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Modelling Atmospheric Erosion for Terrestrial Planets in the Solar System

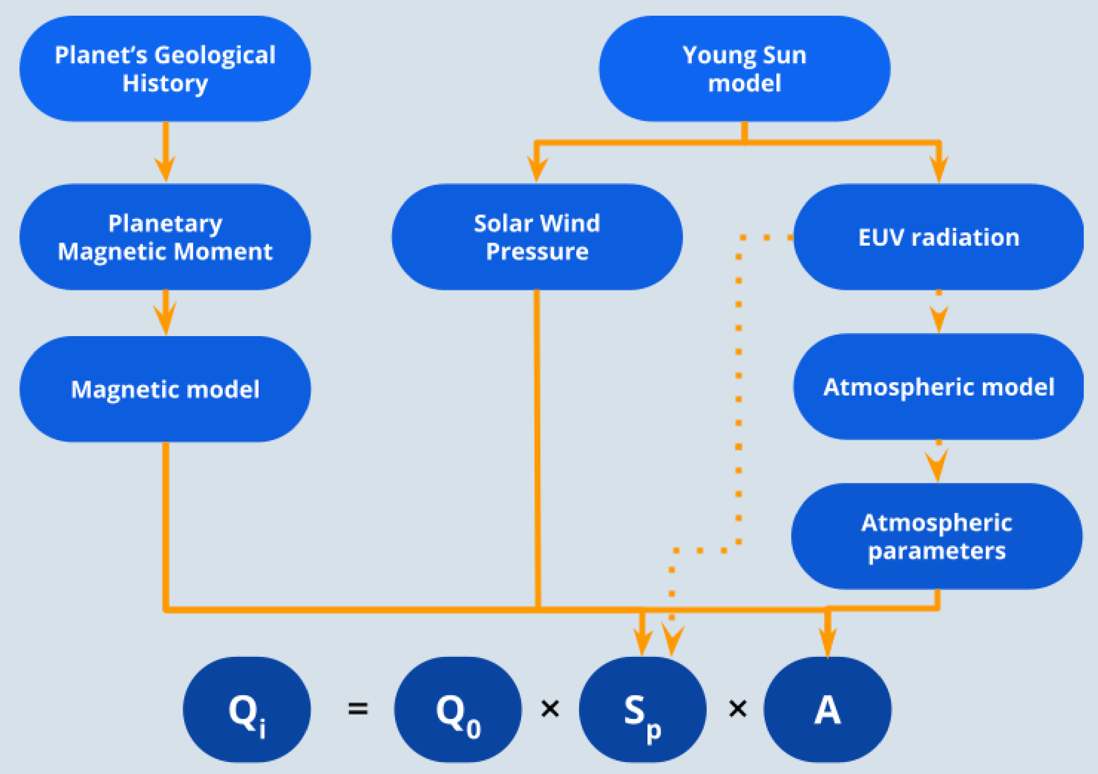
Objective

To **reproduce atmospheric oxygen loss rate for early planetary and solar conditions** in order to constrain the total oxygen loss over geological time scales and to determine its major drivers.

Method: Semi-Empirical Model

Using **in-situ measurements** and **physical considerations** to estimate the effect of solar evolution on the atmospheric loss rate. Physical assumptions are made to describe the contribution of the Solar Wind (**SW**) pressure on each erosion mechanism.

In general, we have:



With Q_i the rate for i process, Q_0 observational rates, S_p physical scaling of the process, and A geometrical scaling. The dotted arrows are work in progress, meanwhile full arrows are implemented in the code.

As starting point of the implementation of the effect of the solar radiation in the UV/EUV range, we will focus on **Earth** and then we will expand to the other planets.

Erosion Mechanisms

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** (Engwall et al. 2009). Solar EUV radiation plays a role changing the **ion density** at the exobase, increasing the escape.

