# Atmospheric Escape Processes and Planetary Atmospheric Evolution: from misconceptions to challenges

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# Motivation

## Solar system atmospheres

- Why Mars and Venus are CO2-rich, while the Earth is $N_2$ $O_2$ rich and "habitable" ?
- What about Titan and its N2-rich atmosphere?
- Could we detect "habitable" worlds around other stars?
- What is this so-called "habitability"?

## Exoplanets as a laboratory for other types of atmospheres?

- Habitable exoplanet atmospheres' characterization with the JWST are limited to M dwarfs
- The exoplanets in the "Habitable Zone" of a red dwarf are subject to high EUV-XUV fluxes.
- What is the effect on their atmosphere.
- Is it possible to shield these atmospheres with a magnetic field?

# Motivation

## Atmospheres! The link between the planet, the stars, and the observer

- For Astrobiology purposes, it is important to characterize the atmosphere
- First, we need to know if it it there!
- Then, we need to know how it responds to its star!
- Finally, we need to understand how it evolves with time!

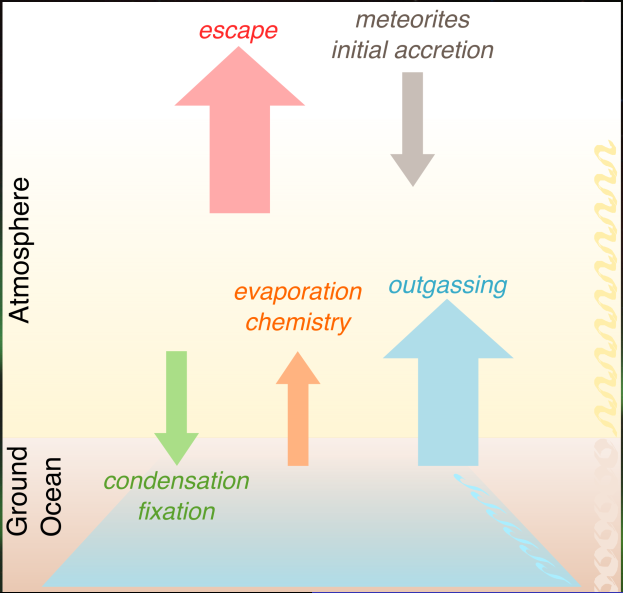
## What the study of the atmosphere brings

- Understanding the composition of the atmosphere is necessary
- Not all atmosphere can sustain liquid water
- Atmospheres' evolution can be studied in several ways

## We need to study the evolution of the atmosphere along with its star

The star evolves, therefore its energetic inputs on planet evolves. Different inputs means different escape types!

# Motivation



escape
meteorites
initial accretion
Atmosphere
evaporation
chemistry
outgassing
Ground
Ocean
condensation
fixation

# Upper atmospheres: where escape happens

## What is the upper atmosphere

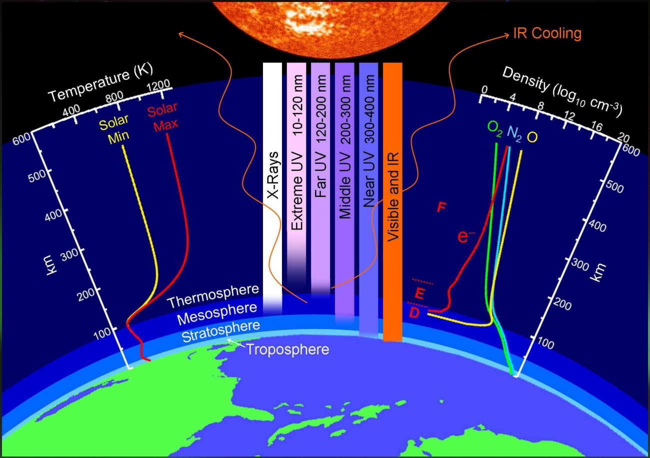
- Thermosphere and ionosphere
- Scale height and exospheric temperature
- At Earth, the limit of space is 100 km. It is also the beginning of the upper atmosphere.
- Aurora (Northern or Southern lights) happens in the upper atmosphere (generally 120-250 km).
- Scale Height: H. (What would be the height of the atmosphere if it had the same pressure everywhere)
- $H(z) = \frac{kT(z)}{m(z)g(z)}$
- Exobase: the scale height equals the mean free path.

