European SpaceCraft for the study of Atmospheric Particle Escape (ESCAPE)

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Scientific goal:

The ESCAPE mission will quantitatively estimate the amount (flux) of escape of the major atmospheric components (nitrogen N and oxygen O) as neutral and ionised species and at thermal and non-thermal forms, escaping from the Earth as a magnetised planet. The goal is to understand the importance of each escape mechanism and to infer the history of the Earth's atmosphere over a long (geological scale) time period. The spatial distribution and temporal variability of the flux of these elements and their isotopic composition will be investigated from the exobase/upper ionosphere (500 km altitude) up to the magnetosphere.

Key Measurements/Science objective #1: First-time comprehensive exploration of the entire exosphere

- *Upper exospheric altitude profiles at different solar/magnetospheric activity conditions*: What is the distribution of the upper exosphere under different conditions? What are the dayside/nightside and the latitudinal asymmetries?
- *Temporal variations of major exospheric species*: How does the exosphere respond to different external conditions?
- *Neutral and ion fluxes*: How are exospheric neutrals ionised at different altitudes, at which rates and under what conditions?
- *Correlation of neutral and ion fluxes with upper atmosphere parameters*: Are there any variations in the exospheric parameters that are not determined only by the conditions at the exobase/upper thermosphere?
- *Neutral and ion fluxes at different incident energies when particle precipitation is present*: How do energetic particle precipitation and the associated energy deposition in the upper atmosphere contribute to escape? How does this influence the role of the different escape mechanisms?

Key Measurements/Science objective #2: First-time detailed composition measurements

- *Isotope ratios for both neutrals and ions*: Knowing the mass dependence of escape mechanisms, what can we learn about the relative importance of the different escape mechanisms? What are the roles of solar illumination and of energetic particle precipitation?
- *Correlation between exospheric neutrals and ionospheric ion outflow*: What fraction of newly-ionised exospheric ions contributes to the ionospheric outflow?
- *Comparison of composition in situ with plasma composition in the magnetosphere*: What does this tell us about recirculation of outflowing ionospheric species? What fraction of the ionospheric outflow is effectively escaping from the magnetosphere?
- *Time dependence of the isotope ratios and the N/O ratio*: Which physical mechanisms determine these ratios? What is the role of different upper atmosphere conditions and what drives composition dynamics at different altitudes, and at different solar zenith angles?
- *Comparison of isotope ratios with those found elsewhere on Earth and in other solar system objects*: How much can the present-day's isotope ratios or N/O ratio tell us about the escape mechanisms in the past (for Earth as compared to other planets)?

Measurement targets:

(1) Density, fluxes, and energy-angle distribution for N^+, N_2^+, O^+, H^+, and He^+, in the magnetosphere and in the upper exosphere/ionosphere.

(2) Neutral and ion densities for different species including their isotope ratios (e.g., N, N_2, O, O_2, He, $^{17}O/^{16}O$, $^{18}O/^{16}O$, D/H) in the upper exosphere/ionosphere (> 800 km).

(3) All the above data will be collected for a wide range of local times and latitudes, solar EUV flux, and solar wind and ionospheric/geomagnetic conditions.

Except for ionised atomic oxygen (O^+), the observational knowledge on these target populations is either missing or very poor; quantitative estimates are unreliable, while we aim at an uncertainty factor of three for the global flux of each component (differences between escape mechanisms are more than an order of magnitude). The lack of comprehensive measurements is partly due to the lack of proper light-weight instrumentation. Fortunately, this problem has been overcome in recent years. It is now possible to make the necessary systematic measurements with a single mission.

1. Why do we need to measure the exosphere (neutrals): Observational knowledge of the exosphere at different solar and geomagnetic conditions is needed in order to understand and model the thermal escape (after photochemical heating), non-thermal escape through the ionisation efficiency, and even the conditions for hydrodynamic escape in the past/future. However, only hydrogen has been studied, by UV imaging, and no direct measurements exist of the exosphere above 1500 km altitude (and above 800 km for nitrogen). We fill this gap with this mission so that a measurements-based model of thermal and non-thermal escape can be constructed.

