Questions on M5 proposals

Proposal Title:

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

Q1: A large number of spacecraft have contributed to research on atmospheric escape.

- **What missing information will be provided by ESCAPE? Which relevant escape mechanisms cannot be monitored by the proposed mission?**

ESCAPE provides both in-situ measurements of **all species** (new), over their **full energy range** (new) and optical monitoring of major **heavy ions from above the exobase** (new). A summary of "new" information on each scientific target, which will be provided by ESCAPE, is given in Table 6.1 of the present document.

Past missions were limited to hydrogen for the extended exosphere, whereas oxygen measurements were limited to altitudes below ~700 km and for nitrogen below ~600 km, and these measurements are quite old (Johnson, 1969), cf. Fig. 1.1. However, nitrogen and oxygen are the two major constituents of the Earth's atmosphere.

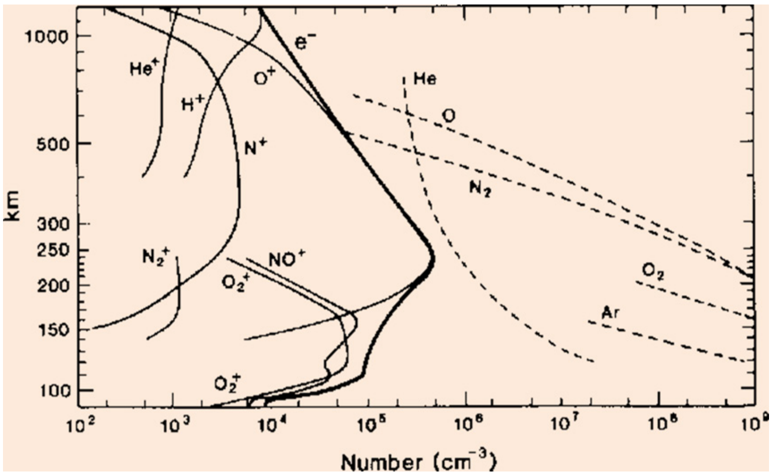

Fig. 1.1
Upper atmosphere altitude density profiles for the major neutral and ionised species. From Johnson, 1969.

Past missions that studied the terrestrial exosphere and/or ion escape include OGO (Orbiting Geophysical Observatory, back to the sixties), DE (Dynamics Explorer), Polar, Akebono, TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics), IMAGE, TWINS. However, **none of these missions had an instrumentation as comprehensive as that of ESCAPE**:

- Dynamics Explorer, for example, did carry a neutral mass spectrometer, but it only had measurements in the 300-500 km altitude range.
- IMAGE and TWINS provided only remote sensing data for the exosphere, and only for the H component (geocorona Lyman-α imaging). Moreover, the imaging was limited to geocentric distances above 3 R_E, due to the saturation of the detector from the emissions from the lower dense exosphere.
- TIMED was designed to study only the thermosphere and the mesosphere (mainly 60-180 km altitudes) and without in-situ measurements. The sensitivity of its UV spectrometer was tuned for collisional high-density regions only.

The following Table 1.1 provides an overview of the past thermospheric / exospheric missions, used for the NRLMSISE-2000 model (which is the standard model of the upper atmosphere and was used in recent studies) and afterwards.

Mission	Altitude range	remote-sensing method	in-situ method for cold neutrals	species
DE-2 (1981-1983)	thermosphere (300-500 km) apogee: 1000 km		mass spectrometer	major species (N_2, N, O, H)
AE-C, D, E (1973-1978)	thermosphere (< 400 km)	UV	mass spectrometer accelerometer	major species (N_2, N, O, H)
Air Force SCs (1968-)	thermosphere (< 220 km)		accelerometer	total mass density
Castor (1975-1979)	thermosphere (250-600 km)		accelerometer	total mass density
San Marco 5 (1988, 2-weeks)	thermosphere (260-690 km)	UV (not used)	accelerometer	total mass density
Jacchia atmospheric model	thermosphere – lower exosphere		satellite drag	total mass density
MSS (1980-1989)	thermosphere (< 250 km)	UV occultation		O_2 density
IS Radars	thermosphere-exosphere	UHF		Temperature
TIMED (2001-now)	thermosphere < 400 km (target: < 180 km)	multi-wavelength UV (from 600 km)		major species (N_2, N, O, H)
IMAGE (2000-2005)	exosphere	Lyman-α		H only
TWINS (2006-now)	exosphere	Lyman-α		H only
GOES (-now)	exosphere	Lyman-α (from 6.2 R_E)		H only

Table 1.1. Relevant past thermospheric / exospheric missions, used for the NRLMSISE-2000 model and afterwards.

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. As a result, **ESCAPE** will observe the **source region**, the polar cap region through which the escaping populations **transit**, and the magnetosphere region from which these populations **may return or definitively escape**. **No other project has ever measured all these regions in one mission**. This unique orbit enables ESCAPE to look at the ouflow of the major neutrals and ions as well as at the recirculation/escape of ions, which previous missions related to atmospheric escape could not address.

ESCAPE will provide these observations under different illumination conditions, dipole tilt, geomagnetic and solar activity levels, and this while monitoring daily and seasonal effects. It will observe both hemispheres and will thus also provide insight in north-south asymmetries.

ESCAPE will measure **isotope fractionation in the terrestrial exosphere and in the escaping populations**, which **was not studied by prior missions**. As discussed in our answers to Q4 and Q8, this is essential for understanding the evolution of the Earth's atmosphere over a geological-scale time period.

The following Table 1.2 (adapted from Table 1.1 of our proposal) shows the major escape mechanisms and the capability of the ESCAPE mission to monitor them. As described in the proposal page 7, each of these mechanisms presents a different mass filtering or isotope fractionation effect.

Type of mechanism	ESCAPE contribution	Determining parameter
(a) Jeans escape	by constructing an observation-based exospheric model	temperature at the exobase and exobase altitude for each species (that determines escape energy)
(b) Photochemical heating	by constructing an observation-based exospheric model	exobase altitude, and density and temperature at the exobase
(c1) Hydrodynamic blow off	by constructing an observation-based exospheric model	temperature at exobase and exobase altitude for each species (that determines escape energy)
(c2) Momentum exchange	by directly observing both input (light neutrals) and output (heavy ions)	neutral fluxes and ion column density
(j1) Charge-exchange < 100 eV	by constructing an observation-based exospheric model	column density of neutrals and flux of outflowing ions in the exosphere
(j2) Charge-exchange > 100 eV	by improving outer exosphere models from IMAGE, TWINS	column density of neutrals and flux of ring current ions in the exosphere
(d) Ion pickup	by improving outer exosphere models from TWINS, IBEX	(magnetopause location and exospheric density there) *1
(f) Atmospheric sputtering	by measuring particle precipitation, sputtered ions, and neutrals density	precipitating particle flux at exobase
(g) Large-scale momentum transfer & instabilities	not a target	*1
(e) by $E_{//}$ & EM waves	by improving observation -based models from Cluster etc.	intensity of $E_{//}$ and EM waves and fields
(i) Plasmaspheric wind and plumes	by improving observation -based models from IMAGE, Cluster, etc.	plasmasphere imaging (from apogee) and cold plasma distributions (in the outer plasmasphere)
(h) Magnetopause shadowing	not a target	*1

*1: Not provided by ESCAPE (apogee within the magnetosphere).

Table 1.2. List of the major escape mechanisms and contribution from ESCAPE.

As can be seen from the above table, **the proposed ESCAPE mission will be able to measure the determining parameters** (e.g. exobase altitude, exospheric density profile) **for the major escape mechanisms,** and **supply valuable information for those for which current knowledge is incomplete, or is limited to modelling studies**.

What is missing from ESCAPE?

As summarized in Table 1.2., two mechanisms are outside the scope of ESCAPE: large-scale momentum transfer and magnetopause shadowing. ESCAPE also will not directly measure the ion pickup by the solar wind (its apogee is within the magnetosphere), but will still contribute to its modelling because ion pickup is directly related to the exospheric density.

For the thermal escape, it would be ideal to measure the populations both in the thermosphere and in the exosphere. However, measuring both would require a tremendous dynamic range for the instruments, and therefore **ESCAPE concentrates on the exosphere** (populations above 500 km altitude), **which is much less investigated than the thermosphere**. And even if we do not perform in-situ measurements below 500 km altitude, we do measure the energy input going down there through energetic particle precipitation. Fortunately, the thermosphere will be partially covered by EISCAT_3D through ion/electron measurements, which further mitigates this issue.

- **How do ESCAPE's capabilities differ from those of other missions due for earlier launch, such as SMILE?**

The **SMILE** (Solar wind Magnetosphere Ionosphere Link Explorer) mission will measure, through X-ray imaging, the interaction between the shocked solar wind, near the magnetopause, and the extended hydrogen exosphere. The signal will be proportional to the charge-exchange process, i.e. to the convolution product of the heavy ion fluxes (solar wind origin) by the local exosphere density, integrated along the line of sight (and not directly to the density). What **ESCAPE** will give is the **background neutrals density,** which is **assumed in SMILE**.

