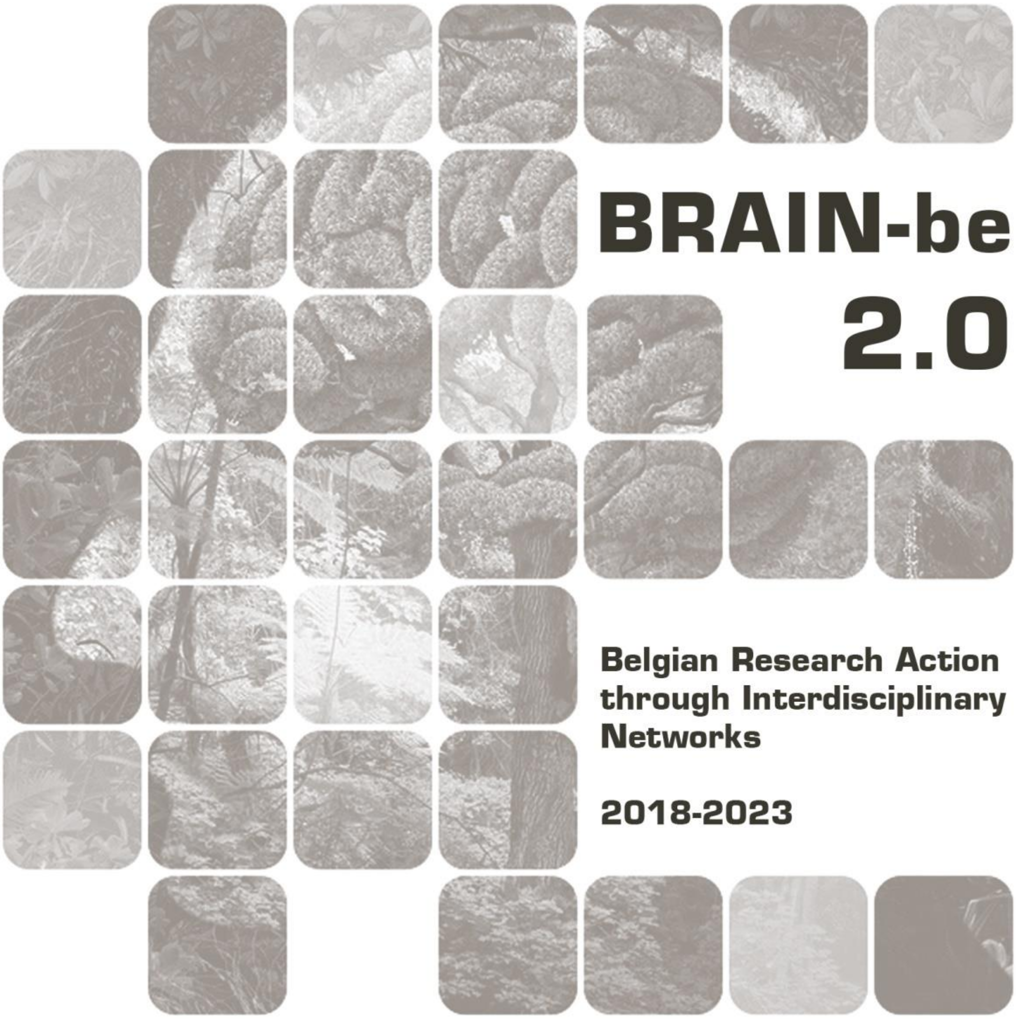

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Belgian Research Action
through Interdisciplinary
Networks

2018-2023

IPA

Impact of Planetary magnetisation on Atmospheric erosion

Romain Maggiolo (Royal Belgian Institute for Space Aeronomy)

Pillar 1: Challenges and knowledge of the living and non-living world

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NETWORK PROJECT

IPA

Impact of Planetary magnetisation on Atmospheric erosion

Contract - B2/202/P1/IPA

FINAL REPORT

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1. INTRODUCTION

The evolution of planets and their capability to build and maintain a hydrosphere and an atmosphere is driven by multiple factors. Some are internal like the composition, structure, and thermal state of their internal core, mantle, lithosphere and crust. Some are related to the planetary environment like the properties of the star and the distance at which the planet orbits around it or the exchange of matter and energy between the planet and space. The evolutional pathway of planetary atmospheres is thus a complex problem that depends on many parameters.

This is evidenced by the differences between the atmospheres of Venus, Earth and Mars despite their relatively similar mass and distance to the Sun. The atmospheric pressure at the ground level on Venus is about 100 times higher than at Earth. Venus' atmosphere is rich in carbon dioxide which greenhouse effect contributes to the high temperature on the Venusian surface. Mars's atmosphere is also rich in carbon dioxide but very tenuous, with a ground pressure about 1/100 of the Earth ground pressure. Among those three planets, the Earth is the only one that contains a large amount of water.

One of the potential reasons for the divergent evolution of the atmospheres of Venus, Earth and Mars is the way their atmospheres interact with the space environment. For Mars, there are clear evidence that the planet was rich in water and lost it into space. Satellite measurements have also shown that the atmosphere of Venus, Earth and Mars are currently slowly leaking into space at a rate of a few kilograms per seconds.

Historically, it has been considered that the presence of a large-scale magnetic field protects planetary atmospheres. Indeed, a large-scale magnetic field leads to the formation of a magnetosphere around the planet. The magnetosphere of magnetized planets is much larger that the planet itself and diverts most of the solar wind particles. Magnetospheres where thus seen as a shield that prevents the solar wind from blowing off planetary atmospheres. Earth possesses a large-scale magnetic field contrary to Venus and Mars and is the only of these three planets to have maintained a stable hydrosphere. Furthermore, Mars was rich in water and was magnetized after it formed. The loss of water from Mars and the loss of its large-scale magnetic field were more or less concomitant. For a long time, it was thus taken as granted that a planetary magnetic field protects planetary atmosphere and is necessary for a planet to maintain a hydrosphere.

However, this paradigm has been challenged during the last decades. Indeed, the accumulation of satellite measurements has shown unambiguously that the Earth magnetosphere is currently leaking into space, at a rate similar or even higher than the atmospheres of Venus and Mars. Furthermore, it seems that Mars was magnetized during a longer period than initially thought and that it may have lost a significant amount of water while still magnetized. The scientific community is thus reconsidering the effect of planetary magnetic fields on atmospheric escape.

In order to assess the effects of planetary magnetic fields on atmospheric stability it is necessary to consider geological time scales. Indeed, atmospheric escape is a relatively slow process (the current atmospheric loss rate is too low to have a significant effect on the atmosphere). Understanding its effect on the long-term evolution of planetary atmosphere requires going back billions of years in time. This complexifies the problem. Indeed, the solar system evolves with time. The Sun is an active star which was much more active in the past, blowing a much stronger solar wind and emitting a much higher flux in the ultraviolet range. The planets have also evolved, their magnetic field has changed but also their atmospheric composition under the effect of a more active Sun but also due to internal process like volcanism or, for Earth, to the development of life.

Only tiny evidence is left from the properties of the early solar system and obviously no direct observations of the solar and planetary conditions billion of years ago exist. Furthermore, it remains very difficult -if not impossible- to properly model the interaction between a planetary atmosphere and a star. It is thus a big challenge to assess the past atmospheric escape of planets and how their magnetization level impacts it. Indeed, even if a large-scale magnetic field do not protect planetary atmospheres for current conditions, it may not have been the case in the past when the Sun was more active.

The difficulty to build physic-based models and the large amount of data related to atmospheric escape gathered during the last decades drive our approach to improve the current knowledge of the past atmospheric escape. We choose an hybrid method: building a semi empirical model. Such model aims at extrapolating observations made for current conditions to past conditions. This extrapolation is made using physical consideration and a magnetic field model. At the start of the project, the preliminary version of the semi empirical model could only artificially vary the planetary magnetic field but was not accounting for the evolution of the Sun. The goal of this project was to implement a dependency on the solar wind and on the solar flux in the ultraviolet range in order to account for the higher activity of the Sun in the past.

2. STATE OF THE ART AND OBJECTIVES

2.1 State of the art

In the solar system, Earth is currently the only planet with an atmosphere rich in water. Venus and Mars, despite their relatively similar mass and distance to the Sun provide very different conditions. Contrary to Earth, they are depleted of water and have CO_2 rich atmospheres, very hot and dense for Venus and cold and tenuous for Mars. Many factors could have impacted the evolution of the atmospheres of these three planets (see the reviews by Lammer et al., 2018 and Dehant et al., 2019). Among them, a difference in the atmospheric escape rate has been suggested as a potentially significant contributor to the diverging evolution of the atmospheres of these three planets, in particular in the young solar system when the Sun was more active than nowadays (e.g., Lammer et al., 2008). It has been alleged that the presence or absence of a large-scale magnetic field on a planet plays a role in the evolution of atmospheres. Indeed, the intensity and morphology of planetary magnetic fields affect the interaction of the planets with the solar wind and thus the escape of ionized material from their atmospheres (Lundin et al., 2007). Magnetized planets like Earth are surrounded by large-scale magnetospheres which isolate them from a direct interaction with the solar wind. On the other hand, unmagnetized planets like Venus and Mars, despite the existence of crustal magnetic fields (for Mars) and of an induced magnetosphere (a small size magnetosphere created by ionospheric currents) interact more directly with the solar wind (see Figure 1). **The paradigm has always been that a large-scale magnetic field prevents the atmospheres from being blown off by the solar wind and thus protects the atmosphere of planets** (e.g., Lundin et al., 2007 and references therein).

However, recent observations around Earth, Mars and Venus challenge the protective effect of planetary magnetic fields on atmospheres. Direct measurements of the ion escape rate were made available by the Venus Express (VEX) probe (2006–2014). Oxygen escape rate estimates generally fall in the range of 3–6 10^{24} s^{-1} for ions in the energy range 10 eV/q–25 keV/q (Fedorov et al., 2011; Nordström et al., 2013). Lundin et al. (2011) tried to compensate for the difficulty to measure low energy ions due to the spacecraft potential. They estimated the oxygen outflow over all energies to be 1.2 10^{25} s^{-1}. Interestingly, Barabash et al. (2007) showed that that ion escape at Venus is dominated by O^+, He^+ and H^+ with an estimated ratio of 1.9 for H^+ and O^+ close to the H/O ratio in water, suggesting that ion outflow may deplete the Venusian atmosphere in water. The Mars Express (MEX) spacecraft, launched in 2003, has provided measurements of escaping planetary ions from Mars for a full solar cycle. Nilsson et al. (2011) estimated the loss rate of oxygen atoms to 3.0 ± 0.3 10^{24} s^{-1}. Since 2014, the MAVEN spacecraft provides measurements of ion outflow from Mars. Jakosky et al. (2018) estimated the average net global loss rate for O atoms to 5 10^{24} s^{-1}, in line with Mars Express results.

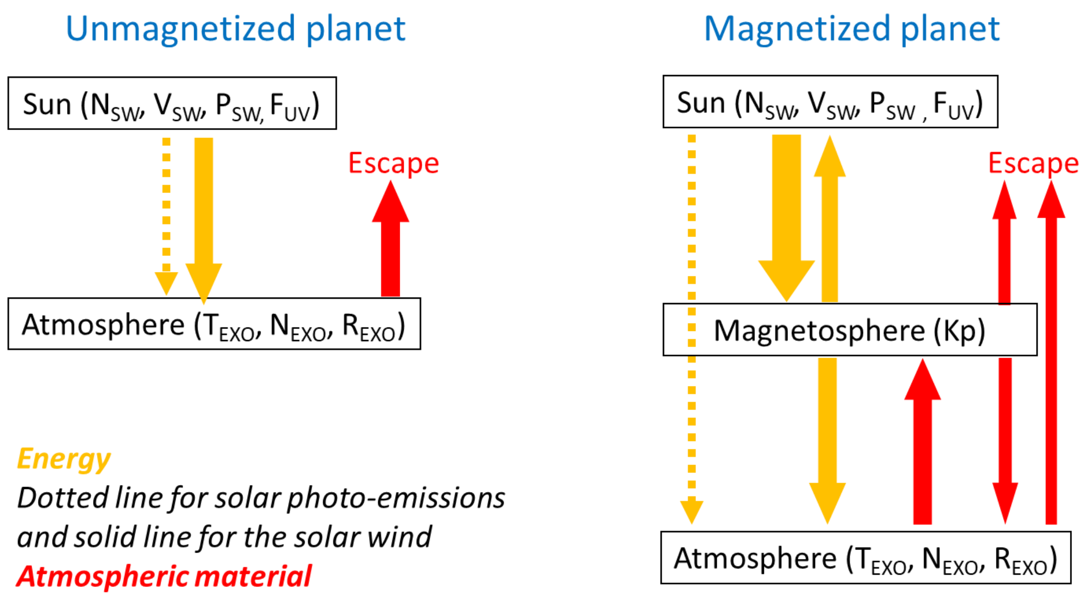

Figure 1: Schematic description of the mass and energy transfer between the Sun and the atmosphere for an unmagnetized planet (left) and for a magnetized planet (right). The parameters that will be included in our semi-empirical model are indicated.

