Atmospheric Escapes

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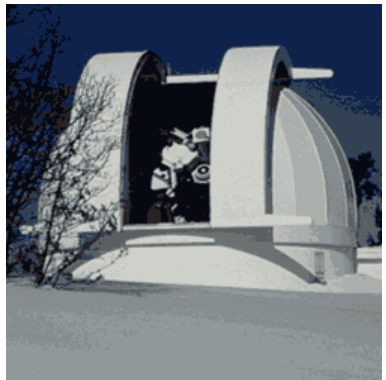


Outline

- Evidences of present atmospheric escape

- Evidences of past atmospheric escape

- Main processes leading to atmospheric escape :
  - *Jeans and Hydrodynamic escapes: see presentation of Eric Chassefière*
  - Impact erosion
  - Photo-chemical induced escapes
  - Ion picked up loss
  - Ionospheric loss
  - Sputtering

- What chronology of Mars' atmospheric escape leads to its present state?

Observed planetary atmospheric escape

- Mars: ~3×10^{25} ions/s
  = present atmosphere lost in less than 100 Myr (Lundin et al. 1989)

- Venus: ~10^{25} ions/s
  = a fraction of a Earth ocean (Shizgal and Arkos 1996)

- The Earth: ~5×10^{24} ions/s
  = 2% of the present atmosphere lost in 3 Gyr (Seki et al. 2001)

$\rightarrow$ Role of the magnetosphere: The Earth

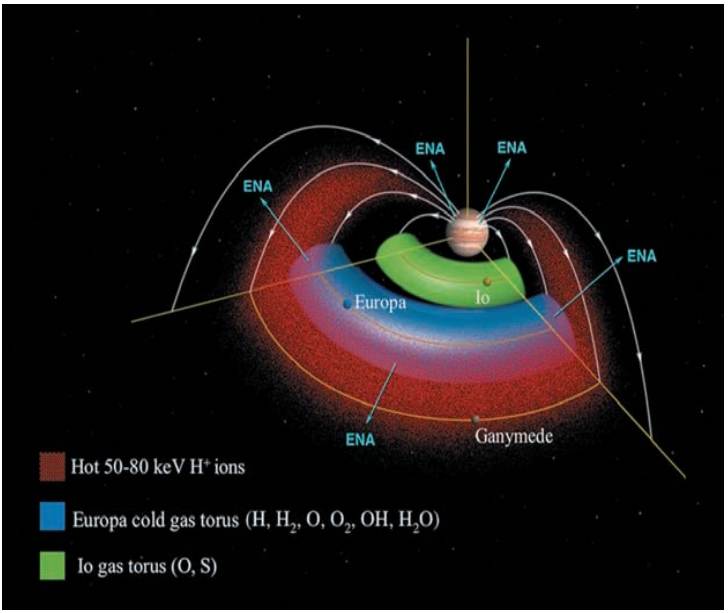
$\rightarrow$ Role of the gravity field:
Mars gravity smaller than Venus and the Earth: Escape Velocity

V_{Mars} = 4.8 km/s V_{Venus} = 10.2 km/s V_{Earth} = 10.8 km/s

$\Rightarrow$ Efficient erosion by impact and non-thermal escapes at Mars

Observed atmospheric escapes for satellites:

The Galilean satellites: Europa and Io



Discovery of a source of ENA from Europa's orbit (Mauk et al. 2003):

- Essentially H ENAs + half of O ENAs

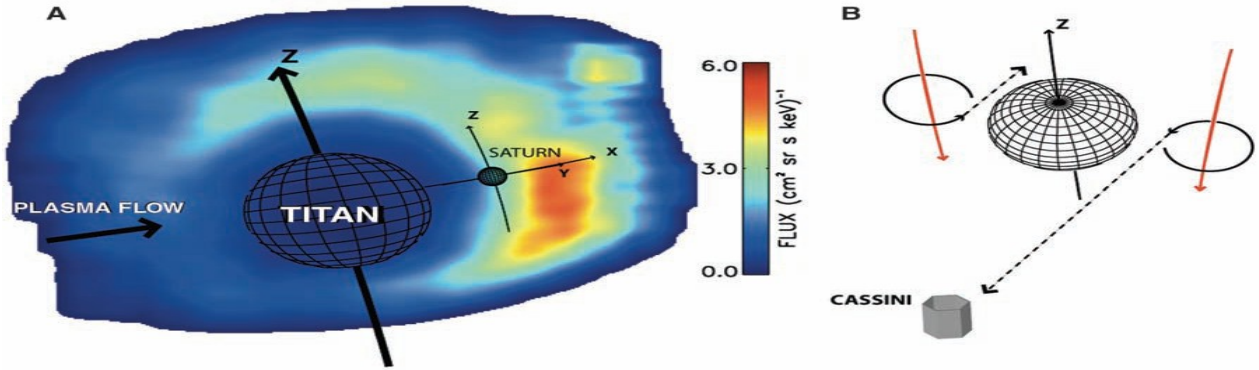
$\Rightarrow$ Neutral cloud of 3.5-8.5 $\times 10^{33}$ atoms/molecules (Mauk et al. 2004) formed by ejection from Europa's surface

Io torus mainly O and S ejected from Io atmosphere: ~10^{33} atoms formed by atmospheric loss and volcanic ejection

$\Rightarrow$ Main sources of plasma in Jupiter's magnetosphere

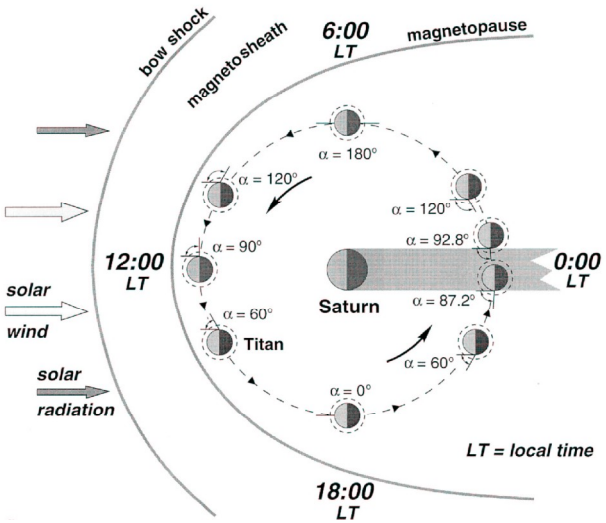
Observed atmospheric escapes for satellites:

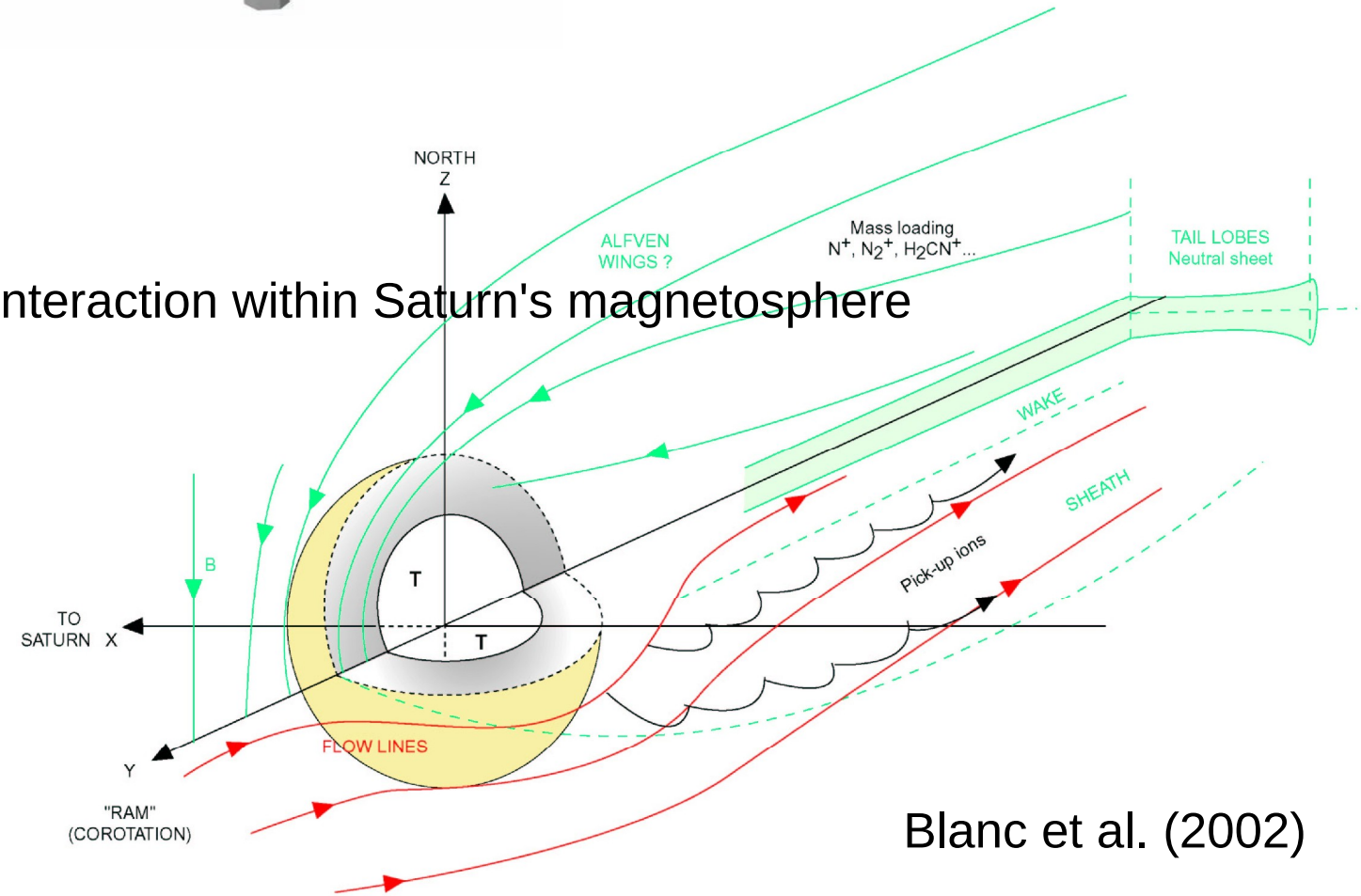
The Kronian satellites: Titan



MIMI/CASSINI measurement of Titan ENA (Mitchell et al. 2005)

Titan's interaction within Saturn's magnetosphere





Blanc et al. (2002)

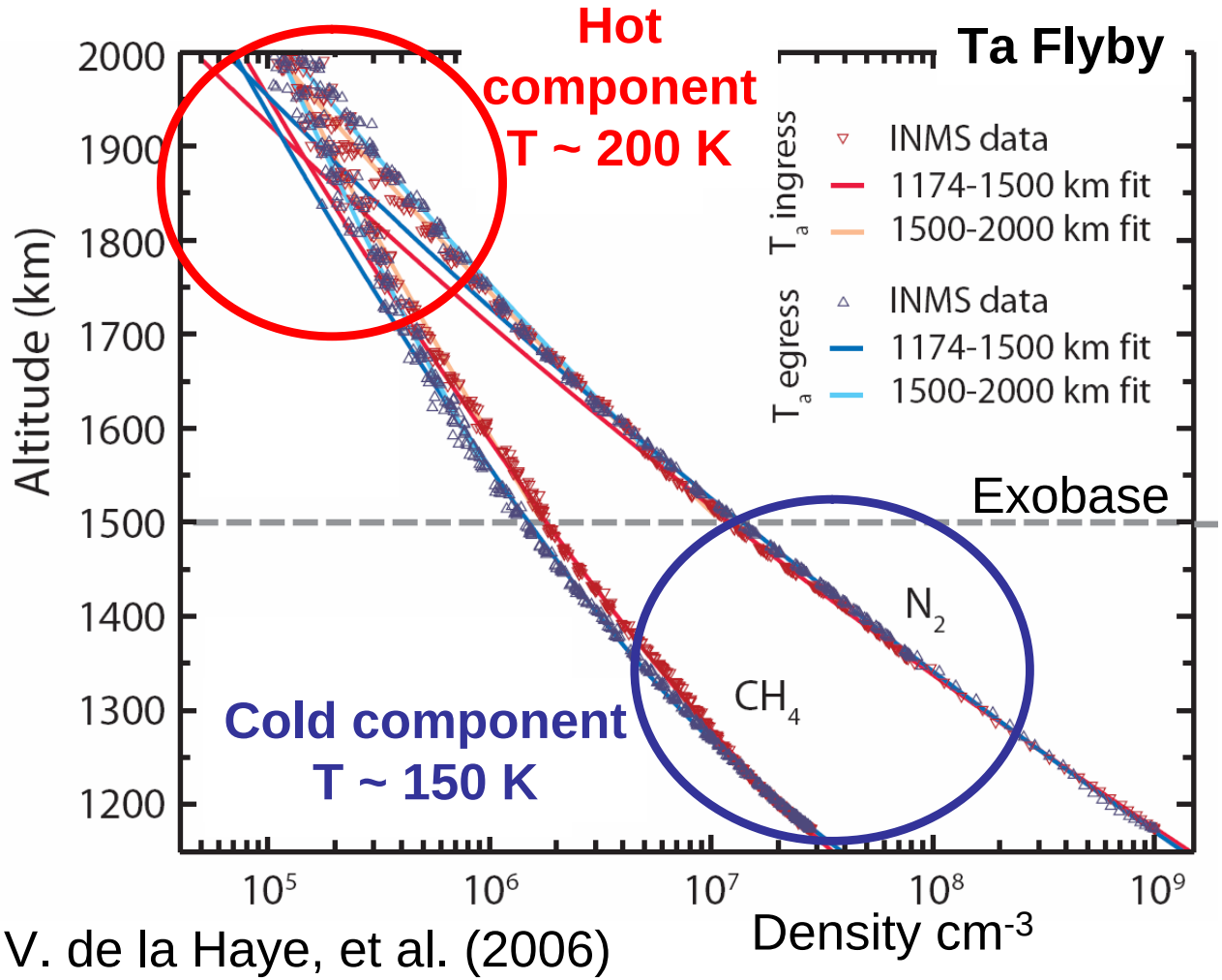
Evidences of present and past atmospheric escapes at Titan

- Isotopic fractionation (Waite et al. 2005):

$$^{14}N/^{15}N = 172 - 215 \ll \text{Earth one } (272 \pm 0.3)$$

$\Rightarrow$Past Titan atmosphere at least 50% thicker than today

- Exospheric density profiles: INMS/CASSINI



V. de la Haye, et al. (2006)

$\Rightarrow$ Significant present atmospheric escape (Yelle presentation)

But :

