Effects of asteroid and comet impacts on the atmospheric evolution of Earth, Mars, Venus

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Plan

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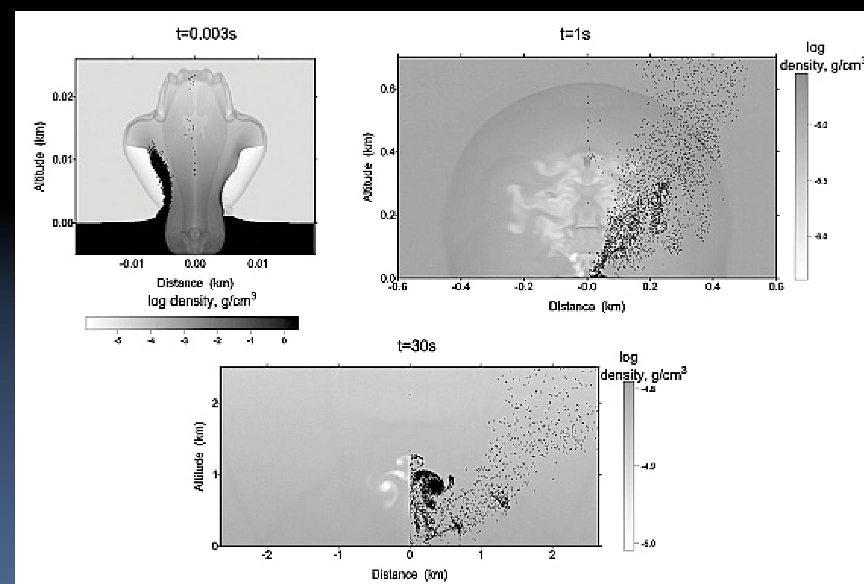
- Models of impact and atmospheric erosion
- The “tangent plane model”
- Atmospheric mass evolution on Mars
- Refinement of the model: inclusion of other parameter effects
- Influence of planetary parameters on atmospheric erosion
- Comparison between Mars, Earth and Venus
- Conclusion

Motivation

- Evidences suggest stable liquid water on Martian surface in the past;
- Stable liquid water implies higher atmospheric mass than today;
- Impacts influence atmospheric mass evolution by erosion and delivery of volatiles;
- *Could impacts explain significant atmospheric loss over the Martian history?*

Models of impact and atmospheric erosion

Simulations by hydrocodes in which equations of motion and equations of state (EoS) are solved.



Nemtchinov et al. 2002

Difficulties:

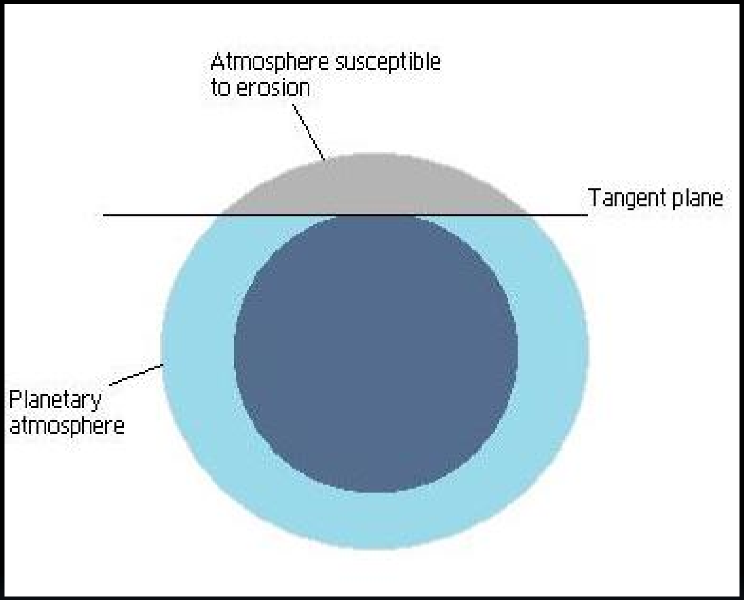
- Choice of an appropriate EoS
- A proper model of the vapor cloud dynamics
- Expensiveness in time and calculations

Can it be simplified ?

- **"Tangent plane model"** (Melosh and Vickery, 1989) ; used to set a global view of the atmospheric mass evolution (Zahnle *et al.*, 1992; Zahnle, 1993; Manning *et al.*, 2006)

- Analytical models can represent basic aspects of impact erosion and delivery;
- Analytical models can reduce time and calculations;
- Number of parameters, scaled with numerical simulation results, is reduced.

The "tangent plane model"



- m_{tan} = atmospheric mass above the plane tangent of the impact surface
- m_{crit} = minimal impactor mass that can eject a mass equivalent to $m_{\tan}$

$$m_{crit} \geq m_{\tan} = \frac{m_{atm} H}{2R}$$

The "tangent plane model"

Principles for one impactor:

- If $m_{imp} < m_{crit}$
  - $m_{esc} = 0$
  - $m_{del} = m_{imp} y_{imp}$ (y_{imp} is the volatiles content of the impactor)
- If $m_{imp} \geq m_{crit}$
  - $m_{esc} = m_{\mathrm{tan}}$
  - $m_{del} = 0$

Atmospheric mass evolution

$$\frac{dM_{atm}(t)}{dt} = \frac{dM_{del}(t)}{dt} - \frac{dM_{esc}(t)}{dt}$$

$$\frac{dM_{esc}(t)}{dt} = \frac{\partial N_{cum}(>m_{crit}(t),t)}{\partial t} 4\pi R^2 \; m_{\tan}(t)$$

= escaped atmospheric mass rate

= flux of impactors of mass greater than m_{crit} proportional to m_{crit}^{-b}

= surface area

= atmospheric mass above the plane tangent to the surface

b characterizes the mass distribution of the impactors flux, b < 1.

$$\frac{dM_{del}(t)}{dt} = \frac{\partial N_{cum}(>m_{crit}(t),t)}{\partial t} 4\pi R^2 \left(\frac{b}{1-b}\right) m_{crit}(t) y_{imp}$$

Importance of the erosion factor is related to the value of m_{crit} parameterized by $\boldsymbol{n = m_{crit}/m_{\tan}}$.