Ionospheric ion outflow observations at Earth obtained before the launch of the Cluster satellites in 2000 are detailed in the review by Yau et al. (1997). The dominant ion species flowing out from Earth ionosphere are H^+, O^+ and He^+. Using measurements from the DE-1 satellite, Yau et al. (1988) estimated that the integrated ion outflow rate ranges between ~2.5 10^{25} s^{-1} and 10^{26} s^{-1} for H^+. Thermal outflow was investigated with the Akebono spacecraft and the estimated flux is of the order of 10^{24} s^{-1} - 10^{25} s^{-1} for O^+ and H^+ (Cully et al., 2003). The Cluster mission launched in 2000 made a big breakthrough. An indirect method to detect low energy ions (hardly measurable by ion detectors) using spacecraft potential and electric field measurements has been developed (see Engwall et al., 2006). It led to a significant upward re-evaluation of the flux of low energy ions (in the eV range) above the polar cap. New estimates made with this method are in the range of $10^{26}s^{-1}$. In addition, Cluster observations at lower latitude in the plasmasphere revealed that it is associated with a low energy (e few eVs) ion escape rate of a similar magnitude, either through the plasmaspheric wind (Dandouras et al., 2013) or via plasmaspheric plumes (Darrouzet et al., 2008). Furthermore, Cluster provided a better characterization of ion outflow from the main outflow regions like the cusp region or the auroral zone and on its dependence on the geomagnetic and solar activity level (e.g., Marklund et al., 2011; Maggiolo et al., 2011; Maes et al., 2016; Nilsson et al., 2012; Schillings et al., 2019). Based on Cluster observations, the flux estimate for energetic ion outflow (from tens of eVs to keVs) at Earth is in the range of 10^{26} s^{-1}.

In addition, planetary magnetic fields may prevent atmospheric erosion by trapping ionospheric ions and returning part of them to the atmosphere. Neutral atmospheric particles are considered the fate of ionospheric ions thanks to their elongated polar orbit and mass discriminating ion detector. Cluster allowed a much better characterization of the fate of outflowing ionospheric ions pointing to a high ionospheric ion loss rate into the solar wind both on the dayside magnetosphere (Slapak et al., 2013) and in the magnetospheric tail (e.g., Haaland et al., 2009, 2012; Nilsson et al., 2012; Slapak et al., 2017). The Earth magnetosphere is thus not efficient at returning outflowing ions into the ionosphere contrary to what was thought before the Cluster era (Seki et al., 2001). Most outflowing ions are lost in the solar wind.

Measurements thus reveal that ion outflow rates from Venus, Mars and Earth are relatively similar (if not higher on Earth).

The observations made by probes around Venus, Earth and Mars challenging the protective effect of planetary magnetic fields on atmospheres are made for current solar and atmospheric conditions. One big limitation for assessing the past escape rate of Venus, Earth and Mars lies in the difficulty to extrapolate observations made for current atmospheric and solar conditions to the past.

Indeed, ion outflow rates at Venus, Earth and Mars are highly variable and significantly increase with solar activity (typically by one order of magnitude, see for instance Yau et al., 1997; Edberg et al., 2011; Nilsson et al., 2011). Observations of Sun-like stars in different stages of their evolution suggest that the Sun had more sunspots and flares in the past, which, undoubtedly, changed the escape conditions of the planets in the solar system (Lammer et al., 2009). Furthermore, atmospheric composition and temperature have varied over time. The Earth's atmosphere is an emblematic example of an atmosphere that has greatly changed, with the apparition of oxygen in large quantities after about 2.5 Gyr ago (Catling, 2014).

Estimating the total atmospheric loss over geological times is a complex task. A first limitation is our limited knowledge of past solar and planetary conditions. The past properties of the Sun can be estimated with stellar models and be constrained by empirically derived values for stars of various ages, as done for instance for the solar wind of the young Sun (e.g., Airapetian and Usmanov, 2016). Past atmospheric parameters and their evolution over time can be inferred by using isotopic ratio. For instance, the deuterium to hydrogen ratio at the surface of Venus suggests that the planets had large amounts of water in its atmosphere (e.g., Taylor et al., 2018). Geological evidence also points to the presence of significant amounts of water on Mars in the past (e.g., Salese et al., 2019 and references therein). We thus rely on models to estimate the past atmospheric properties of the planets, but they always have to be constrained by arbitrary parameters (e.g., Johnstone et al., 2018). Similarly, the past magnetic moment of planets can be inferred from the imprint it has left on rocks; we have evidence for the presence of a large-scale magnetic field on Mars thanks to the detection of a remnant magnetic field in its southern hemisphere.

A second limitation results from the difficulty to model the outflow from planetary atmospheres into space, even for the current atmospheric and solar conditions. Indeed, it remains challenging due to the inherent difficulty to model the coupling between regions with different plasma regimes (the ionosphere, the solar wind and the magnetosphere, see Welling et al., 2016). Furthermore, various escape processes coexist, and they may not require the same method to be modelled accurately. Consequently, the total atmospheric loss over geological times is estimated from the current escape considered as constant without taking into account the varying forcing parameters (i.e., the solar parameters) and the varying atmospheres of planets. Recently, several groups tried to model the past evolution of planetary atmospheres (e.g., Persson et al., 2019 for Venus; Kislyakova et al., 2020 for Earth; Dong et al., 2018 for Mars). However, at this stage no model is able consider all escape processes consistently.

Considering the difficulty to build a model of atmospheric escape and the large amount of data gathered around Venus, Earth and Mars, we thus decided to develop a semi-empirical model of atmospheric escape considering the effect of a varying planetary magnetic moment (Gunell et al., 2018). With this model, we were able to vary the magnetic moment of three fictitious planets with atmospheric properties similar to the present-day atmospheres of Venus, Earth and Mars. Interestingly, this model shows that atmospheric escape does not depend monotonically on the planetary magnetic moment. We identified two peaks of the escape rate, one at low magnetization levels (a few percent or less of the magnetic moment of present-day Earth) and another one at high magnetization levels (about thirty times the magnetic moment of present-day Earth) that corresponds to a peak of cusp ion outflow and is dominated by oxygen.

The starting point of this project is a semi empirical model of atmospheric escape developed at BIRA/IASB (Gunell et al., 2018). It considers three fictitious planets with current Venus-like, Earth-like and Mars-like atmospheric properties for which we artificially vary the magnetic moment. This model is built using the observed outflow rates at Venus, Earth and Mars (Q) and scaling laws. It takes into account seven outflow processes, which, according to our current observational knowledge, account for most of atmospheric lost into space: Jeans escape, dissociative recombination, cross-field ion loss, ion pick-up, sputtering, polar wind and polar cusp escape. The total number flux for each of these processes is described by an analytical formula. It uses escape rates found in the literature except for Jeans escape which is computed analytically and scale them as a function of the planetary magnetic moment using physico-chemical considerations and a magnetic field model. Other parameters are considered as constant.

The main result of the Gunell et al., (2018) semi-empirical model, from which the IPA project started is shown in Figure 2 which shows the estimate of oxygen and hydrogen escape rate for fictitious Venus-like, Earth-like and Mars-like planets with a varying magnetic moment for current solar and atmospheric condition.

At this stage, the output of the Gunell et al. (2018) model could be expressed as $\Phi_O(M_P)$ and $\Phi_H(M_P)$ where Φ_O and Φ_H respectively correspond to the oxygen and hydrogen escape rate and M_P the planetary magnetic moment. All other parameters that could have an influence on the escape rate are kept constant.

2.2 Research objectives

The main objective of this study is to assess the impact of planetary magnetic fields on the escape of planetary atmospheres in order to improve our understanding of the past evolution of the atmospheres of rocky planets. At this stage, we have developed a semi-empirical model of atmospheric escape considering the effect of the planetary magnetic moment for averaged current solar and atmospheric conditions. **We plan to develop this model in order to vary other parameters like the magnetospheric activity level, the solar activity level and atmospheric conditions. We want to be able to assess the impact of planetary magnetic field on atmospheric escape for conditions more representative of the past solar system**.

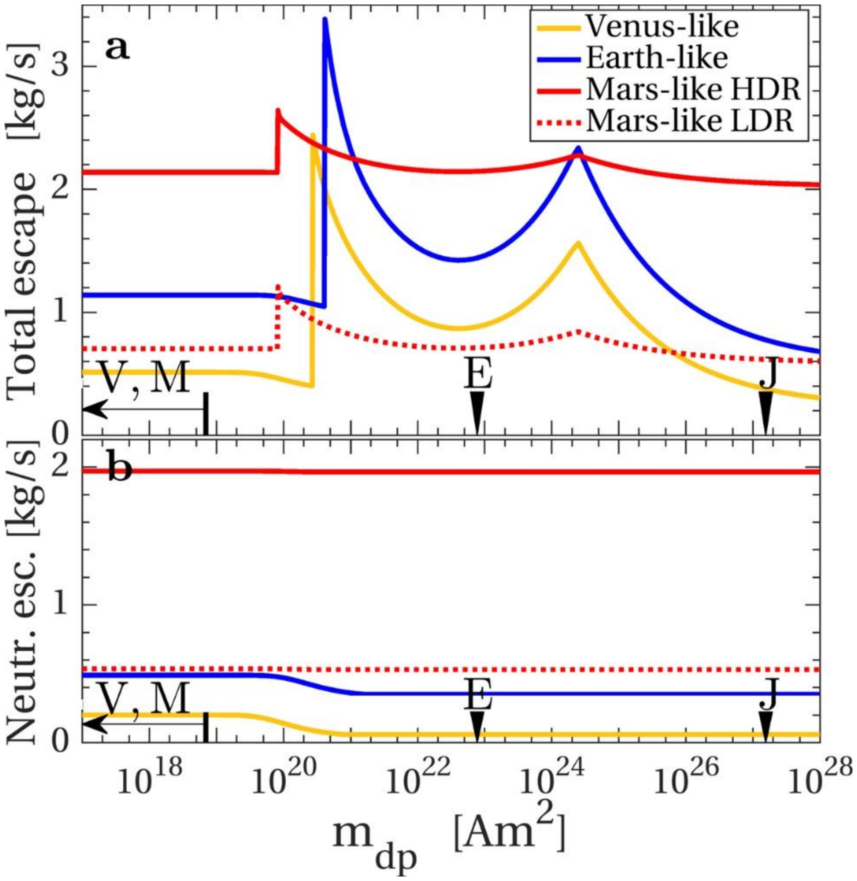

Figure 2: From Gunell et al. (2018). Mass escape rates for Venus-like, Earth-like, and Mars-like planets. Panel a: total mass escape rates. Panel b: neutral mass escape rates. For escape from Mars, the two curves represent high (HDR) and low (LDR) estimates of dissociative recombination of molecular oxygen. The magnetic moments of present-day Earth and Jupiter are marked on the horizontal axis for reference. The horizontal arrow indicates the unmagnetised character of Venus and Mars.