Given its elongated elliptical orbit with apogee high above the pole, **SMILE** will spend relatively little time in the regions of interest for atmospheric escape. Moreover, its instrument suite is limited: X-ray and ultraviolet imagers, for the study of the magnetosheath and of the global distributions of auroras respectively, along with instruments to measure the energetic particles in the solar wind and changes in the local magnetic field. It **will not give any direct information about the in situ composition of the escaping populations**. The auroral UV imager has very specific requirements (very narrow bandwidth to reject daylight), targeted toward the study of the global shape of the polar caps as indicators for the overall state of the magnetosphere, and **cannot measure column densities of exospheric neutrals**.

The **GOLD** (Global-scale Observations of the Limb and Disk) mission, planned by NASA, will provide a UV imaging spectrograph on a geostationary satellite to remotely measure densities and temperatures in Earth's thermosphere (only 132-160 nm, i.e., O and N_2) and ionosphere. GOLD, however, **will not provide any in-situ measurements**. Its main science data product will be the O/N_2 ratio disk measurements, **mostly from below ~150 km altitudes** and at a 30 minute cadence. While some stellar occultation measurement of neutral profiles (at a coarse scale size) will complement the ESCAPE science, the lack of in-situ observations of ions and acceleration processes makes these capabilities distinct. We note also that one of our team members, Sarah Jones, is the GOLD project scientist which could enable good collaboration between the two missions, e.g. utilisation of the GOLD results as initial input for the ESCAPE operations plan preparation.

The Chinese **MIT** (Magnetosphere-Ionosphere-Thermosphere) mission, now approved for a Phase A study, will sample the outflow at ~1000 km, ~6000 km altitude, and in the magnetosphere at ~7 R_E during major conjunctions between the four spacecraft, and plug-in the info into models of magnetospheric dynamics. This will provide multi-point measurements of the ion circulation. However, the onboard instrumentation will have very limited capabilities for the cold ion composition (low $M/\Delta M$) and **will not be able to separate nitrogen from oxygen**, which are the two major constituents of the Earth's atmosphere. We note that one of our team members, Octav Marghitu, is involved also in the MIT science team.

These future missions (not all of them are approved) highlight the importance of understanding atmospheric escape from Earth, as a magnetised planet. However, **only the ESCAPE mission, due to its unique orbit covering all the escape routes from the exobase up to the magnetosphere, and its very comprehensive instrumentation combining high-mass resolution in-situ measurements in the full energy range with remote sensing observations, will be able to monitor and quantify almost all escape mechanisms**. It will thus be able to measure the key parameters, needed for modelling atmospheric escape, and to provide a quantum leap in our understanding of how and at what rate is Earth slowly losing its atmosphere to space.

Q2: ESCAPE is targeting three regions of interest: the exosphere, up-flow region, and inner magnetosphere. Conjugate locations of these three regions are visited at very different times.

- **What are the plans for combining the three sets of observations into a complete and consistent global picture?**

The ESCAPE orbital period is 9 hours and 45 minutes. The time from perigee (exobase / lower exosphere) to the up-flow region is typically 10 to 30 minutes. This should be compared to the characteristic time for variation of the exosphere in response to varying solar activity, which is half-to few days (Zoennchen et al., 2017), as shown in Fig. 2.1. It can thus safely be considered that the observations at the exobase and at the up-flow region are almost simultaneous, and that **the observed conditions at the lower exosphere, during a perigee pass, are also valid for the time of the up-flow region observations**.

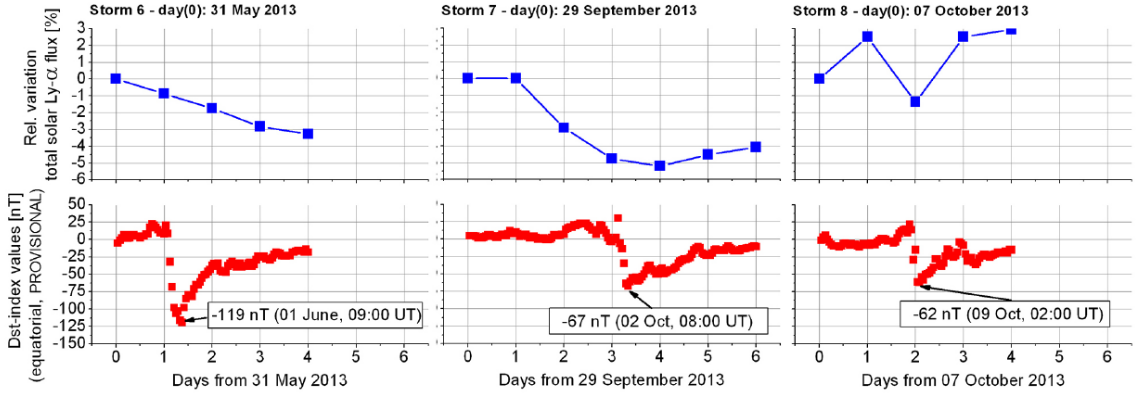

Fig. 2.1. Response of the exosphere to geomagnetic disturbances: relative variation in the total solar Ly-α flux (%) with respect to the geomagnetic storm's reference day. From Zoennchen et al., 2017.

The other important time scale is one to several hours, which correspond to the substorm cycle, the magnetic storm development (e.g. Buzulukova et al., 2010), and the time for the upwelling ions, to be convected to the magnetotail and then injected into the ring current (Delcourt et al., 1993; Welling et al., 2015, and references therein). ESCAPE orbital time from the up-flow region to the ring current region is typically 2 to 3 hours and therefore we also consider using superposed epoch analysis.

Moreover:

1) **ESCAPE is equipped with both in-situ measurement instruments and remote sensing instruments** (auroral and airglow camera + UV imaging spectrometer). The remote sensing instruments allow monitoring any spatial inhomogeneity in the lower exosphere, and thus scale the in-situ exobase measurements to those prevailing at the exobase area which is magnetically conjugate to the upwelling observations.

In this respect, a 3D exosphere model for different activity levels (EUV and geomagnetic) will be used for mapping exospheric parameters along the geomagnetic field lines passing through the spacecraft and comparing then in situ observations with the remote sensing ones.

We mention also that the two degrees of freedom pointable despun platform (elevation + azimuth scans) allows **monitoring of a selected lower exosphere region, and/or performing altitude scans over it**, while acquiring in-situ measurements in the upwelling region. For altitude scans 100 km altitude resolution is adequate. The following Fig. 2.2, where the remote sensing instruments field-of-view is schematically represented by the light-blue cones, gives an example of the operational capabilities for combining in-situ and remote sensing measurements.

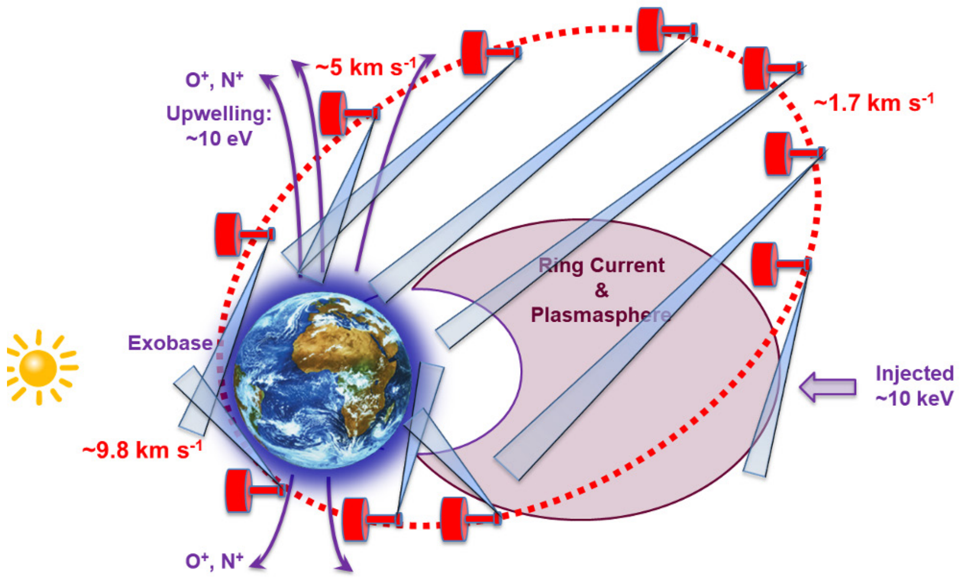

Fig. 2.2. Example of remote-sensing instruments pointing strategy, along the various portions of the ESCAPE orbit. The two degrees of freedom pointable despun platform allows a large flexibility in acquiring imaging data.

2) The required time resolution for the exospheric conditions, as indicated above, is low. When higher time resolution is required we **will use EISCAT_3D data** (construction of which has just started, with progressive commissioning of the system starting in 2021, aiming at full operation from 2022).

- **Please describe how the expansion and contraction of the atmosphere, e.g. as function of solar radiation, will be taken into account in order to assign atmospheric pressure variations with altitudes to the individual retrieved profiles.**

The background pressure changes are indeed an issue in retrieving column densities from UV limb observations. However, ESCAPE's instrumentation includes a full-set of in-situ particle measurements, and **UV observations can certainly take advantage of these in-situ observations**, performed during the same orbit, in interpreting the data.

