9.8 Evaluation of ESCAPE proposal

9.8.1 Requirements

a. Completeness of proposal
   [Is the information of sufficient quality to allow for an informed opinion?]

The proposal, supported by the answers to the questions, demonstrates that the ESCAPE mission is of high scientific quality, comprehensive, and it clearly outlines open issues. It is completed with a high-level overview of the state-of-the-art, scientific challenges that ensue and the logical deduction of the objectives and traceable requirements. The proposal describes the comprehensive set of measurements that are required for establishing exospheric altitude profiles of density, temperature, ions and neutrals composition (including isotope ratios) and their variations in response to environmental changes. In addition instruments are foreseen for recording the upflow mechanisms at exospheric altitudes and the modification of magnetospheric processes by the admixture of heavy ionospheric particles. A management scheme describes the organization of the project through the different mission phases. The responsibility of the core team members is outlined in some detail.

b. Mission scientific value
   [Is the mission of the right scientific calibre to be considered in the frame of the present call?]

The proposal describes a mission dedicated to investigate the escape of neutral and charged particles from Earth's atmosphere. The two main questions are: (1) How and at what rate is Earth losing its atmosphere to space? (2) What are the dominant escape mechanisms and their dependences on the drivers? For accomplishing the related studies a comprehensive suite of particle and field instruments is foreseen. In addition a payload for remote sensing of auroral processes and ring current dynamics is proposed.
The mission addresses fundamental questions regarding the evolution of the Earth's atmosphere. ESCAPE constructively combines remote sensing and in-situ near-Earth space measurements to build a comprehensive and quantitative picture of the exosphere. In addition it monitors the associated fundamental atmospheric escape mechanisms. It promises to provide a critical breakthrough in the understanding of the history and evolution of Earth's atmosphere by studying simultaneously the mechanisms for thermal and non-thermal escape. The strategy is to obtain reliable values in the well-accessible Earth environment for the actual particle gains and losses. These numbers shall be the basis for modelling the past and future evolution of the Earth's atmosphere.

c. Need for access to space
   [Does the proposed science need to be performed from a space facility?]

The process of atmospheric escape takes place in the exosphere (above 500 km). This is an altitude range well accessible by satellites. Very important for achieving the science goals are the in-situ measurements of particles and fields. There is no alternative technique for determining the ion and neutral composition (including the isotope ratios) or their energies remotely from ground. A further important task of this mission is monitoring the distribution of escaped particles in the inner magnetosphere. That also requires in-situ measurements. The admixture of heavier ions to the typical magnetospheric plasma can greatly modify the processes in that region.

9.8.2 Science value

How valuable is the science return of the mission as claimed in the proposal?

Strengths:

The proposal lists a number of key scientific questions. These concern the different types of atmospheric escape mechanisms and the amounts of escaping species from the various locations. These are particularly important if we want to understand long-term impacts on climate and planet habitability.
The issues addressed concern critical features of the evolution of planetary atmospheres. Of particular interest is the determination of the relative escape rates of different species, e.g. oxygen and nitrogen, with the overall aim to understand the present-day anomalous nitrogen-to-oxygen ratio on Earth and its evolution on geological timescales.
By monitoring the effect of the heavy escaped particles on the dynamics of the magnetosphere ESCAPE will provide, as spin-off information, their influence on auroral and magnetospheric activities.

Weaknesses:

It is stated that the results obtained on Earth will be used as a reference for modelling the atmospheric evolution of our neighbour planets Mars and Venus. But since the environmental conditions at these planets are quite different from Earth (e.g. no intrinsic magnetic field, absence of life) the significance of the results is questionable.

Conclusions:

The science return of the proposed mission is valuable. It should provide for the first time a very thorough characterisation of atmospheric loss processes on Earth, thus providing new constraints on the Earth's atmospheric evolution.

9.8.3 Scientific feasibility

a. Can the proposed science be achieved with the proposed mission?

Strengths:

The proposed instrumentation and the mission profile that is foreseen to be fully adequate to properly address the science objectives. The proposed science to diagnose thermal and non-thermal escape is split into two parts. At lower altitudes (500-2000 km), within the exosphere, it is foreseen to obtain a quantitative picture of the various elements populating the topside atmosphere. Vertical profiles of density and temperature shall be obtained for the various different environmental conditions. In addition, the different processes for uplifting the particles in that region will be deduced. Instruments foreseen for providing an inventory of the species available for escape are the mass spectrometer (INMS) providing neutral and cold ion composition. Similarly, the cold ions instrument (WCIMS) provides ion composition and temperature. Electron density and temperature can be derived from the Langmuir probe (SLP). Vertical profiles of neutral density and temperature can be derived from the scans of the UV spectrometer (UVIS).
The other prime task is the quantification of escaped particles in the inner magnetosphere and the dependence on ambient conditions. These measurements are made on the outer part of the elliptical orbit (<6 Re). Accounting for the fact that a large majority of escaped ions in the magnetosphere is cold (few eV) the light ion analyser (MIMS) starts measuring at 5 eV/q and the heavy ion analyser

