Initial conditions and early evolutions of terrestrial planets

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Compared terrestrial planets

MARS

→ Small planet
→ Tenuous atmosphere : 7 mbar CO_2
→ Mean surface temperature : ≈-60°C
→ Water : ≈35 m thick GEL at the surface
→ How much carbonates, hydrates in the crust?

VENUS

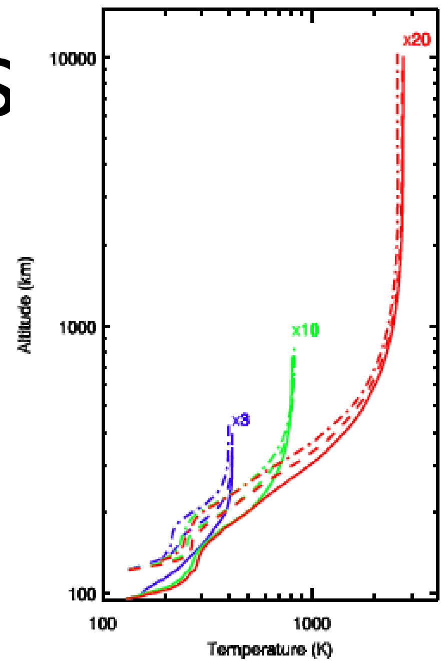
→ Massive atmosphere : 90 bar CO_2
→ Mean surface temperature : ≈730°C
→ Water : a few precipitable centimeters in the atmosphere

EARTH

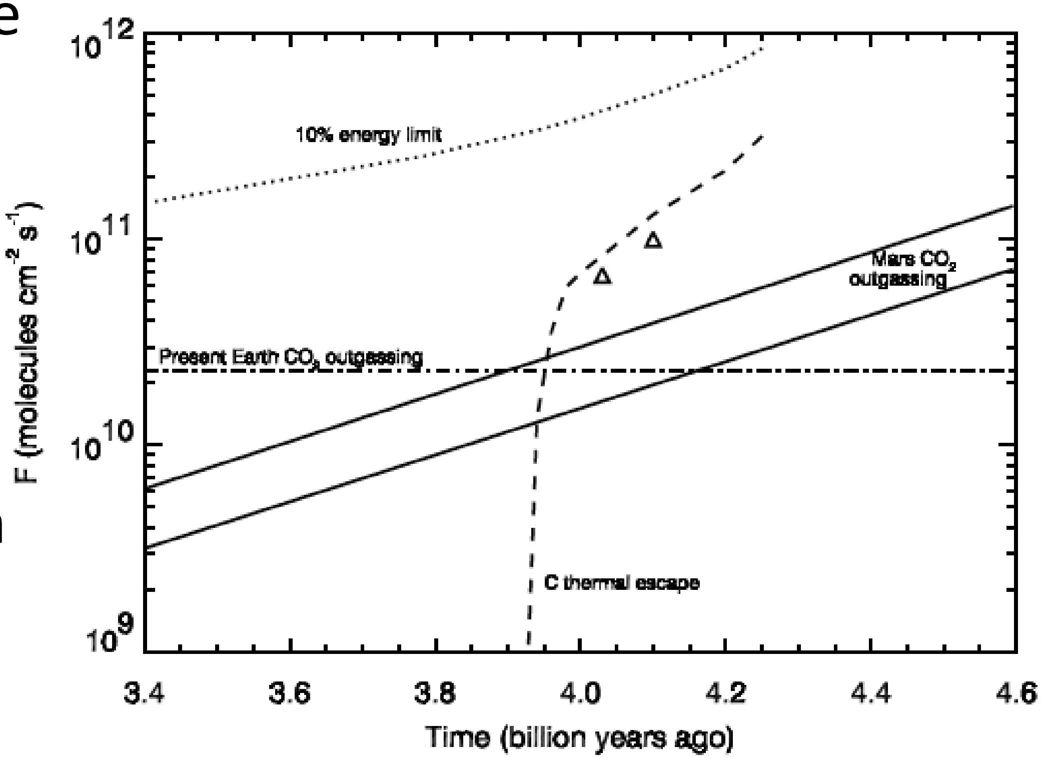
→ Dense atmosphere : 1 bar N_2, O_2 (biotic)
→ Mean surface temperature : ≈15°C
→ 60 bar CO_2 in submarine carbonates
→ Water : 3 km thick GEL (+several terrestrial oceans in the mantle?)

Loss of CO_2 on early Mars

- Initial CO_2 inventory : ≈a few 10 bar (id. Earth, Venus).
- On Mars, loss of 1 bar CO_2/1-10 Myr by hydrodynamic escape (Tian et al., 2009).
- Loss > outgassing until 4 Gyr bp.
- Possible accumulation of CO_2 only at late Noachian (in carbonates?)