3 METHODOLOGY

3.1 Overall Approach

The originality of our approach consists in building a semi empirical model of atmospheric escape. This approach combines the use of measurements made for current solar and planetary conditions and of a magnetic field model and physical considerations to scale them for different solar and planetary environments. We have chosen this approach as it aligns closely with the current state of knowledge in this field. Moreover, our team benefits from extensive expertise in both spacecraft data analysis and modelling the interaction between the ionosphere and magnetosphere. With this approach, we are developing a specific expertise at BIRA/IASB and position our group in the field of atmospheric stability and planetary habitability.

Our overarching methodology to scale current observations combines a scaling of the size of the source region and a physical scaling for each escape mechanism:

$$Q_i = Q_{i,0} \,.S\,.A$$

Where $\boldsymbol{Q_i}$ is the total escape rate of the escape mechanism ***i***, $\boldsymbol{Q_{i0}}$ the reference escape rate for the mechanism ***i*** obtained from observations for current conditions, ***S*** is the physical scaling factor either computed analytically from physical considerations or obtained from the extrapolation of empirical formulas. ***A*** is the effective area or volume of the escape process computed using a magnetic field model and physical considerations. We consider 7 escape mechanisms (Jeans escape, ion pick-up, ion sputtering, dissociative recombination, cross-field ion loss, polar wind, polar cusp escape). We refer the reader to Gunell et al. (2018) for a detailed definition of these 7 escape mechanisms.

The variations of solar and atmospheric conditions can modify the size of the escaping region and the flux density of material escaping from the atmosphere. We proceed step by step to include more parameters in the semi empirical model in order to apply it to past conditions when the Sun was more active, and the planetary environment was different from now. This requires integrating new data into the model, improving the physical scaling of data and, if necessary, producing new datasets if those required for developing the model are not available in the scientific literature. This approach determined the definition of the tasks performed in the project.

We obtained observational results not initially anticipated. We also adapted the development of the model according to needs identified thanks to new scientific collaborations initiated during the project, but also according to issues that emerged during the development of the model.

The task performed during the project thus slightly differ from those proposed initially. While the overall methodology didn’t change, we had to adapt them as summarized below and detailed in the following section.

Below is a summary of the initially proposed work packages and tasks, along with descriptions of the adjustments made during the project. Additionally, we offer a concise update on the status of each task in comparison to the original project methodology.

3.2 Detailed methodology and evolution compared to the initial plan

<u>Work Package 1: Parametrize the effect of varying solar activity.</u>

This Work Package has been performed according to the initial plan with just one change. **We skipped *Task 1.1*** (the dependence on geomagnetic activity as parametrized by the Kp index). Indeed, we quickly realized that this step was unnecessary as geomagnetic activity is defined for current Earth condition only. Geomagnetic indexes cannot be extrapolated to other planets or past conditions.

Task 1.2 (dependence on solar wind density (N_{SW}), velocity (V_{SW}) and dynamic pressure (P_{SW})) and **task 1.3** (dependence on atmospheric parameters (at the level of the exobase: altitude (R_{EXO}), temperature (T_{EXO}) and density (N_{EXO}) of the exobase) and solar EUV/UV flux (F_{UV})) **have been performed according to the initial plan and achieved successfully**. We did not encounter any difficulties in this work package for magnetized planets. The model is currently capable of estimating the escape rate of oxygen and hydrogen for a magnetized planet of variable mass and magnetic field magnitude on geological time scales. It accounts for the influence of solar activity variations, specifically of the solar wind and solar UV/EUV flux and for their effects on the atmosphere. The model was applied to Earth to estimate the quantity of oxygen that has escaped into space over the last 2.5 billion years, since the Great Oxidation Event. **A publication on this subject is being finalized (task 1.4)**. For non-magnetized planets, the current version model requires further refinement in describing the loss of hydrogen and oxygen. Notably, the primary escape mechanism in this regime (ion pick up by the solar wind) sees its effectiveness decrease when the pressure of the solar wind is very strong (which was the case in the early solar system). This decrease in efficiency has yet to be precisely modeled. Nonetheless, despite this limitation, we have identified a high escape rate for weakly magnetized planets, raising the possibility that Mars may have experienced significant water loss during its period of (weak) magnetization (**task 1.4**).

<u>Work Package 2: Observational study of the energy flux of outflowing particles at Earth.</u>

An additional task has been introduced in connection with Work Package 3. Work Package 2 was defined as a preliminary step to compute the energy flux of escaping particles (Work Package 3). While conducting a thorough review of existing literature to identify potential missing datasets we realized that we could use available solar wind data and empirical formulas to assess the effect of the Earth magnetic field on the energy dissipation in the Earth upper atmosphere. **We published a study showing that the Earth magnetic field increases significantly the solar wind energy dissipation in the Earth atmosphere (Maggiolo et al. 2023)**.

The initial goal of this work package, performing a statistical study of the energy flux density of escaping particle in the cusp region of the Earth magnetosphere **is ongoing. We performed the tasks initially planned and decided to complement them with a further detailed data analysis**.

We initiated a collaboration with Audrey Shillings (Umea University, Sweden) a specialist of oxygen escape at Earth. Together we have built a database of Cluster observations of oxygen escape in the cusp region (**tasks 2.1 and 2.2**) and computed the escaping oxygen energy flux from the moments of their distribution function (density and velocity) as originally planned (**task 2.3**). However, the data treatment is not finalized yet as we identified a way to estimate the energy flux more accurately. We indeed realized that using the moments of the oxygen ions distribution function to compute the energy flux may be inaccurate. We thus decided to estimate this energy flux by directly integrating the oxygen energy distribution function. We developed a code to integrate the oxygen distribution function as obtained from the Cluster Science Archive (in pitch angle and energy). This new method is compared with the planed one and one publication on the escaping oxygen energy flux is in preparation (**task 2.4**).

Work Package 3: Develop a semi empirical model of the energy flux of escaping particles.

This work package was initiated but not finalized. The exploratory phase was achieved (**task 3.1).** We identified the mechanisms that dominate the energy flux of escaping atmospheric material and performed an in-depth bibliographical survey of observations related to the energy flux of escaping oxygen and hydrogen at Venus, Earth and Mars. One big limitation, already identified in the project proposal (see Work package 2), is the lack of observation of the energy flux of escaping oxygen and hydrogen from the cusp region, the most energetic escape route for ions at Earth. Thus, we haven't determined yet all the scaling laws to be used in this version of the model (**task 3.2**) and the production of a model for the energy flux and the subsequent interpretation of the results are tasks that remain pending (**task 3.3 and 3.4**)

Work Package 4: Uncertainty and sensitivity analysis

This work package represents a continuous effort to rigorously evaluate the model's accuracy and reliability. Most of the data or empirical formulas ingested in the model are associated error estimates. Furthermore, the past conditions (solar wind and solar UV flux, atmospheric composition, planetary magnetisation) are less constrained than initially anticipated during the project's preparation phase. As a result, we have **re-evaluated our strategy for assessing the uncertainty on the estimate of the flux of escaping oxygen and hydrogen**. Indeed, in order to apply our model to practical case studies, it appeared to be necessary to try various set of input parameters (planetary magnetic field, past solar wind models, past atmospheric composition). We have concentrated our efforts on testing multiple versions of the model with different sets of input parameters to constrain the range of variability in our model's results. Whenever possible, the results of the model were compared to observations. While we still considered the error propagation associated with the input parameters, the absence of precise error information for these parameters led us to the conclusion that this approach alone is inadequate for assessing the uncertainty in our model's results.

Work Package 5: Coordination, project management and reporting

The one-day kick-off meeting (task 5.1) and Mid-term conference (task 5.2) took place online due to the pandemic respectively on March 8, 2021, and March 17, 2022. As the development of the model is continuing after the end of the project, **we have postponed the close-out meeting to 2024**, after the end of the project. In complement we sent Maria Luisa Alonso Tagle, our PhD student working on this project, to a research stay at the Umea university in May 2023 (one week) where Herbert Gunell (member of the follow-up committee) and Audrey Schillings (our collaborator for the observational study) are working. In addition, we invited Audrey Schillings to come to our institute in September 2023. Thanks to this BRAIN project Romain Maggiolo had the opportunity to be invited as a member of the ISSI team "How Heavy Elements Escape the Earth: Past, Present, and Implications to

Habitability". This team groups researchers with various expertise closely related to the project. Note that the project was extended by 6 months and ended in September 2023.

Work Package 6: Data management

This work package was performed according to the proposed methodology. We created a website for the project (**task 6.1**). This website (https://ipa.aeronomie.be/) provides in open access an explanation of the model, a reference list and a list of the various run made with different versions of the semi empirical model, including some case studies (i.e., ancient Earth and ancient Mars) as planed in **task 6.3**. We have established a local database consisting of Cluster O^+ ions measurements from the CODIF instrument in the plasma mantle, as originally outlined in task 6.2. Furthermore, we are currently constructing a local database of the cusp ion energy flux. This database is being created by calculating the ion energy flux from both ion velocity and density, as well as through the direct integration of their distribution function. This task was not originally part of our initial project plan but has been added as an additional component. The evolution of the source code of our model can be followed through GitHub (**task 6.4**).

Additional work:

Below is a brief summary of tasks performed during the project that were not initially planned.

- We hired a PhD student, Maria Luisa Alonso Tagle, to work specifically on the development of the semi empirical model. She started by converting the model from MATLAB to Python and reorganised the program, with one independent module for each escape mechanism. This improves the flexibility of the model (it is now possible to modify, add or remove any escape mechanisms) and allows a better tracking of the various versions of the model. She is now actively participating in the development of the model.
- As stated above, a study not originally planned has been performed (Maggiolo, R., Maes, L., Cessateur, G., Darrouzet, F., De Keyser, J., & Gunell, H. (2022). The Earth's magnetic field enhances solar energy deposition in the upper atmosphere. Journal of Geophysical Research: Space Physics, 127, e2022JA030899. https://doi.org/10.1029/2022JA030899)
- Thanks to this BRAIN project Romain Maggiolo has been invited to be part of an ISSI teams about "How Heavy Elements Escape the Earth: Past, Present, and Implications to Habitability". We had two one-week meetings at ISSI (Bern, Switzerland) and are currently writing a large review paper about "Early atmospheric escape: Evolving atmospheric composition, magnetic field, and space environment with implications for the biogeochemistry of Earth-like planets" that will be submitted to Space Science Reviews.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

4.1 Scientific Results

Work Package 1: Parametrize the effect of varying solar activity.

This constitutes the core of the project. The primary objective of the semi-empirical model created within this project framework is to simulate the atmospheric escape of rocky planets across geological timescales, encompassing billions of years in the past. This ambitious aim allows us to estimate the historical loss of oxygen and water on Venus, Earth, and Mars, providing valuable insights into the mechanisms that determine a planet's habitability. In the future, this model can be adapted to various planetary environments, potentially serving as a tool to assess the potential habitability of exoplanets.

We initially built upon the Gunell et al. (2018) model, which calculates the escape rates of oxygen and hydrogen based on the planetary magnetic moment, while keeping other parameters constant. This model was employed to investigate the impact of a planetary magnetic field on atmospheric escape rates, revealing that magnetized planets can exhibit higher escape rates across a wide range of magnetization levels, primarily due to the escape of ions through polar caps and cusps.

In accordance with our project proposal, we have advanced this model to encompass the influence of solar activity variations and planetary environmental changes. The model now incorporates the number flux dependence on the planetary magnetic moment, on solar wind parameters and on exospheric parameters.

To summarize we started with a model providing the escape rate of oxygen Q_O and hydrogen Q_H as a function of the planetary magnetic moment m_{dp}:

$$Q_O(m_{dp}) \; and \; Q_H(m_{dp})$$

We further developed the model, and it now provides the escape rate of oxygen Q_O and hydrogen Q_H as a function of the planetary magnetic moment m_{dp}, the solar wind density N_{SW} and velocity V_{SW}, the solar wind UV flux F_{UV} and the exospheric density N_{exo} and temperature T_{exo}:

$$Q_O(m_{dp}, N_{SW}, V_{SW}, F_{UV}, N_{exo}, T_{exoSW}) \; and \; Q_H(m_{dp}, N_{SW}, V_{SW}, F_{UV}, N_{exo}, T_{exoSW})$$

This version of the model can estimate the atmospheric escape rate for past solar and atmospheric conditions. We applied the model to two case study which are detailed below.