Values of $n = m_{crit}/m_{tan}$

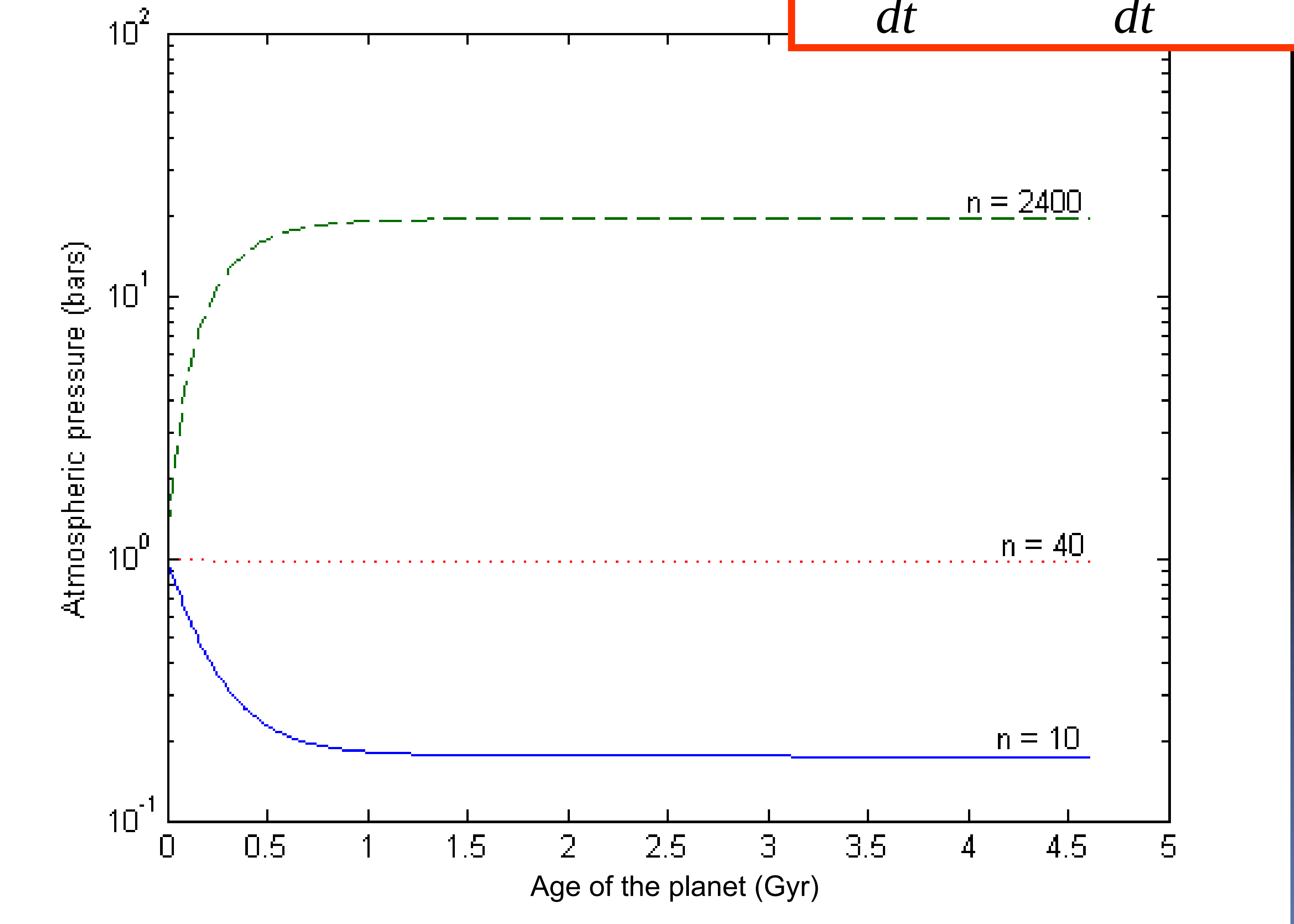
From different hydrocode simulations:

- n = 1 (Melosh and Vickery, 1989)
- n = 10 (Vickery, 1990; Manning *et al.*, 2006)
- n ~ 20 (Newman *et al.*, 1999)
- n ~ 5 – 10 (Hamano and Abe, 2005, 2006)
- n ~ 50 – 2400 (Shuvalov and Artemieva, 2001; Svetsov, 2007)

Article (Pham *et al.*, 2008) published in Astrobiology in April 2009

Atmospheric mass evolution on Mars due to impacts

$$\frac{dM_{atm}(t)}{dt} = \frac{dM_{del}(t)}{dt} - \frac{dM_{esc}(t)}{dt}$$



Inclusion of other parameter effects

- Types of the impactor population (asteroid, comet)
- Impact velocity
- Vaporized fraction of the impactor, following its energy (impact velocity and mass range):
- Impact obliquity

Principles of the tangent plane model

Principles for one impactor:

- If $m_{imp} < m_{crit}$
  - $m_{esc} = 0$
  - $m_{del} = m_{imp} \, y_{imp} \, f_{vap}$
- If $m_{imp} \geq m_{crit}$
  - $m_{esc} = m_{\tan} \, f_{vel} \, f_{obl}$
  - $m_{del} = (1 - f_{vel} f_{obl}) m_{imp} \, y_{imp} \, g_{vap}$

Factor	Value
y_{imp}	0.03
f_{vel}	0.2
f_{vap}	0.69
g_{vap}	0.56
f_{obl}	2.17

Atmospheric mass evolution: new formula

$$\frac{dM_{esc}(t)}{dt} = \frac{\partial N_{cum}(>m_{crit}(t),t)}{\partial t} 4\pi R^2 \; m_{\tan}(t) \times f_{vit} \times f_{obl}$$