$^{12}C/^{13}C = 95 \pm 1$

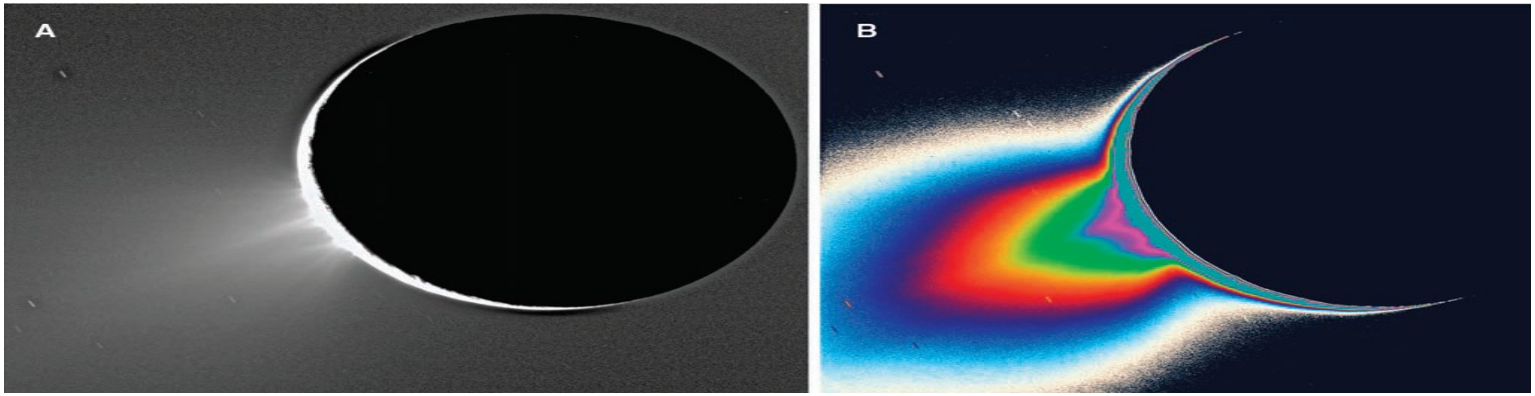
$\gg$

Earth one (89.01 ± 0.38)

$\Rightarrow$ Interior source replenished the CH_4 in Titan atmosphere (Waite et al. 2005)

Observed atmospheric escapes for satellites:

The Kronian satellites: Enceladus



Imaging Science Subsystem/CASSINI (Porco et al. 2006)

CASSINI observed a plume of water and dust in the South pole of Enceladus (probable origin: underground boiling liquid erupting through vents, Porco et al. 2006):

Loss rate ~5.0 10^{27} molecules/s (Hansen et al. 2006)

$\Rightarrow$ Missing source of Saturn OH cloud

Past atmospheric escapes at the Earth and Venus

The Earth:

Xenon is fractionated

Venus:

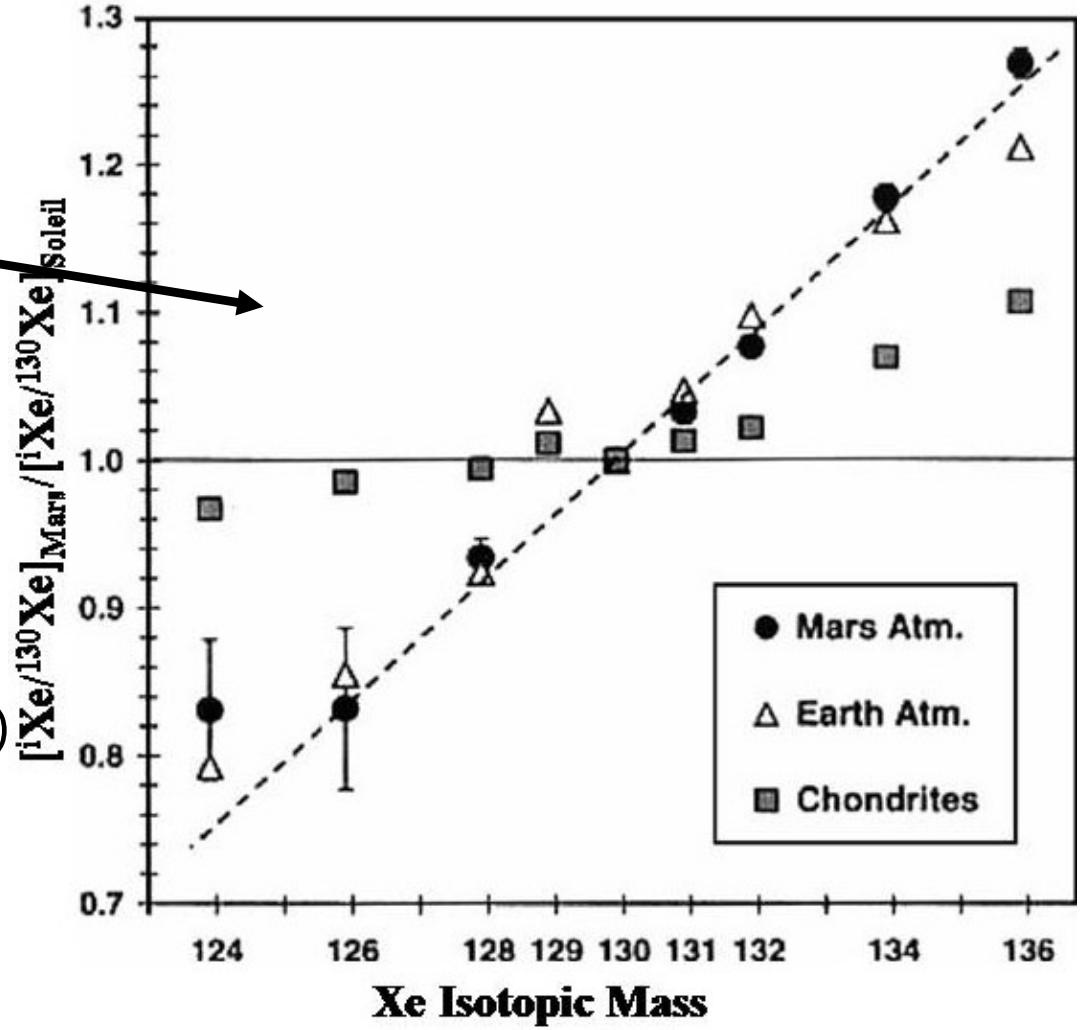
D/H at Venus

=

100 D/H at Earth

(Donahue et al. 1982; De Bergh et al. 1991)

$\Rightarrow$ hydrodynamic escape?



• Venus present content of water is 0.0014% of that of Earth (Kasking and Pollack 1993)

$\Rightarrow$ Where is Venus oxygen (~2×10^{23} g of water disappeared during past)? oxydation of the soil or escape to space?

Past atmospheric escapes at Mars

- D/H ≈ 6 SMOW knowing that initial D/H at Mars is 1.2-1.6 SMOW

  ⇒ Enrichment by a factor of 4-5 of deuterium wrt hydrogen

  ⇒ Total H escape = 4-5 times present content

  ⇒ 80 - 150 m GEL Water escaped

- From geomorphological analysis : >160 m GEL at late Noachian (Carr and Head, 2003)

- From dynamical models of water accretion : ≈600-2700 m GEL accreted by Mars (Lunine et al, 2003)

Hydrodynamic escapes

See presentation of Eric Chassefière:

"Origins of the atmospheres of the terrestrial planets"

Impact Erosion

- Escape or supply?
  - ➢ in the case of Mars 99% of early atmosphere could have been lost (Melosh and Vickery 1989)
  - ➢ in the case of the Earth and Venus: gravity limits early escape
  - ➢ No isotopic fractionation expected
  - ➢ Occurs during the first Gyr
  - ➢Did not contribute significantly to the atmospheric in the last 4 Gyr of Mars but late heavy bombardment?