For the corrections below the altitude of spacecraft coverage there are **a number of thermospheric models** (e.g. DTM, CTIP/CMAT2, TRANSCAR/TRANS4; for a review, see Belehaki et al., 2009) that provide spatio-temporal descriptions of the ionosphere-thermosphere system (at least for selected species). In addition, predictive models are under development, such as the P2-SWE-II carried under ESA's SSA/SWE program. We will use these models after we correct them with our in-situ measurements at high-altitudes.

In other words, **ESCAPE will contribute to the validation of these models, and help their further development**, which is essential for space weather. The corrected models could even help in planning the ESCAPE observations.

To perform this we have a **large and talented modelling team** (cf. page 2 and Annex-B of our proposal), including modellers for the thermosphere, the exosphere, the ring current, and global magnetospheric models as e.g. the BATSRUS model (Glocer et al., 2009, 2013).

Q3: Important auxiliary data for characterising upper atmospheric conditions and outflow processes are solar EUV flux, magnetospheric/geomagnetic activity, and solar wind input.

- **What are the requirements for their accuracy, temporal/spatial resolution?**

For **EUV** flux, we require a **daily average**. This is the minimum requirement, because current thermospheric models use a 1-day value. The F10.7 index, which is the used proxy of the EUV flux, is currently provided also at this cadence of one per day, which corresponds roughly to the variability time scale of solar irradiance. However, a 10 minutes value would give an extra on "extreme events". The S_{10} EUV index (Tobiska, 2008) is such a higher cadence index. ESCAPE will be prepared to take advantage also of this information, when occurrence of smaller scale variability is expected, such as during X-class flares.

During the last deep solar minimum the EUV F10.7 index daily average changed over a ~65 to ~95 typical range, even if during solar minimum the total range is smaller than during other periods. If the measurement accuracy is of 20 % in this range we can still extrapolate.

For the **solar wind velocity / density and geomagnetic activity**, we require **hourly averages** which correspond to a shorter substorm cycle. These inputs changed over a typical range of ~2 to ~20 cm^{-3} (solar wind density), ~300 to ~700 km s^{-1} (solar wind velocity), and ~0 to ~1000 nT (AE index), even during solar minimum over 3 years. We require 10 % accuracy over these ranges for measurements. This is a higher accuracy than for the EUV flux, because these changes are very dynamic.

- **Where are they expected to come from?**

All these quantities **are standard space weather parameters**.

Such parameters are expected to be freely available from the **ESA Space Situational Awareness program – Space Weather Element** (SSA – SWE). At present, the SSA – SWE program provides the data via its General Data Service (http://swe.ssa.esa.int/web/guest/GEN_arv). Alternatively, such data can be obtained from **NOAA's Space Weather Prediction Center** (http://www.swpc.noaa.gov/products-and-data).

Of course, it is hard to say today which will be the specific space assets that will provide these data at the time of the M5 mission, but we can reasonably assume the availability of missions, in Europe or in the USA, providing such parameters that are directly related to space weather. As an example, the NOAA Deep Space Climate Observatory (DSCOVR) spacecraft was launched in 2015 as a replacement of the ageing ACE spacecraft. It is currently supplying solar wind and interplanetary magnetic field measurements, which are available at web sites as https://www.ngdc.noaa.gov/dscovr/portal/index.html#/ and http://services.swpc.noaa.gov/products/solar-wind/.

The NOAA site provides also solar UV data from the GOES satellite series, with better than 10 minutes resolution. Since GOES are considered as a mandatory space environment monitor, we can expect that they will operate even during the 2030's, as well as some solar wind monitor.

The F10.7 index plus three other solar indices at other wavelengths, EUV to X-ray, are available from Space Environment Technologies at http://sol.spacenvironment.net/~JB2008/indices.html.

For the global magnetospheric activity, in addition to the geomagnetic indices we will also have our ENA imaging data, from the ENAI instrument, for monitoring and characterising the storm/substorm events.

Q4: The mission may not be launched in the optimal time period for extreme solar events of the type responsible for most atmosphere loss since the M5 schedule envisages launch near solar minimum.

- **What will be the return of the mission without extreme EUV and solar wind events?**

Being at a low solar activity period is not necessarily a disadvantage. This will allow ESCAPE to examine better the baseline situation of a quiet ionosphere-thermosphere system, which is optimal to study, for instance, Jeans escape. The advantage then is that then the state of the system does not change rapidly, which allows bringing together the data gathered at various points of the orbit in a consistent way.

Even so, **during solar minimum we should still have a significant number of solar and geomagnetic events**. As part of a study, we went back over the last 3 solar minima and found how many hours we had with the Dst activity index value below some threshold. For each solar minimum we found:

Dst below -25 nT : 1278 hr, 1129 hr, and 404 hr

Dst below -50 nT: 334hr, 230 hr, 44 hr

Dst below -75 nT: 115 hr, 59 hr, 8 hr

So there **will always be at least some moderate geomagnetic storms during solar minimum**, even if the last solar minimum was particularly quiet.

According to the Hisaki satellite observations, the exospheric hydrogen column density above ~1000 km altitude increases when Dst < -50 nT, even for events during which the solar EUV flux did not change (Kuwabara et al., 2017). Thus, even during three years around solar minimum the geomagnetic variation level is sufficient.

Regarding the solar UV fluxes, the importance of the UV variation is found in all models of the thermosphere and exosphere. Figure 4.1 shows an example of exobase altitude dependence on the solar UV flux (Tian et al., 2008).

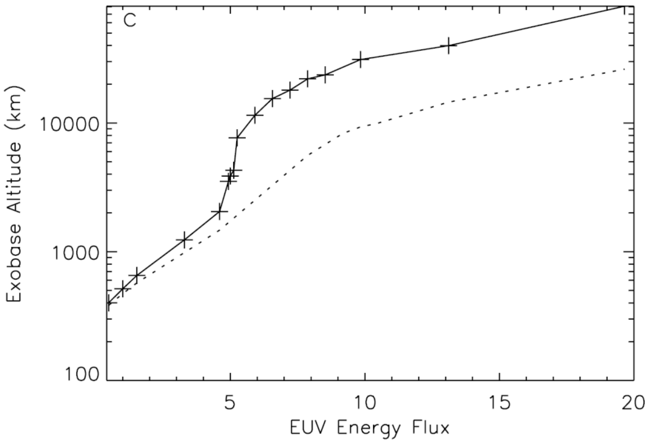

Fig. 4.1.
One of the thermospheric models and its dependence on solar EUV flux. Just a small change of UV can cause a detectable change in the exobase altitude. From Tian et al., 2008.

During the last solar minimum the TIMED SEE Lyman-α data daily value ranged from 3.4 to 3.9 x 10^{11} photons $cm^{-2}s^{-1}$ (>15%) over the period 2007-2009, while it went up to 5.3 (60%) during the recent solar maximum (cf. Fig. 4.2). A 15 % change in solar UV flux will result in a 20-30 km increase of the exobase height according to Figure 4.1.

A similar result is given for the solar F10.7 cm index: during the last solar minimum it was about 430 or 1870 hours where this well-known solar UV proxy was above respectively 100 or 90×10^{-22} W m^{-2} Hz^{-1}. These values have to be compared to a typical low-activity value of ~65, and a maximum range, for extreme events, up to ~200 ($\times10^{-22}$ W m^{-2} Hz^{-1}).

Enhanced EUV from flares are also expected to be present, albeit in reduced numbers, compared to solar max. Just to give an example, in early 2010, i.e. at the beginning of solar cycle 24, there was a series of M-class solar flares. On the 5 April 2010 the first CME of Solar Cycle 24 caused a geomagnetic storm that was intense enough to lead to the loss of the Galaxy 15 Intelsat communications satellite. Another example is the very recent period of high activity in 4 – 10 September 2017, at a time when it would not be expected (late declining phase of solar cycle 24). This interval was one of the most flare-productive periods of this solar cycle, with three X-class flares and multiple partial halo ejecta.

And last but not least, even during quiet periods ESCAPE will provide a lower bound for the escape rates, which is extremely valuable for benchmarking the models. **Low-energy** (few tens of eV) **ion outflow is observed even during periods without substorms** (Parks et al., 2015). And, because of the day-to-day variability, during quiet periods we can still have a suitable range for the EUV radiation flux.

In conclusion: low solar activity conditions allow us to clearly separate escape from a quiet ionosphere-thermosphere from escape from a perturbed ionosphere-thermosphere. And, even during solar minimum, we will still have a significant number of solar/geomagnetic events to monitor the response of the system to high-activity conditions.

The **ESCAPE mission will be able to handle both high and low activity levels and accomplish its objectives**. According to current solar cycle predictions, a 3-year nominal ESCAPE mission will cover the quick rise of the solar activity, from solar minimum towards the maximum. Solar events are usually present at the start of a new solar cycle.