Velocity factor

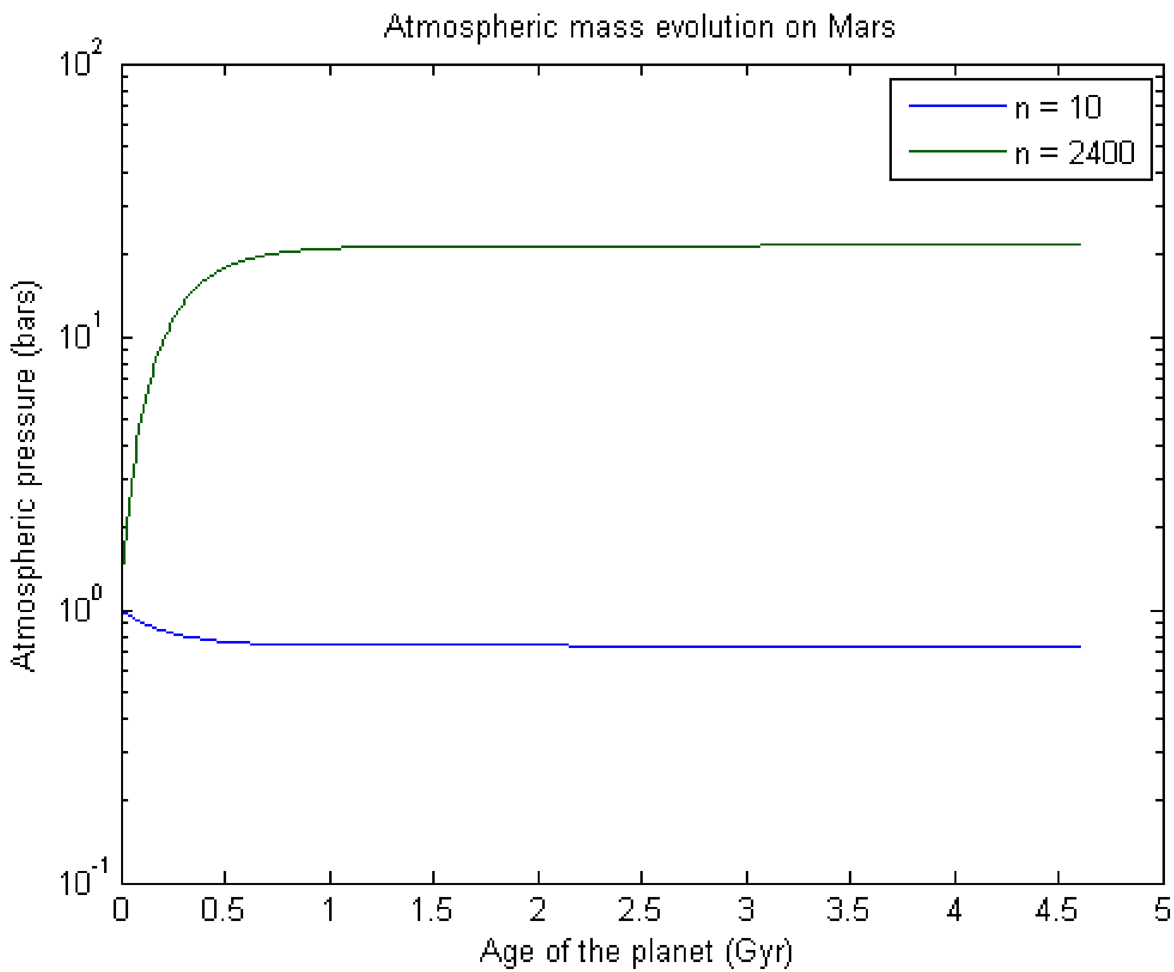
Obliquity factor

Vaporization factors

$$\frac{dM_{del}(t)}{dt} = \frac{\partial N_{cum}(>m_{crit}(t),t)}{\partial t} 4\pi R^2 \left(\frac{b}{1-b}\right) m_{crit}(t) y_{imp} \times f_{vap} + \frac{\partial N_{cum}(>m_{crit}(t),t)}{\partial t} 4\pi R^2 \; m_{crit}(t) y_{imp} \times (1 - f_{vit} f_{obl}) g_{vap}$$

Atmospheric mass evolution on Mars due to impacts for this new model

$$\frac{dM_{atm}(t)}{dt} = \frac{dM_{del}(t)}{dt} - \frac{dM_{esc}(t)}{dt}$$



Inclusion of the influences of velocity, vaporization and obliquity in the model reduces the erosion effect for n = 10

Influence of planetary parameters

Parameters of the planet that influence impact erosion and delivery:

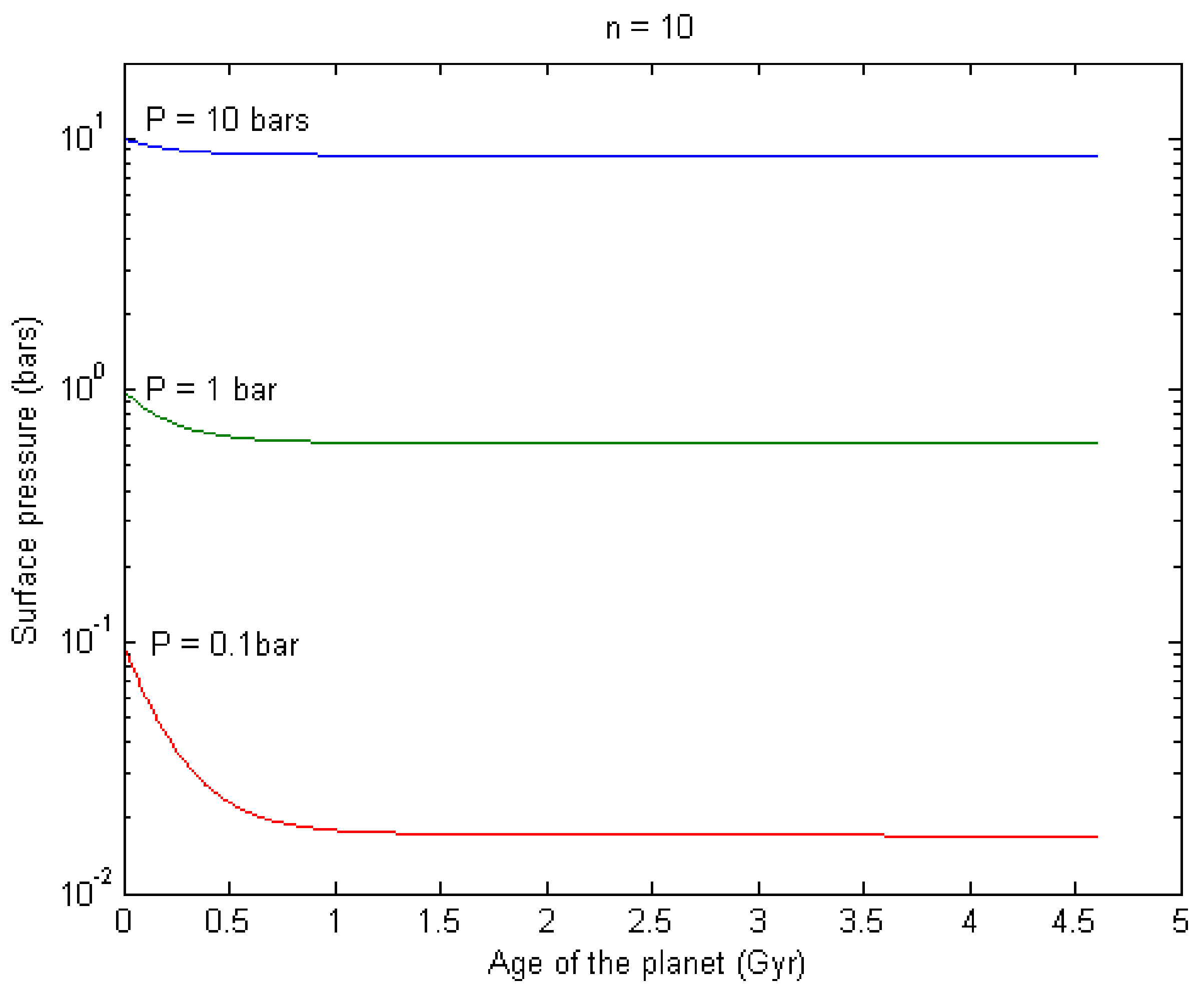
- Initial atmospheric pressure P(t = 4.6 Gyr)
- Planet radius R
- Planet gravity g
- Planet temperature T
- Molar mass m_{mol}