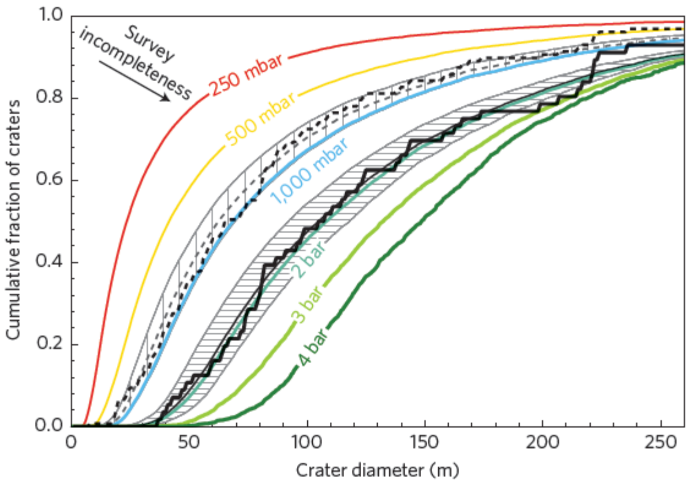


Tian et al., 2009

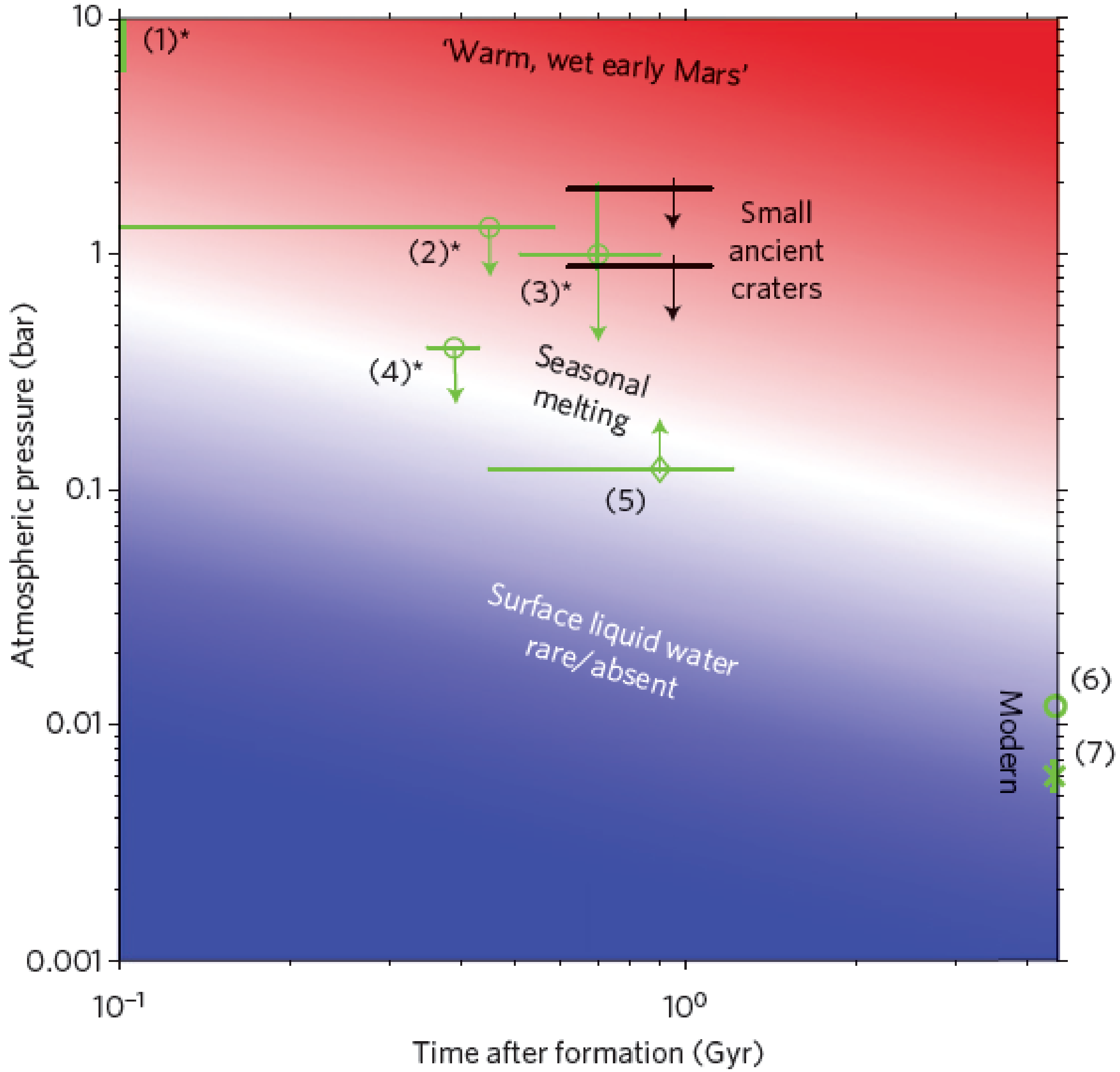


Constraint on early Mars' CO_2 pressure

- CO_2 pressure < 1-2 bar 3.6 Gyr ago from the size of the smallest craters (HiRise/ MRO)

