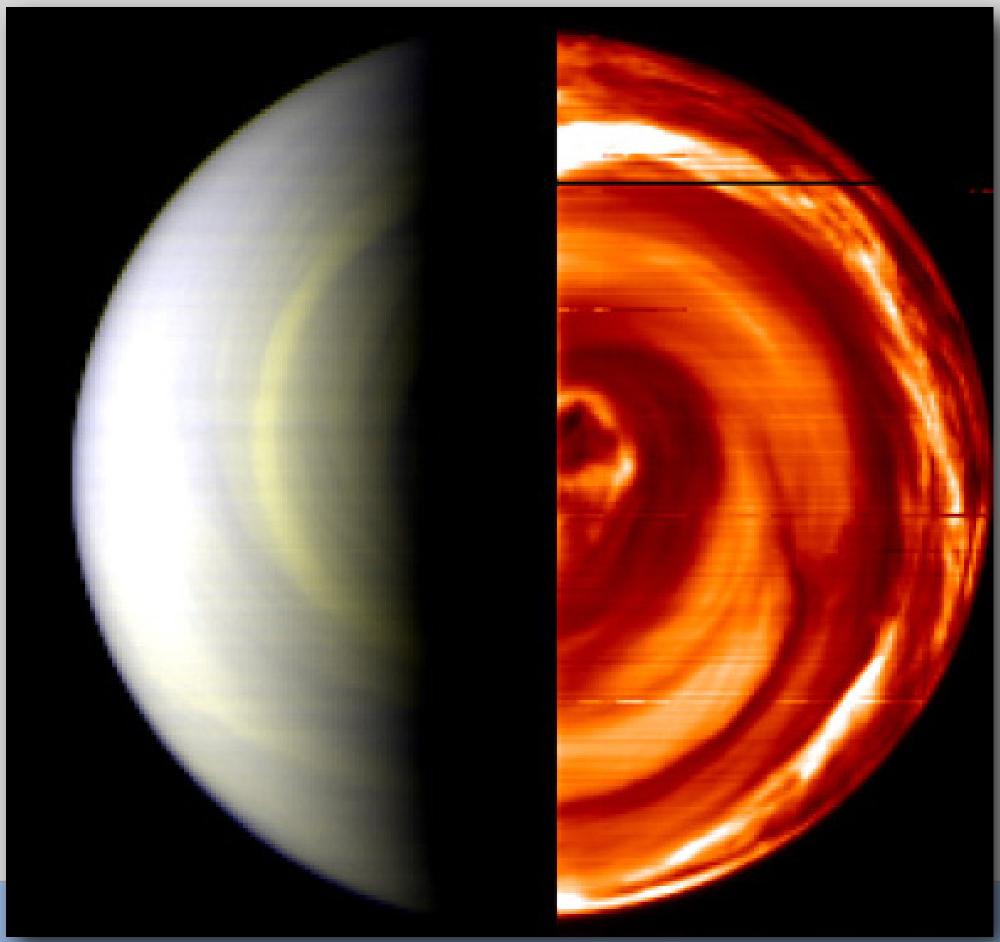
# Planetary atmospheres

## Planetary Sciences Chapter 4

Daphne Stam



SRON
Netherlands Institute for Space Research

# Outline

- What is an atmosphere?
- Pressure, density, and scale heights
- Origin of planetary atmospheres
- Composition of Solar System planetary atmospheres
- Temperature profiles of atmospheres
- Cloud formation
- Temperature profiles of the gas giants
- Examples of clouds on the giant planets
- Temperature profiles of the terrestrial planets
- The greenhouse effect
- The Venus atmosphere
- The Mars atmosphere

# What is an atmosphere?

*Atmosphere = atmos + sphaera = vapor (Greek) + sphere (Latin)*

All Solar System planets and some satellites have atmospheres:

- Dense, $p > 1$ bar (Venus, Earth, gas giants, Titan)
- Tenuous, $p << 1$ bar (Mars, Mercury, Moon, Pluto, Triton)

These atmospheres contain the following gases:

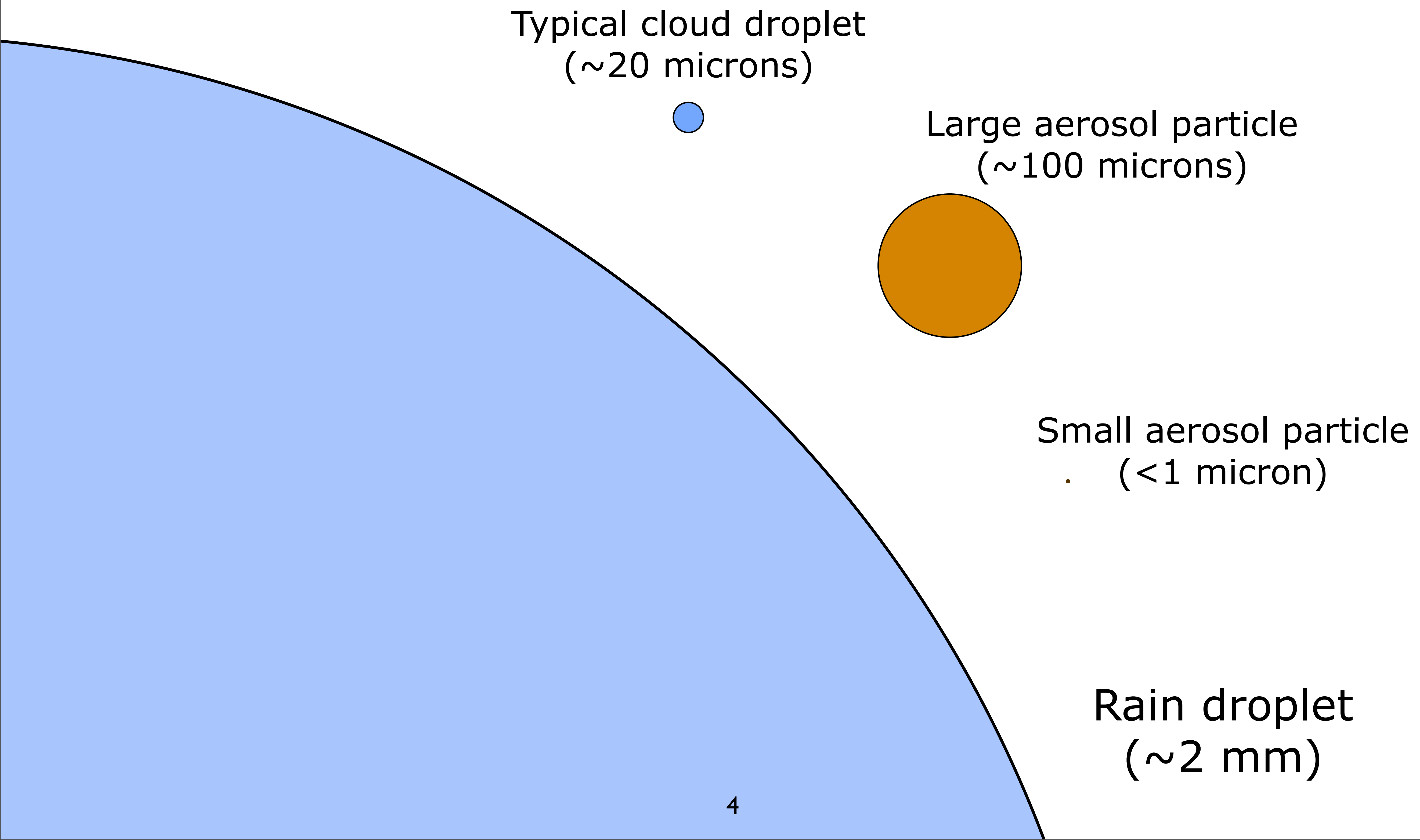
- Carbon dioxide (Venus, Mars), nitrogen (Earth, Titan)
- Approximately Solar composition (gas giants)

And, in addition:

- Aerosol particles
- Cloud particles

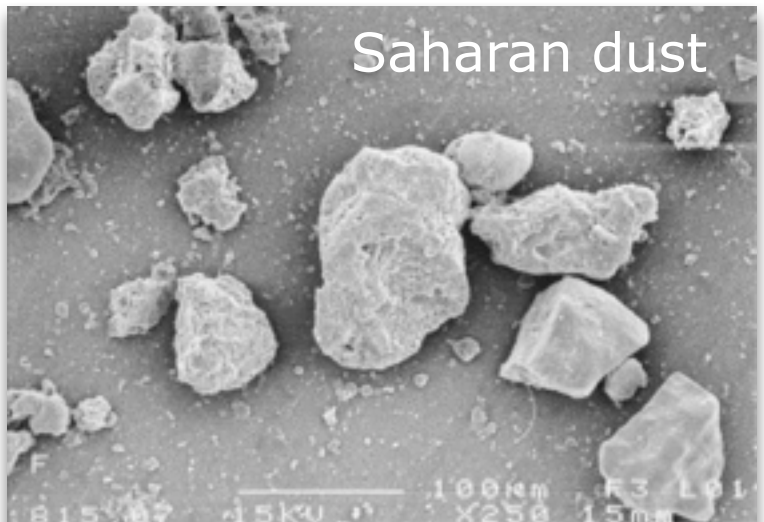
Titan's hazy atmosphere
(Credit: Cassini, NASA/ESA)

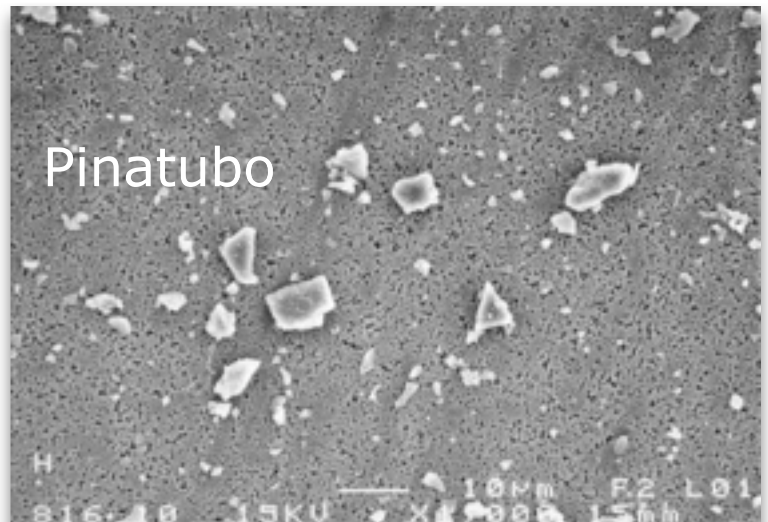
# Cloud and aerosol particles



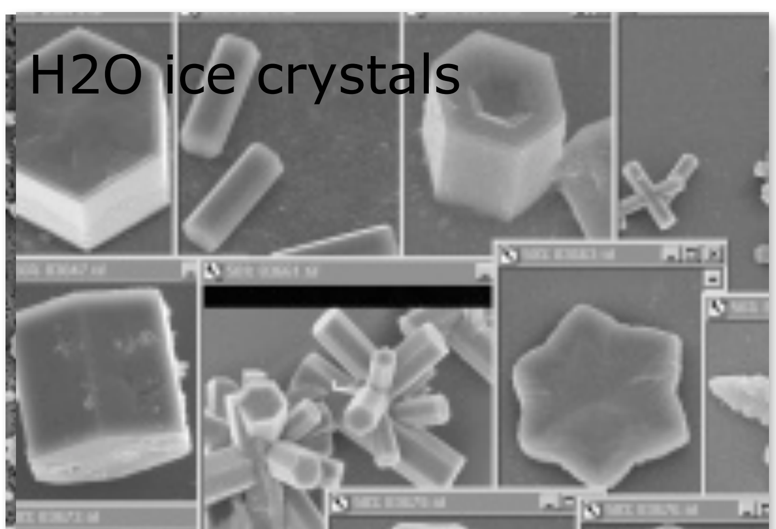
# Typical shapes of cloud and aerosol particles

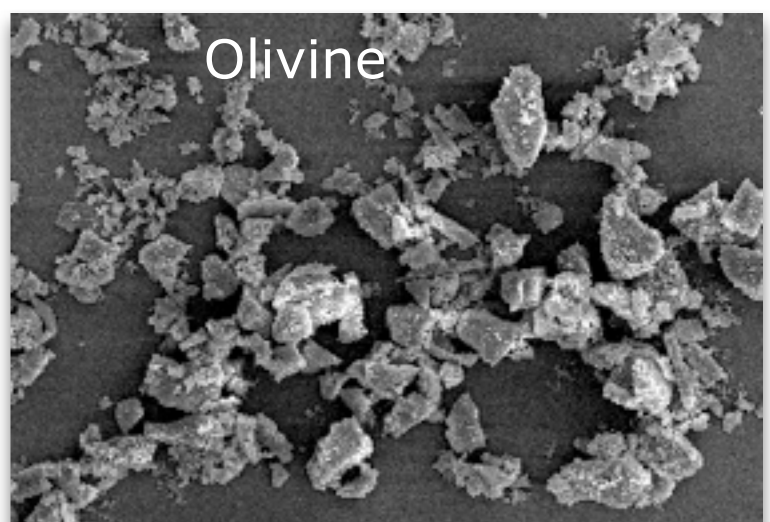
Note that liquid cloud and aerosol particles will be spherical!

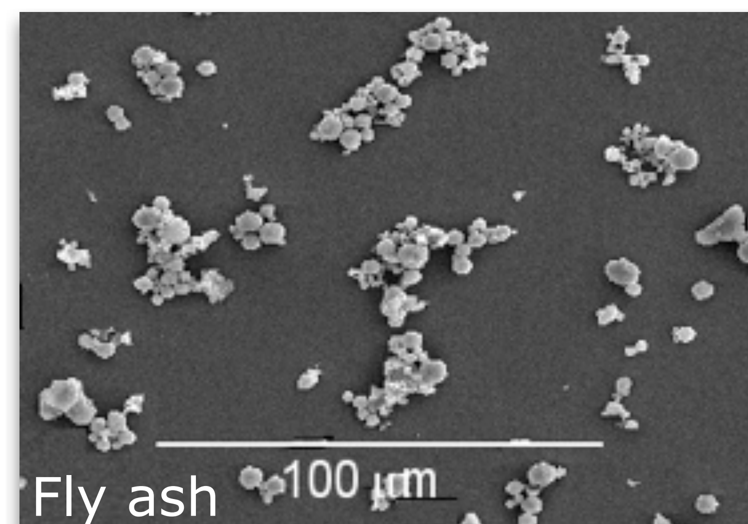


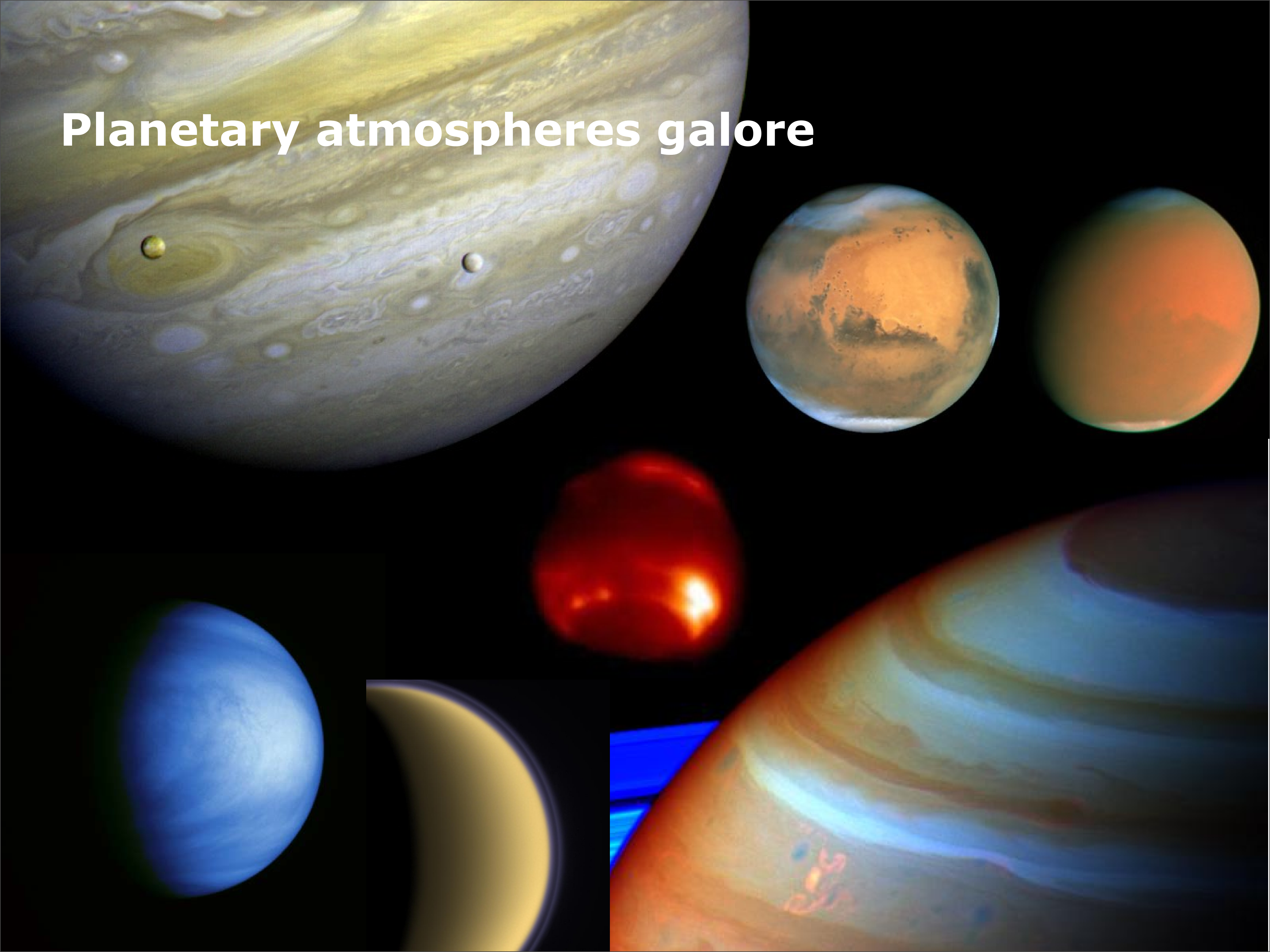




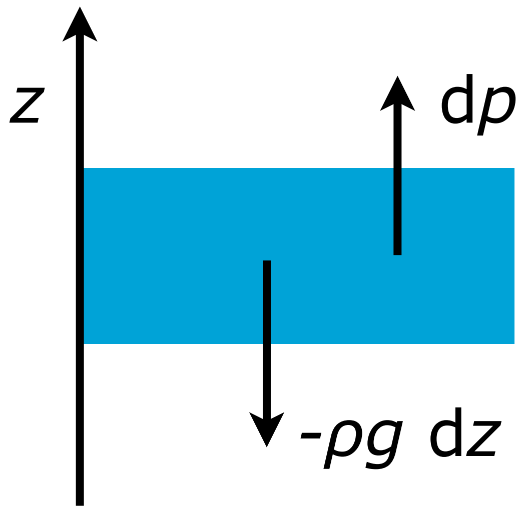
# Planetary atmospheres galore



# Pressure and density 1

Atmospheres can be assumed to be in *hydrostatic equilibrium*, i.e. there is a balance between gravity and pressure:

$$\mathrm{d}p = -\,\rho(z)\, g(z)\, \mathrm{d}z$$




With $p$ the pressure, $z$ the vertical coordinate, $g$ the acceleration of gravity, and $\rho$ the density.

