# Planetary atmospheres and their evolution

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Thanks to: Dr Neil Bowles, Oxford Physics

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# Overview

- Formation and evolution of atmospheres
- Concepts in atmospheric physics
- The terrestrial planets
- The outer planets and Titan

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# Formation and evolution of atmospheres

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# Formation of terrestrial planet atmospheres

- Did the atmosphere
  1. Form with the planet out of the solar nebula?
  2. Outgas later from the interior?
  3. Accumulate from the solar wind?
  4. Arrive later as icy meteorites and comets?
- Obtain clues from the relative abundances and isotopic ratios of the noble gases (accounting for the radiogenic origin of some of these gases)
- For Venus, Earth and Mars it is found that:
  - The ratio of $^{20}Ne$ to $^{35}Ar$ is similar on all 3 planets, but different in the Sun – inconsistent with (1) and (3)
  - Primordial argon decreases by several orders of magnitude from Venus to Earth and from Earth to Mars. Inconsistent with (4)
  - This leaves (2). Also, outgassing is still observed (e.g. volcanoes)
- The atmospheres of the terrestrial planets “evolved” to what they are today -> “secondary” atmospheres

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# Formation of outer planet atmospheres

- Unlike the terrestrial planets, the gas giants were too massive, cold, and distant from the Sun to have lost their original atmospheres
- If so, the giant planets are made up of primitive material from the solar nebula - > “primary” atmospheres
- Both Jupiter and the Sun are ~85% hydrogen, ~15% helium
- The $H_2$/He ratios on all four planets resemble that of the Sun
- Heavier element abundances and noble gas ratios are difficult to measure and interpret, and not all are consistent with the Sun (ongoing research).

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# Processes affecting the evolution of atmospheres

I. Thermal escape to space

II. Condensation, e.g. on permanent polar caps or as permafrost below the surface

III. Dissolving in oceans & subsequent removal, e.g. carbonate formation removes $CO_2$ on Earth

IV. Regolith absorption/chemical combination, e.g $O_2$ ➔ rust

V. Hydrodynamic escape (lighter atoms move heavier ones)

VI. Solar wind erosion (especially if no mag. field, Venus & Mars)

VII. Impact erosion (incoming mass blasts gases into space)

VIII. Sources of gases (e.g. comets, volcanism)

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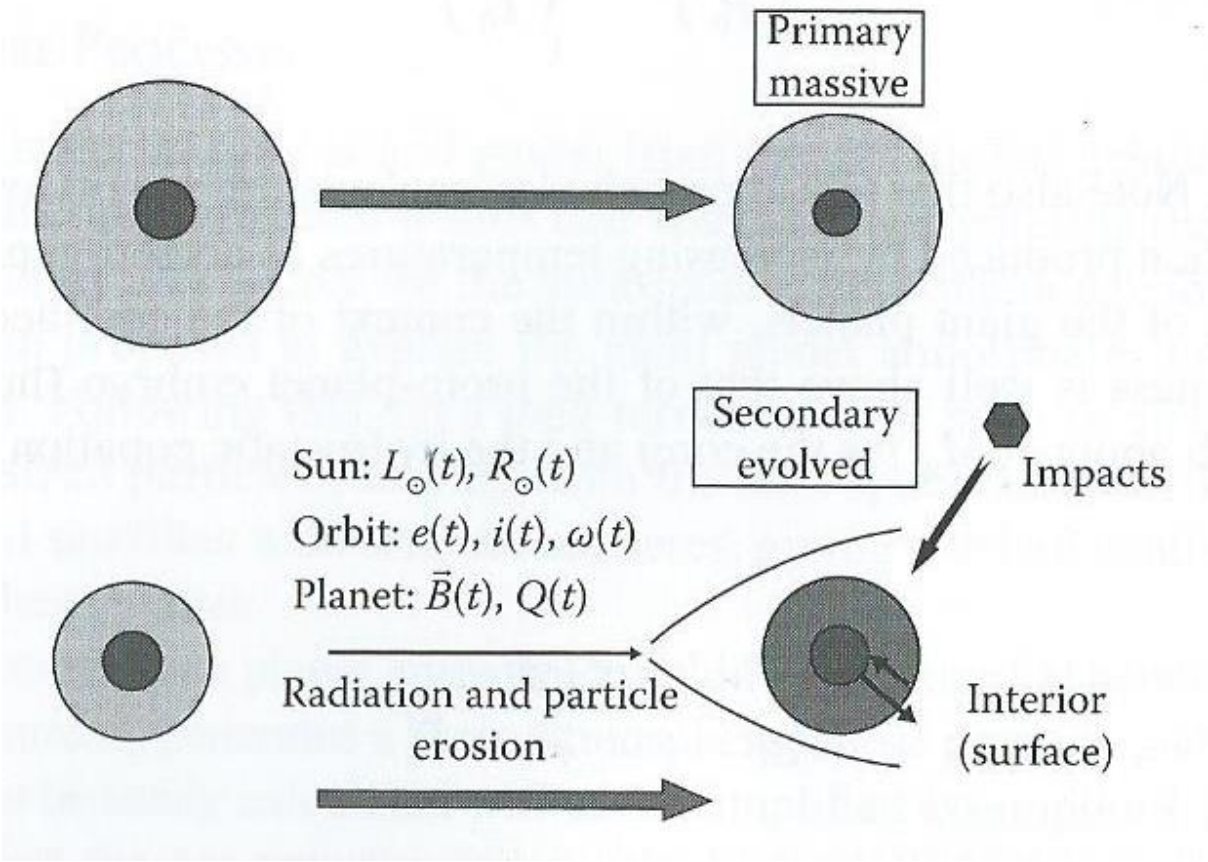
# Schematic of atmosphere evolution

Giant planets

Terrestrial planets




**Factors affecting terrestrial planetary atmospheres**

**Sun**: orbital, luminosity changes

**Orbit:** eccentricity, planetary axis tilt, precession

**Planet:** magnetic field, surface

From Sanchez-Lavega (2011)

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# Basic atmospheric physics

# Hydrostatic equilibrium and scale height

- Hydrostatic equilibrium
  - To a first approximation a planetary atmosphere is in *hydrostatic equilibrium* - the balance between gravity *g* and pressure *p*.

$$dp = -g\rho dz$$

  - For an atmosphere, we can substitute for density $\rho$ using the ideal gas law ($p = \rho RT$) to give

$$\frac{dp}{dz} = -\frac{gp}{RT}$$

  - The solution of this equation is $p = p_0 e^{-z/H}$
  - where *H* is the pressure *scale height* given by $H = \frac{RT_0}{g}$
- This is a useful result – it allows conversion between pressure and height.
- Typical scale heights: Venus 16 km, Earth 8.5 km, Mars 11 km, Jupiter 24 km.

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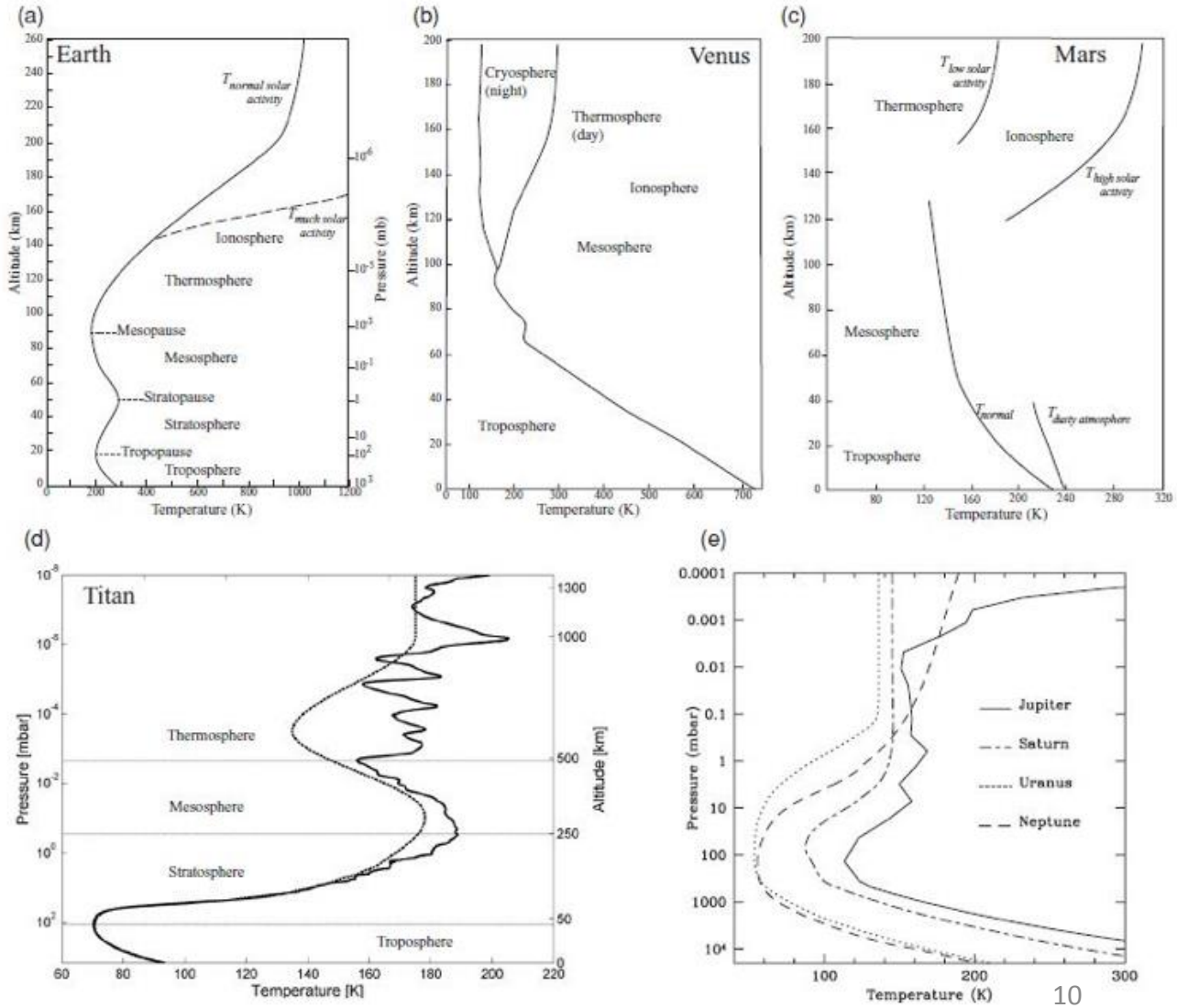
No more equations, I promise

# Thermal structures of solar system atmospheres

- Although varied, there are common structures
- e.g. Troposphere roughly straight-line temperature dependence, and convection is important; stratosphere temperature increases slightly with height due to absorption by molecules of solar radiation