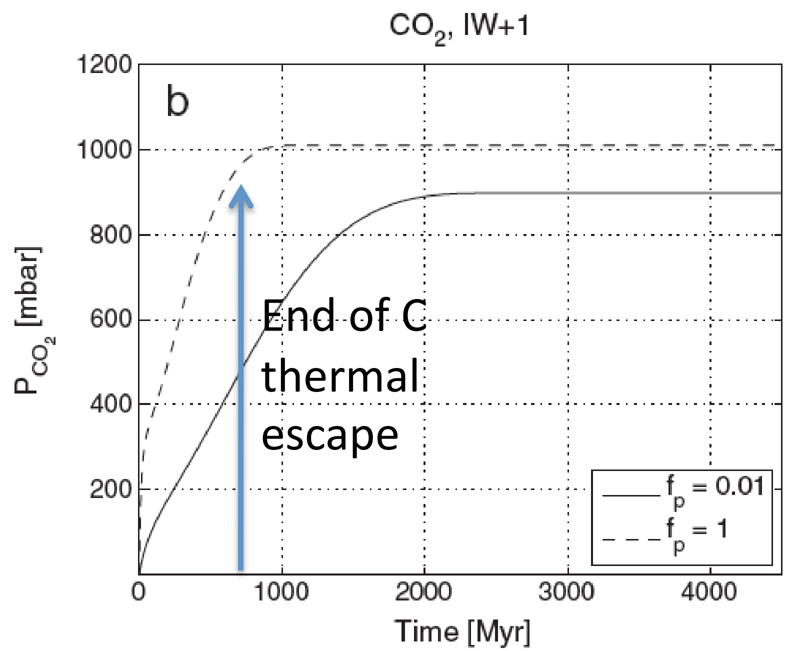


Kite et al., 2014

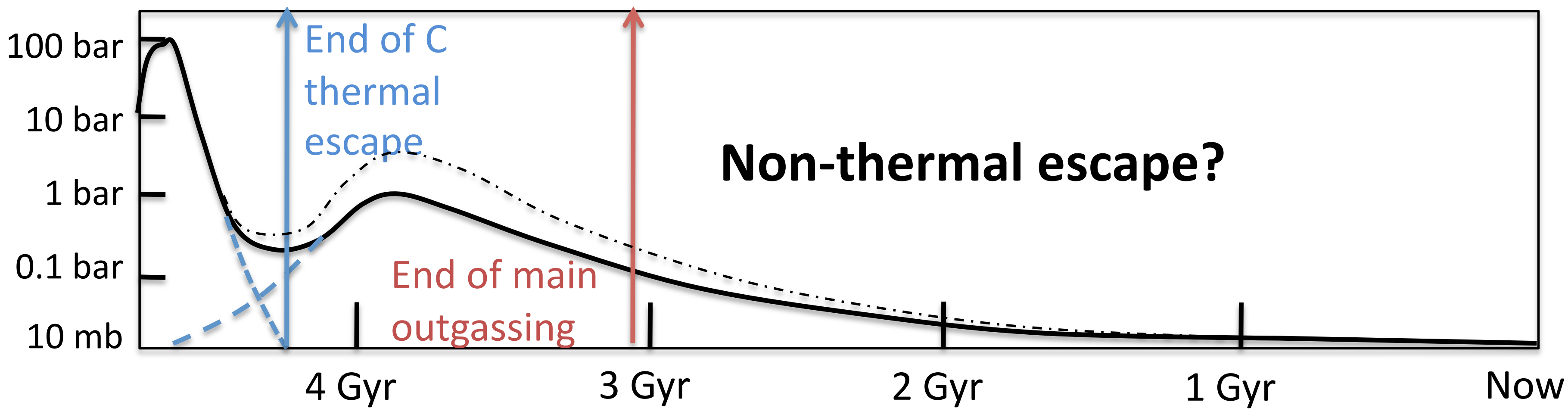


CO_2 volcanic outgassing

- ≈1 bar CO_2 outgassed
- ≈0-0.5 bar outgassed after the end of C hydrodynamic escape
- + cometary input & remnant of initial CO_2?

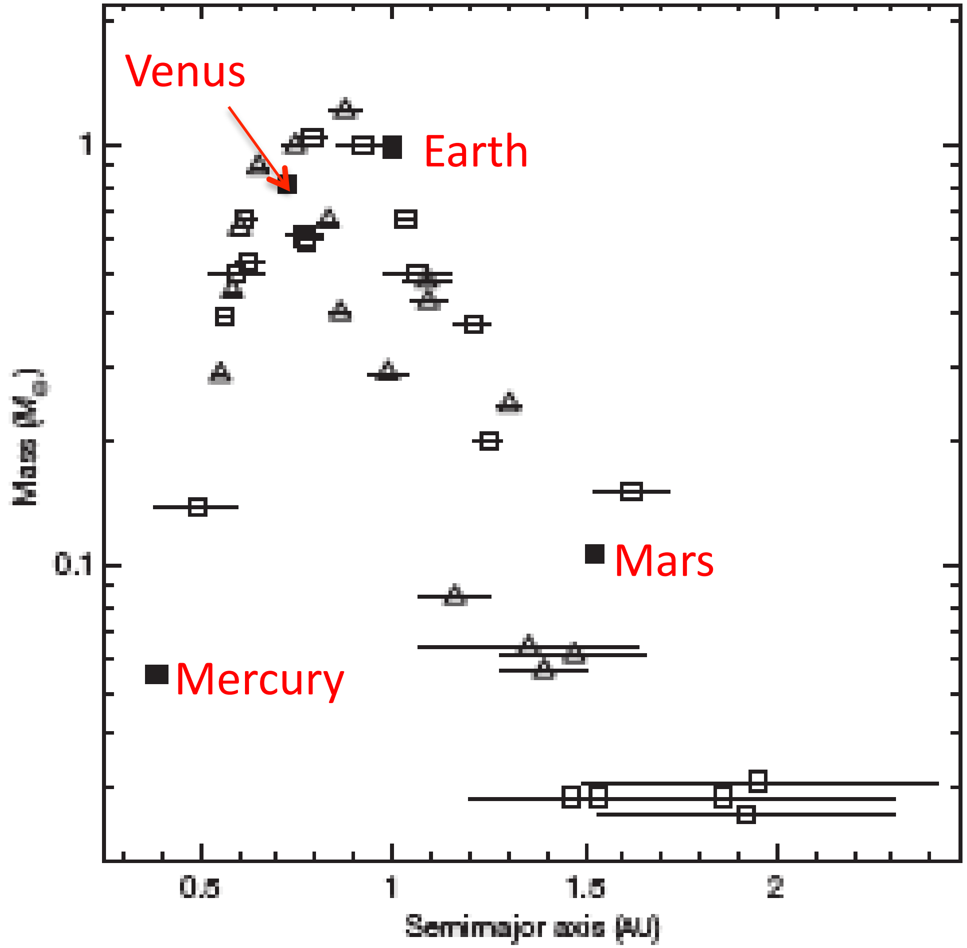


Grott et al., 2011



Why is Mars small?