# Upper atmospheres: where escape happens

**What are the main parameters influencing upper atmospheres?**

- Atmospheric composition
- Solar EUV-XUV (ionization, dissociation)
- Particles (electrons, protons,...)
- Fields (magnetic field, electric field) and their consequences (ion transport, joule heating...). Notably interplanetary magnetic field
- Chemistry (changes composition, heating and cooling)
- Radiative processes ($CO_2$ 15$\mu$m; NO, ...)
- Diffusion, conduction, winds...

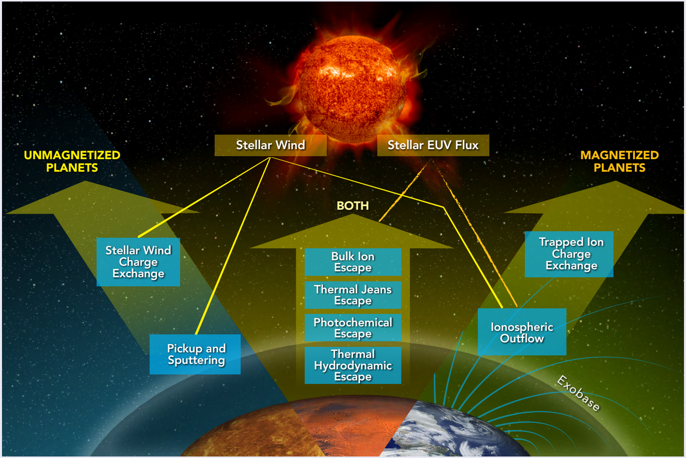
# Upper atmospheres: where escape happens



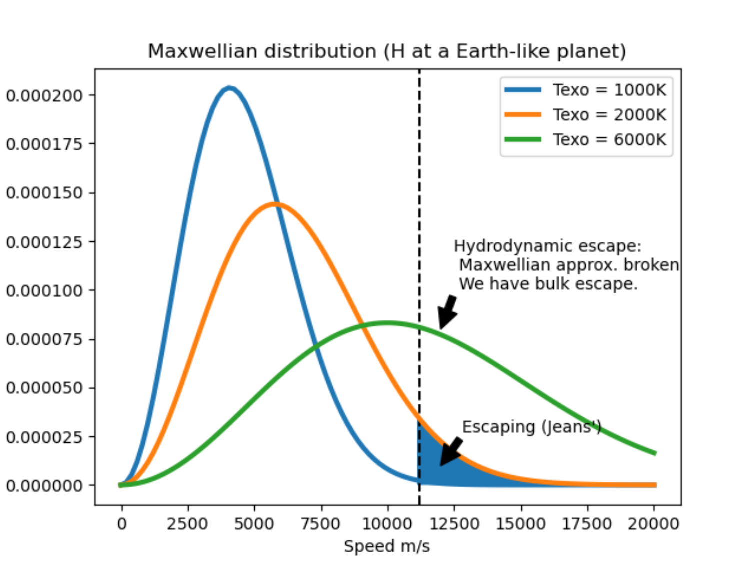

Credit: John Emmert/Naval Research Lab/nasa.gov

# The escape processes

## The different escape processes



# Thermal Escape



# Thermal Escape

## Thermal Escape

- The thermal energy drives the escape of particles
- That thermal energy comes principally from the EUV-XUV fluxes
- (Exceptions in extreme environments)
- 2 main regimes of escape Jeans' (slow) and hydrodynamic (fast)

## By Far: the main escape process in the history of a rocky planet

Exception could happen: to be treaten carefully!
Is not shielded by magnetic fields!

# Thermal Escape

## Jeans' parameter

- $\lambda = \frac{GmM}{kT_{exo}r_{exo}} = \frac{Gravitational energy}{Thermal energy} = \frac{v_{esc}^2}{U^2}$
- Critical $\lambda$: above, the upper atmosphere is dominated by gravity, under, by thermal energy
- $\lambda_{crit} = 1.5$ for atoms, 2.5 for molecules
- Above the critical level, the escape is slow, and should be computed kinetically. Under the critical level, a fluid approximation is best suited.
- Around the critical level, Direct Simulate Monte Carlo is best suited for study (proved that the critical level is sharp)

# Thermal Escape

## Importance of Jeans' escape

- Jeans' escape is the most important escape process for H at Earth, when the solar activity is high.
- The higher the heating, the most important it is to take it into account.
- It is important to understand Jeans' formulae is an approximation. A fully kinetic model is more generalistic.
- The computation of Jeans' escape requires to be able to compute thermospheric temperatures.
- There is some isotopic fractionnation from Jeans' escape.

