Do planetary magnetic fields protect atmospheres?

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BNCGG study day
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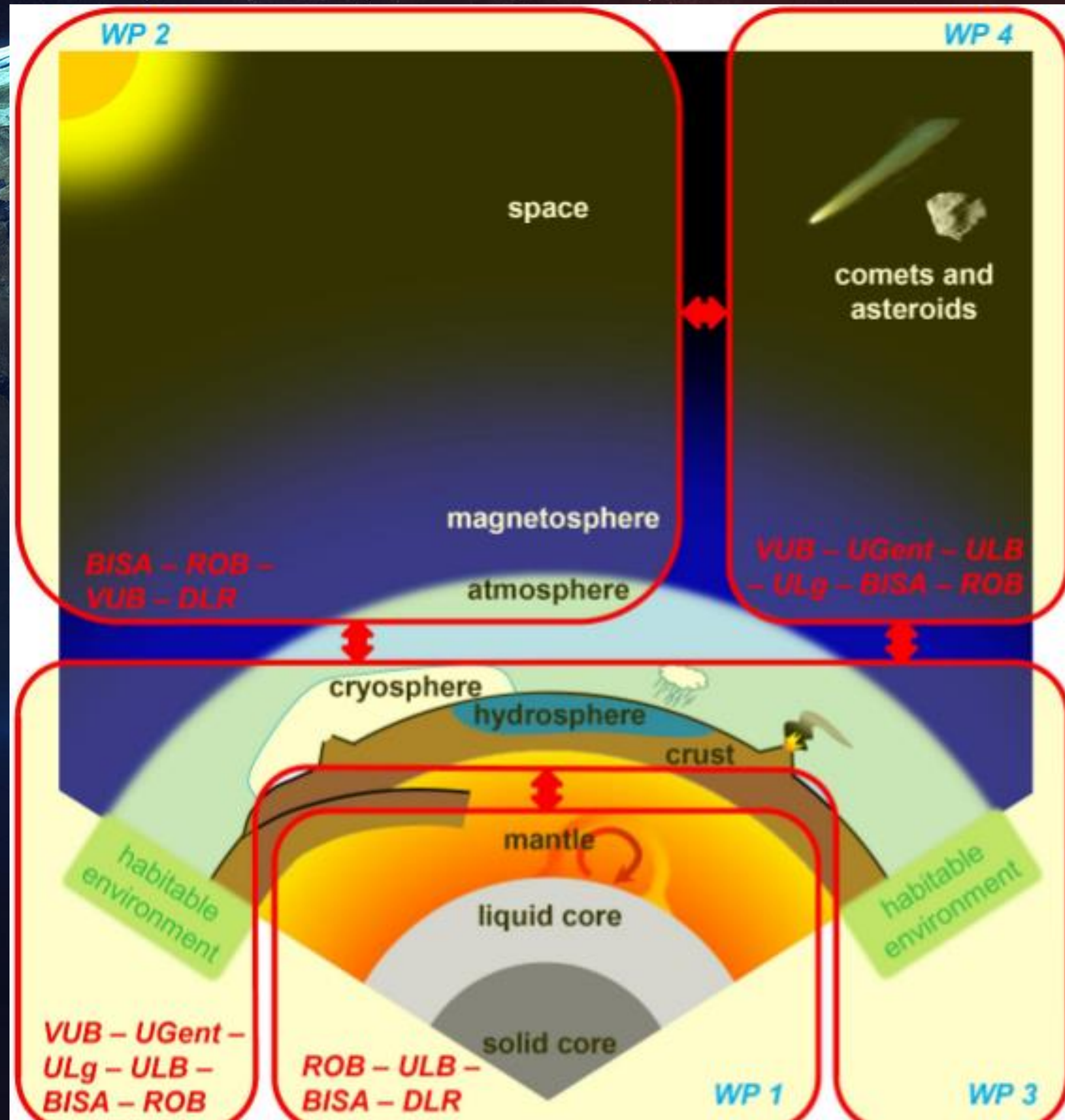
ROYAL BELGIAN INSTITUTE
FOR SPACE AERONOMY

Atmosphere and habitability

From the Interuniversity Attraction Pole (IAP) ‘PLANET TOPERS’ (Planets: Tracing the Transfer, Origin, Preservation, and Evolution of their Reservoirs) 2012-2017



Atmosphere and habitability

Do planetary magnetic fields protect atmospheres?

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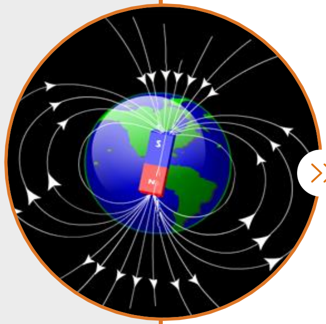
What is the effect of planetary magnetic fields on atmospheric loss into space?

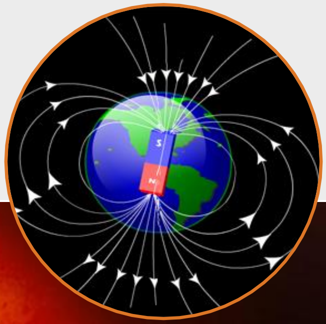


Basic principles

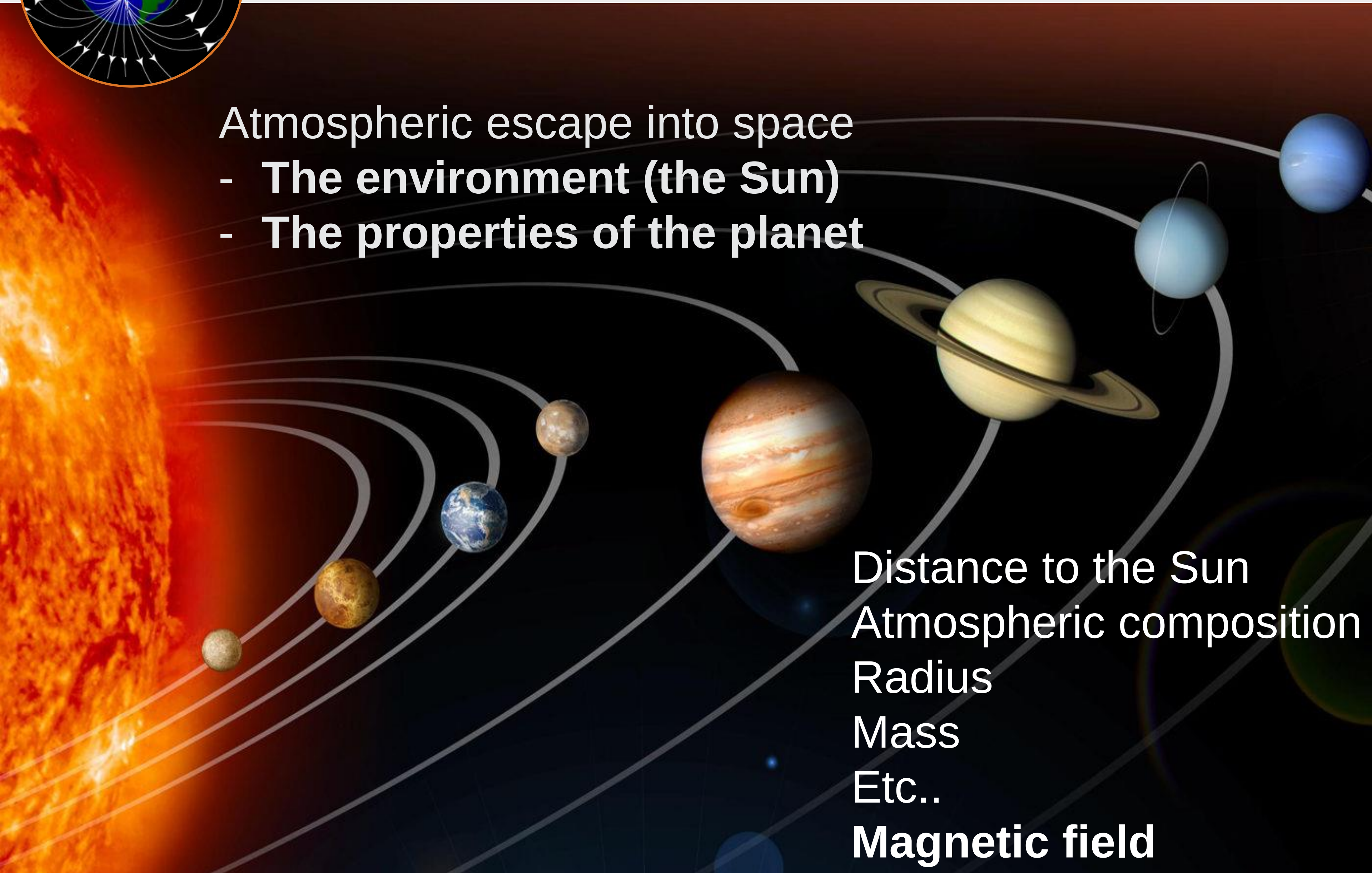
Why it seems obvious that a planetary magnetic field protects the atmosphere

