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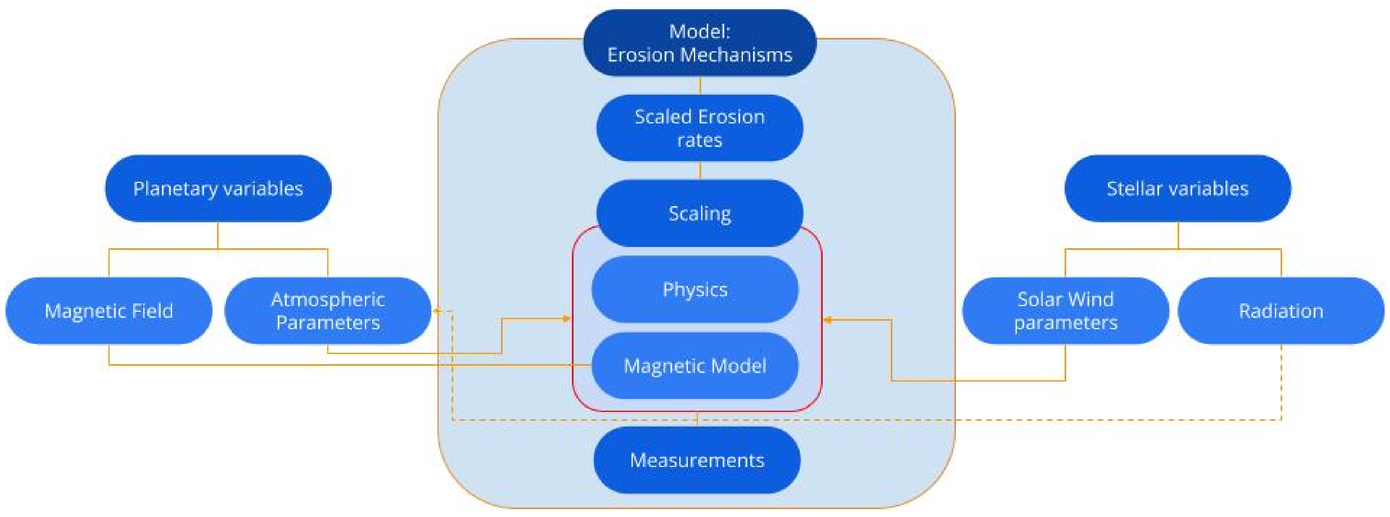
A semi-empirical model of the dependency of atmospheric escape on the planetary magnetic moment and solar wind pressure

Motivation

Exploring the atmospheric erosion on rocky planets is essential to understand long-term evolution of the atmosphere and their 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 key parameters evolve significantly during geological times, an static erosion model is not possible.



There are several reasons to choose a semi-empirical model:

- 7 erosion mechanisms considered simultaneously.
- 3 different planet types.
- Uncertainties of parameters. Particularly in the past.
- Ionospheric-Magnetospheric coupling.
- Resolution scale, several processes simultaneously with different scaling.

In the current work, the model developed by **Gunell et al. 2018** was updated and expanded.

Scaling

These parameters are calculated using the pressure balance and a simple magnetic model.

Stand-off distance r_{MP}: Geocentric distance to the magnetopause or the induced magnetosphere boundary at the subsolar point.

Polar caps solid angle Ω_{pc}: Solid angle of the region where the planetary magnetic field lines can be considered open.

Cross section radius r_{cs}: Cross section of the magnetosphere with the SW.

Atmospheric parameters

Exobase r_{exo}: Geocentric distance of the exobase.
Scale height h_α: For particle α.
Temperature T_{exo}: Temperature at exobase.
Density ρ_{exo}: Particle density at exobase.

Solar Wind parameters

The density ρ_{SW} and velocity v_{SW} are added to the previous model, changing the scaling and erosion rates.

Invariable Erosion Mechanisms

Photochemical escape

It includes: photodissociation, photodissociative ionization, electron impact dissociative ionization, and dissociative recombination. At Mars the last mechanism dominates, where electrons from the SW recombine with O^+, giving them the extra energy to escape.

Jeans escape

Neutral particles at the end of the velocity distribution can escape, if their velocity is higher than the escape velocity.

$$Q_{Je,\alpha} = 4\pi r_{exo}^2 \sqrt{\frac{k_B T_{exo,\alpha}}{2\pi m_\alpha}} \rho_{exo,\alpha} \left(1 + \frac{r_{exo}}{h_\alpha}\right) e^{-\frac{r_{exo}}{h_\alpha}}$$

Where k_B is Boltzmann constant, m_α is the particle α mass, and the other ones are atmospheric parameters.

Variable Erosion Mechanisms

All rates Q have a subscript naming the mechanism, in $[s^{-1}]$. Q_0 is the measured escape rate, and subscript refs corresponds to the values; for current conditions.

Polar cap escape

In polar wind, the outflow is proportional to Ω_{pc}. We use Cluster observations to constrain its dependency on the SW pressure (Engwall et al. 2009).

$$Q_{pc} = 2 \times min\left(1.1 \times 10^{12} e^{0.216 P_{SW}}, q_{max}\right) \Omega_{pc} r_{exo}^2$$

Where P_{SW} is the SW pressure, and q_{max} is the maximum erosion rate per unit of area.