Assume the gas is an ideal gas (no interactions between gas molecules):

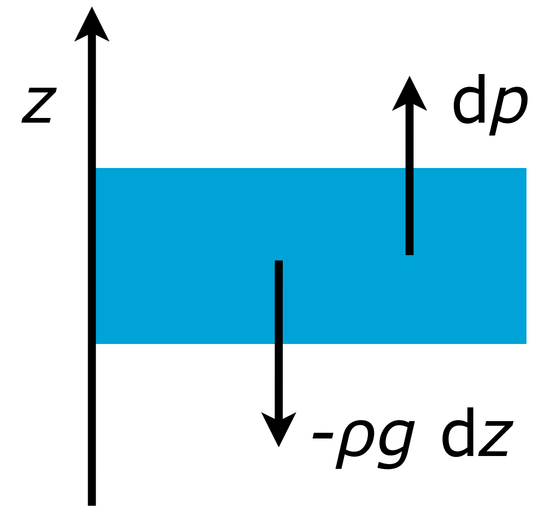
$$p(z) = \frac{\rho(z)\, T(z)\, k}{m(z)}$$

With $T$ the temperature, $k$ Boltzmann's constant, and $m$ the molecular mass

# Pressure and density 2

Combining hydrostatic equilibrium and the ideal gas law, we get:

$$\mathrm{d}p = -\frac{m(z)\, g(z)}{kT}\, p(z)\, \mathrm{d}z$$




The solution to this equation is:

$$p(z) = p(0) \exp\left( -\int_{z0}^{z1} \frac{m(z')\, g(z')}{k\, T(z')}\, \mathrm{d}z' \right)$$

$$= p(0) \exp\left( -\int_{z0}^{z1} \frac{1}{H(z')}\, \mathrm{d}z' \right)$$

With $H$ the *pressure scale height*:

$$H(z) = k\, T(z) / m(z)\, g(z)$$

This is the distance over which the pressure $p$ drops by a factor $e$

# Pressure and density 3

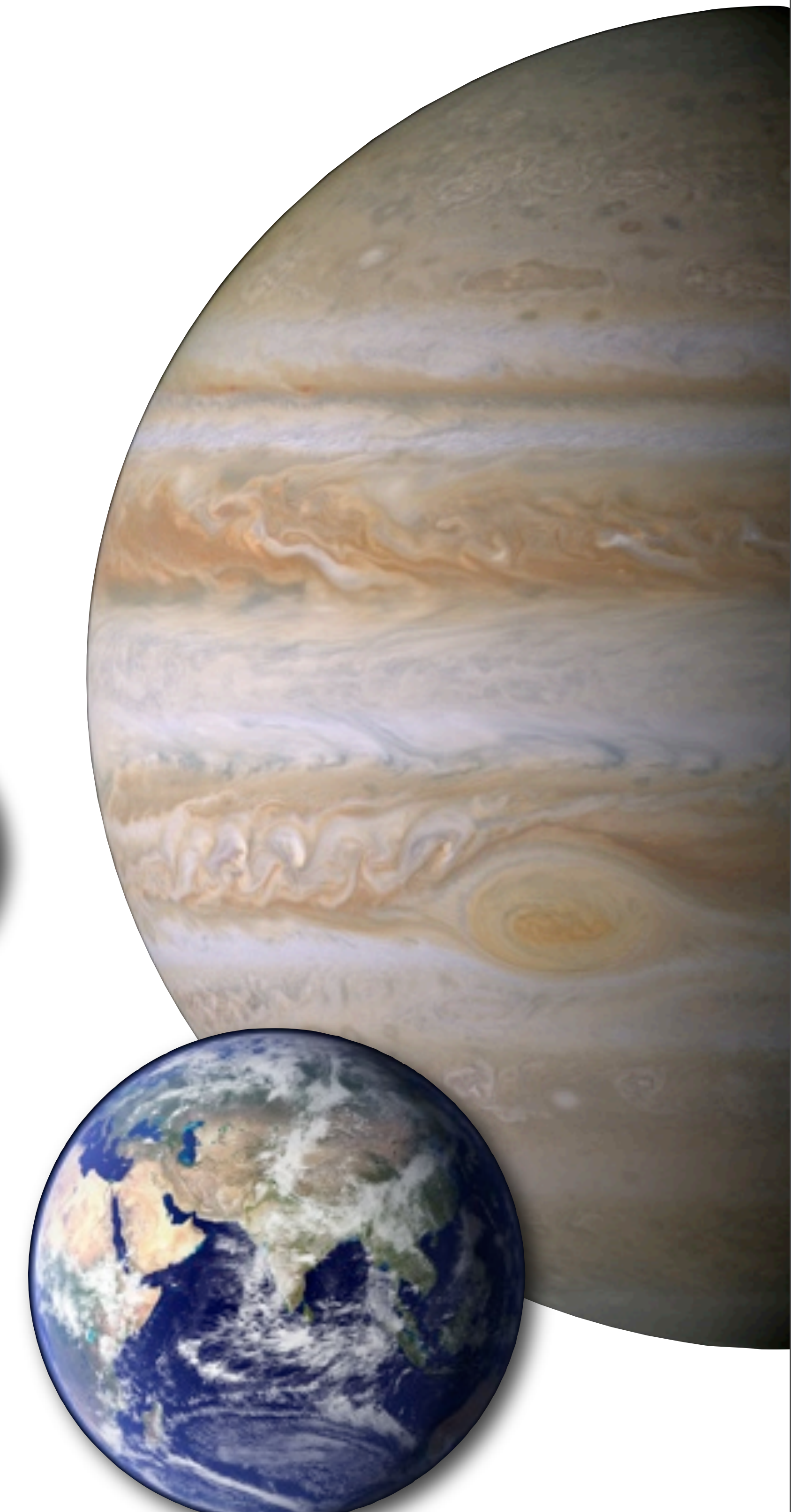
Assume m, g, and T are altitude independent, we get:

$$p(z) = p(0)\ \exp(-z/H)$$

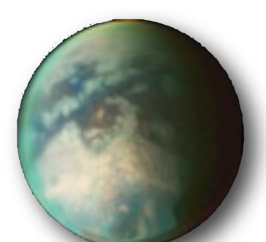
With $H = kT/mg$

Typical pressure scale heights:

- Dense atmospheres $H \sim$ 10-20 km
- Tenuous atmospheres $H >> 20$ km



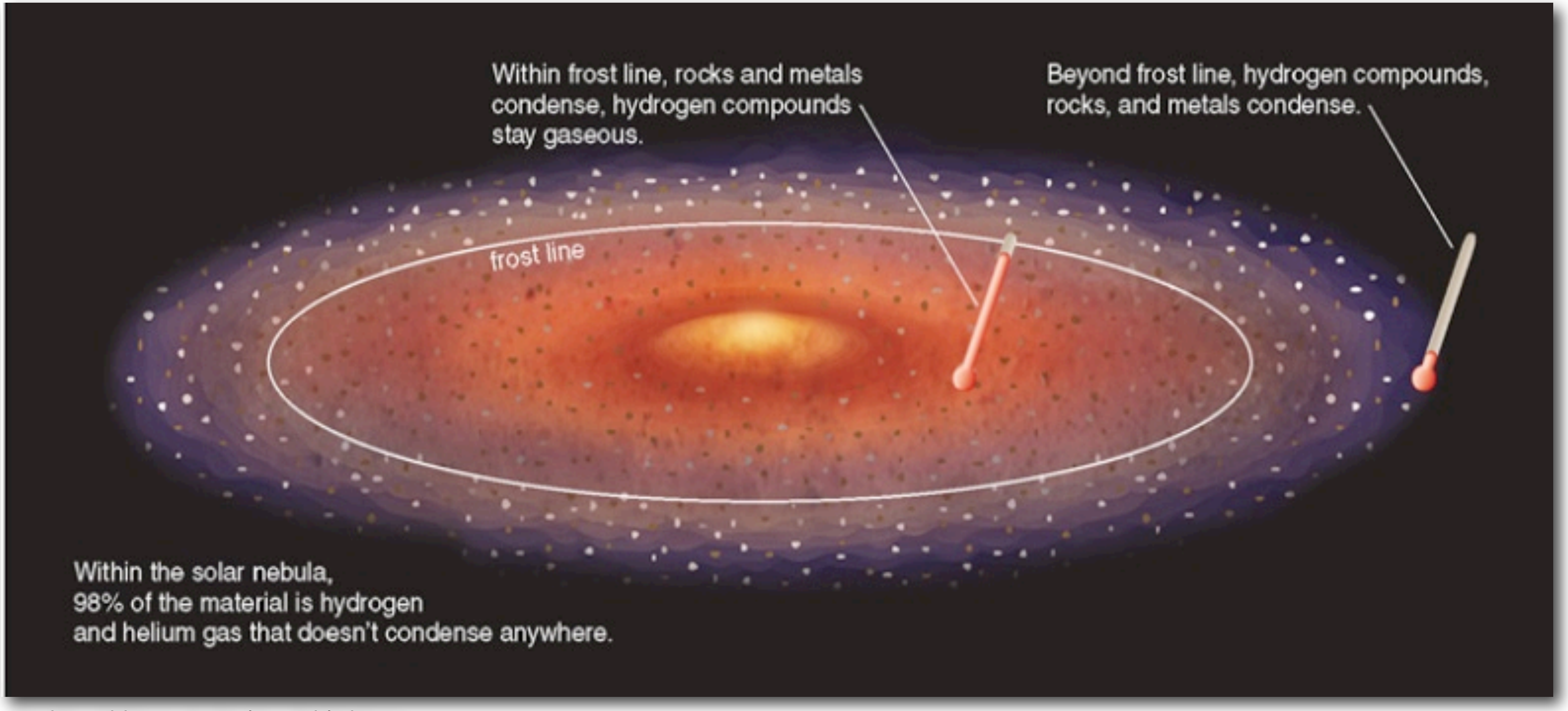
Examples in the Solar System:



- Earth: $H \sim$ 10 km
- Mars: $H \sim$ 12 km
- Titan, $H \sim$ 40 km
- Jupiter, $H \sim$ 20 km

# Origin of planetary atmospheres

The composition and temperature in the protoplanetary disk determines the volatiles that end up in a planet:



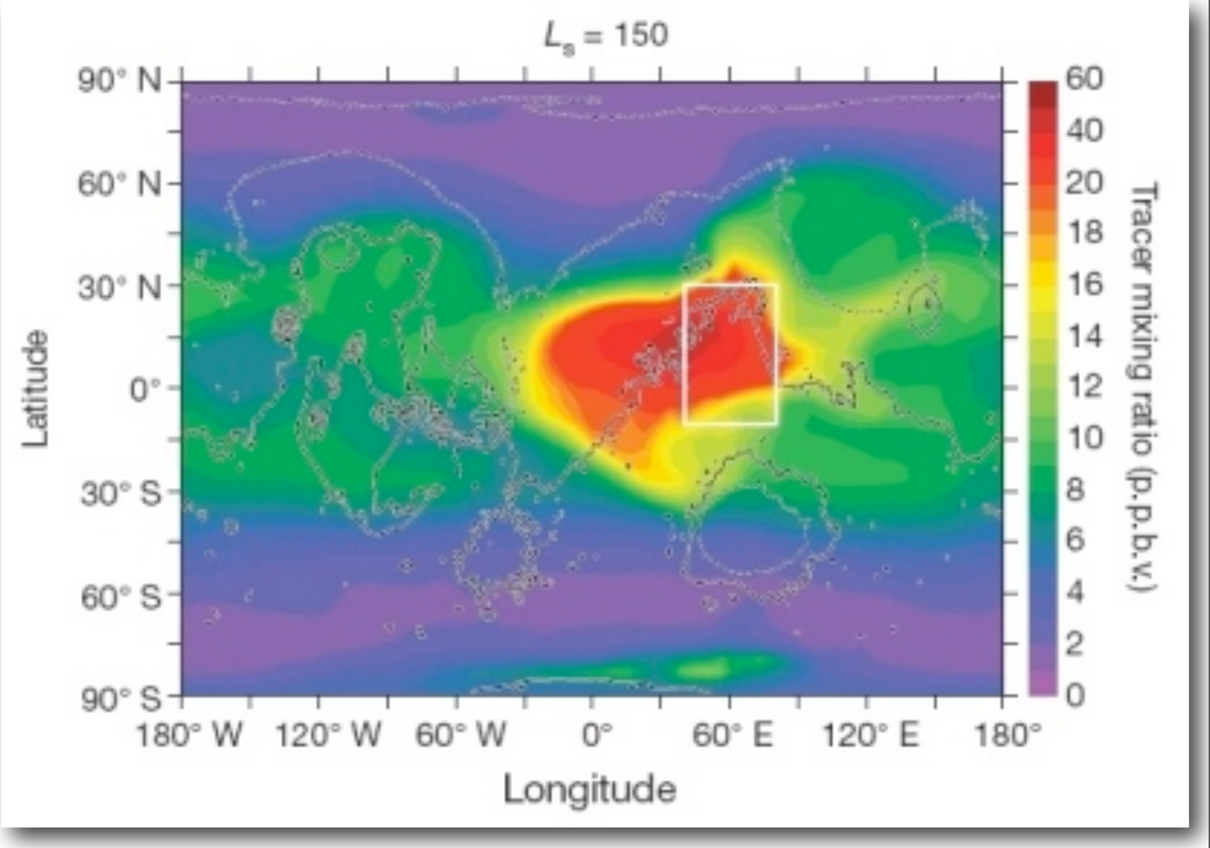

Credit: Addison & Wesley Publishing

The location of the frost/snow/ice line depends on the luminosity of the star, and the density and composition (mixing) of the disk ...

# The composition of planetary atmospheres

Different measures for the amount/abundance/concentration/mixing ratio of gas x in the entire atmosphere (if well-mixed) or at a certain location in the atmosphere (if variable in space/time):

- Volume mixing ratio:
  [volume gas x]/[unit volume]
  [volume gas x]/[volume $H_2$]
- Mass mixing ratio:
  [mass gas x]/[unit mass]
  [mass gas x]/[mass $H_2$]
- Parts per million/billion per volume (ppmv/ppbv)




Simulated methane mixing ratios on Mars [Lefèvre & Forget, 2009, Nature]

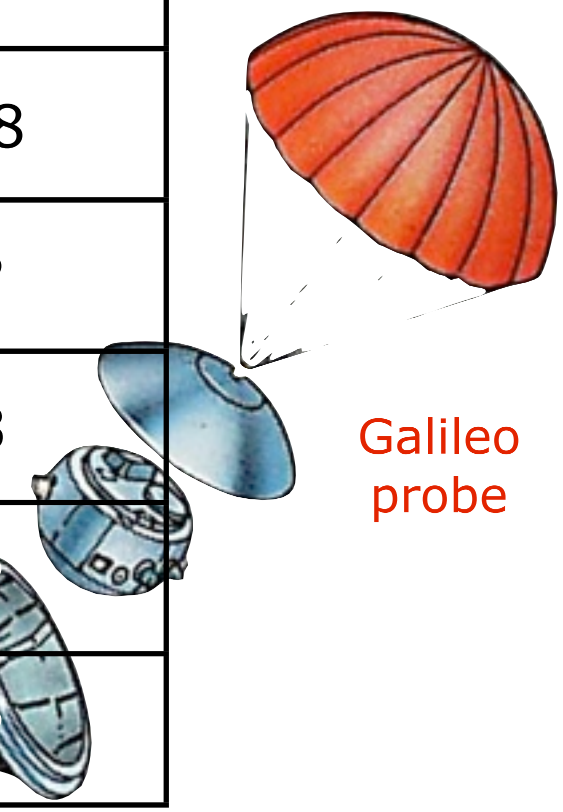
Through the ideal gas law, *pV=nRT*, volume mixing ratios equal number mixing ratios/molar fractions

Other units: Partial pressure, Amagats/Dobson units

# Giant planets' atmospheres

The giant planets got heavy enough to attract gases from the protoplanetary disk:

| | Sun[1] | Jupiter | Saturn[2] | Uranus[3] | Neptune[3] |
|---|---|---|---|---|---|
| $H_2$ | 84 | 86.4 | 97 | 83 | 79 |
| $He$ | 16 | 13.6 | 3 | 15 | 18 |
| $H_2O$ | 0.15 | 0.1 | ? | ? | ? |
| $CH_4$ | 0.07 | 0.21 | 0.2 | 2 | 3 |
| $NH_3$ | 0.02 | 0.07 | 0.03 | ? | ? |
| $H_2S$ | 0.003 | 0.008 | ? | ? | ? |



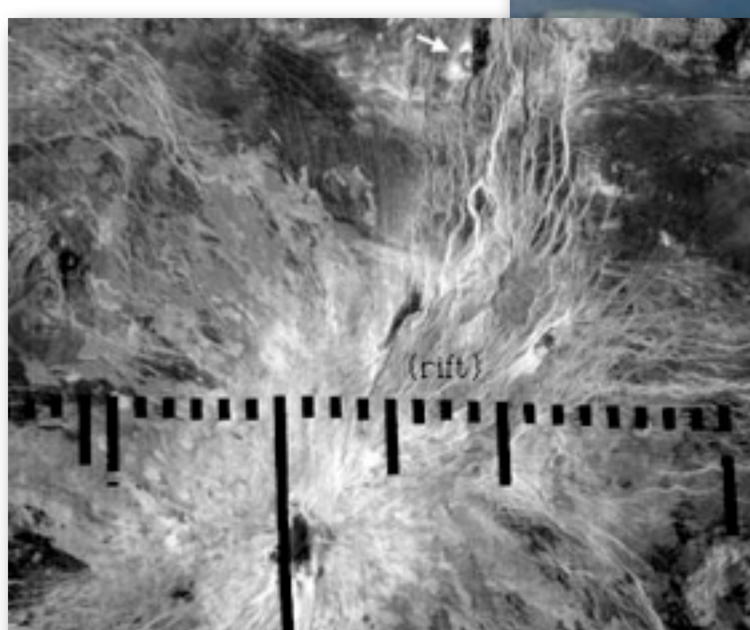
Galileo probe

1. When cooled down to the temperatures of the giant planets
2. Helium depleted due to condensation in metallic hydrogen
3. Enrichment in heavy elements might signal a late formation

# Terrestrial planets’ atmospheres

The small, terrestrial planets could not attract significant amounts of gases in the protoplanetary disk. Their atmospheres formed by out-gassing of planetsimals, volcanic eruptions and meteorite/comet impacts.

Mars: Olympus Mons,
25 km of altitude




Venus: Theia Mons,
4 km altitude

Earth: Chaiten volcano, Chile

Composition terrestrial volcano-gas:
75% $H_2O$, 10% $SO_2$, 2% $CO_2$,
HCl, HF, $H_2S$, CO, ...

