宇宙惑星環境学

担当教員：今村 Imamura・吉川 Yoshikawa・吉岡 Yoshioka

惑星環境科学の問題意識
放射輸送と大気の鉛直構造
大気化学とエアロゾル
大気流出と大気進化
大気力学
惑星大気循環論
太陽-惑星系の共進化
火星と金星の気候形成
巨大ガス惑星
系外惑星の大気
太陽風と惑星プラズマ
太陽系探査

Score will be evaluated based on papers (reports).

The theme for the paper will be given at the end of this course.

Dates of lectures: 10/7, 10/14, 10/21, 10/28, 11/4, 11/11, 11/18, 11/25, 12/2, 12/9, 12/16, 12/23, 1/13, 1/20, 1/27

Lecture material will be linked from ITC-LMS.
Videos will also become available.

Syukuro Manabe
Facts

Ill. Niklas Elmehed © Nobel Prize Outreach

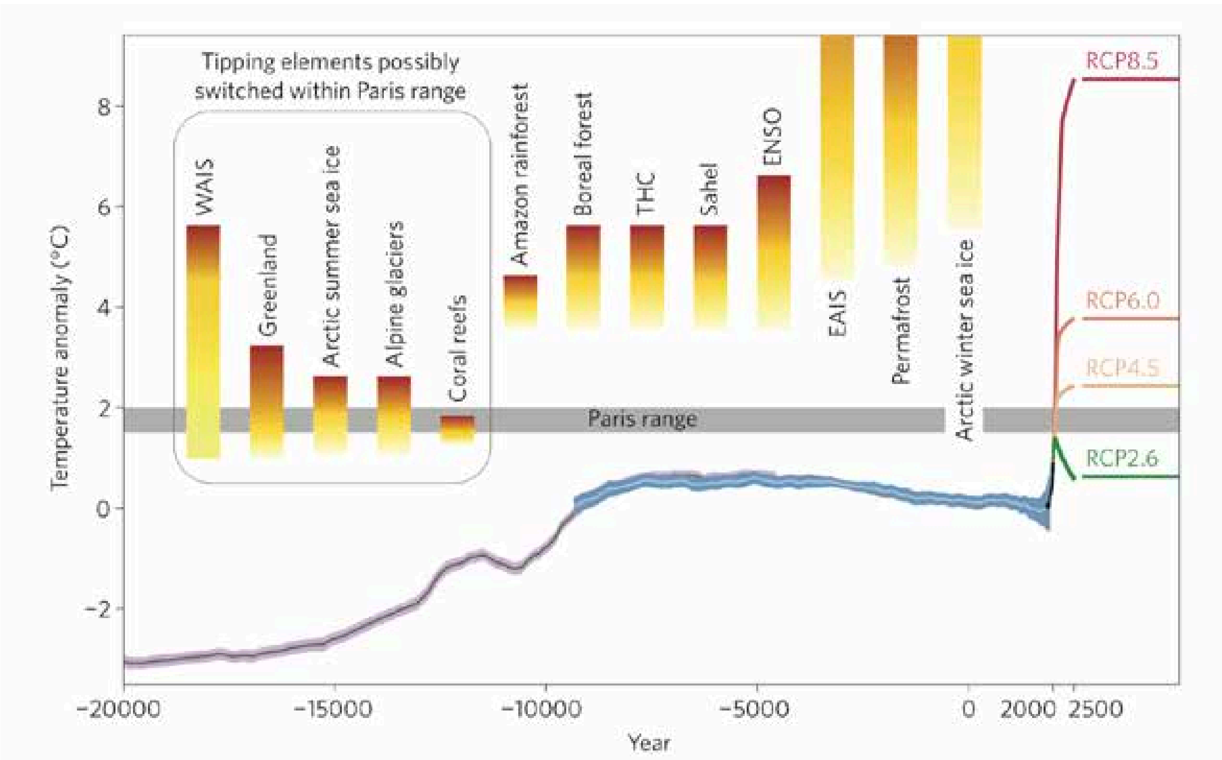
Syukuro Manabe
The Nobel Prize in Physics 2021

Born: 21 September 1931, Shingu, Ehime Prefecture, Japan

Affiliation at the time of the award: Princeton University, Princeton, NJ, USA

Prize motivation: "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming."

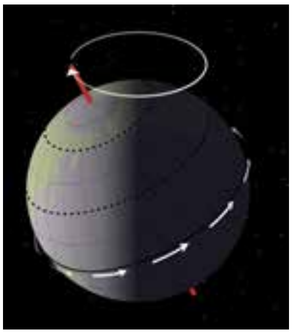
Prize share: 1/4

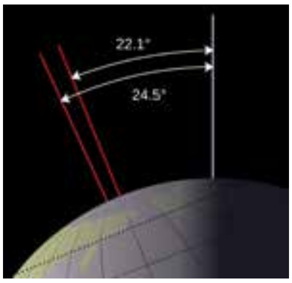


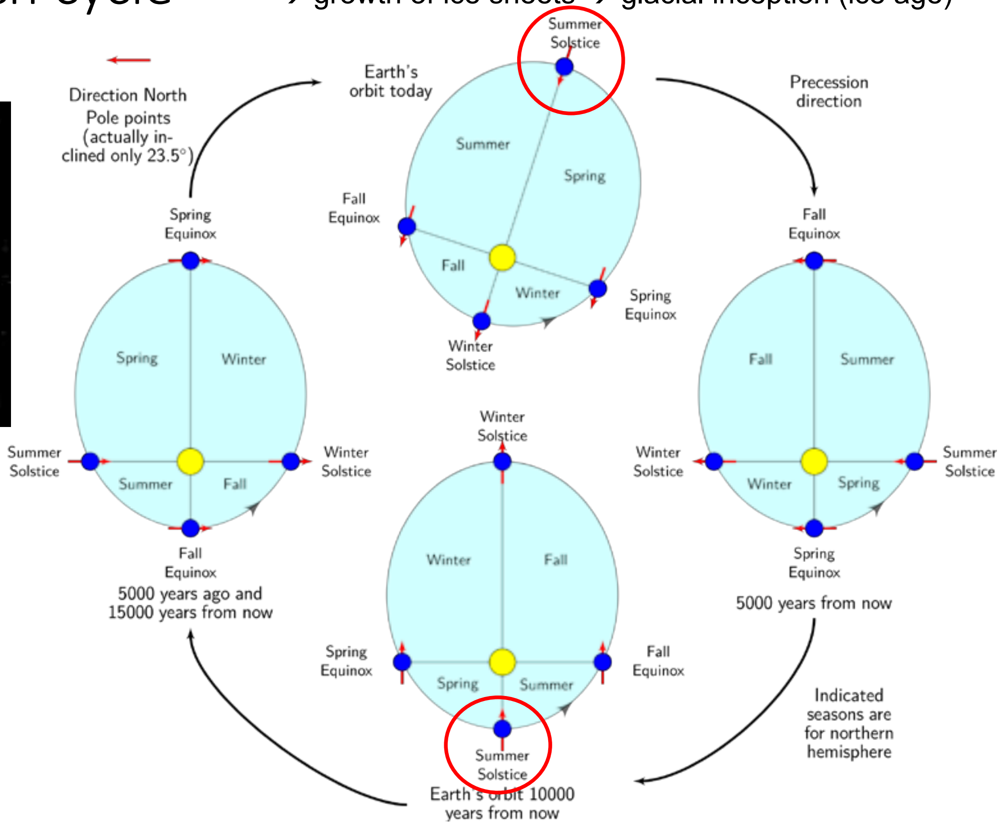
Schellnhuber et al. (Nature Climate Change, 2016)

Milankovitch cycle

low summer insolation in the northern high latitude
→ growth of ice sheets → glacial inception (ice age)