Case study 1: Oxygen escape at Earth since the Great Oxidation Event

Context

The Great Oxidation Event marks a point in time at 2.45 billion years ago, when the amount oxygen on Earth increased abruptly due to the development of life (Figure, 3). Oxygen level rose from a trace gas to levels comparable to the current one (Kump, 2008; Lyons et al., 2014; Laakso and Schrag, 2017).

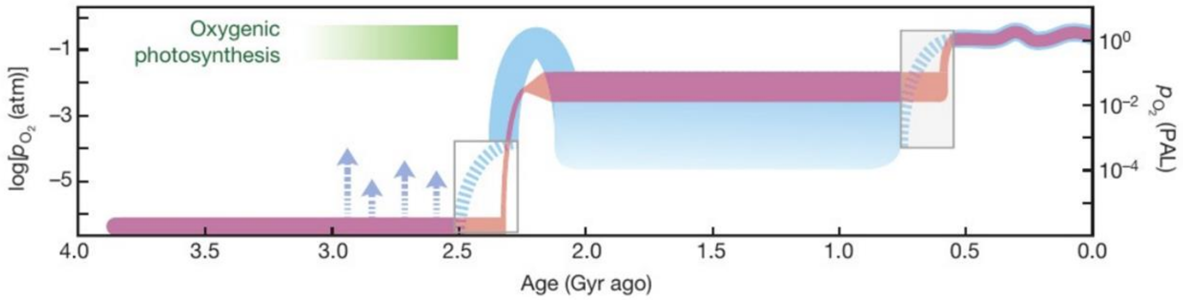

Figure 3: From Lyons et al. 2014. Evolution of the oxygen content in the Earth atmosphere during the last 4 billion years (Gyr). Oxygen levels remains at the level of trace until photosynthesis lead to the production of dioxygen. This increase of the oxygen content in the Earth atmosphere occurred about 2.5 billion years ago and was relatively quick. This event is referred to as the Great Oxidation Event.

Scientific question

How much oxygen and water did the Earth lost into space during the last 2.45 billion years?

State of the art

Modelling oxygen escape for the ancient Earth is challenging due to the different solar and planetary conditions in the past. Thus, few studies have attempted to determine the oxygen loss and therefore the water loss from Earth over geological time scales. The most recent studies (Kislyakova et al., 2020 and Grasser et al., 2023) consider only one escape mechanism, the polar wind.

Method

The most recent iteration of our model encompasses seven distinct escape mechanisms, namely, Jeans escape, ion pick-up, ion sputtering, dissociative recombination, cross-field ion loss, polar wind, and polar cusp escape. These mechanisms have been identified as the main escape route for atmospheric material into space. Our goal is to estimate the losses associated with each of these mechanisms, enabling us to calculate the total oxygen loss over the past 2.5 billion years. For each of the relevant escape mechanisms we account for the varying solar activity through the solar wind (parametrized by its density and velocity), solar UV flux, and Earth's magnetic field (Figure 4). The impact of the varying solar activity on the exospheric density and temperature is considered while maintaining a constant composition of the neutral atmosphere.

We use the best available proxy for the past Earth magnetic field magnitude (Schreider et al. 2019), for the solar wind density and velocity (Carolan et al. 2019) and for the solar EUV flux (Ribas et al. 2005).

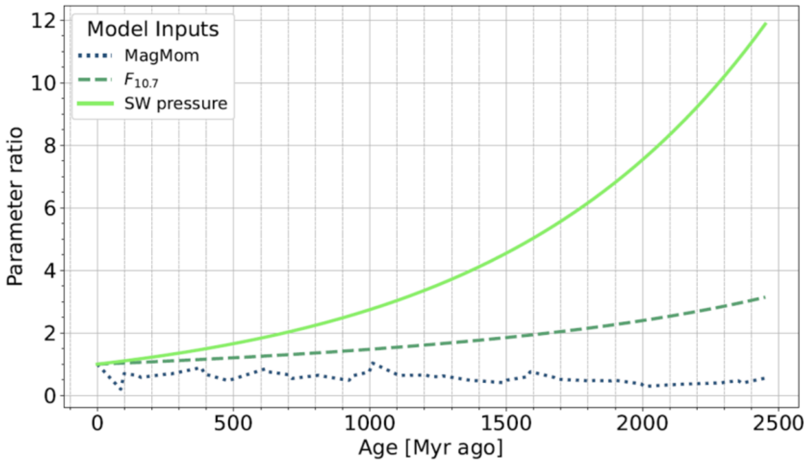

Figure 4: Erosion drivers' evolution with respect to the current values. We show in dotted dark blue the magnetic moment from Schreider et al. (2019), in dashed dark green the EUV radiation proxy F10.7 from Ribas et al. (2005), and in solid light green the solar wind pressure from Carolan et al. (2019).

Results

Initially, we examine the potential increase of the neutral temperature at the exobase due to the higher solar UV flux in the past. As the past exospheric temperature lacks precise determination, we have taken a broad temperature range into consideration. This range spans from the current temperature to a maximum value, representative of an unstable atmosphere within the regime of hydrodynamic escape. It's important to note that this extreme scenario, characterized by hydrodynamic escape, has not occurred within the last 2.5 billion years as the Earth's atmosphere has remained relatively stable during this period.

We demonstrate that Jeans escape remains negligible for oxygen during the past 2.5 billion years, regardless of the atmospheric temperature range considered. Additionally, we have taken into account the compression of Earth's magnetosphere caused by the higher pressure of the solar wind in the past. Our findings indicate that, over the entire range of exospheric temperatures, this compression has not been significant enough to bring a significant amount of neutral oxygen outside of the magnetosphere (Figure 5). This implies that ion pick-up and ion sputtering were negligible for the past 2.5 billion years. As previously discussed in Gunell et al. (2018), it is worth noting that dissociative recombination has consistently remained negligible at Earth due to its strong gravitational field. Atmospheric oxygen escape at Earth was thus dominated by O^+ ion escape through the polar wind process, polar cusp escape and cross-field ion loss.

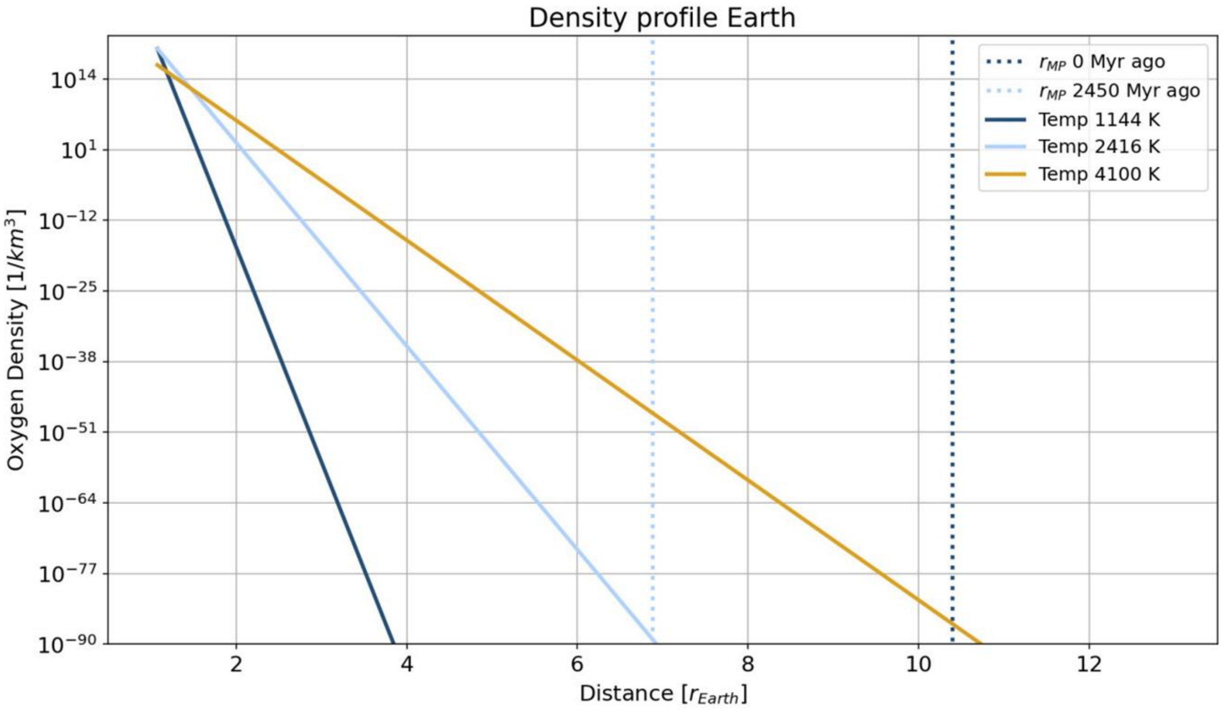

Figure 5: Oxygen density profile of atomic oxygen at Earth for three exospheric temperatures. The vertical dotted lines show the average minimum geocentric distance of the magnetopause (the outer boundary of the Earth magnetosphere) for current solar wind conditions (dark blue) and for the solar wind conditions 2.45 billion years ago (light blue). It shows that only a negligible amount of neutral oxygen is located outside of the magnetosphere.

Conclusions

At approximately 2.45 billion years ago, the total erosion rate of oxygen reaches 1.36 10^{27} atoms per seconds (Figure 6). The total oxygen loss over the last 2.5 billion years is estimated to 28.8% of the current atmospheric oxygen content. Additionally, this research has pinpointed the primary escape routes for oxygen during this period, with polar wind and cusp escape emerging as the predominant contributors to oxygen loss. As a result, non-thermal processes associated with the escape of oxygen atoms at high latitudes have been identified as responsible for most of the oxygen escape during the last 2.5 billion years. If we consider that each oxygen atom lost from the Earth's atmosphere corresponds to one water molecule, the amount of water lost during this time period is relatively insignificant compared to the amount of water present in Earth's oceans.

This study stands as the first to account for the evolving solar conditions in estimating the loss of oxygen from Earth's atmosphere across the main escape routes. It confirms the stability of the Earth atmosphere and hydrosphere with respect of atmospheric escape.

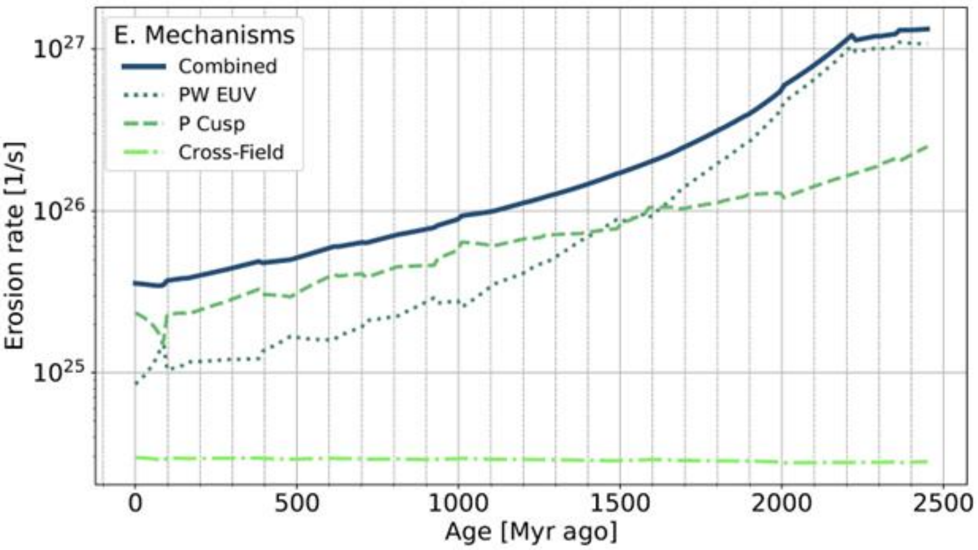

Figure 6: Evolution of the oxygen erosion rate during the last 2.45 Gyr. We show in solid dark blue the total oxygen escape rate, in dashed green the cusp escape rate and in dotted green the polar wind escape rate (both for oxygen).