# Terrestrial planets' atmospheres

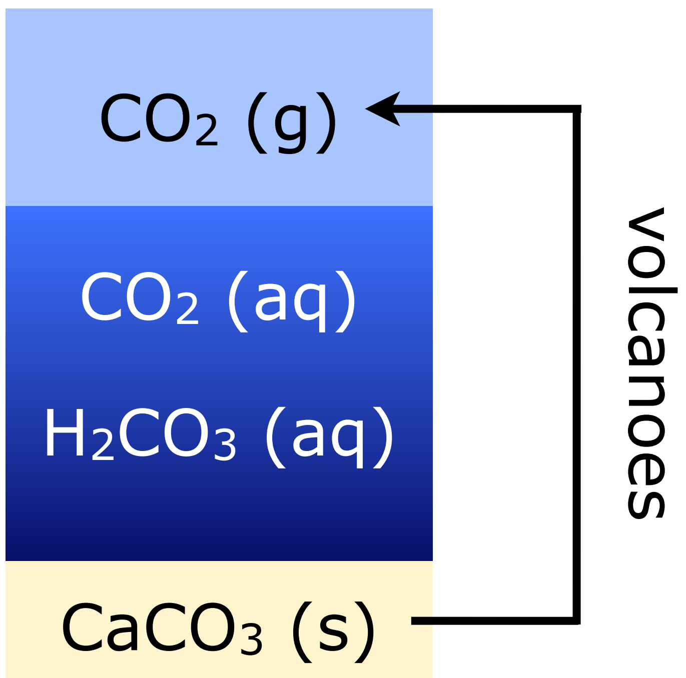
The composition of the atmospheres of terrestrial planets:

| | Venus | Earth | Mars | Titan |
|---|---|---|---|---|
| $p(0)$ [bar] | 92 | 1 | 0.006 | 1.5 |
| $T(0)$ [C] | 470 | 15 | -45 | -180 |
| **$N_2$** | 0.035 | **0.78** | 0.027 | **0.90-0.97** |
| **$O_2$** | 0-20 ppm | **0.2095** | 0.13 ppm | - |
| **$CO_2$** | **0.965** | 345 ppm | **0.953** | 10 ppb |
| **$CH_4$** | - | 3 ppm | - | 0.005-0.04 |
| **$H_2O$** | **50 ppm** | **< 0.03** | **< 100 ppm** | **0.4 ppb** |
| **Ar** | 70 ppm | 0.009 | 0.016 | 0.0-0.06 |
| **CO** | 50 ppm | 0.2 ppm | 700 ppm | 10 ppm |
| **$O_3$** | - | 10 ppm | 0.01 ppm | - |

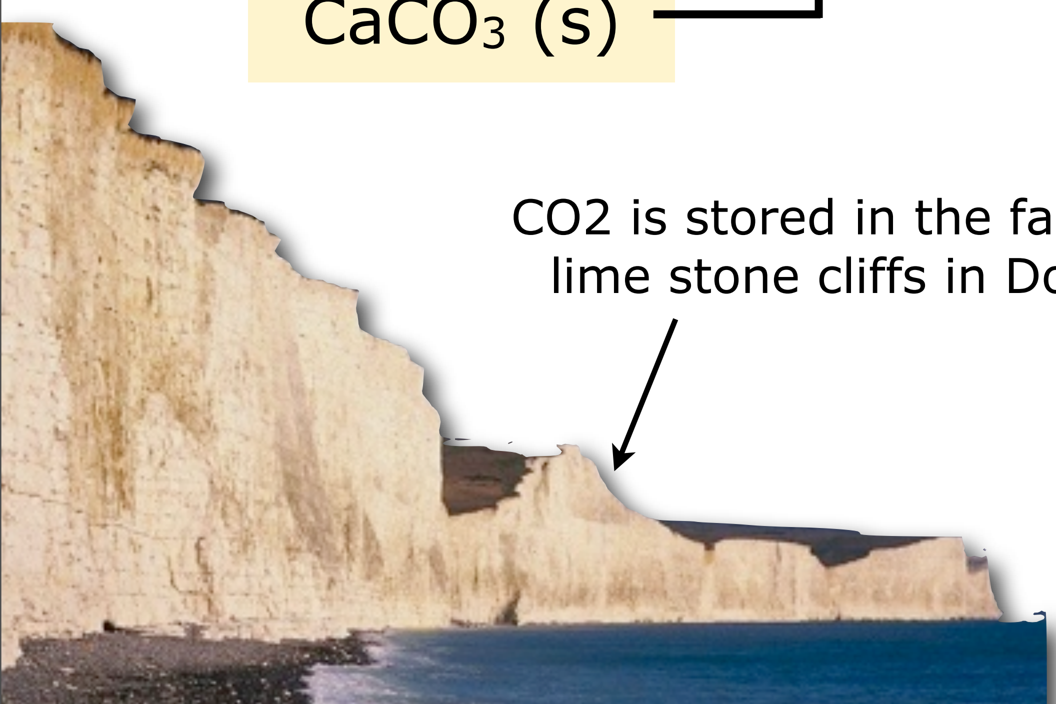
1. Numbers from Table 4.3 of Planetary Sciences
2. All numbers are given in volume mixing ratios, ppm, or ppb
3. There are numerous other trace gases in these atmospheres ...

# Where on Earth did the $CO_2$ go?

The original composition of the Earth's atmosphere should have been very similar to those of Venus and Mars. On Earth, however, atmospheric $CO_2$ can dissolve into the liquid water of the oceans:



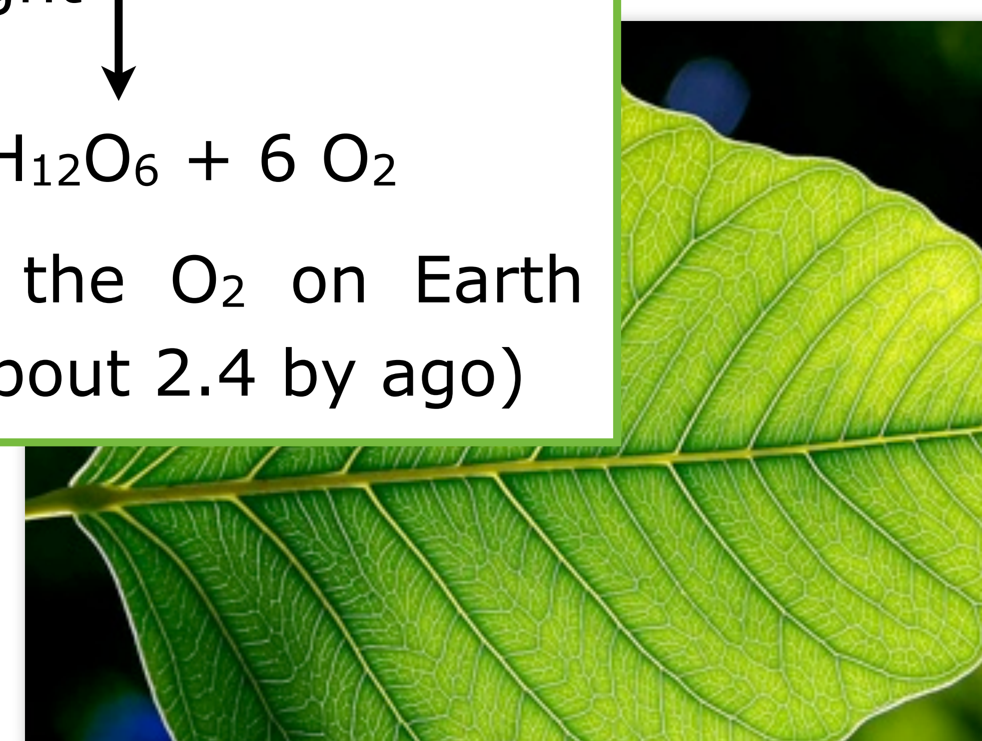

CO2 is stored in the famous lime stone cliffs in Dover



On Earth, $CO_2$ is also used in photosynthesis processes:

$$6\ CO_2 + 6\ H_2O \xrightarrow{\text{light}} 6\ C_6H_{12}O_6 + 6\ O_2$$

Explaining the $O_2$ on Earth (starting about 2.4 by ago)

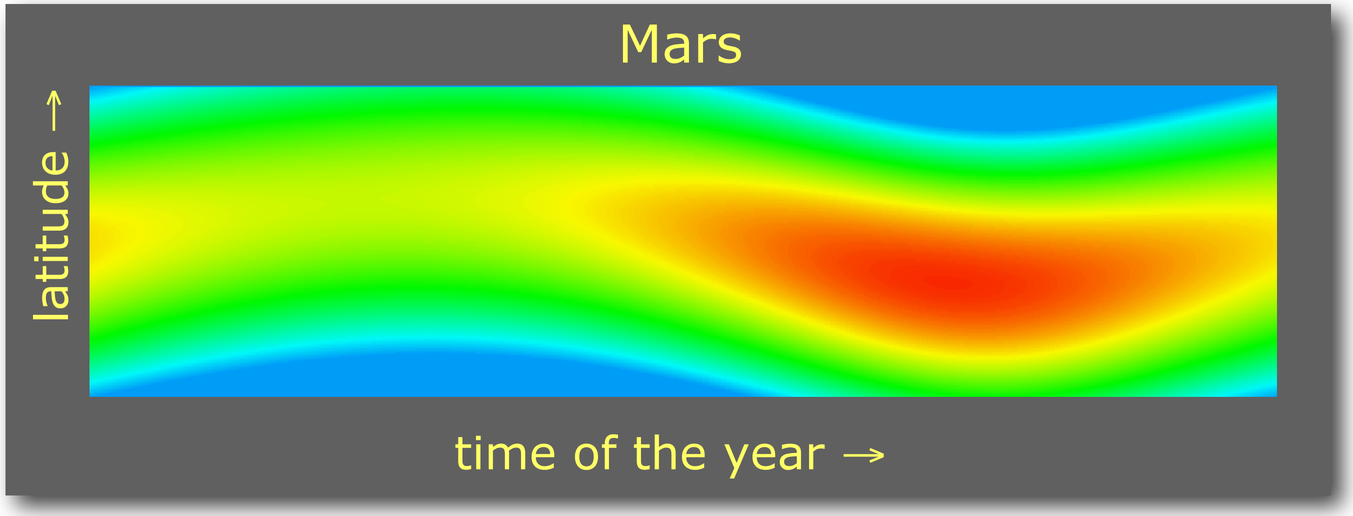


# Temperature profiles of atmospheres 1

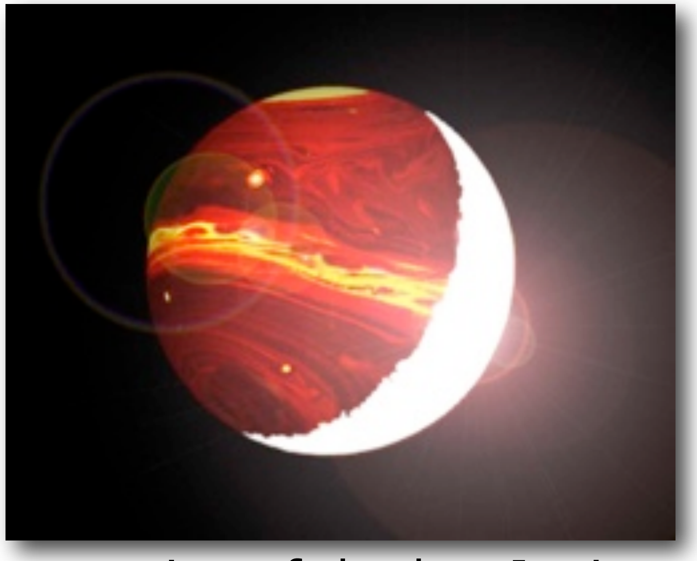
The temperature profile of a planetary atmosphere depends on:

- The solar irradiation
    - orbital distance
    - rotation rate
    - obliquity

Equilibrium temperature



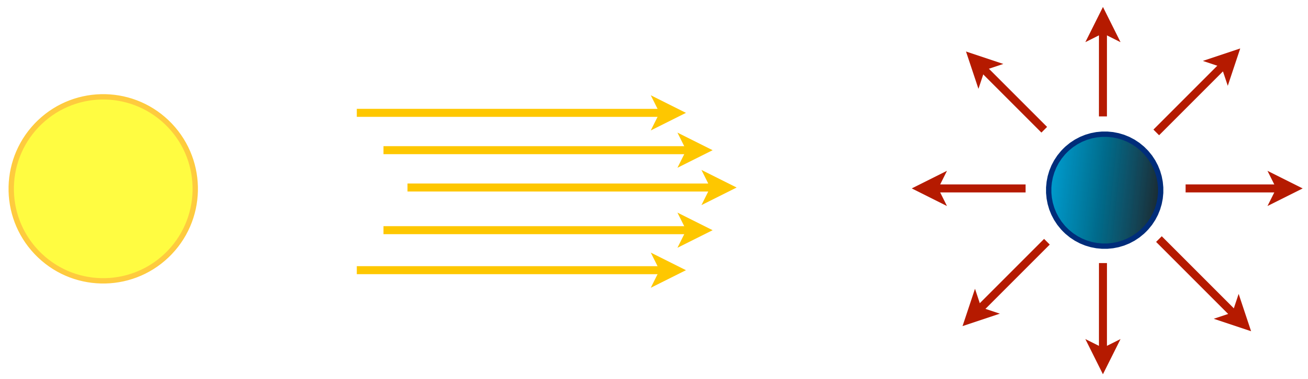

- Surface irradiation
    - internal heat sources
    - surface reflectivity and emissivity
- Atmospheric composition
    - mixing ratios (especially of Greenhouse gases)
    - vertical and horizontal distributions



Artist's impression of the hot Jupiter circling HD149026 (U.C. Santa Cruz)

# A planet's equilibrium temperature

The equilibrium temperature $T_e$ of a planet is calculated under the assumption that the incoming stellar irradiance (flux) is balanced by the outgoing planetary flux.



The equilibrium temperature is given by: $4\pi\ \sigma\ T_e^4 = (1\text{-}a)\ L\ /\ 4d^2$

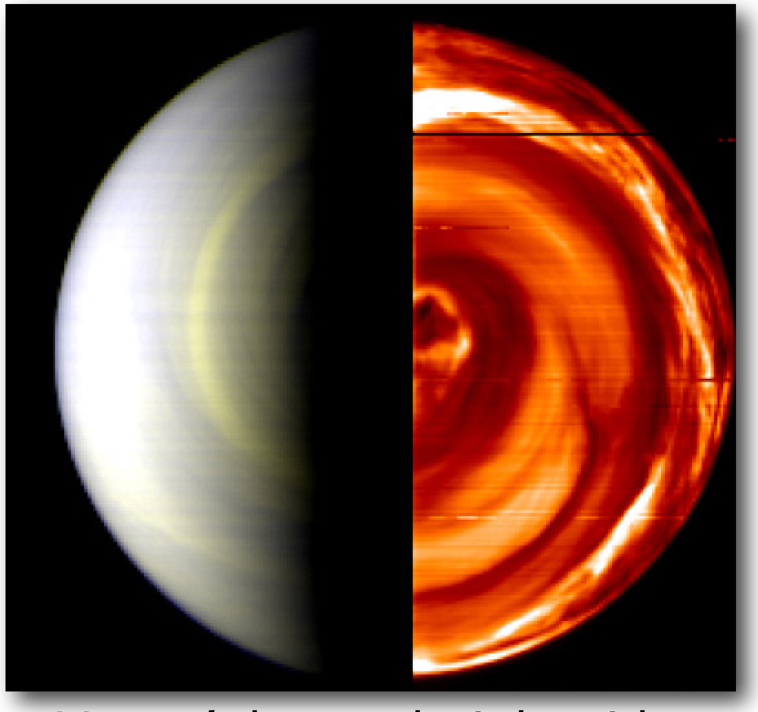
With:

- $\sigma$ the constant of Stefan-Boltzmann ($5.670\ 10^{-8}$ W m$^{-2}$ K$^{-4}$)
- $a$ the albedo of the planet
- $L$ the luminosity of the star
- $d$ the orbital distance of the planet

# Temperature profiles of atmospheres 2

The temperature profile of a planetary atmosphere depends on:

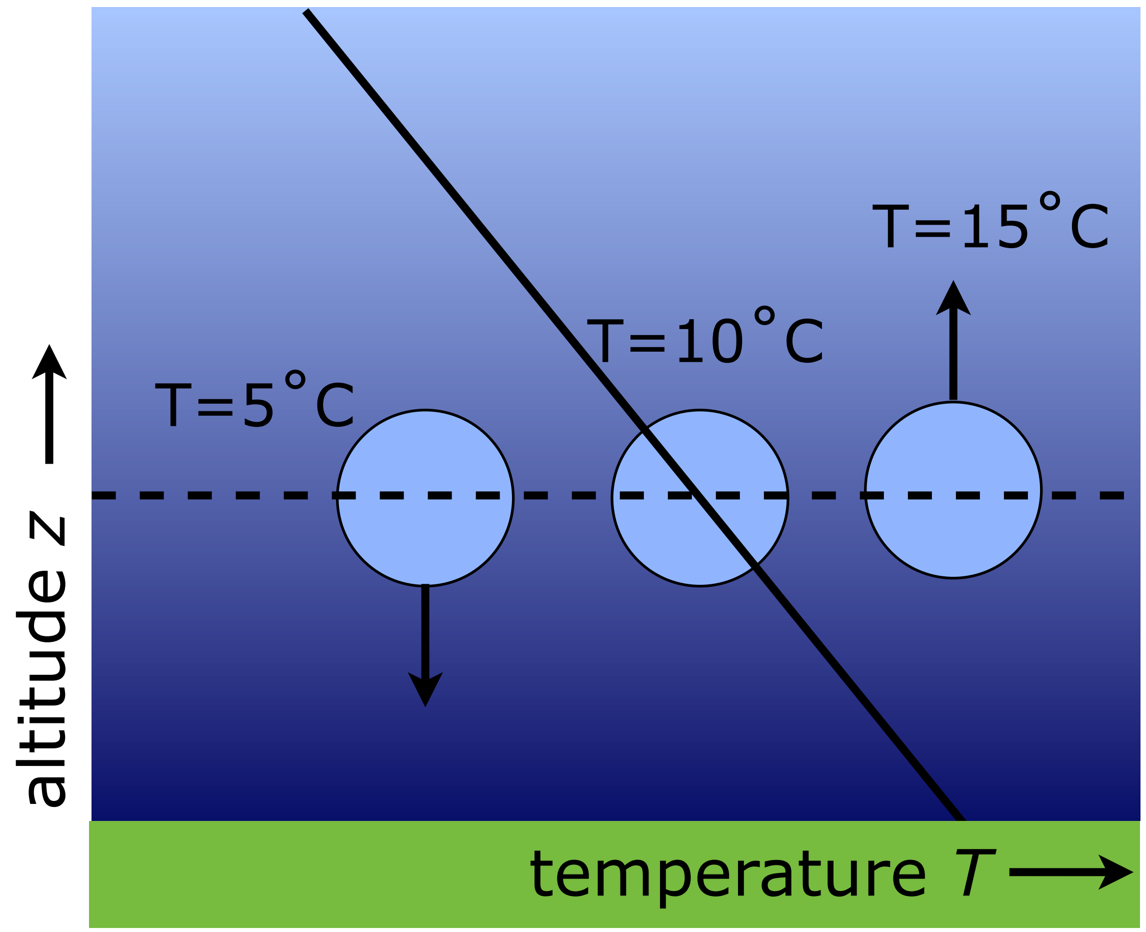
- Aerosol and cloud particles
    - microphysical properties (size, shape, composition)
    - vertical and horizontal distributions
- Chemical reactions
    - reactions in the atmosphere
    - exchange between surface and atmosphere (evaporation)
- Transport of energy
    - **convection**
    - radiative processes
    - conduction (collisions)



Venus' day and night side
(VIRTIS, Venus Express, ESA)

# Convection

Convection is the motion in a fluid or dense gas caused by density gradients that result from temperature differences:



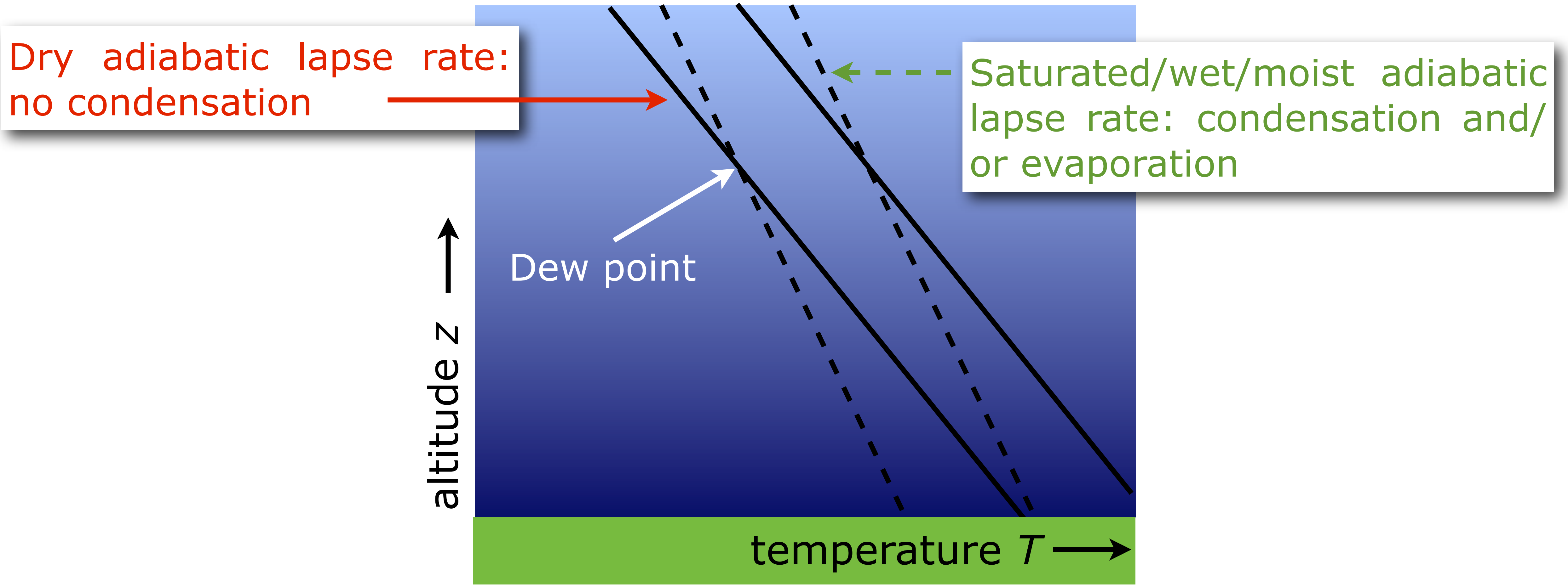

A parcel that is warmer than its surroundings, will expand, its density decreases below that of the surroundings, and the parcel will rise. As it rises, the ambient pressure drops, the parcel expands and cools down. As long as its temperature is above the ambient temperature, it will rise.

