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Atmospheric Erosion for the Terrestrial Planets: A Semi-Empirical Model

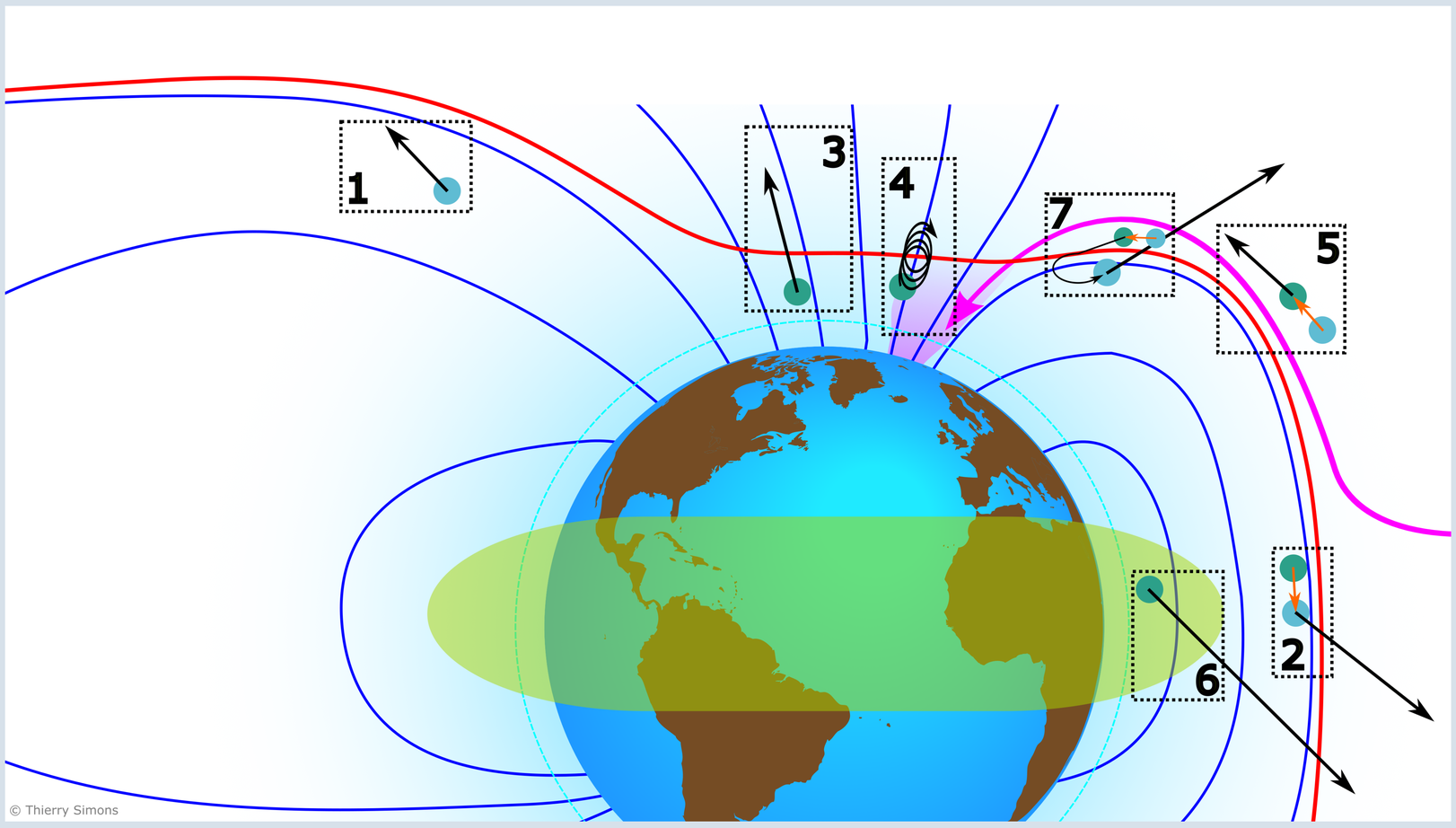
Motivation

Exploring the atmospheric erosion on rocky planets is essential to understand **long-term evolution** of the atmosphere and its capacity to retain water.
The main objective is to **reproduce atmospheric loss for early planetary and solar conditions** in order to constrain the role of the planetary magnetic field and **Solar Wind (SW)** pressure on atmospheric erosion over geological time scales.

Method: Semi-Empirical Model

The diagram below presents the different erosion mechanisms that our model considers.

