# Semi-empirical modelling of atmospheric escape: implications for the Martian atmospheric loss

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# Outline

- Introduction on the semi empirical model: goals, method and previous results
- Implementing the effect of solar wind pressure
- Results: application to oxygen escape at Mars
- Conclusion

# Introduction

**Goal: explore the past atmospheric loss rate of Venus, Earth and Mars**

- The young Sun was more active (higher solar wind density and velocity, higher UV/EUV flux, more CME/CIR)
- Atmospheric parameters have evolved with time
- The planetary magnetic moment has evolved with time

**Use observations of the escape rates as a function of controlling drivers and extrapolate to values of those drivers that prevailed in the early solar system**

# Introduction

**The Sun**

- EUV/UV flux
- Solar wind pressure

**Semi empirical model**

- **Observations (@ Venus, Earth and Mars)**
- Scaling with physical considerations and a magnetic field model

**Escape rate**
(number flux)
For O, H
$Q_i(m_{dp}, P_{SW})$

**Planetary Parameters**

- Mass and radius
- Distance to the Sun
- Exosphere: density, composition, temperature,
- Magnetic field

# Introduction

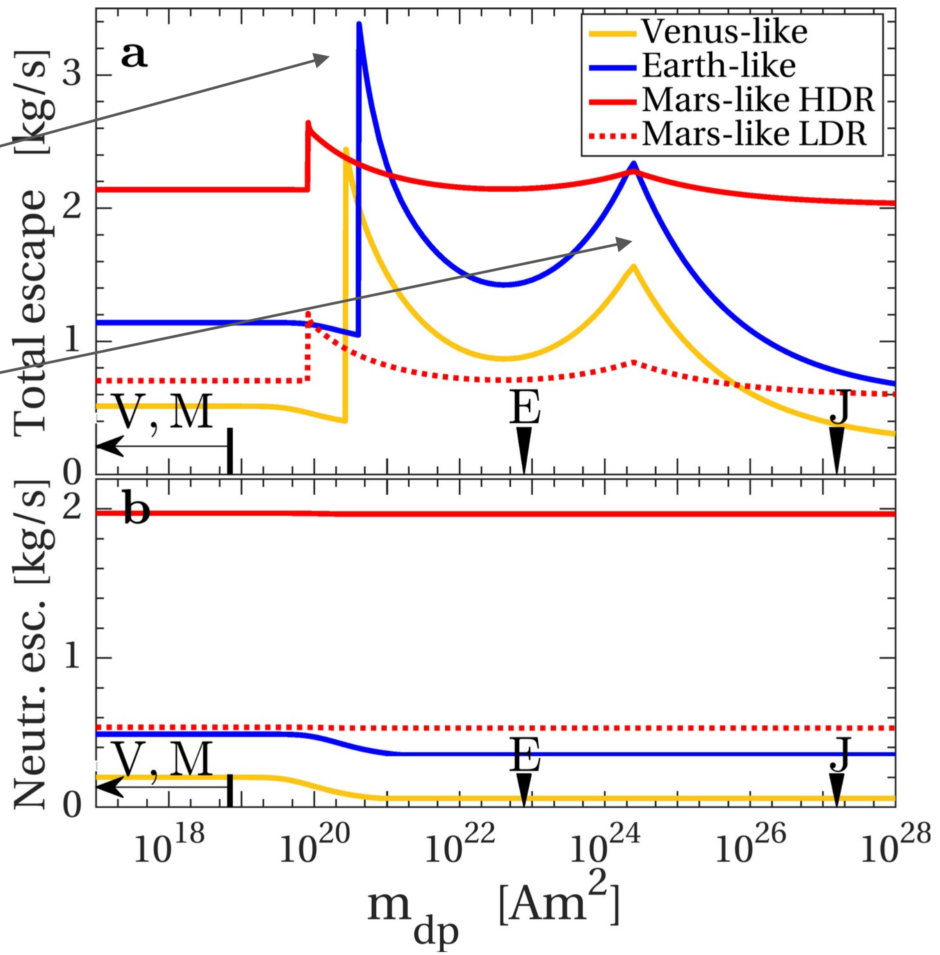
Gunell et al. 2018: $\mathbf{Q_i(m_{dp})}$

Atmospheric escape doesn’t vary monotonically with the planetary magnetic moment

2 peaks:

