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Atmospheric Escape and Planetary Atmosphere Evolution. The complex role of magnetization

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This project is funded by NASA Venus ambipolar field project (ROSES-SSW) and SSAI internal funds



Introduction: Question to the public

What is the role of the magnetic field in the evolution of the atmosphere?

- Does a magnetic field protect the atmosphere from the solar wind?

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What is the role of the magnetic field in the evolution of the atmosphere?

- Does a magnetic field protect the atmosphere from escape?

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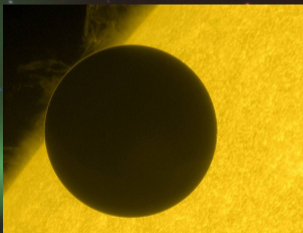
What is the role of the magnetic field in the evolution of the atmosphere?

- Does a magnetic field protect the atmosphere from the solar wind?
- Does a magnetic field protect the atmosphere from escape?
- What does “protect” means?
- Have we been buying that “protection” idea without validating it?
- Let's define “protection” as a significant reduction of the escape rate, i.e. 10 times

Can we use the solar system to answer this question?

Magnetism and Solar System Planets

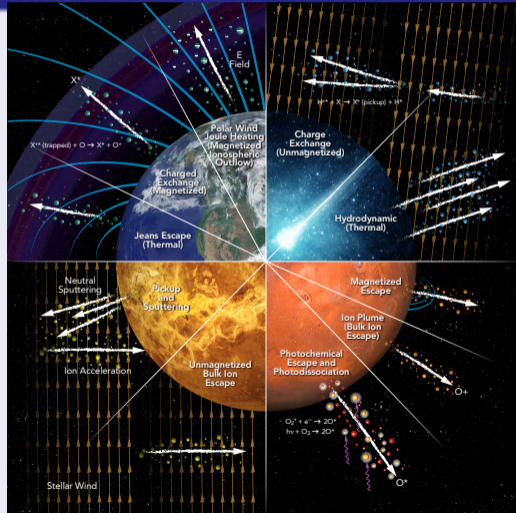
- Earth: B field, atmosphere
- Mercury: B field, no atmosphere
- Mars: remnant B, faint atmosphere
- Venus: no B field, massive atmosphere



Credit: NASA/JAXA/HINODE

Can we use the solar system to answer this question?

The different escape processes



Can we use the solar system to answer this question?

Evaluation at Terrestrial planets

Process	Venus	Earth	Mars
Jeans escape	H: 41 $\mu\text{g/s}$	H: 0.6 kg/s ⁽¹⁾	H: 250 g/s – 1.8 kg/s
Charge exchange/trapped	H: 8 g/s – 80 g/s	H: 2.1 kg/s	H: 15 mg/s – 150 mg/s
Ion pickup	H ⁺ : 16 g/s ; O ⁺ : 0.4 kg/s	Small	O ⁺ : 25 g/s;
	He ⁺ : 3 g/s – 30 g/s		C ⁺ : 3.2 g/s
Sputtering	O: 13 g/s–130 g/s	Small	O: 80 g/s
			C: 2 g/s – 200 g/s
Photochemical escape	H: 60 g/s	Small	O: 1.1 kg/s ⁽⁵⁾ ; C: 20 g/s
Polar wind	N/A ⁽²⁾	H ⁺ : 0.3 kg/s	N/A ⁽³⁾
		O ⁺ : 0.8 kg/s ⁽⁴⁾	
Outflow/K-H/Clouds	O ⁺ : 125 g/s – 250 g/s	O ⁺ : 150 g/s	O ⁺ : 250 g/s

Can we use the solar system to answer this question?

Escape Measurements

- Earth, Mars, and Venus have similar escape rate
- Escape above Martian field enhanced/reduced depending upon conditions (MAVEN observations)
- Earth B field prevents particles in low latitudes, but increase precipitations at high latitudes
- Polar escape enhanced during high solar activities
- Nothing convincing concerning enhanced escape during B field inversions at Earth

Comparison caveats

- Different planets (size, mass, composition, etc.), notably exospheric temperature
- Quiet conditions vs Active conditions affect escape rates greatly

Can we use the solar system to answer this question?