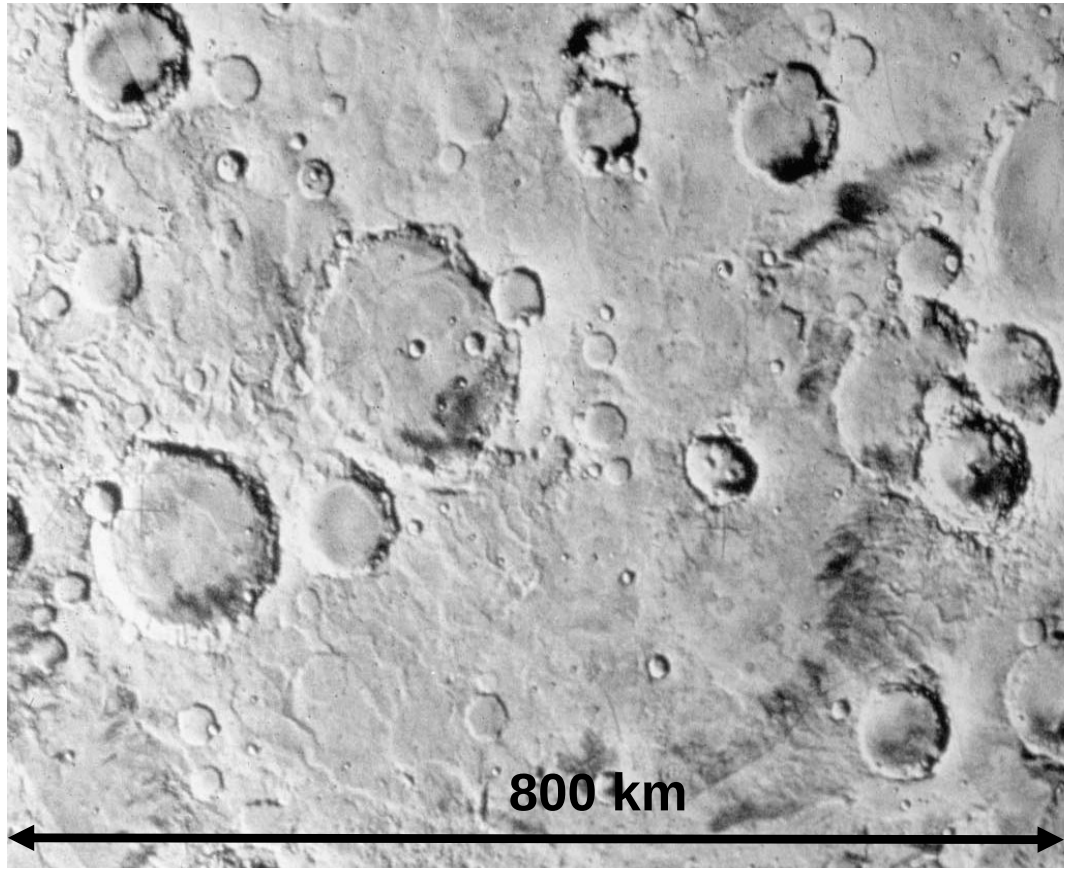


Photo-chemical induced escapes

Recombination of an ion with an electron $\Rightarrow$

Radiative recombination : $AB^+ + e \rightarrow AB + h\nu$

Dissociative excitation: $AB^+ + e \rightarrow A^* + B^+ + e$

Ions formation: $AB^+ + e \rightarrow A^- + B^+$

Dissociative recombination : $AB^+ + e \rightarrow AB^* \rightarrow A^* + B + \Delta \mathbf{E}$

Mars and Venus

$\mathbf{N_2^+ + e \rightarrow N + N}$ ΔE =1.06, 2.44 et 3.44 eV

$\mathbf{O_2^+ + e \rightarrow O + O}$ ΔE = 0.8 à 6.99 eV

$\mathbf{CO^+ + e \rightarrow C + O}$ ΔE = 0.94, 1.64 et 2.90 eV

$\mathbf{CO_2^+ + e \rightarrow CO + O}$ ΔE = 8.3 eV

- Same momentum amplitude but opposite direction for both fragments
- Mass dependency of the energy: $m_A \mathbf{V}_A = m_B \mathbf{V}_B \Rightarrow E_A = (m_B/m_A) \times E_B$
- ΔE depends on the vibrational energy of the initial ion and on the electronic energy of produced atoms.
- Efficient at Mars: $U_{es}(^{16}O)$=2eV $U_{es}(^{14}N)$=1.7eV eV $U_{es}(^{12}C)$=1.6eV
- Not efficient at Earth: $U_{es}(^{16}O)$=9.6eV $U_{es}(^{14}N)$=8.7eV $U_{es}(^{12}C)$=7.5eV
- Works even in the presence of an intrinsic magnetic field.

Ion picked up loss at Mars and Venus

Main processes of ionization:

- Photo-ionization

  $h\nu + X \rightarrow X^+ + e^-$

- Ionization by electronic impact

  $X + e^- \rightarrow X^+ + 2e^-$

- Charge exchange

  $M^+ + X \rightarrow M + X^+$

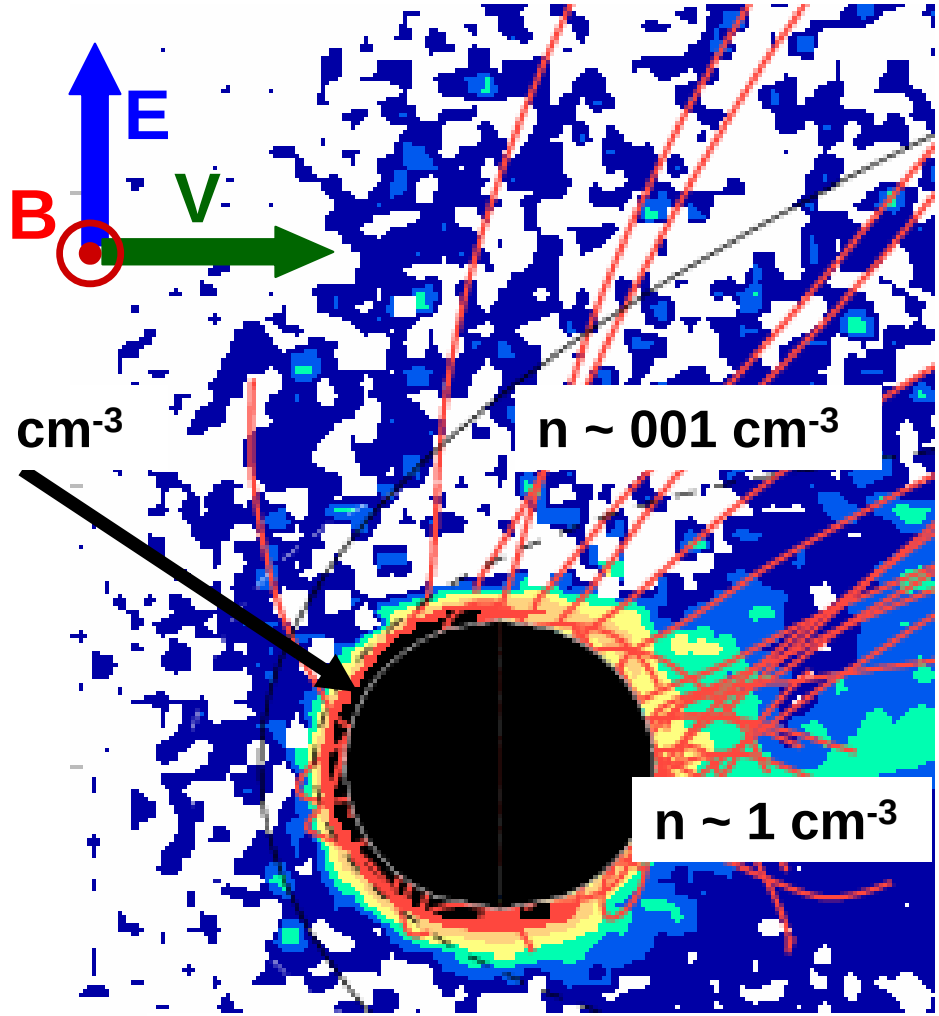
Production of picked up ion accelerated by the Solar Wind :