# Cloud formation

- Clouds form when there is more vapour available than the atmosphere can hold - we call this *saturation*
- *Saturation vapour pressure* (i.e. the amount of vapour an atmosphere can hold) is related to temperature and atmospheric composition
- If a vapour is saturated it can *condense* and form a cloud (assuming suitable *cloud condensation nucleii* are present)
- Clouds can be of any substance as long as it is saturated with respect to the background vapour

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# Atmospheric electricity

**Titan**

- Lightning has been detected on several planets (4±1 out of 7 with atmospheres). (Harrison et al, 2008)
- Every planet has a partially ionised atmosphere because of cosmic rays, energetic charged particles from outside the Solar System
- So far, extraterrestrial atmospheric electricity has only been measured *in situ* on Saturn's largest moon, Titan by the Huygens probe, which landed on 14 January 2005.
- Atmospheric electricity can be described as either "disturbed weather" (lightning) and "fair weather" (non lightning)

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# The terrestrial planets

# Earth

- Water in all three phases
- Widespread water clouds
- 70% liquid $H_2O$ coverage
- $N_2$ – $O_2$ atmosphere
- Surface pressure 1 bar
- Mean surface temperature 288 K
- Life is part of climate
- Lightning flash rate 42 $s^{-1}$

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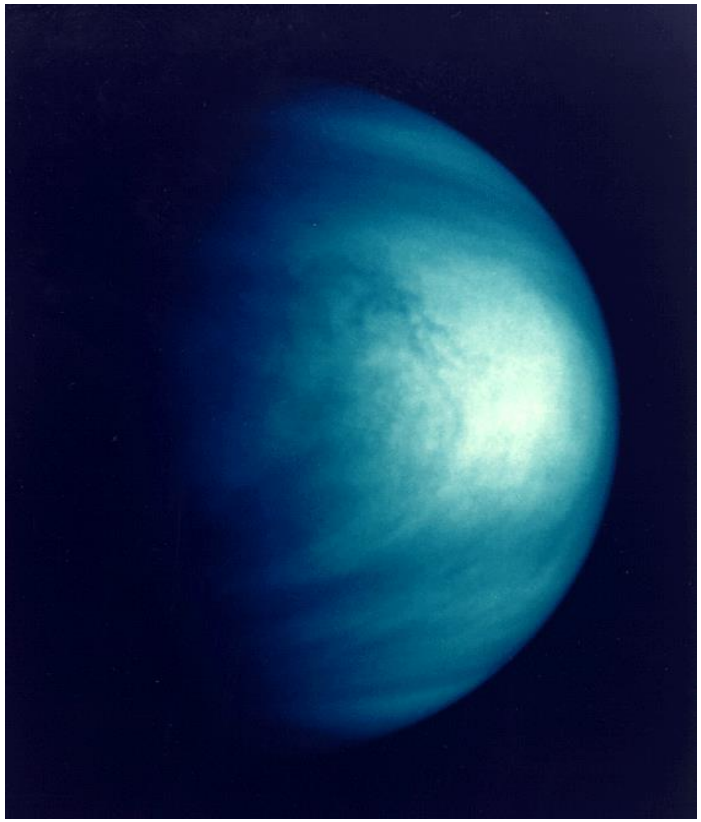
# Venus



- Solid body resembles Earth
- Small inclination and eccentricity – no seasons
- Complete cloud cover of mainly 75%$H_2SO_4$.25%$H_2O$.
- No liquid water & very little vapour
- Surface temperature ~ 730 K
- Equilibrium temperature ~ 240 K
- 500K greenhouse effect (Earth ~ 30K)
- Very thick $CO_2$ atmosphere - 1000 km-atm of $CO_2$ (Earth: $10^{-3}$)
- Surface pressure 92 bars.
- Lightning still controversial

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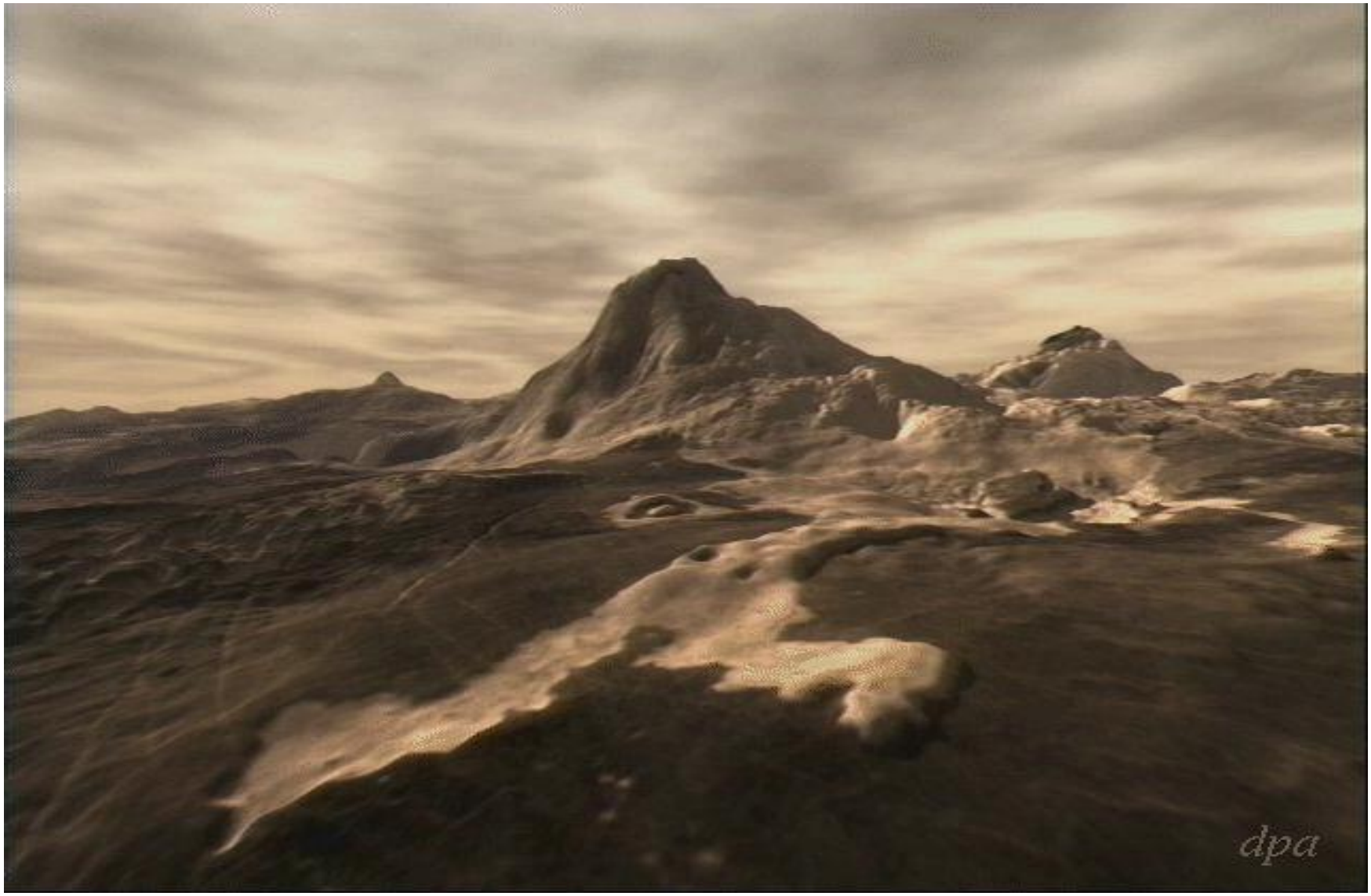
← Venera 9 obtained the first image from the surface of Venus in 1975.

↓ View of a plain in Phoebe Regio from Venera 13 on March 1, 1982

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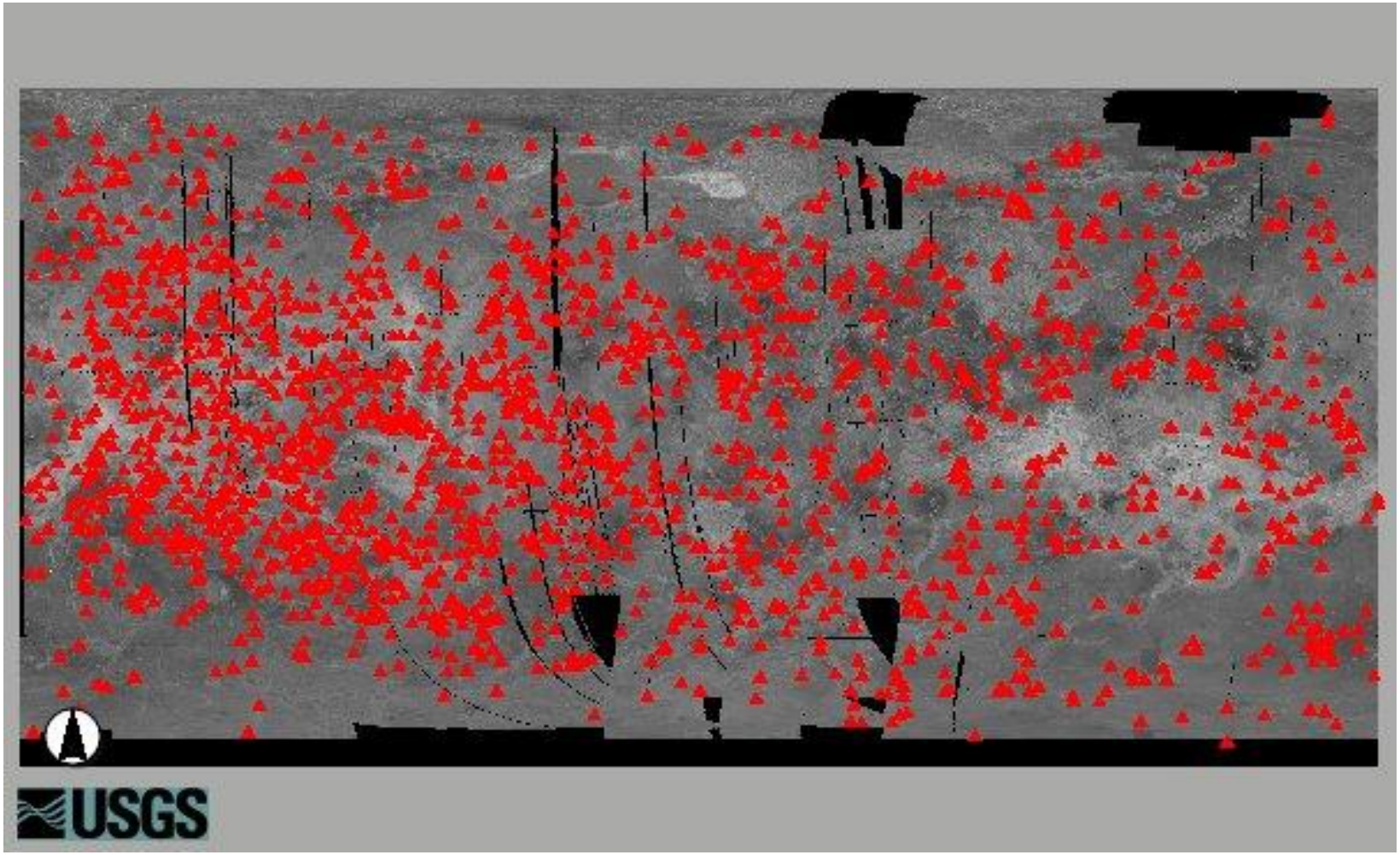
Maat Mons from Magellan Radar Image ca. 1991