- At low magnetic moment and associated with **polar cap escape**

- At large magnetic moment associated with **polar cusp escape**

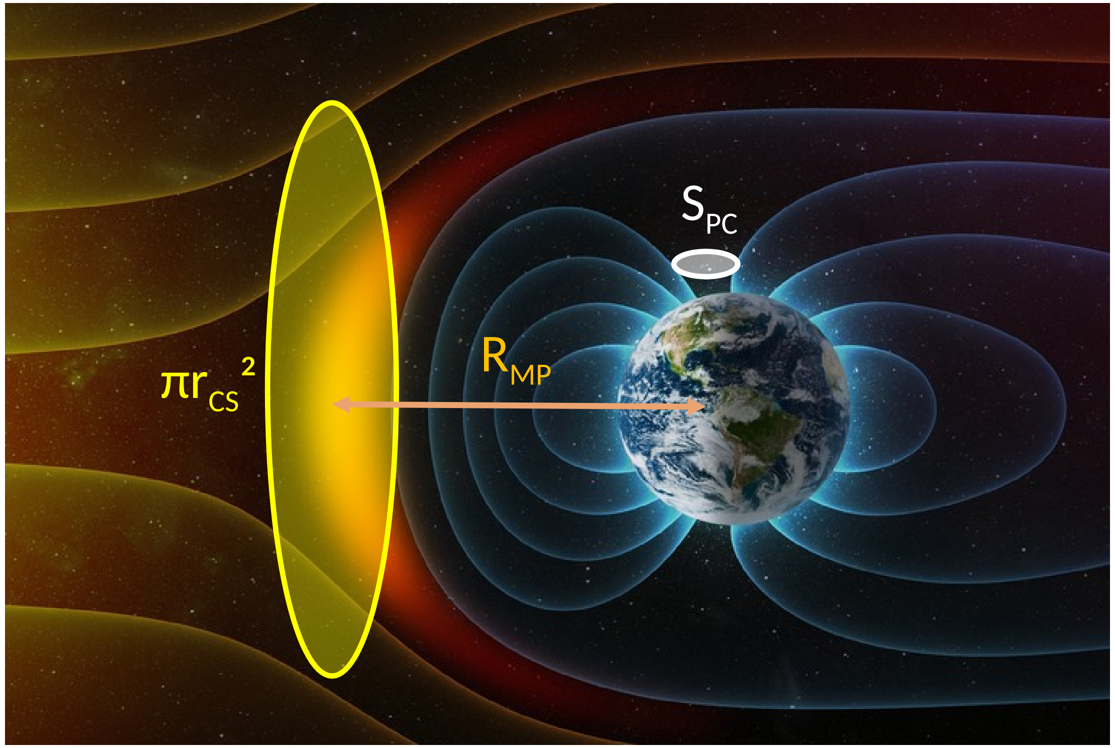



The presence of a strong planetary magnetic field does not necessarily protect a planet from losing its atmosphere

# Introduction

- **7 escape processes** :
- Jean's escape
- Dissociative recombination
- Sputtering
- Ion pick up
- Cross field ion loss
- Polar cusp escape
- Polar cap escape (polar wind)

- Only **hydrogen** and **oxygen**, the most populous exospheric species




Geometrical factors:
- $\pi r_{CS}^2$ : magnetospheric cross section with the solar wind
- $S_{PC}$ : surface of the region of open magnetic field lines
- $R_{MP}$ distance of the magnetospheric subsolar point.
  If $R_{MP} < R_{IMB}$ the planet is considered as unmagnetized.

# Implementing the effect of solar wind pressure

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- **Jean's escape**
- **Dissociative recombination**

Considered as independent of the solar wind dynamic pressure

- **Ion pick-up**

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

Partly proportional to the incoming solar wind number flux. Proportional to the amount of neutrals outside the magnetosphere

- **Sputtering**

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

Proportional to the ion pick up flux and to the number of neutrals 1 gyroradius inside the magnetopause

# Implementing the effect of solar wind pressure

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**Cross field ion loss**

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

- Unmagnetized: Constant value. For mars from Nilsson et al. 2011 (MEX).
- Magnetized: Flux density considered as constant (from André and Cully 2012). Total flux proportional to the surface of closed field lines.

