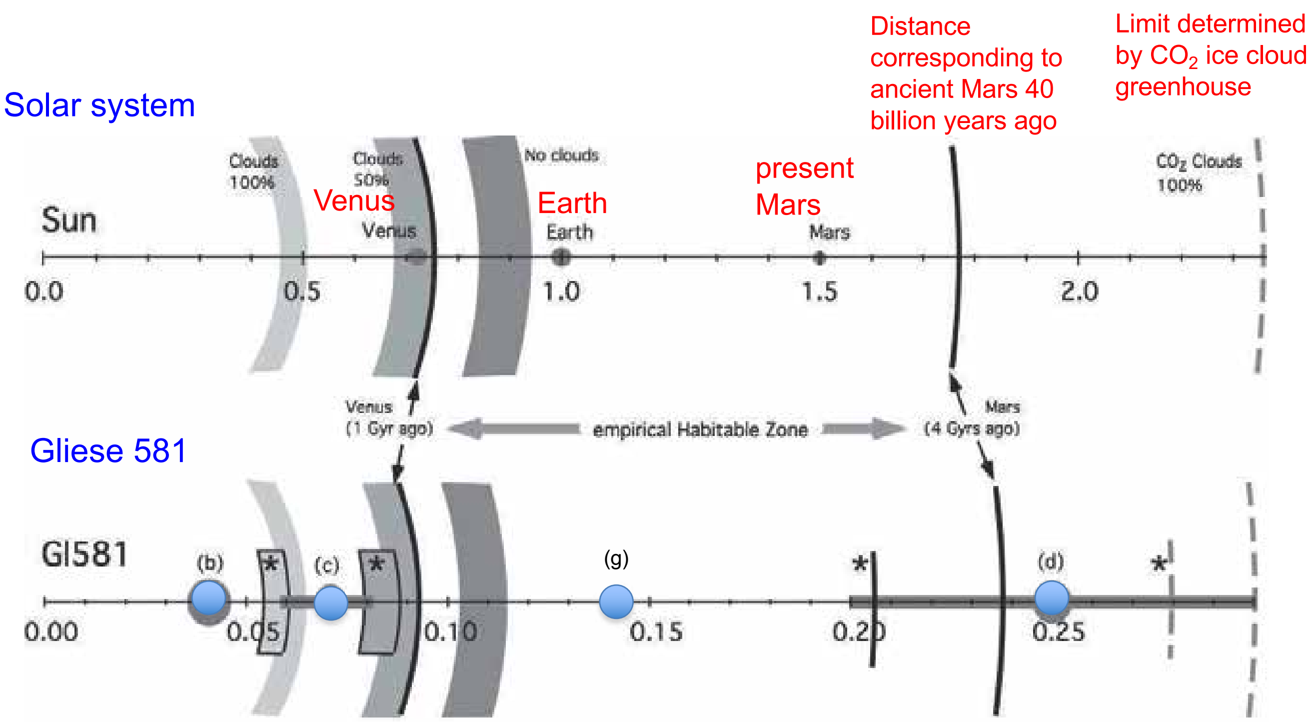
Planetary climate systems I

Diagrams depicting the habitable zone around the Sun and Gliese 581
(Selsis et al. 2007)



Inner edge of habitable zone

- Runaway greenhouse limit
  Complete evaporation of ocean
- Water loss limit
  Escape of water/hydrogen to space

→ How/when did **Venus** lose water and get the thick CO_2 atmosphere ?

Outer edge of habitable zone

- Greenhouse effect by CO_2 and other gases
- Enhancement of cloud albedo in cold, massive atmospheres

→ How/when did **Mars** lose thick atmosphere and freeze ?

Runaway greenhouse effect

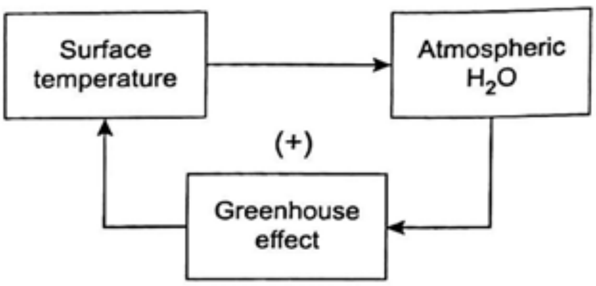
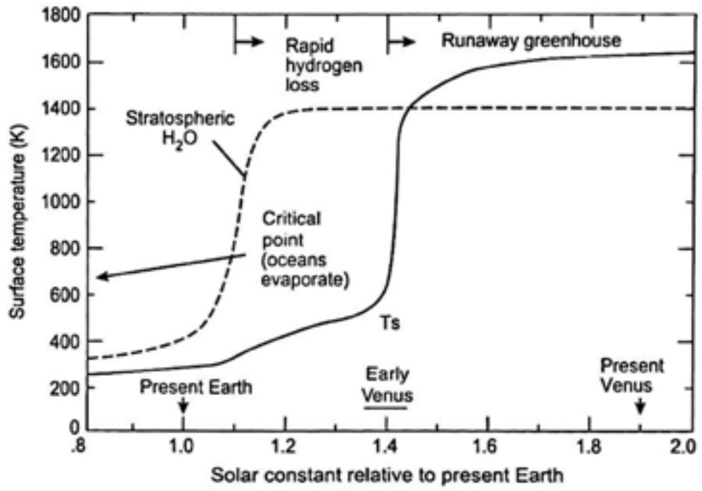


Figure 13.7 Diagram illustrating the positive feedback loop caused by water vapor.

Catling & Kasting (2017)

- An increase in surface temperature causes an increase in atmospheric water vapor, which then increases the greenhouse effect, causing a further increase in surface temperature. (Positive feedback)
- More precisely, a wet atmosphere makes spectral atmospheric windows close up, and thermal infrared radiation cannot escape to cool the planet. If the absorbed solar flux exceeds the outgoing infrared limit, the surface water totally evaporates and the planet's surface heats up.

Runaway/moist greenhouse of early Venus



Albedo = 0.22 is assumed

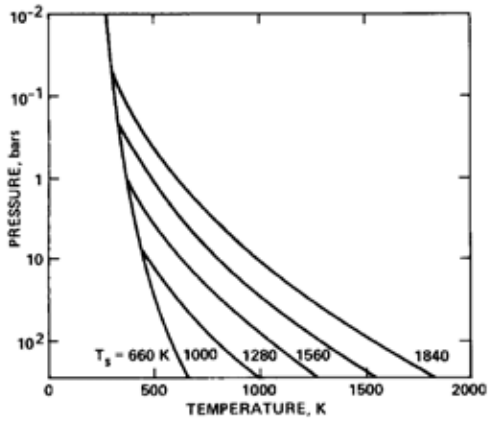


FIG. 6. Temperature versus pressure for selected runaway greenhouse atmospheres. The lower portions of the curves represent dry adiabats. The curve(s) to which they are all joined are moist pseudoadiabats, which are very nearly equivalent to the saturation vapor pressure curve for water.