State of the art

Future developments



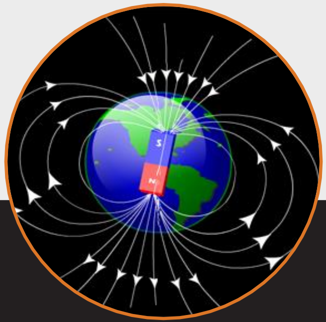
Basic principles



Atmospheric escape into space

- **The environment (the Sun)**
- **The properties of the planet**

Distance to the Sun
Atmospheric composition
Radius
Mass
Etc..
Magnetic field

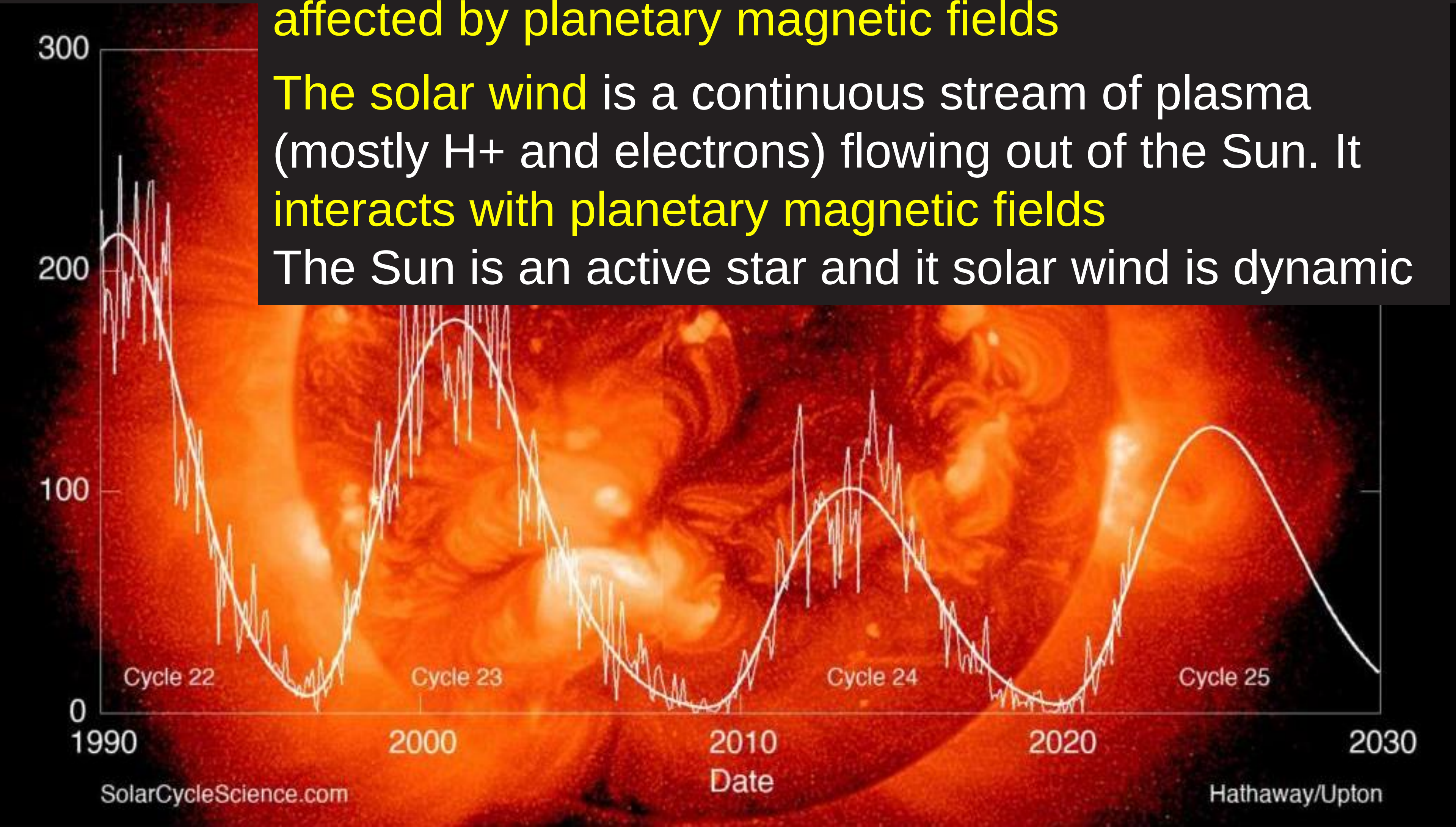


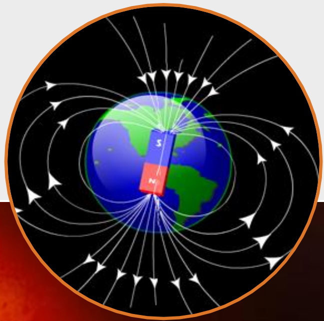
Basic principles

Sunlight is crutial for atmospheric evolution. It is not affected by planetary magnetic fields