- ➢ Mass loading of the solar wind
- ➢ Production of energetic neutral

  ⇒Sputtering
- ➢Atmospheric loss at Mars and Venus

Mars

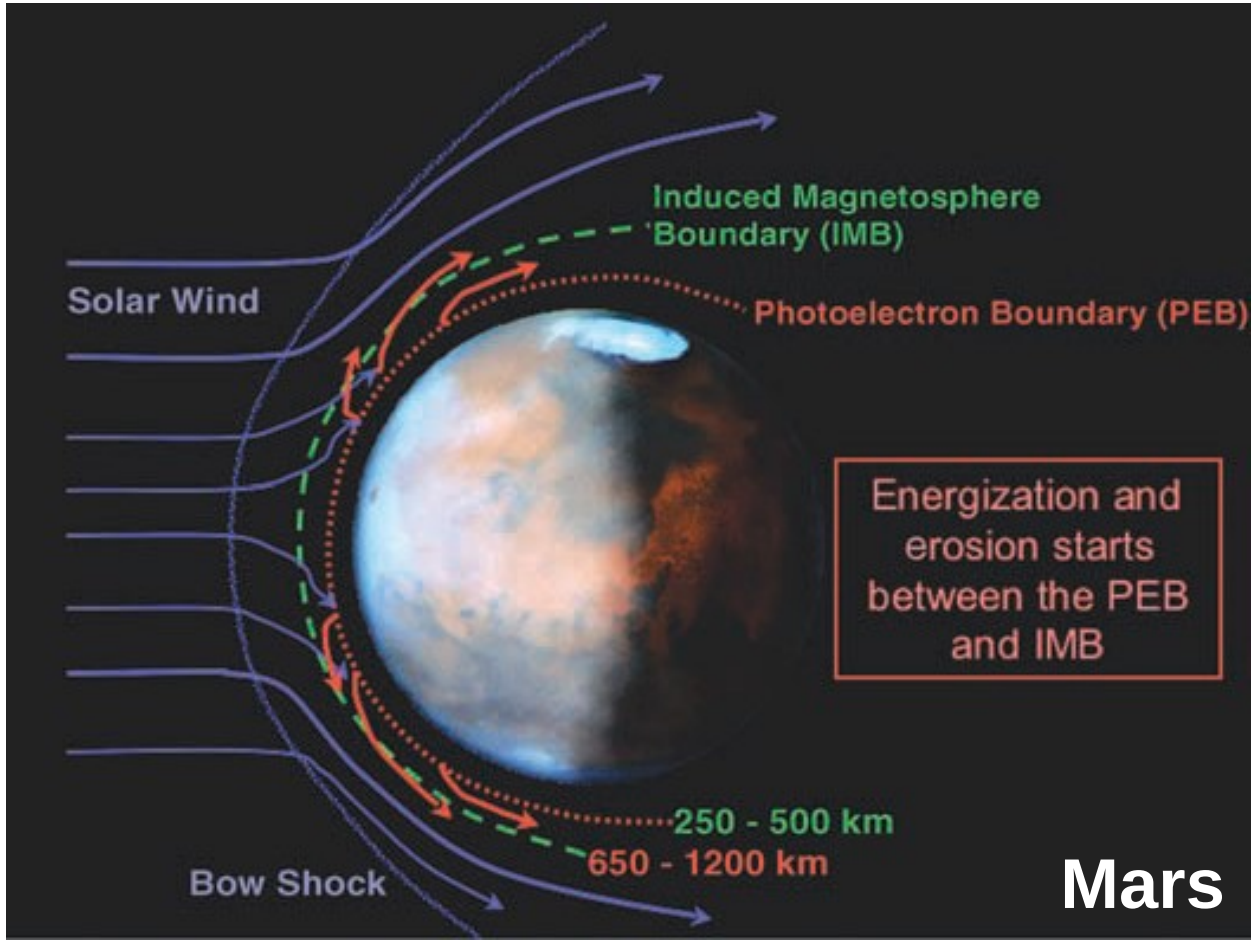
Picked up coronal O^+ / cm^3



n_{H+}(SW) = 3 - 10 H^+/cm^3

Modolo et al. (2004)

Ionospheric loss at Mars and Venus



- At Mars, the solar wind is observed below the ionopause (Lundin et al. 2004)

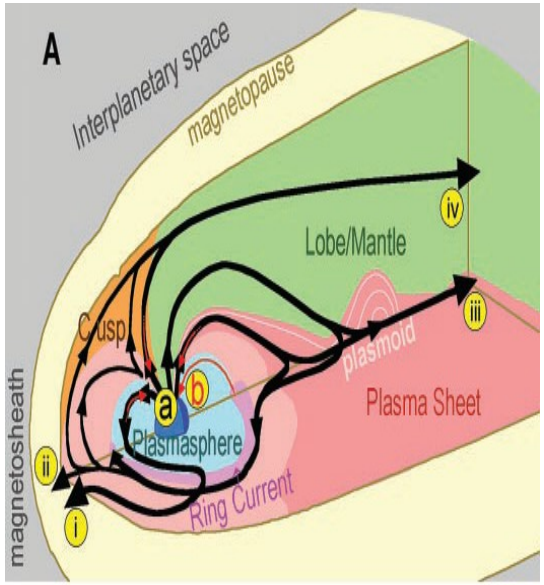
- In the escape flux, a large component is ionospheric plasma:

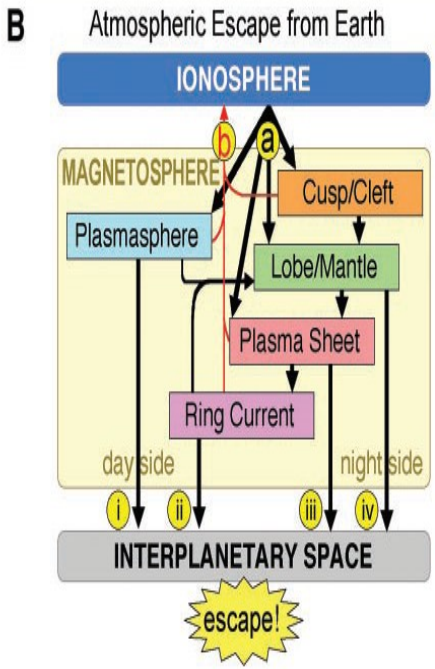
$$CO_2^+/O^+ = 0.2$$
$$O_2^+/O^+ = 0.9$$

(Carlson et al. 2006)

- Atmospheric generated CO_2 photoelectrons observed from an altitude of 250 to 10,000 km 10,000 km altitude in the martian tail near the inner magnetospheric boundary (Frahm et al. 2006)