Kasting 1988; Catling & Kasting 2017

Atmospheric structure in moist greenhouse
(Kasting 1988)

High H_2O mixing ratio in the upper atmosphere
→ Rapid hydrogen escape

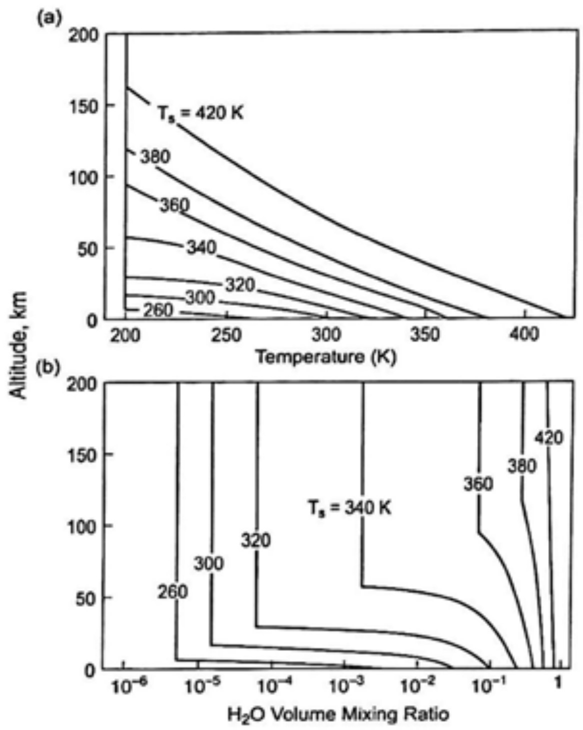


Figure 13.13 Vertical profiles of temperature (a) and water vapor mixing ratio (b) for atmospheres with different surface temperatures, T_s. A 1-bar N_2/O_2 background atmosphere is assumed. (From Kasting, (1988). Reproduced with permission from Elsevier. Copyright 1988.)

Earth's CO_2 cycle (carbon cycle)

- CO_2 dissolves in the ocean and buried in the crust.
- CO_2 buffer may have stabilized the Earth's climate.

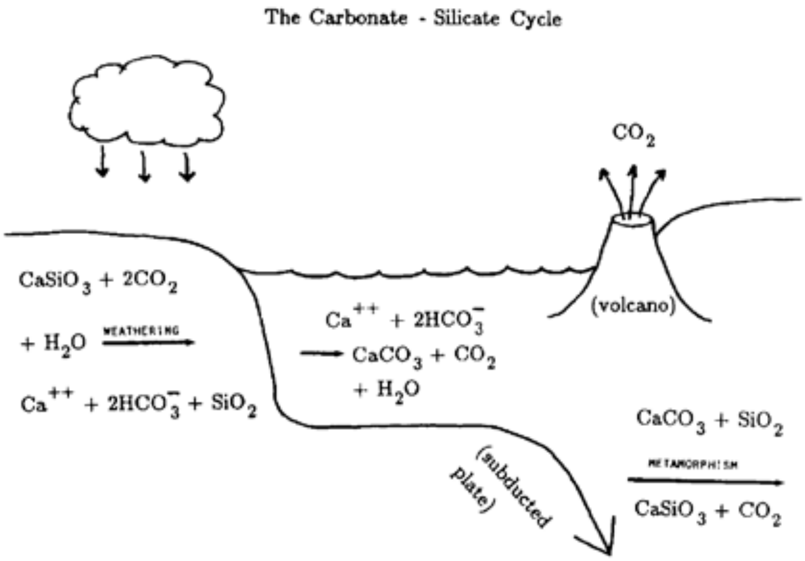
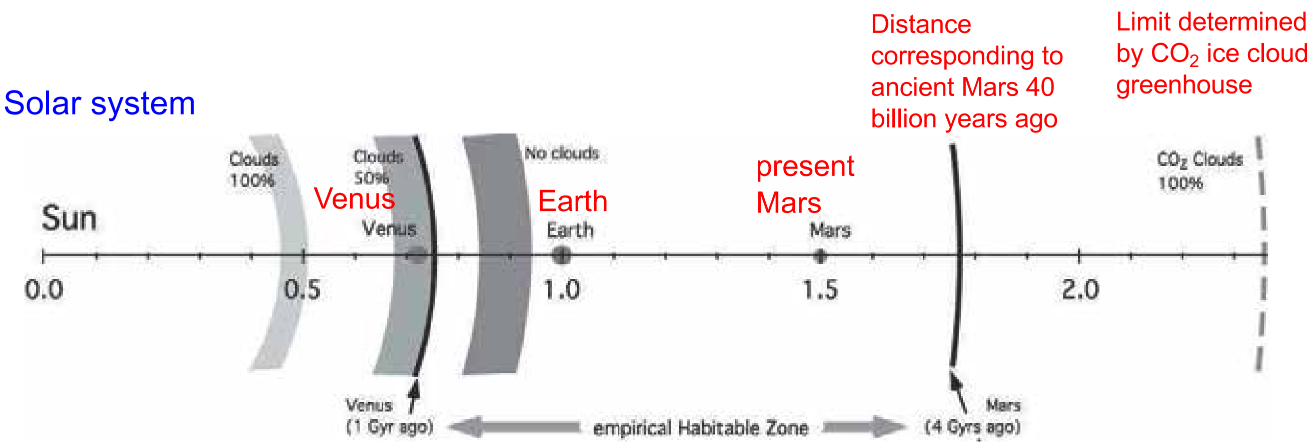
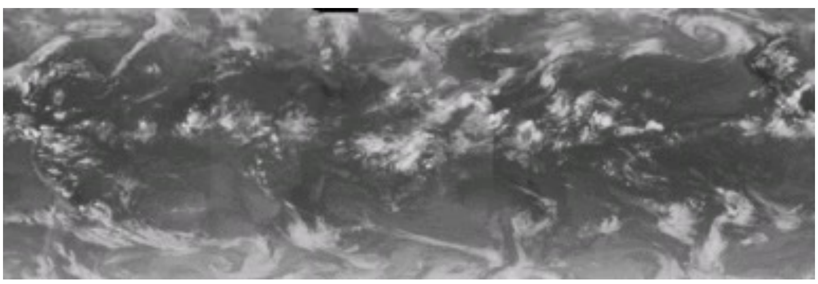