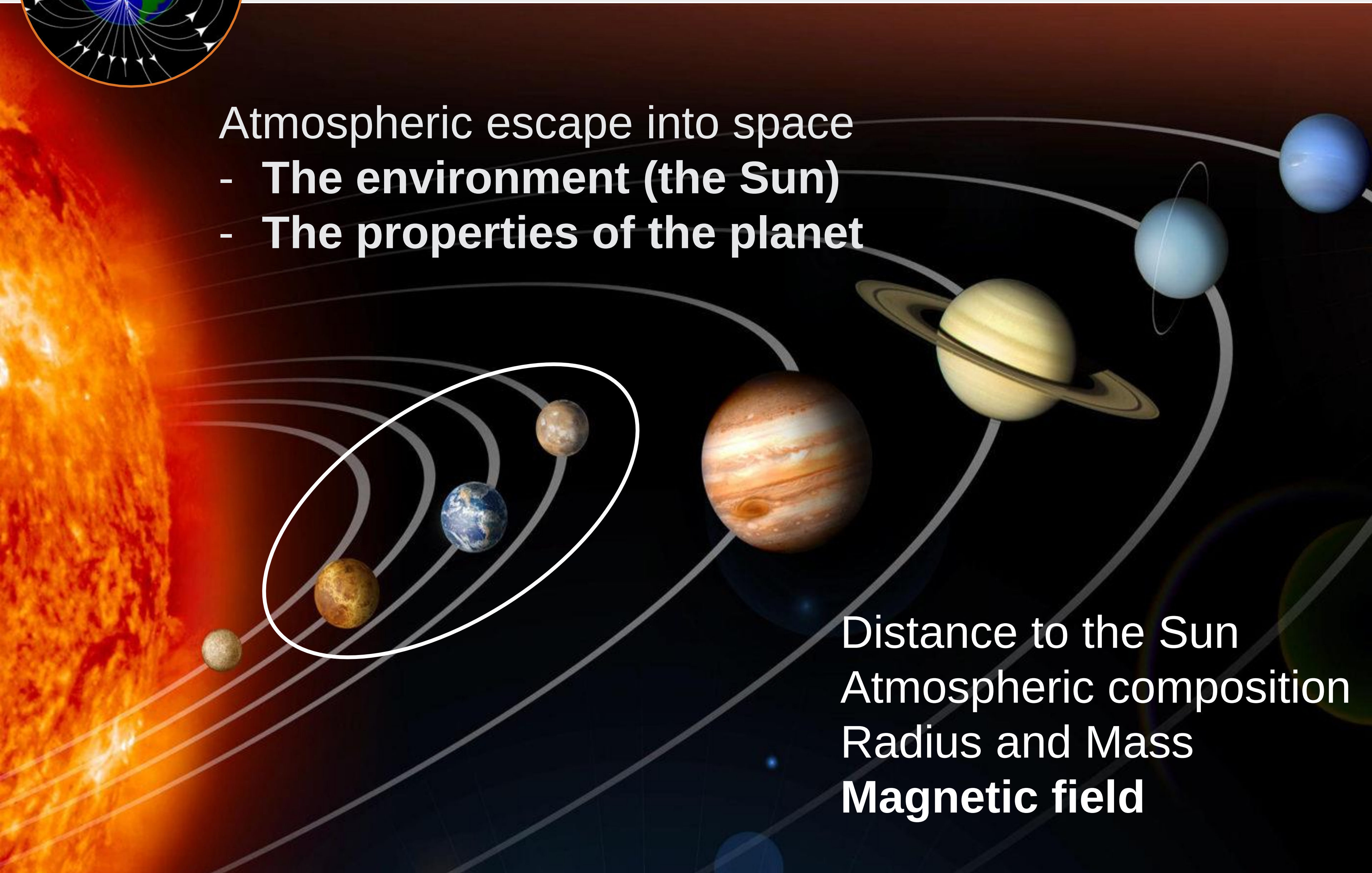
The solar wind is a continuous stream of plasma (mostly H+ and electrons) flowing out of the Sun. It interacts with planetary magnetic fields

The Sun is an active star and it solar wind is dynamic





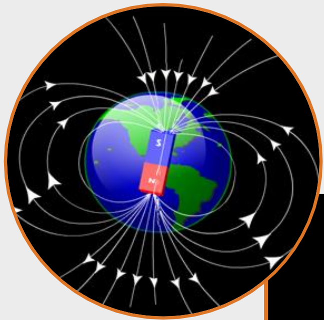
Basic principles



Atmospheric escape into space

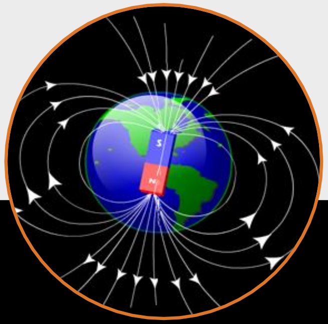
- **The environment (the Sun)**
- **The properties of the planet**

Distance to the Sun
Atmospheric composition
Radius and Mass
Magnetic field



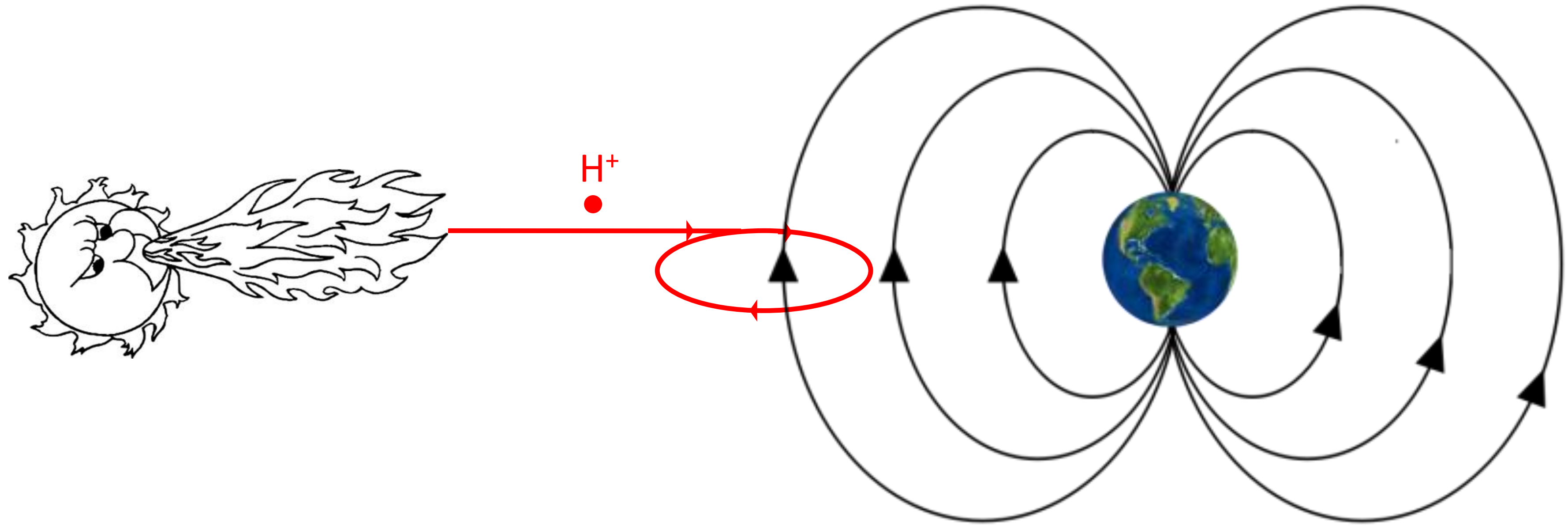
Basic principles

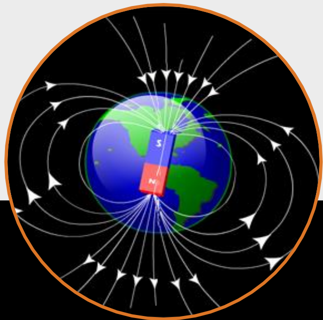
	Distance to the Sun	Radius	Mass	Magnetic Field	Ground pressure	Water
Venus 	108 millions de km	6052 km	4,87 10^{24} kg	No	93 Bar	Negligible
Earth 	149 millions de km	6370 km	5,97 10^{24} kg	Yes	1 Bar	Yes
Mars 	228 millions de km	3390 km	6,39 10^{23} kg	No	0,006 Bar	Negligible



Basic principles

Due to the Lorentz force, charged particles from the solar wind tend to gyrate arount the magnetic field instead of flowing through it