- The small size of Mars is the reason why Mars rapidly lost its early atmosphere.
- Explained by Jupiter's early gas-driven migration to 1.5 AU (then back), truncating planetesimal disk at 1 AU (Walsh et al., 2011).

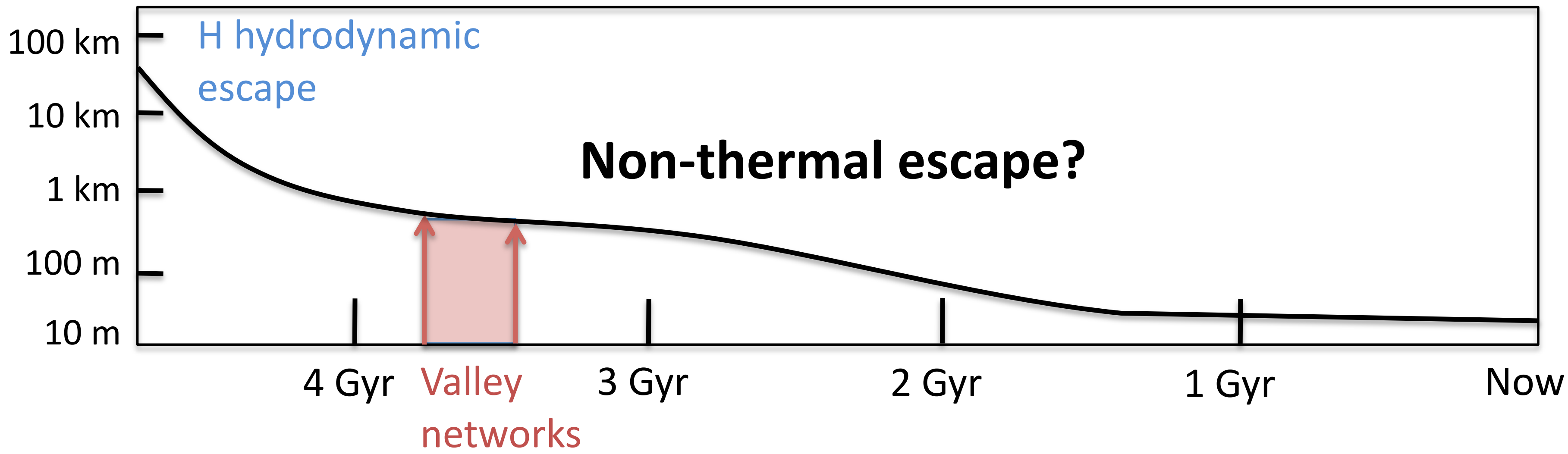


Walsh et al., 2011

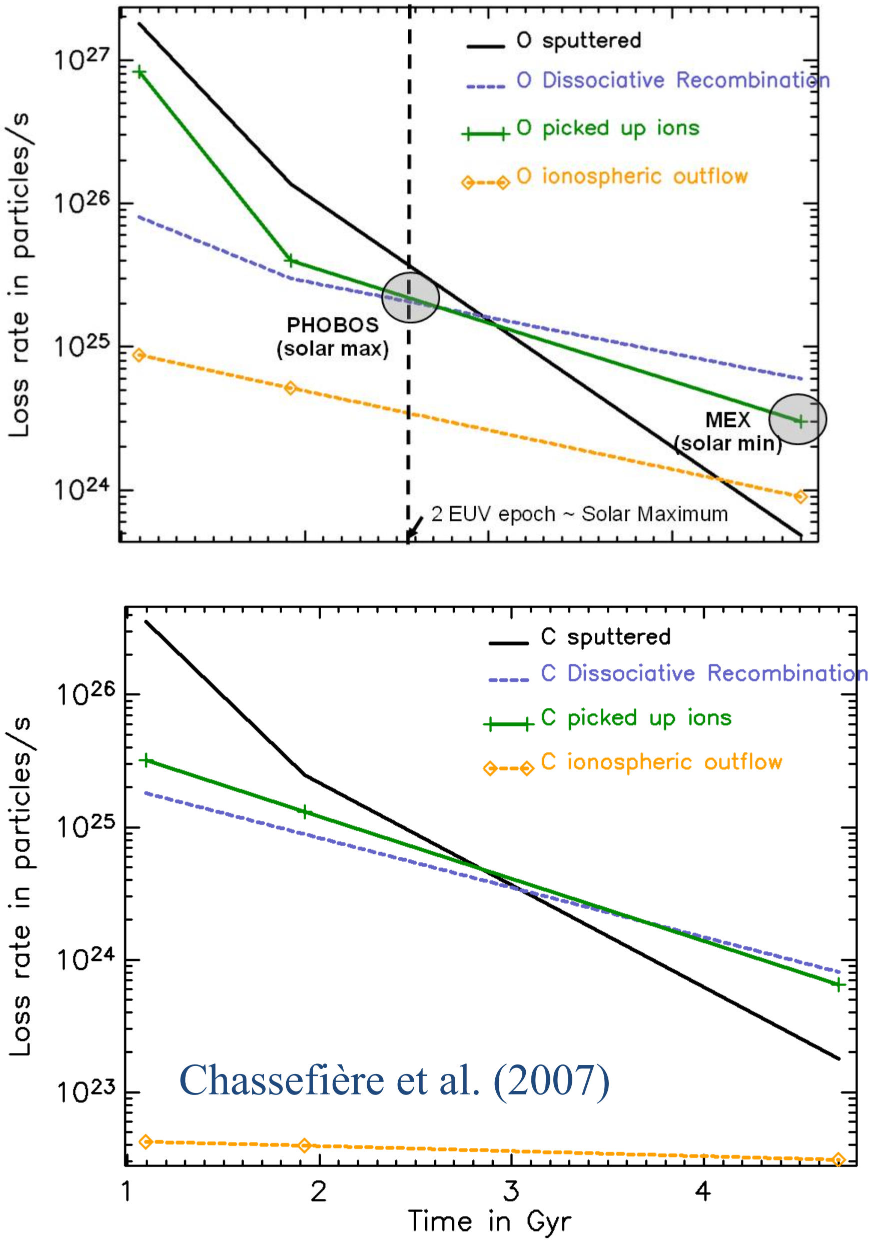
Nice model

Loss of H_2O on early Mars

- Initial inventory up to several Earth oceans : several 10 km thick GEL (Raymond et al., 2006).