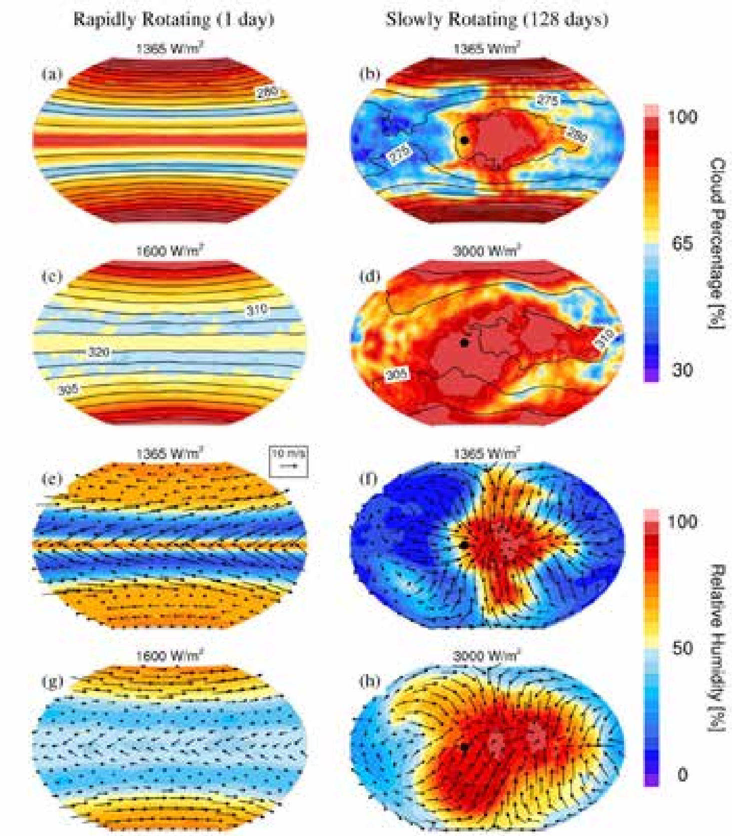
Fig. 5. A schematic representation of chemical weathering reactions of terrestrial continental silicate rocks by CO_2 dissolved in water, the subduction of the resultant carbonate rocks, their thermal decomposition at depth, and the outgassing of the released CO_2.

Cloud cover and habitable zone

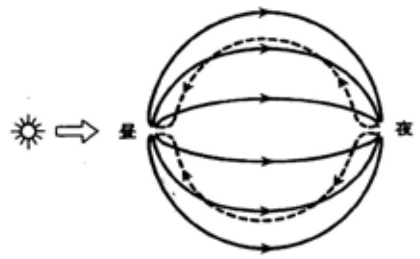




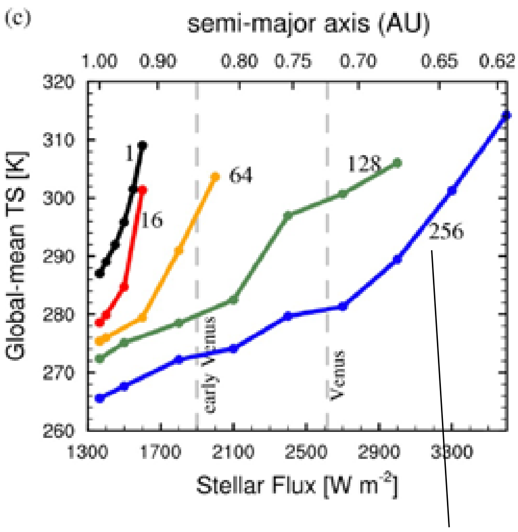
STRONG DEPENDENCE OF THE INNER EDGE OF THE HABITABLE ZONE ON PLANETARY ROTATION RATE (Yang et al. 2014, ApJ)



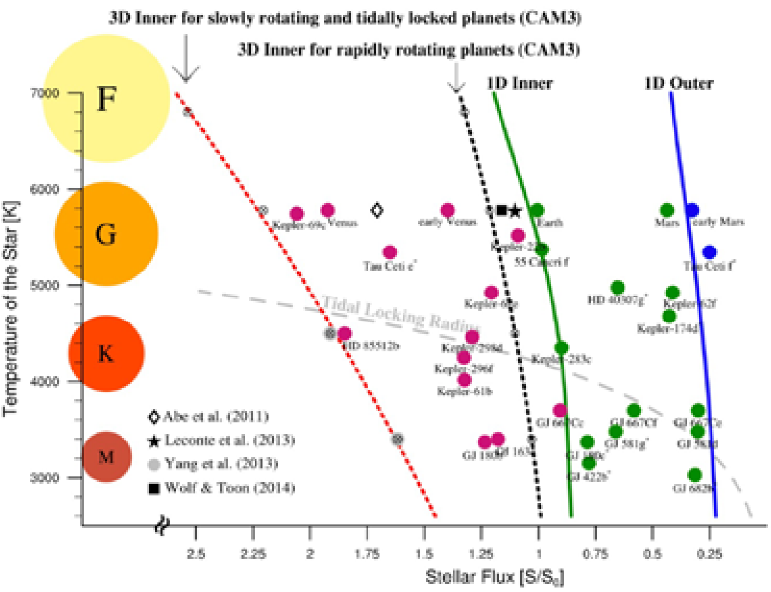
- Atmospheric circulation affects the albedo
- subsolar-to-antisolar circulation on slow rotators can generate thick clouds on the illuminated side



subsolar-to-antisolar circulation (Y. Matsuda)



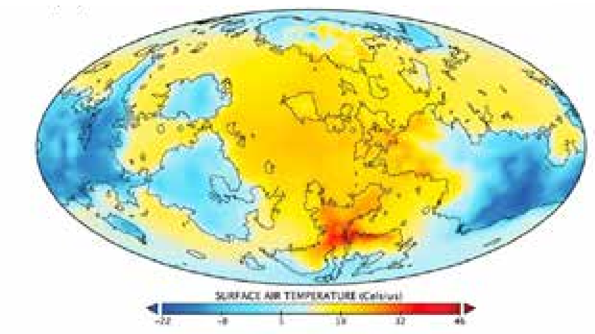
rotation period



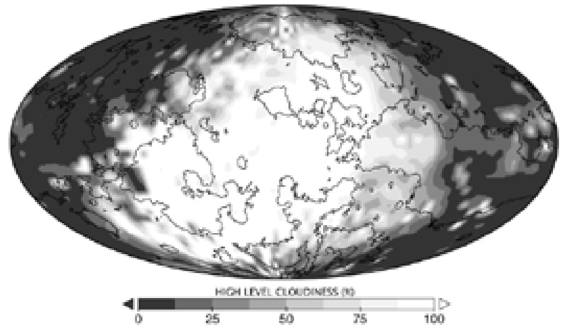
“Was Venus the first habitable world of our solar system?“
Way et al. (2016)