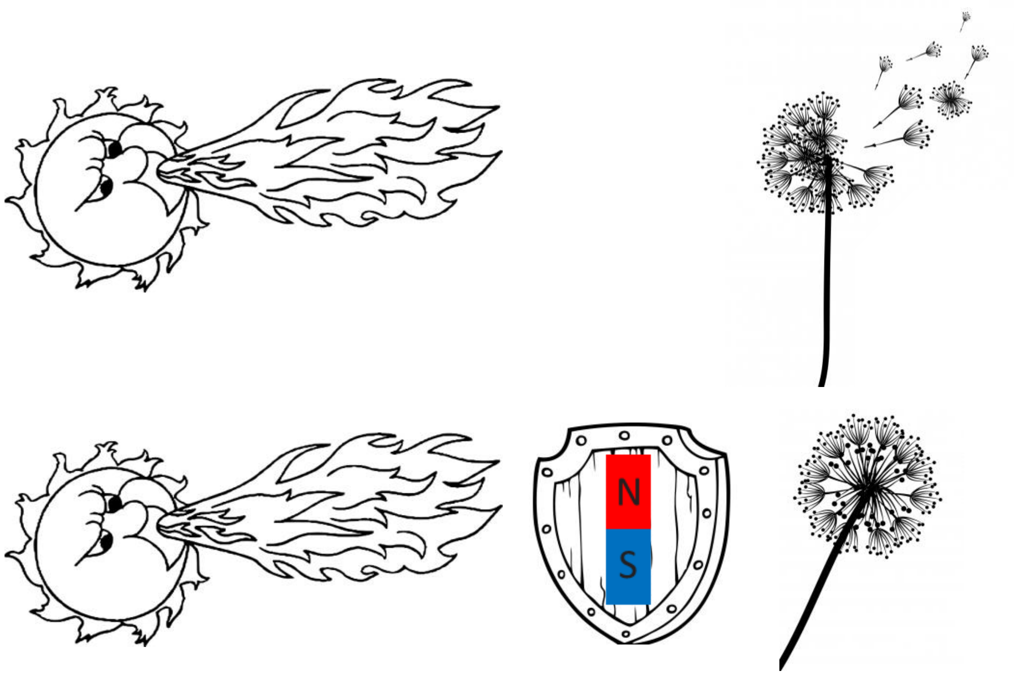




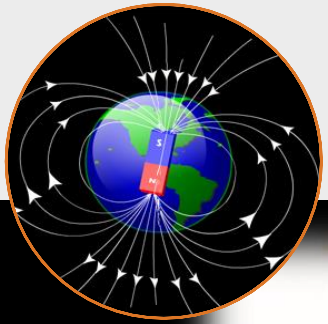
Basic principles

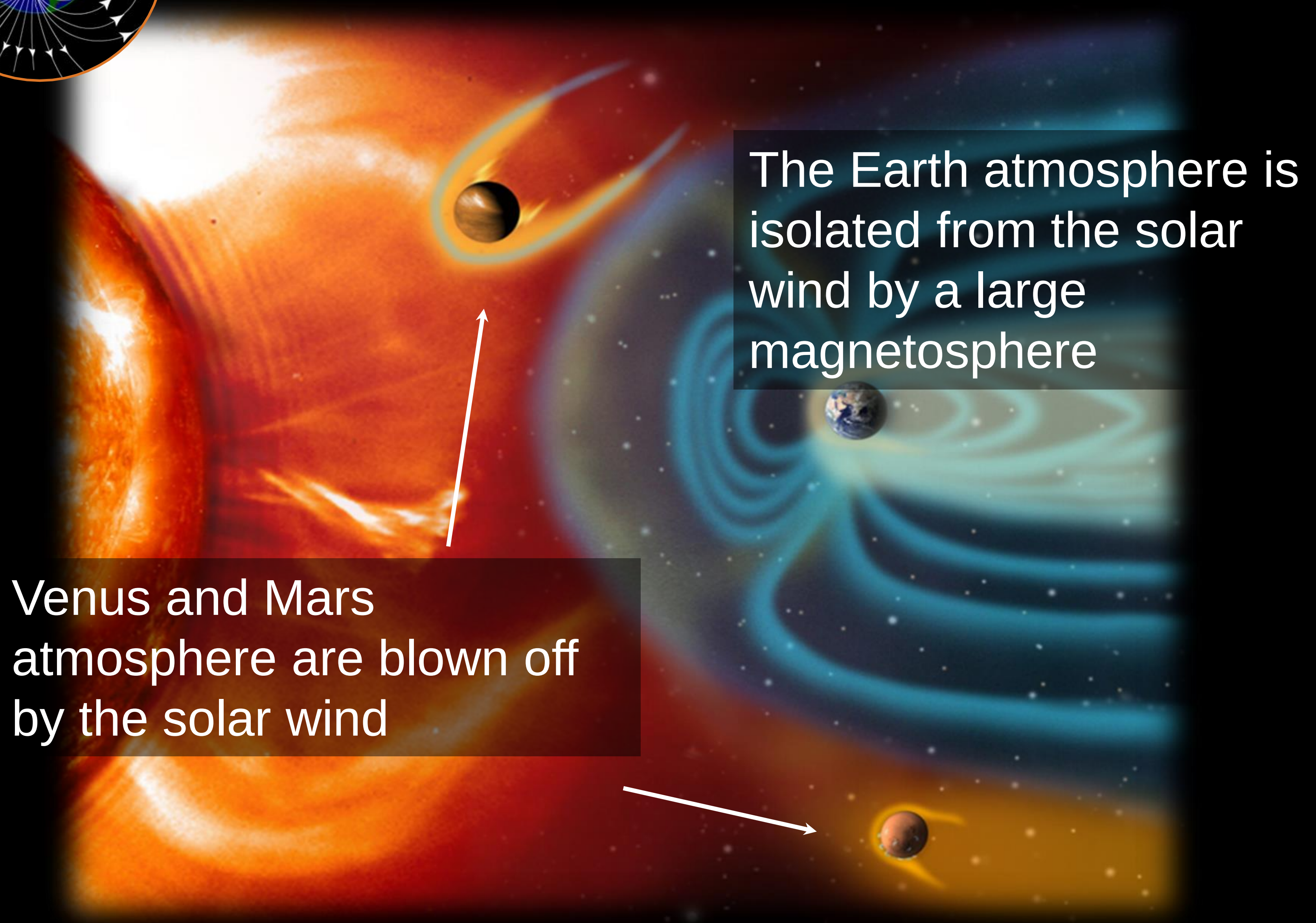
A planetary magnetic field prevents the solar wind from directly interacting with the atmosphere

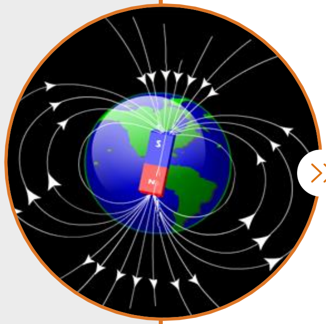
It thus seems obvious that it reduces atmospheric escape into space



Basic principles







Atmospheric escape: basic principles

State of the art

Why it is not obvious that a planetary magnetic field protects the atmosphere

Future developments

State of the Art

O^+ ions originating from the earth ionosphere detected in the Earth magnetosphere (ASTEX1, NASA, 1972)

VOL. 77, NO. 31 JOURNAL OF GEOPHYSICAL RESEARCH NOVEMBER 1, 1972

Satellite Observations of Energetic Heavy Ions during a Geomagnetic Storm

E. G. Shelley, R. G. Johnson, and R. D. Sharp

The relatively large fluxes observed for the heavy ions, i.e., at times comparable to or larger than the kev proton fluxes, suggest an ionospheric source, since the ratio of ^{16}O and other ions in this mass range to hydrogen ob-

State of the Art

Earth
IMP-7 (NASA, 1972-1978)
Dynamic Explorer 1&2 (NASA, 1981-1991)
Akebono (ISAS, 1989-2015)
Polar (NASA, 1996-2008)
Fast (NASA, 1996-2009)
Cluster (ESA, since 2000)

Mars
Mars 2, Mars 3 and Mars 5 missions (USSR, 1971-1974)
Mars Express (ESA, since 2003)
Maven (NASA, since 2014)

Venus
Pioneer Venus Orbiter (NASA, 1980-1992)
Venus Express (ESA, since 2006)