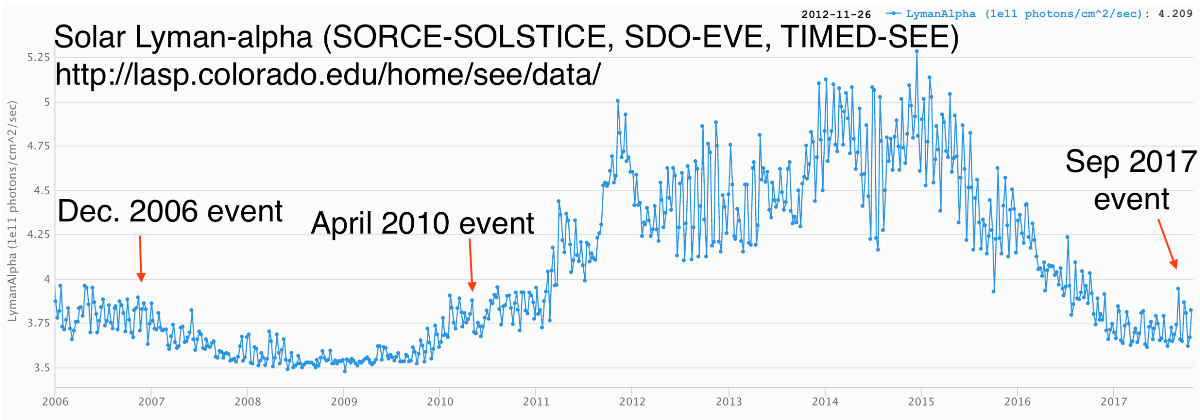

Fig. 4.2. Solar cycles 23 (declining phase) and 24: solar Lyman-α daily averages.

- **What is the approach for scaling up escape rates to large solar/solar wind inputs?**

Linear scaling of the escape flux, with respect to the solar EUV flux, has been used for Mars and Venus (Lundin, 2011; Lundin et al., 2013).

For the Earth, the recent study by Slapak et al. (2017) shows that the non-thermal ion escape flux is proportional to exp(Kp), cf. Fig 4.3. Therefore, we will start with a linear (or simple exponential if it is better) fitting on the dependence on the external condition, i.e. a multi-variable linear fitting.

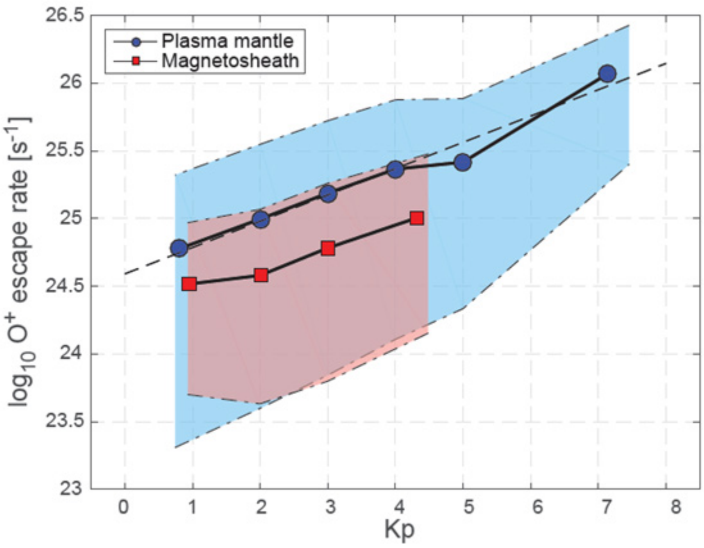

Fig. 4.3. Average O⁺ escape rates for the plasma mantle and from the dayside magnetosheath as a function of the Kp index. The dashed black line is a least squares fit to the average escape rates for the plasma mantle. The thin dot-dashed lines correspond to estimated upper and lower O⁺ escape rates in the plasma mantle (blue area) and in the magnetosheath (red).

From Slapak et al., 2017.

- **How important are the modifications of the exosphere by (i) sporadic extreme solar EUV events, (ii) strong magnetic storms, (iii) upwelling from the lower thermosphere layers? Please quantify the uncertainties associated to these contributions.**

Identifying the variation ranges in terms of different drivers is exactly one of the topics that ESCAPE is going to study. Today, as shown below, we only have sparse information.

For the terrestrial exosphere, between 3 and 8 R_E geocentric distances, Zoennchen et al. (2017) found hydrogen column density variations up to ~10 - 23 % during geomagnetic storms, after a previous solar event (8 storms sample, solar activity range: from very low to medium), cf. Fig. 2.1. Interestingly, the largest variations occurred for "weak" storms during the solar minimum 2008.

While large solar storms can lead to large changes in H density, small storms also have a significant effect (Qin et al., 2017). Densities in the thermosphere / exosphere transition region below 1 -2 R_E decrease by ~30 %, while those above this height increase by ~40%. Increase in upwelling ion flux can be by one order of magnitude (Wilson et al., 2004).

However, this variation level is smaller than the solar cycle variation which is by a factor of 2, and which is shown in Fig. 1.5 of our proposal (Zoennchen et al., 2015). The large hydrogen density variation is also observed at Mars. The MAVEN IUVS measurements show that the densities of both H and D vary by an order of magnitude over a Martian year, during which the Sun-Mars distance changed by a factor of 1.2 and EUV flux by a factor of 1.4 (Clarke et al. 2017).

The **exobase altitude** itself may vary significantly depending on the EUV flux, as shown at Earth for O and N by Tian et al. (2008) who modelled the **response of the thermosphere to extreme solar EUV conditions**, cf. our Fig. 4.1.

On Mars, the variation level of the exobase, as a function of solar activity, is estimated between 190 km and 250 km (Krasnoplosky, 2002).

These are nominal variations and linear fitting will work to some extent. Then the question is what is the deviation from such a linear model during "extreme events", because they normally add a nonlinear departure from this linear fitting, as is seen here in Fig. 4.1 and in the proposal's Fig. 1.1. Assuming that we will experience such extreme events during the mission life-time, we plan to correct our estimate in the following way:

For a UV event and a geomagnetic event, first we have to use past (or on-going) results on the thermosphere and on the ion escape. Although we cannot make a solid estimate, it is possible to reflect the observed parameters in the thermospheric model, and then scale our results from it into the exospheric model. Between these two events, the UV dependence has a longer history of modelling and hence we expect less error. On the other hand, when scaling back in history, the UV range is much larger than the geomagnetic activity range, and hence the UV-related error would then become larger.

Our actual limited knowledge demonstrates thus the **need for comprehensive measurements of the exosphere to identify its drivers and quantify precisely their influence, which will be achieved by ESCAPE**.

- **Please explain in more detail how Escape results can be used to deduce atmospheric evolution from the present-day isotope ratios. (pg. 14-15 top)**

Different scale heights of different isotopes result in different ionisation heights, preferentially removing lighter isotopes. Exobase altitude and isotope ratios there are particularly important for the quantitative estimation of the isotope fractionation due to thermal escape. If the atmosphere below the exobase is convective, we expect very similar isotope ratios between the exobase and the surface. Since a higher exobase implies a smaller escape velocity, isotope fractionation in such a case will be much smaller. And since the isotope fractionation reflects the mass ratio at the altitude where the escape starts, the isotope ratios in the entire exosphere become an important parameter.

Such isotope fractionation analysis has been used for other planets to understand their atmospheric evolution, as in the case of Mars. The measurement by MAVEN of the $^{38}Ar/^{36}Ar$ ratio, between the homopause and exobase altitudes, was used to deduce that 66 % of the atmospheric argon has been lost to space (Jakosky et al. 2017). This indicates how the altitude profile is important rather than the surface value.

For the Earth, Fig. 4.4 (from Scherf and Lammer, communication, 2017) shows a possible scenario of how ^{15}N could have been enriched to the present value. The solid black line corresponds to the exobase distance for a present day atmosphere and the red line to one with a 1000 times higher CO_2 content. About 4 Gyr ago there was a mixture of CO_2/N_2 but some nitrogen escaped, most likely via ion pick up, due to an extended upper atmosphere and a smaller, more compressed magnetosphere: The early magnetosphere, highly compressed due to a higher solar wind kinetic pressure, would give no protection to the upper atmosphere erosion against solar wind ion pick up. Higher CO_2 contents would have cooled the thermosphere and would have yield less expansion. By reproducing the **$^{15}N/^{14}N$ isotope anomaly**, compared to the chondritic initial value, **would show how much CO_2 was in the atmosphere, so that the right amount of ^{14}N was lost compared to ^{15}N.** Fractionation of $^{15}N/^{14}N$ started because of escape.