(Sim A) Solar flux: 1.46 x Earth, Rot. period: Modern Venus

Surface air temperature

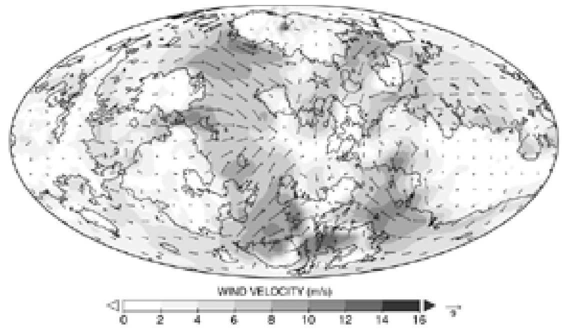


Cloudiness



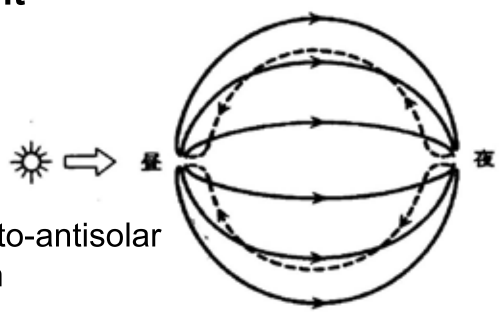
- Global mean surface air temperature of 11° C despite an incident solar flux at Venus’s orbit ~46% higher than that received by modern Earth
- This is the result of this world’s slow rotation which generates a strong circulation with rising motion and accompanying high thick clouds on the dayside that reflect a substantial fraction of the incident sunlight.

Surface level winds



Rotation period >> Radiative time constant

(Venus: 243 days) (Earth: 100 days)



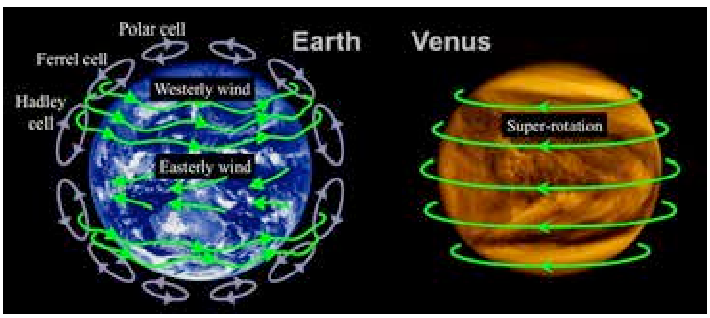
Subsolar-to-antisolar circulation

（松田 2000）

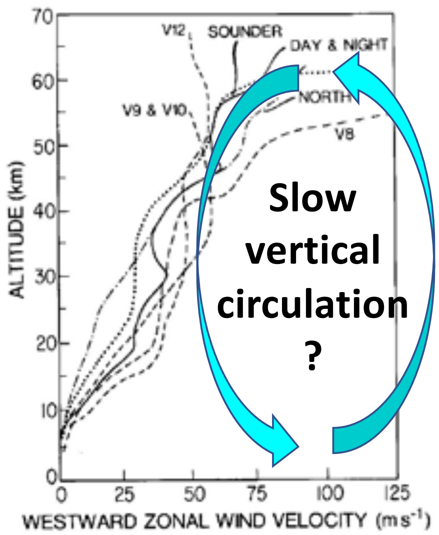
Rotation period << Radiative time constant

(Venus: 243 days) (Venus: 50 years)

Axi-symmetric circulation



Conditions for superrotation

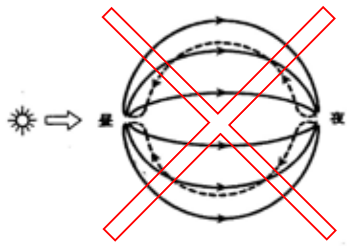


✓ Slow planetary rotation

- On slow-rotating planets, atmospheric waves caused by planetary-scale dynamical instabilities unknown in Earth's meteorology lead to an acceleration of the atmosphere.
(When the planet rotates rapidly, atmospheric waves accelerate the atmosphere at high latitudes like the Earth)

✓ Long radiative relaxation time

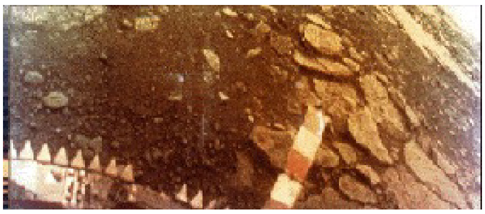
- A dense atmosphere has a large heat capacity and a longer relaxation time. The vertical circulation slows down, making it difficult to smooth out the velocity change with altitude and making it easier to maintain the superrotation.

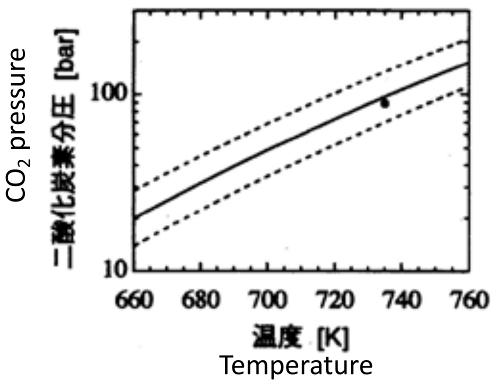


Carbonate buffer hypothesis

The observed surface condition coincides with the CO_2 equilibrium partial pressure over the calcite–quartz–wollastonite assemblage. (Urey 1952)

$$\underset{\text{(calcite)}}{CaCO_3} + \underset{\text{(quartz)}}{SiO_2} = \underset{\text{(wollastonite)}}{CaSiO_3} + CO_2$$





(はしもと・阿部、1998)

(Stabilization?)
When volcanism increases atmospheric CO_2, carbonate formation is enhanced due to the increases in CO_2 pressure, leading to the removal of CO_2.

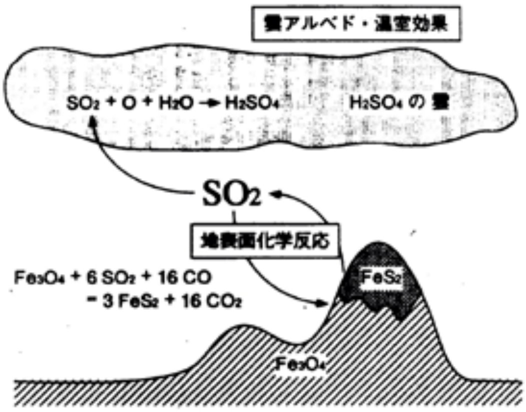
(Destabilization?)
An increase in CO_2 leads to an increase in temperature via the greenhouse effect, which enhances carbonate decomposition. The positive feedback destabilizes the system. (Hashimoto et al. 1997)

Stabilization of Venus' climate by a chemical-albedo feedback

(Hashimoto & Abe, 2000)

The atmospheric SO_2 abundance might be controlled by the equilibria with the pyrite-magnetite assemblage.