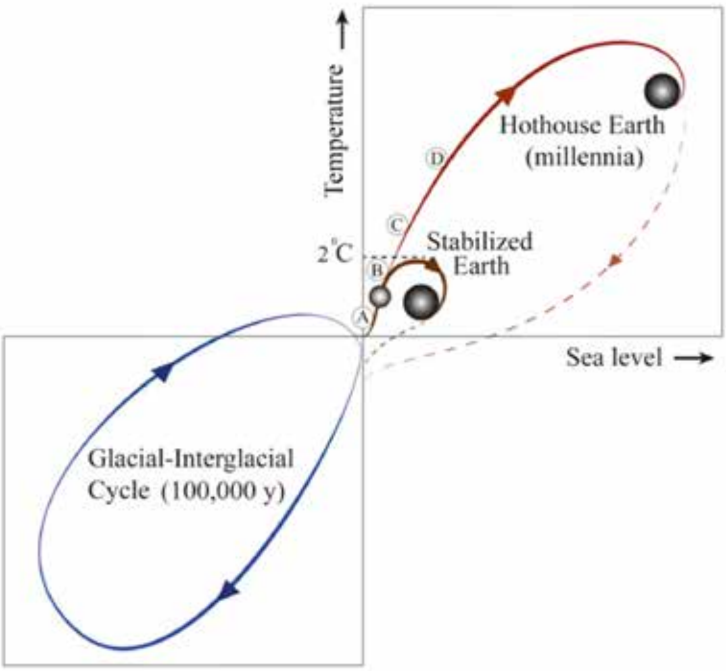




from Wikipedia

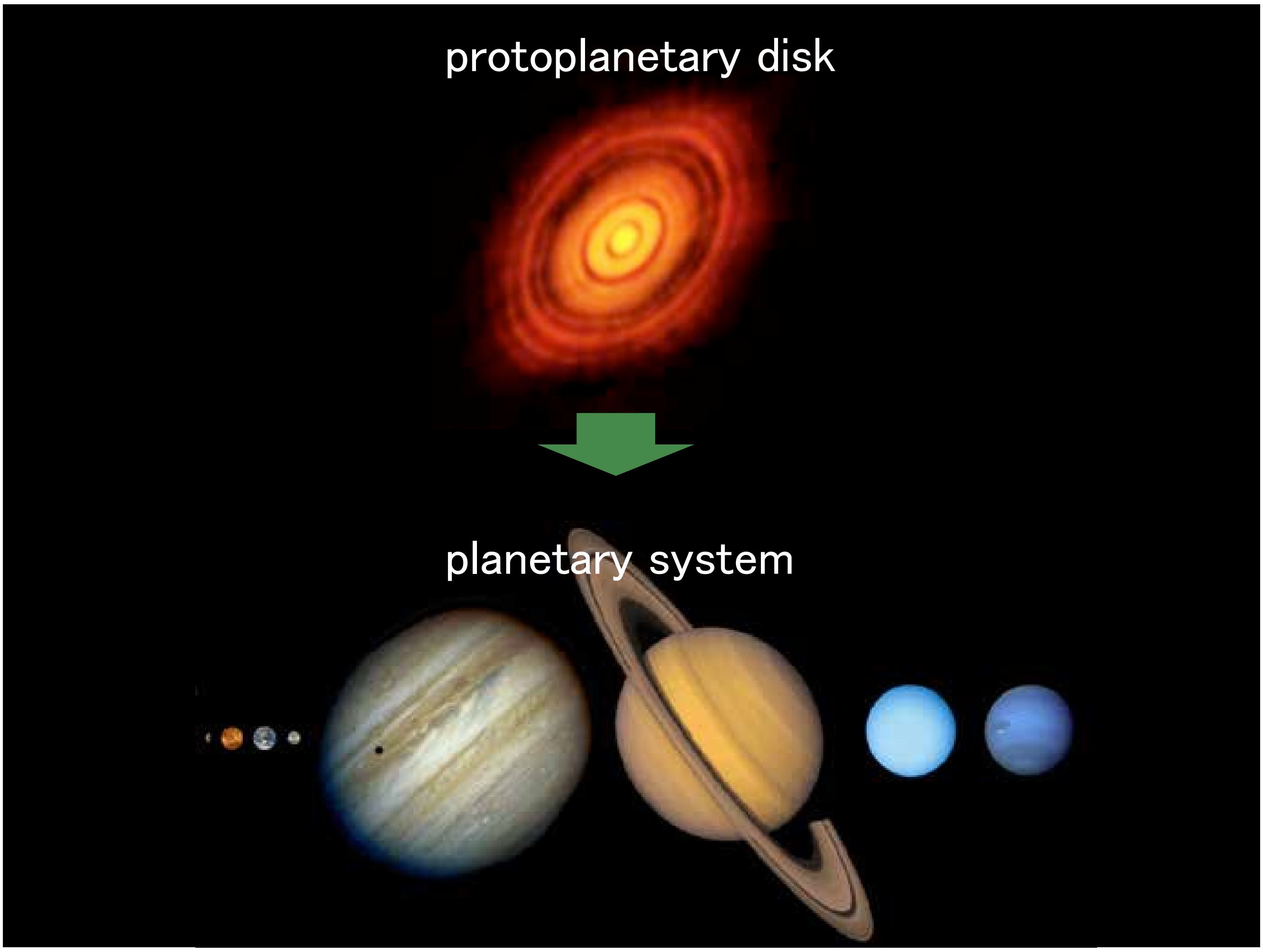
high summer insolation in the northern high latitude
→ decay of ice sheets → Interglacial (warm interval)

Possible future pathways of the climate against the background of the glacial–interglacial cycles



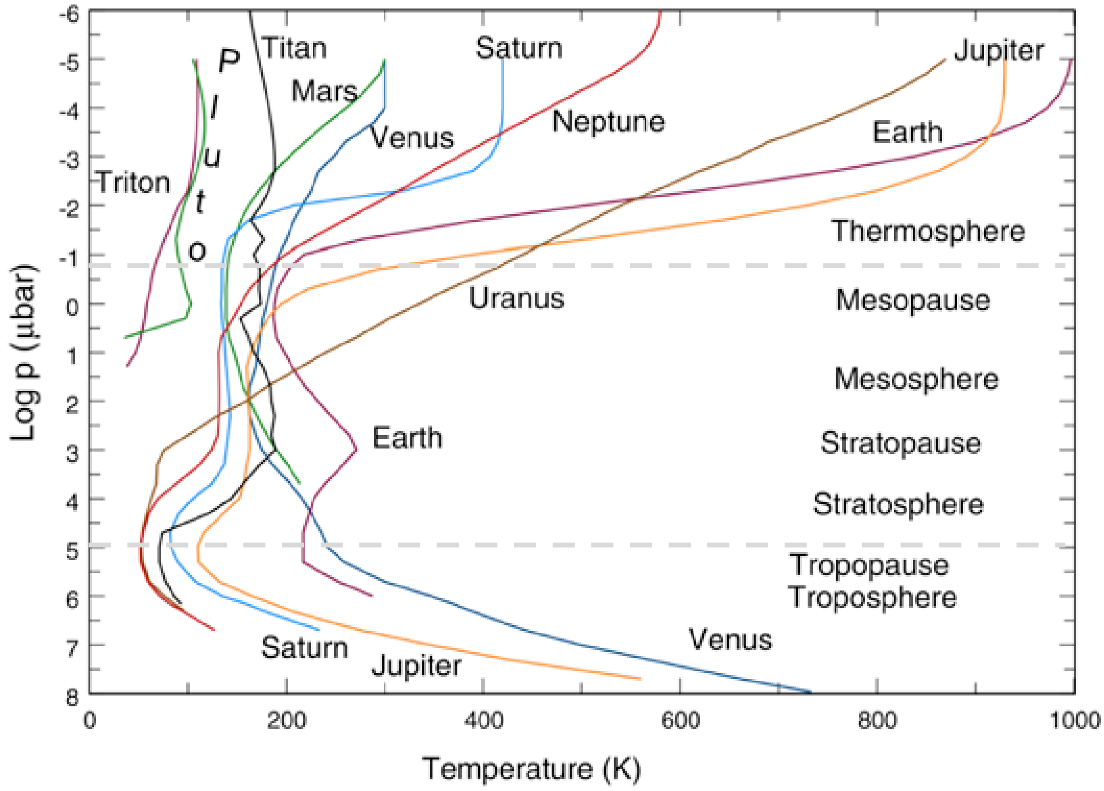
Steffen et al. (PNAS, 2018)

- What physical/chemical processes control the climate ?
- Existence of stable/unstable solutions of climate systems ?

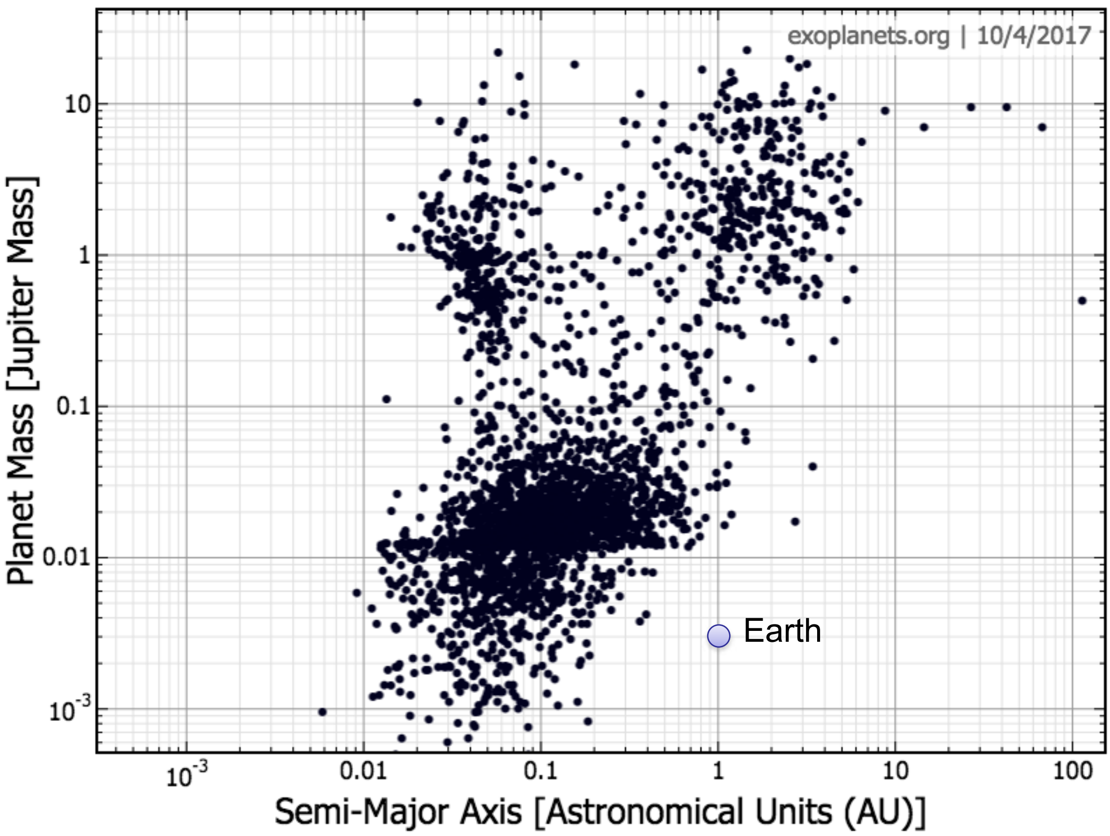


Vertical temperature profiles of planetary atmospheres

(Mueller-Wodarg et al.)