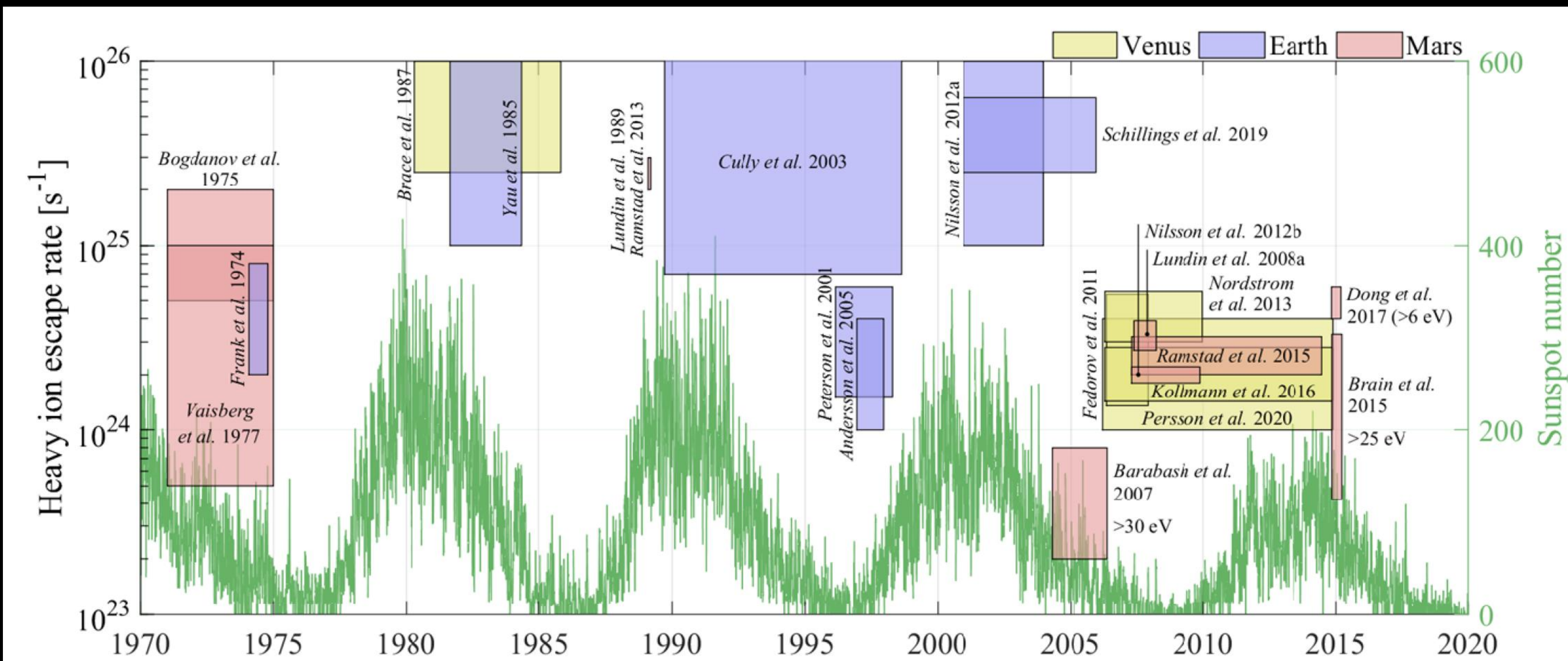
State of the Art

Earth: 10^{25}-10^{26} s^{-1}

Venus and Mars: 10^{24}-10^{25} s^{-1}

Higher escape rate at Earth

High variability



State of the Art

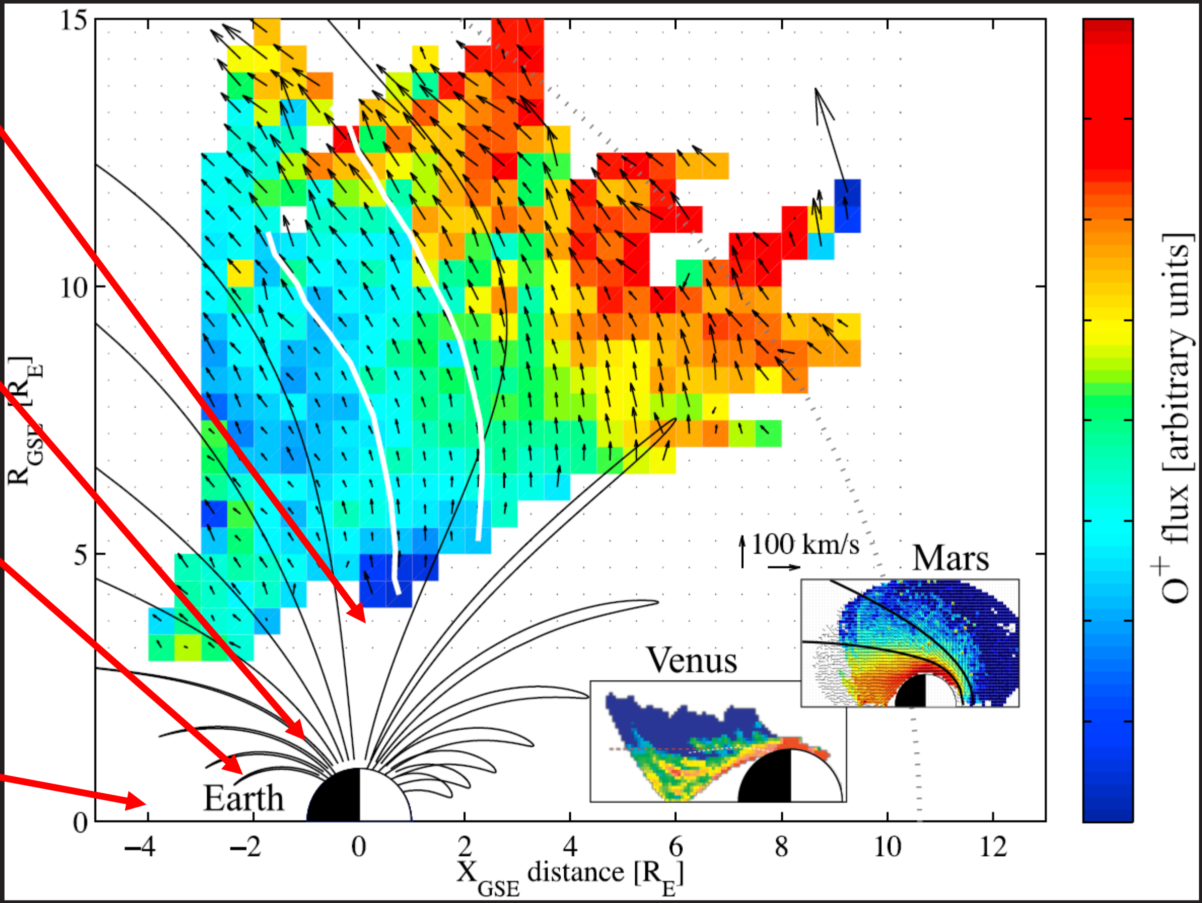
Many escape routes, in particular for magnetized planets

Polar cap
Maggiolo et al. (2006, 2011, 2012)
Maes et al. (2015, 2016)

Auroral zone
De Keyser et al. (2010a, 2010b, 2011, 2013)
Echim (2008, 2009, 2019)
Gunell et al. (2013a, 2013b, 2015)

Plasmasphere
Darrouzet et al. (2006, 2008, 2009, 2013, 2021)

Spatial distribution of ionospheric ions in the magnetosphere
Maggiolo et al. (2014)

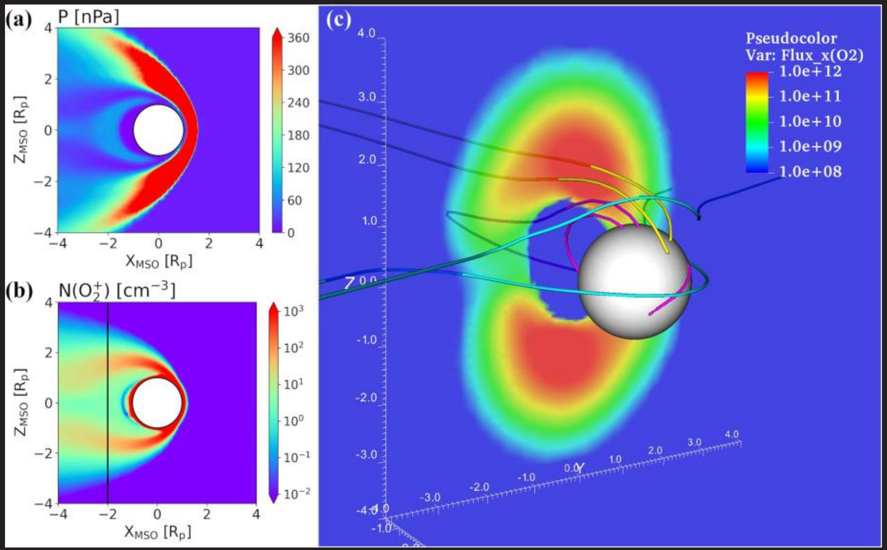


State of the Art

Models

- Difficult to model atmospheric escape from Earth: requires a model coupling the atmosphere/thermosphere, the ionosphere, the magnetosphere and the solar wind (*see Welling and Liehmond 2016*)