Ionospheric loss at the Earth





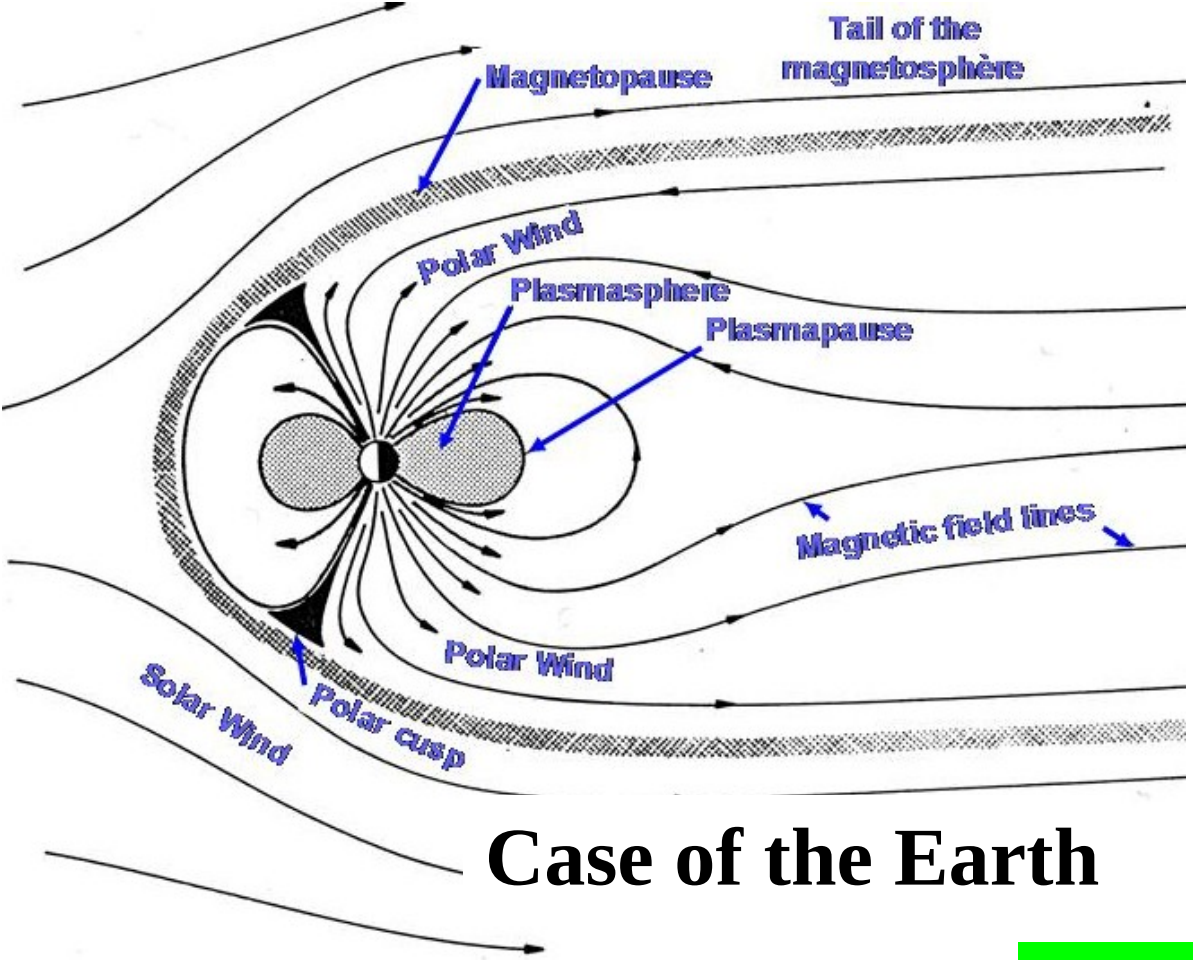
From Seki et al. (2001)

- Polar outflow of O^+ ions = loss of 18% of the present atmospheric O over 3 Gyr
- Four escape routes observed with high-altitude spacecraft: Total oxygen loss rate ~ one order of magnitude smaller

$\Rightarrow$ A substantial return flux from the magnetosphere to the low-latitude ionosphere.

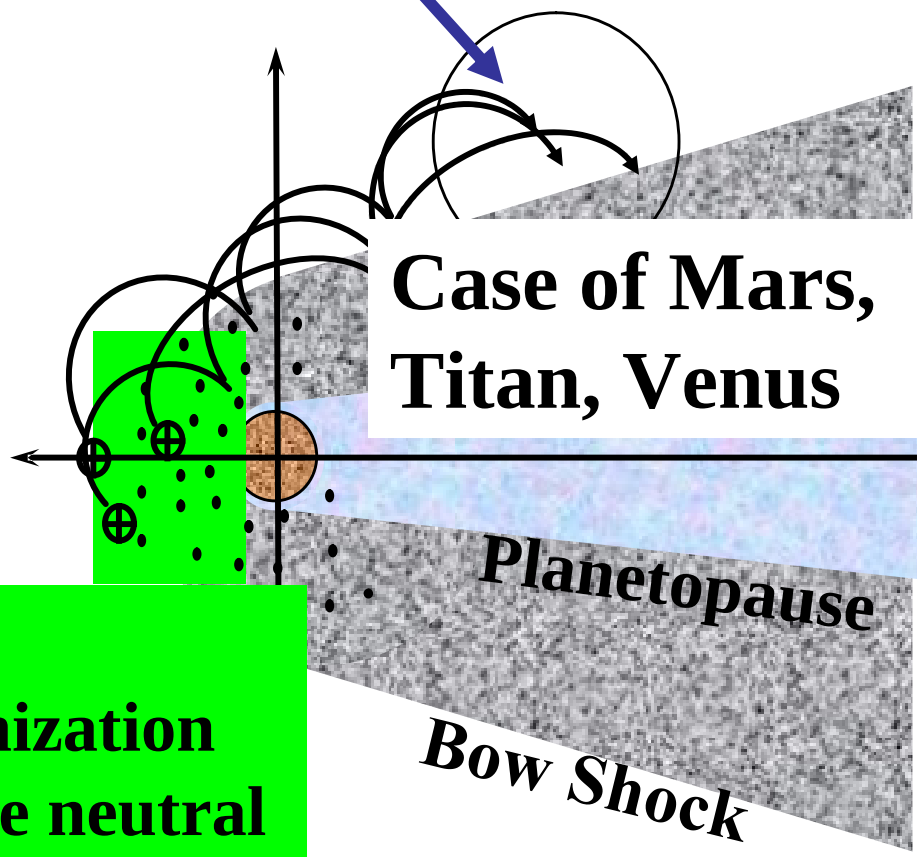
$\Rightarrow$ Net oxygen loss over 3 Gyr ~2% of the current atmospheric oxygen content.

Sputtering



Case of the Earth

Picked up Ions by the Interplanetary Magnetic Field



Case of Mars, Titan, Venus

Ionization of the neutral corona

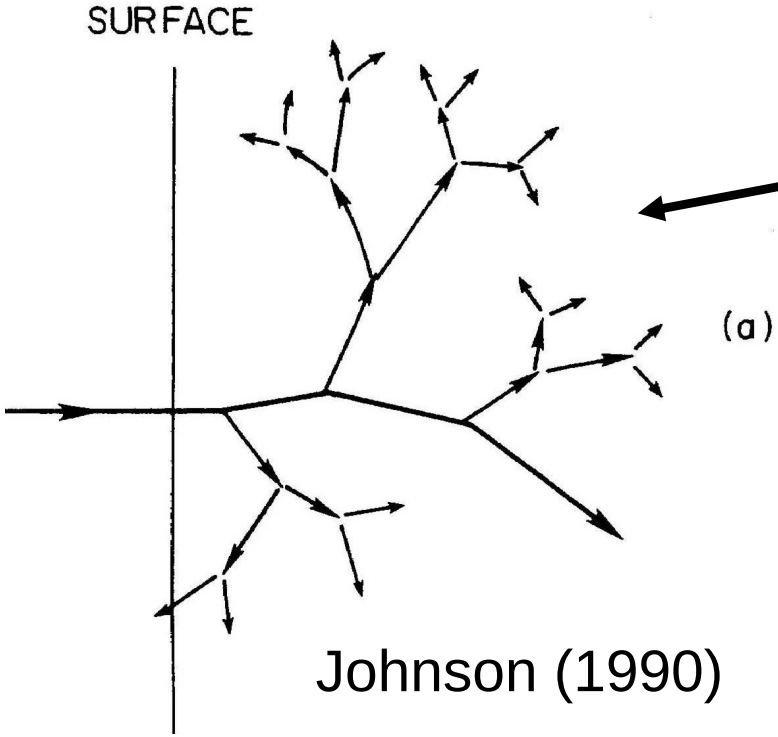
- The Earth: atmospheric escape only possible through the poles
- Mars, Venus, Titan: erosion of the atmosphere by sputtering is possible

⊙ Interplanetary Magnetic field frozen in the solar Wind or magnetic field of gas giant planet

Sputtering: collisional regimes

Efficiency :
Number of escaping particles / number of incident particles = Y

- Single scattering regime: ~ Only one particle interacts with the incident particle, light impactor with energy = keV $\Rightarrow$ Y < 0.1,



Johnson (1990)

- Linear cascade:
Number of moving particle
>
Number of incident particles
Incident energy = keV - few 100 keV
Y ~ 1
(Mars with O (10 keV) Y ~ 3)

- Non-linear cascade: a very large number of particles move.
Impactor with large nuclei and energy > 100 keV, Y >> 1