Important arguments for the role of the magnetic field from solar system observations

- Non-magnetized planets have induced magnetic field / magnetized planets have compressed magnetic fields during large events
- The Earth's magnetic field is observed to increase the quantity of energy deposited in the upper atmosphere (Maggiolo et al., 2023)
- Extreme solar events can lead to enhanced escape at Earth, especially of O^+
- Thermal escape (especially hydrodynamic) is one of the dominant escape process in the history of exoplanets atmosphere

The point

- We do not have strong solar system observations showing that the magnetic field is “protecting” (as defined previously)
- The magnetic field affect **the way** the atmosphere is escaping

Maybe the young solar system or other exoplanets can help us to answer this question?

Can we use exoplanets/early solar system to answer this question?

Exoplanets

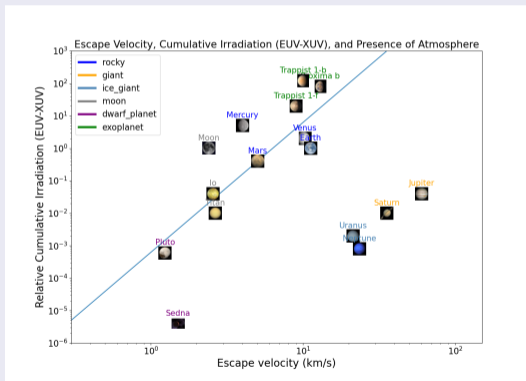
- Observation of different systems (hot Jupiters, super-Earths, etc.)
- A lot of hydrodynamic escape is observed
- Evidence of non-thermal escape is difficult to obtain

Theoretical work

- Several models of escape have been developed but do not take all the escape processes into account
- Garcia-Sage et al. (2017) show how polar escape can be important for magnetized planets
- Garraffo et al. (2016,2017) show how stellar wind can directly penetrate the magnetic field inside the Alfvén surface
- These results are difficult to compare directly with non-magnetized planets models

Can we use exoplanets/early solar system to answer this question?

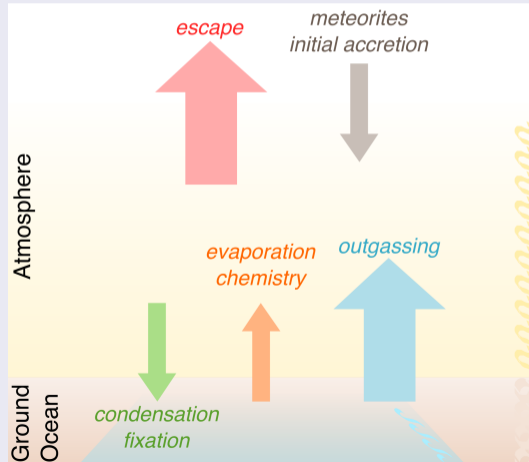
The role of EUV-XUV flux: we need to find a counter example to show the impact of particles / magnetic field



(Gronoff and Kubyskhina submitted, based on Zahnle and Catling 2017)

Can we use exoplanets/early solar system to answer this question?

Problem: observing an atmosphere is not enough if we do not know the initial inventory of volatiles



Conclusions

Review paper on atmosphere escape

Gronoff et al. 2020

Overall Magnetic field escape

- Escape is extremely important to understand the origin, evolution and habitability of atmospheres.
- Currently: no decisive argument on whether the magnetic field protects from or enhance atmospheric escape
- The field protects from some escape processes while enhancing other: it affect escape
- It may be that there is no general answer to this question: in some condition it protects, in other it enhances or is neutral

The controversial (?) point of view

Let's not take the protecting role of the magnetic field (against escape) for granted, if that argument is made, it has to be proven.