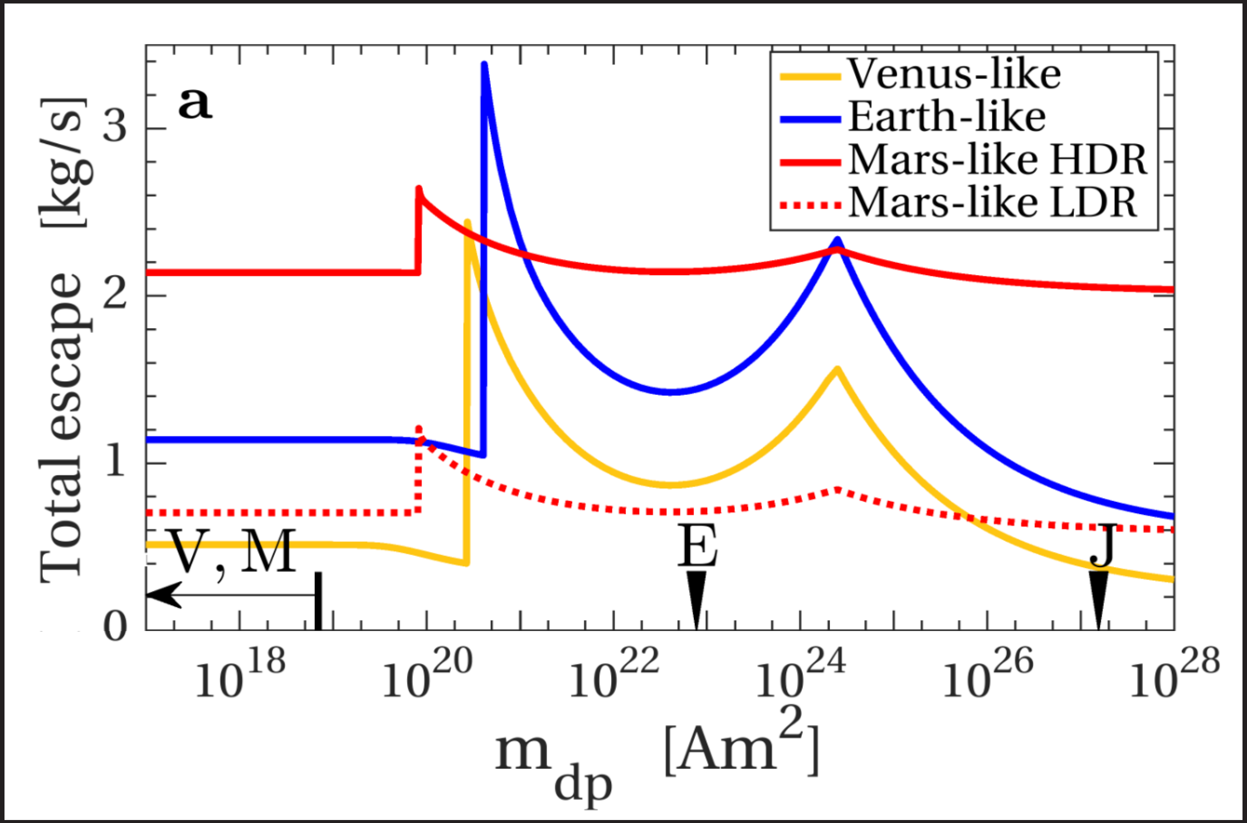
- Easier (not easy!) to model escape for unmagnetized planets



State of the Art

Our approach : semi empirical modelling

(Gunell et al. 2018)



The escape rate does not vary linearly with the planetary magnetic moment

1 peak for low magnetic moment, 1 for high magnetic moment

State of the Art

The accumulation of measurements shows that

- The current atmospheric escape is higher at Earth
- High variability (~1 order of magnitude) of the measured escape rate

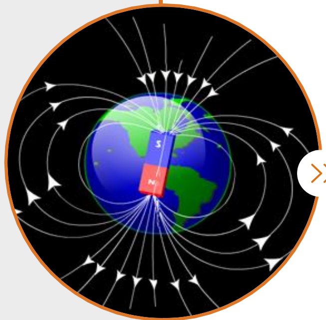
Current escape rates:

- 10^{25}-10^{26} s^{-1} (Earth)
- 10^{24}-10^{25} s^{-1} (Venus, Mars)

On geological time scales:

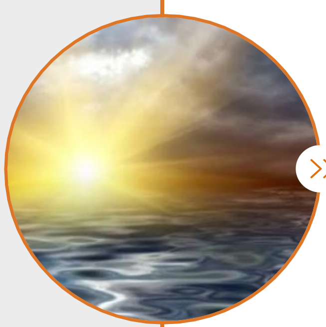
A few centimeters to a few meters of water, not enough to remove an ocean