Venus has more volcanoes than any other planet in the solar system. Over 1600 major volcanoes or volcanic features are known (see map), and there are many, many more smaller volcanoes. No one has yet counted them all, but the total number may be over 100,000 or even over 1,000,000. [Oregon State University]

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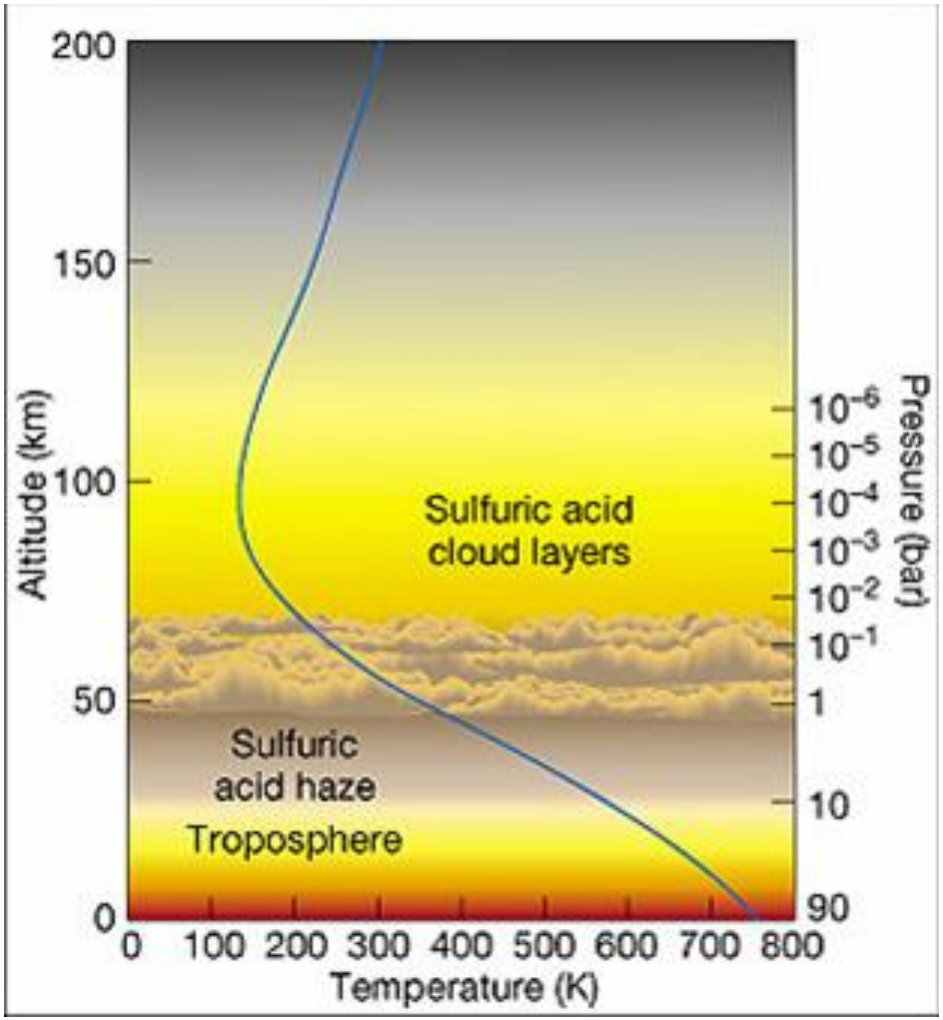
# The nasty Venusian Atmosphere

- 96.5% $CO_2$, 3.5% $N_2$
- 150 ppm $SO_2$
- 20 ppm $H_2O$
- $H_2SO_4$ clouds!
- Super extreme 'green house'
- Day longer than year and retrograde.
- Upper atmosphere super rotates at $100 ms^{-1}$ for latitudes <50 degrees
- Radio emissions have been attributed to lightning but no optical evidence or credible mechanism yet

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# Mars

- Thin $CO_2$ atmosphere
- Thin $CO_2$ and $H_2O$ clouds.
- Surface Pressure ~7 mb (variable)
- Surface temperature 218 K (very variable)
- Lightning is expected but has not yet been observed

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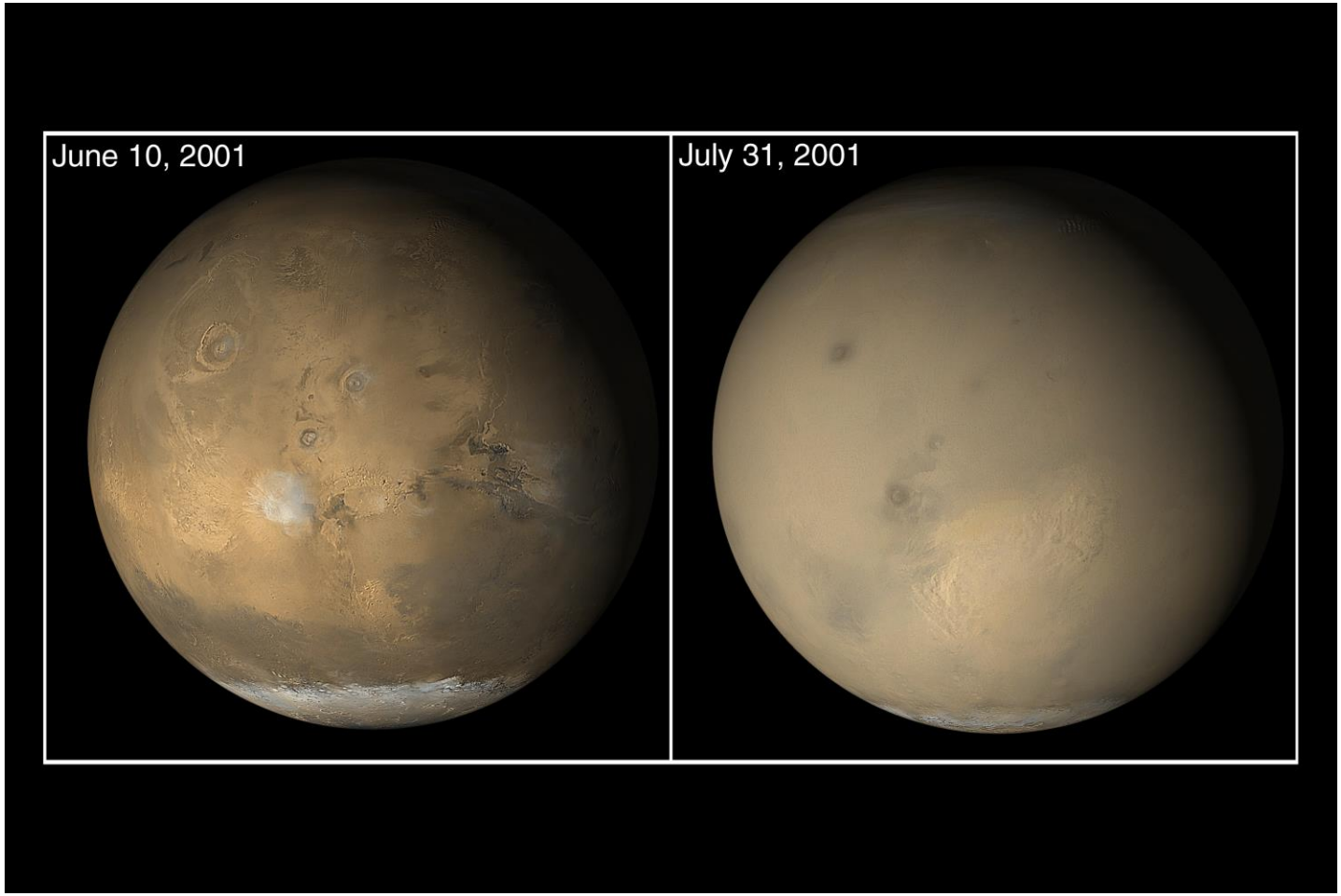
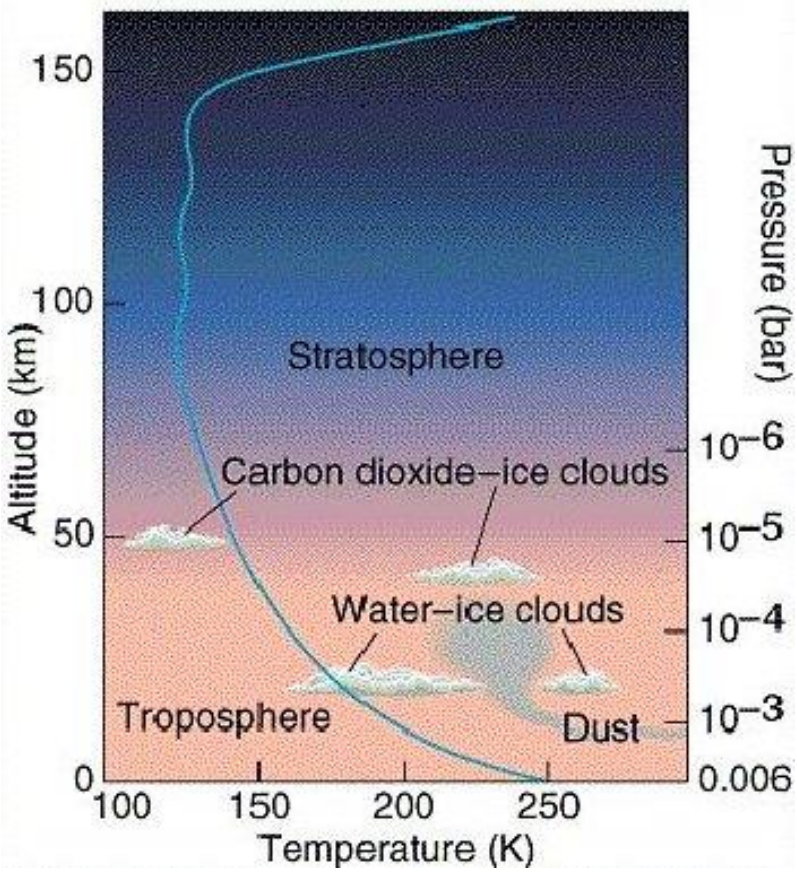
# Mars dust storms




MGS MOC images of the 2001 global dust storm.