Reference:

M. L. Alonso Tagle, R. Maggiolo, H. Gunell, G. Cessateur, J. De Keyser, I. Dandouras, G. Lapenta, V. Pierrard, A. C. Vandaele, Evolution of Atmospheric Oxygen Escape on Earth since the Paleoproterozoic era, to be submitted to Journal of Geophysical Research: Space Physics.

Case study 2: Oxygen escape at Mars

Context

Mars was once rich in water during the first hundreds of millions of years after it formed, some 4.5 billion years ago. Since then, it has lost most of it to become the dry planet we know now. Mars also had a large-scale magnetic field during few hundred million years. Historically, the vanishing of this magnetic field was regarded as the key factor responsible for the depletion of water on Mars. However, a recent study indicate that Mars remained magnetized for a longer period than previously thought (Mittleholz et al., 2020). This suggest that Mars may have lost a significant amount of water while magnetized (Figure 7).

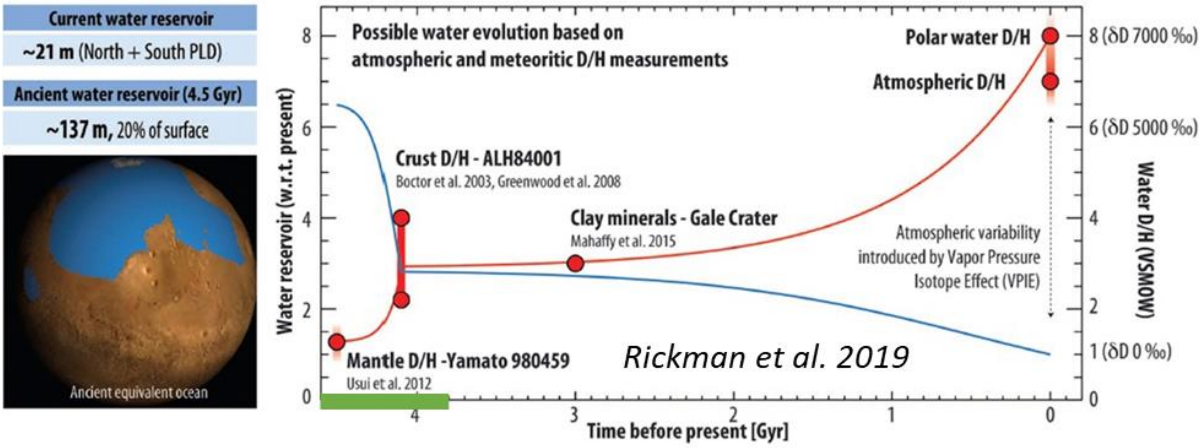

Figure 7: Adapted from Rickman et al. (2019). The blue line shows the estimated amount of water on Mars (water reservoir) since its formation as estimated from the D/H ratio (red line). The green line on the horizontal axis represents the period when Mars was magnetized according to Mittleholz et al. (2020).

Scientific question

How did Mars lose its water? Did Mars lose most of its water while it was magnetized or while it was unmagnetized?

State of the art

While it has long been thought that Mars has lost most of its water while unmagnetized, two recent studies suggest that atmospheric escape at Mars may be slightly higher for a weakly magnetized Mars compared to an unmagnetized Mars (Sakai et al. 2018, Egan et al. 2019).

Method

We use the same version of the semi empirical model as the one used for case study 1. Each of the seven escape mechanisms is scaled to take into account solar wind conditions at Mars. We consider a constant Martian atmospheric composition, like the current composition. While this simplification is a significant approximation, it can be justified based on two key considerations. First, atmospheric escape starts at the exobase, an altitude where collisions become negligible allowing atmospheric particles to escape rather than thermalize through collisions. The exobase is the low altitude boundary of our semi empirical model. The properties of the exobase, its temperature and density, are primarily determined by physical principles, such as the mean free path being equal to the pressure scale height. These properties are weakly dependent on the characteristics of the neutral atmosphere located below the exobase. The primary aspect influenced by the neutral atmosphere is the altitude of the exobase. Second, available information regarding the past atmospheric composition of Mars is limited, presenting a challenge for our analysis. Given this constraint, we acknowledge that our results need to be considered within the context of this limitation. While our research improves our understanding of the different escape mechanisms at Mars since its formation and the factors influencing them, it is important to recognize that providing a precise estimate of the escape rate on geological timescales remains beyond the scope of our project.

In order to assess the effect of the Martian magnetic field on the oxygen escape at Mars, we artificially varied the Martian magnetic moment for various and fixed levels of solar wind pressure.

Results

Mars has a much lower gravity compared to Earth and no global magnetic field since more than 3.5 billion years. Unlike Earth, a substantial portion of neutrals from the exosphere are located outside of the Martian magnetosphere making ion pick up and ion sputtering are non-negligible. Additionally, due to the lower Martian gravity, photochemical escape and Jeans escape cannot be neglected. The result of our simulation is summarized in Figure 8.

The blue line in the figure represents our estimation of the oxygen escape rate for a Mars-like planet under current solar conditions, plotted against its magnetic moment. Two prominent peaks are observed in the escape rate profile: one at a low magnetic moment, predominantly influenced by escape through polar wind, and another at a higher magnetic moment, dominated by escape in the polar cusp region. The left part of the plot, where the escape rate is independent of the magnetic moment corresponds to the unmagnetized regime. In this regime, the planetary magnetic field is insufficient to counterbalance the solar wind pressure, leading to the formation of an induced magnetosphere created by induced currents flowing in the ionosphere. This corresponds to the current situation for Mars. This simulation shows that for current conditions, the escape rate at Mars is weakly dependent on its magnetic moment and could even be slightly higher if Mars were magnetized.

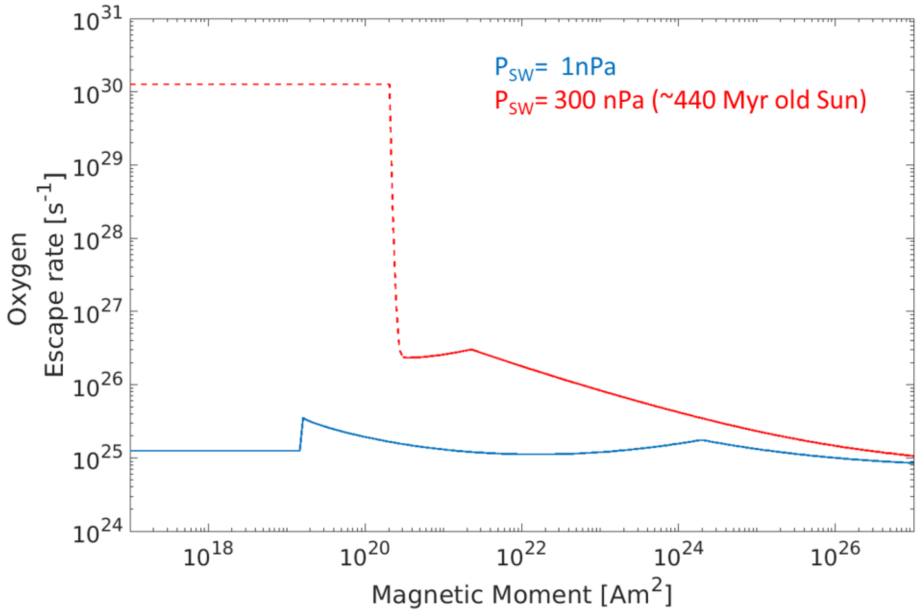

Figure 8: Total oxygen escape rate for Mars as estimated from the semi-empirical model. In blue for current solar wind pressure levels, in red for a high solar wind pressure corresponding to the solar wind condition at Mars ~440 million years after it formed.

The red line in the figure corresponds to solar conditions approximately 4 billion years ago when the Sun was more active, resulting in a significantly higher solar wind pressure (averaging around 300 nPa compared to the current 1 nPa). Under these past solar conditions, the escape rate is notably elevated, aligning with the levels required to deplete a substantial amount of water on Mars. In the magnetized regime, the escape rate at Mars as a function of the magnetic moment displays only one peak at low magnetic moment - approximately 10 times higher than the magnetic moment threshold below which Mars falls into the unmagnetized regime. This singular peak is a result of the merging of the polar wind escape and cusp escape peaks when the solar wind pressure is high. The presence of this peak in the oxygen escape rate at low magnetic moments implies that even a weak magnetic field could lead to intense oxygen escape at Mars.

However, accurately modelling the escape rate in the unmagnetized regime for high solar wind pressure conditions (represented by the red dotted line) remains a challenge. The current scaling employed for the unmagnetized regime assumes that the escape rate of ion pick-up and ion sputtering is proportionate to the quantity of neutrals situated outside of the magnetosphere.

This assumption relies on the hypothesis of a constant efficiency of ion pick-up and sputtering, which proves invalid for elevated solar wind pressure levels. Indeed, the cross-section for ion pick-up decreases by several orders of magnitude in proximity to the planet (Curry et al. 2012). To address this limitation, we are actively working on incorporating the decrease in efficiency of ion pick-up and sputtering into our model. Our current efforts involve developing a formula that relates the efficiency decrease of ion pick-up and sputtering to the density of neutrals located outside the magnetosphere.

This study aims at providing the first estimate of the time evolution of the past atmospheric escape for Mars. As Mars has been first magnetized and then unmagnetized, this goal will be achieved when both escape regimes are correctly implemented in the model.

Work Package 2: Observational study of the energy flux of outflowing particles at Earth

Case study 1: Impact of the Earth magnetic field on the solar wind energy dissipation in the Earth's upper atmosphere

Context

The Sun is the dominant energy source for ionizing atmospheric material and energizing a fraction of it to energies above the gravitational binding energy. Solar energy is conveyed to the atmosphere primarily through solar ultraviolet (UV) and extreme ultraviolet (EUV) radiation, as well as via the solar wind. While the dissipation of stellar UV/EUV radiation in the atmosphere remains independent of the planetary magnetization level, the dissipation of stellar wind energy is intricately linked to the magnetic environment of the planet.

The Earth intrinsic magnetic field generates a large-scale magnetosphere which has two opposite effects. On the one hand, it efficiently diverts the solar wind flow from the upper atmosphere and only a small fraction of the solar wind energy flux it intercepts eventually ends up being dissipated in the upper atmosphere. On the other hand, a large-scale magnetosphere dramatically increases the area of interaction between the solar wind and the Earth and thus the amount of solar wind energy that may potentially be funneled into the upper atmosphere.

This study focuses on a particular aspect of the chain of processes leading to ion loss: the energy transfer from the Sun to the upper atmosphere. The goal is to assess the protective effect of planetary magnetic fields on the upper atmosphere, and more specifically to assess if the Earth's magnetosphere enhances the solar energy dissipation in the Earth's upper atmosphere as first suggested by Maggiolo and Gunell (2021).

Scientific question

Does the presence of a large-scale magnetic field reduce or enhance the solar wind energy dissipation in the Earth upper atmosphere?

Method

We compare the energy dissipated by the solar wind in the Earth's upper atmosphere to the maximum energy that would be intercepted by the induced magnetosphere of a hypothetical unmagnetized Earth, which corresponds to the maximal solar wind energy that could be dissipated in the upper atmosphere of the Earth if it were unmagnetized.

We compute the incoming solar wind energy from the 1-hour resolution solar wind parameters propagated to the nominal magnetospheric bow shock (Figure 9). The solar wind density, velocity, temperature, composition, and the interplanetary magnetic Field (IMF) are obtained directly from in-situ measurements by the ACE spacecraft located at the Lagrange L1 point. The energy carried by the solar wind and IMF is the sum of the kinetic energy of the bulk flow of the particles, the enthalpy of the solar wind plasma and the electromagnetic energy. At Earth, the solar wind energy flux is dominated by the kinetic energy of the wind which is roughly two orders of magnitude larger than the electromagnetic energy (Lockwood, 2019) while the contribution of enthalpy is negligible (Le Chat et al., 2012).