- Amount of outgassed H_2O : 20-60 m thick GEL (Grott et al., 2011).
- ≈500 m thick GEL required to carve outflow channels (Carr and Head, 2003)
- Present inventory : ≈35 m thick GEL (Christensen, 2006).



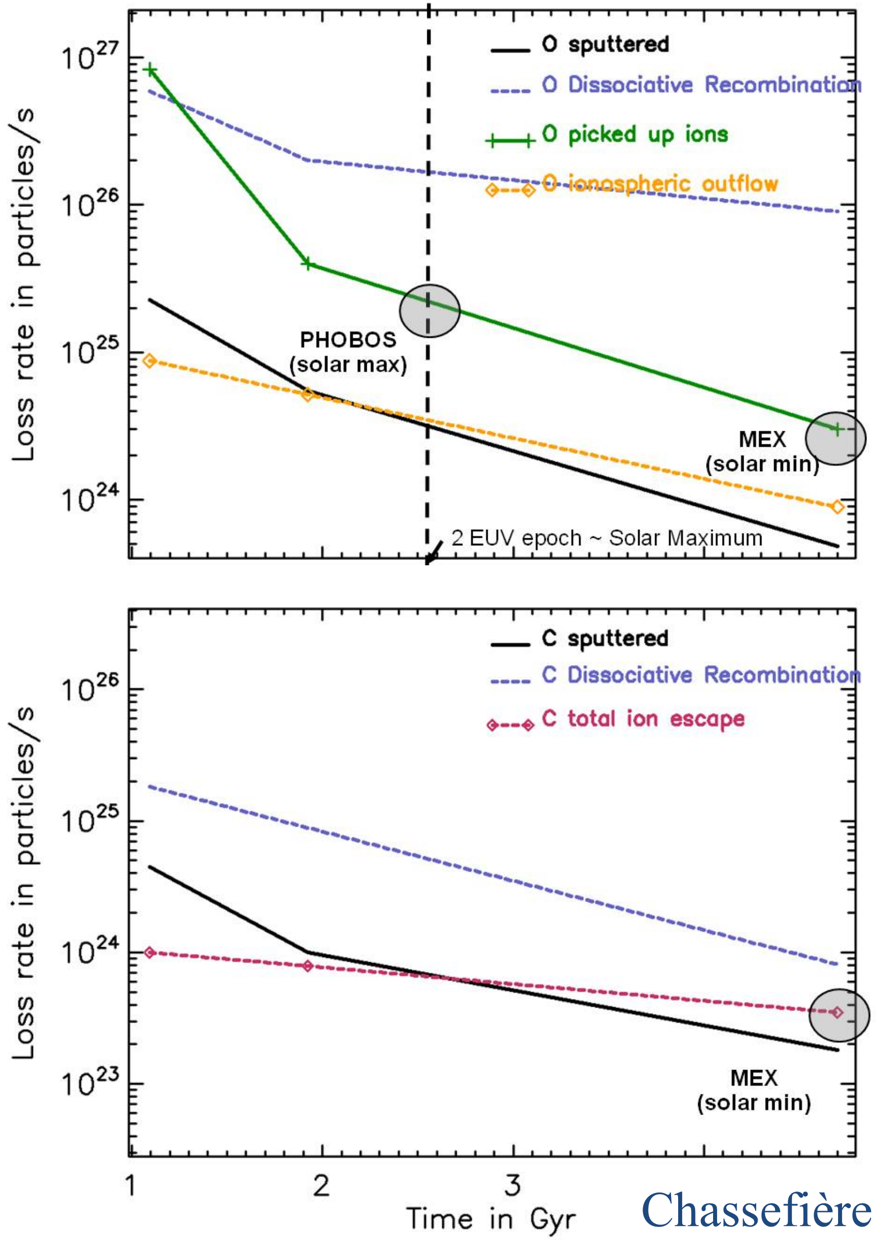
Non-thermal escape : initial estimates



- Sputtering rate estimated using gas-dynamic simulation of Mars' interaction with the solar wind (Luhmann et al., 1992)
- Dissociative recombination estimated from Luhmann et al. (1992)
- Ion escape: Ma et al. (2004)