Influence of planetary parameters

We start from the parameters of present Mars with

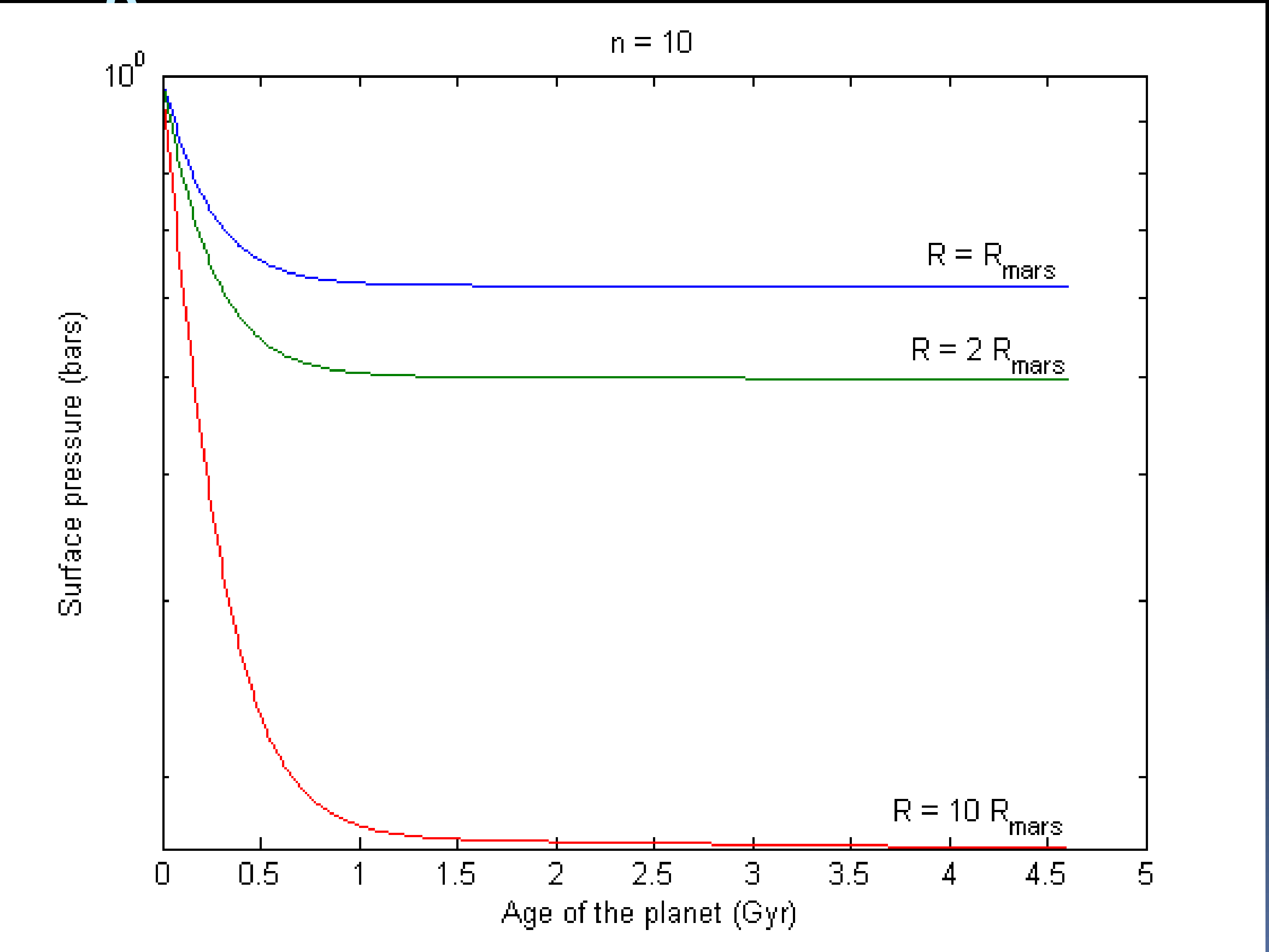
- $n = 10$:
- $R_{Mars} = 3390$ km
- $g_{Mars} = 3.72$ m/s^2
- $T_{Mars} = 215$ K
- $m_{molMars} = 44.01$ g/mol

Effect of the initial surface pressure P(t = 4.6 Gyr)



The atmospheric pressure variation relatively to the initial pressure is less pronounced with higher P(t = 0)