Isotopic fractionation by non-thermal escape

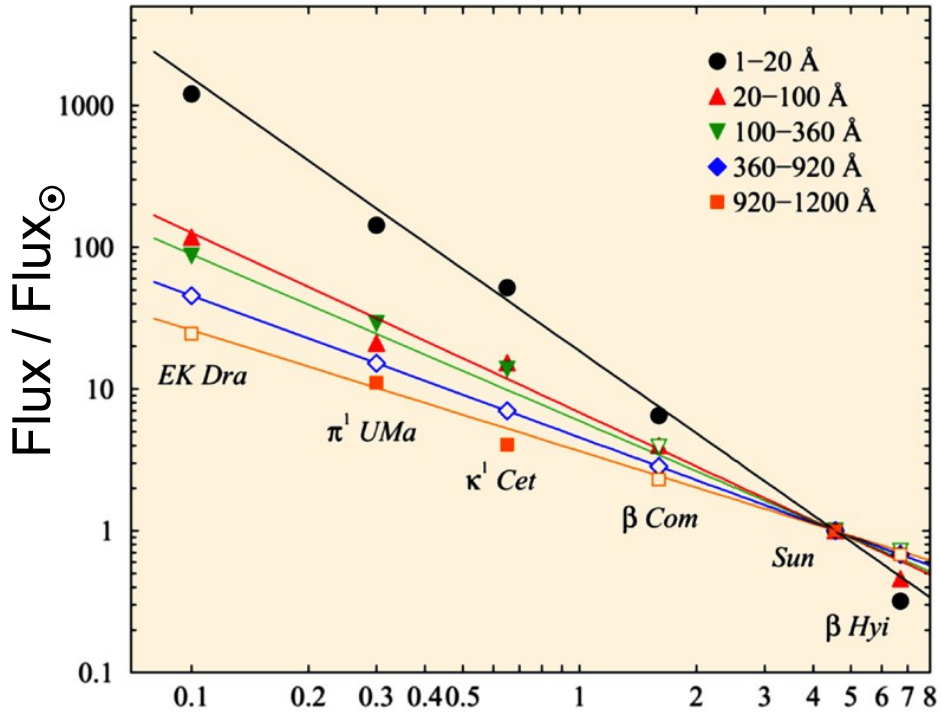
- Sputtering: all isotopes of the same element, in a given altitude range, are ejected at the same rate, because high energy collision processes are involved.

- Dissociative recombination: small effect due to mass dependency of the energy release

⇒ The main reason of isotopic fractionation in the case of non-thermal escape, unlike thermal escape, is diffusive gravitational separation of isotopes between the homopause (≈120 km on Mars) and the exobase level (≈250 km).

⇒ Escape rates of the isotopes of a same element essentially dependent on the gravitationally fractionation.

Past evolution of the Sun



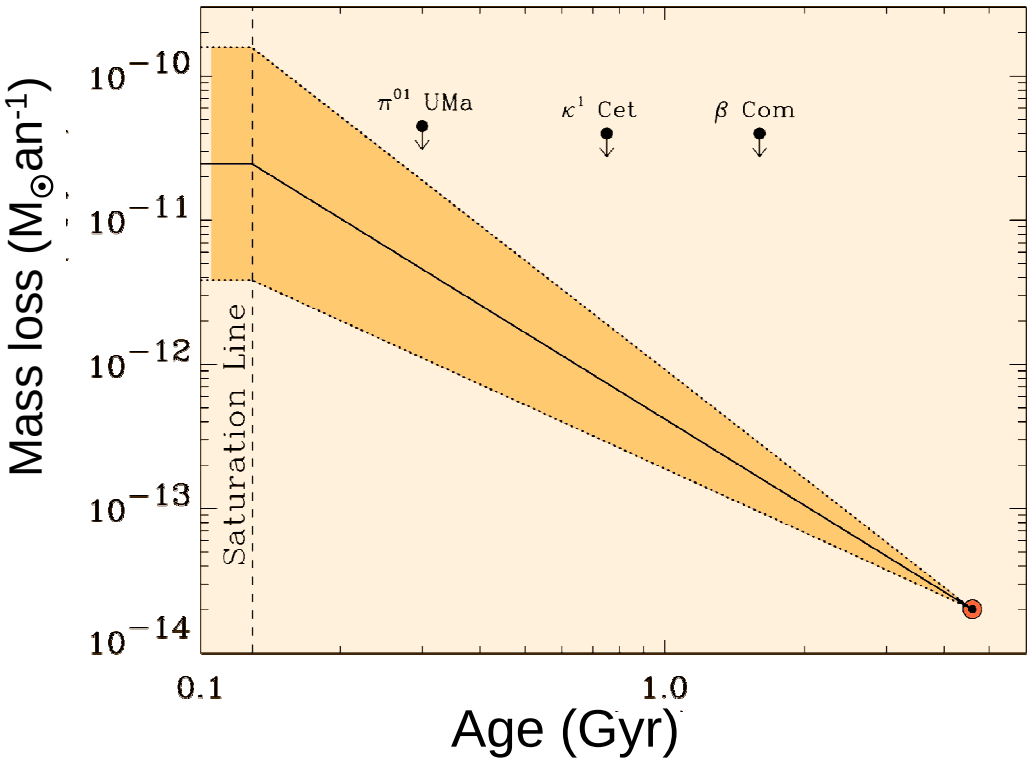
XUV flux (1-1200 Å) decrease with a power in -1.2

_ 3 times larger than today

2.5 Gyr ago

_ 6 times larger 3.5 Gyr ago

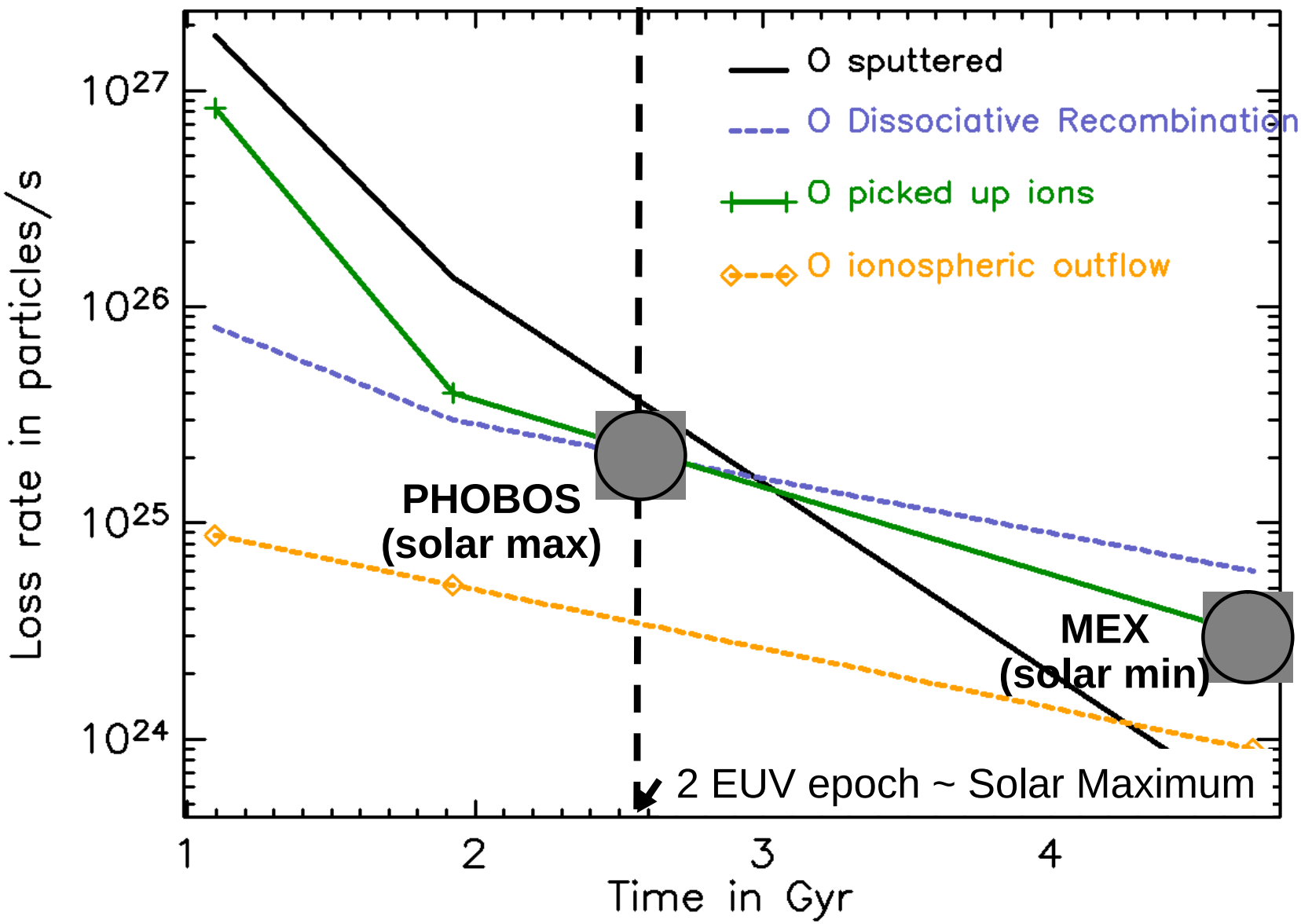
Ribas et al. (2005)