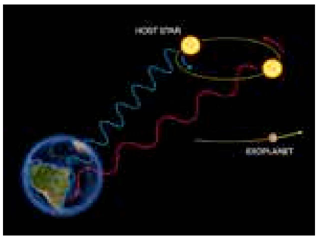


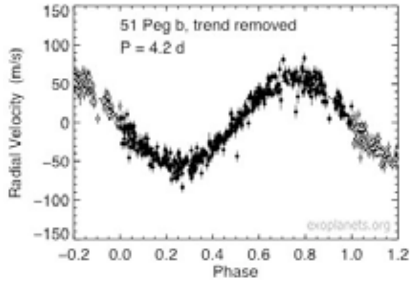
Extrasolar planets (Exoplanets)



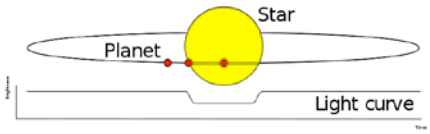
Detection methods

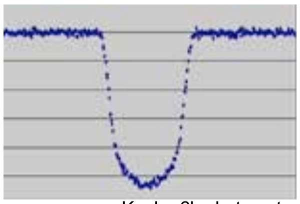
- Doppler method





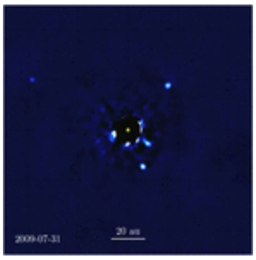
- Transit method



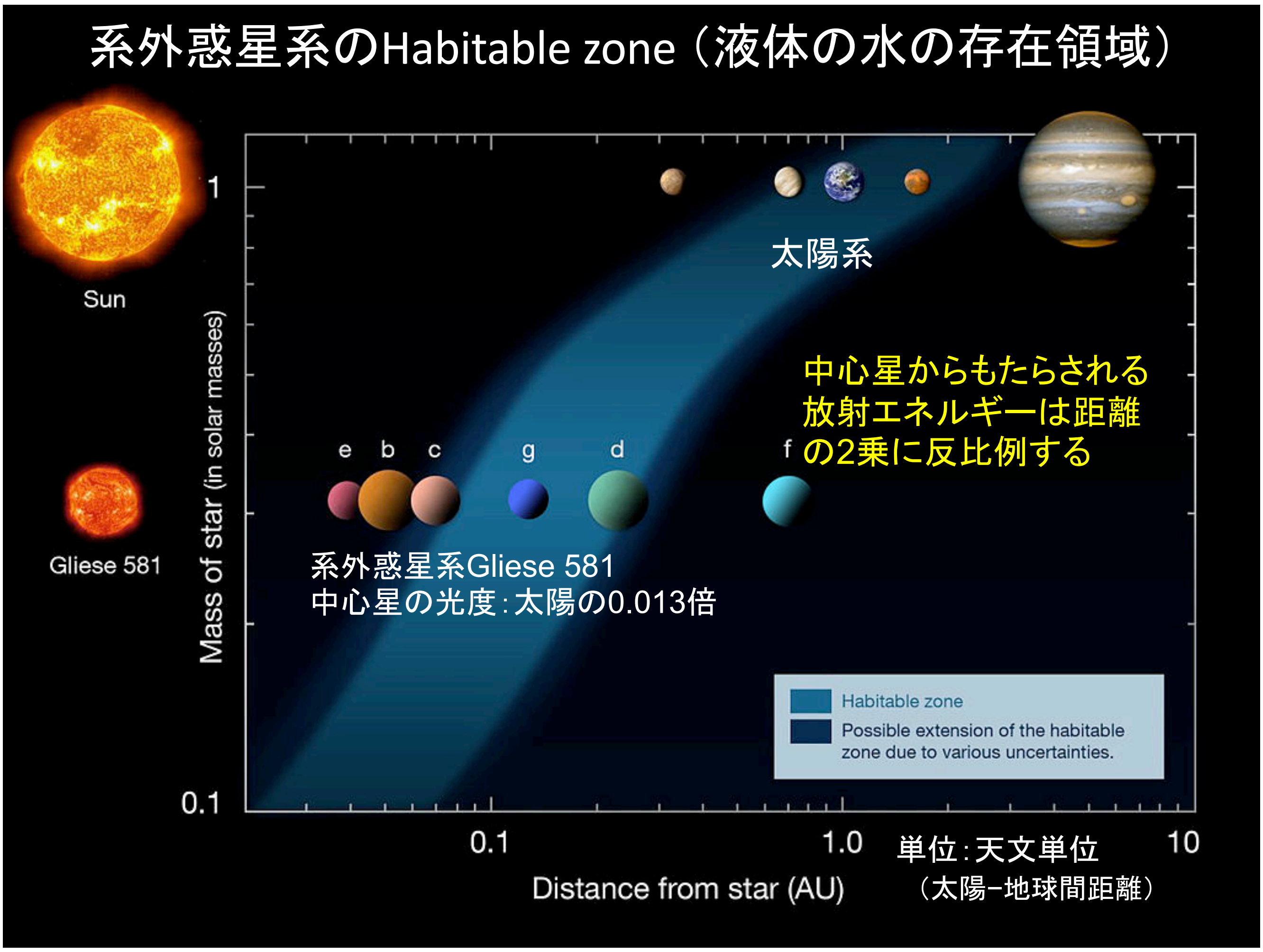


Kepler 6b photometry

- Direct imaging



By Jason Wang, et al



Inner edge of habitable zone

- Water loss limit

  Escape of water/hydrogen to space

- Runaway greenhouse limit

  Complete evaporation of ocean

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

Outer edge of habitable zone

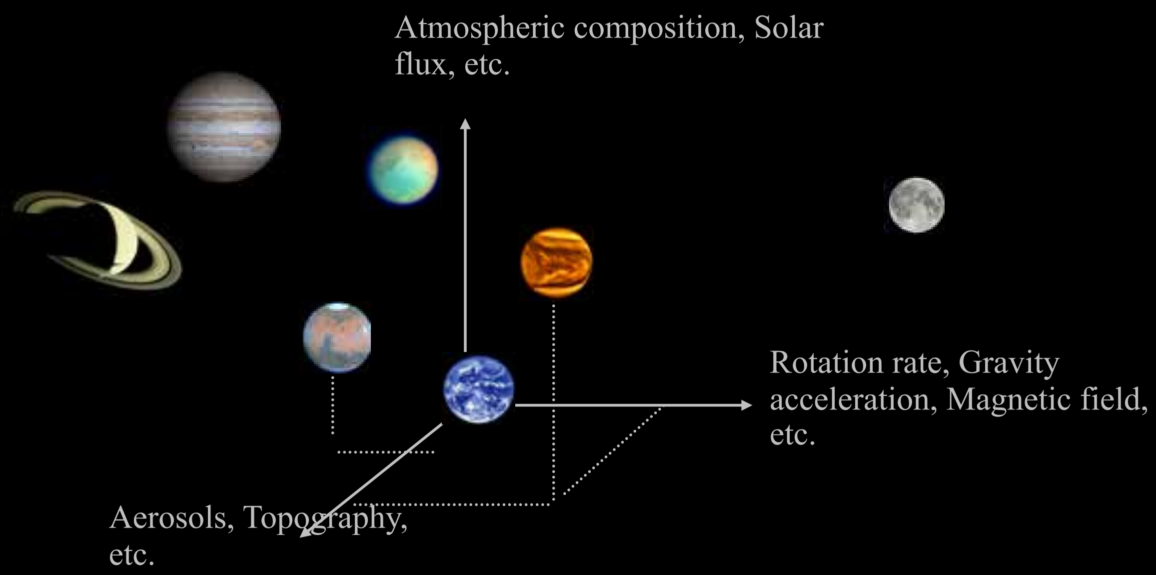
- Greenhouse effect by CO_2 and other gases
- Enhancement of cloud albedo in cold, massive atmospheres

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

Solar system exploration for understanding the habitability in the universe

- A huge number of extrasolar planets (exoplanets) have been discovered. Habitability of those planetary systems is a major scientific interest.
- The habitability on planets is governed by various physical/chemical processes. Solar system exploration reveals those processes and the way of resultant differentiation of the planets into different worlds.
- Historically, solar system exploration has been led by US, Russia and Europe. Now other countries (Japan, China, India) also contribute.

Universal understanding planetary environment in multi-parameter space



‘Comparative planetology’

How is the climate of a terrestrial planet controlled ?