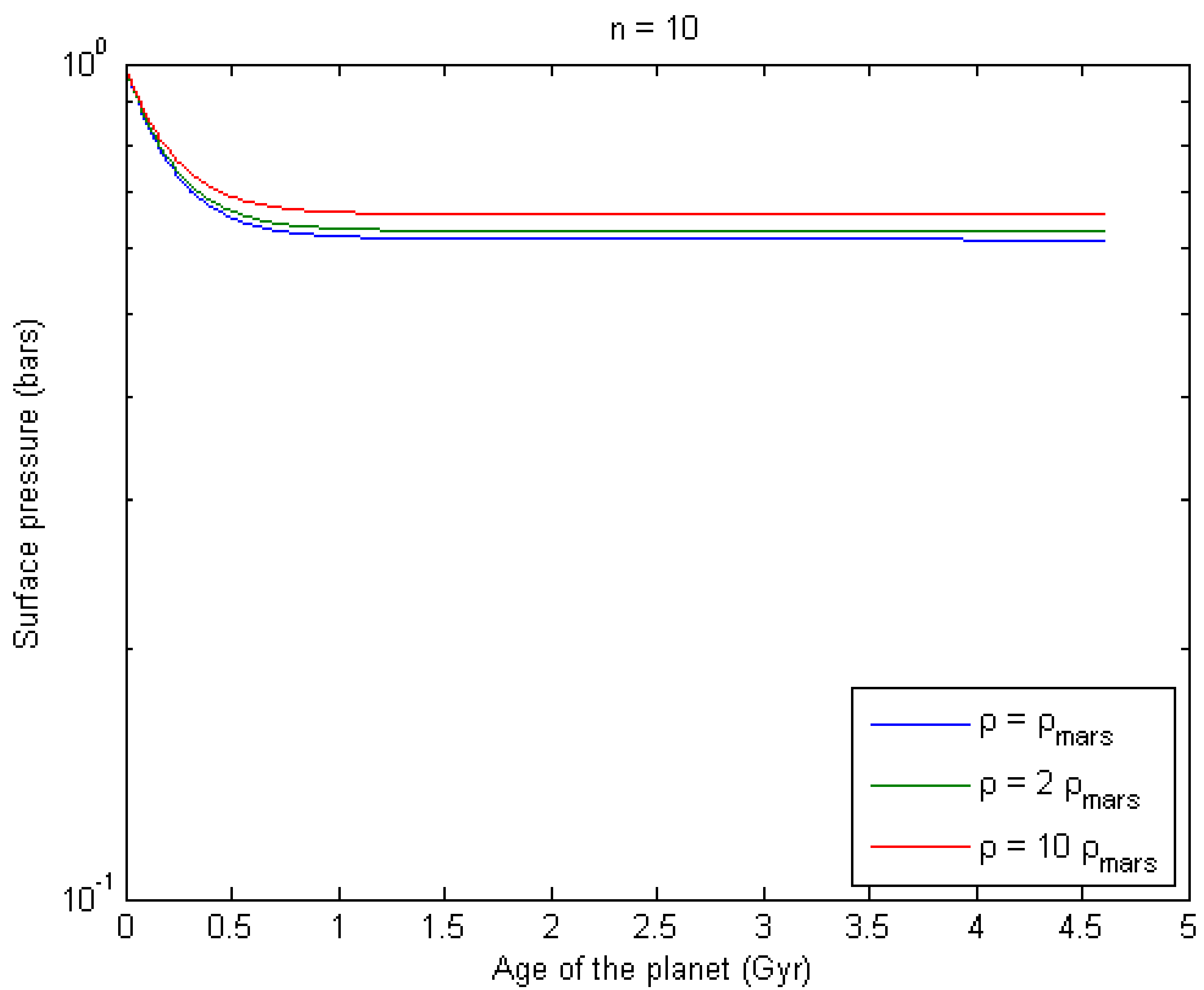
Effect of the planet radius *R*



For the same impact flux density, a greater planet radius leads to higher erosion rate.

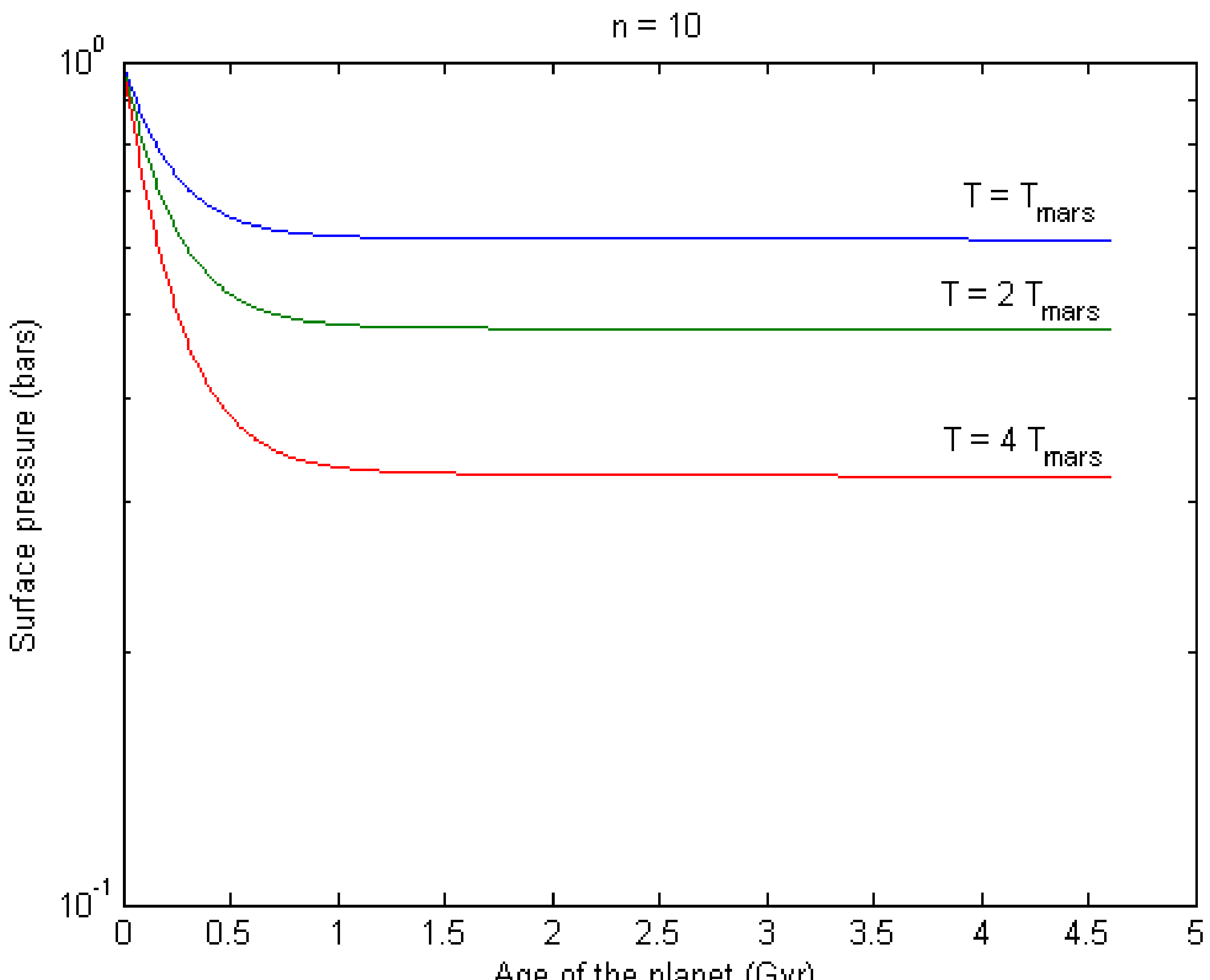
The density ρ of the planet is set as a constant: $\rho = \rho_{Mars}$