# Adiabatic lapse rates

An adiabatic process is a process in which no heat is exchanged with the surroundings:

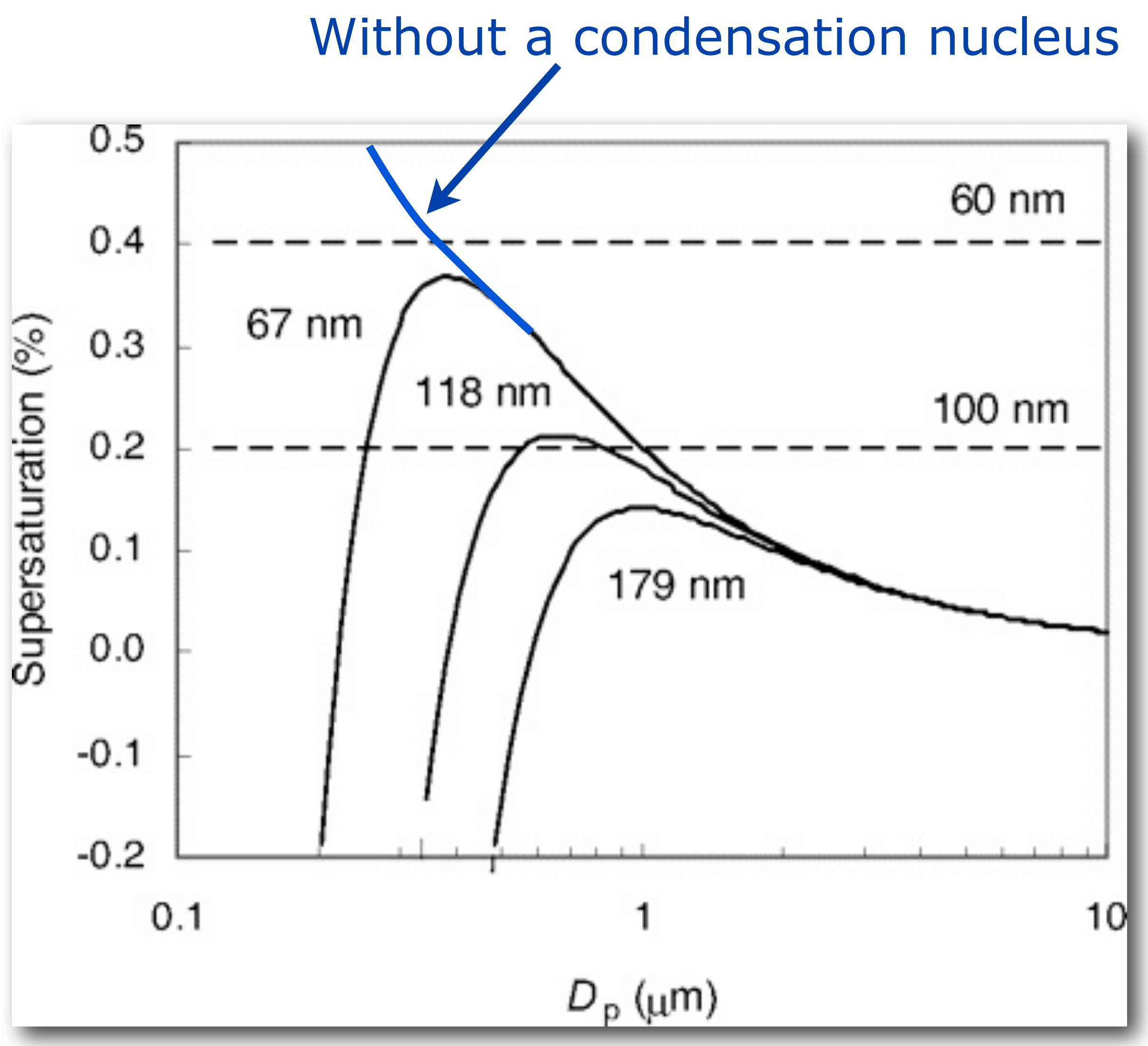
- a parcel of air expands and cools down
- a parcel of air is compressed and heats up

In a part of an atmosphere where convection is the dominant energy transport process, the temperature gradient follows an *adiabatic lapse rate*:

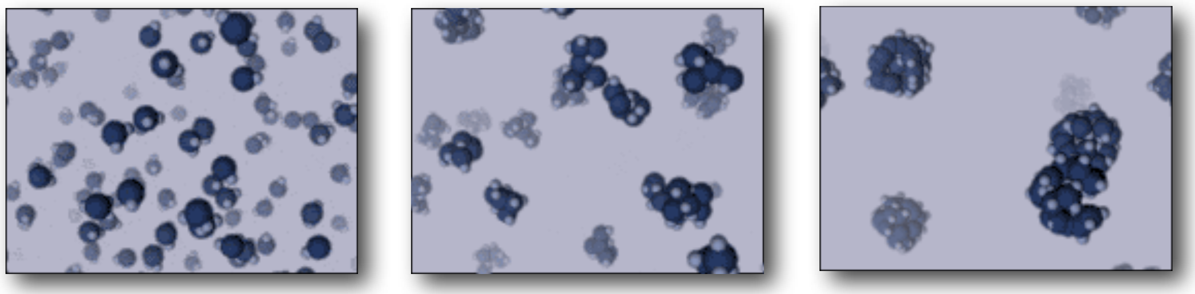


# Cloud formation

For cloud particle condensation to start, liquid and solid cloud particles require a surface to overcome the surface tension. Several types of aerosol particles can serve as cloud condensation nuclei:

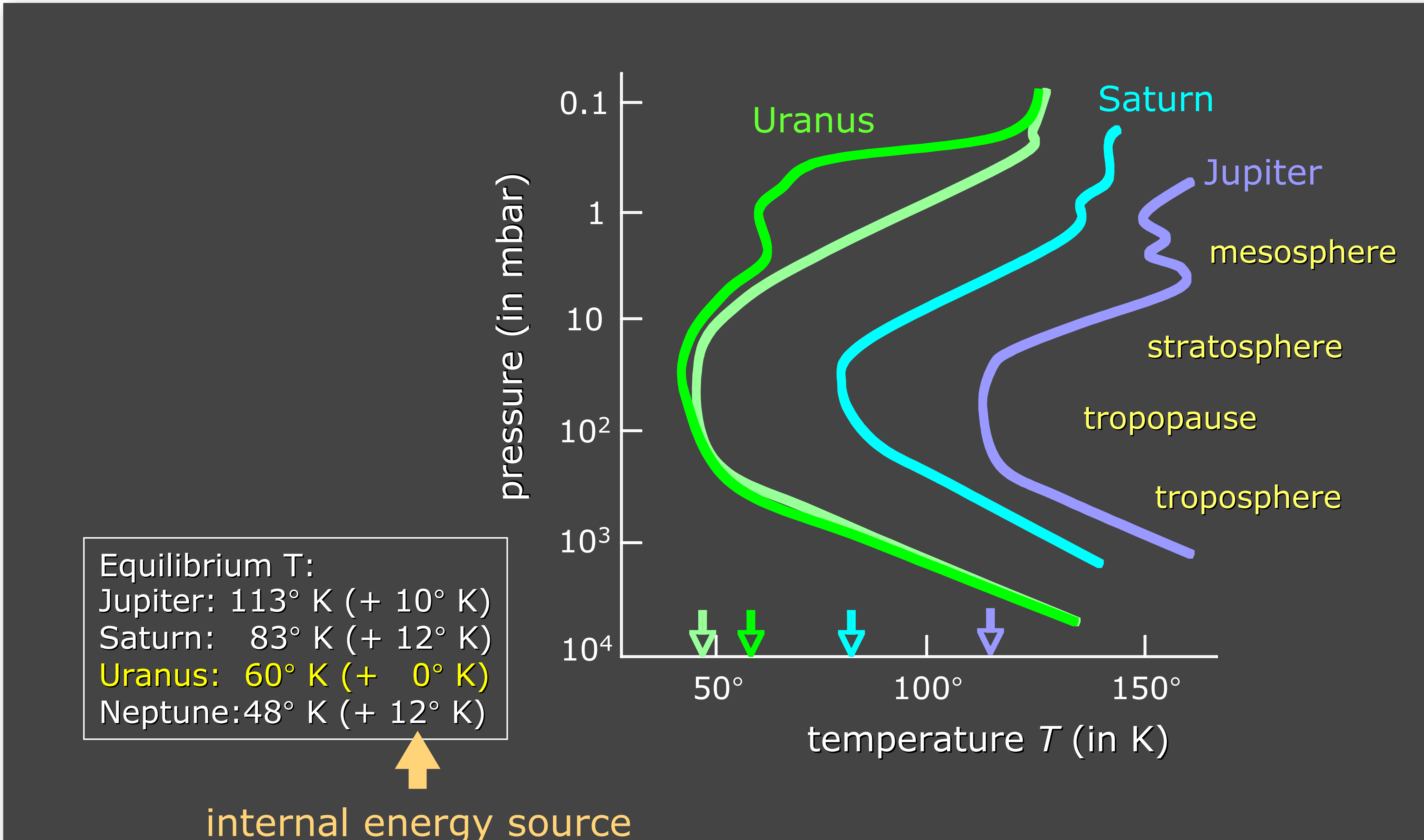



Cloud particle sizes as functions of the supersaturation ratio $S$ for different sizes of soot particles [Zhang et al., 2008].



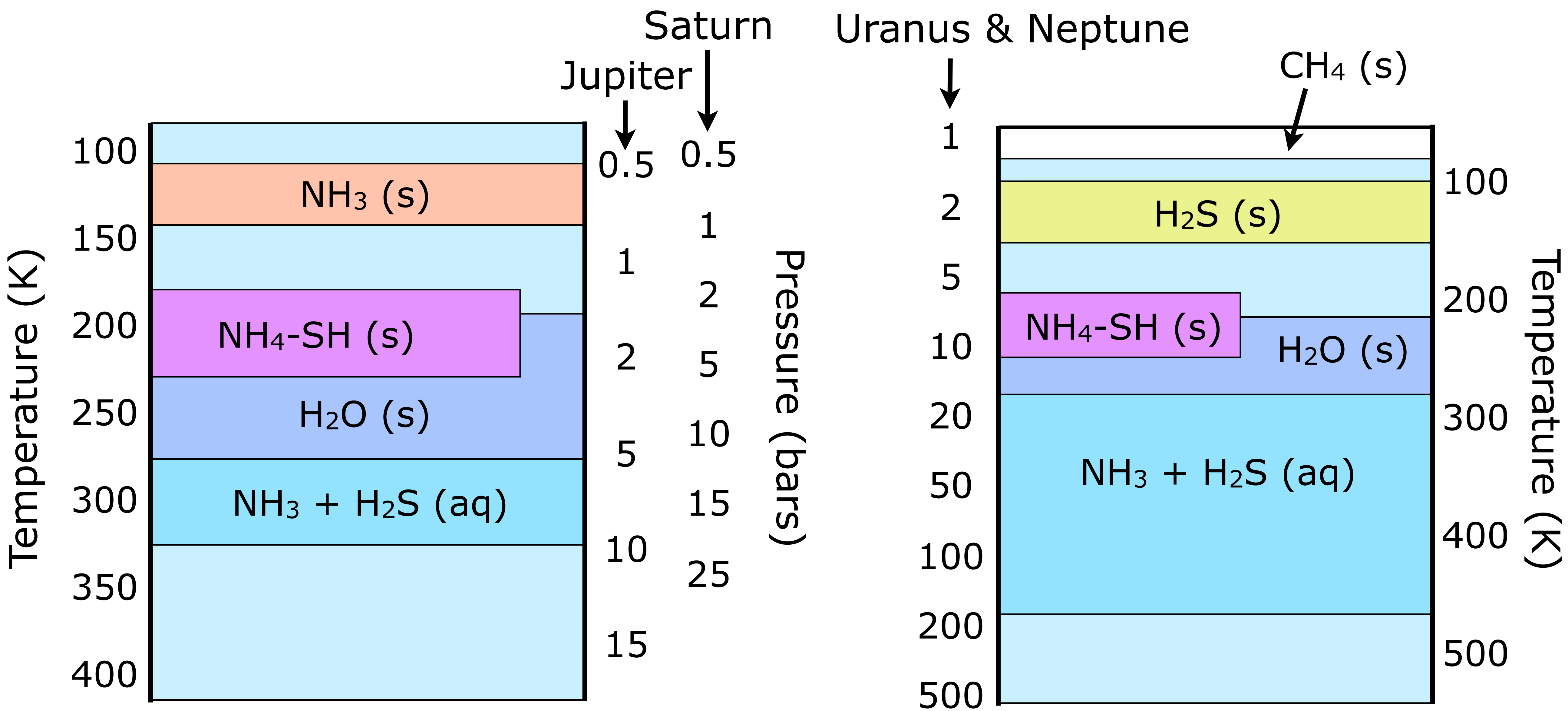
Supersaturation:
The vapour pressure of a gas is larger than the saturation vapour pressure above a plane liquid surface at that temperature

# Temperature profiles on the giant planets



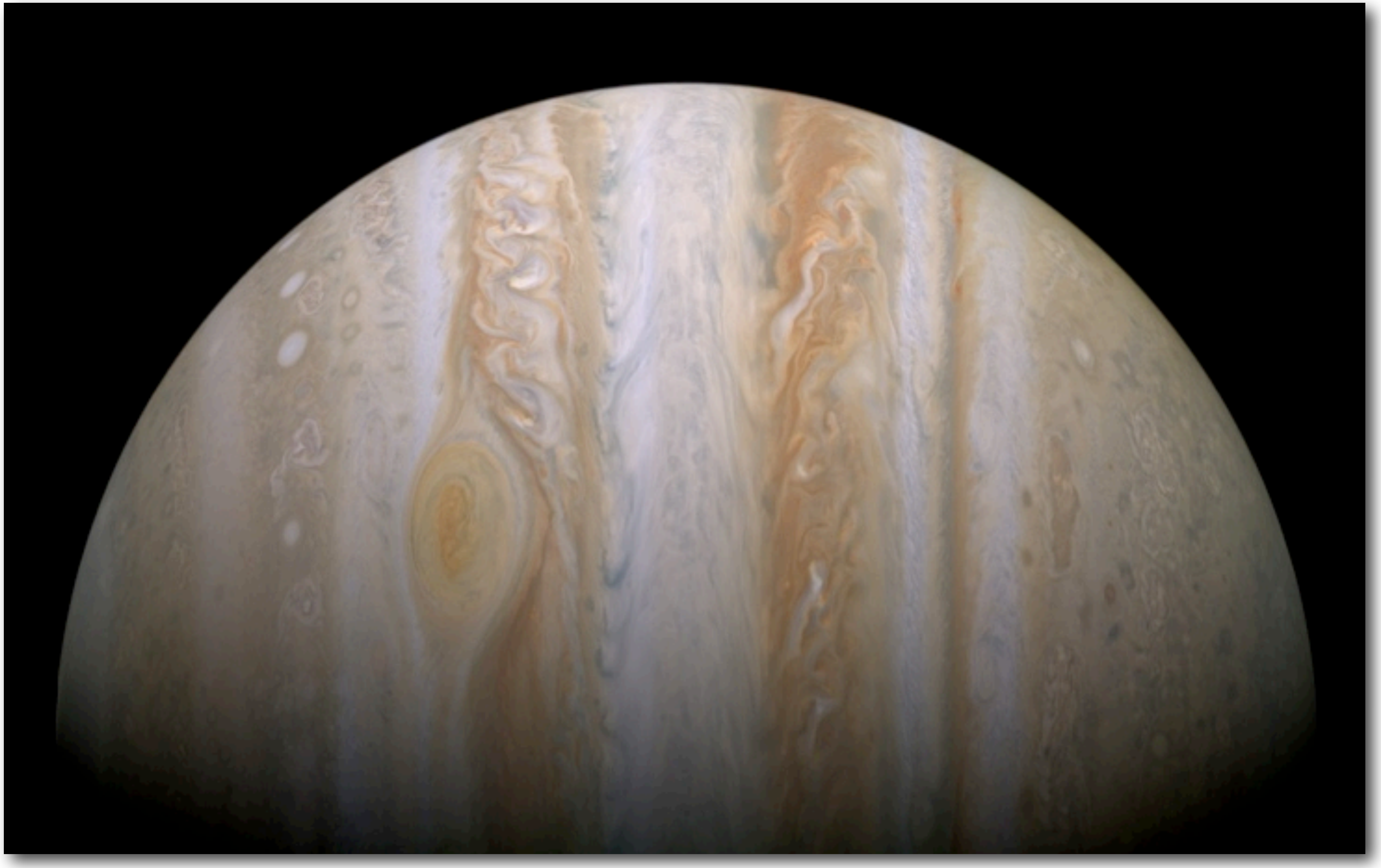
# Clouds on the giant planets

Sketch of the cloud layers in the giant planet atmospheres as suggested by model atmosphere calculations (de Pater et al., 1991). These clouds result from condensation of $CH_4$, $NH_3$, $H_2S$, and $H_2O$:



# Examples of clouds on Jupiter 1

The clouds on Jupiter are divided into belts (dark) and zones (bright). Belt clouds appear to be deeper in the atmosphere than zonal clouds. Winds in belts blow in the opposite direction from those in the zones:

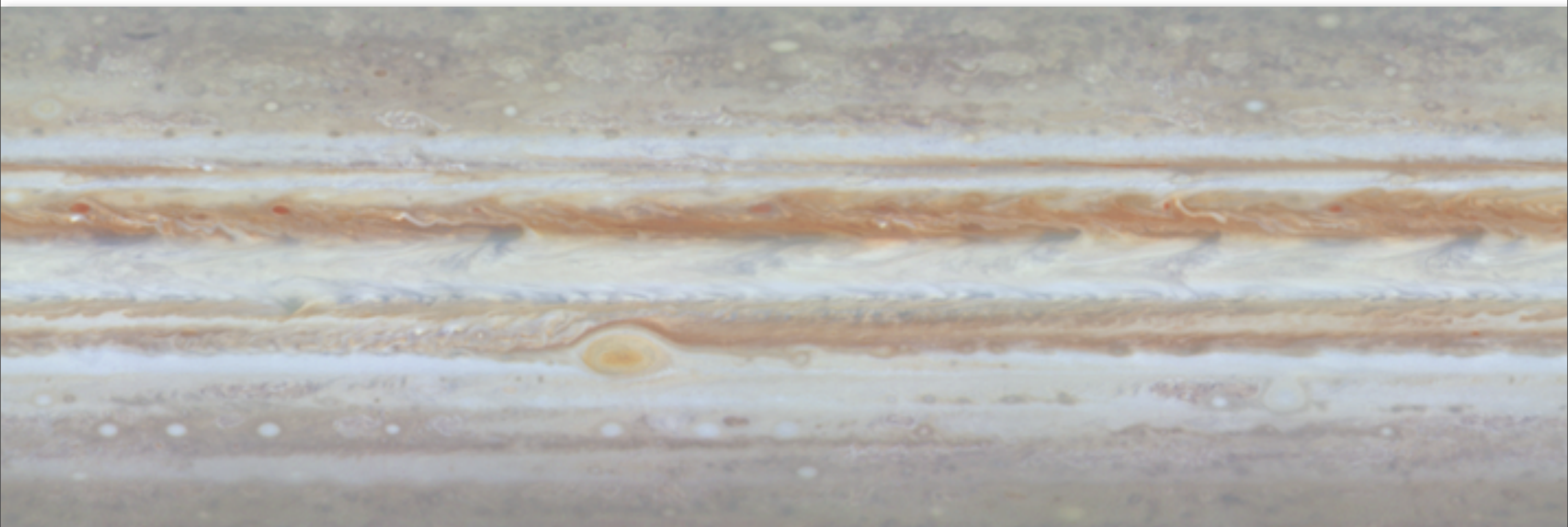


Great Red Spot: anticyclonic storm that has lasted for at least 200 years. Changes shape and colour in time.