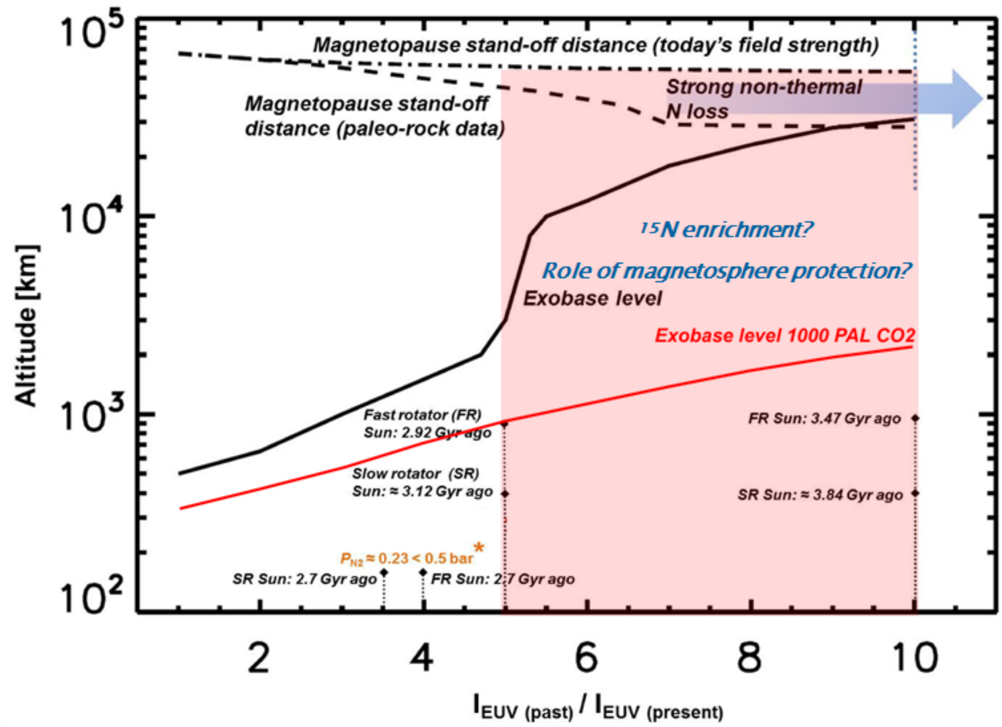

Fig. 4.4. Possible scenario of how ^{15}N could have been enriched to the present value. The solid black line corresponds to the exobase distance for a present day atmosphere and the red line to one with a 1000 times higher CO_2 content.

An analysis of the Xe isotopes in comet 67P/Churyumov-Gerasimenko has been used to understand Earth's early history (Marty et al., 2017) and shows that the present-day Earth atmosphere contains 22 ± 5 % cometary xenon, in addition to the chondritic (or solar) xenon. Fractionation of xenon isotopes on Earth is higher than that of nitrogen isotopes (Marty et al., 2013, 2017), suggesting that it has been subject to a higher escape.

Cf. also our answer to Q8, concerning the use of isotope ratios to deduce atmospheric evolution.

When modelling the past (atmospheric evolution) using isotope ratios, we need also to take care of some additional effects. One is the photochemical and hydrodynamic escape, which can override Jeans escape and result in a completely different isotope fractionation. Another is the uncertainty in the EUV models. The history of the geomagnetic field needs also to be taken into account.

The role of photochemical escape and hydrodynamic escape in the past, when the solar EUV flux was much more intense and the resulting exobase altitude was much higher, is discussed in our answer to Q5 (cf. also Fig. 4.1).

We also note that the Solar EUV flux history, which is included in any atmospheric escape rate calculations relevant to long-term evolution of the atmosphere, can be a source of uncertainty. Figure 4.5, from Tu et al. (2015), gives the EUV flux history for three different assumptions of solar rotation, 4.5 billion years ago. Therefore we have to consider a wide range of EUV values if we want to apply the ESCAPE results on this time scale.

Concerning the geomagnetic field strength, the past field is now well modelled, as shown in

Figure 4.6. Between 3.3 to 4.2 Gyr ago its value could be only 10 % of the current value (implying that the magnetopause could be only 15 000 km away), causing a large ion pick-up escape. The ESCAPE mission can contribute to estimate this amount, through exospheric modelling.

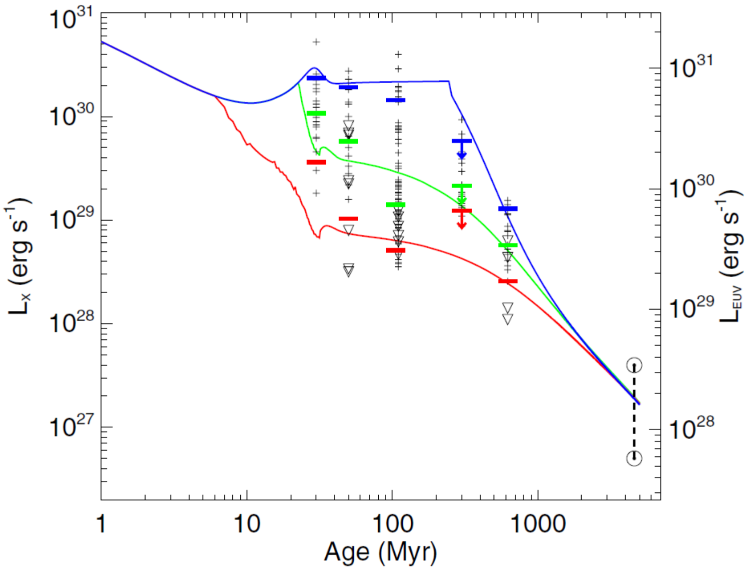

Fig. 4.5. Model of the Solar X-ray and EUV flux history for three different assumptions of solar rotation 4.5 billion years ago.
Red: slow rotator
Green: medium rotator
Blue: fast rotator
From Tu et al., 2015.

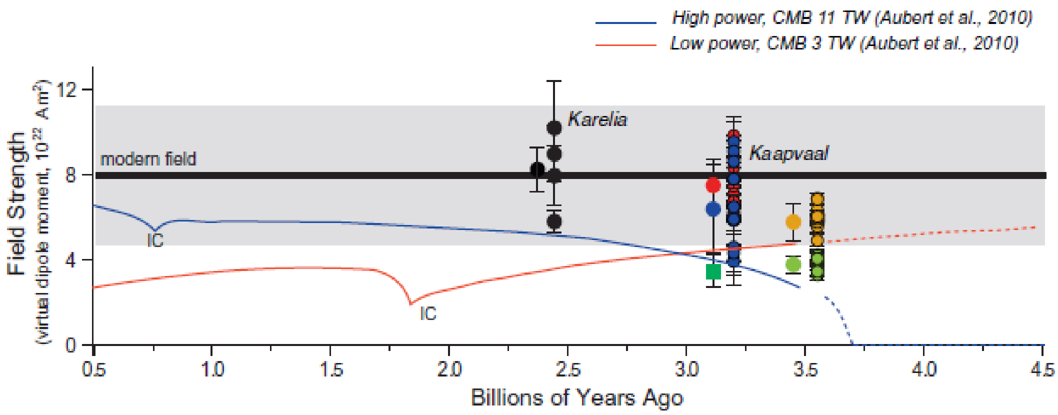

Fig. 4.6. Estimated geomagnetic field strength (blue and red lines) from measurements of ancient rocks. From Tarduno et al., 2014.

Q5: The thermal escape of neutrals will be dealt with by assuming the form of the super-thermal part of the distribution function (pg. 9).

- **What is the range of uncertainties resulting from the assumed distribution function for your model of atmospheric escape mechanisms and outflow rates?**

On page 9 of the proposal we say that we will use the approach of Brinkmann (1970). In that study they used Monte Carlo modelling to estimate the corrections to the neutral escape rate from the Jean's escape rate (which assumed a Maxwell-Boltzmann distribution function throughout the atmosphere and only gravitational forces acting on the particles). There are three things to take from this:

1) That paper shows the **deviation for H and He from the Jeans calculation**, assuming a Maxwell-Boltzmann distribution function, **is at most 30%**.

2) Using either the result of this study, or conducting our own modelling for the correction in a similar manner, we can reduce the uncertainty due to a simple Jeans escape calculation.

3) As will be answered to Q6, the WCIMS instrument measures in-situ distribution functions of neutrals with an accuracy of ΔT=200 K. Therefore, the error coming from temperature measurements will be less than 50%.

We should also note that in a follow-on paper Brinkmann (1971) compared their result to other calculations with more significant deviation from the Jeans escape calculation, but concluded that the older estimates should not be trusted.

So to summarize, **using the simplest assumption (Jeans escape which implies a Maxwell-Boltzmann distribution and absence of non-gravitational forces) the error should be within a factor of 2, even after including temperature measurement errors.** This is lower than our requirement for a factor of 3 in the escape fluxes (driven by the 100 km altitude resolution requirement).

Concerning **photochemical escape and hydrodynamic escape**, the uncertainty estimation is more tricky, because it increases drastically when the exobase altitude exceeds 12 700 km for O and 13 700 km for N (~3 R_E geocentric distance). Table 5.1 summarizes the kinetic energies obtained by the photochemical reactions, and corresponding altitudes from which the particles with these energies can escape. These altitudes are actually possible according to thermospheric model simulations (Tian et al., 2008.), as shown in Fig. 4.1. If the exobase altitude is lifted to about 3 R_E, photochemical escape becomes very important (orders of magnitude increase) and might even trigger hydrodynamic escape. But this relation (exobase altitude and temperature for different solar EUV conditions) is strongly model-dependent, without solid observations to constrain them. Therefore, **it is extremely important to measure the exobase parameters** (altitude and temperature) **for different external conditions** (EUV, geomagnetic, and solar wind conditions) **to reduce drastically the uncertainty in the past photochemical and hydrodynamic escape**.