During the last 4.1 Gyr
Up to **100 mbar of CO_2**
+
Up to **120 m of water**
lost to space

Revisited non-thermal escape fluxes



- Sputtering rate estimated using magnetospheric hybrid simulation of Mars' interaction with the solar wind (Chaufray et al. 2007)
- Dissociative recombination estimated from Valeille et al. (2010)
- Ion escape: Lundin et al. (2009) MEX/ASPERA at present solar Minimum + Ma et al. (2004)

During the last 4.1 Gyr
Up to **10 mbar of CO_2**
+
Up to **5 m of water**
lost to space

Chassefière and Leblanc (2011)

Why sputtering estimate changed so much?

ORIGINAL SCENARIO

⬈ UV/EUV flux ⇒ ⬈ ionization ⇒ ⬈ pick-up ion
⇒ ⬈ ion bombardment ⇒ ⬈ sputtering

From solar minimum to solar maximum:
Sputtering increases by ~50 (Luhmann et al., 1992)

+

⇒⬈ exospheric production ⇒ ⬈ pick-up ion
⇒ ⬈ sputtering by factor <2 (Johnson & Luhmann, 1998)

From 1 EUV to 2 EUV ⬈ sputtering by factor 100

BUT

NEW SCENARIO

⬈UV/EUV flux ⇒ ⬈ ionization ⇒ ⬈ ionospheric pressure
⇒ ⬈ planetopause alt. ⇒ ⬊ S.W. interaction ⇒ ⬊ sputtering

From solar minimum to solar maximum:
Sputtering increases by only 4 (Chaufray et al., 2007)

Crustal sinks required during last 4 Gyr

- Strong thermal -hydrodynamic- escape of C (from CO_2) and H (from H_2O) expected during the first half billion years

  → **Mars lost most of its volatiles (CO_2/H_2O) before 4 Ga.**
- Non-thermal escape postdating hydrodynamic escape cannot explain the loss of more than 10 mbar/5 m thick GEL of CO_2/H_2O during the last 4 Gyr

  → **CO_2 and H_2O crustal sinks (carbonates, hydrates) are required for trapping 1 bar/ 500 m thick GEL of CO_2/H_2O**.
- Potential important roles of clathrates as an intermediate reservoir of volatiles, frozen into the cryosphere

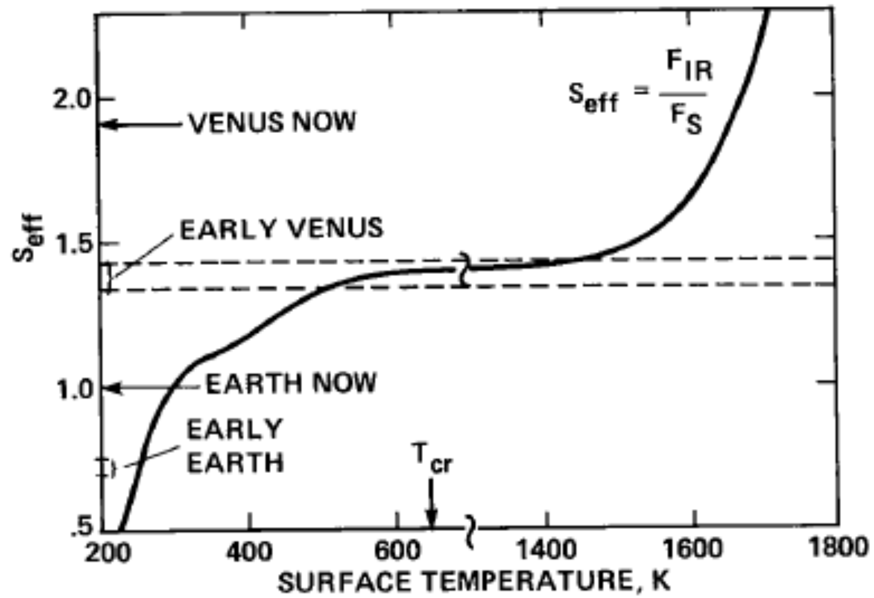
  → **up to a few bar of CO_2, and a few 0.1 bar of SO_2, possibly trapped in Mars' cryosphere 4 Gyr ago** (Chassefière et al., 2013).

Consequences and questions

- Non-thermal escape didn't play a strong role in removing Mars atmosphere 3.6-3.8 Gyr ago.
- **It is highly improbable that the cessation of the magnetic dynamo resulted in a significant escape of atmosphere and further desertification.**
- Volatiles present in the atmosphere or trapped in the cryosphere 4 Gyr ago have been (likely) **stored in the crust** through hydrothermal geochemical reactions (carbonation, hydration, ...).
- If so, what has been the **mechanism triggering hydrothermal activity at the end of the Noachian?** Tharsis formation, late heavy bombardment...?
- **Crucial role of atmosphere-subsurface interactions** (outgassing/ physical-chemical trapping processes)