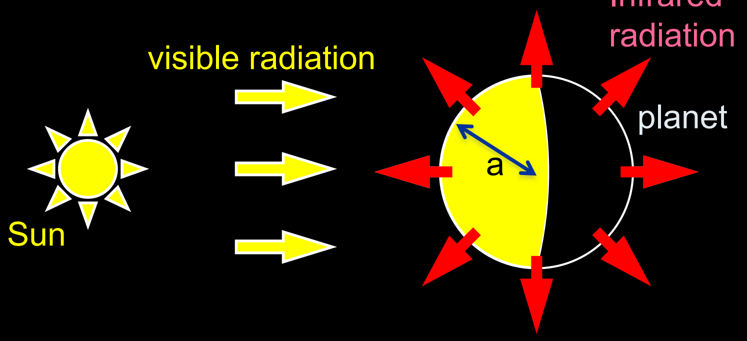
Venus as hot as 460℃

Earth water planet, habitable world

Mars as cold as −60℃

→ A simple energy budget analysis

Energy budget of Earth



Incident solar flux = Outgoing infrared flux

$$\boxed{(1 - A)\, S\, \pi\, a^2} = \boxed{4\, \pi\, a^2\, \sigma\, T^4}$$

A : Albedo (0.3 for Earth)

S : Solar constant (1370 W m^{-2} for Earth)

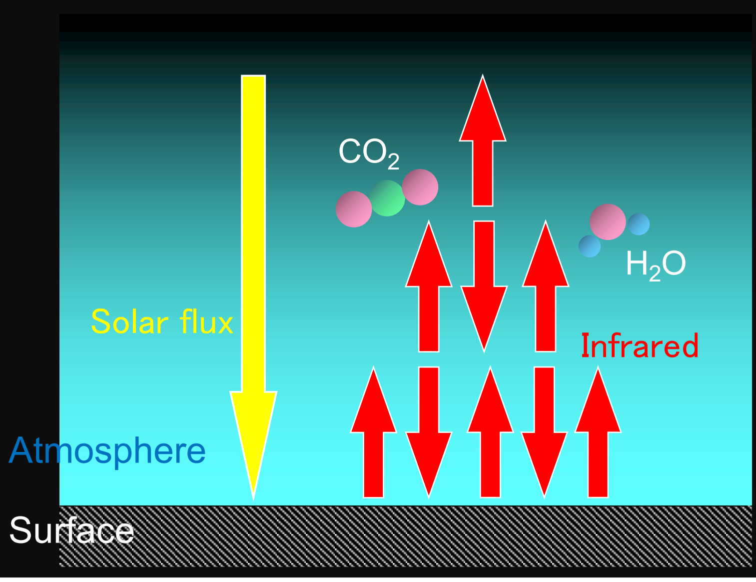
a : Planetary radius

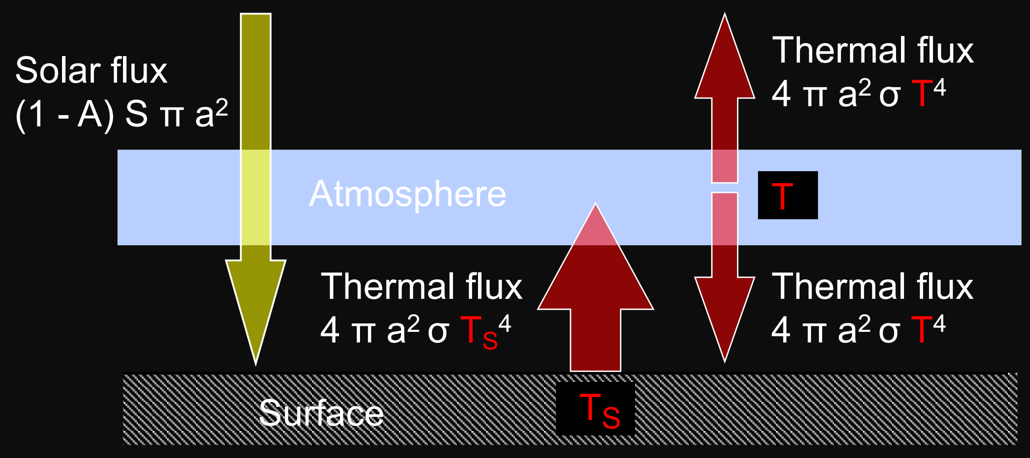
σ : Stefan-Boltzmann constant

T : Surface temperature

Substituting the values for Earth, we obtain $T = 255$ K

- In reality the mean surface temperature is around 15℃
  → Greenhouse effect by water vapor and CO_2
- Infrared-active gases absorb thermal infrared radiation emitted from the surface and prevents escape of energy to space





Energy balance

Top of atmosphere: $(1 - A) S \pi a^2 = 4 \pi a^2 \sigma T^4$

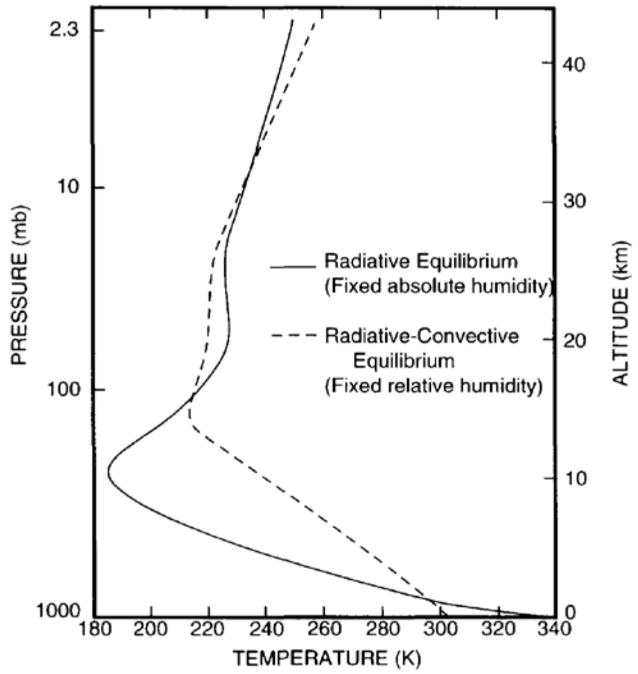
Surface: $(1 - A) S \pi a^2 + 4 \pi a^2 \sigma T^4 = 4 \pi a^2 \sigma T_S^4$

Solving these, we obtain

$$T_S = \sqrt[4]{2} \times T = 1.19\, T$$

T is equal to the surface temperature in the absence of the atmosphere. The surface temperature T_S increases as a result of the "greenhouse" effect.

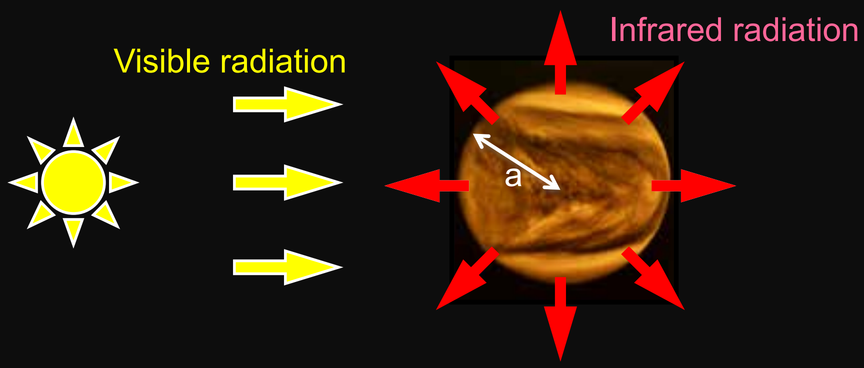
Radiative-convective equilibrium solution for Earth's atmosphere
(Manabe and Wetherald, 1967)



Salby (1996)

Figure 8.23 Temperature under radiative equilibrium (solid line) and radiative–convective equilibrium (dashed line) from calculations that include mean distributions of water vapor, carbon dioxide, and ozone. Adapted from Manabe and Wetherald (1967).

Energy budget of Venus



$$(1 - A)\, S\, \pi\, a^2 = 4\, \pi\, a^2\, \sigma\, T^4$$

A : Albedo (0.78)

S : Solar flux (2617 W m^{-2})

Substituting the values for Venus, we obtain T = 224 K

In spite of the proximity to the Sun, the energy input to Venus is low due to the reflective cloud. Venus should freeze.

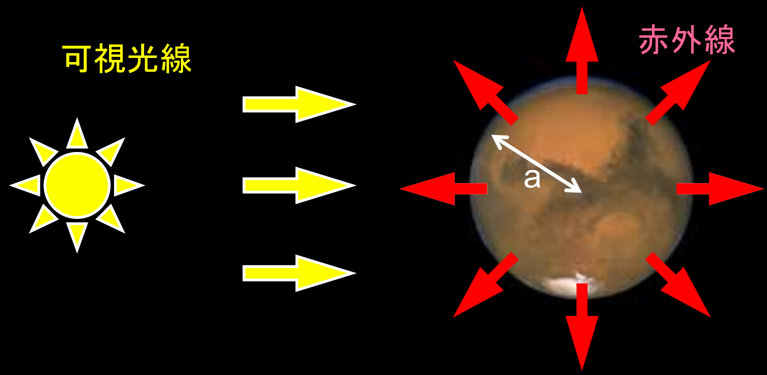
Greenhouse effect on Venus ?

- Atmospheric composition
  - CO_2 96.5 %
  - N_2 3.5 %

- Surface pressure = 92 atm
  - Thick atmosphere
  - The amount of CO2 is 300,000 times larger than that of Earth

Greenhouse effect increases the surface temperature up to 460° C

Energy budget of Mars



$$(1 - A)\, S\, \pi a^2 = 4 \pi a^2 \sigma T^4$$

A：Albedo　　（0.16）

S：Solar flux　　（589 W m^{-2}）

Substituting the values for Mars, we obtain T ＝ 216 K

In spite of the low albedo, the large distance from the Sun leads to a freezing world

Greenhouse effect on Mars ?

・Atmospheric composition

CO_2 95 %

N_2 2.7 %

Ar 1.6 %

•Pressure 0.006 atm

Thin atmosphere

Water vapor, which also plays a major role in the greenhouse effect on Earth, is also scarce.