**Polar cap escape**

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

Flux density depends on the solar wind pressure (empirical formula derived from Cluster observation, Engwall et al. 2009) and proportional to the surface of the polar cap

- We assume an $O^+/H^+$ ratio of 1/10
- $q_{max}$: the maximum ion flux that the ionosphere can supply (Barakat et al. 1987)
- When $H^+$ reach saturation, we consider that both $O^+$ and $H^+$ saturate

# Implementing the effect of solar wind pressure

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**Polar cusp escape**

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

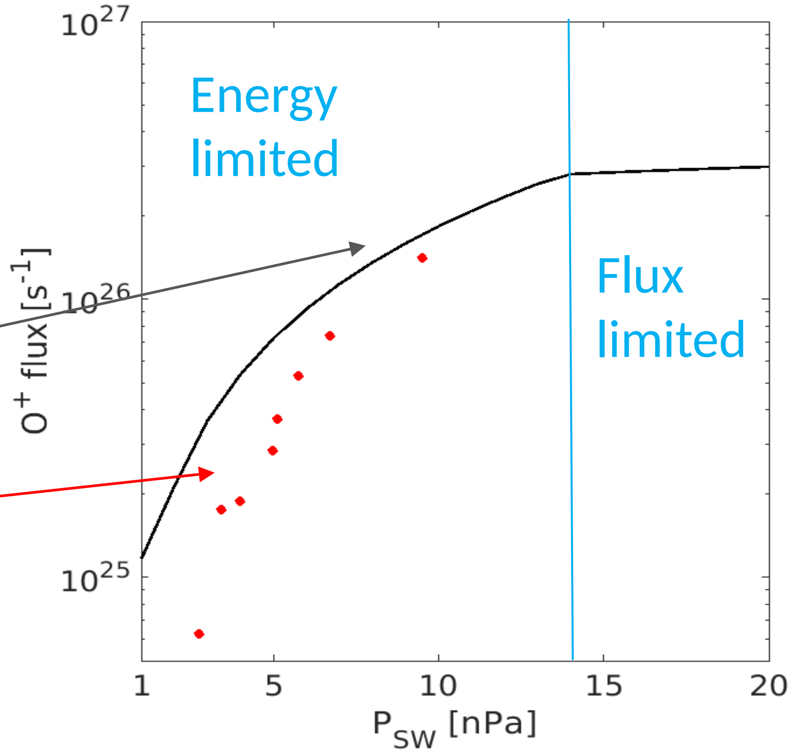
Flux density proportional to the incoming solar wind energy flux, total flux proportional to the surface of the polar cap

- $Q_{max}$: the maximum ion flux that the ionosphere can supply (Barakat et al. 1987)

- Comparison with independent data for Earth

Model, reference flux from Polar observations (Pollock et al. 1990)

Cluster observations (Schillings et al. 2019)



# Results: application to oxygen escape at Mars

**This is not the full picture!**

- The following plots corresponds to a hypothetical Mars-like planet with a varying magnetic field. **Mars atmospheric/exospheric parameters are the current ones**.

- Only the solar wind dynamic pressure varies (we consider high solar wind pressure levels representative of the young Sun). **The higher EUV/UV flux of the young Sun is not taken into account**.

  - Mars exospheric parameters for $O^+$: $r_{EXO}$= 3609,5 km; $n_{EXO}$= 4. $10^{10}$ $m^{-3}$; $T_{EXO}$= 4100 K

  - $q_{MAX}$ (from Barakat et al. 1987): 1 $10^{13}$ $m^{-2}s^{-1}$ for $O^+$

  - Solar wind dynamic pressure:

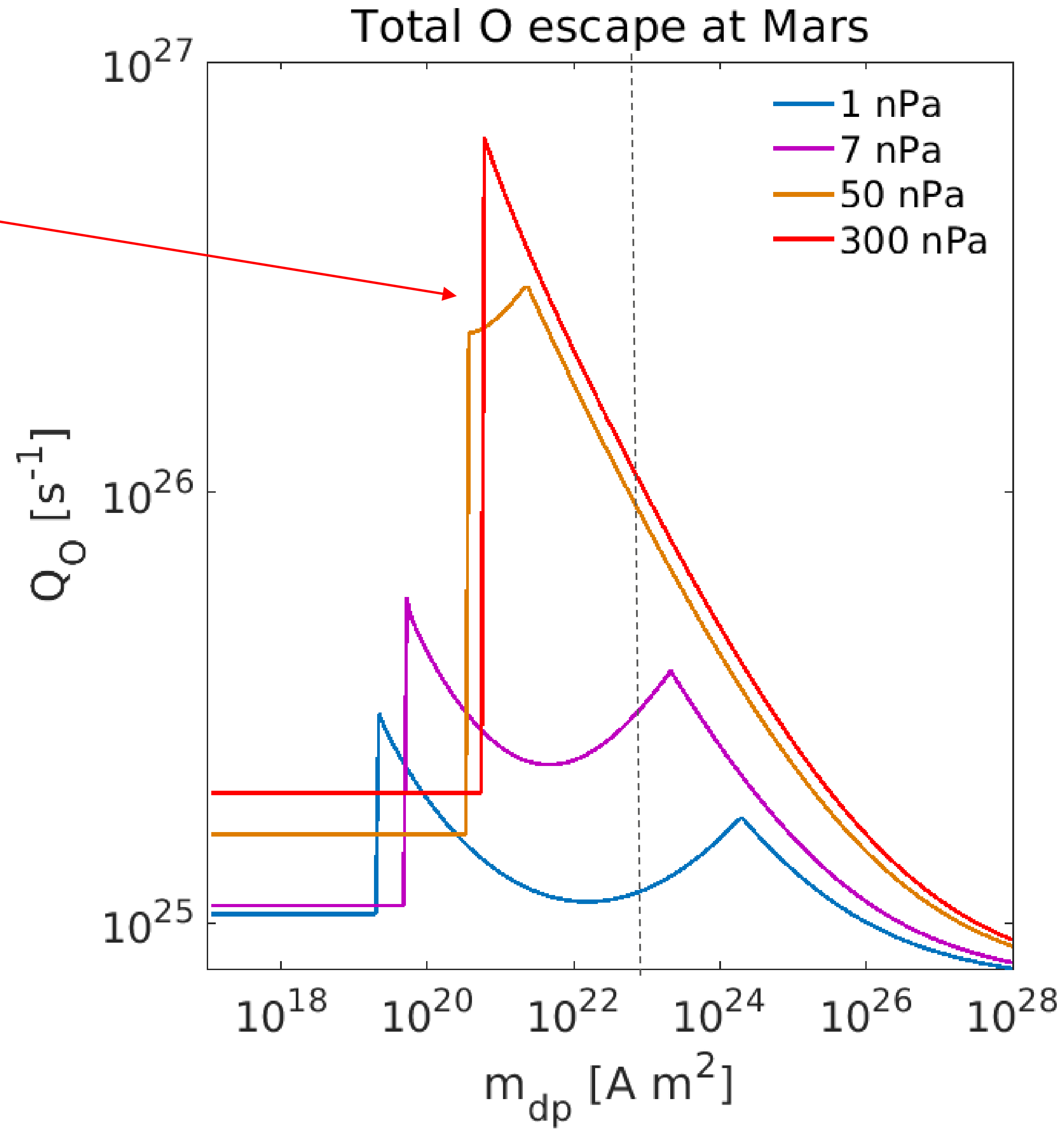
    - 1 nPa: low solar wind pressure for the current Sun
    - 7 nPa: high solar wind pressure for the current Sun
    - 50 nPa: solar wind pressure for a 1.1 Gyr old Sun
    - 300 nPa: solar wind pressure for a 440 Myr old Sun

} See Carolan et al. 2019

# Results: application to oxygen escape at Mars

The escape rate peaks for low magnetic moment and high solar wind pressure

At its highest, the escape is dominated by polar cap and polar cusp escape




Other studies indicating that weak global dipole field of the planet results in enhanced atmospheric escape rate:

Kallio and Barabash (2012)

Sakai et al. (2018)

Egan et al. (2019)