- Solar Wind density could have been 10 times larger 3.5 Gyr ago
- Solar Wind velocity could have been 1 to 2 times larger 3.5 Gyr ago

Wood et al. (2002)

Loss postdating dynamo extinction: Mars



* Based on photoelectron measurements (J.-A. Sauvaud, 2005, personal communication)

From Chassefière et al. (2005)

Escape to space by sputtering: Mars

⇒ Flux of reimpacting keV picked up ions strongly dependent on solar EUV flux

$$\Phi_{\text{pick-up Ion}} \propto \Phi_{\text{EUV}}^{4.5\pm0.3}$$

⇒ Flux of ejecta by sputtering strongly non-linear with solar EUV flux :

$$\boxed{\Phi_{\text{sput}} \propto \Phi_{\text{EUV}}^{4.8\pm0.3}}$$

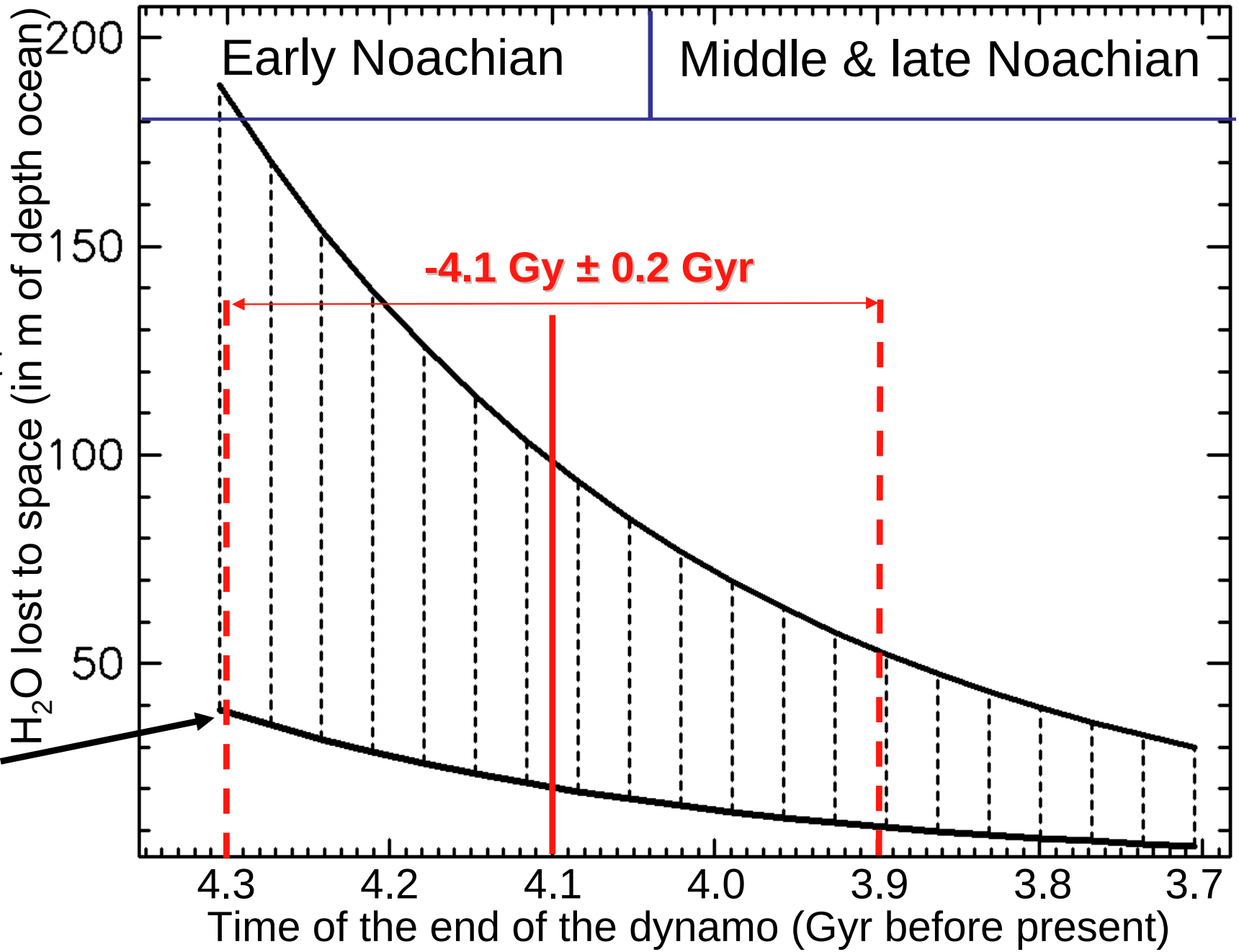
⇒ Other key parameters: height of the exobase, exospheric scale height, solar wind velocity and past history of Martian atmosphere

⇒ Main sources of uncertainty:

- Did the increase of mass loading of the solar wind protect or not Mars' atmosphere?
- When did Mars dynamo collapse?

Uncertainty on sputtering : Mars dynamo

Assuming that 30 m GEL of water was lost since the end of the hydrodynamic escape from the D/H ratio.
(Krasnopolsky and Feldmann, 2001)



Possible Mars' chronology

Hydrodynamic and large impact

Pick-up ion
Sputtering
Dissociative recombination

End of the Martian dynamo
Building of Tharsis
Late Heavy Bombardment

Bibring et al. (2006)

Conclusions

- Are Mars, Venus, Titan... atmospheres in equilibrium?

- No direct evidence of neutral escape - Only ion escape has been observed

- But neutral escape may have been more important than ion escape in the past

- Undirect evidence of a neutral escape = a hot corona

- Isotope fractionation = tracers of a or no past cumulated escape

$\Rightarrow$ In situ measurements of neutral and ion escapes needed

$\Rightarrow$ Isotopic ratio measurements

$\Rightarrow$ A datation of the dynamo in the case of Mars is needed

Conclusions (cont'd)

Atmospheric escapes applied to extra-solar planets:

- detection of an hydrogen atmospheric escape of HD209458b a gas giant planet (1.3 Jupiter Mass at 8.6 stellar radii) with an escaping rate > 10^{10} gs^{-1} (Vidal-Madjar et al. 2003)

- detection of oxygen O I and carbon C II at large distance from HD209458b with an velocity dispersion larger than 15 km/s (Vidal-Madjar et al. 2004)

$\Rightarrow$ Hydrodynamic escape of H dragging O and C?