"before"*1		"after"	portion	extra energy	escape altitude*2
O_2^+ + e-	→	O + O	26%	6.99 eV	12 700 km (3 200 km)
O_2^+ + e-	→	O + O(^{1}D)	47%	5.02 eV	20 200 km (6 900 km)
$O^+(^2P)$ + e-	→	O^+ + e-	?%	5.00 eV	20 300 km (7 000 km)
$O^+(^2D)$ + e-	→	O^+ + e-	?%	3.31 eV	
N(^{2}D) + O_2	→	NO + O	?%	3.76 eV	21 000 km (11 400 km)
N_2^+ + e-	→	N(^{4}S) + N(^{4}S)	?%	5.82 eV	13 700 km (3 700 km)
N_2^+ + e-	→	N(^{4}S) + N(^{4}D)	?%	3.44 eV	
H_2^+ + e-	→	H + H	?%	10.91 eV	0 km

*1: The actual production rate strongly depends on the UV absorption cross-section, for which the temperature dependence is poorly known.

*2: Altitude from which the particles with this energy can escape (with escape velocity). Inside parentheses is the case when all the energy is given to one species only.

Table 5.1.
Major photochemical heating reactions (> 4 eV) for N and O atoms (e.g., Tian et al., 2008).

- **Quantify the improvement in thermal escape over the current state of the art.**

One big step forward in estimating the thermal escape is that the density profile will be obtained from in-situ direct observations and the temperature will be obtained from in-situ direct observation of the distribution functions, using particle instruments. In other words, the estimate of the thermal escape will no longer be dependent mainly on models (optical limb observations use many assumptions in estimating temperatures and distributions), but **we will have a strong observational base**.

Any observed systematic difference from the Jeans escape predictions could be explained either by non Maxwell-Boltzmann distributions and/or by other forces present and acting on the particles, especially radiation pressure (cf. Beth et al., 2016). Preliminary calculations by A. Beth, member of the ESCAPE science team, show that **radiation pressure effect, on light atoms** (essentially H) **should increase the escape rate by 20 %**, for a Maxwell-Boltzmann distribution. **For heavier atoms (O and N)**, any deviation from Jeans escape rates could not be due to the radiation pressure, and **should thus reveal a suprathermal tail**, in the distribution functions, as the driving factor.

So, modelling the suprathermal tail (and its altitude profile) is the key, for which ESCAPE provides a new observational tool to tune any differences from a Maxwellian distribution.

Moreover, we will be able to determine escape rates for individual species separately.

Q6: The required data ranges are listed in Table 2.1 and in the surrounding text.

- **How do these requirements compare to the instrument resolutions listed in Table 3.1 and to the requirements that should be met for the scientific interpretation of the results?**

The following Table 6.1 summarises the **relationship between the scientific targets,** the **corresponding measurement requirements** (cf. Table 2.1 of the proposal), and the ESCAPE **instrument capabilities** (cf. Table 3.1 of the proposal). The relation between the first two is described in the proposal section 2.2, and here we just converted it into a table. The relation between the proposal Tables 2.1 and 3.1 is also briefly described in section 2.3 of the proposal, but here we give some additional information.

#1: What is the quantitative state of the atmosphere at altitudes of 500-2000 km?			
Scientific task	**Measurement requirement** (cf. proposal Table 2.1)	**Corresponding scientific instrument capability** (cf. proposal Table 3.1)*1	**What is new?**
(1) Determine exospheric altitude **density** profiles and **temperature** profile as a function of different drivers such as solar EUV, solar wind and geomagnetic conditions.	neutrals: 1–10^6/cc cold ions: 0.1–10^3/cc UV: ~10^{-2} - 10^5 R Temp: 500–1500 K	INMS neutr.: 0.1-10^6/cc/min ions: 10^{-4}-10^3/cc/min WCIMS: > 500K, ΔT=200K UVIS: 10^{-2} cnt/min sr^{-1} R^{-1} (integrate to achieve 10^{-4}) SLP: quality check	**Particles**: much higher resolution than ever (per min/100 km) **Optics**: He, He^+ O & O^+
(2) Establish **isotope ratios** for both neutrals and ions and compare them with those found at the Earth's surface and in other solar system objects.	neutrals: 10^{-2}–10^3/cc cold ions: 10^{-4}–10^1/cc	INMS neutr.: 0.1-10^6/cc/min (integrate to achieve 10^{-2}) ions: 10^{-4}-10^3/cc/min SLP: quality check	**Particles**: New, except some Earth flybys by planetary missions
(3) Determine exospheric altitude profiles of **ion/neutral ratios** and estimate ionisation / neutralisation efficiencies.	Simultaneously: neutrals (1–10^6/cc) & cold ions (0.1–10^3/cc)	INMS neutrals: 0.1-10^6/cc/min WCIMS ions: 10^{-1}-10^3/cc/min SLP: quality check	**Particles**: much higher resolution than ever (per min/100km)

(4) Measure **temporal and spatial variations** of the density of major exospheric species.	neutrals: 1–10^6/cc cold ions: 0.1–10^3/cc	INMS/SLP: same as (1) UVIS: 10^{-2} cnt/min sr^{-1} R^{-1} (at lowest altitudes, except for H)	**Particles**: see (1) **UV**: per minute at highest density region
(5) **Correlate** such variability with **upper atmosphere parameters**, and with different **incident energies** when particle precipitation is present.	neutrals: 1–10^6/cc cold ions: 0.1–10^3/cc * electrons: 10^{7-11} [*2] * aurora: 10^{2-6} R * field: 1–10^2 W/km^2 EISCAT_3D: monitor activity & measure ionisation	INMS/SLP: same as (1) UVIS: same as (4) ESMIE: 10^{6-12} [*3] AMC: >1 cnt/sec sr^{-1}R^{-1} WAVES: >1 W/km^2 MAG: 5 nT accuracy	**Particles**: much higher resolution than ever (per min/100km), and with better parameters
#2: What are the dominant escape mechanisms, and their dependence on drivers?			
Task	**Measurement requirement** (cf. proposal Table 2.1)	**Corresponding scientific instrument capability** (cf. proposal Table 3.1)*1	**What is new?**
(6) Estimate **thermal escape flux** for neutral and ion species for different conditions.	results from (1) and (5) ENA: 10^{2-5} [*2]	INMS/SLP: same as (1) WCIMS: same as (1) ENAI: 10^{2-5} [*3]	Parameters of models will be based on direct observations
(7) Estimate the **prevailing escape mechanisms** and the relative importance of thermal or non-thermal escape for different driver conditions.	results from (6) outflowing ions: 10^{5-9} [*2] ENA: 10^{2-5} [*2]	INMS/SLP: same as (1) WCIMS: same as (1) MIMS: 10^{4-9} [*3] NOIA: 10^{4-9} [*3] ENAI: same as (6)	Escape other than non-thermal ion escape, to scale to the past
(8) Estimate the response of the **ionisation / neutralisation** efficiencies, **isotope** fractionation and the **N/O ratio** to different drivers.	results from (2) & (3) outflowing ions: 10^{5-9} [*2]	INMS/SLP: same as (2) WCIMS: same as (3) MIMS/NOIA: same as (7) ENAI: same as (6)	New in space except for suprathermal N^+/O^+ ratio
(9) Estimate the degree of **recirculation of plasma** after it has left the ionosphere.	return ions: 10^{6-9} [*2] outflow: 10^{5-9} [*2]	EMS: 10^{4-9} [*3] MIMS/NOIA: same as (7) INMS/SLP: same as (1) ESMIE/MAG: same as (5) ENAI: same as (6)	Higher traceability of outflowing ions with respect to the return flow

*1: converted to 1-min resolution from 1-sec / 5-sec values in proposal Table 3.1

*2: units are [keV cm^{-2} s^{-1} sr^{-1} keV^{-1}] or [cm^{-2} s^{-1} sr^{-1}]

*3: units are [keV cm^{-2} min^{-1} sr^{-1} keV^{-1}] or [cm^{-2} min^{-1} sr^{-1}]

Table 6.1.
Scientific task –measurement requirement – instrument capability traceability matrix.

For **particle and optical measurements**, the proposal Table 3.1 is given in one-five second resolution. To compare it with the proposal Table 2.1 requirements, we converted it into observations over a minute, which allows us to improve the lowest threshold by a factor of 10-60.

In addition, we can use **INMS** for neutral density and **WCIMS** for ion density for "simultaneous" measurements, whereas we can also use INMS for ion isotope measurements (by time-sharing between the INMS ion and neutral modes). WCIMS has two detection heads and can simultaneously measure ions and neutrals, but it is not designed to resolve isotopes.

Concerning the required accuracy of exobase temperature measurements, our target of a factor of 3 accuracy in the upwelling flux during increased escape events (i.e., increased exobase temperature) implies a factor of 5 accuracy in the temperature, in the Jeans escape model, and therefore a WCIMS accuracy of $\Delta T=200$ K (for $T>500$ K) is more than adequate.

The **UVIS** observations accuracy requirements are more complex, because of different emission intensities and column densities for different species. We have summarised them in the following Table 6.2. Since UVIS has a pixel sensitivity of 10^{-2} counts min^{-1} sr^{-1} R^{-1}, we expect a 100 km resolution for H every minute, even with the 103 nm (Lyman-β) emission line. However, for the other lines (He, He^+, N, O, O^+ and N), we take a statistical summation to obtain a 100 km resolution and get an average view, or we look at lower altitudes (upper thermosphere) for dynamic changes. Summation will be over 10-100 spectrograms by assuming horizontal uniformity (after model correction by EUV level). Such a statistical method is common practice in obtaining average views.