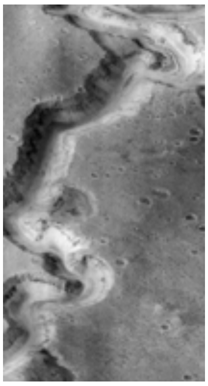
$$\underset{\text{(pyrite)}}{3\,FeS_2} + 16\,CO_2(\text{gas}) = \underset{\text{(magnetite)}}{Fe_3O_4} + 6\,SO_2(\text{gas}) + 16\,CO(\text{gas})$$



(はしもと･阿部、1998)

A decrease in surface temperature removes some atmospheric SO_2. This reduces the photochemical production of H_2SO_4 clouds, leading to a decrease in the cloud albedo and a resultant increase in the temperature. This negative feedback stabilizes the system. (Hashimoto & Abe, 2000)

Ancient Martian climate: clue to the outer edge of the habitable zone



Valley network distribution (Ramirez & Craddock 2018)

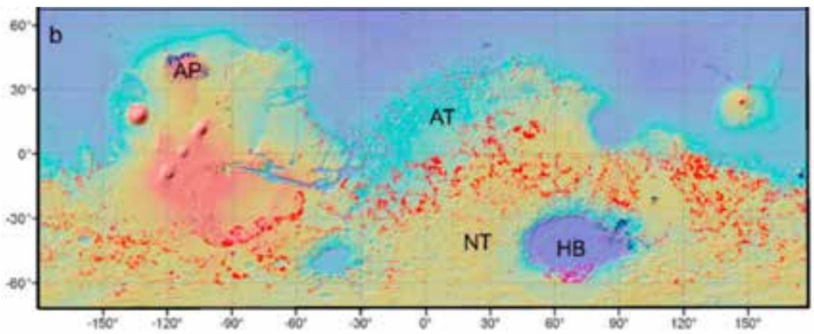


Table 1 Martian isotope ratios and atmospheric loss*

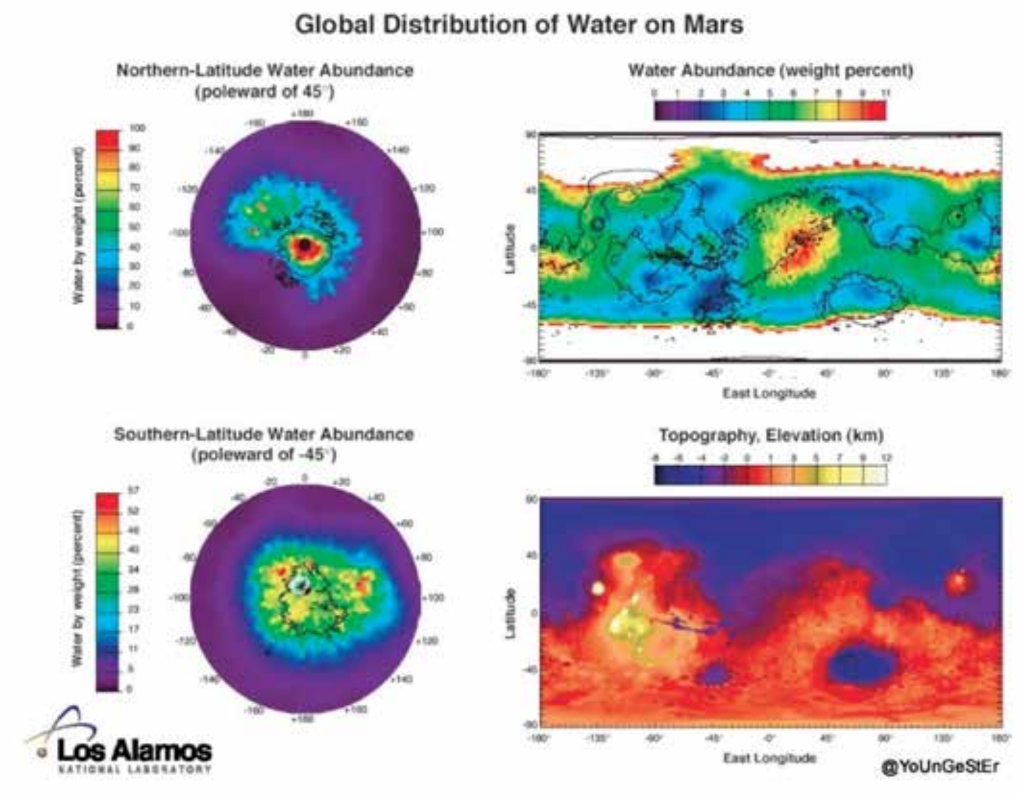
Isotope ratio	Measured value†	Amount lost to space (%)‡
D/H	5	~60–74
$^{38}Ar/^{36}Ar$	1.3	~50–90
$^{13}C/^{12}C$	1.05–1.07	~50–90
$^{15}N/^{14}N$	1.7	~90
$^{18}O/^{16}O$	1.025	~25–50

*Values taken from refs 57–59, 62, 77 and 78, and references therein.
†Value estimated, observed or derived for martian atmosphere relative to terrestrial.
‡Calculated assuming Rayleigh fractionation. D/H range includes uncertainty in escape processes. Other ranges are based on uncertain timing of outgassing relative to escape.

Jakosky & Phillips (2001)

Subsurface water on Mars

Mars Odyssey Neutron Spectrometer (NS) and High-Energy Neutron Detector (HEND)



Three possibilities

- The greenhouse effect was bigger in the past because of a thicker atmosphere that contained higher concentrations of greenhouse gases.

- The fluvial features were caused by many temporary warm episodes associated with impacts. The energy released from impacts would have heated the surface of early Mars, vaporized ice into steam, and produced rainfall that eroded river valleys.

- The fluvial features were produced in a rather cold environment. Fluvial erosion might be produced in response to fortuitous combinations of orbital parameters, allowing localized snowmelt. Brines can exist as liquids at temperatures below 273 K.

(Catling and Kasting 2017)

Possible evolution of Martian climate

Chassefiere et al. (2007)