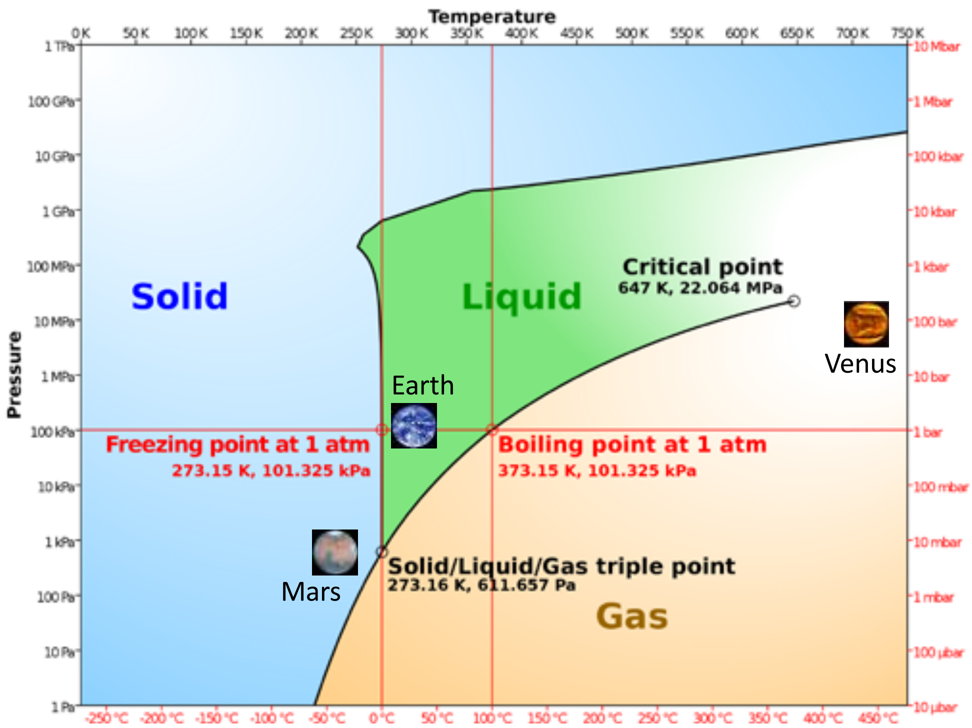
Greenhouse effect on Mars is as small as several Kelvins.

Energy budget and temperature

	Solar flux (W/m^2)	Albedo	Absorbed energy (W/m^2)	Greenhouse effect	
				off	on
Venus	2617	0.78	576	-50°C	470 °C
Earth	1370	0.30	959	-18°C	15 °C
Mars	589	0.16	495	-57°C	-53°C

Phase change diagram for water

From Wikipedia



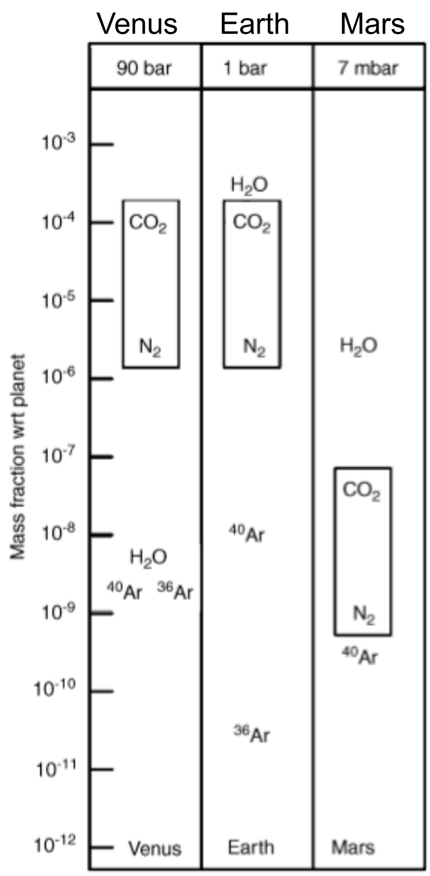


Fig. 1. Mass fraction with respect to planetary mass of volatiles on the terrestrial planets (by taking into account all known reservoirs, in particular terrestrial carbonates for CO_2).

Chassefiere et al. (2007)

Volatile species on the terrestrial planets

- H_2O seems to have been lost from Venus
- The amounts of CO_2 and N_2 on Mars are 1000 times smaller than those on Earth and Venus, while ^{40}Ar, which is considered to have degassed after the planet's formation, exists with a similar amount. This implies that Martian CO_2 and N_2 have been lost just after the planet's formation.

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.

The Carbonate - Silicate Cycle

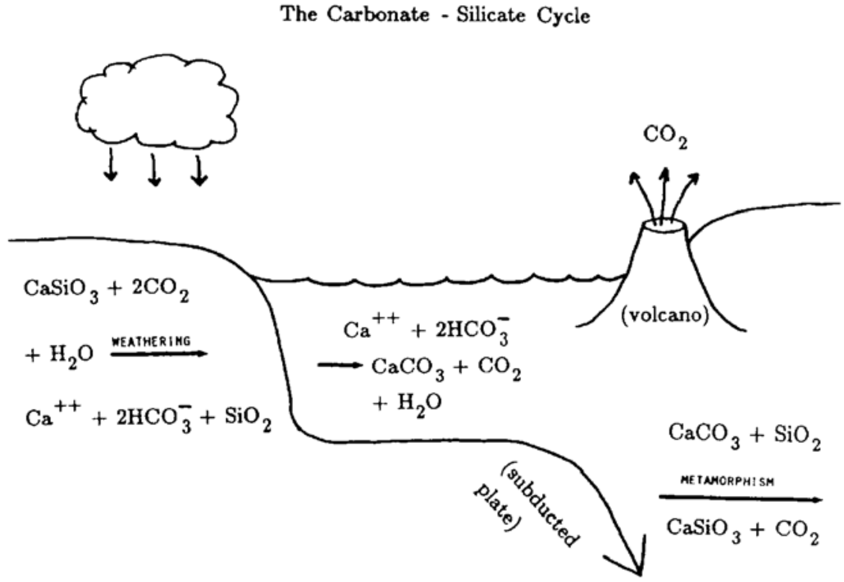
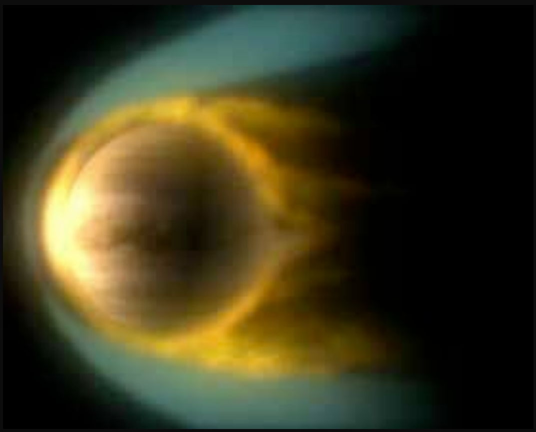
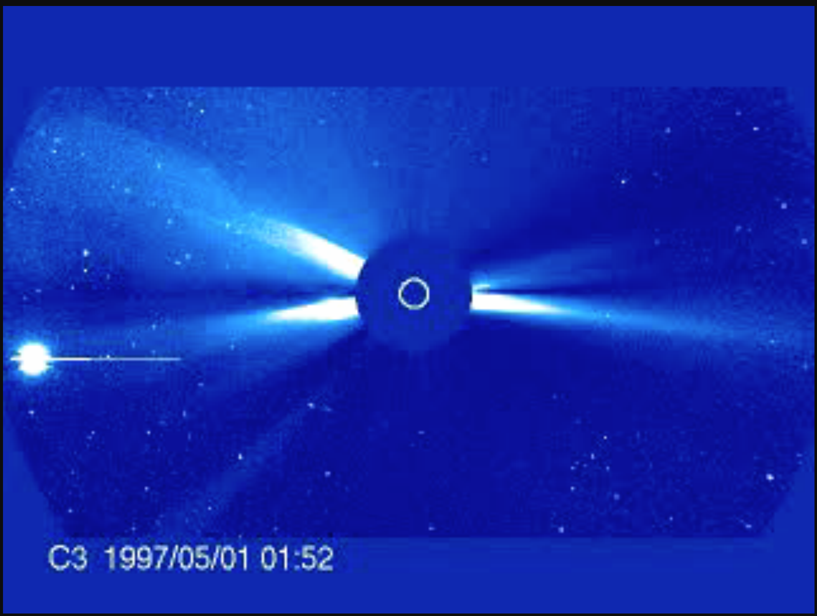


Fig. 5. A schematic representation of chemical weathering reactions of terrestrial continental silicate rocks by CO_2 dissolved in water, the subduction of the resultant carbonate rocks, their thermal decomposition at depth, and the outgassing of the released CO_2.

- Venus may have had an ocean in early stage of its evolution.
- The ocean evaporated and water vapor was lost to space through 'atmospheric escape'. Once the ocean disappeared, CO_2 and S-containing species will have been released to the atmosphere.