Jupiter as seen by Cassini during its fly-by [NASA/ESA]

# Examples of clouds on Jupiter 2

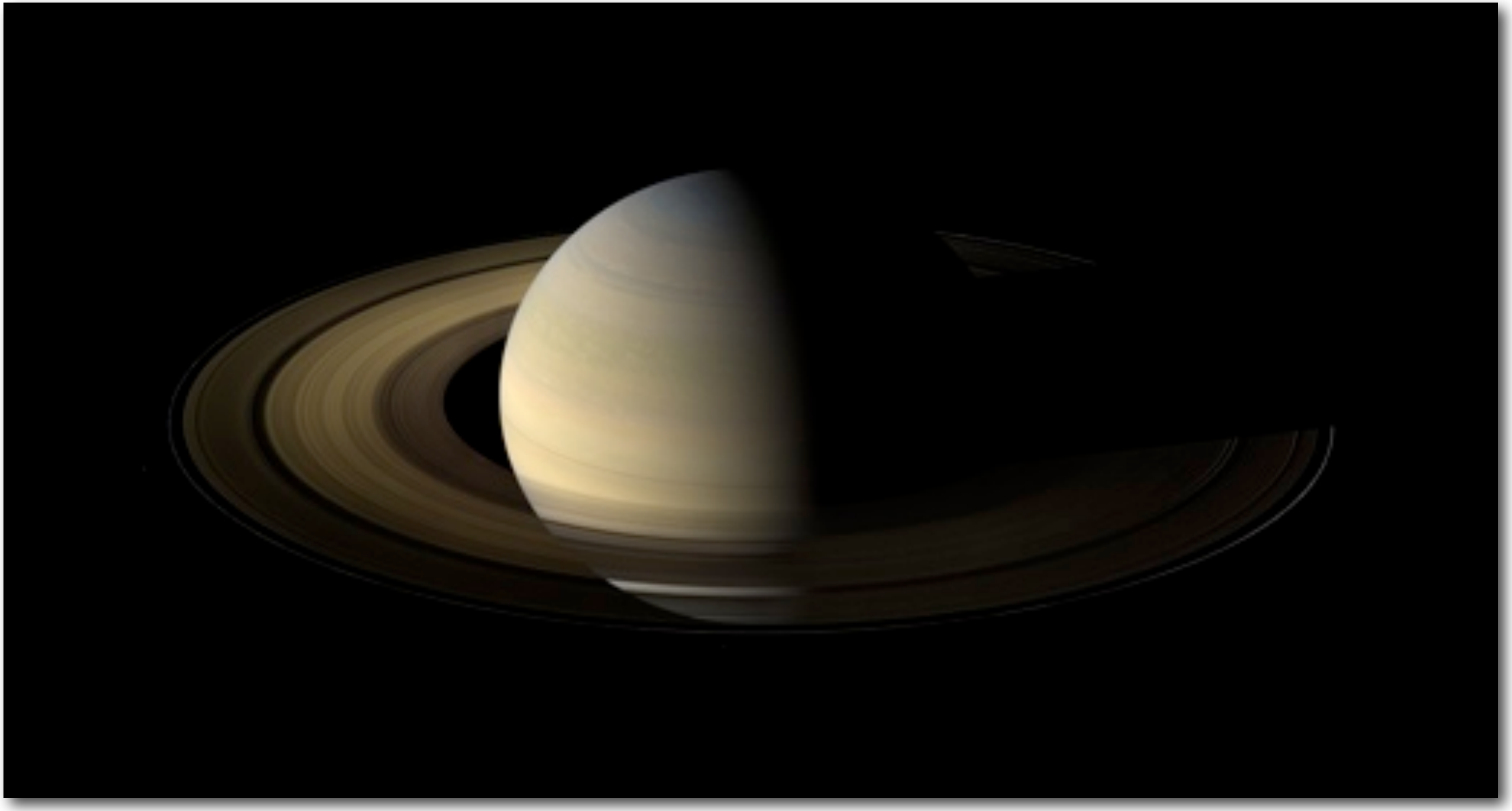
Movie of the moving clouds, vortices and white ovals on Jupiter. Dark spots are moons or shadows of moons:



Jupiter as seen by Cassini during its fly-by [NASA/ESA]

# Examples of clouds on Saturn 1

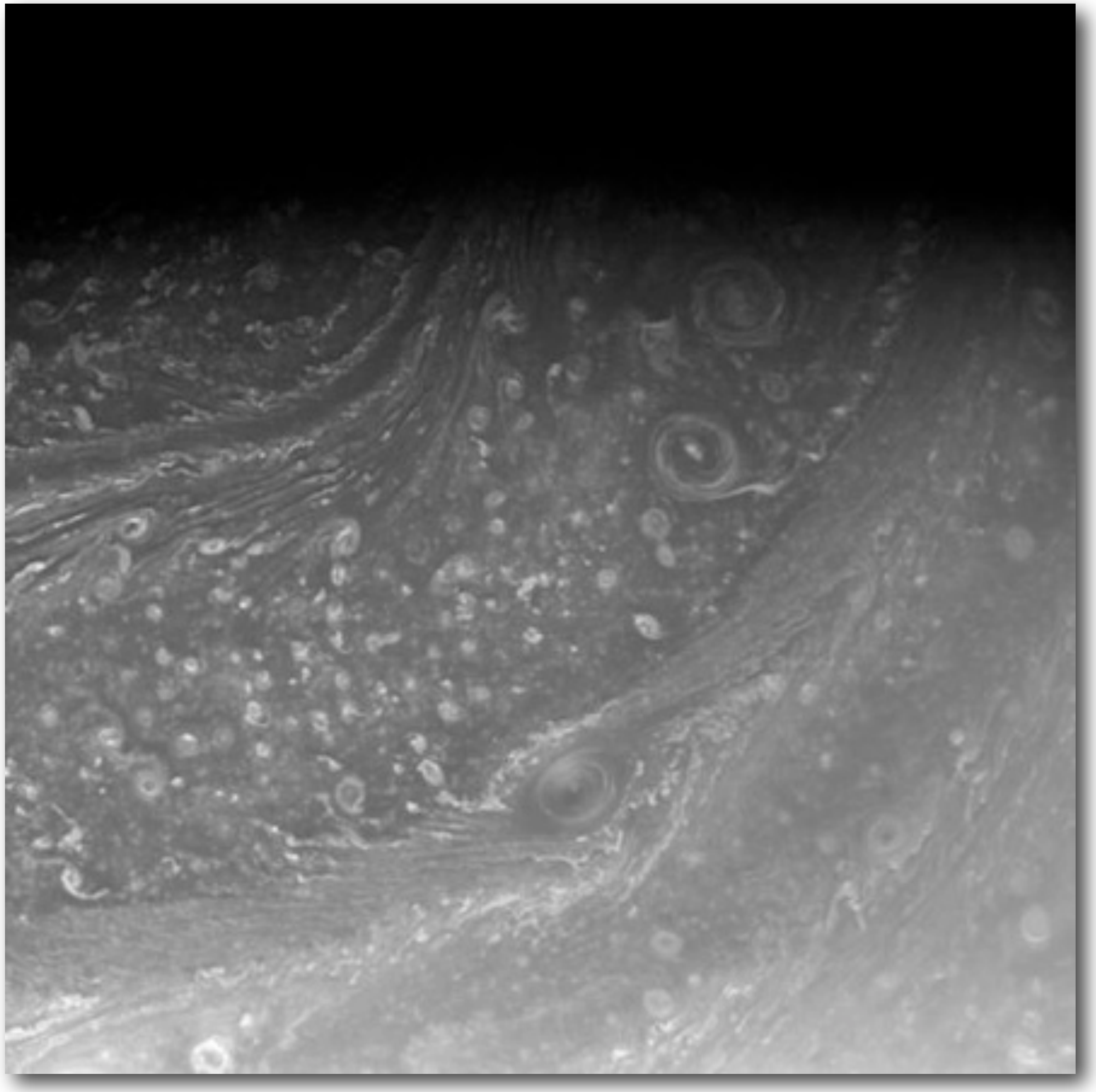
The zones and belts of Saturn are less pronounced than Jupiter's. Saturn has a layer of photochemical haze extending above the clouds:



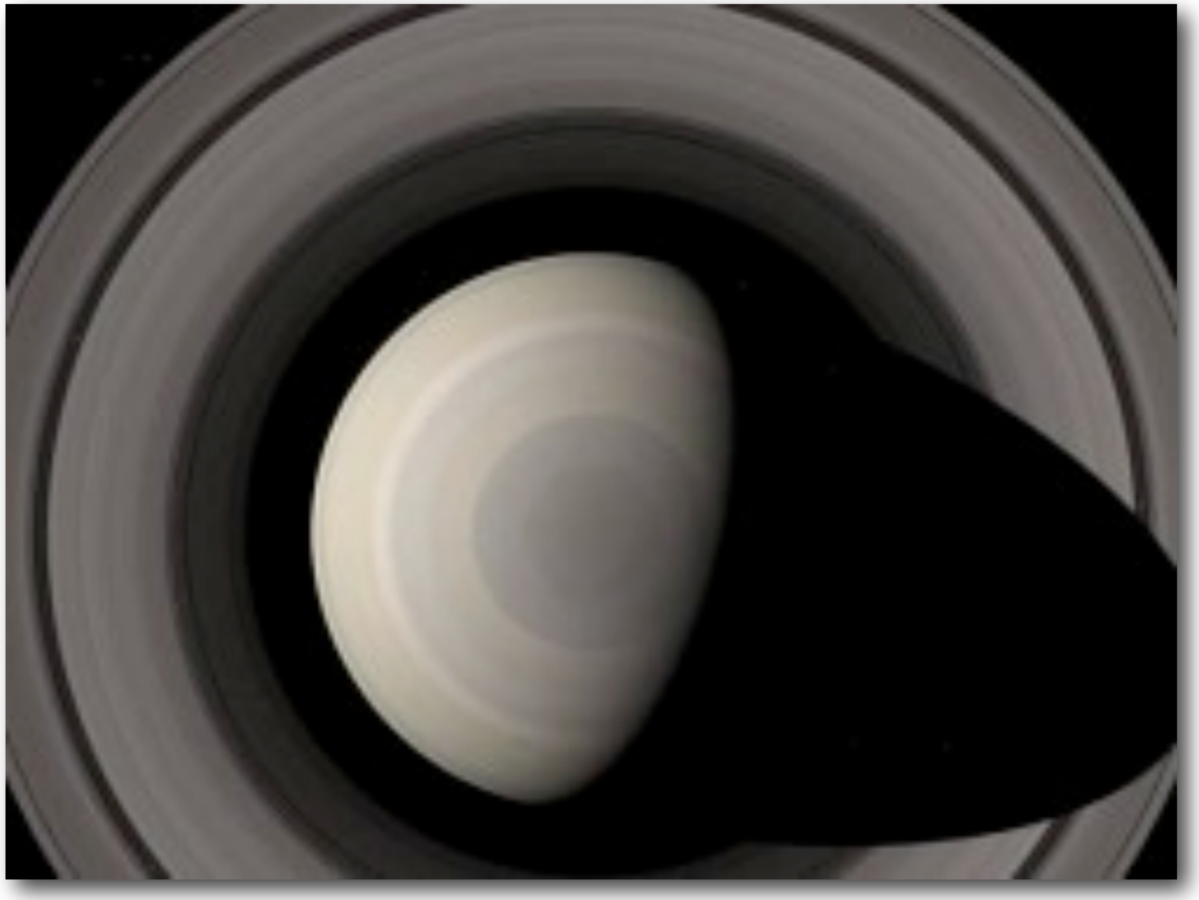
Credit: Cassini, NASA/ESA

# Examples of clouds on Saturn 2

Around Saturn’s north pole, clouds rotate in an hexagonal shape, that was already observed by Voyagers 1 and 2, and thus seems a persistent feature:



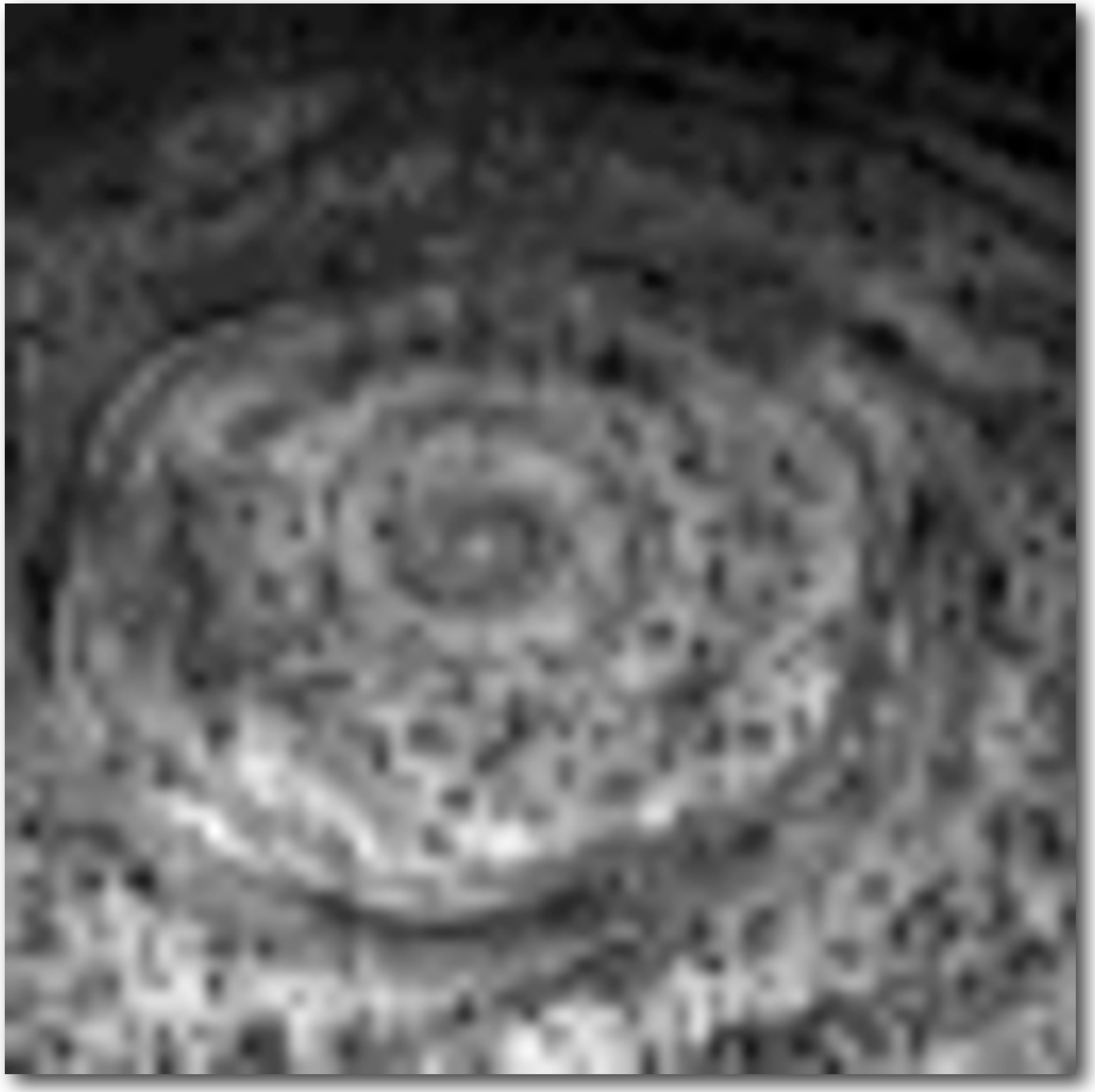
Saturn’s North polar region, with the hexagon on the upper left. Credit: Cassini, NASA/ESA



Saturn’s North polar region, with the hexagon. Credit:Voyager 1, NASA.