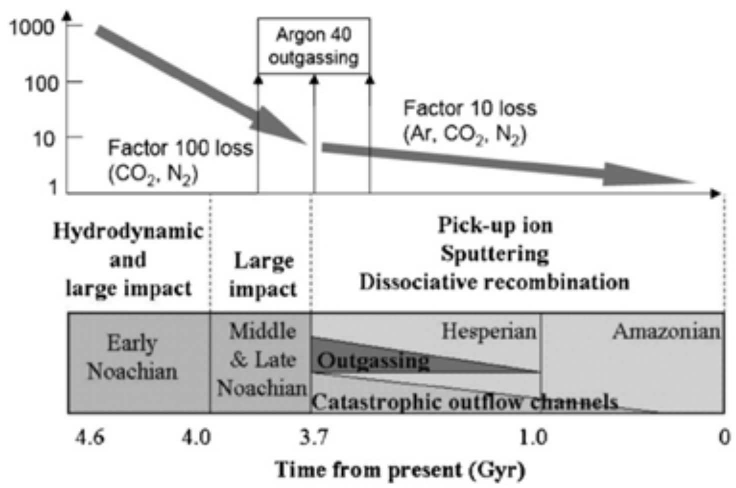
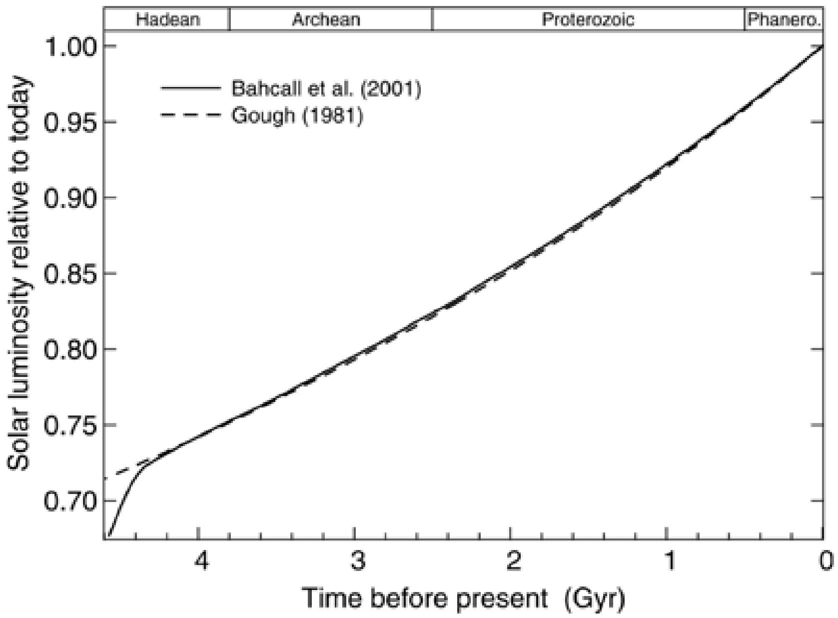


Fig. 3. Schematic chronology of atmospheric escape on Mars. A factor of 100 loss is expected to have occurred during the heavy bombardment period, by impact loss and possibly hydrodynamic escape. In the subsequent period, by using radiogenic argon as a tracer of sputtering escape, an additional loss by a typical factor of 10 occurred.

Long-term trend of solar luminosity



Feulner (2012)

Theoretical models for the stellar interior show that the luminosity of the Sun had to change over time, with the young Sun being considerably less luminous than today.

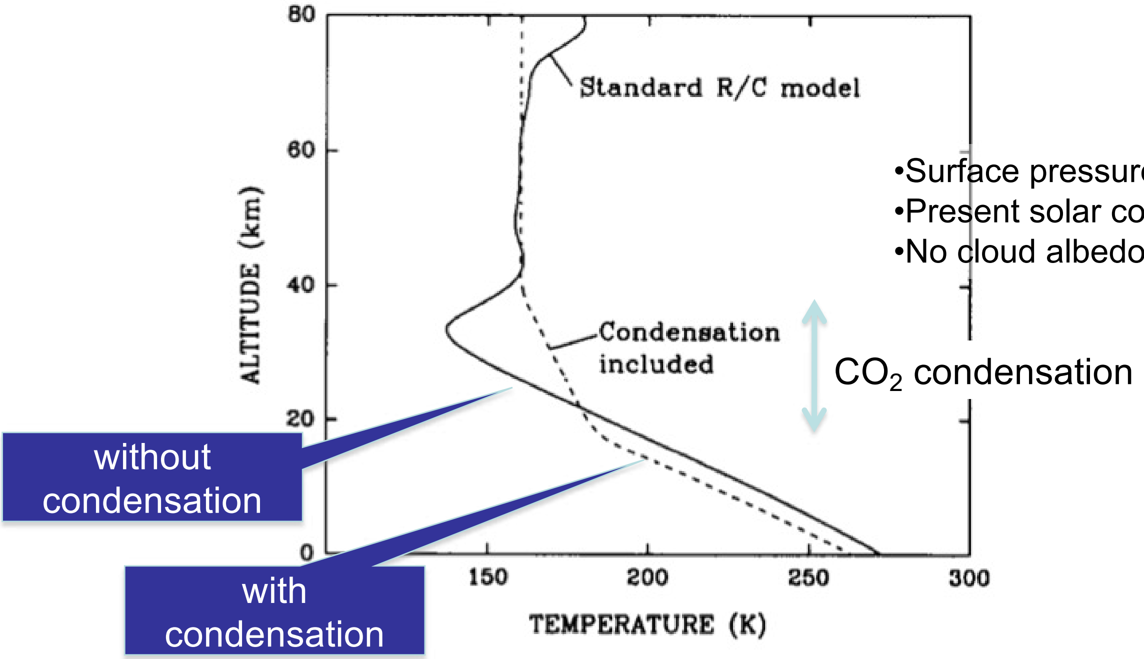
Can the ancient Mars be warm with CO_2 greenhouse effect ?

Kasting (1991)

- The ancient Sun was 25% dimmer than the present
- CO_2 greenhouse has been expected to warm the ancient Mars

- Warm lower atmosphere causes convection, which induces condensation of CO_2 in the upper atmosphere. The associated latent heating raises the temperature at upper levels, and at the same time cools the lower atmosphere so that the net energy balance is maintained.

Effect of CO_2 condensation



- Surface pressure of 2 bar
- Present solar constant
- No cloud albedo

→When the solar constant is less than 86% of the present value, the surface temperature cannot exceed 273 K.

CO_2 ice clouds traveling above the Mars Curiosity rover on December 12th, 2021

Greenhouse effect due to CO_2 ice clouds

Forget & Pierrehumbert (1997)

- CO_2 ice clouds scatter infrared radiation emitted from the surface, thereby causing greenhouse effect.
- CO_2 ice clouds also have cooling effect via increase of the planetary albedo. However, thick CO_2 atmosphere itself has a high albedo even when no cloud exists, and thus the effect of cloud albedo is relatively minor.
  - For example, cloud-free 2-bar CO_2 atmosphere has an albedo of 0.38. Addition of CO_2 clouds increases the albedo to 0.65, thereby reducing the solar absorption by 40%. At the same time the clouds absorbs 60% of the infrared radiation emitted from the surface.