Movie provided by ESA

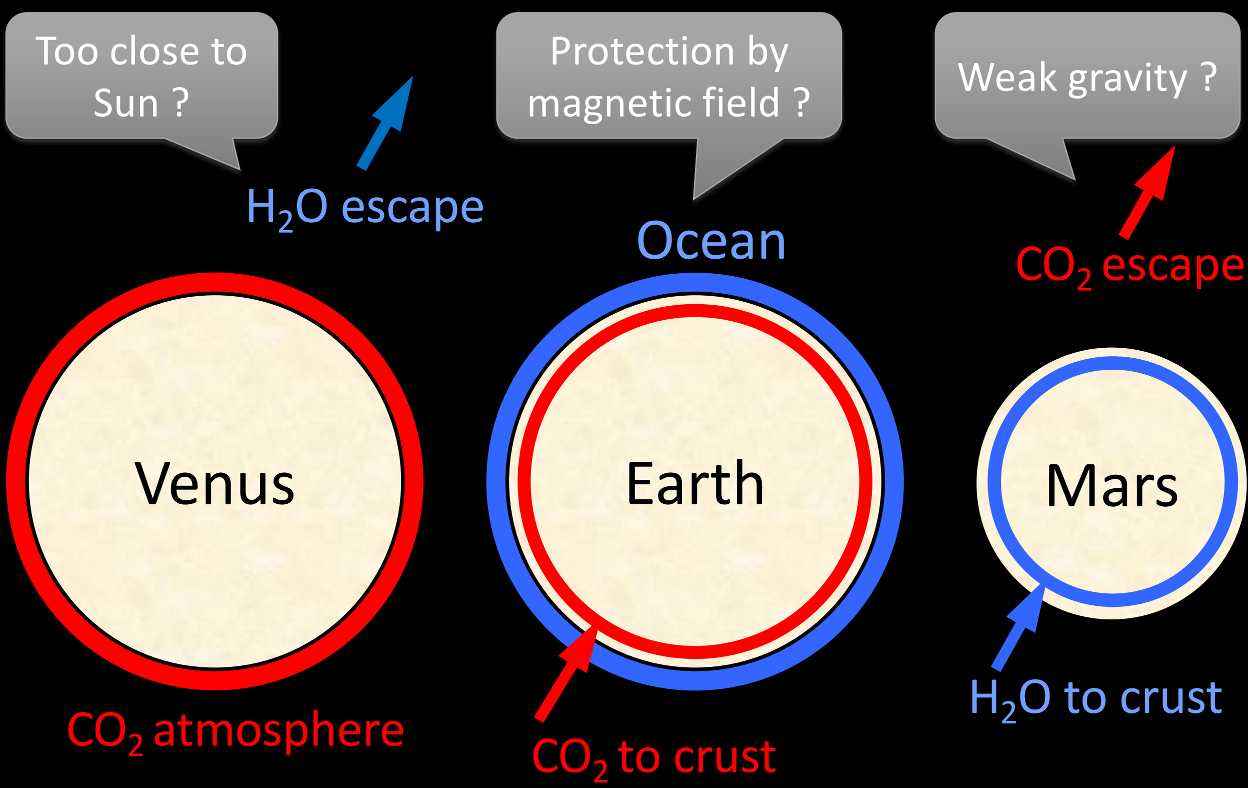


Solar wind observed by SOHO/LASCO

- Mars may have had a thick CO_2 atmosphere in early stage of the revolution and have sustained a warm, humid environment via its greenhouse effect.
- The loss of CO_2 to space may have caused cooling of the climate.

Movie provided by ESA

Possible scenarios

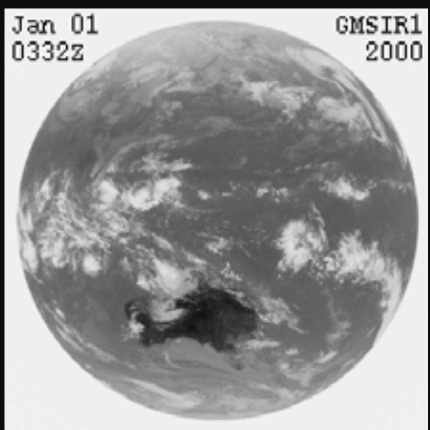


Energy budget and temperature

	Solar flux (W/m²)	Albedo	Absorbed energy (W/m²)	Greenhouse effect	
				off	on
Venus	2617	0.78	576	-50℃	470 ℃
Earth	1370	0.30	959	-18℃	15 ℃
Mars	589	0.16	495	-57℃	-53℃

How is albedo controlled ?

- Cloud amount mostly determines the albedo.
- If the Earth's albedo drops to 0.2 from the present value of 0.3, Earth would lose water through escape to space.



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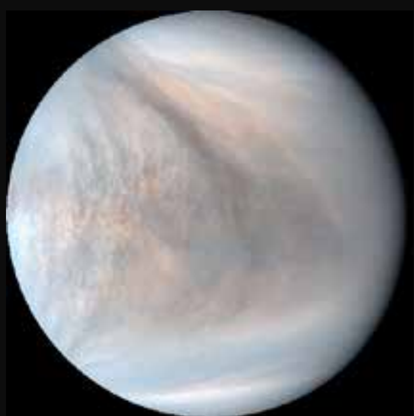
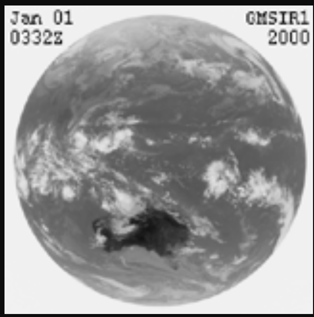
Earth's cloud created by various atmospheric motions. Albedo = 0.3



Venus' sulfuric acid cloud. Albedo = 0.8

Atmospheric circulation



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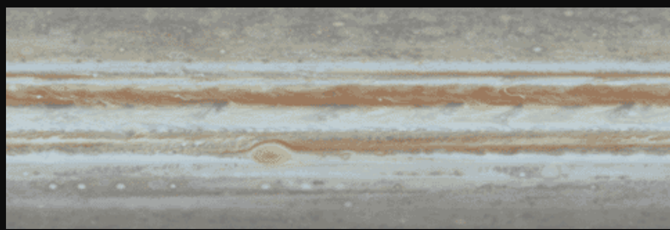
Earth

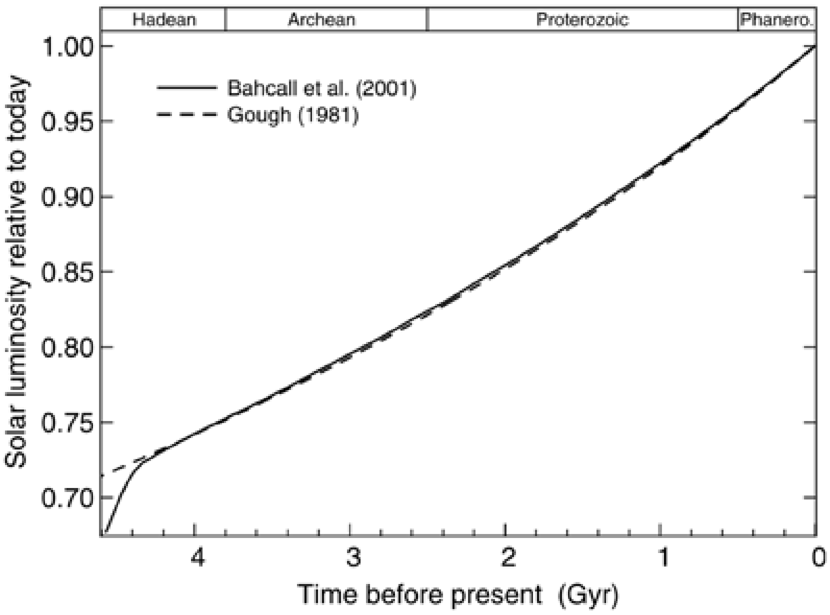
Venus

Mars



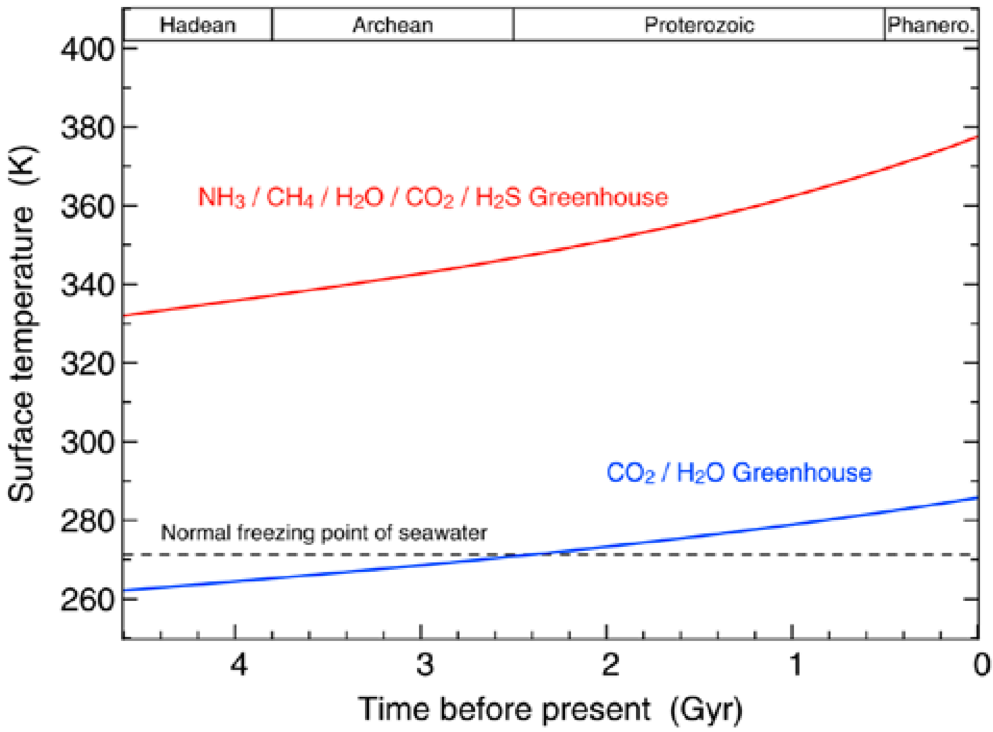
Jupiter

Long-term trend of solar luminosity



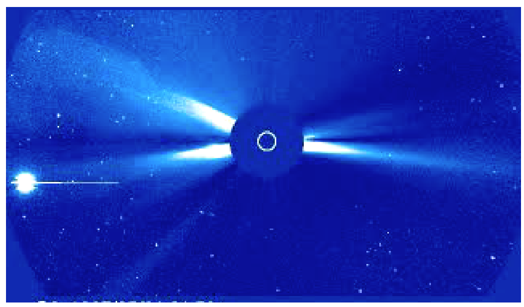
Feulner (2012)

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.