The rate of energy dissipation in the Earth's upper atmosphere is derived from observations. Empirical formulas relating the energy dissipation in the upper atmosphere to geomagnetic indices are obtained from the literature. Solar wind energy dissipates through various mechanisms. Joule heating, particle precipitation and waves are the three main pathways for energy dissipation in the upper atmosphere. Other processes may contribute to a lesser extent. Ionospheric Joule heating refers to the energy dissipated by collisions between plasma and neutrals due to their resulting relative motion (Vasyliūnas and Song, 2005). This is the dominant channel for solar wind energy dissipation in the upper atmosphere.

The solar wind data and the geomagnetic indices for the time period considered in this study (from 1 January 1963 to 31 December 2020) are extracted from the OMNI data set through the OMNIWeb (http://omniweb.gsfc.nasa.gov).

Results

The solar wind energy intercepted by the induced magnetosphere of a hypothetic unmagnetized Earth is estimated to 88.2 GW for a radius of the induced magnetosphere of 1.2 R_E, 103.5 GW for a radius of 1.3 R_E and 120 GW for a radius of 1.4 R_E.

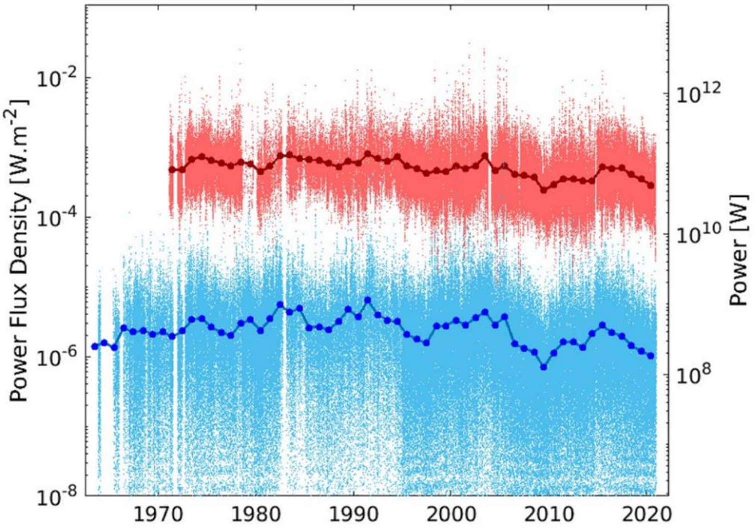

Figure 9: From Maggiolo et al. (2023). Solar wind energy input at 1 astronomical unit. The left vertical axis represents the solar wind power flux at Earth. The right vertical axis represents the total power intercepted by the induced magnetosphere of a hypothetical unmagnetized Earth. The radius of this induced magnetosphere is fixed to 1.2 Earth radii at the terminator. The red scattered points correspond to the 1 hour averaged solar wind kinetic energy while the blue scattered points represent 1 hour averaged the solar wind Poynting flux. The red and blue dots and solid lines show the yearly average of the solar wind kinetic energy and Poynting flux.

The average dissipated power in the ionosphere from 1963 to 2020 is estimated between 132 and 181 GW with a contribution of Joule heating estimated between 99.2 and 110 GW and a contribution of particle precipitation estimated between 32.4 and 70.6 GW (see Table I).

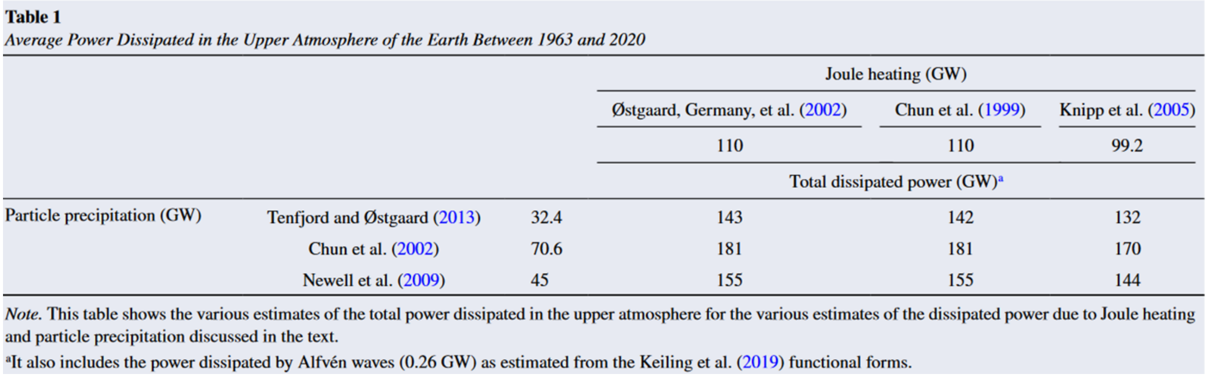

Table 1

Average Power Dissipated in the Upper Atmosphere of the Earth Between 1963 and 2020

			Joule heating (GW)		
			Østgaard, Germany, et al. (2002)	Chun et al. (1999)	Knipp et al. (2005)
			110	110	99.2
			Total dissipated power (GW)[a]		
Particle precipitation (GW)	Tenfjord and Østgaard (2013)	32.4	143	142	132
	Chun et al. (2002)	70.6	181	181	170
	Newell et al. (2009)	45	155	155	144

Note. This table shows the various estimates of the total power dissipated in the upper atmosphere for the various estimates of the dissipated power due to Joule heating and particle precipitation discussed in the text.

[a] It also includes the power dissipated by Alfvén waves (0.26 GW) as estimated from the Keiling et al. (2019) functional forms.

Table I: From Maggiolo et al. (2023). Average energy dissipated in the Earh upper atmosphere as estimated from various empirical formulas found in the literature.

The solar wind energy dissipated in the Earth's upper atmosphere is thus higher than the solar wind power that would be intercepted by the induced magnetosphere of a hypothetical unmagnetized Earth. This result is valid for all the different methods we used to estimate the energy dissipated in the Earth's upper atmosphere and when considering a larger induced magnetosphere. It implies, without any assumption on the solar wind energy dissipation in the upper atmosphere of a hypothetical unmagnetized Earth, that the Earth's magnetic field increases solar wind energy dissipation in the upper atmosphere. This increase should range between a factor of 10 to a factor of

1000 depending on the proportion of solar wind energy intercepted by the induced magnetosphere of an hypothetical unmagnetized Earth that would end up dissipated in its atmosphere.

Reference

Maggiolo, R., Maes, L., Cessateur, G., Darrouzet, F., De Keyser, J., & Gunell, H. (2022). The Earth's magnetic field enhances solar energy deposition in the upper atmosphere. Journal of Geophysical Research: Space Physics, 127, e2022JA030899. https://doi.org/10.1029/2022JA030899

Case study 2: Energy flux of escaping oxygen from the cusp/mantle region and its dependency on solar wind parameters and geomagnetic indices

Context

The cusp/mantle region is the region of open magnetic field lines magnetically connected to the dayside high latitude ionosphere. This region forms an entry point in the magnetosphere where solar wind can directly precipitate in the ionosphere, transferring energy to ionospheric particles which leads to an intense and energetic ionospheric ion escape. At Earth, it is the dominant escape route for oxygen. Interestingly, most ions escaping from this region directly escape into interplanetary space without without returning to the atmosphere (e.g. Nilsson et al. 2012). Oxygen ions flowing out in the cusp/mantle region have energies from a few hundreds to a few thousand eV, representing the primary energetic escape route for ionospheric ions (ion escape in the auroral zone occurs in the same energy range, but on closed magnetic field line and thus with a significant return rate into the atmosphere).

Oxygen escape from the cusp/mantle and the fate of this ion have been extensively studied by the ESA Cluster satellites. The polar elliptical orbit of these satellites is well-suited for measuring escaping ions from the high-latitude ionosphere. While numerous studies have focused on the number flux of escaping oxygen from the cusp/mantle region (e.g., Schillings et al. 2019), no studies to our knowledge considered the energy flux. No coupling efficiency for Earth (i.e., the ratio between the incoming solar wind energy and the energy flux of escaping ionospheric ions) is available, contrary to Mars and Venus (Ramstad et al. 2017, Persson et al., 2021). There is thus a need to compute the energy flux of escaping particles, to better understand the effect of the Earth magnetic field on the energy coupling between the solar wind and ion escape and to further develop our semi empirical model.

Scientific question

How do oxygen escape from the cusp/mantle region depends on solar wind drivers? How does it relate to geomagnetic activity? What is the energy coupling efficiency between the solar wind and oxygen escape from the cusp/mantle region?

Method

We start from the database developed by Schillings et al. (2019) to isolate the cusp/mantle region from other magnetospheric regions. We then compute the energy flux of oxygen ions using two different methods. Initially, we utilize the moments of the distribution function—specifically, the oxygen velocity and density—to compute the energy flux ($\Phi_E=1/2\ m_{O+}\ n_{O+}\ V_{O+}^3$). Additionally, we directly integrate the oxygen energy distribution function ($\Phi_E=\int f(E)dE$). The Cluster data utilized in this study are publicly accessible via the Cluster Science Archive (https://csa.esac.esa.int/csa-web/).

Results

At this stage, we are in the process of refining the methodology for computing the energy flux of escaping O^+ ions. A comparative analysis between the two methods has brought certain issues to light.

One notable challenge is associated with the mantle database from Schillings et al. (2019), where it was observed that certain observations, initially classified as part of the mantle, are, in fact, made on closed field lines of the plasmasheet region. To address this, an additional condition has been implemented regarding the location of Cluster satellites. Observations are now restricted to the dayside magnetosphere by imposing that the magnetic local time (MLT) of the footprint of magnetic field lines, where observations are made, falls within the range of 8:00 to 16:00 magnetic local time (MLT), corresponding to the typical MLT of the cusp/mantle region (e.g., Newell et al. 1989).

Another challenge arises from the presence of two distinct ion populations: the escaping oxygen ions and a hotter, more isotropic ion population, originating either from the magnetosphere or the magnetosheath. This secondary population introduces biases in the estimation of the energy flux of escaping oxygen ions by both methods. For the moment-based approach, it leads to an underestimation of the upflowing oxygen velocity, resulting in a significant underestimation of the energy flux. Conversely, the presence of hot isotropic ions contributes to an overestimation of the upflowing energy flux of oxygen ions when computed through the integration of the distribution function, as the energy flux of isotropic ions is also considered. These issues are evident in Figure 10, which illustrates the comparison between the two methods. Notably, the energy flux of oxygen ions computed from the moments can exhibit low values, well below the energy flux computed by integrating the energy distribution function.

As a response to the identified challenges, our ongoing efforts involve a meticulous reprocessing of the data to eliminate isotropic ions, thereby isolating the outflowing oxygen ions in order to compute as precisely as possible their energy flux. Our current approach consists in a partial integration of the energy distribution function within a restricted range of pitch angles (the angle between the particle velocity and the magnetic field) and energy.

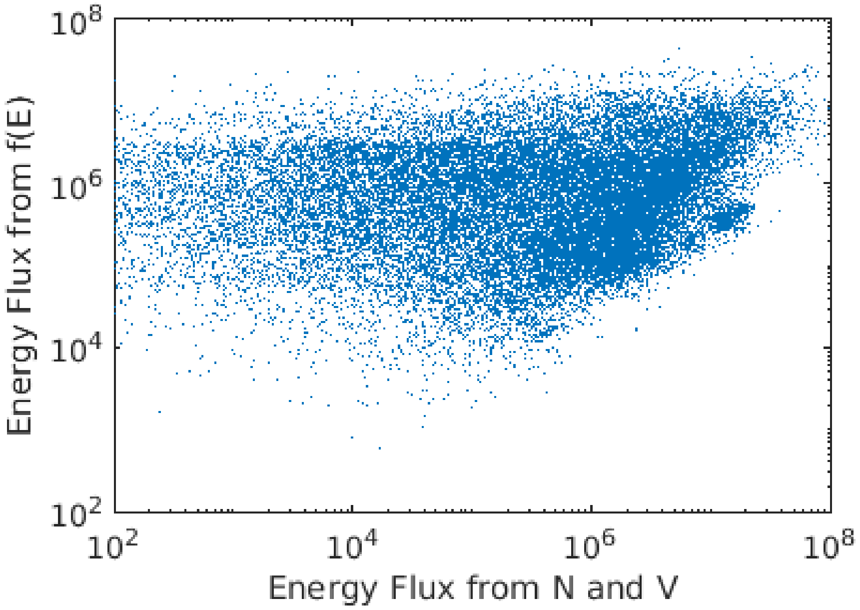

Figure 10: Scatter plot of the energy flux of oxygen ions escaping in the cusp/mantle region (in particles.$s^{-1}m^{-2}$*). The horizontal axis corresponds to the energy flux computed from the ion velocity and density (the same method as used in Schillings et al. 2019to compute the number flux) and the vertical axis to the energy flux computed from the integration of the energy distribution function of oxygen ions (the new method we decided to use). We note that the energy flux estimated from the distribution function rarely goes below* 10^4 O^+ *ions* $s^{-1}m^{-2}$*, contrary to the energy flux estimated from the ion density and velocity.*

Work Package 4: Uncertainty and sensitivity analysis

Assessing the accuracy and reliability of our model is pivotal in validating both our methodology and the outcomes derived from the semi-empirical model. This must be done considering the accuracy targeted by our model. We aim at estimating the past atmospheric escape rate of Venus, Earth and Mars over geological time scales. Going that far back in time means that the input parameters of our model are weakly constrained (the atmospheric composition, the solar EUV/UV flux and the solar wind). It also means that no direct observations can be compared with the output of the model. Furthermore, the input of the model (solar and planetary parameters) and the observations made for current conditions come most of the time without an error estimate. Consequently, the results obtained with our model must be interpreted carefully, considering the large uncertainty on the results of the model.