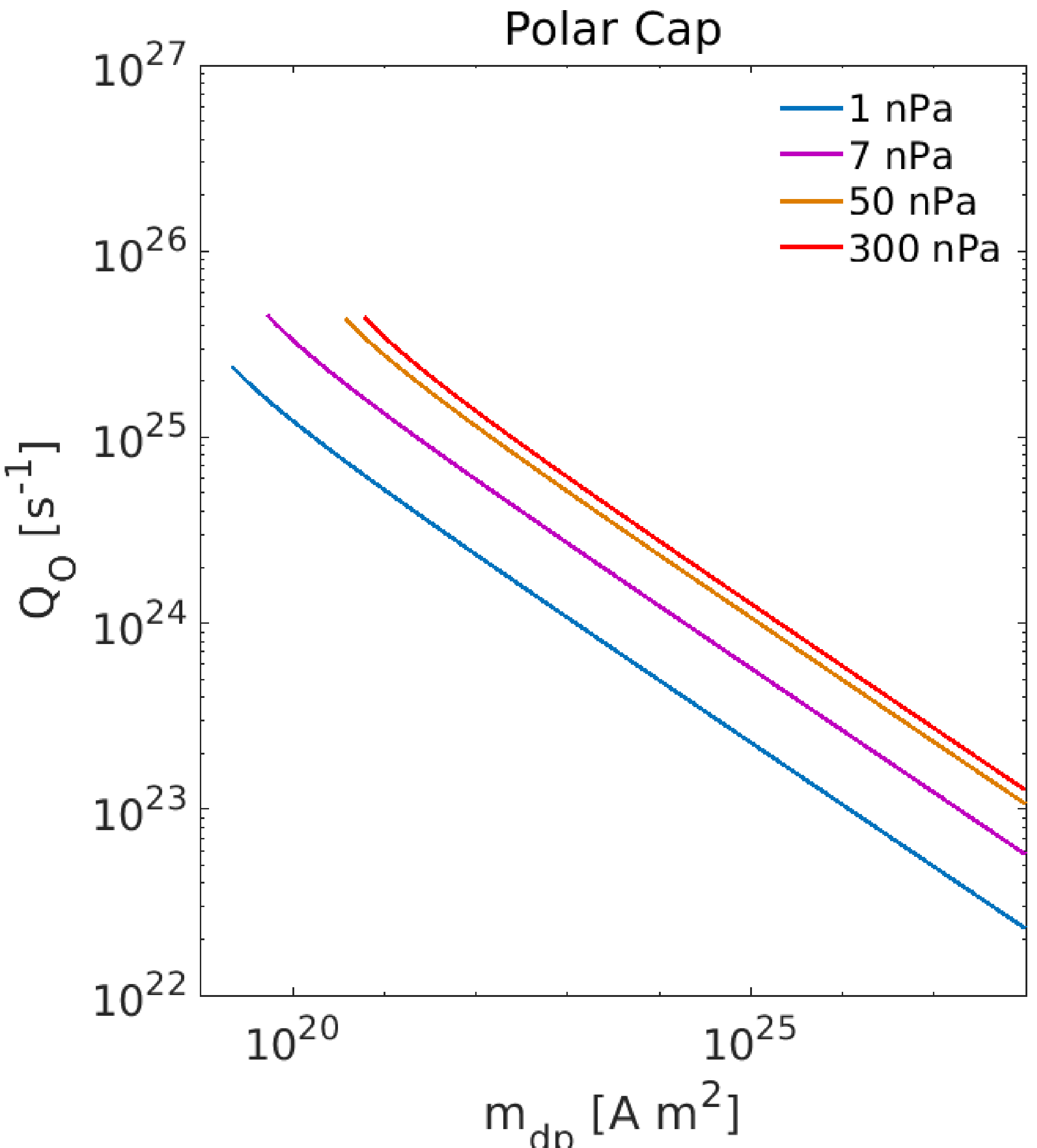
# Results: application to oxygen escape at Mars

**Polar cap escape**

The flux density increases with $P_{sw}$ until saturation

The polar cap solid angle
- decreases with $M_{dp}$
- increases with $P_{sw}$

Polar cap escape always peaks for low planetary magnetic moment



# Results: application to oxygen escape at Mars

**Polar cusp escape**

The magnetospheric cross section
- increases with $M_{dp}$
- decreases with $P_{sw}$