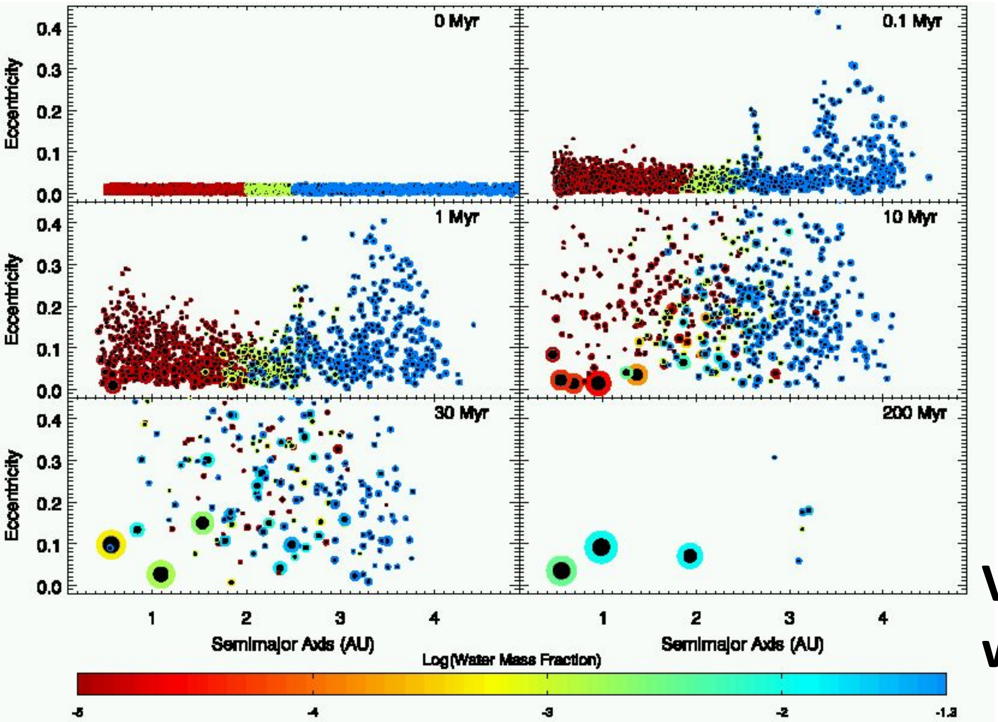
An Earth-sized planet : Venus

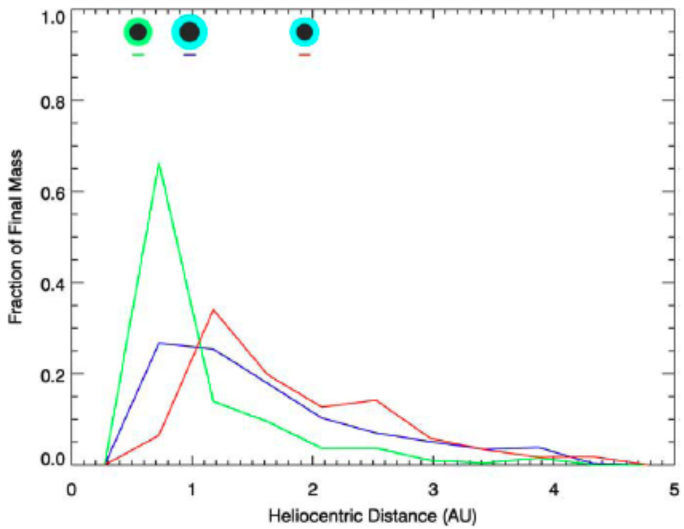
- Initial water endowment probably similar to that of Earth : large scale radial mixing of planetesimals in primitive nebula.
- Possible formation of an Earth-like water ocean in « faint young Sun » conditions (Kasting, 1988).
- Further runaway (Rasool and de Bergh, 1970) or moist greenhouse in the course of Sun illumination increase.
- Further photodissociation of H_2O in upper atmosphere and hydrodynamic escape of H, yielding the present massive CO_2 atmosphere (Kasting and Pollack, 1983; Chassefière, 1997)