2. Why do we need to measure the isotope ratios (for both ions and neutrals): The isotope ratios of escaping ions and neutrals are considered to be different for different escape mechanisms, hence the present day's isotope ratios of a planetary atmosphere have been used as a qualitative measure for the relative amount of total escape from that planet, compared to the original inventory. For example, high $^{15}N/^{14}N$, $^{17}O/^{16}O$, and D/H ratios in the Martian atmosphere have been interpreted as a consequence of a gravity-mass-filter (responsible for a huge loss of nitrogen compared to its original inventory). However, this argument relies on two assumptions that are not very realistic: (i) thermal escape (including hydrodynamic escape) obeys full gravity mass-filtering, and (ii) non-thermal escape causes nearly no mass-filtering.

Theoretically, different types of non-thermal escape mechanisms must result in different degrees of gravity mass-filtering. For example, the altitude where pre-accelerated cold ions still feel gravity is not at ground level but at some unknown high altitude. Accordingly, the degree of mass-filtering for each escape mechanism is not well known. Therefore, direct observations are needed to correctly model and understand the origin of the isotope ratios. Such a model will be a strong tool in estimating also the past history of the other planets and moons.

3. Why do we need to study the nitrogen ions: While O^+ is normally formed from atomic O, N^+ is normally formed after N_2^+ dissociation due to the very different chemical binding energies of N_2 and O_2. Therefore, the ionisation height and the dependency on solar and solar wind activity are quite different between these two elements abundant in the atmosphere, despite their similar molecular masses. Accordingly, changes in the N^+/O^+ ratio are expected to be different from those in the N/O ratio, depending on the ionospheric and exospheric conditions. Inversely, the N/O ratio provides information on the ionospheric/exospheric temperature and density. Combining this with the isotope ratios, we can gain a better understanding on the escape mechanisms and their relative contributions.

As a direct spin-off of such measurements, the mission also contributes to the understanding of the following topics:

* **Planetary Evolution** (implications of isotope and N/O ratios of a planet in terms of the escape history).
* **Ionospheric Physics** (ionisation chemistry at the topside ionosphere for different conditions and auroral activity levels).
* **Thermosphere-Exosphere-Ionosphere Coupling.**
* **Magnetospheric Dynamics** (orbit covers all routes of ion transport in the inner magnetosphere).

Relevant recent missions:

* TWINS, GOES and Hisaki: The EUV Lyman-alpha (hydrogen line) measurements indicate that the exosphere is very dynamic, depending on the solar and geomagnetic activities.
* e-POP (onboard CASSIOPE, 330 km – 1400 km): Low-energy (< 100 eV) ion measurements indicate that N^+ and O^+ obey different dynamics.

* Mars Express and MAVEN (at Mars): The measurements show dynamic changes in exospheric conditions even at Mars, and a strong dependence of escape on solar and solar wind activity.

A summary description of the proposed space mission:

All key measurements will be achieved with a single slowly spinning spacecraft (spin period of 22–26 s) for making in situ measurements, equipped with a despun platform and/or despun mirrors for remote sensing measurements. To maximise the utility of the despun platform, the spin axis will point perpendicularly to the Sun-Earth line (as on Cluster). The orbit must have a high-inclination (> 75°) at around 500 km x 33000 km altitude (~10 hr orbital period) to cover the polar cap, inner magnetosphere, exosphere, and topside ionosphere at all local times. Such a high-inclination orbit maximises geomagnetically conjugate observations with the EISCAT_3D ground-based radar facility. At the time of the mission, the EISCAT_3D project will be fully operational, allowing semi-continuous conjugate observations of the ionosphere (particularly escape) when the spacecraft is at high latitudes, because EISCAT_3D can continuously monitor the ionosphere over 10–20 degrees of latitudinal span (ESCAPE would become the first mission to take advantage of the instantaneous 3D coverage capability of this facility).