# Hydrodynamic escape

## Importance of hydrodynamic escape

- The fluid approach is an approximation: boundary conditions, including with plasma and solar wind, are not taken into account.
- The hydrodynamic escape of H for the "early" rocky planets and bodies (Earth, Mars, Venus...) is at the origin of isotopic fractionation.
- The light gas in hydrodynamic escape should not be diffusion limited; otherwise the hydrodynamic escape would not occur.
- The transition between Jeans' and Hydrodynamic escape is sharp, as computed by DSMC models.

# The non-thermal escape processes

## What is a non-thermal escape?

- Suprathermal processes: when we cannot approximate a particle distribution by a Maxwellian.
- EUV-XUV lines in the solar spectrum are an example of non-thermal distribution.
- Auroral electrons are another example.
- Processes that are discrete (e.g. from a chemical recombination) leave atoms with energies well above escape velocity, regardless of the local temperature

## Sources of non-thermal escape?

- Photochemistry. (Recombination, dissociations...)
- Ion acceleration in fields
- Charge exchange
- Sputtering processes

# Photochemical escape

## Photochemical escape

- Photodissociations, electron impact dissociation
- e.g. $CO_2 + h\nu \rightarrow CO + O^*$
- Ion recombination
- $O_2^+ + e \rightarrow 2O^*$
- Major non-thermal escape process at Mars. (Main source of O loss)

# Ion escape

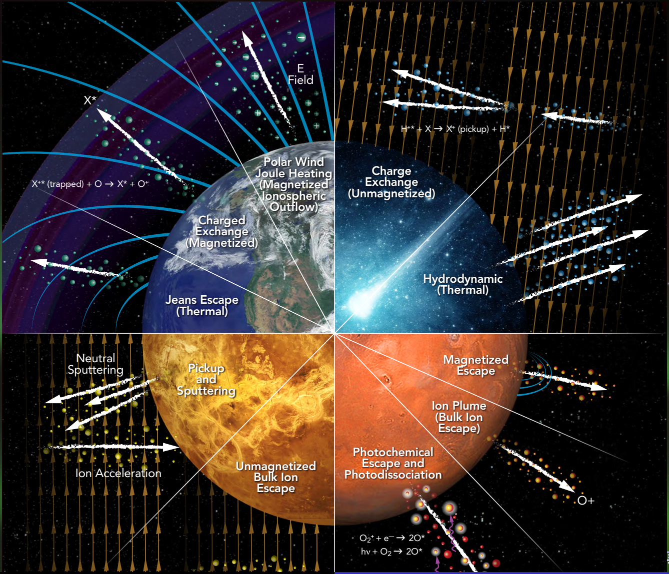
## Non-magnetized ion escape

- Charge exchange: $H^{+*}$ (solar wind) interacting with the neutral atmosphere (e.g. comets)
- Bulk ion escape (Ionosphere swept by the IMF).
- Ion pickup and sputtering (Major process for Early Mars)
- Pickup: an ion is created from neutral atmosphere, and accelerated by solar wind. A $O^{+}$ can be accelerated up to the solar wind speed!
- Sputtering, the ion impacts the atmosphere, releasing its energy in heating or transferring kinetic energy to several neutral atoms that escape.

## Magnetized ion escape

- Charge exchange: $H^{+*}$ from non-thermal process is trapped in the magnetic field. It interacts with the neutral atmosphere to become an ENA $H^{*}$.
- Charge exchange is the main source of H escape during low solar activity.
- Ionospheric outflow / Polar wind (main source of O escape at Earth)

# Summary of escape processes



# Summary of escape processes

- Hydrodynamic escape was the main escape process in the Early Solar System
- Now: Earth's H escape is diffusion limited. Jeans' escape (Solar Max) Charge-Exchange (Solar Min)
- Venus' escape is dominated by non-thermal processes
- Mars' escape is driven by extreme solar activity
- The story of the solar system planets atmosphere can be probed through isotopic fractionation
- But some paradox exists (and we need to visit Venus to have a better idea)

# On the role of the stellar activity

## Stellar activity and evolution

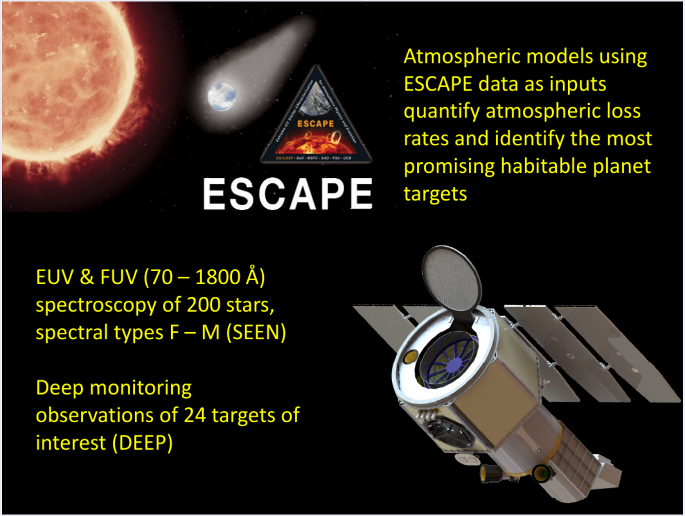
- Stellar activity: Flares
- Stellar activity: Coronal Mass Ejection
- Stellar activity: Solar Energetic Particle Events
- Stellar evolution: rotation and activity