# Martian Atmosphere

- It's cold: Average surface temperature of 214K, can vary between 148K polar winter to 290K in southern summer.
- Low atmospheric pressure – global mean of 6.4mbars, but varies due to $CO_2$ sublimation
  - 95% $CO_2$
  - 2.7% $N_2$
  - 1.6% Ar
  - 0.13% $O_2$
  - 0.03% $H_2O$ -> But highly spatially and temporally variable!
- Dust is important:
  - Contributes to thermal properties of atmosphere
  - Likely to generate lightning

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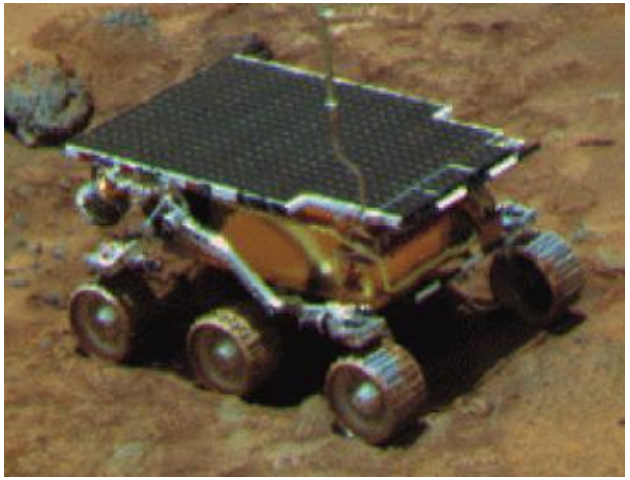
# Atmospheric electricity on Mars

Electrical processes are likely to be significant on Mars. Charge exchange almost certainly occurs between particles in dust devils. Discharges also predicted (like terrestrial volcanic lightning?).



- Charged red dust seen stuck to the wheels of rovers is the only evidence for Martian atmospheric electrical processes.
- Laboratory experiments suggest that discharges should occur under Martian conditions
- In situ electric field measurements are needed (DREAMS instrument on ExoMars lander)

# Composition of Terrestrial Planet Atmospheres

| | Venus | Earth | Mars |
|---|---|---|---|
| Carbon dioxide | 0.96 | 0.003 | 0.95 |
| Nitrogen | 0.035 | 0.770 | 0.027 |
| Oxygen | ~0 | 0.21 | 0.0013 |
| Water vapour | ~0.00001 | ~0.01 | ~0.003 |
| Sulphur dioxide | 150 ppm | 0.2 ppb | ~0 |
| Carbon monoxide | 0.00004 | 0.12 ppm | 0.007 |
| *Surface Pressure (bar)* | *92* | *1* | *0.007* |
| *Clouds* | *$H_2SO_4$* | *$H_2O$, $HNO_3$, $H_2SO_4$* | *$H_2O$, $CO_2$* |

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# The outer planets and Titan

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# The Outer Planets and Titan…

- The outer solar system has the Gas Giants Jupiter and Saturn and the ice giants Uranus and Neptune.
- All four were visited by the Voyager spacecraft in the 1970s and 1980s
- Galileo mission to Jupiter in 1995-2003
  - Orbiter and atmosphere entry probe
  - Problems with High Gain Antenna reduced science return, but still managed lots of science.
- Cassini Mission to Saturn 2004-
  - Hugely successful mission to Saturn, joint NASA/ESA/ASI
  - ESA Titan (moon of Saturn) entry probe 'Huygens'
- Nothing since Voyager to Uranus and Neptune so we have to rely on ground based or Hubble Space Telescope observations, with occasional measurements from Spitzer and Herschel space telescopes
- Jupiter, Saturn and Neptune have internal heat sources, Uranus does not (it's not really known why)

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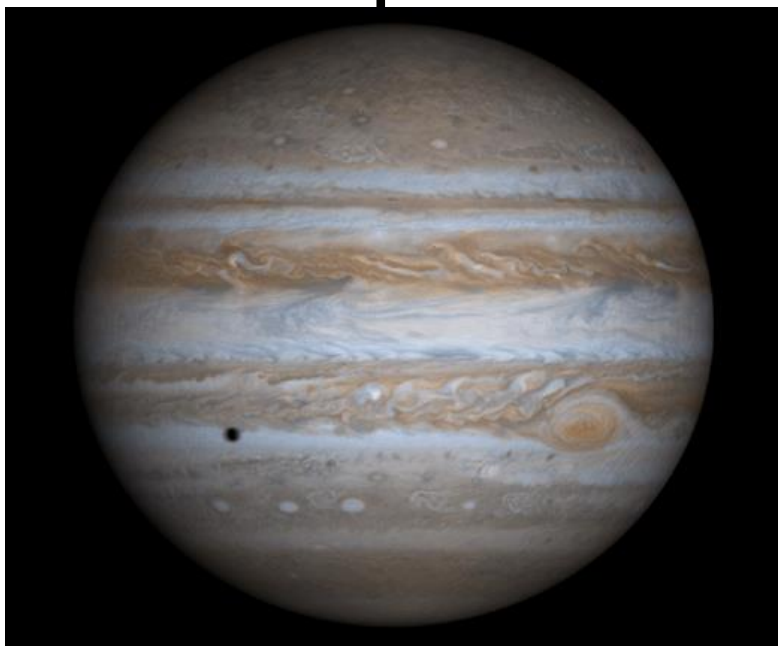
# Jupiter



| | |
|---|---|
| Mean distance from sun | 5.202561AU |
| Sidereal Orbital Period | 11.8623 yrs |
| Equatorial Radius at 1bar | 71492 km |
| Polar Radius at 1bar | 66854 km |
| Fast Rotation rate | 9h 55m |
| Volume | 1321.6 × volume of Earth |
| Low density | $1.325 \times 10^{3}$ kg.m$^{-3}$ |

- Handy Facts about Jupiter:
  - 3x larger than Saturn.
  - Massive magnetosphere.
  - Very dynamic atmosphere driven by a large internal heat source.
  - Large long lived storms (e.g. Great Red Spot) the size of the Earth.
  - Banded appearance of light coloured ‘zones’ and dark coloured ‘belts’.
  - Extensive system of Moons and a faint ring.

***Jupiter as seen by Cassini, December 2000***

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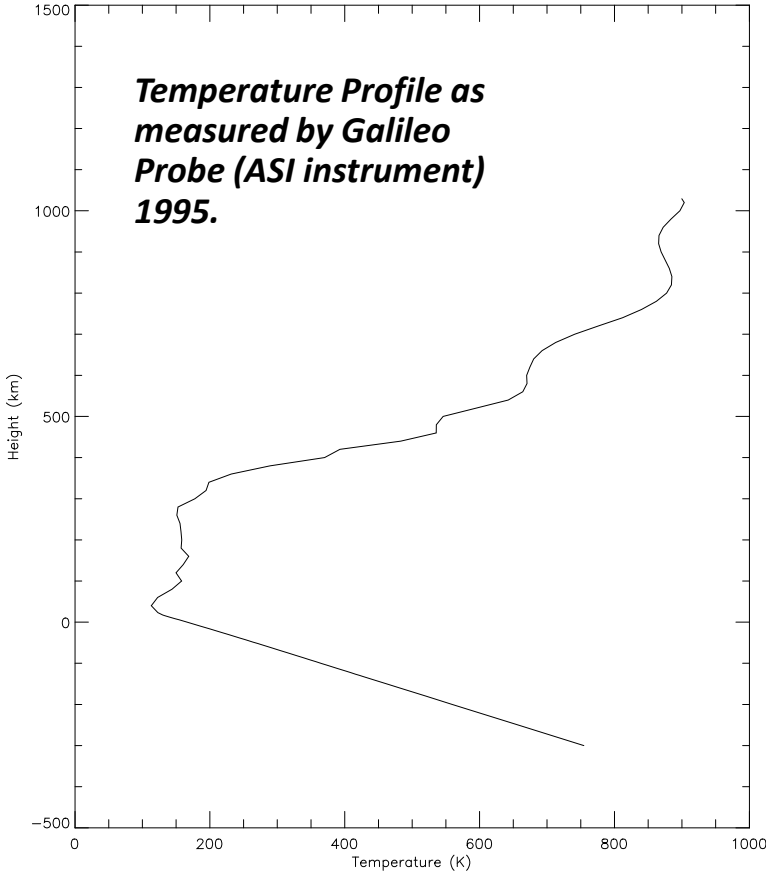
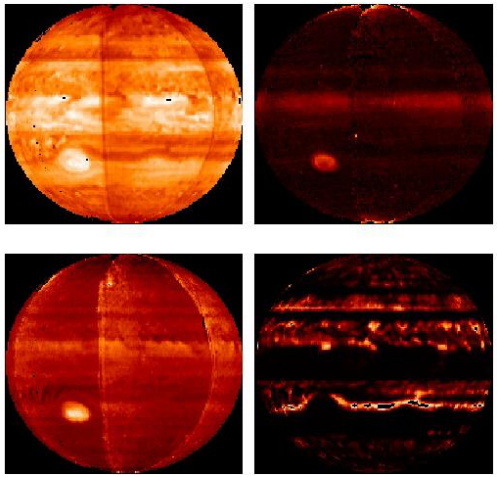
# Jupiter's Atmosphere




- Atmospheric Composition:
  - Mainly Hydrogen (86.4%) and Helium (13.6%) with trace amounts other gases.
  - Trace amounts of Methane, Water Vapour, Ammonia, Phosphine, Arsine, Germane, ethane, benzene etc.
    - Near Infrared spectrum dominated by Methane, Ammonia and Phosphine absorption, except around 5µm where thermal emission from the deep interior is seen.
    - Cause of cloud colours (e.g. Great Red Spot) poorly understood
- Temperature structure.
  - 0 km = 1bar level.