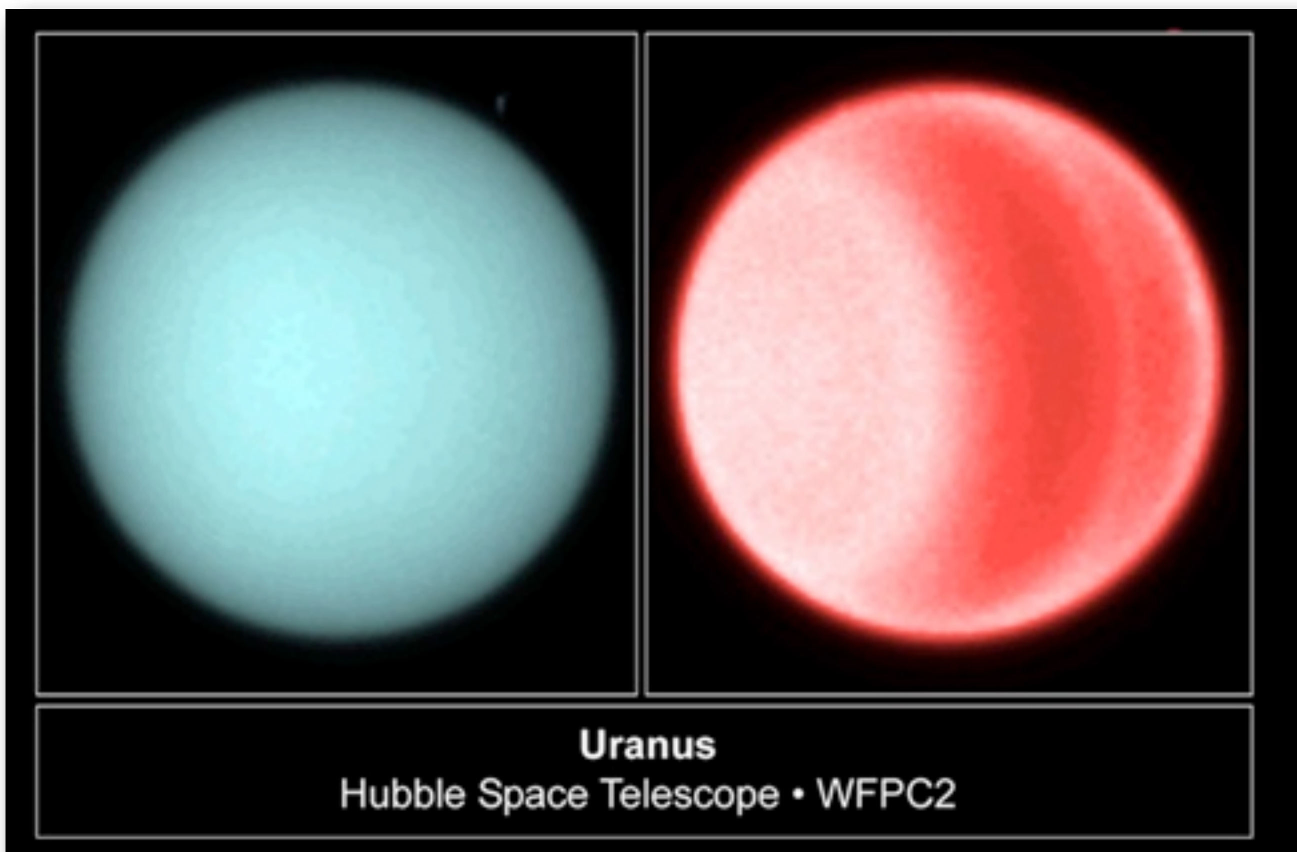
# Examples of clouds on Saturn 3

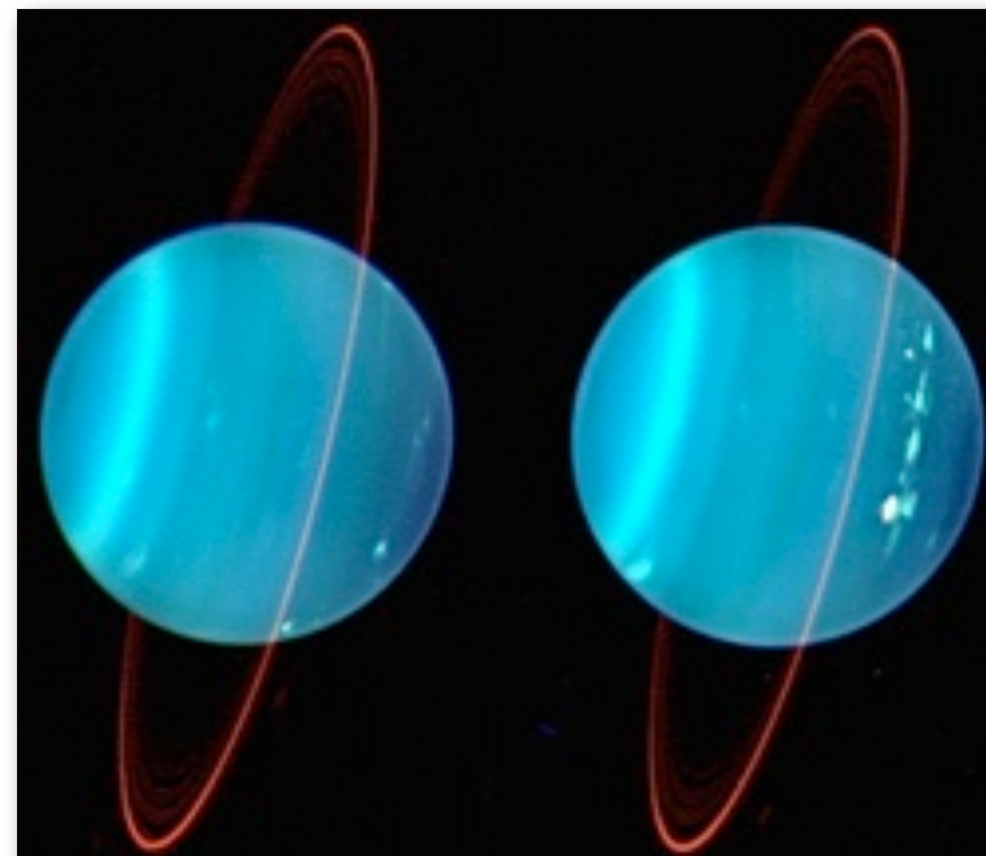
The hexagon rotates at the same rate as Saturn itself. Below: a movie from infrared observations by Cassini [NASA/ESA]:



# Examples of clouds on Uranus

At visible wavelengths, Uranus is featureless. At near infrared wavelengths, methane ice clouds become visible. The planet just passed its equinox, and the changing seasons are expected to strongly influence the cloudiness:

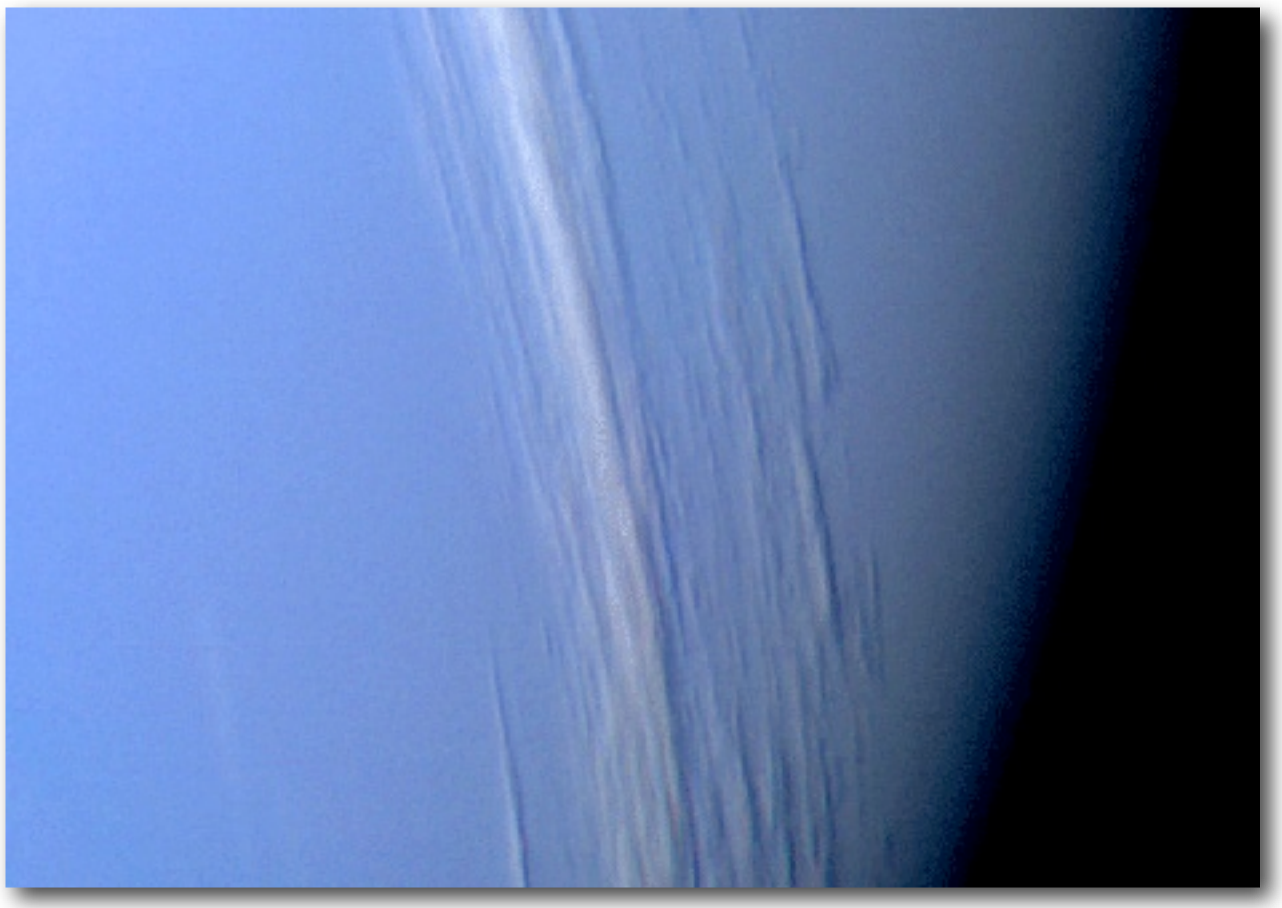


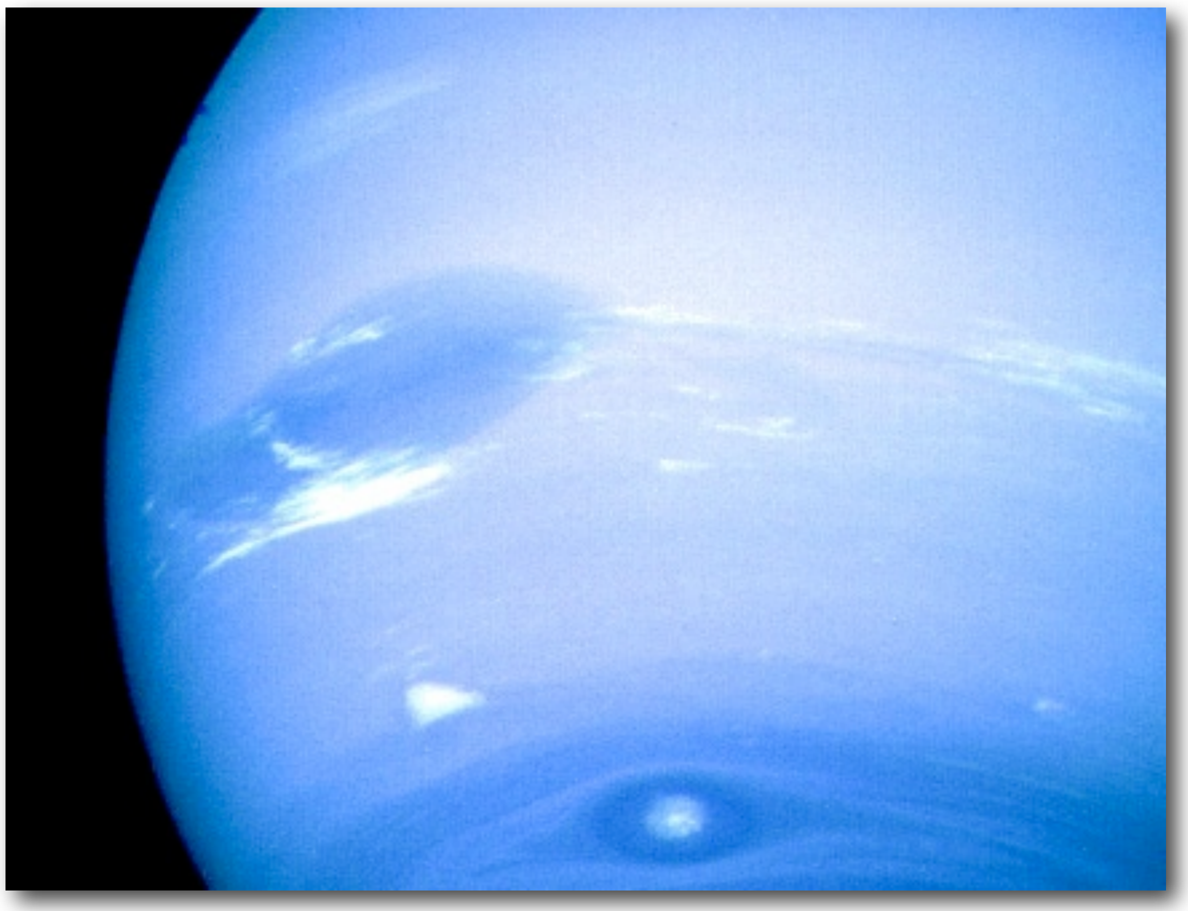



Credit:Karkoschka et al. (Keck telescope)

# Examples of clouds on Neptune

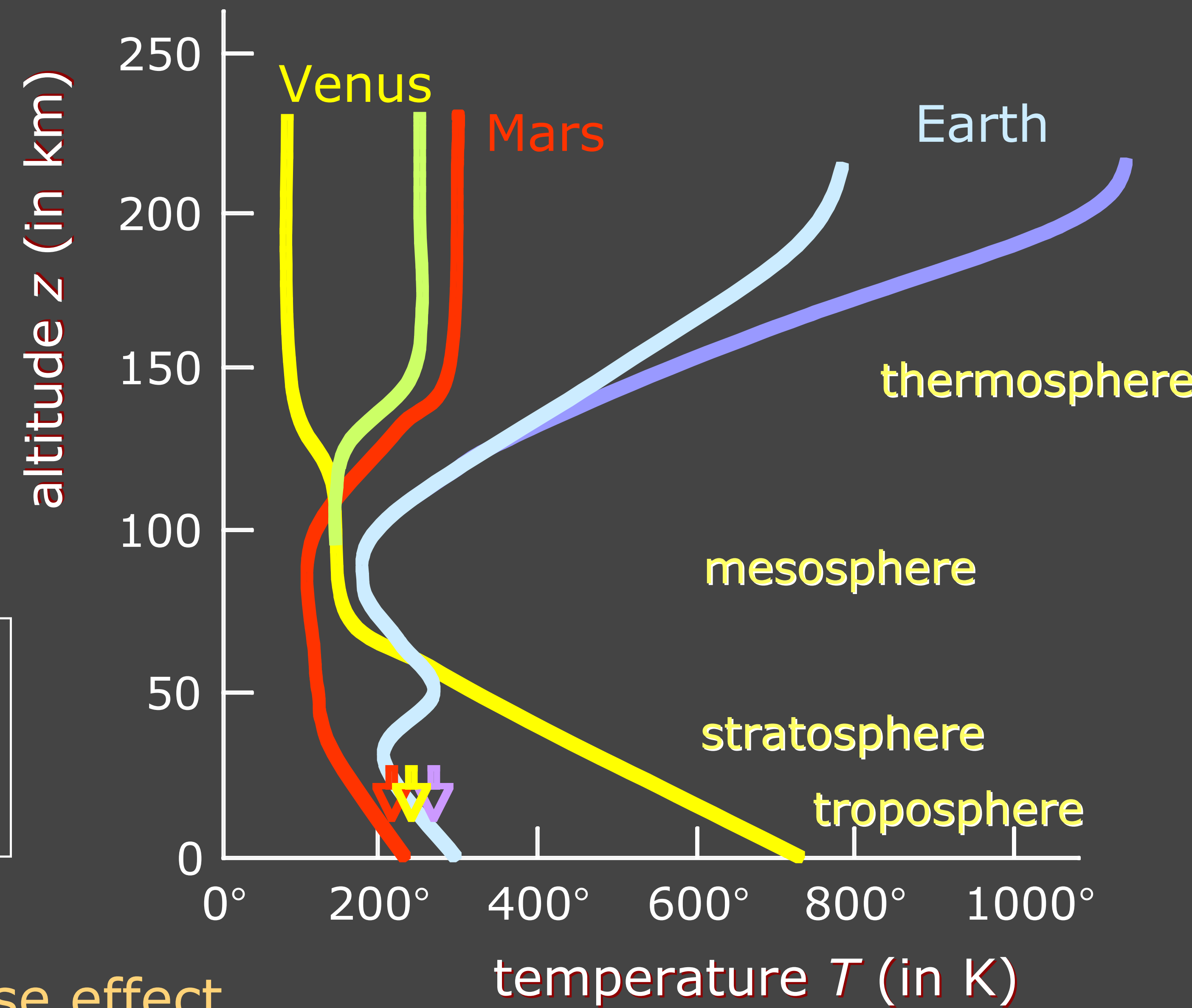
Neptune is known for its vigourous cloud systems of methane ice, possibly due to its strong internal heat source. A famous storm is the Dark Spot that Voyager observed, and that seems to have disappeared since then:





Credit: Voyager 2, NASA

# Temperature profiles on terrestrial planets



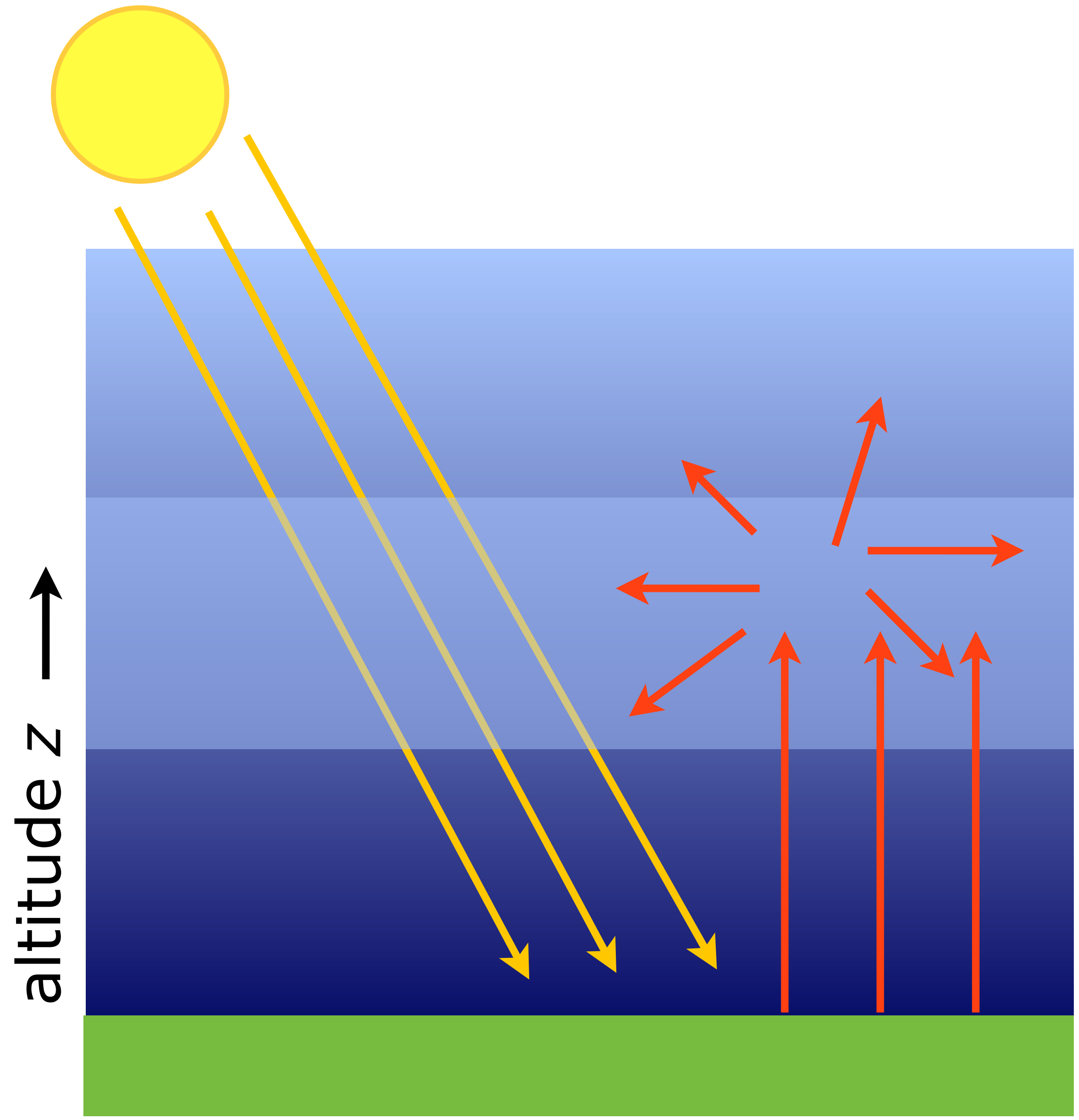

Equilibrium T:
Venus: 240° K (+ 500° K)
Earth: 253° K (+ 35° K)
Mars: 222° K (+ 6° K)

natural greenhouse effect

# The greenhouse effect

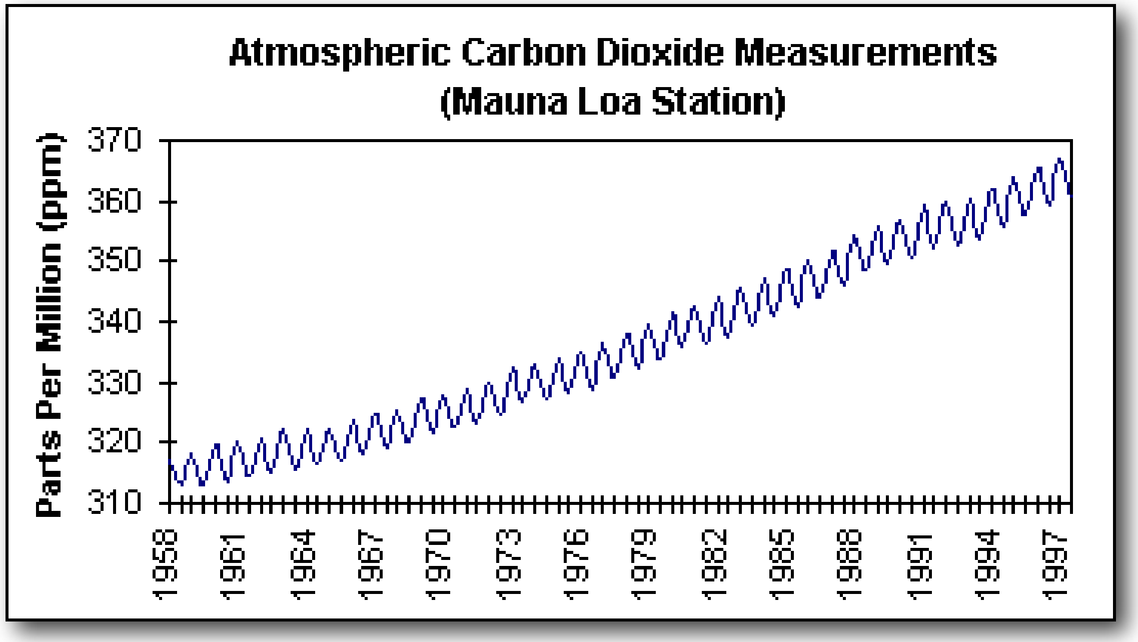
The surface temperature of a planet can be raised substantially above its equilibrium temperature if it is overlain by an atmosphere that absorbs infrared radiation. Typical greenhouse gases are: $H_2O$ and $CO_2$

