subsystem Sweeping Langmuir Probe					12,60	20,00%	2,52	15,12
Subsystem WAVES					7,40	11,89%	0,88	8,28
Subsystem Energetic Neutral Atoms Imager					6,00	20,00%	1,20	7,20
Subsystem UV Imaging Spectrometer					8,50	20,00%	1,70	10,20
Subsystem Auroral Airglow Camera					14,20	20,00%	2,84	17,04
Subsystem Active Spacecraft Potential Control					3,50	20,00%	0,70	4,20
Subsystem Energetic Mass Spectrometer					9,60	20,00%	1,92	11,52
Subsystem PLDPU					6,00	20,00%	1,20	7,20
	DPU Particle Instruments	1	3,00	20,00%	3,00	20,00%	0,60	3,60
	DPU Cameras	1	3,00	20,00%	3,00	20,00%	0,60	3,60
Subsystem Wide field Cold Ions Mass Spectrometer					5,00	20,00%	1,00	6,00
Total dry mass without system margin					104,20	18,41%	19,18	123,38
System margin						20,00%	24,68	148,06
Total wet mass including all margins								148,06

Total system mass (bus + payload + propellants), including margins: **~700 kg**

Total system power, including margins: **~450 W**

ESCAPE total mission cost for ESA: **~340 M€** (<< the 550 M€ ESA M5 ceiling)

Covering area of EISCAT_3D



High sensitivity in more than 500 km diameter (grey area) ≈ 15° longitudinal range

⇓

5 % of polar orbits traverses this region in average

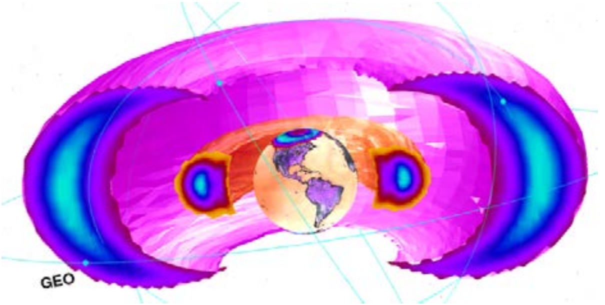
+

More conjugacies if we consider geomagnetic tracing

ESCAPE:
Relevance to Space Weather

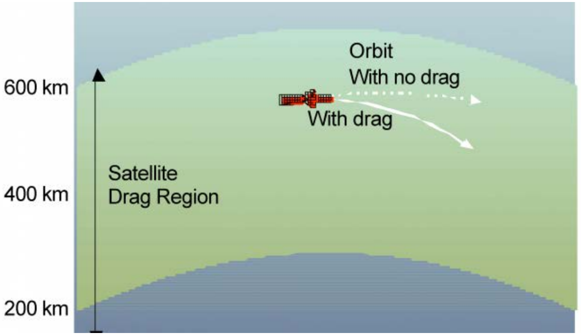
1. **Direct monitoring of the radiation belts**

   Real-time monitoring of the penetrating particle fluxes through the energetic ion instrument counting rates and singles / doubles / triples counting rates



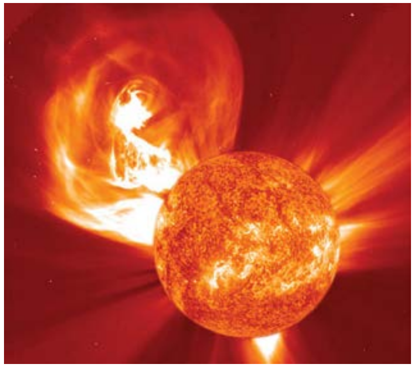
2. **Atmospheric expansion monitoring during space weather events**