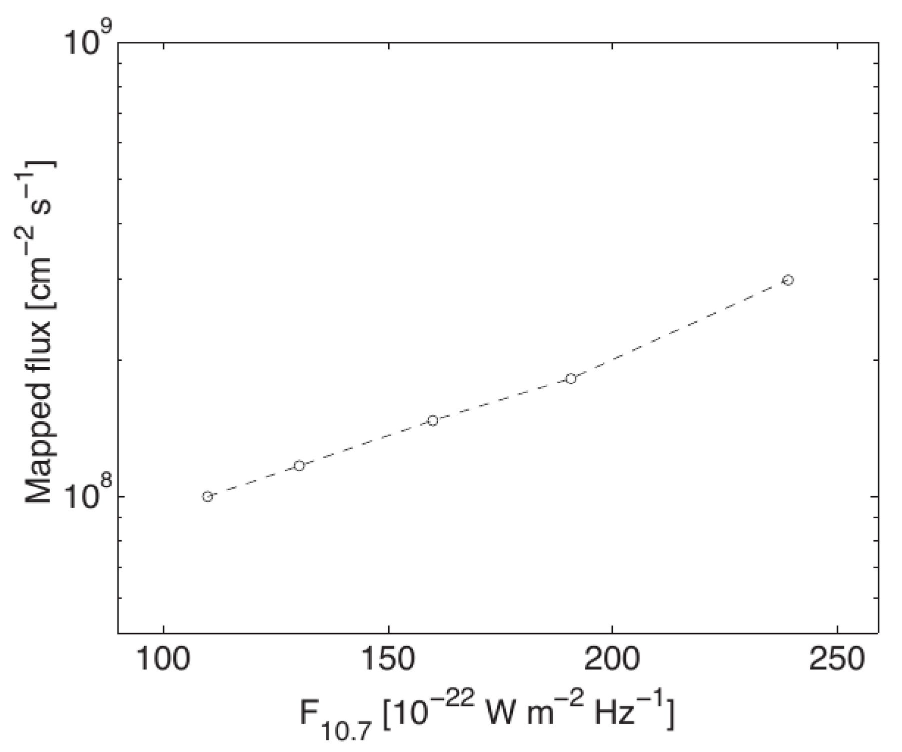


Figure 9 from Engwall et al. 2009. The mapped ionospheric flux as a function of $F_{10.7}$, a solar radiation proxy.

Other studies show no variation with EUV radiation (Kitamura et al. 2015).

Photochemical escape

Relevant only for **Mars**, where the recombination of O^+ with SW electrons allows the escape. It would depend on the **ion density** at the exobase, but this effect is negligible on Earth.

Jeans escape

In a Maxwellian distribution, the particles with velocities higher than the escape velocity escape. It depends on the **atmospheric parameters**, related to EUV radiation.

We define the Jeans parameter to find a maximum exobase temperature possible to **prevent hydrodynamic escape**.

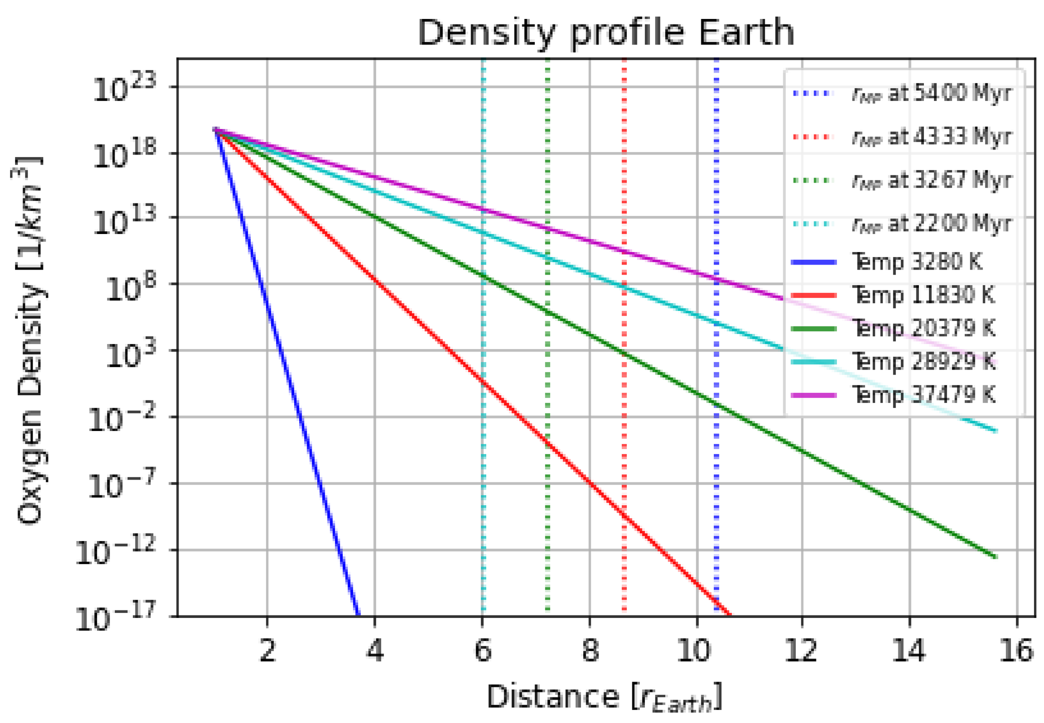
Polar cusp escape

Incoming energy from the **SW** intercepted by the planetary magnetosphere. This process energizes ions in the cusp, giving them the extra energy to escape. Its dependency with **Solar EUV radiation** is studied in Schillings et al. 2019, without an strong influence on the escape flux.

Ion pickup

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

We studied the **density** profiles at different **temperatures** on **Earth**, and compare them to the subsolar point distance evolution. It shows that the amount of neutrals outside of the Earth's magnetosphere is **negligible** for all levels of **SW** pressure and solar **EUV flux**, showing that ion pick-up doesn't contribute to the oxygen escape at **Earth**.