Effect of the gravity *g* (or planet density *ρ*)



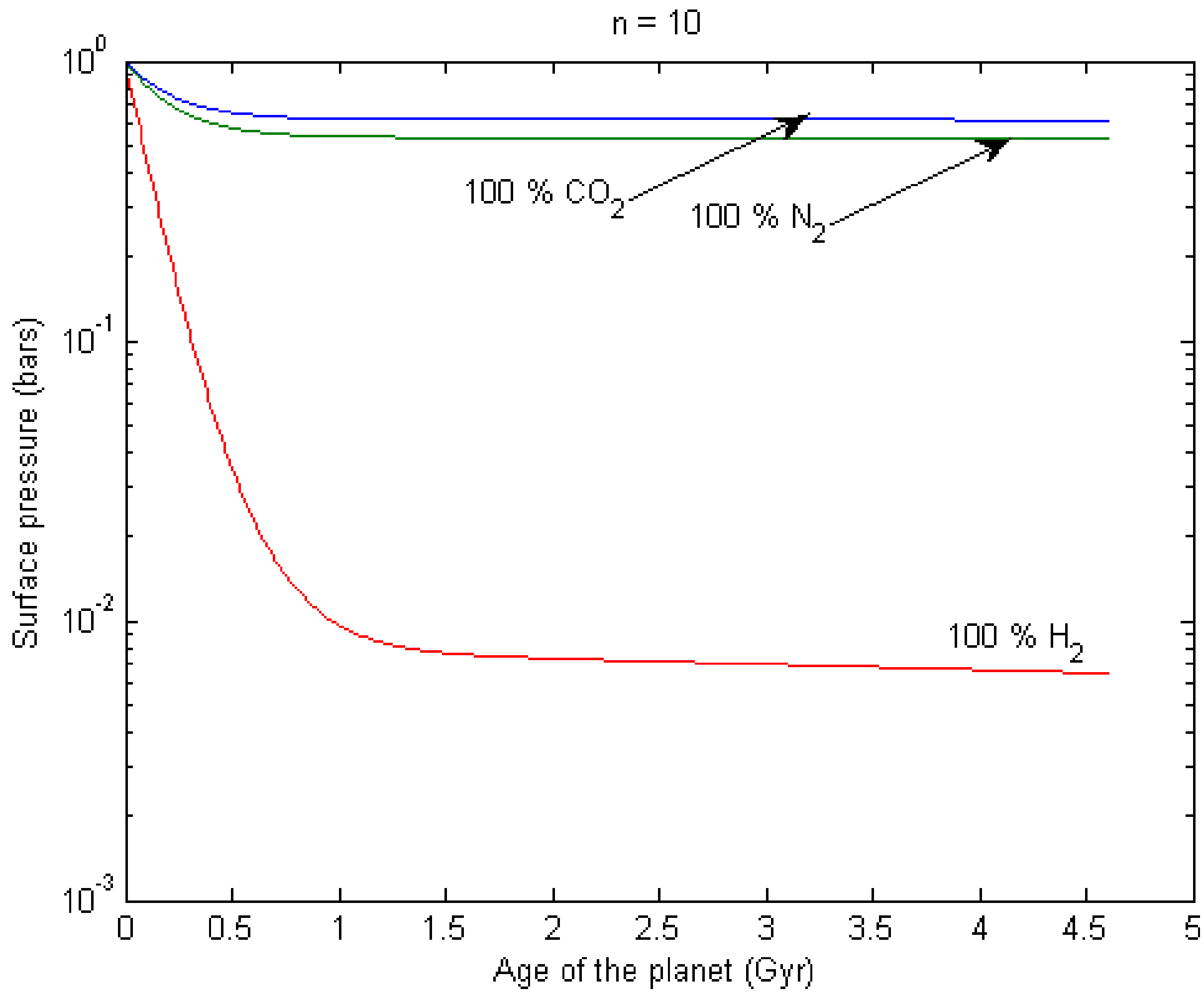
Planet density doesn't influence significantly impact erosion

Effect of *T*



Higher temperature means higher atmospheric scale height, which leads to higher erosion rate

Effect of the atmospheric composition



Primordial atmosphere of hydrogen may be totally escaped by impacts

$(\text{Parameter})/(\text{Parameter})_{ref} = 2$

$(\text{Parameters})_{ref}$ are the present Martian parameters with n = 10 and P(4.6 Gyr) = 1 bar

Parameters	$(dM_{esc}/dt/m_0)/(dM_{esc}/dt/m_0)_{ref}$*	$(\Delta m_{atm}/m_0)/(\Delta m_{atm}/m_0)_{ref}$**
$n = m_{crit}/m_{\tan}$	0.85***	0.38
P	0.73	0.83
R	1.25	1.31
g	0.97	0.96
T	1.28	1.35
m_{mol}	0.78	0.74

