TF-075

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A semi-empirical model of the dependency of atmospheric escape on the planetary magnetic moment

Introduction

Exploring the atmospheric erosion on rocky planets is essential to understand long-term evolution of the atmosphere and their capacity to retain water. The role of the planetary magnetic field in the longevity of planetary atmospheres remains debated.
A semi-empirical model describing atmospheric escape was developed by **Gunell et al. 2018**, for **Earth-**, **Mars-**, and **Venus-** like planets. This model uses in-situ measurements and physical considerations to estimate the effect of planetary magnetization on the atmospheric loss rate. We add a dependency on **Solar Wind** (**SW**) dynamic pressure using physical assumptions and in-situ observations to describe its effect on each of the seven erosion mechanisms implemented in the model. The main objective is to **reproduce early planetary and solar conditions** in order to constrain the role of the planetary magnetic field and solar wind pressure on atmospheric loss over geological time scales.

Geometrical parameters

Three parameters describe the geometry of the problem. They are estimated by considering the pressure balance between the SW and the planetary magnetic field (either intrinsic or induced). Magnetic field lines are traced using a simple magnetic field model.

Stand-off distance r_{MP}: Distance to the magnetopause or the induced magnetosphere boundary.

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

Cross section radius r_{cs}: Amplitude of the last closed magnetic field line, indicating the cross section of the magnetosphere with the SW.

Other parameters that have an effect in the processes are: **exobase r_{exo}** and **scale height density h_α**.

IPA website

For more information about the project.

https://ipa.aeronomie.be/

References

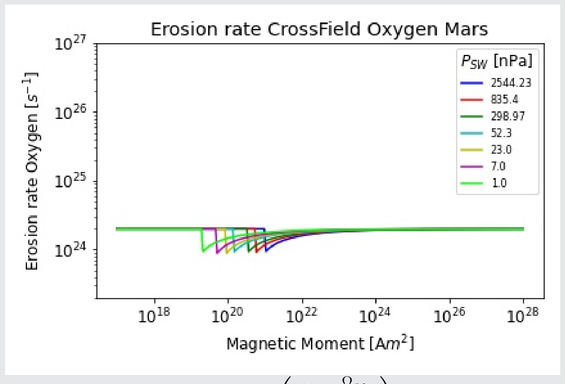
- Carolan, S. et al. (2019). "The evolution of Earth's magnetosphere during the solar main sequence". In: *Monthly Notices of the Royal Astronomical Society* 489, pp. 5784–5801. DOI: 10.1093/mnras/stz2422.
- Engwall, E. et al. (2009). "Survey of cold ionospheric outflows in the magnetotail". In: *Annales Geophysicae* 27, pp. 3185–3201. DOI: 10.5194/angeo-27-3185-2009.
- 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.

Erosion Mechanisms

To ilustrate our results, we consider Oxygen escape on Mars, for the same SW pressures (Carolan et al. 2019) in each process. Two of them are independent of the magnetic moment and SW pressure: **Jeans escape** and **Photochemical escape**.

Cross-field ion loss

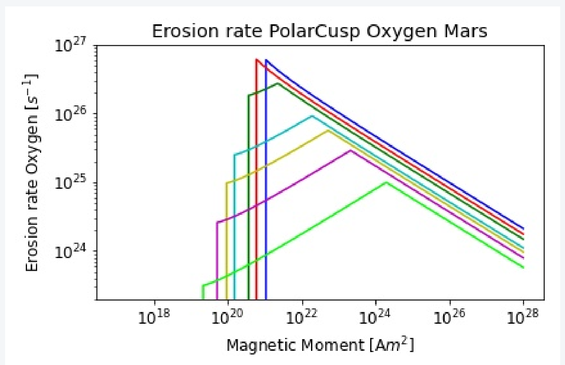
This includes all escape processes across magnetic field lines like plasmaspheric plumes, plasmaspheric wind. This process depends on Ω_{pc}.