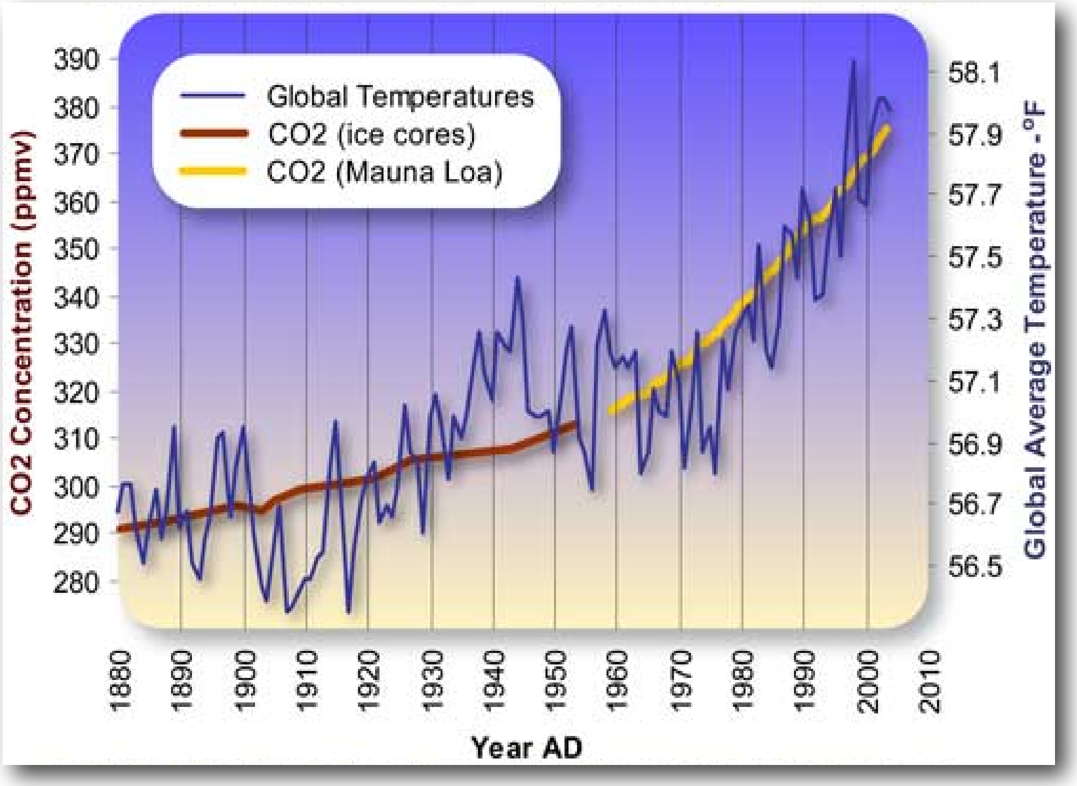
1. The visible light heats the surface
2. The surface emits infrared radiation
3. The infrared radiation is absorbed in the atmosphere
4. The atmosphere emits infrared radiation
5. The surface heats up
6. Goto 2 until the surface is warm enough to emit thermal radiation that can escape the atmosphere



# The rise of $CO_2$ in the Earth's atmosphere

The amount of greenhouse gas $CO_2$ is not constant in the Earth's atmosphere, it depends e.g. on the ambient temperature, pressure, and the amount of vegetation. It also depends on the activities of its inhabitants:

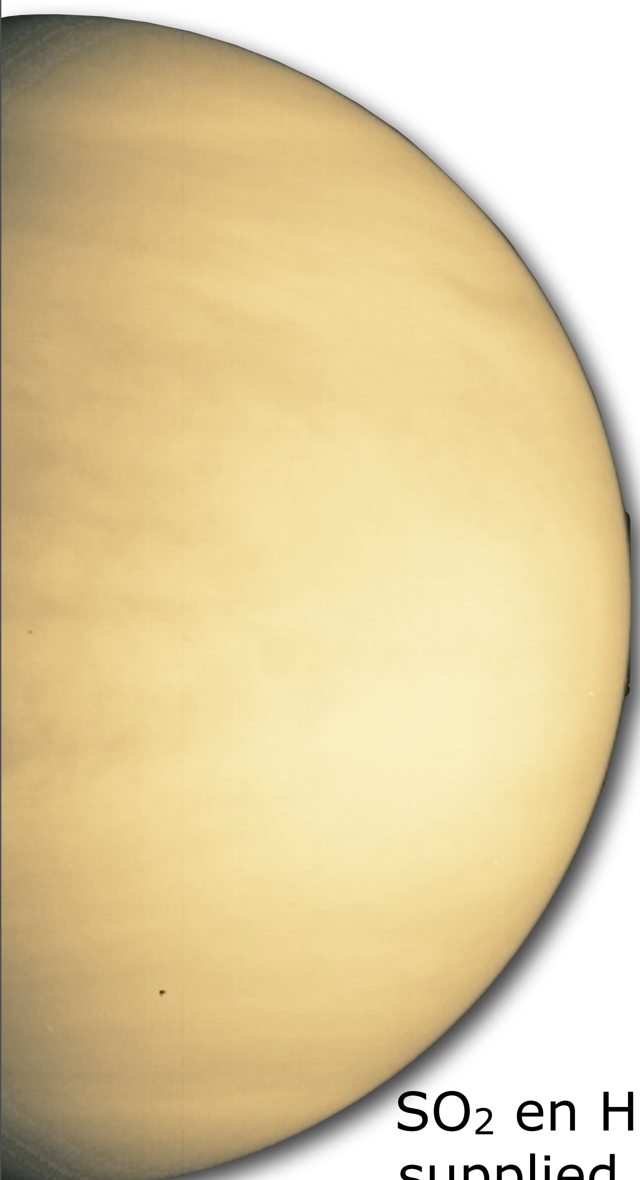


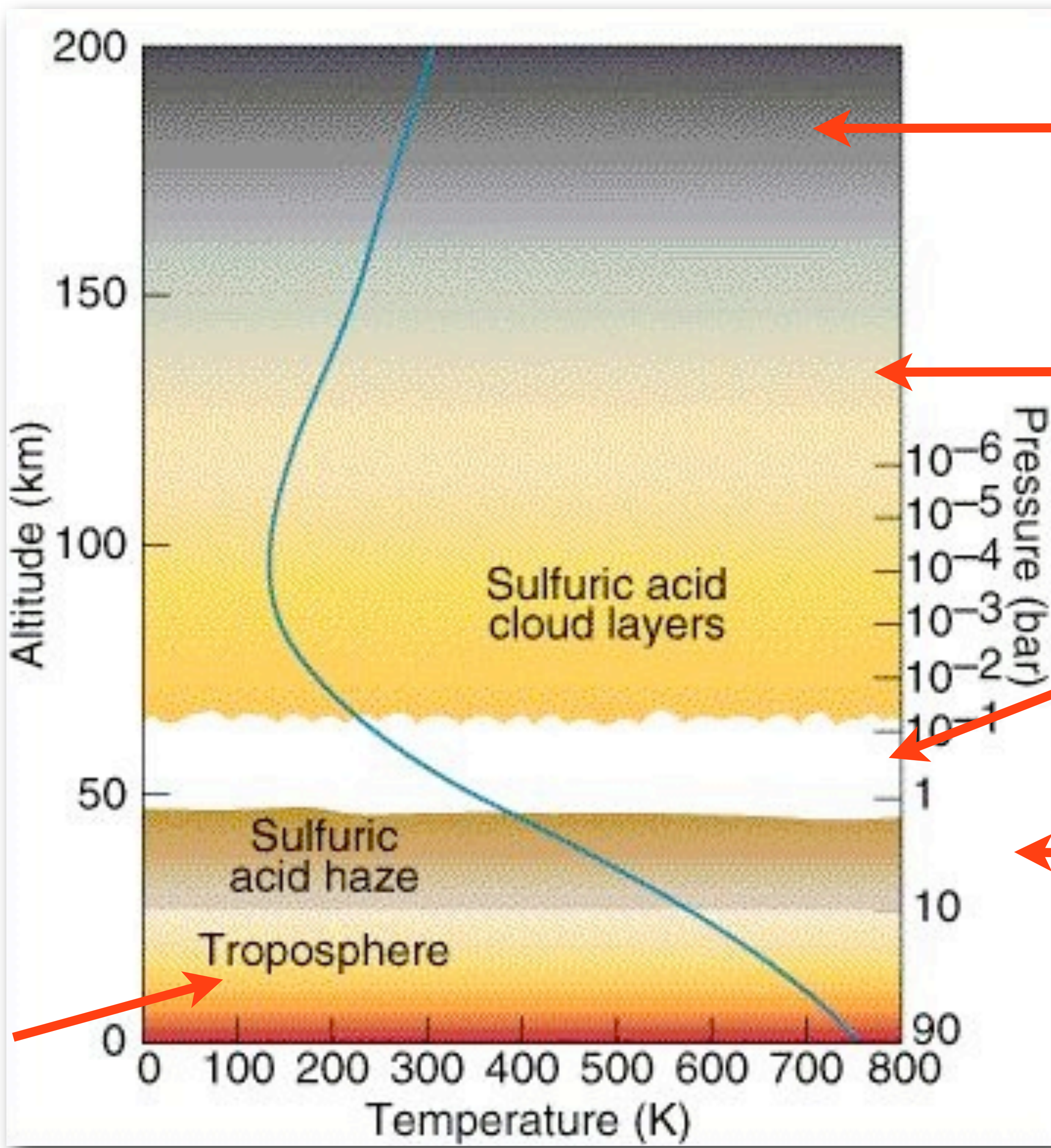




There might have been major changes in atmospheric $CO_2$ in the past: the young sun was very faint and with the current amount of $CO_2$, the young Earth would have been an ice/snow-ball, yet there are indications that the young Earth had liquid water ...

# Venus: the runaway greenhouse effect

Venus was long thought to have a moderate climate (Te=240 K, lower than for Earth), in the 1960 it was found out that the surface is incredibly hot, and that the clouds are made of sulfuric acid:






H (D) and O atoms escape and are being removed by the solar wind (there is no magnetic field!)

$H_2O$ is dissociated by UV-light

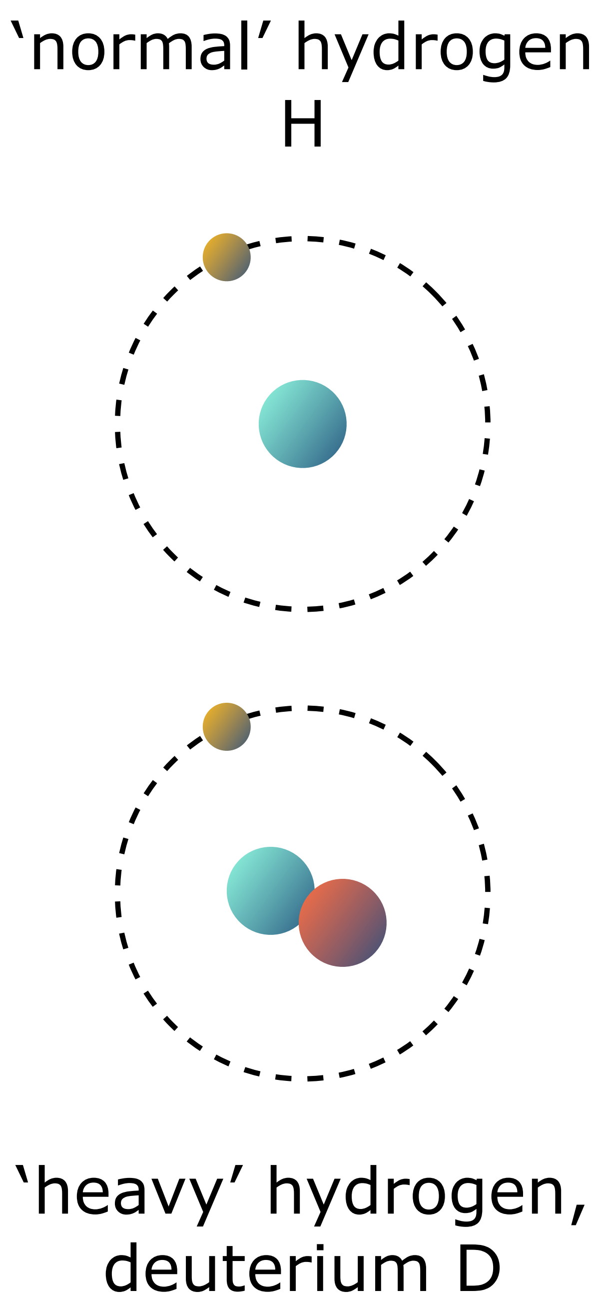
$H_2SO_4$ clouds scatter and absorb sunlight

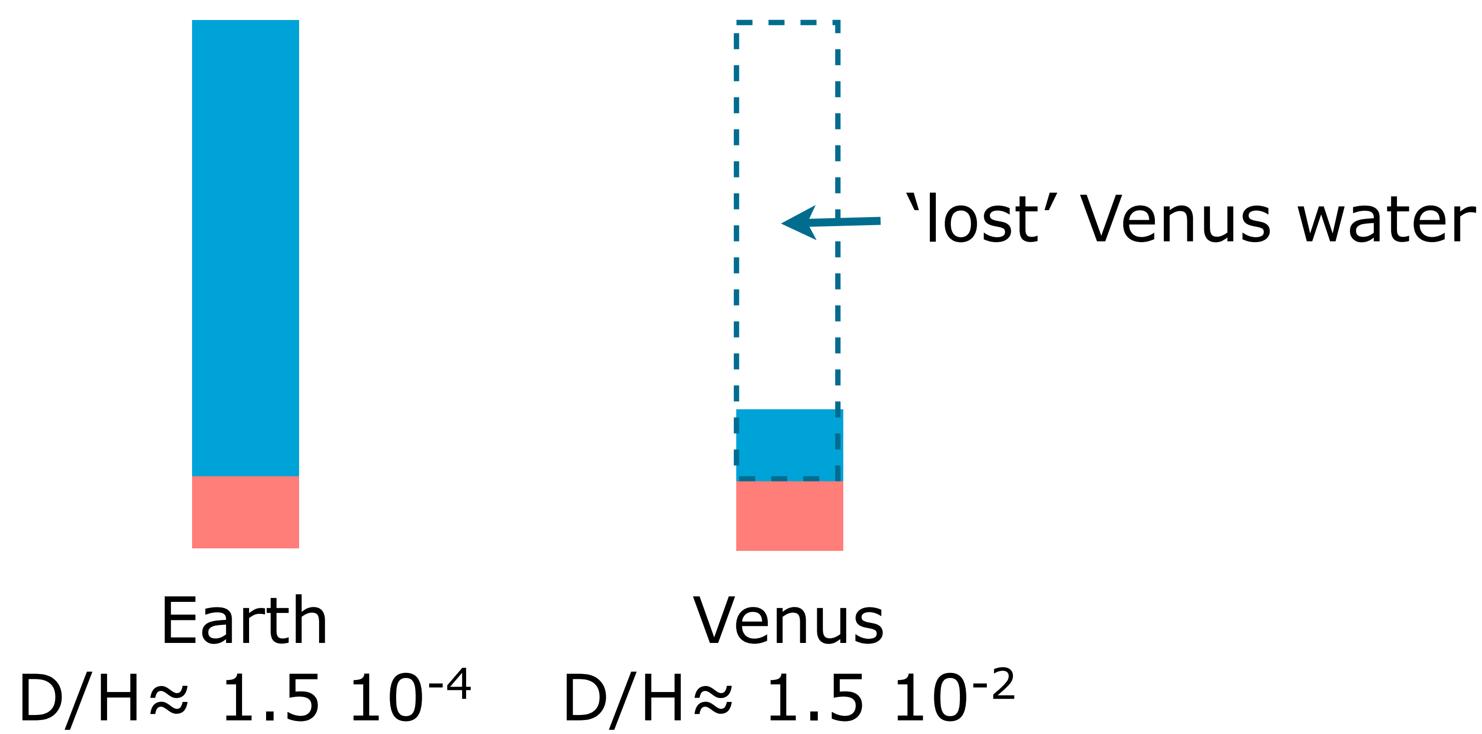
no tropopause: no"cold-trap"

$SO_2$ en $H_2O$ supplied by volcanoes?