The lines in blue are the planetary magnetic field lines, in red the magnetopause, the dashed cyan is the exobase. Incoming energy from the SW is represented in pink, and in yellow is the plasmasphere. Neutrals are shown in light blue and ions are in dark green.



The model was initially developed in **Gunell et al. 2018**. In the current work, we updated and expanded it.

Scaling

Processes are scaled showing their dependency on:

Planetary magnetic moment: Scales the magnetopause (MP) location and polar cap area, in combination with SW pressure.

Solar Wind pressure: In addition, SW density and its velocity affects differently some mechanisms.

Geometry: Each mechanism is constrained to a specific region, which size is related to MP location.

Atmospheric parameters: Fixed to the current values for Venus, Mars, and Earth.

Mechanisms

1. Jeans escape

In a Maxwellian distribution, particles with velocities higher than the escape velocity escape.

2. Photochemical escape

Relevant only for Mars, where the recombination of O^+ with SW electrons allows the escape.

3. Polar cap escape

Polar wind refers to ion escape along the open field lines, in the polar cap. It is driven by the ambipolar electric field. Cluster observations are used to constrain its dependency on the SW.

4. Polar cusp escape

Incoming energy from the SW intercepted by the planetary magnetosphere. This process energizes ions in the cusp, giving them the extra energy to escape.

5. Ion pickup

Exospheric atoms are ionized by the interaction with the SW: by photoionization, electron impact or charge exchange. Then, they are picked up by it.

6. Cross-Field ion loss

Ions trapped in the plasmasphere can eventually escape through the plasmaspheric wind or via the detachment of plasmaspheric plumes.

7. Sputtering

Picked up ions accelerated by the SW can reimpact magnetospheric neutrals, giving them enough energy to escape. Relevant only for Oxygen atoms.

General Erosion Rates

In general, we have:

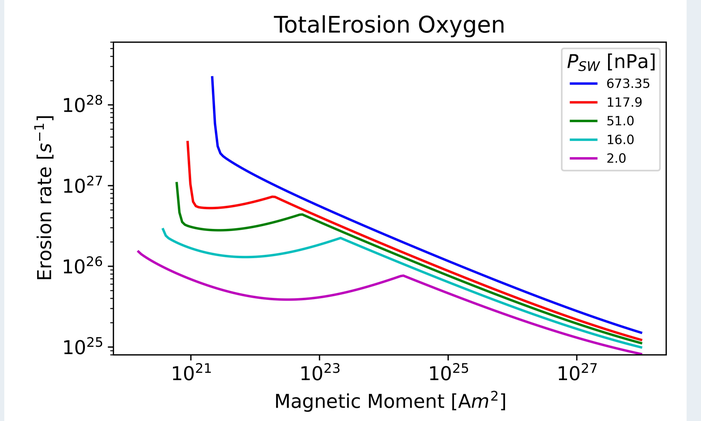
$$Q_i = Q_0 \times S_p \times A$$

With Q_i the rate for i process, Q_0 observational rates, S_p physical scaling of the process, and A geometrical scaling.

Total Oxygen Escape

Combination of the previously referred mechanisms in the magnetized regime.

Earth escape



Analysis

It is shown that:

- Escape rates vary with SW pressures from the current Sun (purple) to the young Sun (blue) (Carolan et al. 2019). **Higher SW pressures increment the erosion significantly**.
- **Ion pickup** and **Sputtering** dominate the Oxygen loss for the higher SW pressure.
- At low SW pressure there are 2 peaks, corresponding to **Polar cap** escape and **Polar cusp** escape respectively. At high SW pressures they merge, forming one single peak.
- A **weakly magnetized planet** gives the ideal conditions for erosion. It **allows 4 different mechanisms** to scavenge the atmosphere simultaneously: **Polar cap** escape, **Polar cusp** escape, **Ion pickup**, and **Sputtering**.

Future Development

The next steps in the project are:

- Reduce the uncertainty of the unmagnetized regime.
- Study the impact of the different parameters on the erosion.
- Add the EUV radiation effect to the atmospheric parameters and erosion rates.

References

Carolan, S. et al. (2019). "The evolution of Earth's magnetosphere during the solar main sequence". In: *Monthly Notices of the Royal Astronomical Society* 489, pp. 5784–5801. DOI: 10.1093/mnras/stz2422.

Gunell, H. et al. (2018). "Why an intrinsic magnetic field does not protect a planet against atmospheric escape". In: *Astronomy & Astrophysics* 614.L3, pp. 1–8. DOI: 10.1051/0004-6361/201832934.