Polar cusp escape

We consider that the polar cusp escape rate is proportional to the solar wind energy that is intercepted by the planetary magnetosphere. This process depends on Ω_{pc} and r_{cs}. The incoming energy flux is a function of the SW parameters.

$$Q_c = min\left(Q_{0,c} \frac{r_{cs}^2}{r_{cs,E_{ref}}^2} \frac{\rho_{SW} v_{SW}^3}{\rho_{SW,ref} v_{SW,ref}^3}, Q_{max}\right) \frac{\Omega_{pc}}{\Omega_{pc,E_{ref}}} \left(\frac{r_{exo}}{r_{exo,E_{ref}}}\right)^2$$

Ion pickup

Magnetospheric atoms are ionized by the SW via: photoionization (β_{photo}), electron impact (β_{elec}) and charge exchange (β_{ce}). Then, they are picked up by it. It is a function of r_{MP}, and SW particle flux.

$$Q_{pu} = Q_{0,pu} \left(\beta_{photo} + (\beta_{elec} + \beta_{ce}) \frac{\rho_{SW} v_{SW}}{\rho_{SW,ref} v_{SW,ref}}\right) \left(\frac{2h_\alpha^3 + 2h_\alpha^2 r_{MP} + h_\alpha r_{MP}^2}{2h_\alpha^3 + 2h_\alpha^2 r_{exo} + h_\alpha r_{exo}^2} e^{\frac{r_{exo} - r_{MP}}{h_\alpha}}\right)$$

Cross-field ion loss

This includes all escape processes across magnetic field lines like plasmaspheric plumes, plasmaspheric wind. This process depends on Ω_{pc}.

$$Q_{cf} = Q_{0,cf} \left(\frac{1 - \frac{\Omega_{pc}}{4\pi}}{1 - \frac{\Omega_{pc,ref}}{4\pi}}\right)$$

Sputtering

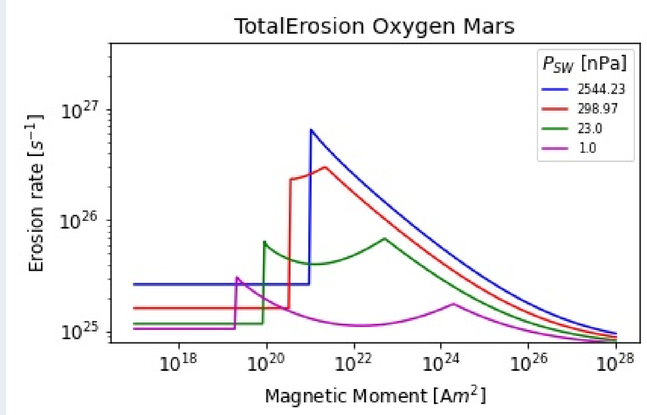
Some of the ionospheric ions swept up and accelerated by the SW reimpact the ionosphere exospheric atoms, giving them enough energy to escape. Thus, it depends on ion pickup, r_{MP}, and the gyroradius r_g of the O ions. The last parameter is a function of the SW pressure.

$$Q_{sp} = Q_{0,sp} \frac{Q_{pu}}{Q_{pu,ref}} \times \frac{\int_{r_{MP}-r_g}^{r_{MP}} r^2 e^{-\frac{r}{h_O}} dr}{\int_{r_{MP,ref}-r_{g,ref}}^{r_{MP,ref}} r^2 e^{-\frac{r}{h_O}} dr}$$

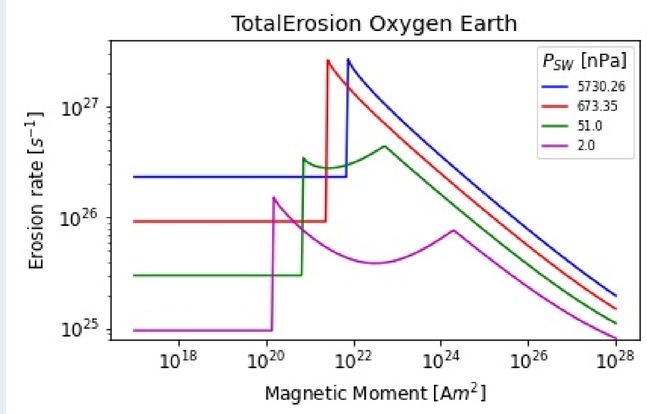
Total Oxygen Escape

Combination of all the previous processes.

Mars escape



Earth escape



It is shown that:

- Rates are varied with SW pressures from the current Sun (purple) to the young Sun (blue) (Carolan et al. 2019). **Higher pressures increment the erosion significantly**.
- At lower pressures there are 2 peaks, corresponding to **Polar cap** escape and **Polar cusp** escape respectively. At high SW pressures they merge, forming one single peak.
- The **highest loss** is found for higher SW pressure with a **weakly magnetized planet**.
- It is realistic to expect higher erosion rates in the past, due to the SW pressure. As far as 2 orders of magnitude higher than the current ones.

Conclusions

Semi-empirical modelling allows estimating at best all measurements related to atmospheric escape around rocky planets (from Cluster, VEX, MEX, Maven).
Such approach has obviously limitations. However, it helps to **constrain atmospheric escape** for conditions that are not accessible to measurements and difficult to model.
With this model we see that:

- Atmospheric escape is not linearly dependent on the **planetary magnetic moment**.
- The **maximum escape** rate occurs for weakly magnetized planets and high solar wind pressure.
- The ion production rate in the ionosphere is the main limiting factor of atmospheric escape.
- In the early solar system, solar EUV/UV flux was higher and thus also the ionization rate in the upper atmosphere.

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.
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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.