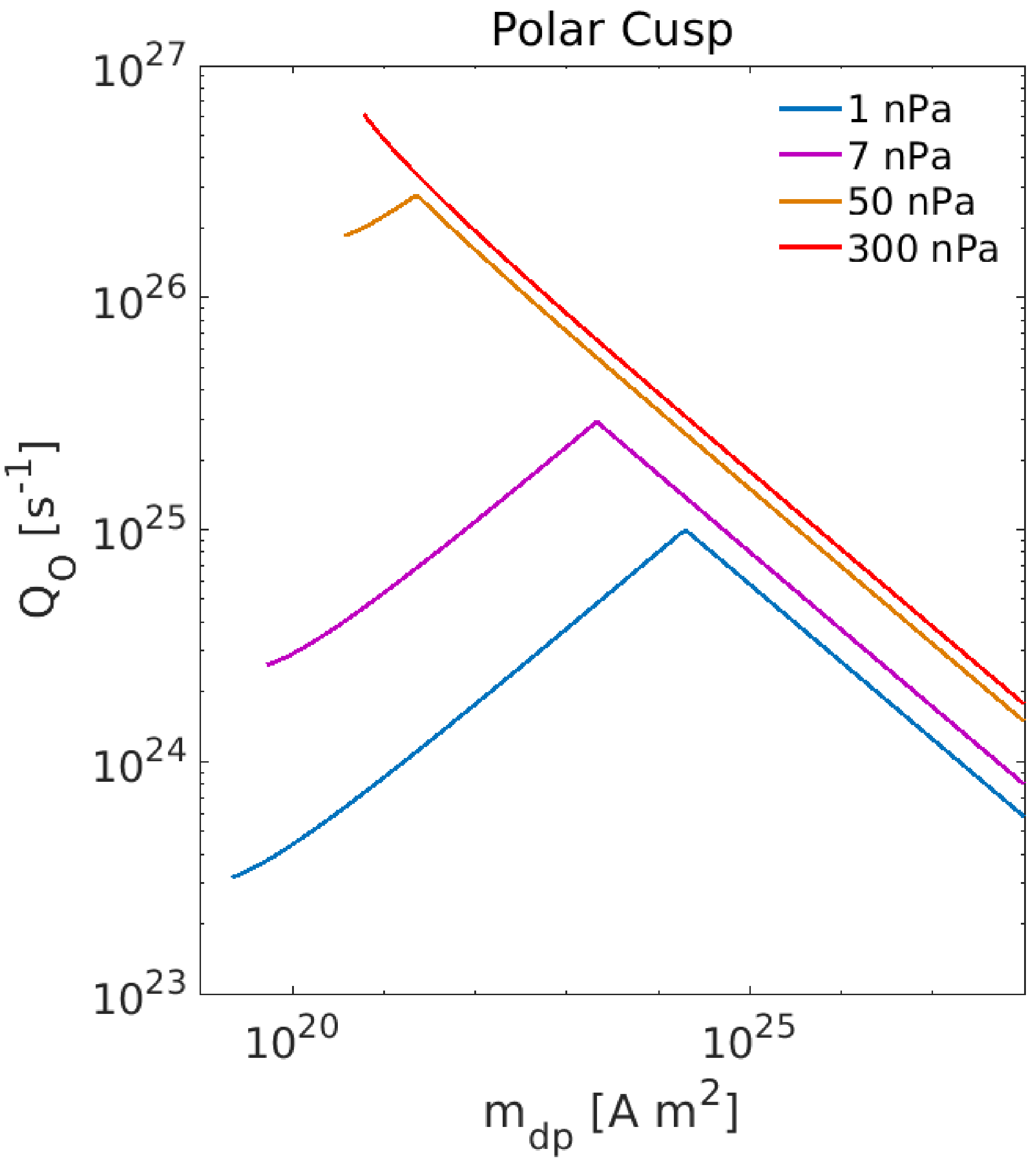
The solar wind energy density increases with $P_{sw}$ and $M_{dp}$