Still difficult to model consistently atmospheric escape



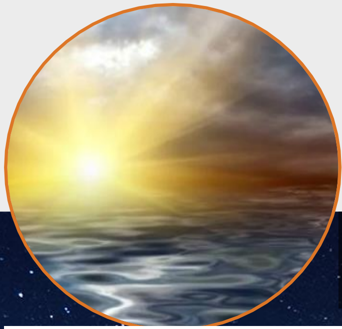
Atmospheric escape: basic principles

State of the art

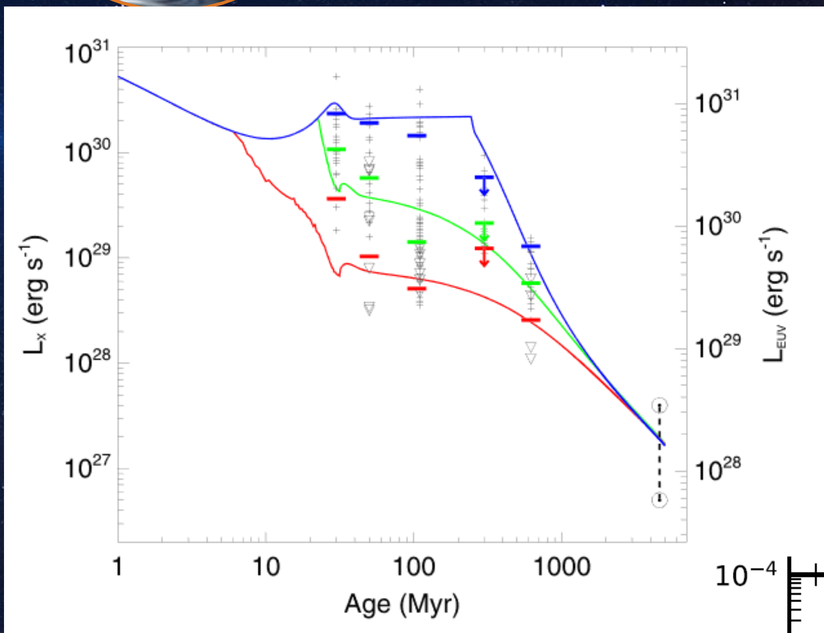


Future developments

Champ magnétique et habitabilité

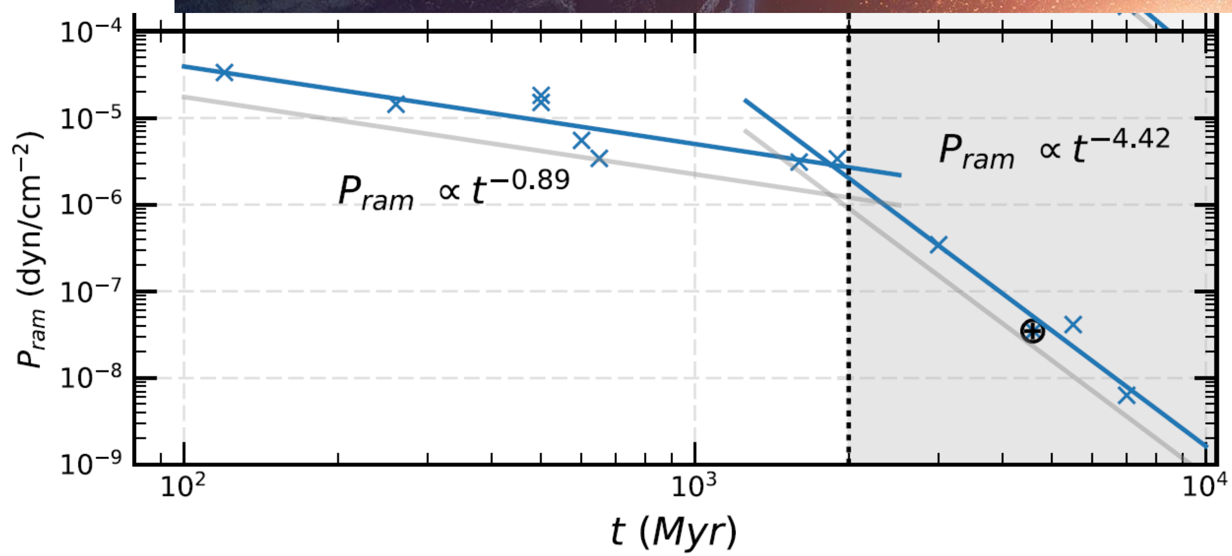


The Sun has evolved with time



The solar EUV/UV flux was higher

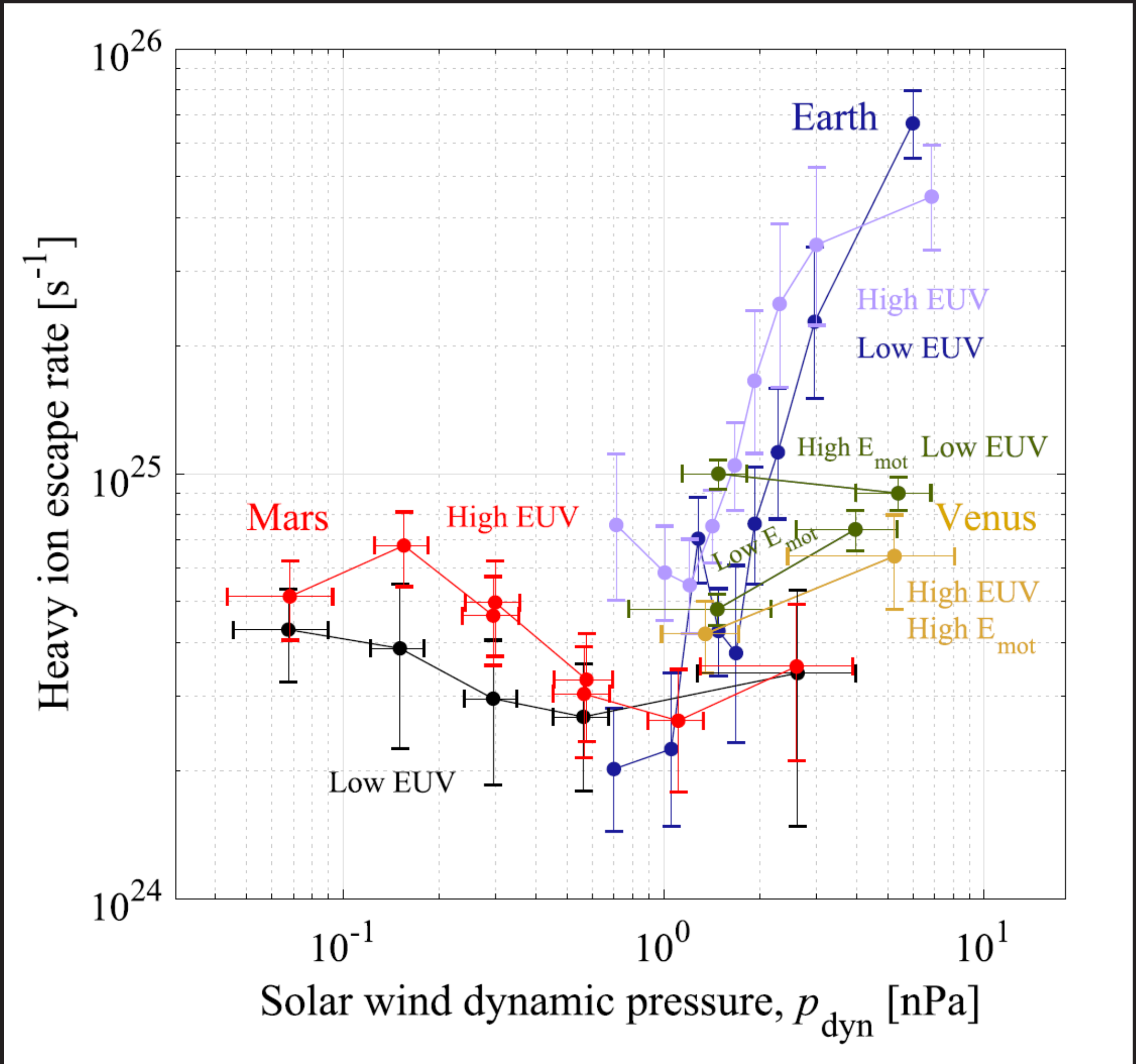
The solar wind was more intense in the past