## Effect of activity on atmospheres

- Flares: increase heating and ionization (thermal + non-thermal)
- Coronal Mass Ejection: increase solar wind (non-thermal)
- Solar Energetic Particle Events (lower atmosphere effects)

# On the role of the stellar activity

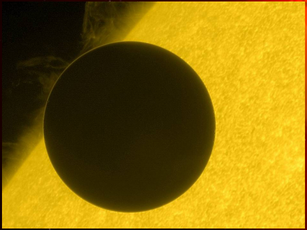
## ESCAPE! PI: K. France. In PHASE A for NASA/SMEX



# On the role of the magnetic field

## Magnetism and Solar System Planets

- Earth: B field, atmosphere
- Mercury: B field, no atmosphere
- Mars: remnant B, faint atmosphere
- Venus: no B field – maybe in the past–, massive atmosphere

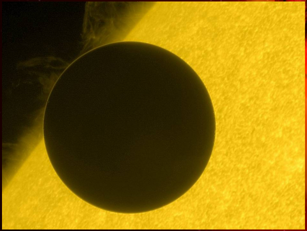


Credit: NASA/JAXA/HINODE

# On the role of the magnetic field

## Magnetism and Solar System Planets

- B field = Atmosphere is not valid in a naive way

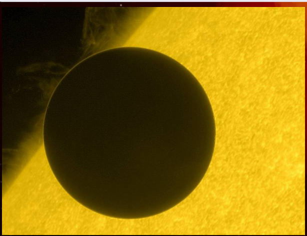


Credit: NASA/JAXA/HINODE

# On the role of the magnetic field

## 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



Credit: NASA / JAXA / HINODE

# On the role of the magnetic field

## Overall Magnetic field escape

- 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
- The question may be ill posed
- Mass and EUV-XUV irradiance seems to be the main driver of an atmosphere presence (See the "Cosmic Shoreline" paper)
- A better question would be considering this atmospheric composition/planet mass/stellar activity, how much escape does the magnetic field prevents/enhances
- But how does it affect composition?

## Magnetic field escape

See the question of Proxima b in Garcia-Sage et al. 2017 (I have extra slides too ;-) )

# Conclusions

## Conclusions

- Escape is extremely important to understand the origin, evolution and habitability of atmospheres.
- It is important to address the activity of the star to study the habitability of its planets.
- Magnetic fields are not shielding planetary atmospheres (it is more complex)

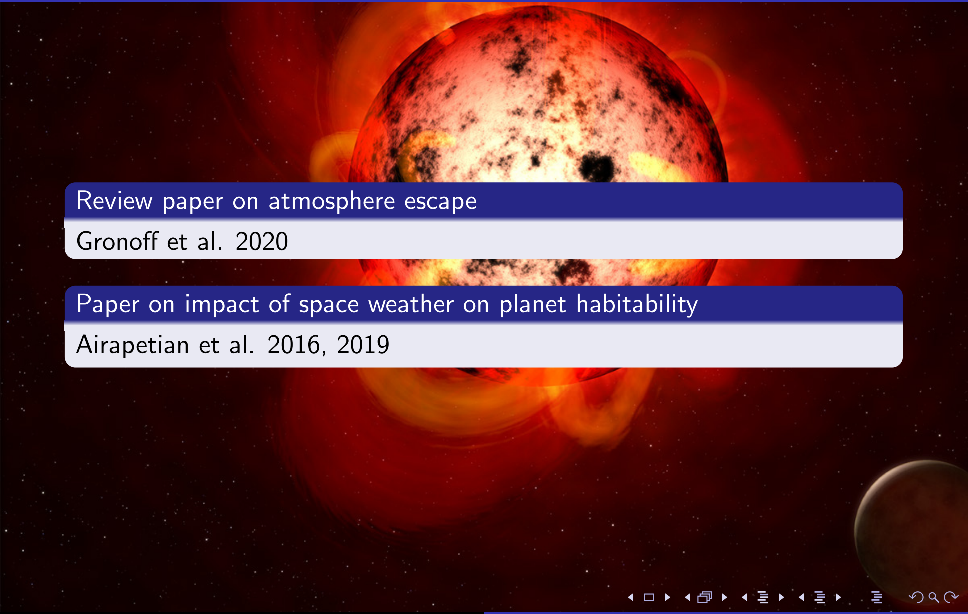
## Future work

- Ambipolar field leading to escape at Venus
- Stellar Energetic Particle events modifying the exoplanetary chemistry
- More escape? Depends on Funding