⇩

The flux density increases with $P_{sw}$ and $M_{dp}$ until saturation

The polar cusp solid angle
- decreases with $M_{dp}$
- increases with $P_{sw}$

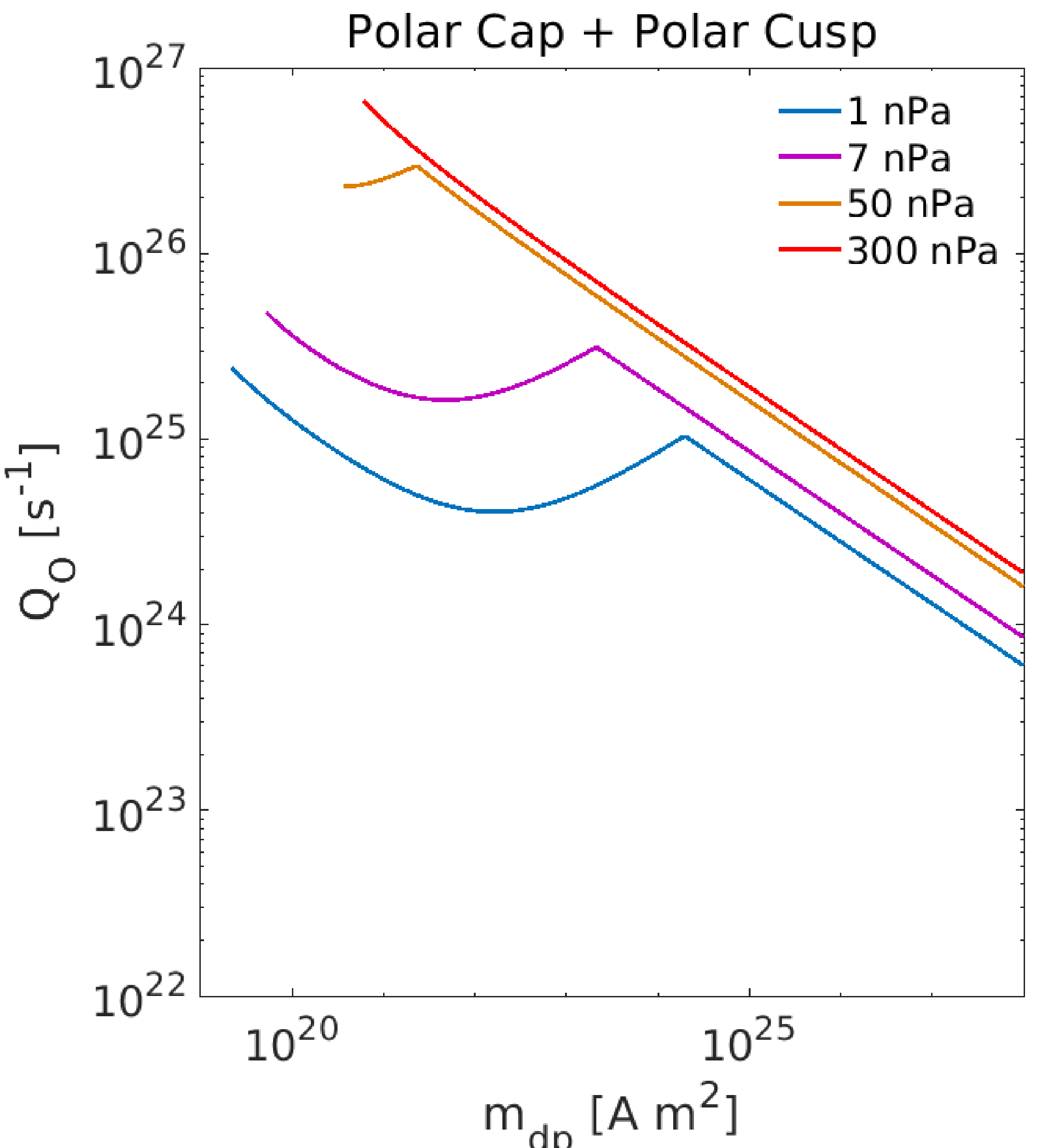
The polar cusp escape peaks when the saturation is reached. This peak shifts to lower planetary magnetic moments when the solar wind pressure increases



# Results: application to oxygen escape at Mars

**Polar cap + polar cusp escape**

- For high solar wind pressure levels, the peak of polar cusp and polar cap escape "merge"
- The $O^{+}$ escape from the polar ionosphere is dominated by polar cusp escape
- The escape rate is maximum for low magnetic moments, at the limit of the unmagnetized range