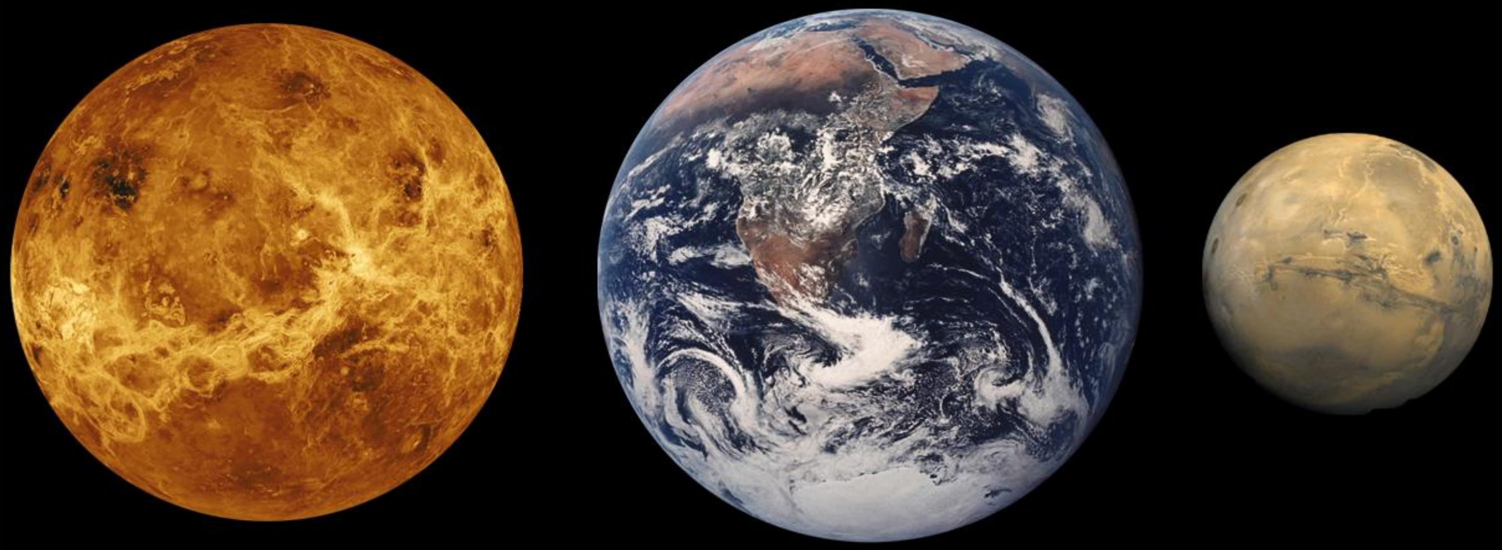
* $m_o = m_{atm}(t = 0)$

** $\Delta m_{atm} = m_{atm}(t = 0) - m_{atm}(t = 4.6\text{ Gyr})$

*** For the delivery rate, this ratio equals 1.70

Comparison between Mars, Earth and Venus

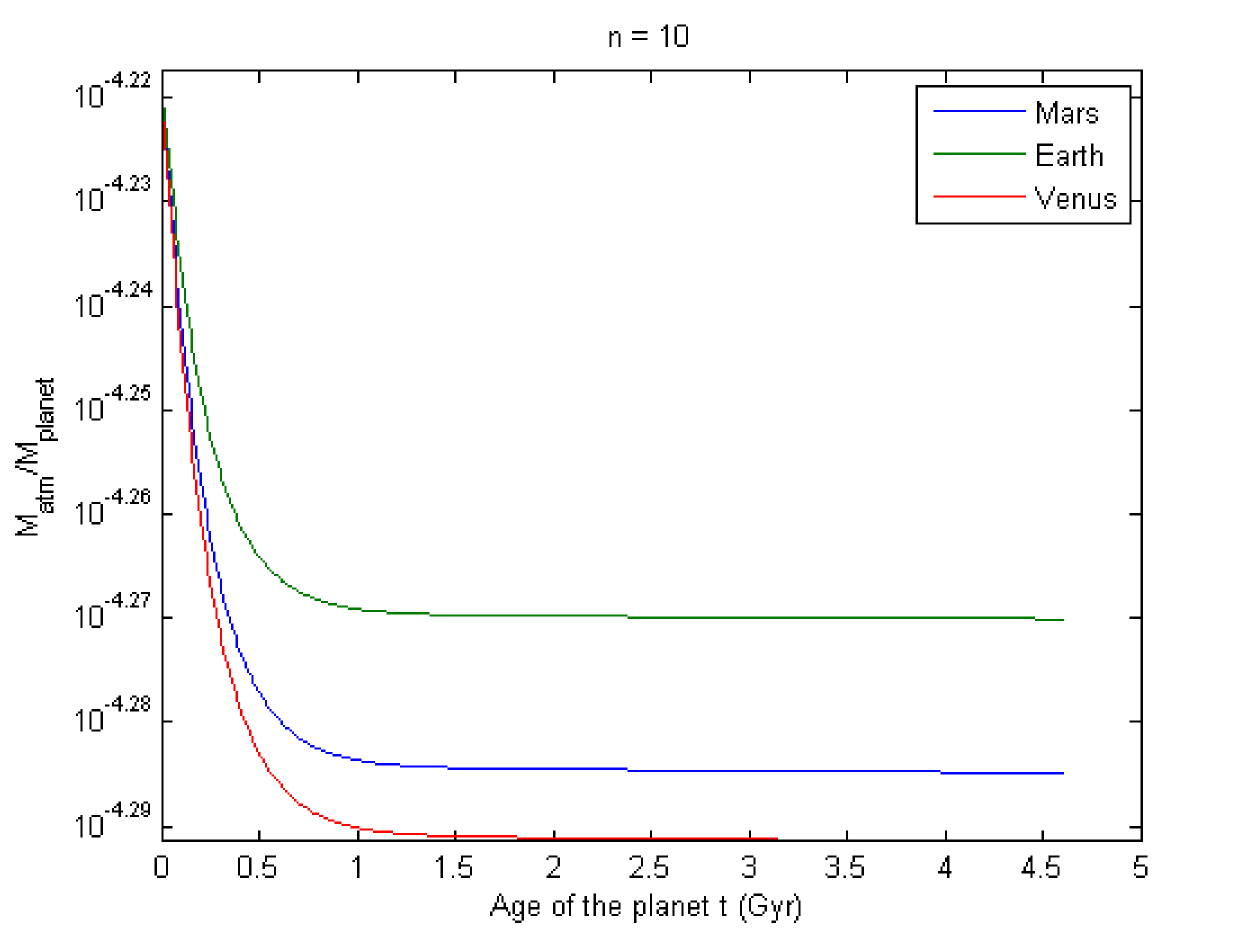
Planet	**Mars**	**Earth**	**Venus**
R (km)	3390	6369	6052
g (m/s^2)	3.72	9.81	8.87
$\mathbf{M_{planet}}$ (kg)	$6.4\ 10^{23}$	$5.96\ 10^{24}$	$4.86\ 10^{24}$
ρ ($10^3\ kg/m^3$)	3.93	5.51	5.24
T (K)	215	288	737
H (km)	10919	8427	15701
Molar mass (g/mol)	44.01	28.96	44.01



- We set the respective parameters of each planet so that the ratio of the initial atmospheric mass to the planet mass are the same, i.e.

$$\frac{M_{atm1}(t=0)}{M_{planet1}}=\frac{M_{atm2}(t=0)}{M_{planet2}}=\frac{M_{atm3}(t=0)}{M_{planet3}}$$