***Jupiter as measured by the NIMS instrument on Galileo at 1.61, 2.17, 3.01 and 4.99$\mu$m (from Taylor and Irwin (1999)).***



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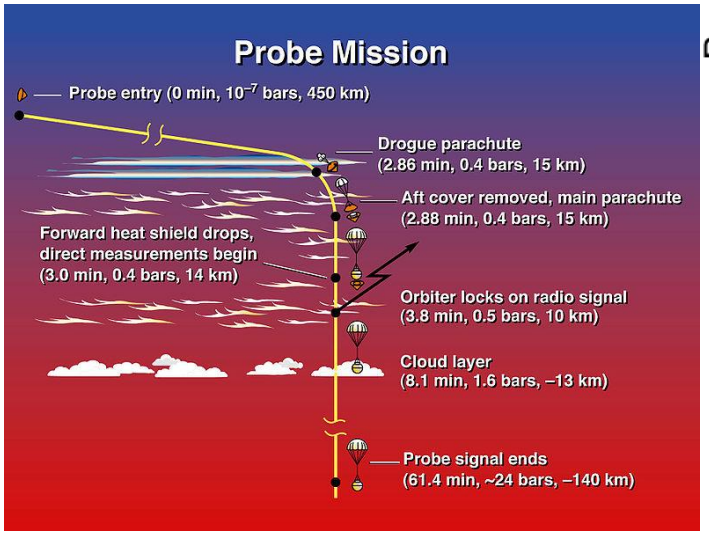
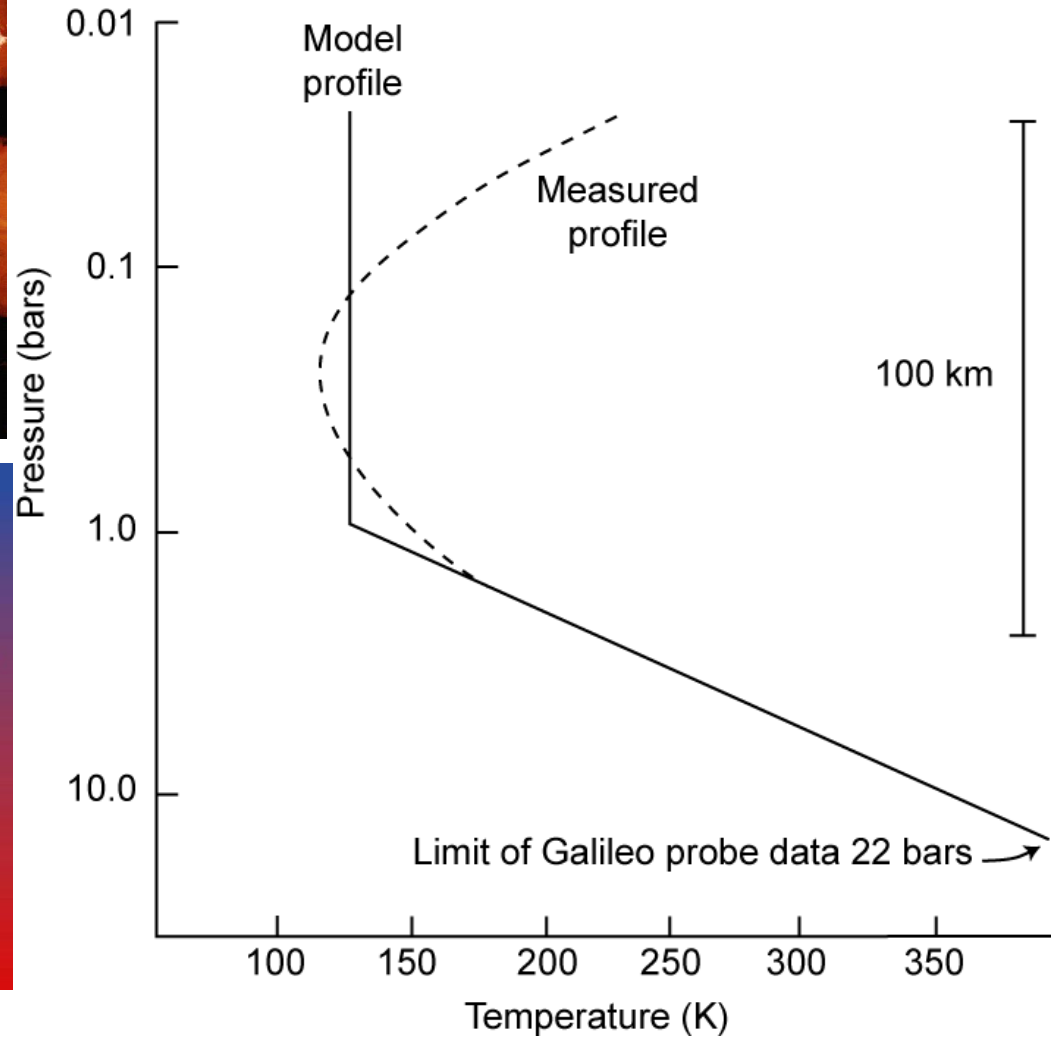
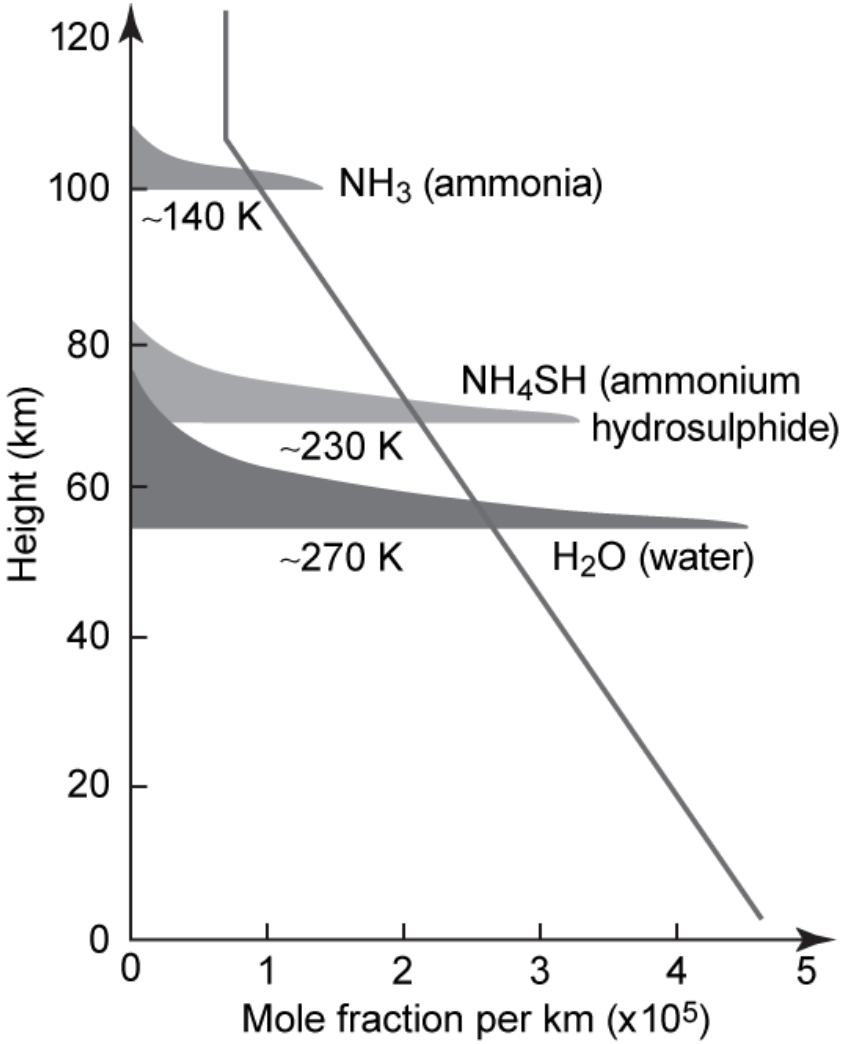
# Jupiter's temperature profile




Radiative convective model vs Galileo Probe measurements

# Vertical Cloud Structure on Jupiter




- Assuming 'solar' composition of the atmosphere, clouds of water ice, ammonium hydrosulphide and ammonia ice form at the levels shown.
- Neglects dynamics including vertical motions and rain-out.
- Neglects photochemistry.

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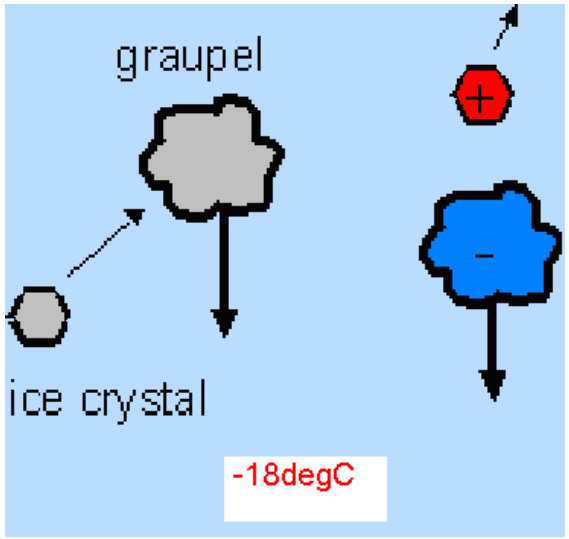
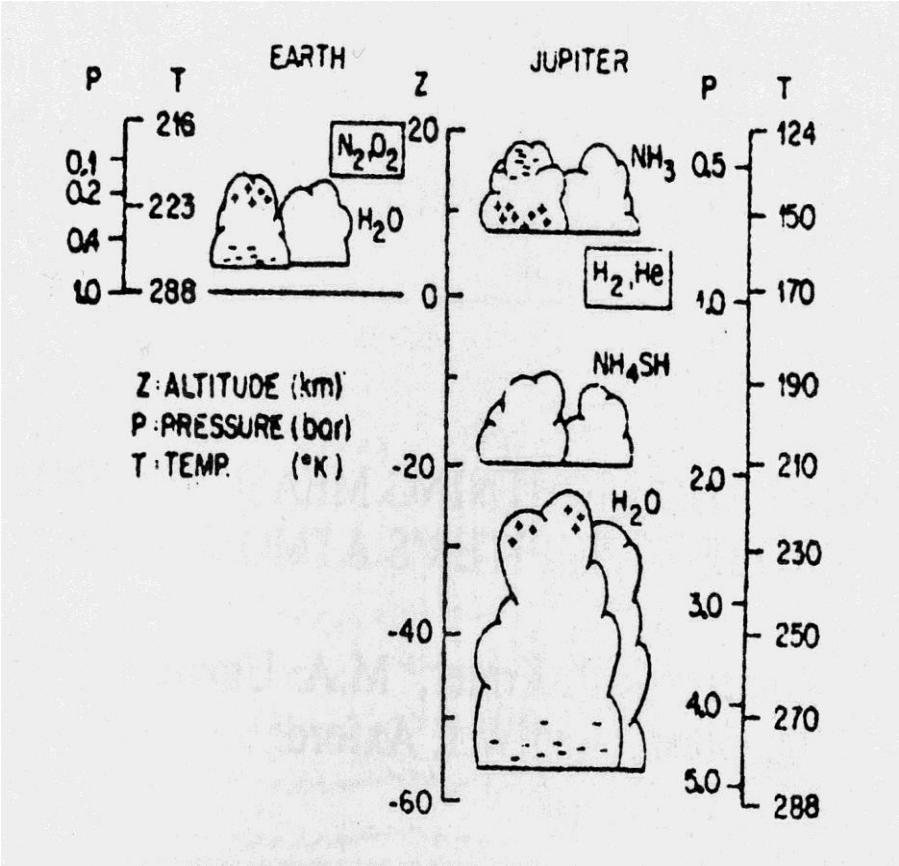
# Electrical storms on Jupiter

- Lightning observed by flybys of Voyager1 (1979), Galileo (1997), Cassini (2000/2001) and New Horizons (2007)
- Lightning observations associated with the areas thought to contain water clouds
- Assumed to be a similar mechanism acting as in terrestrial thunderclouds