(NOIA) at 10 eV/q. In order to allow for proper operation in this low-energy range an active spacecraft potential control (ASPOC) is foreseen. Other escaping ions have been accelerated to high energies. They are sampled by the energetic ion analyser (EMS). An energizing mechanism is transverse heating by electromagnetic waves, which are monitored by the WAVES instruments. Another process is charge exchange between energetic ions and neutrals. The escaping fast particles are monitored by the energetic neutral atoms imager (ENAI).
The single-spacecraft payload combines in-situ and remote-sensing measurements, and superposed epoch analysis allows to construct density profiles over large parts of the orbit. The eccentric polar orbit offers the bonus of natural perigee evolution to survey the lower exosphere and the inner magnetosphere at all latitudes.

Weaknesses:

ESCAPE is a very ambitious mission with a long list of proposed measurements. The rather short dwell time in certain regions, e.g. the exosphere, is due to the highly eccentrically orbit. It may be challenging to derive altitude profiles that improve current atmospheric models for all the required measurements, e.g. temperature, compositions and energy spectra for the ions and neutrals with the required accuracy. It is known that these quantities vary strongly with local time, season and solar/magnetic activity. The largest escape rates occur during rare high-activity periods, for which it is difficult to build reliable statistics.
Measurements at low and high altitudes generally do not occur at conjugate locations (on the same magnetic field lines). This requires a combination of remote sensing with in-situ measurements and indirect comparisons between source-region conditions and the quantification of atmospheric outflow effects in the inner magnetosphere.
Even if the various escape mechanisms at Earth, both hydrodynamic and electrodynamic, are planned to be studied in detail to allow for a successful transformation of the relevant processes to neighbouring planets, constraining the modelling of their atmospheric evolution will be extremely challenging. These models involve a large number of parameters, and the proposal doesn't provide a convincing case of the effectiveness of the mission in this respect.

Conclusions:

Overall, the proposed mission is well equipped with a suitable scientific payload providing the required measurements. In several cases the measurement ranges of the instruments are even overlapping. Possible interferences between the various instruments have been addressed in the proposal.
It was not made clear whether composition and temperature in the lower part of the orbit (exosphere) can be obtained with the required accuracy due to the short dwell time of the satellite in that region. The limitations are inherent to highly eccentrically orbits. For mitigation, supporting measurements from other facilities such as radars (e.g. EISCAT_3D) or LEO satellites may be included in the concept. There are remaining doubts on the relevant applications to other planets.

b. Are there any issues not mentioned in the proposal that could hamper the proposed scientific return?

Living organisms actively contribute to the evolution of the terrestrial atmosphere, thus adding a significant contribution to the atmospheric evolution which cannot be captured with ESCAPE. This could hamper the proposed scientific return regarding past and future evolution of the Earth's atmosphere. Likewise, the application of the results obtained on Earth to other planets will probably be complicated by the effect of biological activity.

9.8.4 Timeliness of mission

Is the M5 time frame appropriate for this mission? Why?

From the scientific point of view there are no strong arguments for a particular time interval. During the proposed 3-year minimum mission time varying parts of a solar cycle are covered. Solar minimum phases should be avoided. A strong argument for the timeliness is the development state of the required instruments. Taking advantage of recent technological development, the instruments INMS and WCIMS are capable of separating between Nitrogen and Oxygen ions and neutrals. The differentiation between these elements is one of the important requirements.
Concerning synergies with ground-based observations the time frame is appropriate, as EISCAT_3D will have been operating for a few years ("mature and ready for observations by 2029"). A much later launch could reduce the value of synergy because of the aging facility.

9.8.5 Competitiveness and complementarity with other projects

a. Are there other space- or ground-based facilities addressing similar science goals?

Ion outflow has been a continuing topic of interest since the 1970's. The available capabilities of many space missions on polar orbits (e.g. DE-1, DMSP, FAST, Cluster, ePOP) have been sufficient for a comprehensive study of atmospheric escape. None of them provided an optimized dataset to reveal the properties of the exosphere and associated escape mechanisms simultaneously and in the necessary detail.
Similarly, ionospheric radars like EISCAT are able to monitor important properties of upflowing ions. But these are very localized and cover only the lower part of the affected region. All our knowledge is thus based on poor or patchy measurements from different missions and instruments that are either difficult to combine and not targeted specifically at mass resolution.

b. If so, how does the proposed mission compare with them or complement them?