Emission line	Emission rate [photons/s/sr]	column density*1	multiply by column density*2	from a 100 km slice of 2000 km observed from 5000 km
H-β (103 nm)	$9\cdot10^{-6}$	10^{12}–10^{13} cm^{-2}	10^{2}–10^{3} R	10^{0}–10^{1} R sr
H-α (122 nm)	$1.6\cdot10^{-3}$	10^{12}–10^{13} cm^{-2}	10^{4}–10^{5} R	10^{2}–10^{3} R sr
He (58 nm)	$6\cdot10^{-6}$	10^{11}–10^{12} cm^{-2}	10^{1}–10^{2} R	10^{-1}–10^{0} R sr
He^+ (30 nm)	$1.3\cdot10^{-5}$	10^{8}–10^{9} cm^{-2}	10^{-2}–10^{-1} R	10^{-4}–10^{-3} R sr
O (99 nm)	$8\cdot10^{-9}$	10^{10}–10^{12} cm^{-2}	10^{-3}–10^{-1} R	10^{-5}–10^{-3} R sr
O^+ (83 nm)	$1.5\cdot10^{-6}$	10^{7}–10^{9} cm^{-2}	10^{-4}–10^{-2} R	10^{-6}–10^{-4} R sr
N (95 nm)	10^{-8}	10^{10}–10^{12} cm^{-2}	10^{-3}–10^{-1} R	10^{-5}–10^{-3} R sr
N (113 nm)	very small	10^{10}–10^{12} cm^{-2}	very small	very small
N^+ (91 nm)	very small	10^{7}–10^{9} cm^{-2}	very small	very small
N^+ (108 nm)	very small	10^{7}–10^{9} cm^{-2}	very small	very small

*1: 10^{9}–10^{13} cm^{-2} for neutrals and 10^{7}–10^{10} cm^{-2} for ions, depending on species.

*2: to convert from photons s^{-1} sr^{-1} to R, we multiply by $4\pi\cdot10^{-6}\cdot$[column density] in cm^{-2}.

Table 6.2.
Estimation of EUV emissions.

- **How do you plan to correct for the effect of outgassing on the mass spectrometer neutral compensation measurements in the dilute exosphere?**

Particular care has been taken to **minimise outgassing**:

The proposed ESCAPE spacecraft has a **constant attitude with respect to the Sun**, in order to maintain a constant spacecraft surface exposure to sunlight. This helps to avoid evaporation of eventual condensed volatiles if cold shadowed surfaces were to be suddenly exposed to sunlight. The spin axis is thus Sun-pointing.

A **chemical cleanliness program**, to minimise outgassing, has been foreseen and included in the proposed mission budget.

To avoid contamination of the measurements, the attitude and orbit control subsystem is **hydrazine-free**, and will use an inert cold gas, Xenon or Krypton. The Xenon requirements for attitude control have been calculated to 7.6 kg for a three-year mission, and adequate margins are available if needed for any contingency, or for eventual mission extension.

Since the spacecraft will be flying along an elliptical orbit, it would not be difficult to estimate the amount of outgassing from measurements performed at high altitude, and then to subtract this background from the measurements. Moreover, it is possible to model the (slow) evolution of outgassing with time, e.g. as has been done for Rosetta (Schläppi et al., 2010). Note, however, that such a background removal only works if the corresponding mass peaks do not hide other species in the mass spectra, hence the efforts to limit spacecraft outgassing whenever possible – both in terms of the level of outgassing and in terms of reducing the number of species (or their fragments) that contribute to the background.

Finally we can examine the time series of sun-side / eclipse differences in the mass spectrometer INMS data.

- **The ambient field strength will go up to 50,000 nT at perigee. Why then is the Magnetometer (MAG) measurement range limited to ±8,000 nT? A comparison with high-quality geomagnetic field models would allow for in-orbit calibration of the MAG and determination of spacecraft disturbance fields.**

It is true that the ambient magnetic field intensity will locally exceed 40 000 nT, close to perigee, and **there is no technical reason to limit the MAG upper range at +/- 8 000 nT**. Some calibration parameters (alignment and gain) can be even better calibrated when the field is higher than 8 000 nT. But it also works at 8 000 nT, based on our current experience with the MMS mission. Our MAG instrumentation will be able to measure up to **+/-** 50 000 nT without any problem.

It would definitely make sense to measure the magnetic field over the full orbit, while the focus is still kept at the lower field ranges (up-flow region), where the performance should be best. This aspect will be further studied in phase A.

Concerning the MAG performance, we also note that eventual spacecraft disturbances could be investigated along the entire orbit (and not limited to the high field region). This is due to the dual sensor approach which allows MAG to measure as gradiometer. As long as both sensors are active, spacecraft disturbances can be detected continuously. That being said, the electromagnetic cleanliness requirements are pretty benign for this mission.

Q7: ESCAPE measurements are regarded as reference for atmospheric escapes on other planets and moons (e.g. pg. 6-7).

- **Explain the relevance of escape mechanisms observed at Earth for the modelling of atmospheric evolution on other planets given the very different conditions there.**

As mentioned in the Executive Summary of our proposal, the majority of the escape mechanisms at different planets are operating at Earth, and it is essential to gain a more quantitative knowledge of Earth's escape rates in order to assess each escape mechanism at different planets, for many of which the actual knowledge is only qualitative.

Among those mechanisms, neutral escape is known to be very important presently at Mars and in the past at Venus, but behaviour of neutral escape in response to the external drivers has basically been ignored in the observations of atmospheric escape at Earth, simply because its amount is presently small. Contrary to neutral escape, one of the reasons that we have relatively good knowledge on the ion escape from Mars and Venus is that we know the basics of how it works from terrestrial observations.

For planets that have shared a common origin with Earth, as Venus and Mars, formed out of the same protoplanetary nebula, it is important to know how the different escape mechanisms made these planets so different, and what would be in the future. For example, **comparison with these non-magnetised planets will help to understand how much the magneto-sphere protects the terrestrial upper atmosphere** and if it is relevant for Earth-like planets. This applies even to neutral escape, because the existence of the magnetosphere influences the exosphere and the exobase through the geomagnetic storms.

ESCAPE will also supply the information necessary to **tune the models for the atmospheric evolution of exoplanets considered to be in the habitable zones** of their stars (Lammer et al., 2011). Atmospheric loss affects exoplanetary habitability in terms of surface water inventory, atmospheric pressure, the efficiency of greenhouse warming, and the dosage of the UV surface irradiation. Thermal escape models suggest that, for example, exoplanetary atmospheres around active K-M stars should undergo massive hydrogen escape, while heavier species including oxygen will accumulate forming an oxidizing atmosphere. Non-thermal oxygen ion escape could be as important as thermal, hydrodynamic H escape in removing the constituents of water from exoplanetary atmospheres (Airapetian et al., 2017a).

Note also that comparative planetology is a subject of active research, as illustrated e.g. by the sessions of Europlanet conferences and by topical workshops in the area. ESCAPE is expected to be in an optimum vantage point to substantially contribute to it.

- **Describe how the improved models help to interpret the MAVEN results (related to Fig. 1.8), as an example.**

Comparing with MAVEN/MEX results, we can **quantify the effect of the magnetic field, planetary size and distance from the Sun on the atmospheric escape**. This is important for the **past Mars when the magnetic field was stronger**, since the planet had a dynamo 4 billion years ago.

Observations related to atmospheric escape from Mars are hard to interpret since Mars combines features of a non-magnetized planet with those of a magnetized one, given its remnant crustal magnetic fields. ESCAPE will shed light on various escape mechanisms, and in particular also to those that involve magnetic fields, so that the resulting improved knowledge can advance models used both for interpreting the present-day MAVEN results, and for studying the history of atmospheric escape for various scenarios regarding the past evolution of Mars' magnetic field. **ESCAPE will in particular help to understand the escape mechanisms that operated on Mars 4 billion years ago, when the planet had a dynamo**, and which are **important in order to understand the evolution of its atmosphere and the fate of the water inventory**, that MAVEN alone cannot of course understand: scaling observations back to the past (when the dynamo was active) is difficult without similar measurements from a magnetized planet.

Another example of how ESCAPE measurements could help interpret the MAVEN results is the measurement, by ESCAPE, of the non-thermal population of neutral nitrogen atoms on Earth. This would **provide constrains on photochemical reactions for hot N, also existing on Mars**, but for which there are no direct measurements of density or escape, and our knowledge is currently based only on modelling studies (e.g. Fox, 1993; Fox and Hać, 1997). MAVEN can measure the source of photochemical hot nitrogen (N_2, N_2^+), but not directly the non-thermal population of neutral atomic nitrogen.

With the data provided by ESCAPE, we will also be able to find out how common are such "non-uniform, variable" D/H ratios (cf. Fig 1.8 of our proposal) in the exosphere, and we could diagnose how much of this variability could be explained by the change in the convection below the observation point. This in turn gives us the information on the effective isotope ratio at the altitude where the thermal / photochemical escape works (cf. our answer to Q4). The MAVEN observations could then benefit from these results.

Q8: Living organisms are an important factor for the atmospheric composition (pg. 5).