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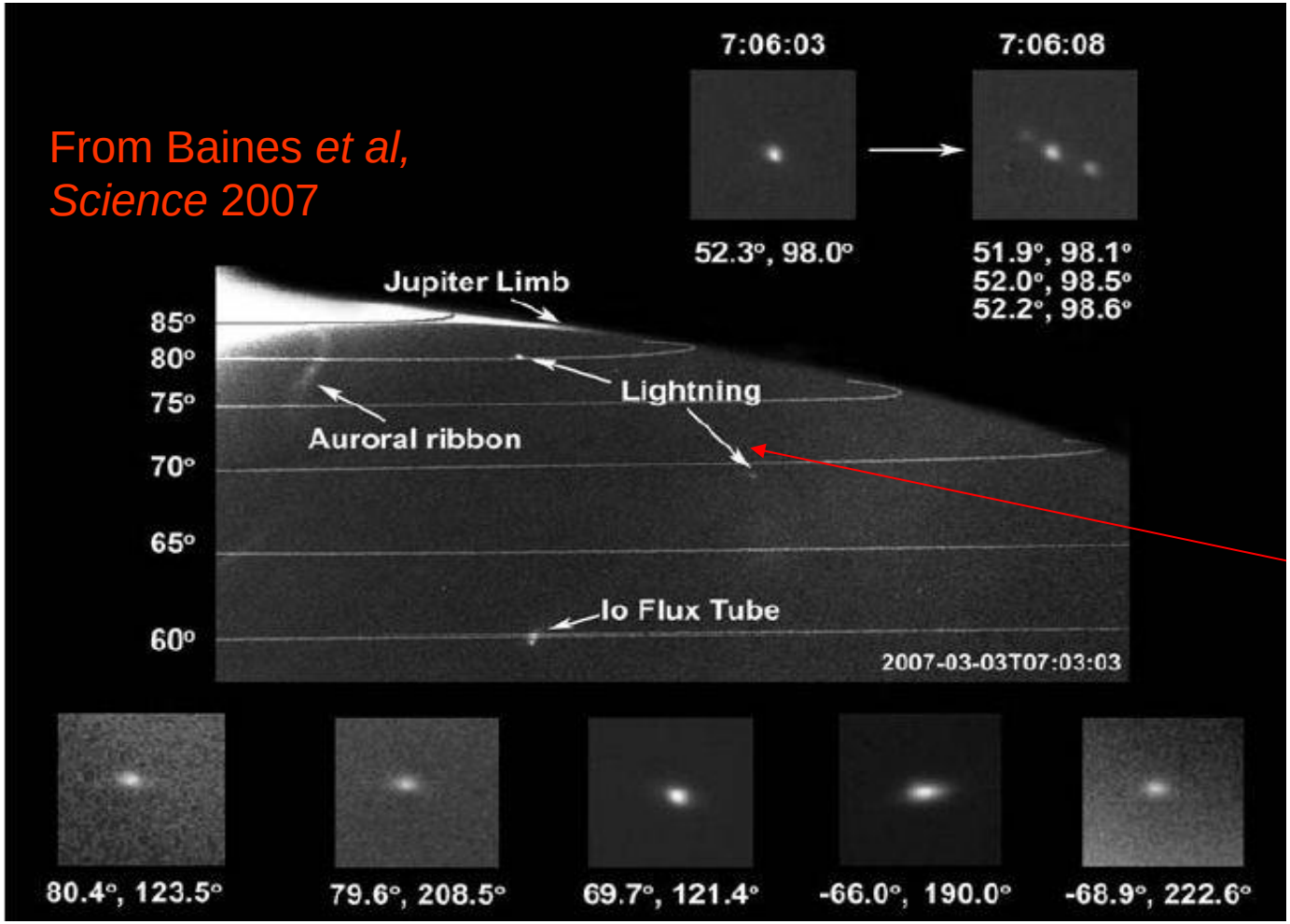
# Jovian lightning imaged by *New Horizons*




Multiple flashes in mid-latitudes

First observations of lightning near poles

Note diffuse images

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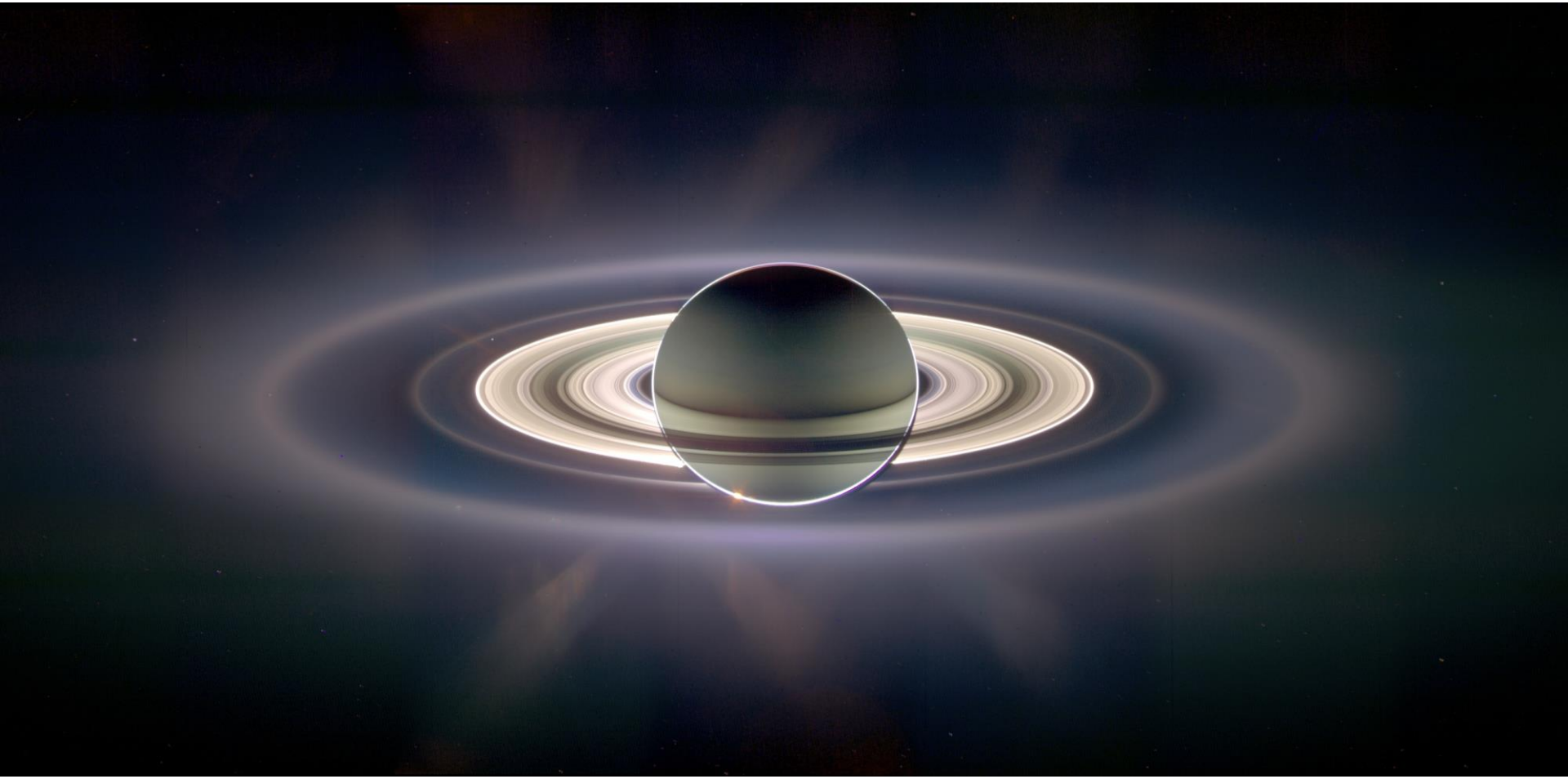
# Saturn, seen by Cassini



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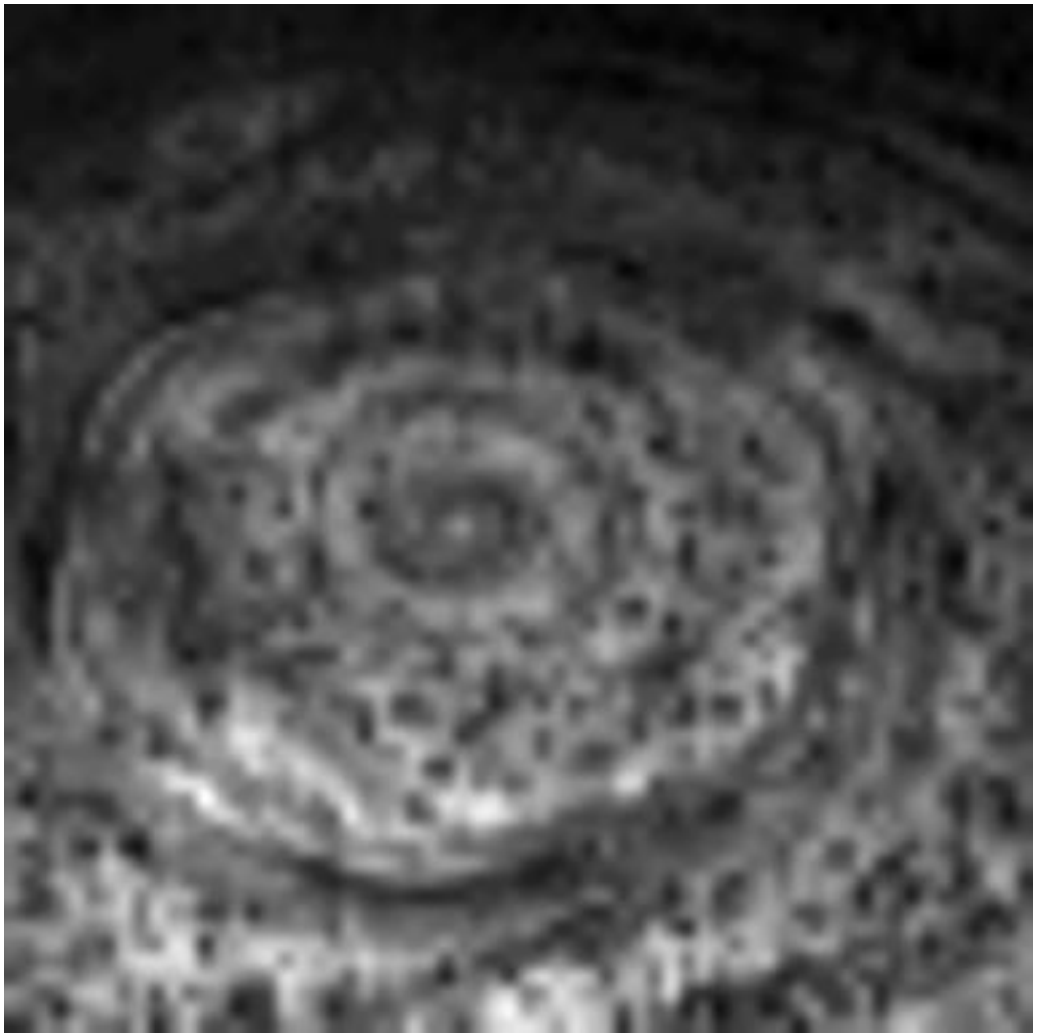
# Saturn’s rich atmospheric dynamics