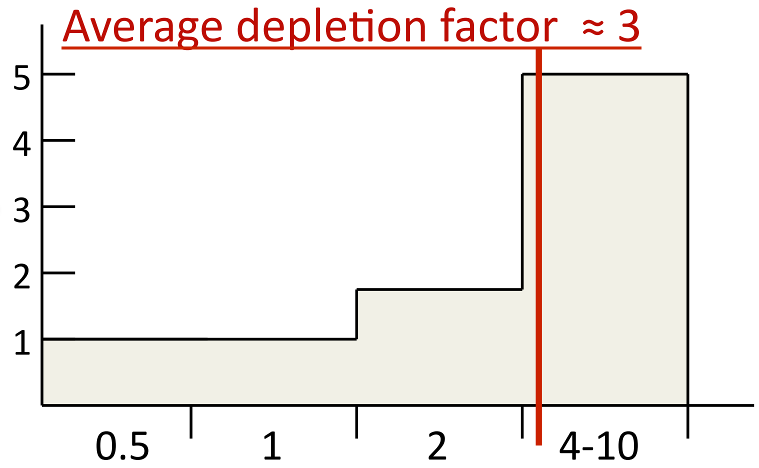
Kasting, 1988

Accretion history and initial water content



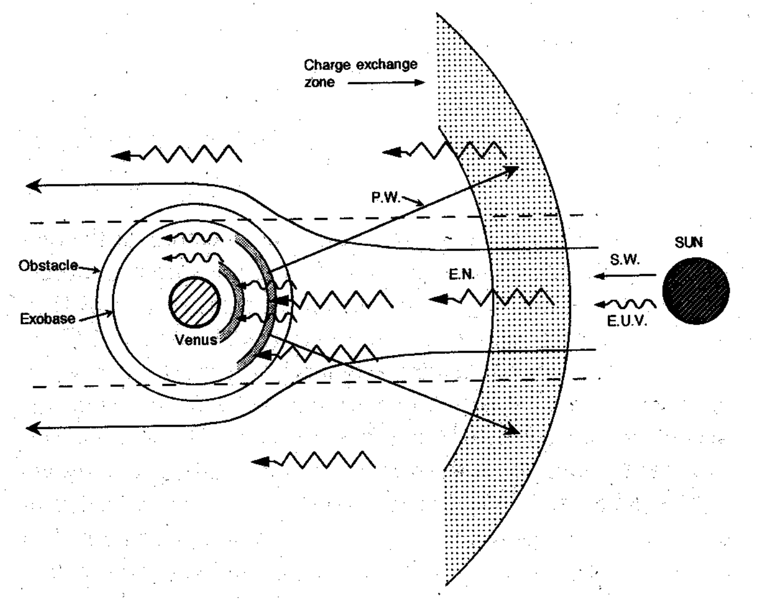


Venus generally endowed with less water (but large stochastic variations)



From the 9 simulations of Raymond et al (2006) and O'Brien et al (2006), histogram of the Venus wrt Earth water depletion factor

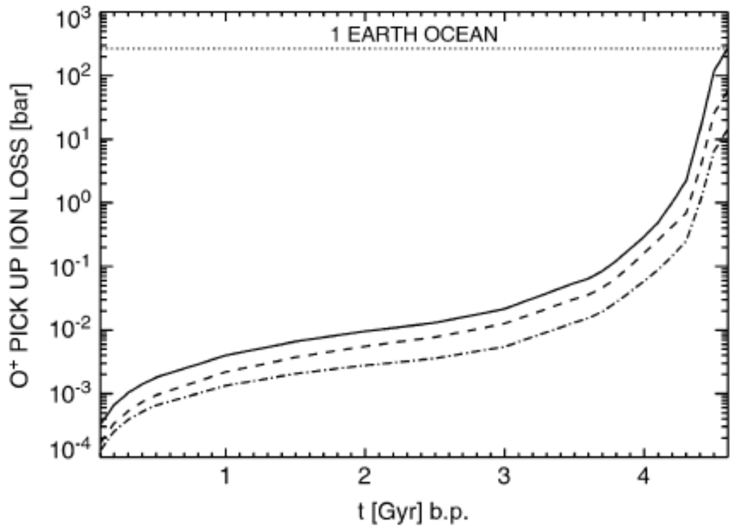
Thermal and non-thermal escape



EUV+**Solar wind**-powered hydrodynamic escape (Chassefière, 1996, 1997) :

- Potential removal of 1 or several TO in a few 10 or 100 Myr (Gillmann et al., 2009).
- Efficient (but incomplete) removal of oxygen through frictional escape.

In the case of a very strong primitive solar wind flux, **pick-up ion escape** may have removed the oxygen content of 1 terrestrial ocean (Kulikov et al., 2006).



Early magma ocean phase

- Big impacts during the main accretion phase can melt the whole planet
- Duration of the cooling phase of the magma ocean under a massive H_2O-CO_2 atmosphere : **≈0.1/1/10 Myr for Mars/Earth/Venus** (Elkins-Tanton, 2006; Lebrun et al., 2013; Hamano et al., 2013)
- Venus close to the critical distance from the Sun inside which magma ocean never cools : **did a water ocean ever form on Venus and, if so, how long did it last?**
- Mars and Earth : possibility of **sequential water oceans** on these planets during main accretion, potentially **increasing impact-induced hydrodynamic escape** (Genda et al., 2006) *(lower shock impedance ocean vs ground)*

Cf following talk by Massol et al.

Combined effects of hydrodynamic escape and planet's type

	Planet inside critical distance (type II)	Planet outside critical distance (type I)
Slow escape *(big or far from Sun planet)*	- Magma planet (?)* (→ *solid planet after loss of all H_2O*) - No water ocean - Massive CO_2 atmosphere **→ Venus?** *(big and close)*	- Solid planet - Water ocean - Moderate atmosphere (CO_2 trapped in carbonates) **→ Earth?** *(big and far)*
Fast escape *(small or close to Sun planet)*	- Solid planet - No water ocean - No atmosphere **→ Mercury?** *(small and close)*	- Solid planet - No water ocean - Moderate to tenuous atmosphere **→ Mars?** *(small and far)*

* If type I planet close to the critical distance, a water ocean could have formed and further evaporated due to the increase of the solar constant.

Conclusion

- **Disk-protoplanets dynamics/interactions → initial conditions** : size/position of final planet (radiative budget & greenhouse effect, strength of thermal escape, duration of magma ocean cooling…)
- Interplay of **energy/matter exchange fluxes** at BOTH interior-atmosphere and atmosphere-interplanetary space interfaces + **disk dissipation kinetics** (driving impact history) → **early evolution (first ≈1 Gyr)**
- **Why did Mars and Venus evolve divergently? Mars small** (early magma ocean crystallization, early escape of most volatiles–including CO_2-)/ **Venus close to (inside?) critical distance** (slow magma ocean crystallization, H_2O remaining a long time in the interior/atmosphere system and finally escaping –but not CO_2-).
- On Earth, **magma ocean rapidly crystallized : a water ocean formed, preventing most H_2O from escaping**.
- Other favourable factors for Earth : rotation axis stabilized by the Moon, more rapid decrease of impactor fluxes than at Mars distance, right distance from the Sun to easily achieve positive surface temperature.