The spacecraft should contain a full suite of particle instruments (hot ions and returning energetic ions with N/O separation capability, cold ions and neutrals with isotope separation capability, hot electrons), with the capability of spacecraft potential control and measurement of particles at only a few eV. The latter can be done with a Langmuir probe on a 5 m boom. In addition, a magnetometer (no need of high accuracy) on its own 5 m boom is needed to understand the particle data. A spacecraft DPU is required for handling the data.

The spacecraft should also feature a UV spectrometer to obtain line-of-sight integrated images in various emission lines, including the nitrogen ions and neutrals through nitrogen emission lines (at least UV: 91 nm, 108 nm, 123–139 nm; and possibly visible: 391 nm, 428 nm) within integration times as short as 0.1 s. Since the spacecraft is spinning, we need a despun platform or despun mirrors with a pointing mechanism such that the field-of-view (FOV) of the UV spectrometer gradually changes to include the limb direction during one full orbit. The UV spectrometer has a narrow FOV (telescope type), requiring a pointing accuracy of less than 1 degree, which determines the requirement for the accuracy for the spacecraft attitude. The altitude resolution of the images is expected to be 100 km or better.

Another baseline optical instrument is a CCD camera to monitor the auroral and airglow activity as one of the parameters setting the ionospheric conditions, such that the local (in-situ) measurements can be interpreted in the global context. The acquired images will be also used for outreach purposes.

On the other hand, the wave instrumentation should be a simple one (i.e., search coil on a 5 m boom) because ESCAPE does not aim to quantify the microphysics of escape mechanisms. All past missions relevant to ion escape measurements for the Earth (e.g., Cluster) were focused on the mechanisms to energise ions, with emphasis on the wave-particle interaction mechanisms and the auroral acceleration mechanisms. Therefore, these missions (including even THOR under study) carried extended wave and field measurements for both DC and AC electric and magnetic fields. ESCAPE will take a completely different approach by focusing on the consequences of such escape mechanisms through ion and neutral observations with high mass resolution, up to isotope ratios: what the isotope ratios of the solar system objects mean, why plenty of volatiles exist in the inner solar system planets, what are the relative roles of thermal and non-thermal escape on planetary evolution. Without such knowledge we cannot diagnose the evolution of the chemical properties of the atmosphere. Therefore, the resources of the spacecraft give priority to the particle instruments. A higher accuracy of the wave measurements (e.g. longer booms) and a higher time resolution of the particle measurements are considered as optional.

Another instrument is an energetic neutral atom (ENA) imager, to monitor the geomagnetic storm and substorm activity in terms of ion injections and the interaction between energetic magnetospheric ions and the exosphere.

The total mass and power of scientific payloads, including shielding, is less than 100 kg and 100 W. Since apogee is just below the geosynchronous distance a Soyouz-type launcher is capable of lifting the spacecraft, with a total mission budget of about 450–500 M€ for ESA, including operations.

A description of an enabling international partnership scheme the authors are considering

The mission is complete with an ESA-built single spacecraft, including instrument contributions from the USA and Japan. Furthermore, we make comparisons with ground-based observations at the conjugate ionosphere. One unique system would be EISCAT_3D that is most likely mature and ready for conjugate observations with ESCAPE by 2029-2030.

<u>The technical requirements</u> : They are moderate and fairly easily achievable:

* Despun platform or despun mirror on a slowly spinning spacecraft (spin period of 22–26 s).
* Nitrogen-free propulsion system for attitude control (cold gas), and if possible also for orbit control.
* A conductive surface for the spacecraft body.
* Free field-of-view of particle/optical instruments from solar panels and booms.
* 3D coverage of the tophat type particle instruments every spin.
* Moderate magnetic cleanliness (5 nT at magnetometer sensor locations on a boom at 5 m and at 3 m).
* Minimum EMC cleanliness (at only 1–10 Hz, and three times easier than Cluster).
* 1 GByte/day data telemetry with 10 GB onboard memory.