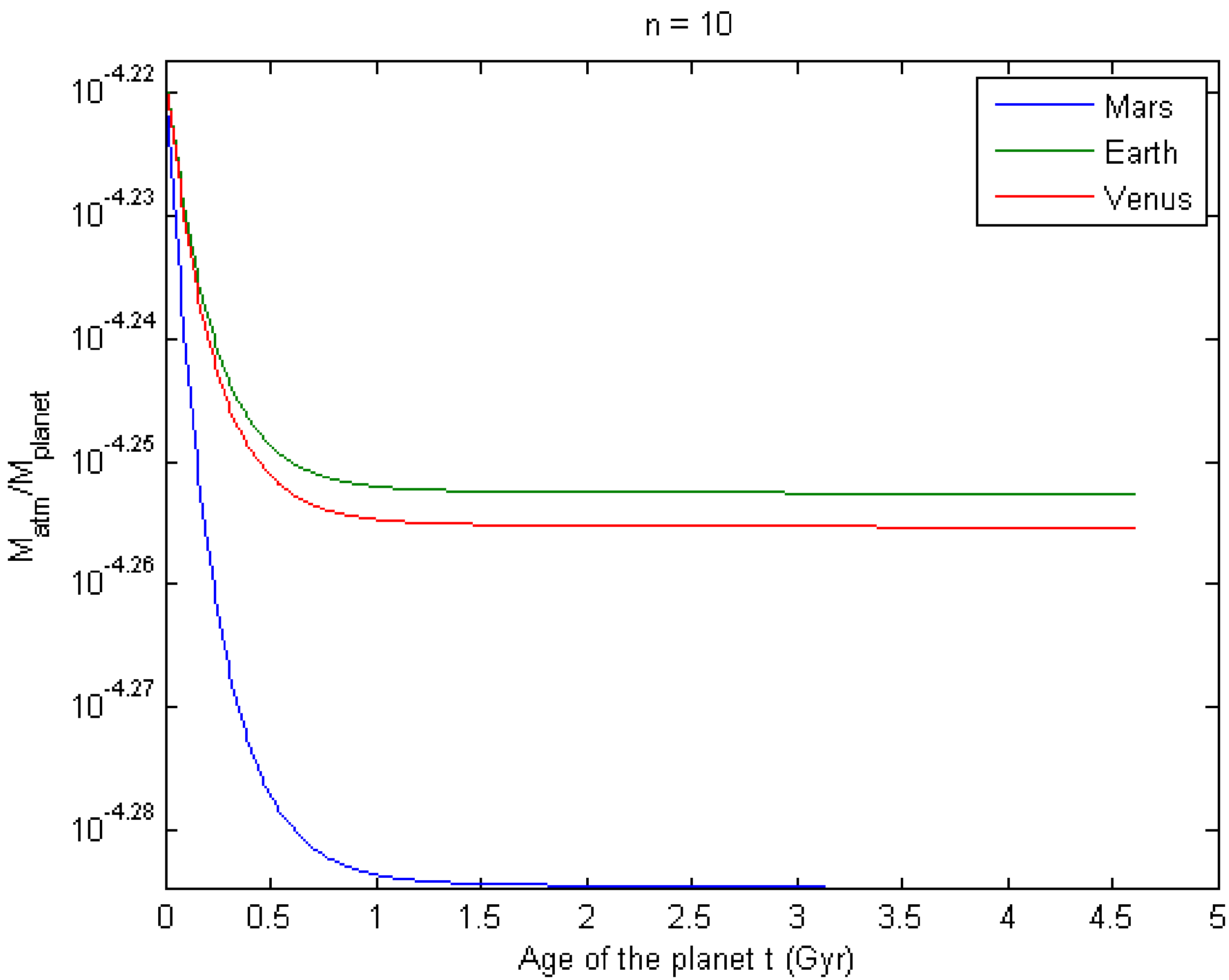
Comparison between Mars Earth and Venus



With the same initial atmospheric content, the atmospheric erosion for the three planets is of the same range.

For commodity, we use the same velocity and vaporization factor and the same impact flux density for the three planets. Here the initial pressure of Mars is equal to 10 bars

If the 3 planets have the same temperature and the same atmospheric composition



T = 215 K

m_{mol} = 44 g/mol

Smaller size and gravity of Mars means a higher erosion rate than the two other planets

Conclusion

- Elaboration of an analytical model
  - Set a global view of atmospheric evolution upon impacts
  - Reduction of physical parameters and time calculations
  - Adjustment of parameters from numerical simulation results
- The critical mass m_{crit} mainly determines the magnitude of impact erosion.
- Inclusion of impact velocity, vaporization and obliquity factors in the model decrease the variation of the atmospheric mass through the time.
- Impacts can hardly explain a large atmospheric escape on Mars unless specific conditions are met.

Conclusion

- Not only the mass and the size of the planet influence impact erosion,
- Initial surface pressure, atmospheric composition and planet temperature have also a significant effect.
- Erosion will be less efficient for larger and more massive planets with the same temperature, initial atmosphere inventory and atmospheric composition.
- Time variation of the planet temperature must be included in the model.

Thank you for your attention

Effect of the type of impactor

- Volatiles content: ~ 30 % for comets, ~ 1 % for asteroids)
- Erosion efficiency : comets are more efficient than asteroids (higher mean impact velocity)
- Part of comets in total impact flux on Mars still not well defined.
  - Estimation from Olsson-Steel (1987) :
    - Asteroids = 94 % of the total impact flux
    - Comets = 6 % of the total impact flux
- Calculations are done by averaging comets and asteroids contributions from their relative impact flux estimations.
- Mean volatiles content : $y_{imp} \approx 0.03$

Effect of velocity on atmospheric erosion

- Minimal velocity required for atmospheric erosion (Melosh and Vickery (1989), Zahnle (1993)) :
  - Dependence on:
    - Planet escape velocity;
    - Energy of vaporization of the impactor (13 MJ kg^{-1} for asteroids and 3 MJ kg^{-1} for comets);
    - Impactor and surface target materials (following whether it is a compact, a porous or a wet medium)
  - From calculations :
    - $v_{min} \approx$ 15 km/s for asteroids
    - $v_{min} \approx$ 12 km/s for comets
- Probability that $v \geq v_{min} = f_{vel} \approx 0.2$

Dependence on impact energy and velocity for impactor vaporization

- Vaporization of the impactor increases with velocity, and is dependant with impactor material;
  - Energy for impactor vaporization:
    - Asteroids ~ 13 MJ kg^{-1}
    - Comets ~ 3 MJ kg^{-1}
- Fraction of impactor vaporized averaged by velocity and mass range (from calculations) :
  - For $m < m_{crit}$: $f_{vap} \approx 0.69$
  - For $m \geq m_{crit}$, $v < v_{min}$: $g_{vap} \approx 0.56$

Effect of impact obliquity

- Oblique impacts more probable than vertical ones;
  - 50 % of impacts between 30 and 60°, maximum frequency at 45°(Pierazzo and Melosh, 2000);
- Oblique impacts more efficient on atmospheric erosion (showed from simulations);
  - Estimation of the mean efficiency from Svetsov (2007)
  - => $f_{obl} \approx 2.17$