*Saturn North Polar Hexagon from Cassini VIMS (NASA)*

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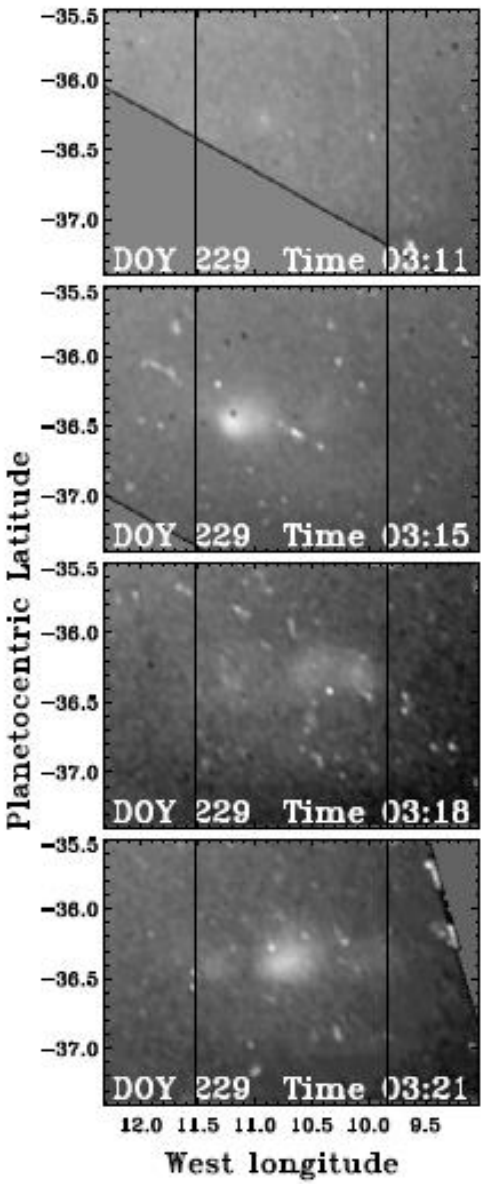
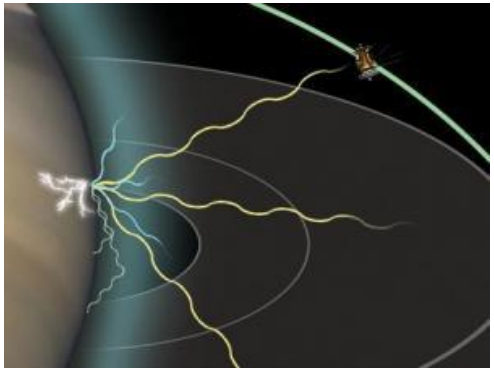
# Lightning on Saturn

- "Saturn Electrostatic Discharges" (SEDs) were first detected by a radio receiver on the Voyager 1 spacecraft in 1980.
- The Cassini spacecraft, currently orbiting Saturn, has detected radio emissions from lightning with its Radio and Plasma Wave Science instrument.
- Lightning optically detected from Cassini (Dyudina et al, 2010)
- "SEDs" have also been detected from Earth.
- Amateur observers have helped with tracking the storms.



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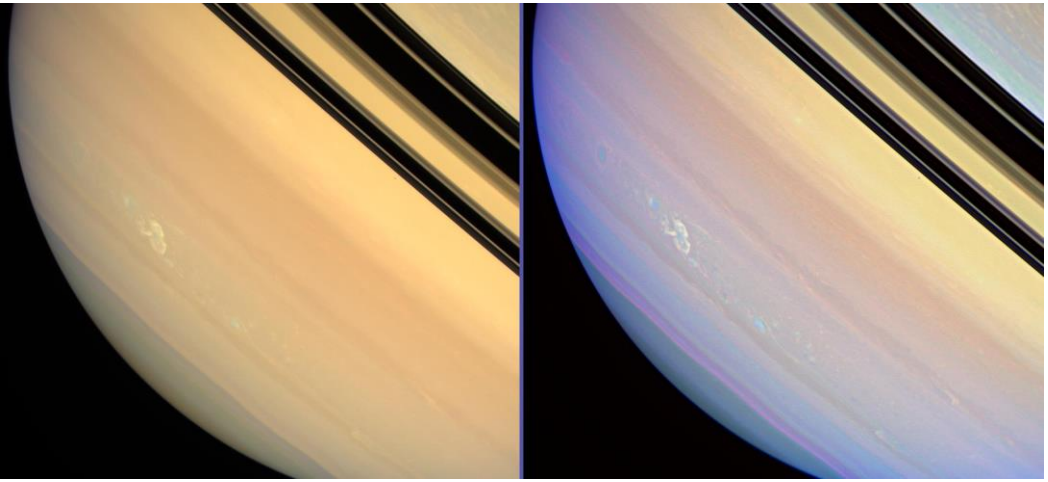
# Characteristics of Saturn's storms

- Cassini has linked the radio emissions with particular storms, which have been photographed.
- Storms only seen near the equator and in "storm alley" at 35ºS
- Storms are huge, powerful and long-lived.
  - Storm pictured below was active for 7.5 months
  - Radio emissions are 10,000x stronger than terrestrial storms
  - One Saturn storm is same size as Earth's atmosphere (Fischer et al, 2008)
- Longest-lived storm lasted from 14th Jan 2009 to at least mid-September 2009, and is also at 35ºS



Long-lived electrical storm on Saturn (Nov 2007 to mid-July 2008)

(left: natural colour, right: enhanced colour)

Image: NASA

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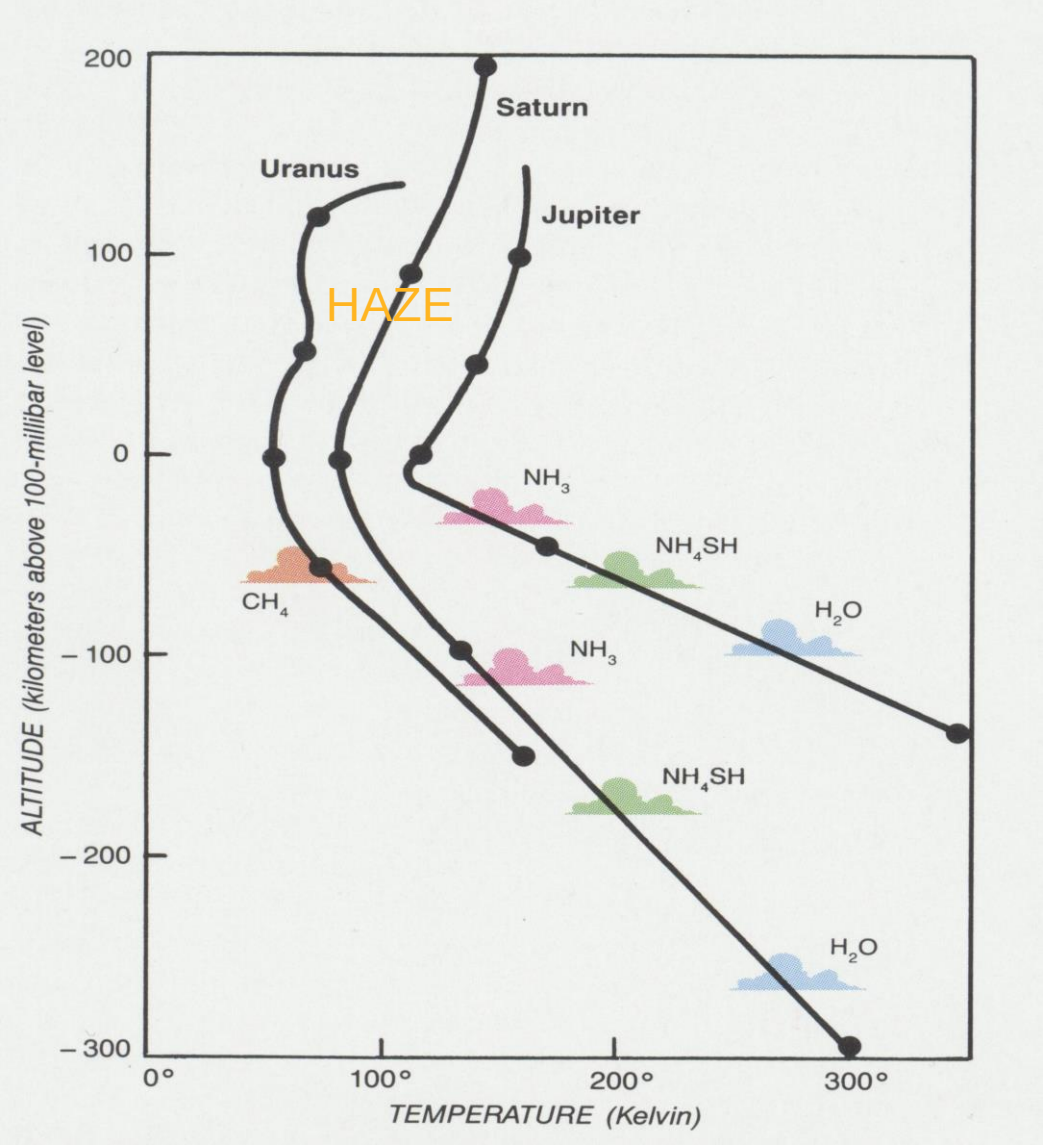
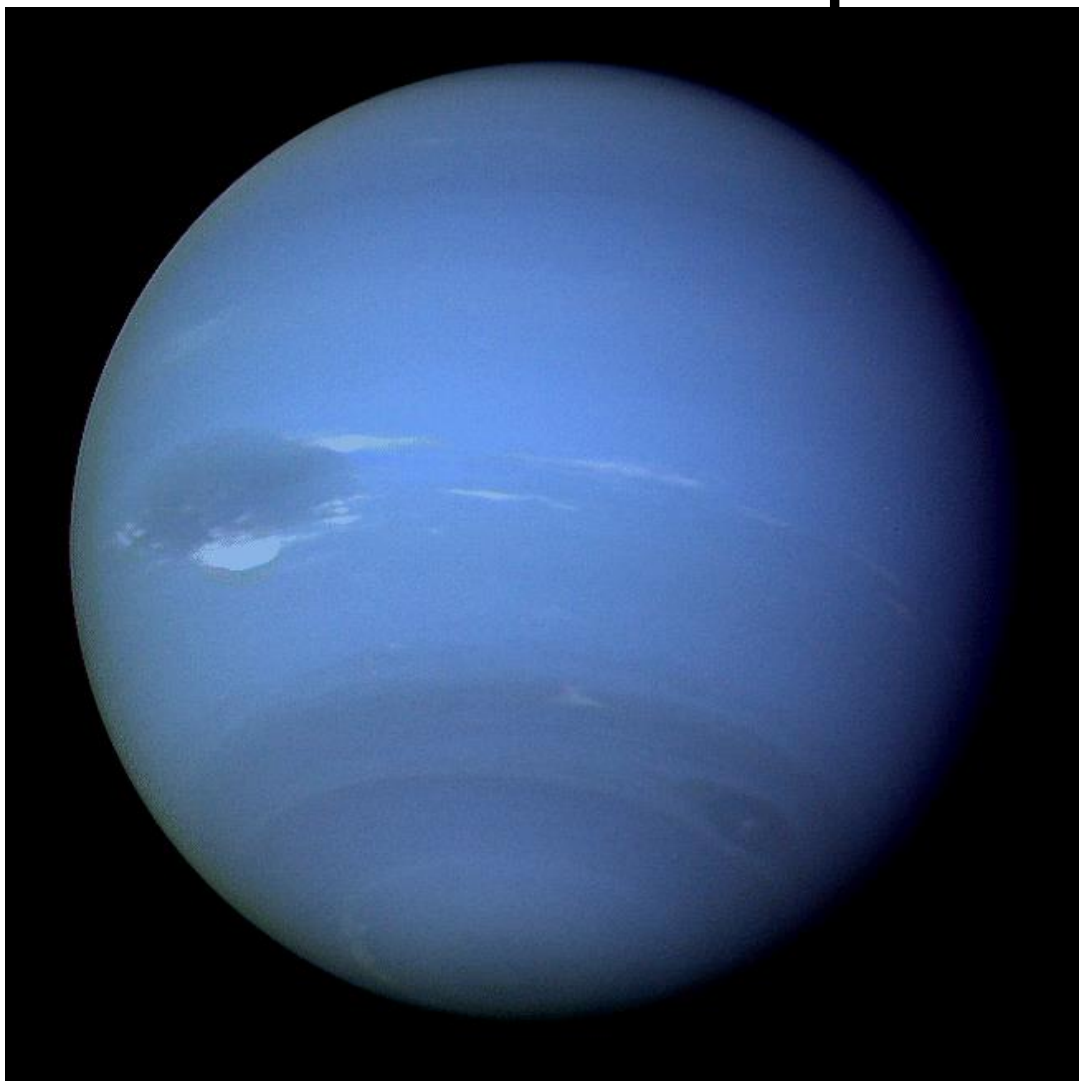
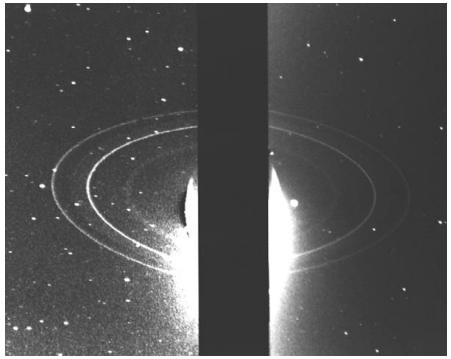
# Vertical cloud structure on Uranus, Saturn and Jupiter