Full lines are neutral oxygen **density** profiles for Earth at different exobase **temperatures**, dotted lines are subsolar point distance for different solar ages according to Carolan et al. 2019 **SW** model.

Sputtering

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

As shown before, this effect is negligible on **Earth** due to the low density above the magnetopause by the time of the Great Oxygenation Event.

Cross-Field ion loss

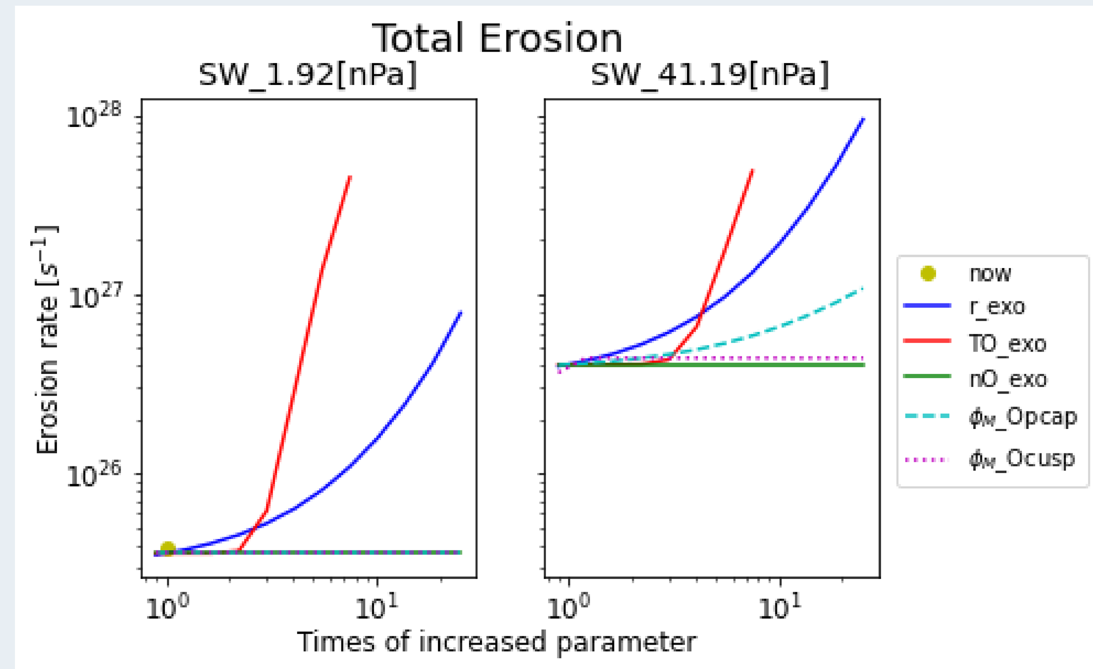
Ions trapped in the plasmasphere can eventually escape through the plasmaspheric wind or via the detachment of plasmaspheric plumes. It depends on the ionospheric **ion density** and the **SW** pressure, but it is not clear the relation, thus for the moment, it is only dependant on the volume of the closed field lines.

Atmospheric Parameter Impact

Before selecting the atmospheric model to determine the **atmospheric parameters**, we arbitrarily varied them in order to assess their effect on the oxygen escape rate.

We present the results for the total erosion on **Earth**.

Atmospheric Parametric Variation for two different SW pressures: now and ~2.5 Gyr Ago



Effect of **atmospheric parameters** on the total erosion rate with current and ~2.5 Gyr Ago **SW** pressure.

In this figure we have the exobase distance (r_exo) in blue, exospheric temperature (TO_exo) in red, exobase density (nO_exo) in green, maximum erosion rate for polar wind (ϕ_M_Opcap) in light blue, and maximum erosion rate for cusp escape (ϕ_M_Ocusp) in purple. The yellow dot shows the current values of the parameters.

- The exospheric **temperature** plays a significant role via an increase of **Jeans escape rate**.
- The **maximum ion production rate** is a **key limiting factor** for **cusp and polar cap escape**, it was likely higher in the past due to the higher ionization rate associated with the high solar **EUV flux**.
- The increase of exospheric **temperature and density** is constrained by the **atmospheric stability**, above a given level they would result in **hydrodynamic escape**, an escape regime not experienced by **Earth** during the last 3 billions years.

Analysis and Conclusions

- **Ion Pickup and Sputtering** are **negligible** for **Earth**, independently of the atmospheric expansion.
- Our model has a **maximum temperature** for the **stability** of the atmosphere, ~9 times the current one.
- **SW pressure** changes the effect of the **atmospheric parameters** on the erosion rate.
- Crucial erosion mechanisms to study young **Earth** are: **Polar Wind, Polar cusp, and Jeans escape**.

References

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