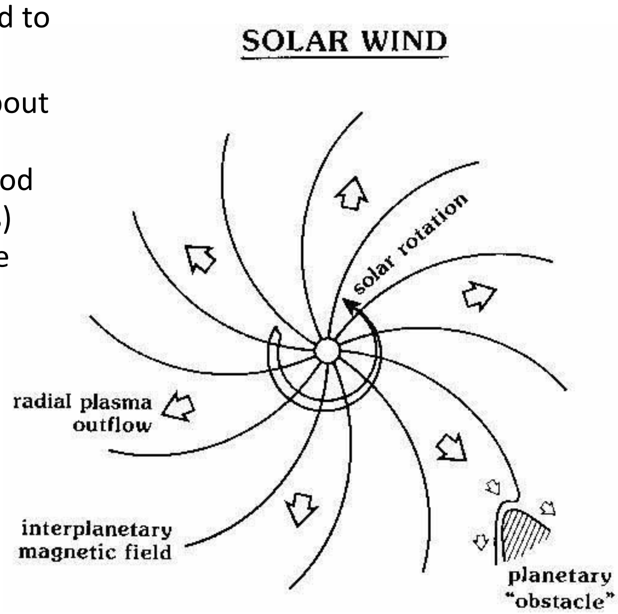


Feulner (2012)

Stellar evolution

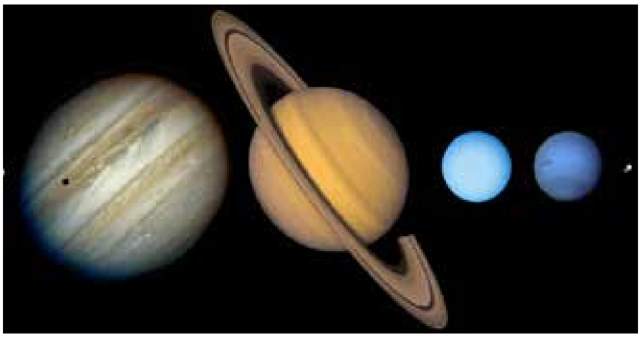


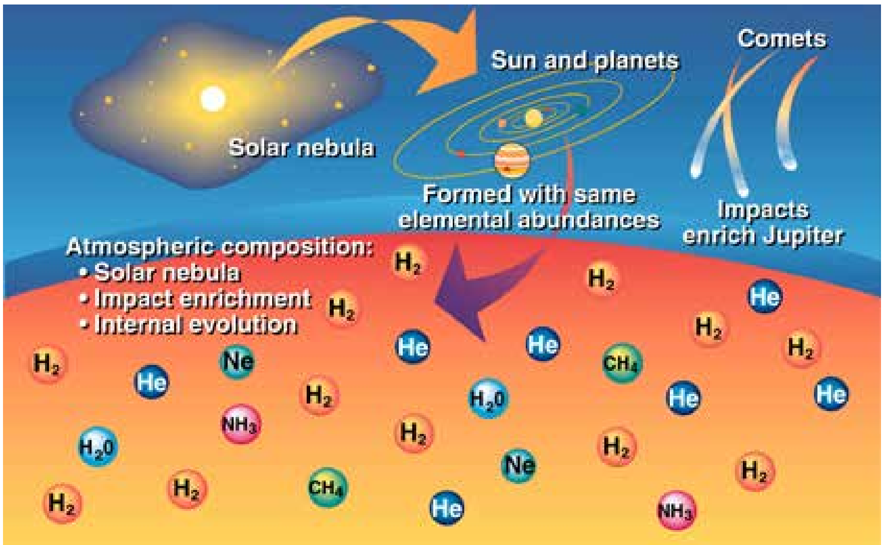
- UV radiation from the Sun and late-type stars originates in magnetic chromospheric and transition-zone regions which have been heated to temperatures of ~10^4– 10^5 K. Magnetic activity driven by the star's rotation is believed to be critical for this heating.
- For stars with masses ≤$1.5M_{Sun}$ and ages of about a few 100 Myr, angular momentum loss by a stellar wind brakes rotation. The rotation period of the young Sun was much faster (~few days) during the first 500 Myr after the arrival at the main sequence.



©NASA

Gas giants





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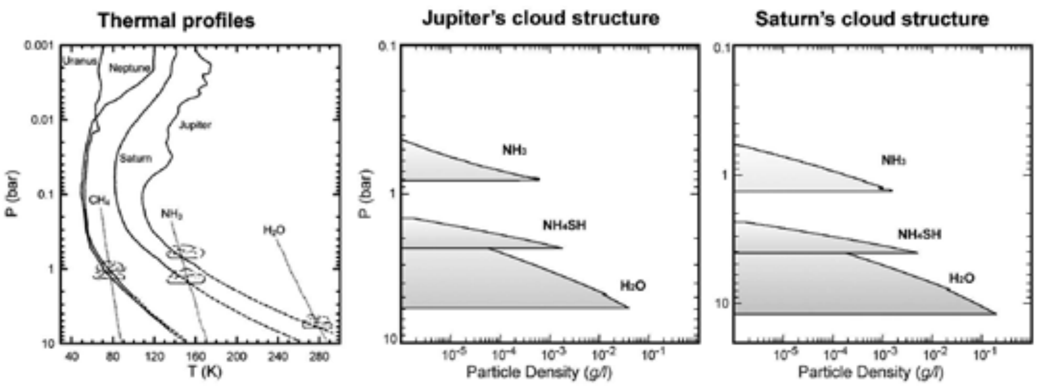
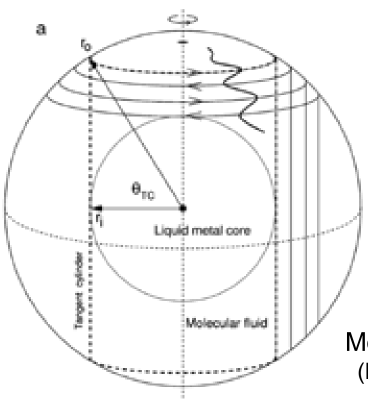
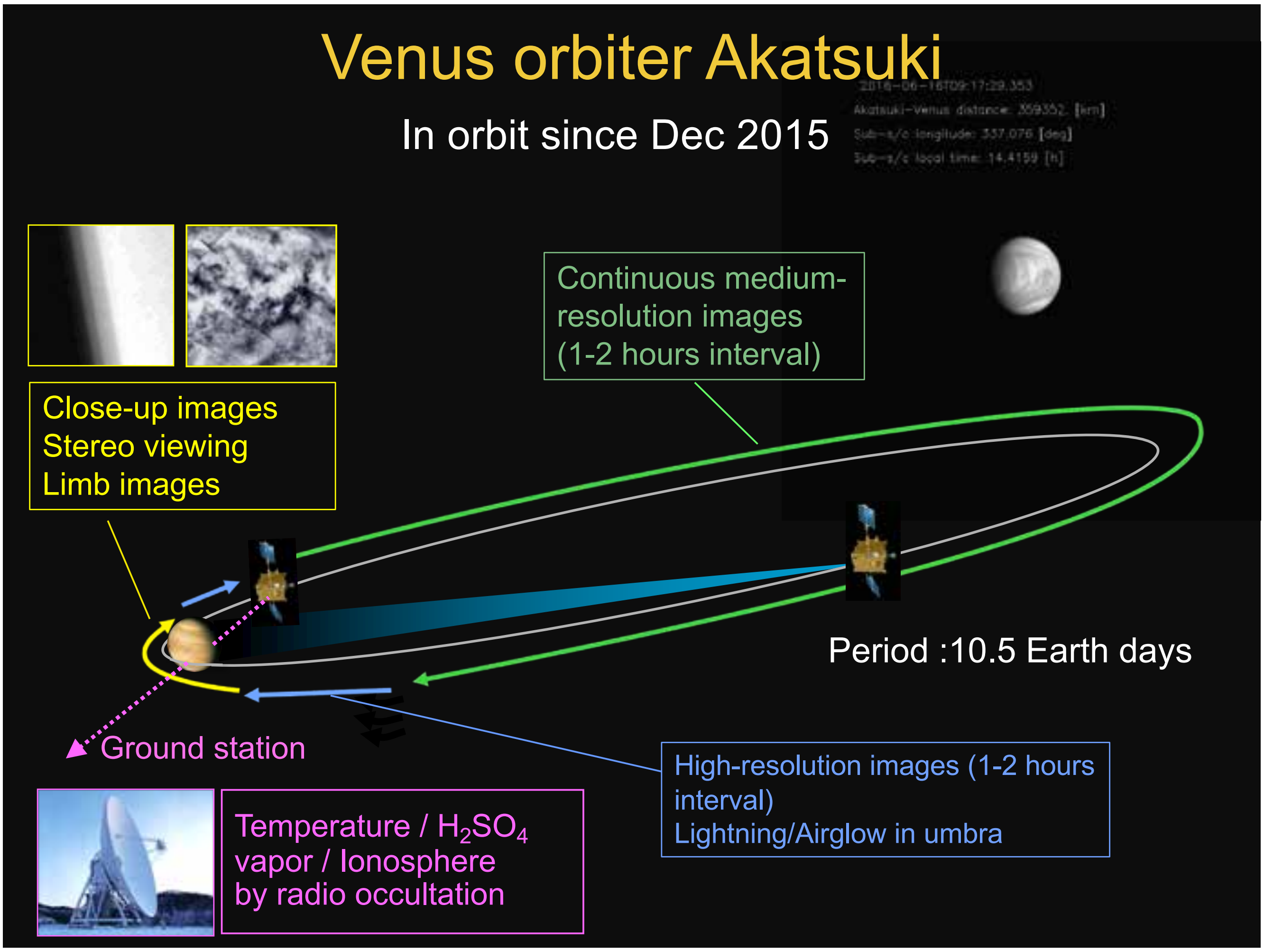
Internal structure of gas giants