The error propagation through the empirical formulas used in the model is relatively straightforward. We thus focused our efforts on testing various set of input parameters and different scaling method. This has been done step by step during the development of the model and some examples are highlighted below.

Magnetic field model

A critical component of our model lies in the planetary magnetic field model, employed to scale observations. This magnetic field model plays a crucial role in estimating the interaction area with the solar wind and determining the effective area or volume where escape processes are active. To enhance the robustness of our model, we conducted tests with various magnetic field models, including an untilted dipole, a tilted dipole, and a dipole combined with the Chapman Ferraro current system– a magnetic field model that includes the contribution of currents flowing at the magnetopause. For each version of the model, we computed the geometrical factors used to scale observations (the standoff distance of the magnetopause, the radius of the magnetopause used to compute the magnetopause cross section with the solar wind and the surface of the polar cap where magnetic field lines directly connect the upper atmosphere to the interplanetary space). Results, as illustrated in Figure 11, reveal that while considering the tilt of the magnetic dipole has a marginal impact on simulation outcomes, the incorporation of Chapman Ferraro currents is essential for accurate modelling of the magnetic field surrounding the Earth.

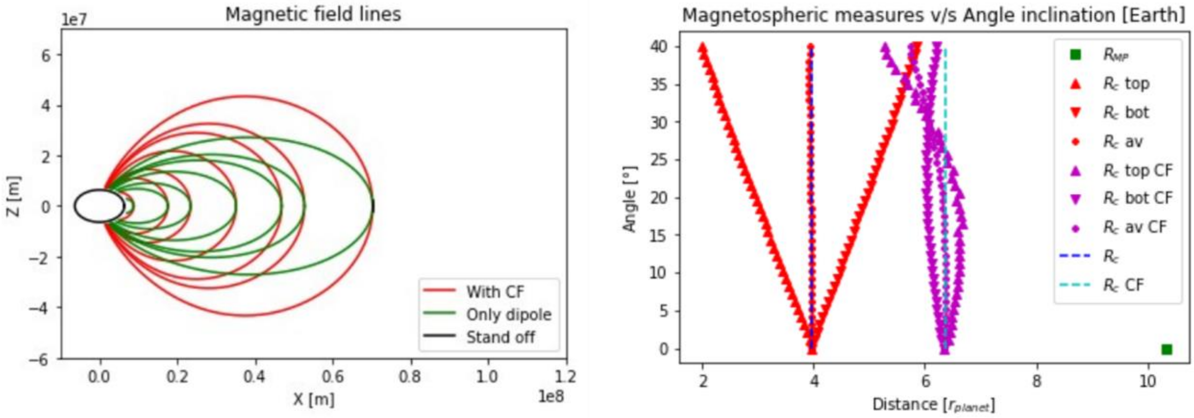

Figure 11: Left panel: magnetic field line geometry in the XZ_{GSM} plane (the Sun is on the right; the Z axis is perpendicular to the ecliptic plane). It illustrates the difference of the geometry of magnetic field lines from a simple dipolar magnetic field model (in green) and of a dipolar magnetic field model considering external currents with the Chaman Ferraro model (in red). Right panel: Geometrical factors used to scale observations in the semi empirical model. R_C is the radius of the magnetosphere at the subsolar point (in Earth radii, horizontal axis) used to compute the magnetospheric cross section with the solar wind. The dark blue dotted line is for a simple dipolar model with no tilt and the light blue dotted line a dipolar model with Chapman Ferraro currents. The red points correspond to the average value of R_C (between the two hemispheres) as a function of the dipole tilt (vertical axis) for a simple dipolar model and the purple points to the average value of R_C for a dipolar model with Chapman Ferraro currents.

Input parameters

A parametric analysis is made for each input parameters in order to assess which input parameters have the strongest impact of the model output. This involved initially establishing a realistic range of values for each parameter and subsequently running the model across this range, keeping the other parameters constant. This parametric study reveals the parameters exerting the most significant effect on the results.

In the past, the Sun was more active emitting a higher flux in the UV/EUV range which changed the temperature, density and altitude of the exosphere compared to current conditions. Furthermore, the ionisation rate in the upper atmosphere was higher, leading to an increased maximum ion production rate. This maximum ion production rate is a limiting factor constraining the quantity of ions that can be extracted from the ionosphere. Among those quantities, the exospheric temperature and altitude have the highest impact on the escape rate, while the exospheric density and the maximum ion production rate in the cusp region have the lowest impact (see Figure 12).

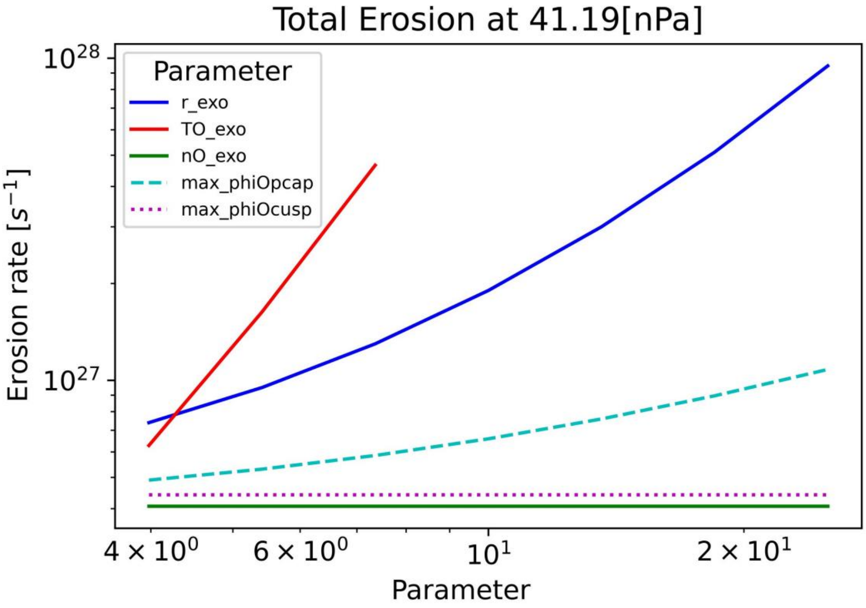

Figure 12: Total oxygen escape rate as a function of exospheric parameters for a solar wind pressure of 41.19 nPa at the Earth level, corresponding to the average solar wind pressure some 1.4 billion years ago. The horizontal axis shows the relative value of each of these parameters with respect to their current value. Note that the exospheric temperature cannot exceed 7 times the current value, otherwise the atmosphere would be unstable, in the regime of hydrodynamic escape.

Physical processes

We follow a similar approach when adding a new process or driver in the semi empirical model. This allows understanding which mechanism has a strong influence on atmospheric escape. For example, we compare the past oxygen escape rate from the polar wind region by considering solely the higher solar wind pressure in the past or incorporating both the higher solar wind pressure and solar UV/EUV flux (Figure 13). As expected, a higher solar UV/EUV flux leads to higher polar wind escape rate. However, the effect of solar UV/EUV flux on the oxygen escape rate in the polar wind remains limited. Indeed, the primary factor contributing to a higher polar wind escape rate in the past is not directly tied to the elevated solar UV/EUV flux, which primarily enhances the polar wind flux density. Instead, the principal driver is the increase in the polar cap size—the region where polar wind escape occurs—due to the compression of the magnetosphere caused by a higher solar wind pressure.

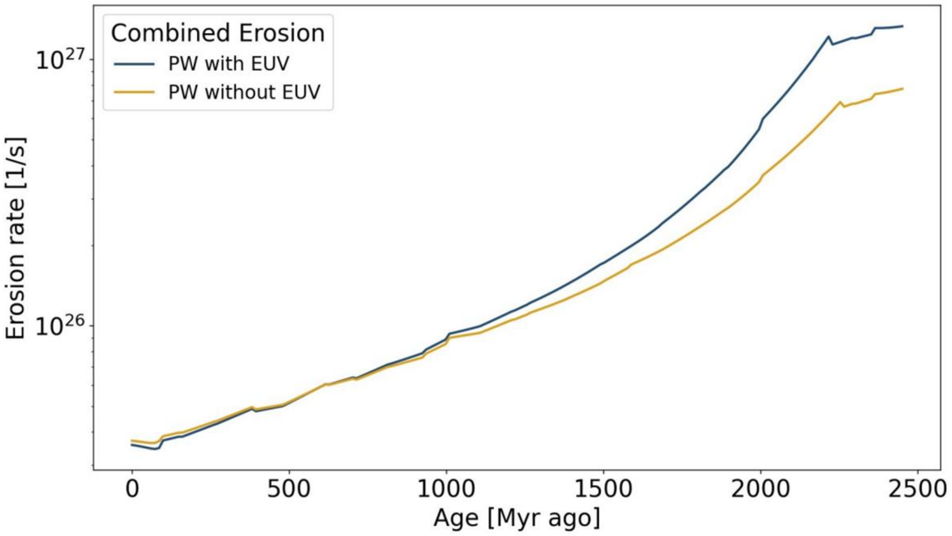

Figure 13: Past oxygen escape rate through the polar wind process during the last 2.5 billion years. In blue, both the past variations of the solar wind pressure and solar UV/EUV flux are considered. In orange, only the past variations of the solar wind pressure are considered. This plot shows that the main driver of the polar wind escape rate is the solar wind pressure which changes the size of the polar cap, the region where polar wind is effective. Solar UV/EUV flux has an impact on the exospheric density, temperature and altitude and thus on the flux density of the polar wind. However, it does not modify the size of the polar cap and has a limited impact on the total escape rate.

Comparison with observations

Obviously, no measurements for the past escape rate at Venus, Earth and Mars are available. However, comparison with observation is possible owing to the inherent variability of solar activity. Satellite observations of atmospheric escape span only a few decades but thanks to the variation of solar activity over the 11-year solar cycle, these observations are made for various solar activity levels. This variability enables a meaningful comparison of the escape rate's dependency on solar activity, with the understanding that the range of variation in solar parameters observed over the 11-year cycle is limited compared to their fluctuations over geological timescales. For example, the solar wind pressure at Earth typically fluctuates between 1 to 10 nPa, depending on the solar activity level. In contrast, the solar wind pressure hundreds to billions of years ago could have surpassed several hundred nPa. Moreover, any comparisons of the model output with current observations must be conducted using independent data—information not integrated into the model.

In Figure 14, we compare the variation of the oxygen flux escaping from the cusp region, as estimated by the semi-empirical model, with independent observations from the Cluster satellite. The model scales the average oxygen flux measured by the Polar satellite, incorporating its dependency on solar wind pressure. The Cluster data presented in Figure 14 were collected from 2001 to 2005, encompassing various solar wind pressure levels. The variation of the oxygen flux from Cluster measurement is thus purely observational and shows a good agreement with our scaling. However, we must keep in mind that Cluster observations are limited to a short range of solar wind pressure values. For instance, the semi-empirical model predicts that the oxygen flux saturates for solar wind pressures above ~15 nPa, entering a regime known as "flux-limited" where the ionospheric source reaches saturation. Unfortunately, under current solar wind conditions, the solar wind pressure seldom exceeds 15 nPa, making it impossible to access the saturation regime through observations.