Element	Explanation
Science #1	* **First-time systematic exploration of the entire exosphere**
Science #2	* **First-time systematic composition measurements including isotope ratios**
Spacecraft	- Single slowly spinning spacecraft with a despun platform and/or despun mirrors - Cold gas propulsion for attitude control. Ion engine can also be considered - Moderate (Cluster level) magnetic cleanness and EMC requirements
Payload	* **Possible payload configuration: PI, PI institute, funding agency** - Cold ion and neutral mass spectrometer (M/ΔM > 1000): P. Wurz (PI), U. Bern, **Switzerland**. SSO - Light hot ions (M < 20, N/O separation, 10 eV/q – 30 keV/q): I. Dandouras (PI), IRAP, Toulouse, **France**. CNES - Heavy hot ions (M > 10, N/O separation, 10 eV/q – 30 keV/q): M. Wieser (PI), IRF, Kiruna, **Sweden**. SNSB - Energetic ions/electrons (H^+, He^+, O^{++}, N^+, O^+, N_2^+, 20 – 200 keV): L. Kistler (PI), Univ. New Hampshire, Durham, **USA**. NASA - Electrons (10 eV – 20 keV): A. Fazakerley (PI), UCL/MSSL, London, **UK**. UKSA - UV spectrometer (85 – 140 nm; optional: 391 nm and 428 nm): I. Yoshikawa (PI), Tokyo University, **Japan**. JAXA - Spacecraft potential (Langmuir probe): J. De Keyser (PI), BIRA-IASB, Brussels, **Belgium**. BELSPO - Magnetic field (5 nT accuracy): R. Nakamura (PI), IWF, Graz, **Austria**. ALR/FFG - Aurora/airglow camera (670 nm and 762 nm): T. Sakanoi, Tohoku U., **Japan**. JAXA - ENA imager (0.5 – 30 keV): A. Milillo (PI), INAF/IAPS, Rome, **Italy**. ASI - Waves (5 Hz – 20 kHz): B. Grison (PI), ASCR/IAP, Prague. **Czechia**. PRODEX J.-L. Pinçon (Co-PI), LPC2E, Orléans, **France**. CNES - Supplemental cold ion/neutral analyser (M/ΔM > 50): N. Paschalidis (PI), NASA/GSFC, **USA**. NASA * **Mandatory subsystems (by ESA)** - Spacecraft DPU, 5 m booms, Active spacecraft potential control
Orbit	- elliptic (500 km x 33000 km altitude with ~10 hr orbital period) - high-inclination (> 75°) to maximise geomagnetic conjugacy with EISCAT_3D - apogee will be either gradually increased or decreased
Duration	* 3 year nominal mission with instrument design good for 5 years
Radiation	* Shielding is required to keep < 50 KRAD for 3 years
Resolution	* < 2 minutes & 100 km in altitude
Science Operations	- ESA (ESOC/ESAC) is responsible for operation, data collection/archiving/distribution. - Real-time detection of the radiation belts (high-penetrating flux regions) to change to a reduced operation/observation mode. No other spacecraft-level special mode is planned. - Instrument level mode-change will not affect the allocated telemetry. - Level 2 (calibrated) data delivery within 6 months. - Key parameters or equivalent data (open access) within 12 months.
Collaborations	* USA (NASA): instrument provision (energetic ions/electrons and cold ions/neutrals) * Japan (JAXA): instrument provision (UV spectrometer and auroral camera) * EISCAT: conjugate ground-based 3-D observations (ions and electrons at > 500 km)
Cost estimate	500 M€ (250 M€ for spacecraft and ESA-built subsystems, Operations: 80 M€, Launch: 80 M€, other 90 M€)

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