   Data for updating the models for satellite drag



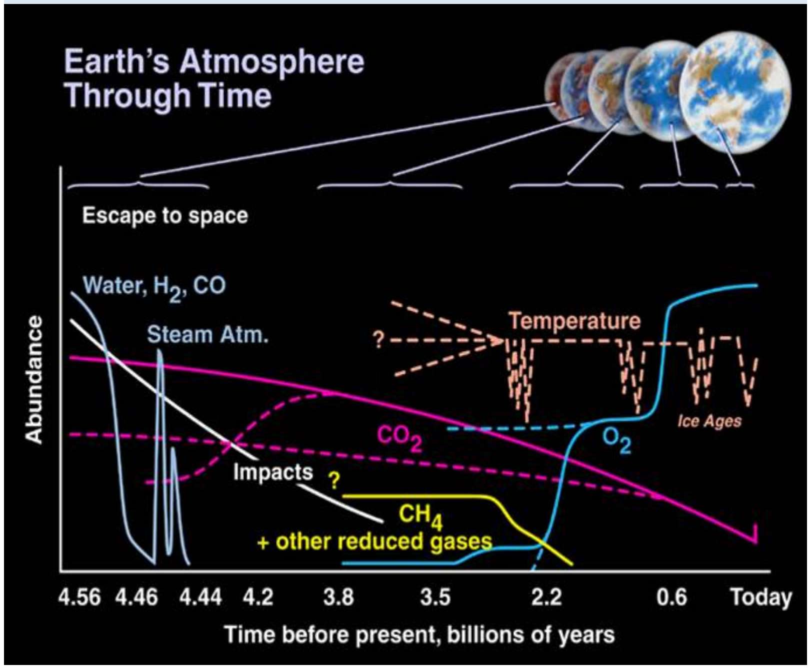
3. **Role of solar activity in the atmospheric composition evolution (space climatology)**

   Atmospheric escape rates during solar storms can be used as a proxy to understand atmospheric evolution during the very active “early Sun” (1-2 billion years ago)

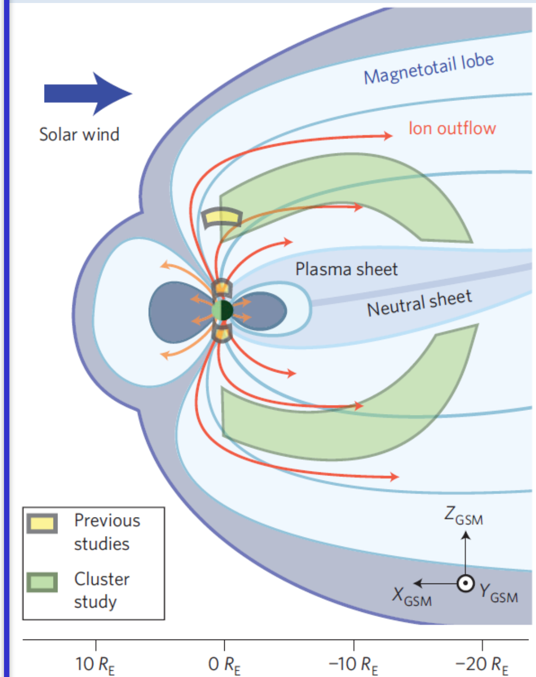


ESCAPE objectives are interdisciplinary

History of the Earth's atmospheric composition over a long (geological scale) time period

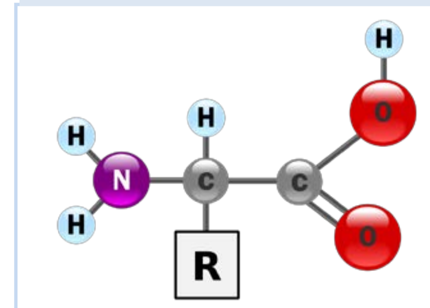


Ion and neutral escape



Ion – neutral interactions

Implications for habitability: nitrogen & oxygen are essential elements for life



Atmospheric evolution of exoplanets

Comparative planetary atmospheres evolution

Some Unique Features of the ESCAPE Mission

 # 1: **ESCAPE will provide a quantum leap in our knowledge of how and at what rate is Earth slowly losing its atmosphere to space** :

- First time comparison of neutral / thermal escape and ion / non-thermal escape
- First time observation of the escape sources, allowing to give robust numbers (n, T) for the exospheric parameters
- First time thorough observations of isotope ratios in the geospace environment

 # 2: **Unique observational strategy**:

- Unique combination of in-situ and of remote sensing measurements
- Priority in high-mass resolution so that O - N separation becomes possible
- Low perigee while keeping a wide altitude range: 500 – 33 000 km

 # 3: **Timely mission** :

- European EISCAT_3D has just started its construction and will be available
- We do not know as much on the exosphere of Earth as we now know on planetary exospheres
- Reference data for studying exo-planetary / planetary atmospheres and habitability

 # 4: **Interdisciplinary objectives bridging different communities** :

- Basic ionization processes
- Neutral atmospheric science + space plasmas physics
- Comparative planetology
- Atmospheric evolution and habitability

Many thanks to the ESCAPE team members, for helping prepare and promote the proposal.

It is a pity that the ESCAPE mission proposal was not selected by ESA for a Phase A study.

On Friday morning, at the Forum *"Towards an international mission to study atmospheric erosion and exosphere?"*, let's discuss possible follow-on options.