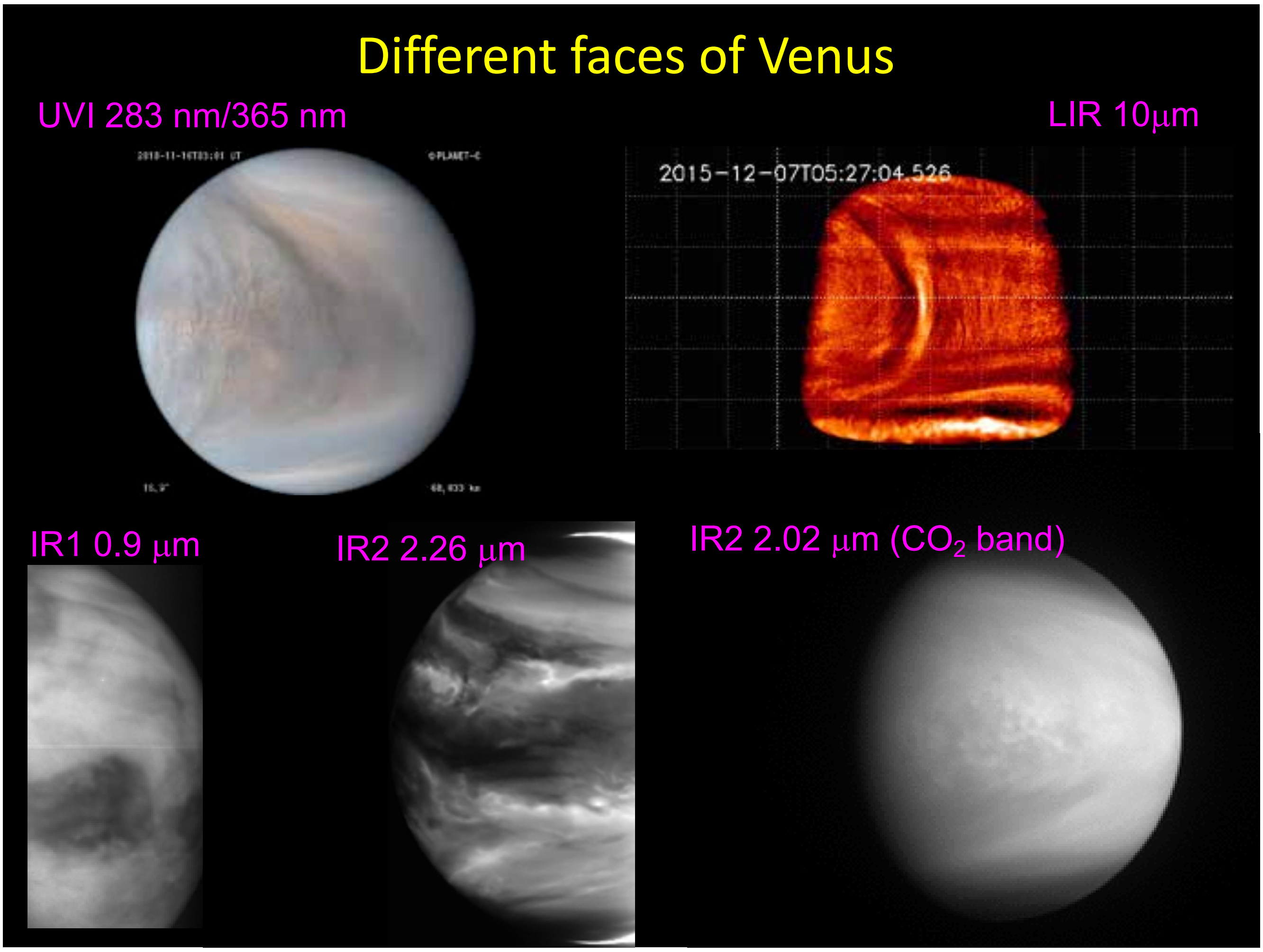


Sanchez-Lavega et al.



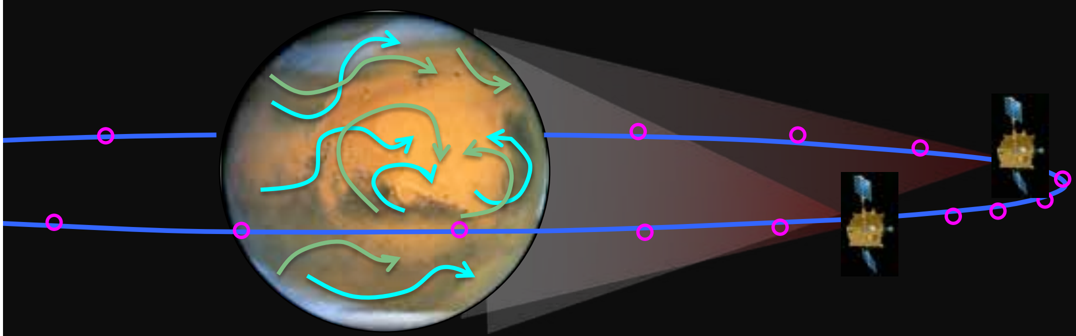
Model by Busse (1976)
(Heimpel & Aurnou 2007)


Venus orbiter Akatsuki
In orbit since Dec 2015
Close-up images
Stereo viewing
Limb images
Continuous medium-resolution images
(1-2 hours interval)
Period :10.5 Earth days
Ground station
Temperature / H_2SO_4 vapor / Ionosphere by radio occultation
High-resolution images (1-2 hours interval)
Lightning/Airglow in umbra

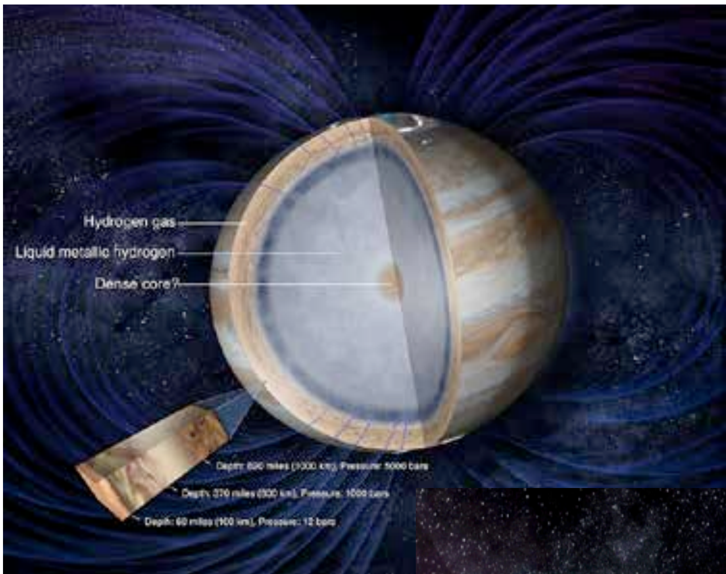

Different faces of Venus
UVI 283 nm/365 nm
LIR 10μm
2015-12-07T05:27:04.526
IR1 0.9 μm
IR2 2.26 μm
IR2 2.02 μm (CO_2 band)

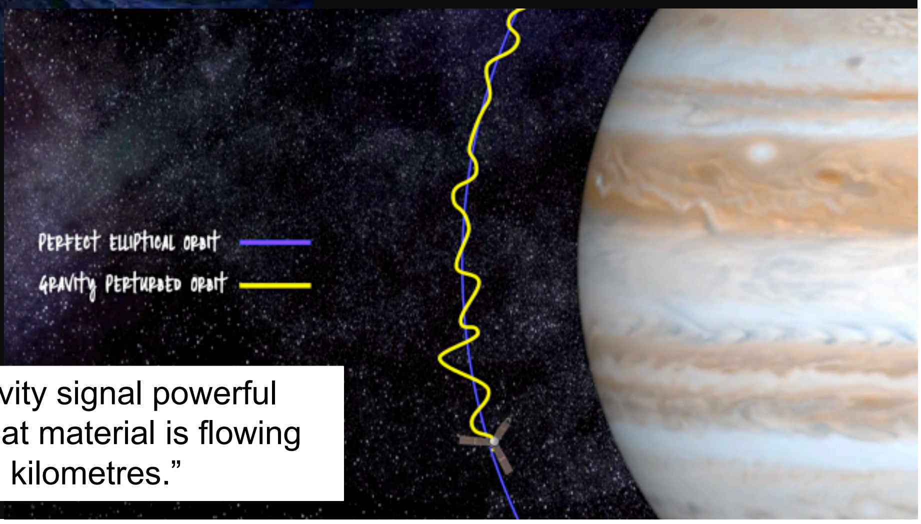
Martian Moons Exploration: MMX

- Launch: 2024
- In orbit: 2025-2028
- Continuous high-resolution mapping of dust, clouds and atmospheric constituents from a high orbit to reveal the material circulation in the Martian atmosphere



Doppler tracking of Juno spacecraft





"Juno detected a gravity signal powerful enough to indicate that material is flowing as far down as 3,000 kilometres."

Questions

- How are the compositions, amounts and albedo of those planetary atmospheres controlled ?
- How does the climate system work and evolve with time depending on the condition of the planet ?
- How dose a star-planet system evolve with time?