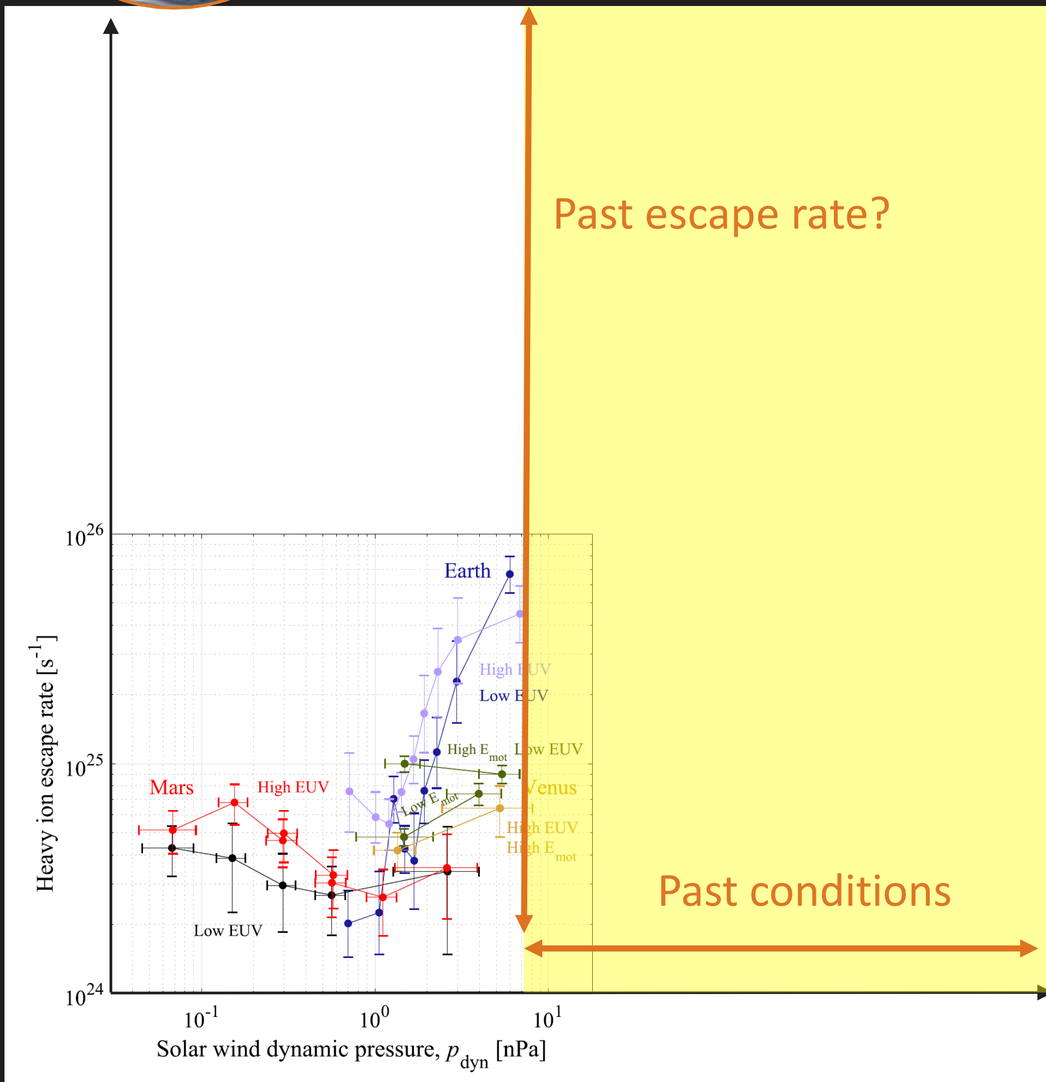
Champ magnétique et habitabilité

Strong dependence of the escape rate:

- on the solar EUV flux
- on the solar wind pressure



Champ magnétique et habitabilité



The past atmospheric escape remains an unexplored territory

- No direct measurements
- Well outside the range of current solar conditions
- Different atmospheric composition
- Different magnetic field (e.g. Mars)

Champ magnétique et habitabilité

Semi empirical model

$\phi\ (Mdp) \Rightarrow \phi\ (Mdp, P_{SW}, \varphi_{EUV})$

See Poster by M. L. Alonso Tagle

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, O^+ and H^+

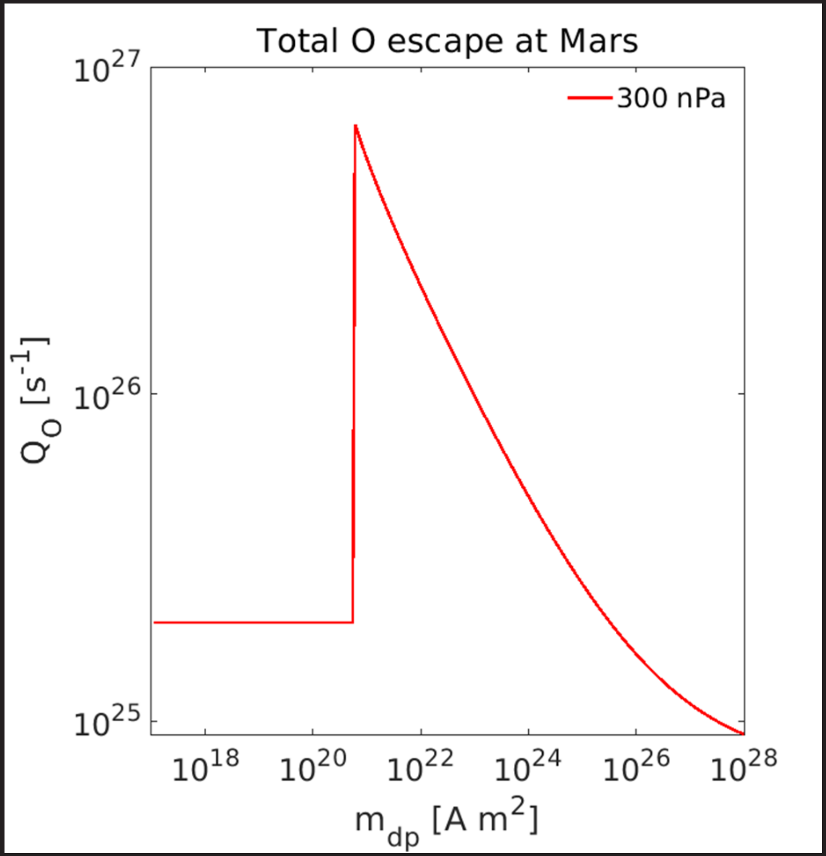
$Q_i(m_{dp}, P_{SW})$

Planetary Parameters

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

Champ magnétique et habitabilité

Preliminary results.



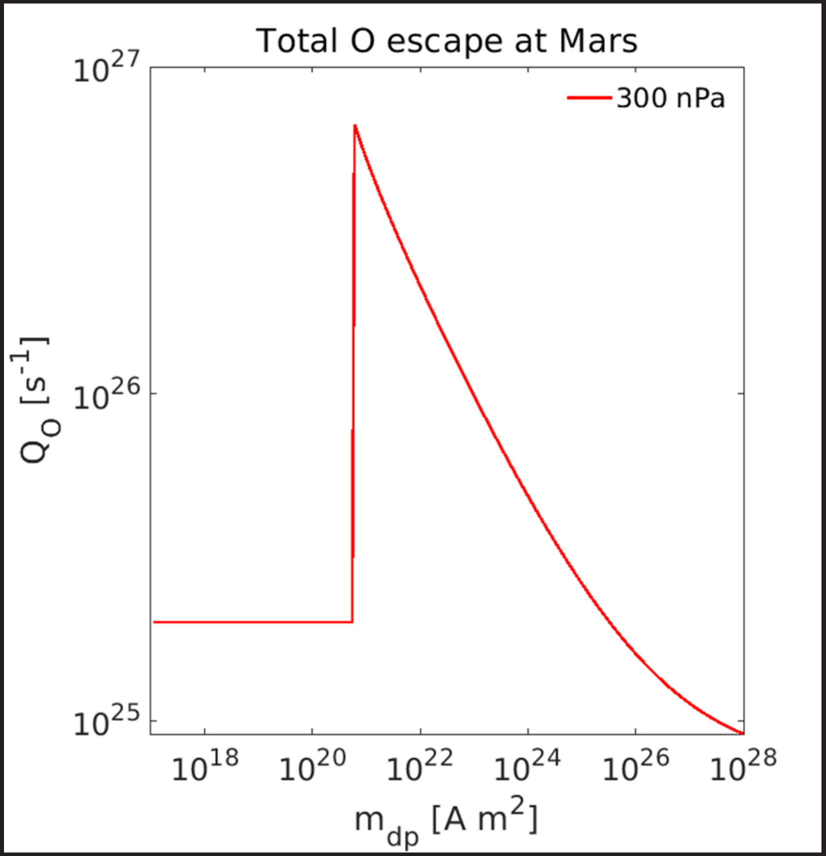
Higher escape rate for weakly magnetized planets.

- Both unmagnetized and magnetized escape process coexist and
- Escape from the polar regions maximizes

Champ magnétique et habitabilité

This could correspond to Early Mars :

- The Martian dynamo was active between 4.5 and 3.7 Ga ago
- Mars had a relatively dense atmosphere and liquid water
- The solar wind pressure was high at that time (hundreds of nPa)



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

Conclusion

Do planetary magnetic fields protect atmospheres?
No evidence for current conditions

Current escape rates @ Venus, Earth and Mars relatively limited

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The big challenge is to characterize the past atmospheric escape rate to determine atmospheric loss rate over geological time scales

Much higher energy input from the Sun
Probably much higher escape rate
Critical regime for weakly magnetized planets?