## Review paper on atmosphere escape

Gronoff et al. 2020

# Thank you



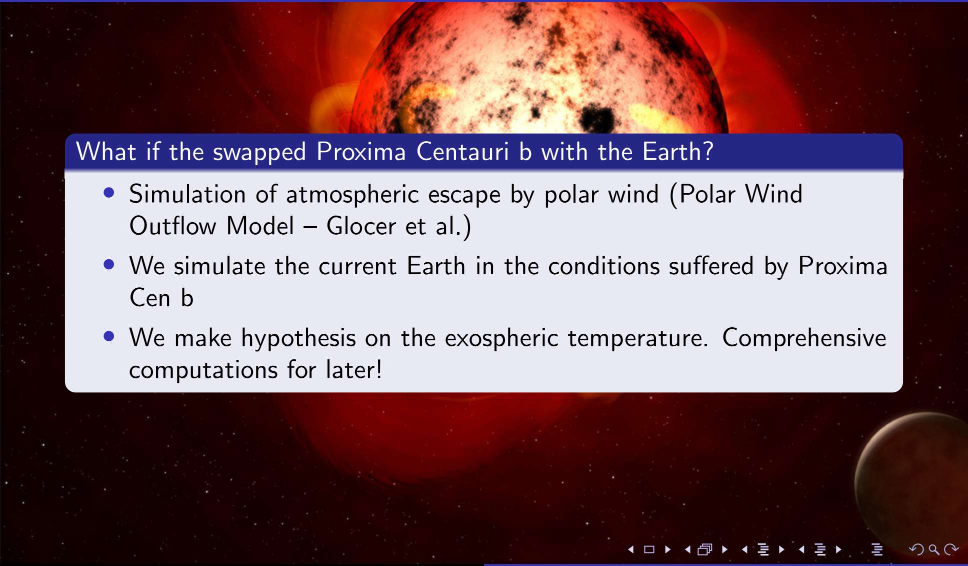
**Review paper on atmosphere escape**

Gronoff et al. 2020

**Paper on impact of space weather on planet habitability**

Airapetian et al. 2016, 2019

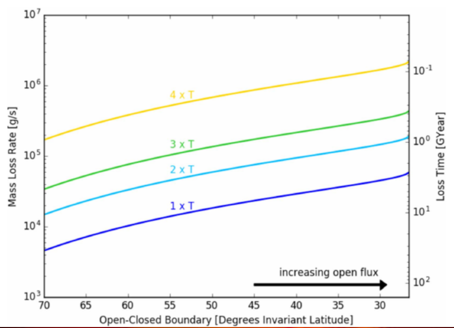
# On the Magnetic Protection of the Atmosphere of Proxima Centauri b



### What if the swapped Proxima Centauri b with the Earth?

- Simulation of atmospheric escape by polar wind (Polar Wind Outflow Model – Glocer et al.)
- We simulate the current Earth in the conditions suffered by Proxima Cen b
- We make hypothesis on the exospheric temperature. Comprehensive computations for later!

# On the Magnetic Protection of the Atmosphere of Proxima Centauri b




## No magnetic protection!

The notion of magnetic protection works for certain ion escape processes. A better question is what is the balance between each escape processes in function of stellar parameters (wind, EUV, etc)

# On the Xenon paradox

## What is the Xenon paradox

- Mass fractionation of Xe isotopes, while Kr isotopes (lower mass) are not fractionated
- Hydrodynamic escape cannot explain it

## Proposed solutions based on escape

Zahnle et al. 2019 proposed $Xe^+$ ion escape, however, this requires high ($10^9$) diffusivity coefficients and a specific thermosphere.

## Escape is probably not the solution to the Paradox

- Organic haze allows to trap Xe in the mantle (Avice 2018).
- History of Xe isotope exchange with the mantle (Parai & Mukhopadhyay 2018) lead to opposite conclusion w/r to plate tectonics (Sobolev 2019) if Xe escape was high in the past.
- Measurements of Xe at Venus would give more insight.