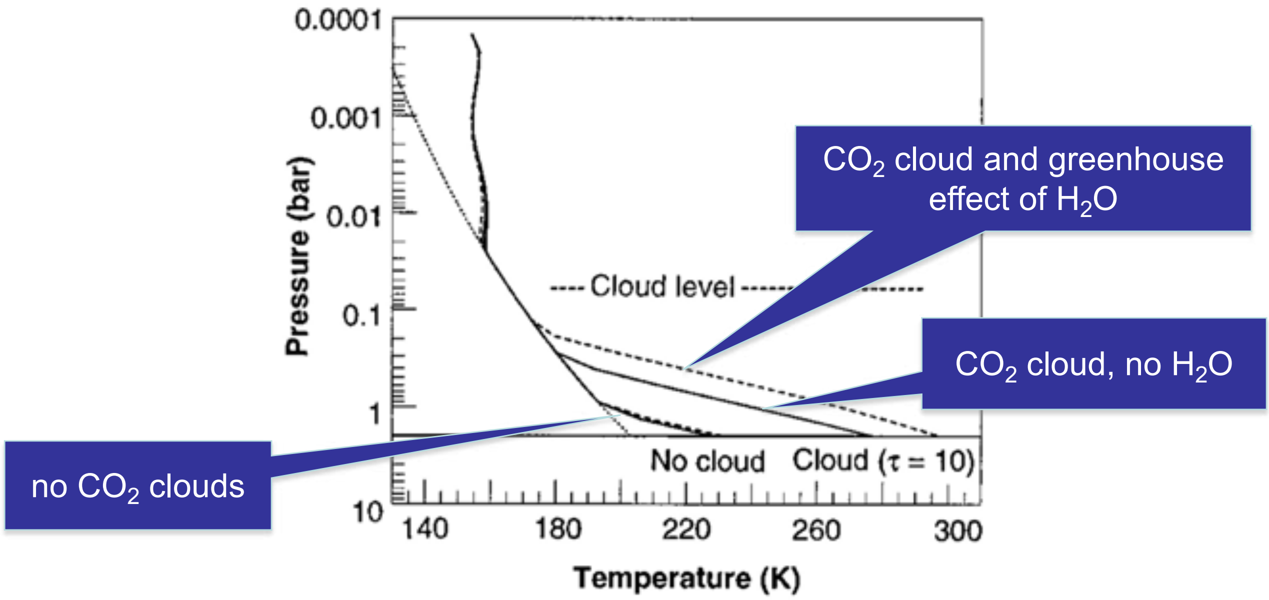


Fig. 2. Calculated mean temperature profiles for a 2-bar CO_2 atmosphere, assuming a 25% reduced solar luminosity corresponding to the early Mars conditions. The effect of the cloud from Fig. 1 (τ = 10, r = 10 μm) is shown in the cases of a wet (fully saturated troposphere; dashed curves) and a dry (solid curves) atmosphere. The dotted curve shows the CO_2 condensation temperature profile.

3D modelling of the early Martian climate under a denser CO_2 atmosphere: Temperatures and CO_2 ice clouds

(Forget et al. 2013)

- 3D global climate simulations of the early martian climate performed assuming a faint young Sun and a CO_2 atmosphere with surface pressure between 0.1 and 7 bars
- Previous studies had suggested that CO_2 ice clouds could have warmed the planet thanks to their scattering greenhouse effect. However, even assuming parameters that maximize this effect, it does not exceed +15 K. As a result, a CO_2 atmosphere could not have raised the annual mean temperature above 0° C anywhere on the planet.
- This is consistent with a cold early Mars scenario in which nonclimatic mechanisms must occur to explain the evidence for liquid water.

Mean surface temperature vs. Surface pressure (column CO_2 amount)

- Surface temperature increases up to 2 bar. Above 2– 3 bar, bar Rayleigh scattering by CO_2 gas more than compensates for the increased thermal infrared opacity of the atmosphere. Increasing the atmospheric thickness does not result in an increase of the mean surface temperature.
- Taking into account the radiative effect of CO_2 ice clouds results in a global warming of the surface by more than 10 K resulting from the CO_2 ice cloud scattering greenhouse effect.
- The collapse of the atmosphere into permanent CO_2 ice caps is predicted for pressures higher than 3 bar.

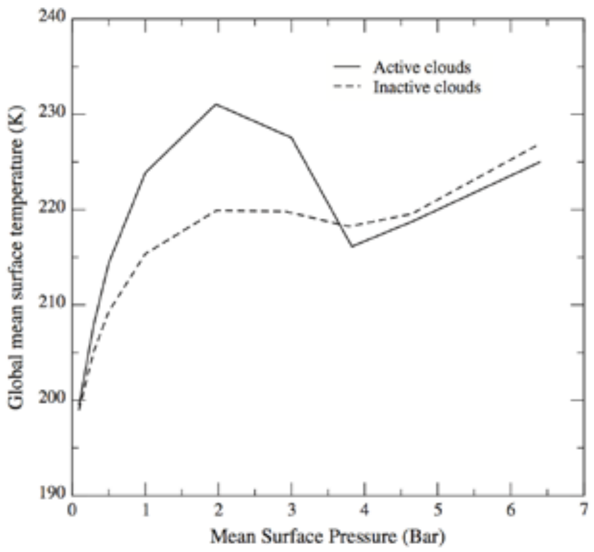
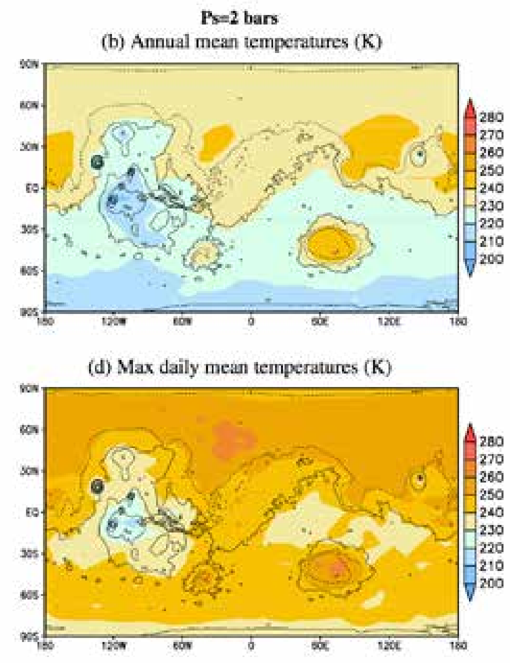


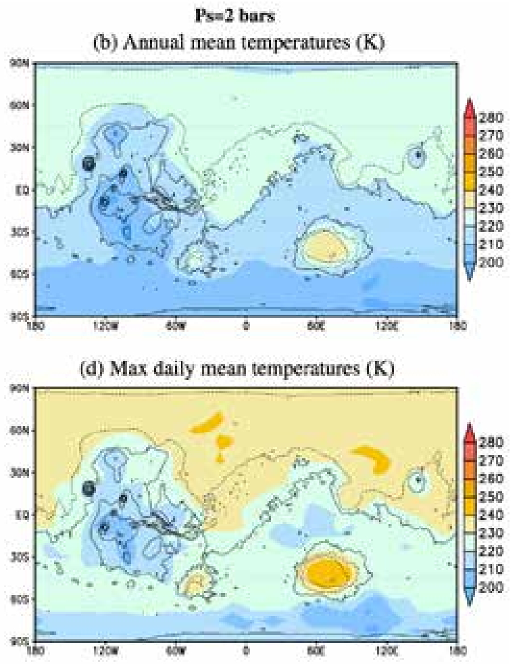
Fig. 1. Global mean annual mean surface temperature (K) as a function of surface pressure in our baseline simulations (obliquity = 25°, [CCN] = 10^5 kg^{-1}, circular orbit) with and without radiatively active CO_2 ice clouds.