- **Since biological activity strongly influences the Earth's atmospheric evolution, what are the implications for the extrapolation of obtained results to lifeless planets?**

Atmospheric escape is one of the major factors of habitability of extrasolar planets. The magnetic activity from a planet-hosting star, in the form of XUV emission from stellar flares and dynamic pressures from stellar winds and coronal mass ejections, supplies the energy flux into the magnetosphere-ionosphere-thermosphere system. If thermal, hydrodynamic and non-thermal escape of neutrals and ions (nitrogen and oxygen from atmospheric molecules) contributes to the erosion of an exoplanetary atmosphere at geological times scales (0.1-1 Gyr), then this will make the terrestrial planet lifeless, resembling to current Mars (Lammer et al. 2008; Airapetian et al. 2017a). Life as we know it requires, but is not limited to, a nitrogen-rich atmosphere (Airapetian et al. 2017b). The high abundance of atmospheric nitrogen was critical for the initiation of life on the early Earth, because fixation of nitrogen is needed to create linkages of long chained molecules such as proteins, RNA and DNA (Airapetian et al., 2016). Thus, escape of nitrogen along with oxygen escape becomes a critical factor of habitability. Moreover, reduced atmospheric pressure cannot support an efficient greenhouse effect and liquid surface water. **The ESCAPE mission will provide critically important measurements of escape of nitrogen and oxygen and will characterise their relative contribution during geomagnetic storms. This will provide important implications for the role of stellar forcing on the rate of atmospheric escape and habitability of terrestrial exoplanets around stars with evolving magnetic activity**.

Concerning the **oxygen content of the terrestrial atmosphere,** modern isotope analysis-based methods, using standard $^{13}C/^{12}C$ measurements, found a **change in the O_2 content of 15 % within only 100 million years** (Fig. 8.1), which is **not explained by the biological history** (Berner, 2006). Its effect on the biosphere is not yet identified. It would be useful to identify the solar conditions that can produce such a huge escape, as just one of the possible explanations.

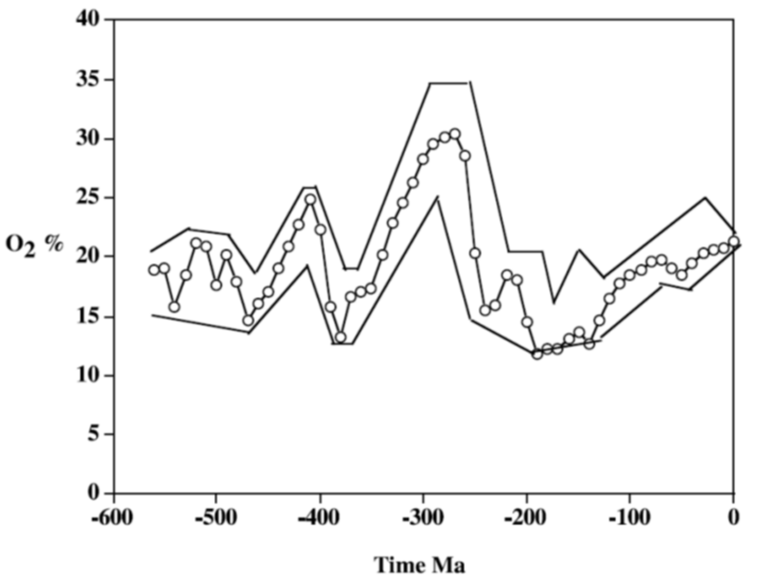

Fig. 8.1. Plot of the O_2 atmospheric content versus time, for the standard GEOCARBSULF model, with a crude estimate of the range of error based on sensitivity study. From Berner, 2006.

On the other side, **the biological effect is small: about 5 ‰ in the isotope ratios**, cf. Cartigny and Marty (2013), Zerkle and Mikhail (2017), Zerkle et al. (2017):

As an example, the $^{15}N/^{14}N$ ratio was chondritic in the primordial mantle. This was outgassed and should have been the same in the early atmosphere. **At present the atmospheric nitrogen is enriched in ^{15}N (thus heavier) by about 35 ‰ compared to the interior, while the biological effect is effective only near the surface upper crust and is about 5 ‰ in the**

isotope ratio. In Fig. 8.2, from Cartigny and Marty (2013), we can see that the paleorock data show a **possible escape effect between 3.5 and 4 Gyr**.

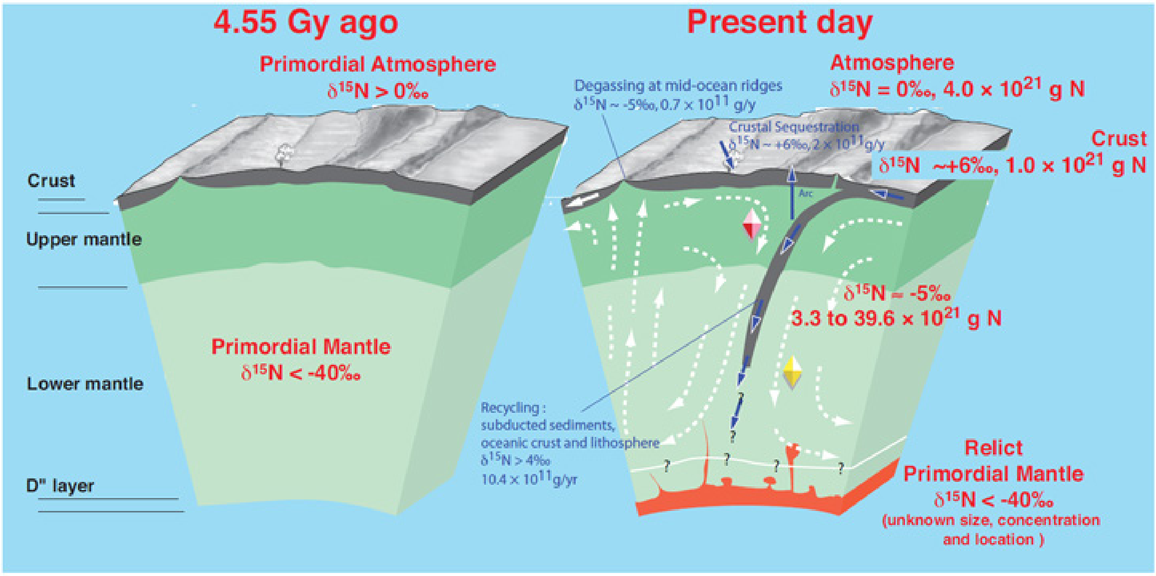

Fig. 8.2. Illustration of the nitrogen isotope disequilibrium between internal and surface reservoirs of the Earth. There is a marked isotopic contrast between the mantle (^{15}N depleted) and the Earth's surface (^{15}N enriched). From Cartigny and Marty, 2013.

Q9: The proposal lists, besides the Lead Proposer, four Core Team Members.

- **What is the particular role of these four persons? For instance, the role of the Interdisciplinary Analyses Coordinator seems interesting but vague (pg. 50).**

The core team provides a compact and efficient management team, for quick decision making as necessary, and is working in cooperation with the instrument PIs and the ESCAPE Science Working Team. Particular roles of the core team members are:

- Iannis Dandouras: Mission PI and single point of contact with ESA. Overall mission coordination.
- Masatoshi Yamauchi: Mission Co-PI, works in close cooperation with mission PI. He is advisor for specific science issues and is also a liaison with the EISCAT_3D project.
- Johan De Keyser: Advisor for technical issues, including radiation environment and cleanliness programs.
- Octav Marghitu: Bridge between different science disciplines. Since there are several science branches affected by atmospheric escape, such an interdisciplinary coordination is necessary and is a distinct role from the specific science issues. Will also coordinate global monitoring of the auroral and magnetospheric activities.
- Henri Rème: Advisor on mission management.

We note also that the ESCAPE science team has a well-balanced combination of young and promising scientists, and of experienced senior scientists. Given the mission preparation and operations schedule, young science team members, already actively involved in the mission proposal, can and will in the future step-in in the core team and replace retiring core team members.

For the operational phase the core team will include, for operations planning, three additional members: a **particle instruments coordinator,** a **fields and waves instruments coordinator,** and a **remote sensing instruments coordinator** (consortium concept). These three categories of science instruments can each be considered as a single instrument suite, with individual instruments operating in a common mode, which will streamline operations planning and management.

- **In addition to outreach, is it this coordinator's role to facilitate extending the science return to other planets, exoplanets and astrophysical spectroscopy corrections or is this about global monitoring of the auroral and magnetospheric activities?**

We have already a team of scientists for interdisciplinary analyses, as shown in page 2 and in Annex-B of our proposal, and a coordinator is necessary for this activity. The expertise of the interdisciplinary coordinator qualifies him, in the first place, for global monitoring of the auroral and magnetospheric activity. At the same time, he will work towards ensuring an efficient interaction framework for "Model and interdisciplinary analyses" in relevant fields, like planetary science, astrophysics, astrobiology, habitability and emergence of life. In this task he will work in close collaboration with several experts, mentioned as indicated above in page 2 and in the Annex-B of our proposal.

Some other team members with a specific role are:

- Lynn Kistler: Scientific contact with NASA.
- Feng Tian and Mike Liemhon: Modelling team coordination.
- Helmut Lammer, Vladimir Airapetian, Arnaud Beth: Planetary and exoplanetary exospheres modelling.
- Joachim Saur: Special liaison for astrophysical spectroscopy corrections.

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