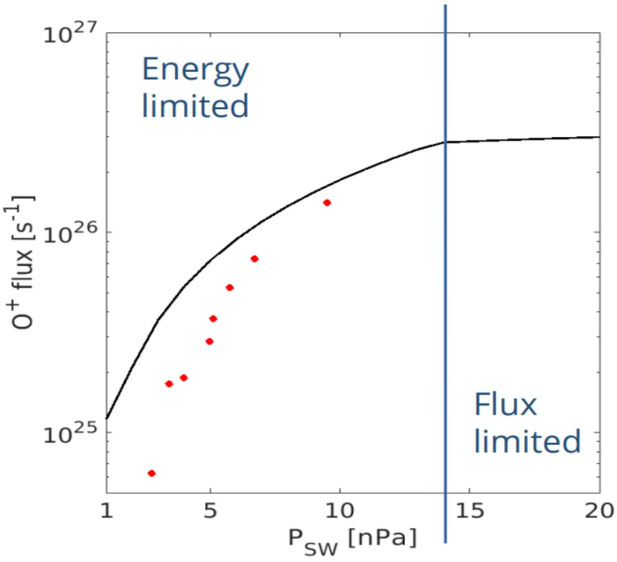

Figure 14: Oxygen escape from the cusp/mantle region for Earth as a function of the solar wind pressure. The black line shows the results from the semi empirical model obtained using measurements from the Polar satellite (Pollock et al., 1990) and scaled as a function of solar wind pressure. The red dots show the oxygen escape rate as a function of the solar wind pressure measured by the Cluster satellite from Schillings et al. (2019).

4.2 Added Value

Semi Empirical model

We develop and own a semi empirical model of atmospheric escape that consider the changing planetary and stellar conditions. To our knowledge our model is the only semi-empirical model of atmospheric escape. Our approach is unique and gives us a unique expertise and a unique tool.

Modelling atmospheric escape into space is still very challenging owing to the number of escape processes, to the large uncertainty on stellar and planetary parameters and on the difficulty to make a physical model due to the variety of time and spatial scales to model (Welling et al. 2016). Our approach takes advantage of the large amount of data related to atmospheric escape gathered around Venus, Earth and Mars aiming to minimize challenges associated with modelling physicochemical processes of atmospheric escape.

We developed a unique model that can already be used to constrain the past atmospheric escape at Earth. We are close to be able to apply it for the past atmospheric escape at Venus and Mars. In the future, this model can evolve in order to be applied to exoplanets.

Competences

This project represents a big step for our division, the "Space Physics" since this **allows us to set foot in the field of the study of the habitability of planets**. In our opinion, this represents a logical evolution of our group's research area. Since the detection of the first exoplanets in the 1990s and with the development of interplanetary probes, the search for life in environments other than Earth has seen a spectacular leap. Through this project we have expanded our expertise and gained competences related to atmospheric stability and planetary habitability.

Before the start of this project, we already had recognized expertise in the field of coupling between the ionosphere and the magnetosphere and associated ion escapes. **We have acquired new skills concerning paleomagnetism, stellar physics and the evolution over geological time of planetary atmospheres,** through the collaborations initiated during this project.

Collaborations and visibility

Thanks to the development of our model and to the competences gained through this project, **we are beginning to be recognized as a player in the field of planetary habitability**.

A big achievement made possible by the IPA project is our involvement in the ISSI team "How Heavy Elements Escape the Earth: Past, Present, and Implications to Habitability". The lead proposers of this scientific team invited Romain Maggiolo to join this team after attending presentations that discussed the model developed as part of this project.

List of new scientific collaborations initiated thanks to the IPA project:

- ISSI team "How Heavy Elements Escape the Earth: Past, Present, and Implications to Habitability":
  Raluca Ilie (University of Illinois in Urbana-Champaign, USA), Rona Oran (Massachusetts Institute of Technology, USA), David Catling (University of Washington, USA), Claire Nichols (University of Oxford, UK), Caue Borlina (Purdue University, USA), Aline Vidotto (Leiden University, Netherlands), Jun Yang (Peking University, China)
- Audrey Schillings (Umea University, Sweden)

Our visibility increased as a result of our participation in this team and numerous presentations delivered at international conferences (see section 5 Dissemination and Valorisation).

4.3 Recommendations

Planetary habitability: a growing field of research in which Belgium must be involved.

During the last two decades, several missions were sent to study the interaction between the atmosphere and the space environment of Venus (ESA Venus Express) **and Mars** (ESA Mars Express, NASA MAVEN and ESA/Roscosmos Exo Mars TGO). **Among the twelve missions selected in the frame of the ESA Cosmic Vision program, three will be dedicated to exoplanets** (PLATO, ARIEL and CHEOPS) and **one will be sent to Venus** with a main objective to understand the diverging evolution of Venus and Earth (EnVision). Recently, ESA announced the final three missions preselected for ESA's next medium science mission M7. One of them, M-Matisse (Mars Magnetosphere ATmosphere Ionosphere and Space-weather SciencE) aims at studying the atmosphere, ionosphere and magnetosphere of Mars.

This shows the **interest in the field of exoplanets and exploration of the rocky planets of the solar system planets**. The big scientific question behind these missions is to understand how and where life can develop.

According to our current definition and knowledge of life, the presence of a stable atmosphere and of liquid water are essential conditions for a planet to support life.

We think that **it is essential for Belgium to continue and develop its research efforts in this area**. This will allow Belgian researchers **to participate in the scientific analysis of data and in instrumental development for future missions** from major space agencies.

Financing the development of new tools to maintain Belgium on the forefront of space research on the long term.

One lesson learnt from this project is that upstream funding to develop research tools such as the semi-empirical model developed in this project is essential to building future scientific results. A tool like this semi-empirical model brings its results after a development and validation phase which is necessary and can take time. The phase of scientific results, i.e., publication in peer-reviewed journals, follows with a certain delay. The proportion of statutory researchers is lowering; more and more researchers are financed by projects. **Funding fundamental research projects and the development of tools and models** paves the way for future scientific results. Maintaining top-level scientific expertise **is necessary to be able to be involved in future missions of the major space agencies**, for the analysis and processing of data and for the development of instruments **and thus lead to positive economic outcomes for the Belgian space industry.**

5. DISSEMINATION AND VALORISATION

International conferences

- IUGG 2023

R. Maggiolo, L. Maes, M.L. Alonso Tagle, G. Cessateur, F. Darrouzet, J. De Keyser, H. Gunell, *The effect of the Earth's magnetosphere on the solar wind energy dissipation in the ionosphere: Evolution over geological time scales*, A12p-308, IUGG The 28th General Assembly, Berlin, July 11-July 20, 2023. (poster)

M.L. Alonso Tagle, R. Maggiolo, H. Gunell, G. Cessateur, J. De Keyser, G. Lapenta, V. Pierrard, A.C. Vandaele, *Estimation of the total oxygen loss from Earth with a semi-empirical model of atmospheric escape*, IUGG23-2858, IUGG The 28th General Assembly, Berlin, July 11-July 20, 2023. (oral)

- EGU 2023

M. L. Alonso Tagle, R. Maggiolo, H. Gunell, J. De Keyser, G. Cessateur, G. Lapenta, V. Pierrard, A. C. Vandaele, *Evolution of the oxygen escape from Earth over geological time scales*, EGU23-7046, EGU General Assembly 2023, Vienna, 23–28 April 2023. (oral)

R. Maggiolo, M. L. Alonso Tagle, H. Gunell, J. De Keyser, G. Cessateur, G. Lapenta, V. Pierrard, A. C. Vandaele, *Investigating the past atmospheric escape rate from Mars using a semi-empirical model*, EGU23-12193, EGU General Assembly 2023, Vienna, 23–28 April 2023. (poster)

- ESLAB 2023

M. L. Alonso Tagle, R. Maggiolo, H. Gunell, J. De Keyser, G. Cessateur, G. Lapenta, V. Pierrard, A. C. Vandaele, *Modelling Atmospheric Erosion for Terrestrial Planets in the Solar System*, Planet ESLAB, ESTEC Noordwijk, 22-24 March 2023. (Poster)

- AGU 2022

M. L. Alonso Tagle, R. Maggiolo, H. Gunell, J. De Keyser, G. Cessateur, G. Lapenta, V. Pierrard, A. C. Vandaele, *Atmospheric Erosion for the Terrestrial Planets: A Semi-Empirical Model*, P45B-04, AGU Fall meeting 2022, San Francisco 12-16 December 2022. (oral)

- COSPAR 2022

R. Maggiolo, M. L. Alonso Tagle, H. Gunell, G. Cessateur, F. Darrouzet, J De Keyser, V. Pierrard,A. C. Vandaele, *Semi-empirical modelling of atmospheric escape: implications for the Martian atmospheric loss*, C3.2-0003-22, COSPAR 2022 44th General Assembly, Athens, 16-24 July 2022. (oral)

M. L. Alonso Tagle, R. Maggiolo, H. Gunell, J. De Keyser, G. Cessateur, G. Lapenta, V. Pierrard, A. C. Vandaele, *A semi-empirical model of the dependency of atmospheric escape on the planetary magnetic moment,* C3.2-0047-22, COSPAR 2022 44th General Assembly, Athens 16-24 July 2022. (oral)

- EGU 2022

R. Maggiolo, L. Maes, G. Cessateur, F. Darrouzet, J. De Keyser, H. Gunell, *How does the presence of a large-scale magnetic field impact the solar wind energy dissipation in the Earth's upper atmosphere?*, EGU22-9693, EGU General Assembly 2022, Vienna & Online, 23–27 May 2022. (oral, highlight)

National conferences

- BNCGG 2022

R. Maggiolo, *Do planetary magnetic fields protect atmospheres?*, National Committee for Geodesy and Geophysics, Study day on 'Belgian contributions to Earth Sciences in a Changing World', Brussels November 4 2022, (oral invited)

M. L. Alonso Tagle, R. Maggiolo, H. Gunell, J. De Keyser, G. Cessateur, G. Lapenta, V. Pierrard, A. C. Vandaele, *Atmospheric Erosion for the Terrestrial Planets: A Semi-Empirical Model*, Study day on 'Belgian contributions to Earth Sciences in a Changing World', Brussels November 4 2022, (poster)

- CmPA meeting 2022

M. L. Alonso Tagle, R. Maggiolo, H. Gunell, J. De Keyser, G. Cessateur, G. Lapenta, V. Pierrard, A. C. Vandaele*, A Semi-Empirical Model of the dependency of Atmospheric Escape on the planetary Magnetic Moment and Solar Wind Pressure*, CmPA retrospective in honor of prof. Stefaan Poedts, Leuven, September 6-9, 2022. (poster)

Seminars

M. L. Alonso Tagle, *Evolution of the oxygen escape from Earth over geological time scales*, Umea University Sweden, May 15, 2023.

R. Maggiolo, *Les champs magnétiques planétaires protègent-ils les atmosphères ?* BIRA/IASB Open Doors, Brussels September 24-25 2022.

6. PUBLICATIONS

Published in peer-reviewed journals

Maggiolo, R., Maes, L., Cessateur, G., Darrouzet, F., De Keyser, J., & Gunell, H. (2022). The Earth's magnetic field enhances solar energy deposition in the upper atmosphere. Journal of Geophysical Research: Space Physics, 127, e2022JA030899. https://doi.org/10.1029/2022JA030899

In preparation for peer-reviewed journals

M. L. Alonso Tagle, R. Maggiolo, H. Gunell, G. Cessateur, J. De Keyser, I. Dandouras, G. Lapenta, V. Pierrard, A. C. Vandaele, Evolution of Atmospheric Oxygen Escape on Earth since the Paleoproterozoic era, to be submitted to Journal of Geophysical Research: Space Physics.

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