Surface temperature

for present-day ground albedo of 0.22

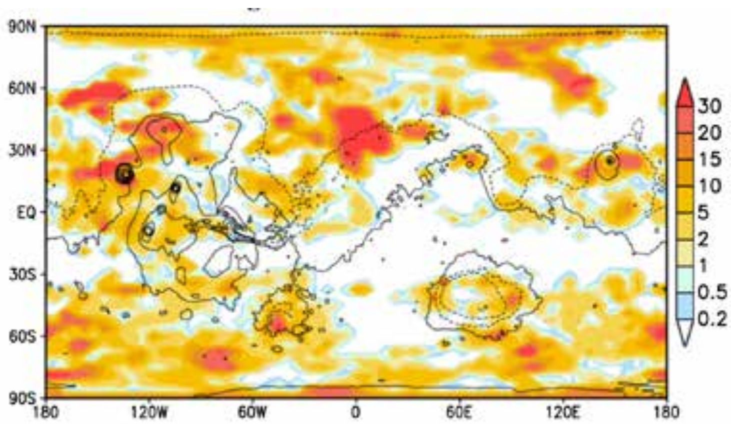


for ice-covered ground albedo of 0.4



Annual mean surface temperatures are always significantly below 0°C.

An example of the instantaneous CO_2 ice clouds coverage for a mean surface pressure 2 bar



- CO_2 ice clouds cover a major part of the planet but not all. Their behavior is controlled by a combination of large scale ascents and descents of air, stationary and travelling waves, and resolved gravity waves related to the topography.
- The mean cloud warming remains lower than 15 K because of the partial cloud coverage and the limited cloud optical depth.

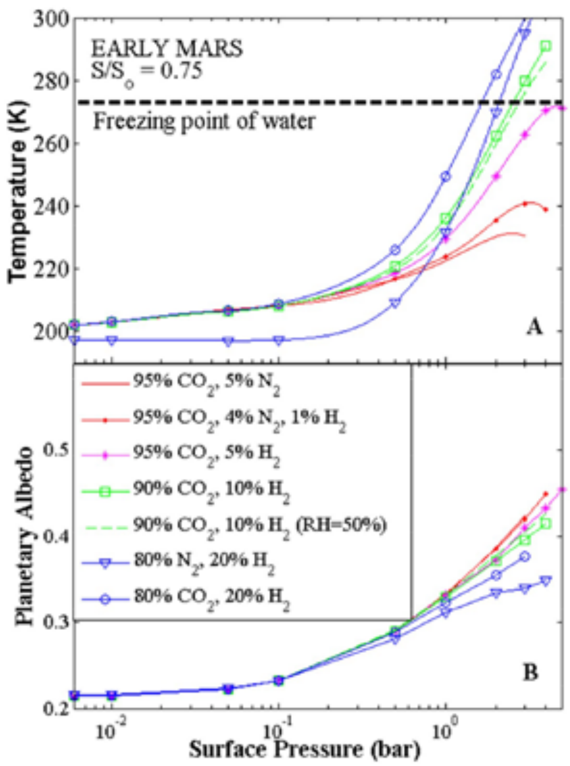
Other greenhouse gases?

- Ammonia (NH_3) : 500 ppm of NH_3 in a 4–5 bar CO_2 atmosphere could raise surface temperatures to 273 K. However, NH_3 is photochemically unstable and would require shielding to survive.
- Methane (CH_4) : even at concentrations of 500 ppm CH_4 does not significantly boost the greenhouse effect of a pure CO_2/H_2O atmosphere. CH_4 would require strong sources to sustain the above concentrations.
- Sulfur dioxide (SO_2) & hydrogen sulfide (H_2S) : An obvious source for these gases is volcanic activity. SO_2 needs to build up to concentrations around the 10 ppm level or higher. SO_2 readily converts to aerosols, and these aerosols should have a net cooling effect on surface temperatures. Furthermore, SO_2 is highly soluble and will washout quickly when conditions become warm enough for rainfall.

(Forget et al. 2013)

H_2–CO_2 greenhouse ?

(Ramirez et al. 2014)



- Collision-induced absorption band of H_2 caused by the foreign-broadening by the background CO_2 atmosphere
- Reduced mantle conditions could have favored enhanced outgassing of H_2 over long timescales. Hydrogen is continuously replenished by volcanism that offsets losses to space.
- An atmosphere containing -4 bar of CO_2 and 5% H_2 would have brought Mars' average surface temperature up to the freezing point of water.

(Ramirez & Kaltenegger 2017)

Outer edge of the habitable zone

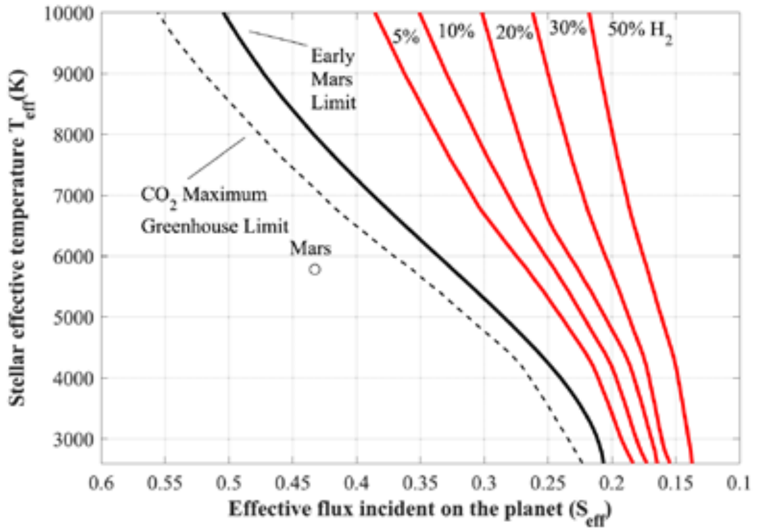


Figure 1. Effective stellar temperature vs. incident stellar flux (S_{eff}) for the outer edge. The CO_2 maximum greenhouse limit (dashed) is shown along with the empirical outer edge (solid black) and outer edge limits containing 5%, 10%, 20%, 30%, and 50% H_2 (red solid).

The model atmospheres contain 1 bar of N_2, H_2 with concentrations of 1%, 5%, 10%, 20%, 30% and 50%, and CO_2 with the saturation partial pressure at 273 K.

Diagrams depicting the habitable zone around the Sun and Gliese 581 (Selsis et al. 2007)