The ESCAPE mission is more focused; thus, it will provide major advances in our understanding of the outflow processes from the quantitative characterisation of the exospheric inventory and its dependence on external drivers. This has not been provided by any of the previous missions. With the help of the advanced instrumentation quantitative flow rates from the different source regions can be expected.

c. Is the science output of the mission self-contained or does it require complementary data from other missions or from ground-based observations?

The mission is mostly self-contained. It will perform all the measurements that are required to describe the chain of processes from the source region out to the inner magnetosphere. Complementary environmental data like solar EUV flux, magnetic activity monitoring, and solar wind input are needed and expected to be available as standard space weather products.
Supporting ground and LEO space-based data will enhance the significance of the scientific output. A synergy with EISCAT_3D for conjugate observations is foreseen.

d. What is the expected impact of the proposed mission in the relevant scientific field(s)?

Strengths:

The ESCAPE mission proposes to investigate fundamental processes of atmospheric evolution, which are of growing interest among a larger range of scientific communities. Technically it is now possible to perform the measurements relevant for atmospheric losses sufficiently accurately. The results will include the composition of the upper atmosphere and the isotopic ratios. All the various acceleration processes shall be determined, independent of their relevance for the atmosphere on Earth. These are needed for better constraints on fundamental escape models. A complete overview of acting processes will help to understand the long-term atmospheric evolution also of other planets boosting renewed enthusiasm for this science topic.
The provision of auroral imaging movies may be a noteworthy by-product for a wider space science community.

Weaknesses:

It is not clear whether all relevant species in the exosphere can be measured with sufficient accuracy and their variability fully characterized. The contribution of living organisms to the Earth's atmospheric evolution is expected to greatly complicate the application of results from Earth to the atmospheres of other planets.
The present range of environmental variations (e.g. solar activity) may not be sufficient for drawing general conclusions on atmospheric evolution over geological timescales.

Conclusions:

The impact of the proposed mission is relevant for the investigation of the terrestrial atmosphere. But there are many variables influencing our environment, and some of them have not been well addressed. It may be doubted that the results obtained by ESCAPE have great impact on the interpretation of planetary atmospheres.

9.8.6 Is the proposed scientific collaboration scheme likely to produce the promised results? Why?

Strengths:

This proposal is supported by a strong team of PIs. All of them have successfully participated with their instruments in other satellite missions. Also the modelling and interpretation team includes strong partners who have convincing track records in magnetospheric and planetary physics. The leadership and advanced experience of the committed experts makes it likely the scientific goals will be achieved.

Weaknesses:

The core science team consists primarily of magnetosphere / space physics experts. The scientific objectives may suffer from the lack of upper atmosphere / thermosphere experts.

Conclusions:

The team of proposers has a lot of expertise needed for the instrumental equipment of the mission and the scientific interpretation of the derived data. An inclusion of additional experts on complementary fields would enhance the scientific yield.

9.8.7 Overall assessment of the proposal

The ESCAPE mission proposes to measure the loss of ions and neutrals from the Earth's atmosphere into space, and to investigate the processes at work. The mission has been designed in order to fulfil the two main tasks (i) conduct detailed surveys of the exospheric inventory and its dependence on environmental conditions, (ii) quantify the amount and composition of escaping atmospheric particles. Planet Earth provides a relatively easy access to the relevant regions and it possesses a wide range of processes that are important for particle outflow.

The derived results may provide some information applicable also to other planets. However, the environmental conditions are quite different on Venus and Mars. Also, the influence of living organisms on the atmosphere has not been considered in sufficient detail. Both these facts make the transfer of obtained results to neighbouring planets questionable.

The mission is relevant because the results will be of interest for several disciplines (e.g. atmosphere and space physics, planetology). It is timely because the available instruments (both on ground and space) provide the resolution that is required for addressing the proposed scientific goals.

There are unavoidable limitations of such a single-satellite mission. Obtaining a sufficiently detailed inventory of the exosphere with all the dependences to the various environmental conditions will be challenging. The spacecraft will pass the perigee region within a short time (some ten minutes) on its very eccentric orbit. Statistical analyses (superposed epoch analysis) are required for connecting the outflow measurements to prevailing conditions in the source region. For improving the comparisons dedicated EISCAT_3D radar measurements are planned in close conjunction with ESCAPE.