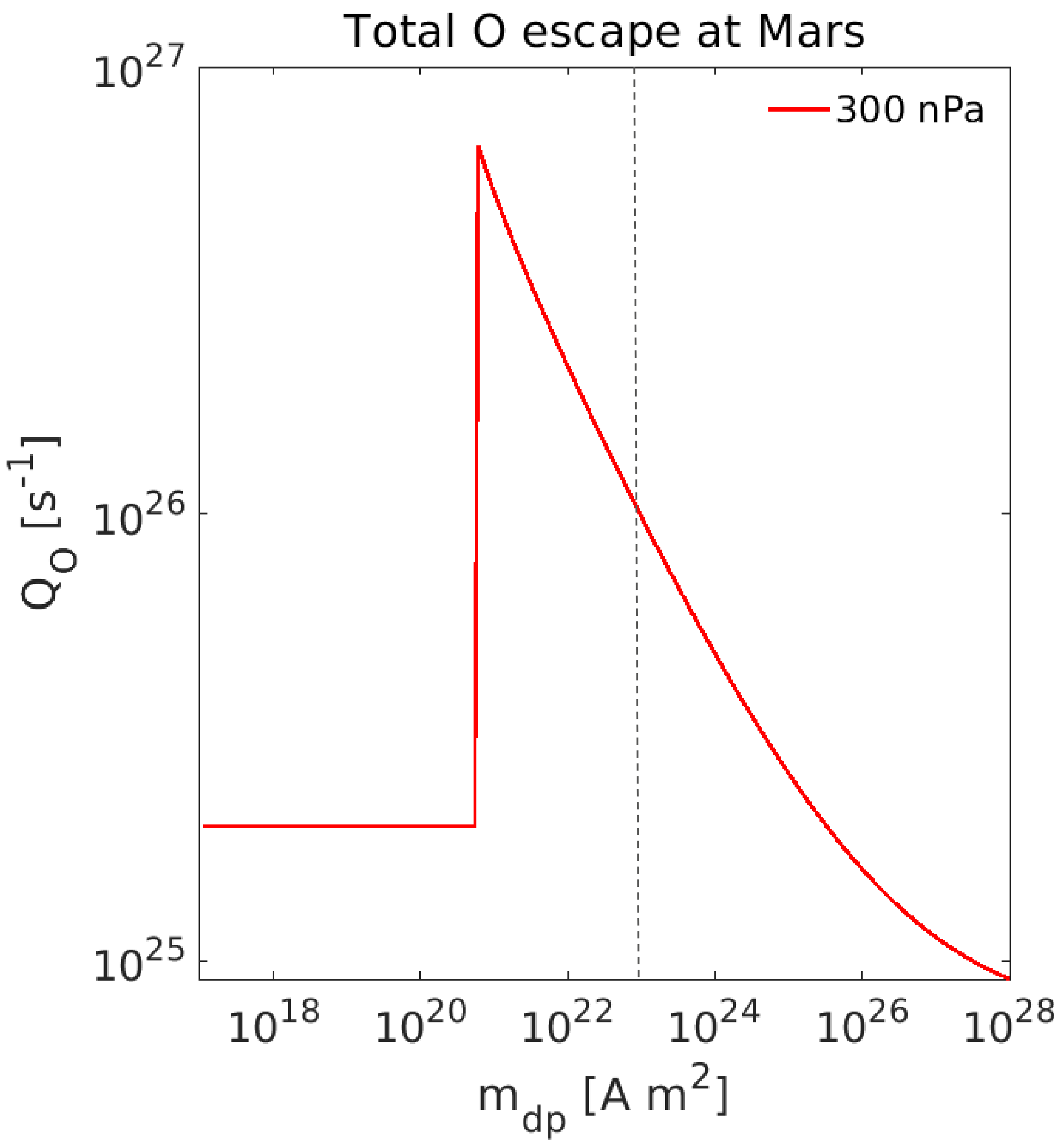
# Conclusion

The oxygen escape rate maximizes for a weakly magnetized Mars and a high solar wind pressure

**This could correspond to Early Mars** :

- The Martian dynamo was active between 4.5 and 3.7 Ga ago (Mittleholz 2020)
- Mars had a relatively dense atmosphere during the Noachian eon and liquid water (e.g. Scherf and Lammer 2020 and references therein)
- The solar wind pressure was high at that time (hundreds of nPa, e.g. Carolan et al. 2019)

Our model suggests a potential substantial escape through the polar regions of early Mars' paleo-magnetosphere



# THANK YOU!
# MORE INFO?

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