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

Polar cusp escape

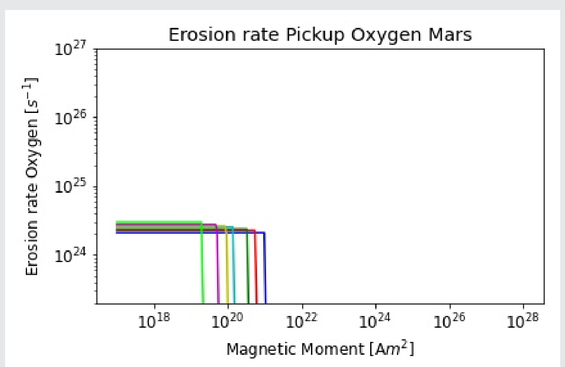
We consider that the polar cusp escape rate is proportional to the solar wind energy that is intercepted by the planetary magnetosphere. This process depends on Ω_{pc} and r_{cs}. The incoming energy flux is a function of the SW parameters.



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

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.



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

Photochemical escape

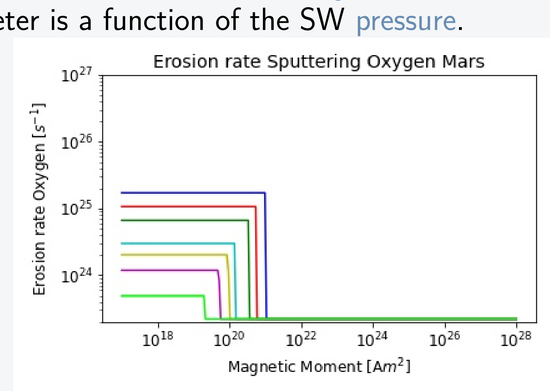
It includes: photodissociation, photodissociative ionization, electron impact dissociative ionization, and dissociative recombination. In Mars the last mechanism dominates, where electrons from the SW recombine with O^+, giving them the extra energy that they require to escape the planet.

Jeans escape

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

Sputtering

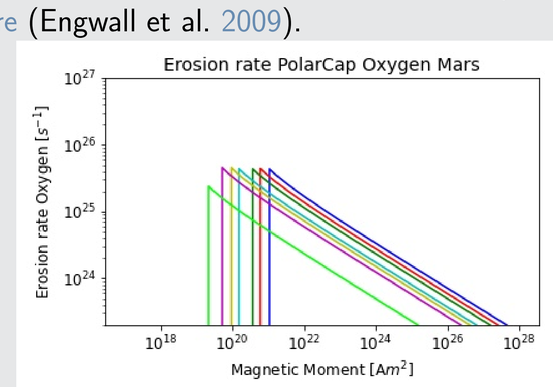
Some of the ionospheric ions swept up and accelerated by the SW reimpact the ionosphere exospheric atoms, giving them enough energy to escape. Thus, it depends on ion pickup, r_{MP}, and the gyroradius r_g of the O ions. The last parameter is a function of the SW pressure.



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

Polar cap escape

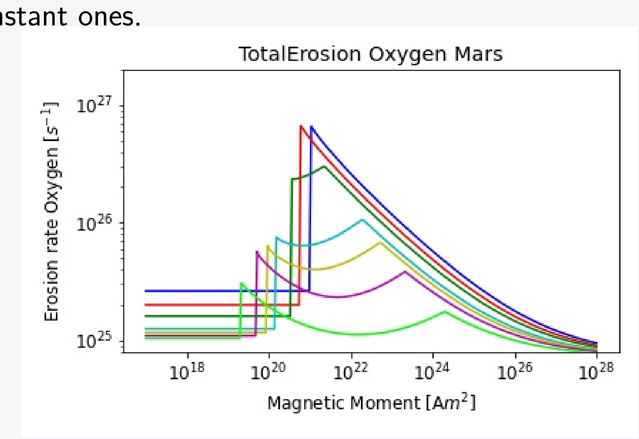
In polar wind, the outflow is proportional to Ω_{pc}. We use Cluster observations to constrain its dependency on the SW pressure (Engwall et al. 2009).



$$Q_{pc} = 2 \times min\left(1.1\times10^{12}e^{0.216P_{SW}}, q_{max}\right)\Omega_{pc}r_{exo}^2$$

Total escape

Combination of all the following processes, including the constant ones.



Remark: a different y-scale was used.

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 momement**.
- 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.