# Venus: where did the water go?

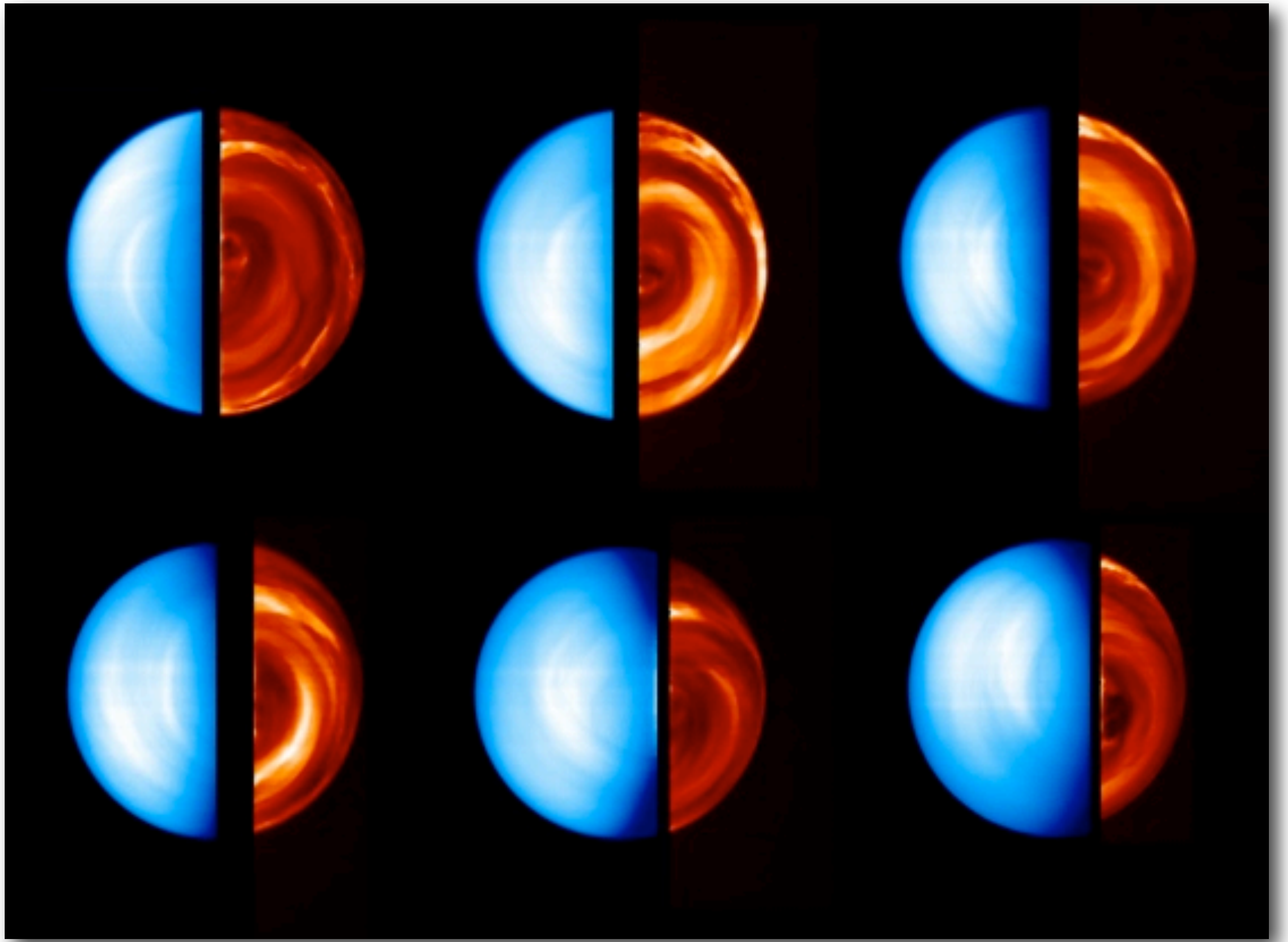
The young Venus probably had a similar amount of water as the Earth. This can be deduced from the amount of the hydrogen isotope deuterium:



# Examples of clouds on Venus

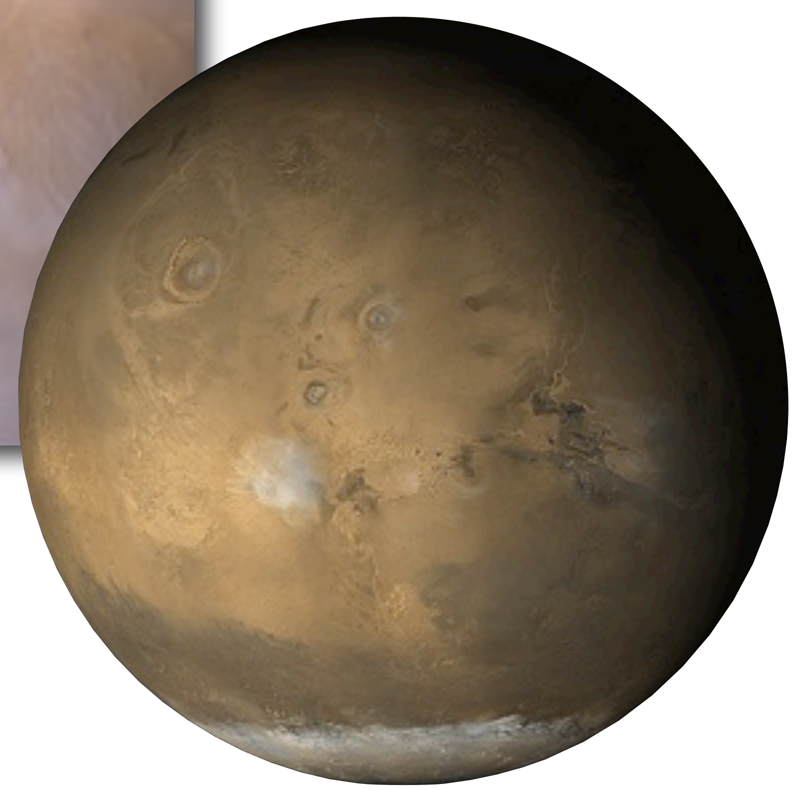
The clouds on Venus super-rotate with speeds of 100 m/s at the equator, sweeping around the planet in 4 Earth days (60 times faster than the planet itself rotates). Air moves downward in enormous vortices at the poles (view on the south pole):



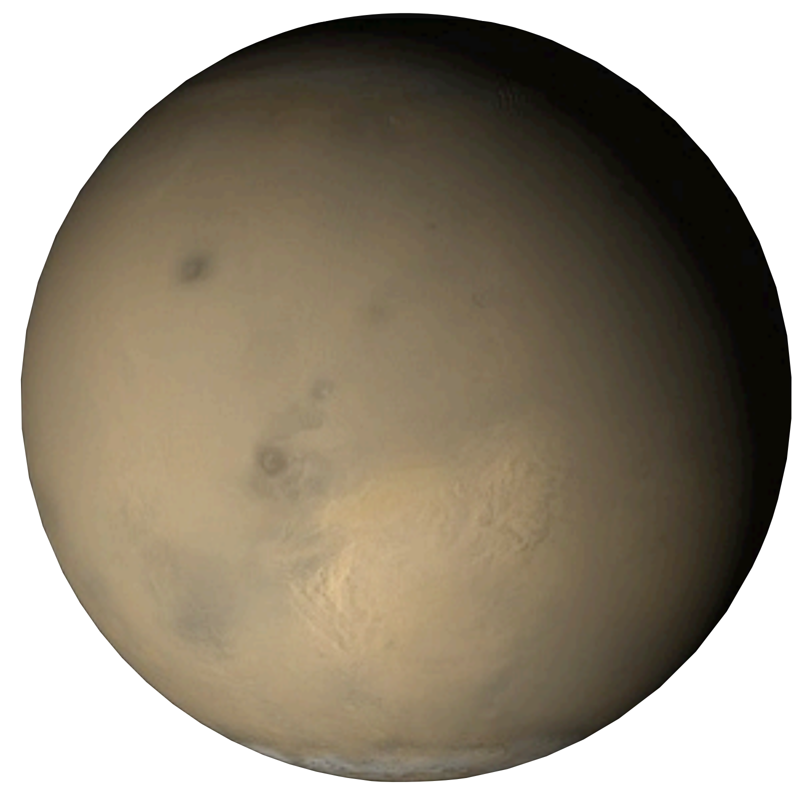
Bright @ 1.7 μm: low, warm clouds; Dark @ 1.7 μm: upper, cold clouds; VIRTIS/VEX/ESA

# Mars: a sun- and dust-driven atmosphere

Mars has a very thin gaseous atmosphere, with almost no greenhouse effect. The surface pressure increases by ~25% during the warm, southern summer, because of sublimating $CO_2$ ice on the south pole. Also in the southern summer, dust is swept up in local, regional, or global storms:

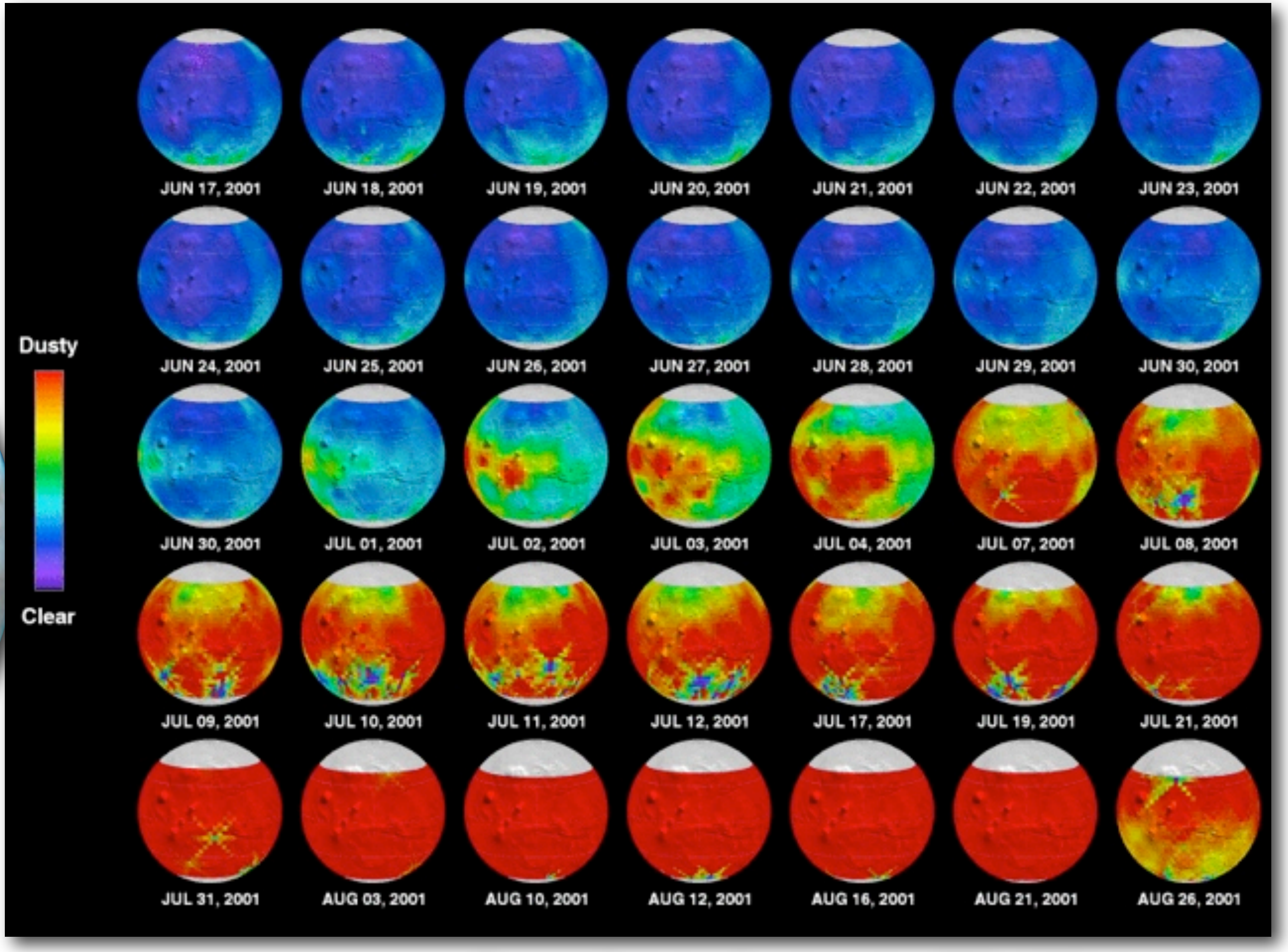
10 June 2001



3 July 2001

# Temperature changes on Mars

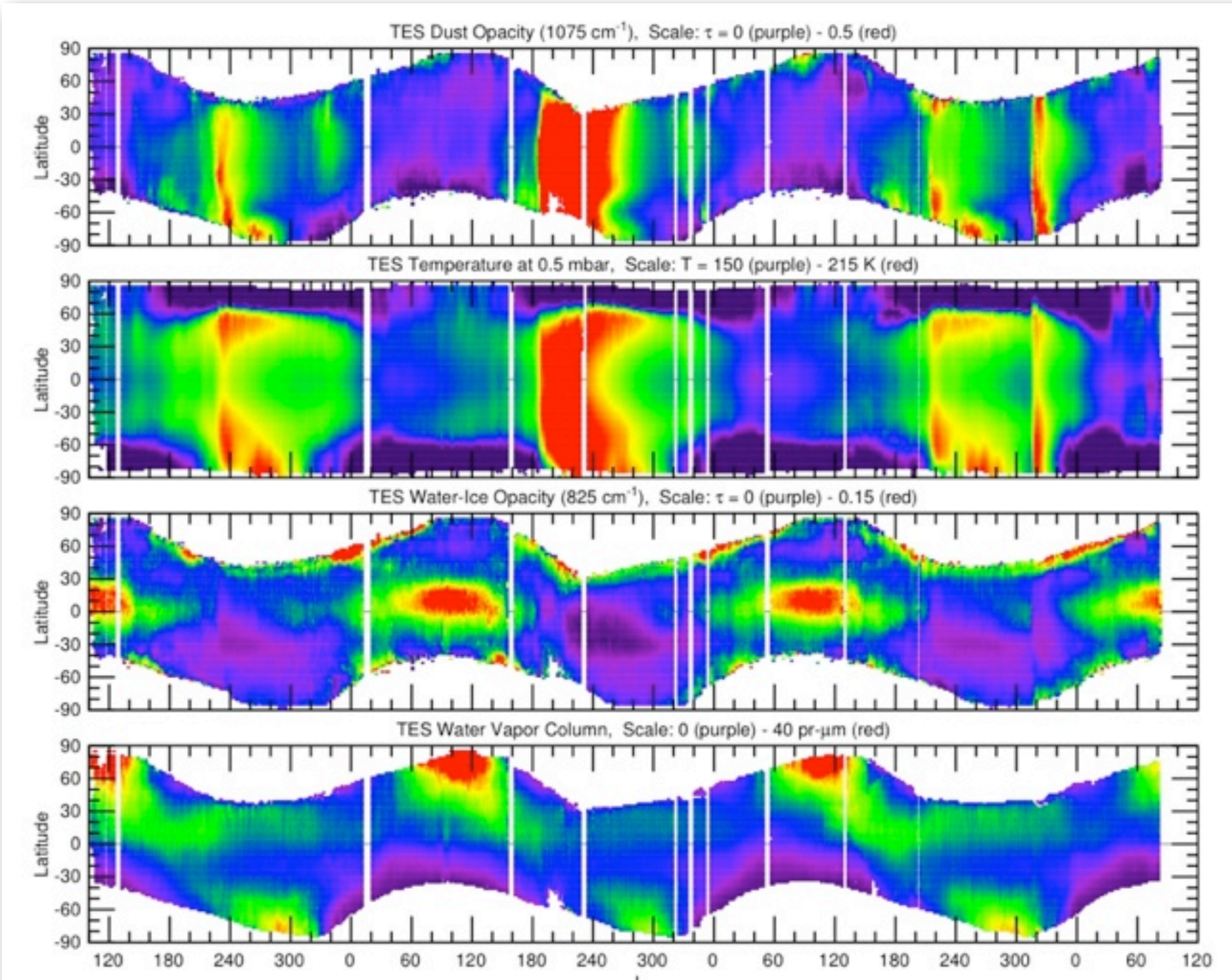
Dust storms have a major influence on the temperature of the Martian atmosphere and surface. During a global storm, that can develop within days, the temperature can increase more than 20 degrees:




Thermal Emission Spectrometer (TES, MGS) observations

# Seasonal variations on Mars

The Mars atmosphere shows strong seasonal variations:




Dust optical thickness

Surface temperature

Water-ice optical thickness

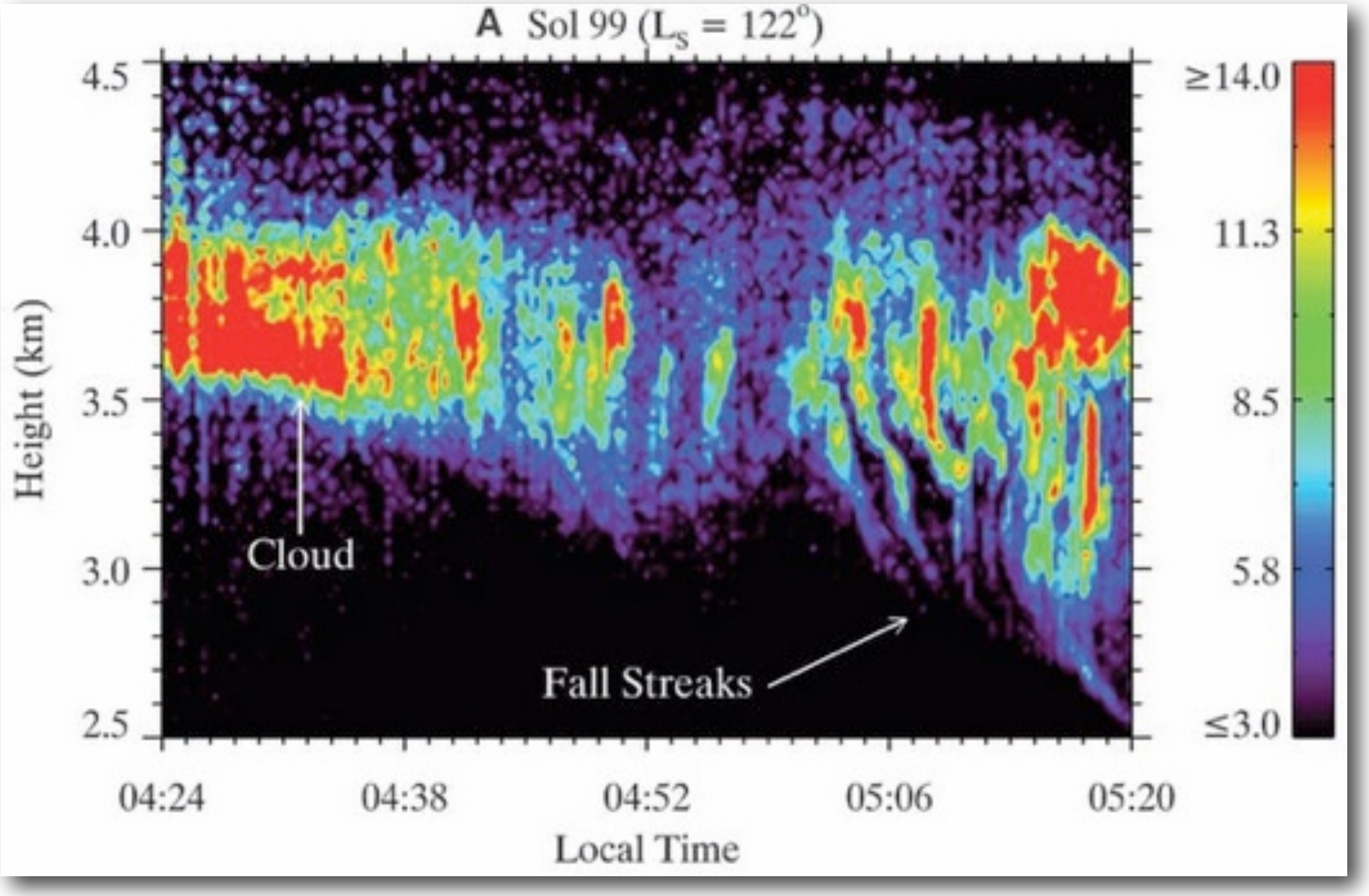
Water-vapour column

TES/MGS

# Examples of clouds on Mars

Thin, cirrus-like water ice clouds are a common sight in the Mars atmosphere. It can also get cold enough (-80 degrees C) in the Mars atmosphere to have $CO_2$ ice clouds.

Water ice clouds as seen by the Mars Pathfinder (NASA)




Water ice clouds with streaks of snow as seen by the Phoenix mission (NASA)

# Clouds

- Cloud formation and/or evaporation strongly influence the atmospheric temperatures as heat is released and/or absorbed
- Clouds strongly influence atmospheric radiation fields because they:
  - scatter incoming light and thermal radiation
  - absorb incoming light and thermal radiation
  - emit thermal radiation themselves
- Clouds transport heat through an atmosphere
- Clouds transport volatiles through an atmosphere
- Cloud particles can act as nuclei for chemical reactions (PSCs!)