# Neptune



- Much more active than Uranus even though further from the Sun
- Strong winds
- Weak rings



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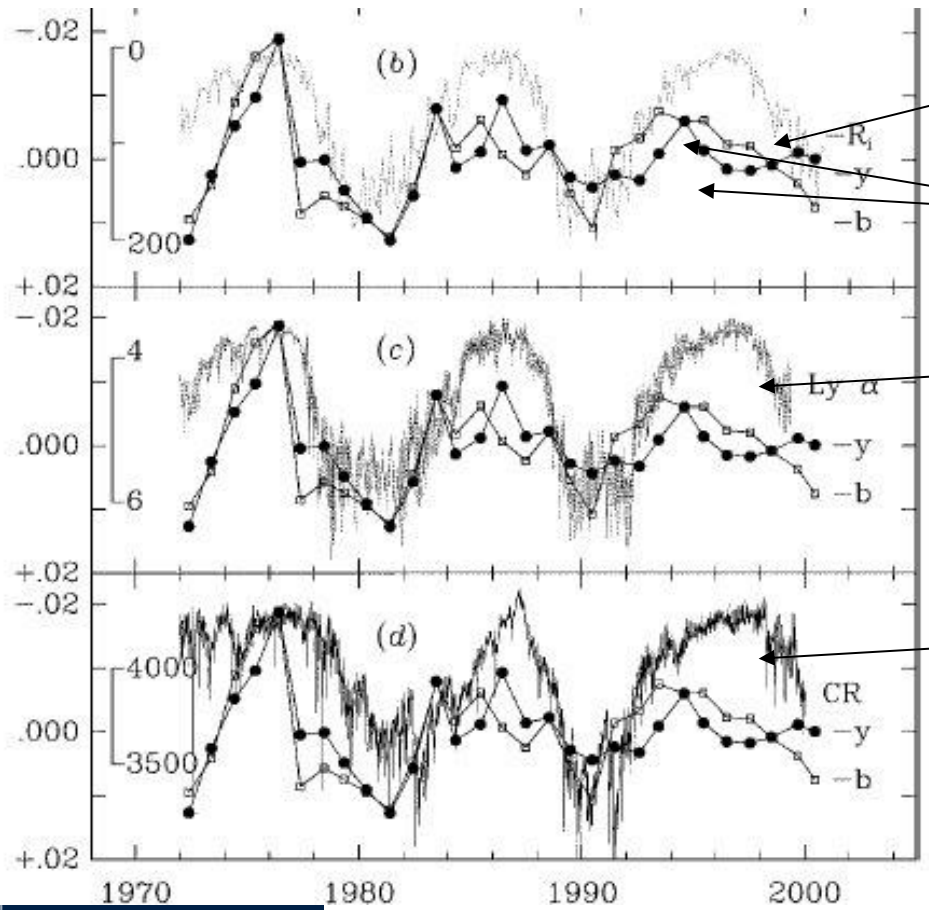
# Neptune's albedo and solar activity

Anticorrelation between Neptune's photometric albedo and solar activity seen from 1972-1996 (Lockwood and Thomson, 2002); supported by infra red observations 1975-2007 (Fletcher et al, 2010)



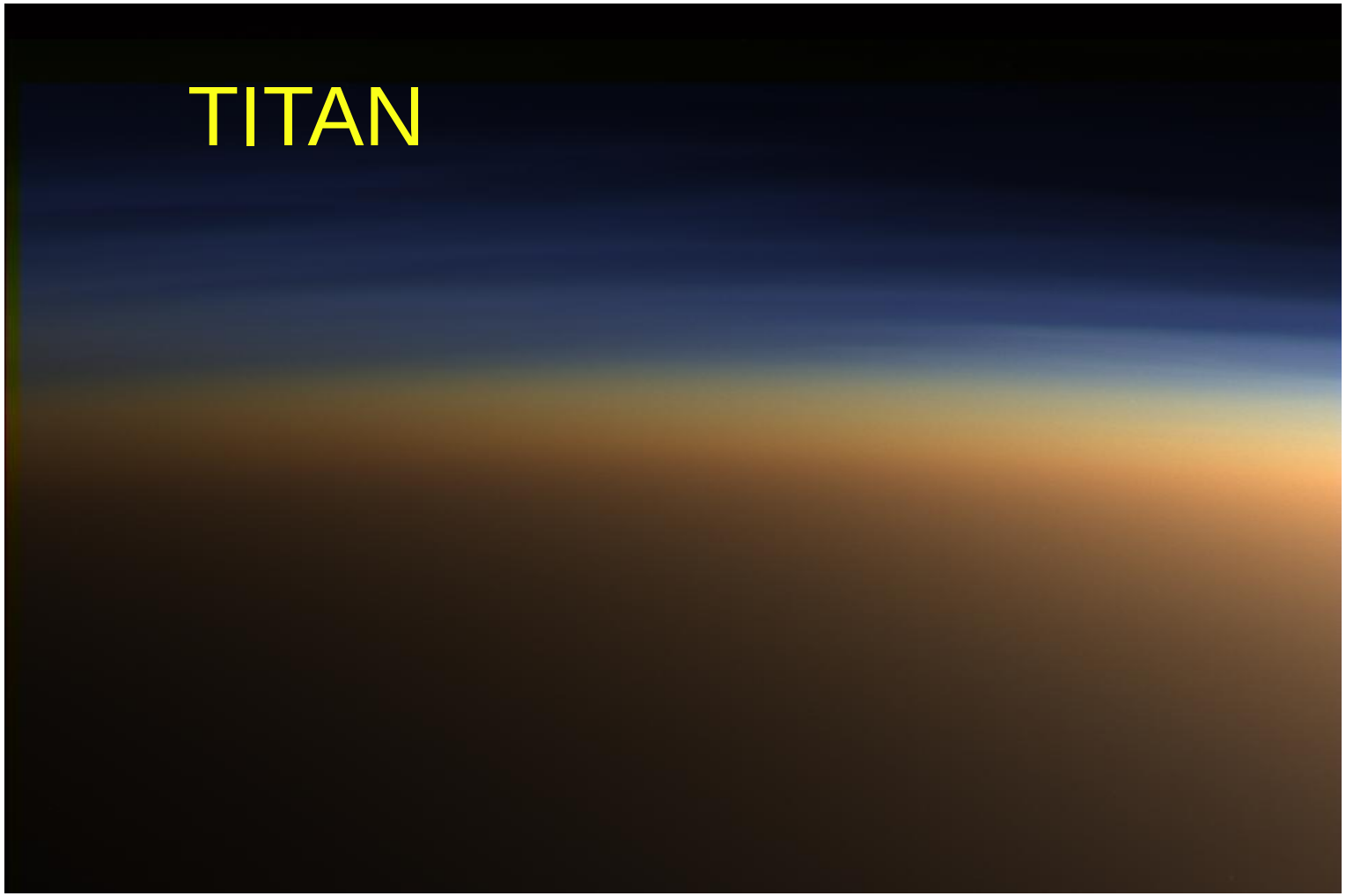

Sunspot number

Albedo

Lyman-alpha (UV) flux (121.6 nm)

Cosmic rays (neutrons measured at Earth)

Statistical arguments favoured the UV mechanism, but recent work suggests cosmic ray "signatures" are present in albedo data.

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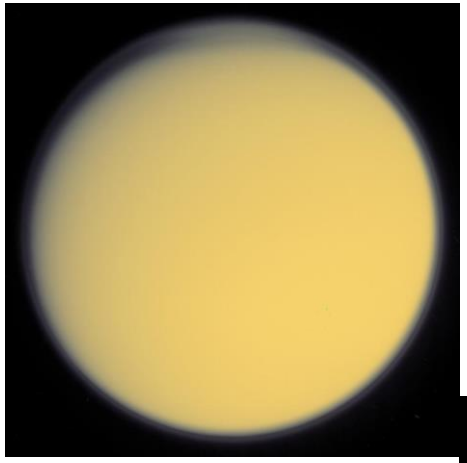
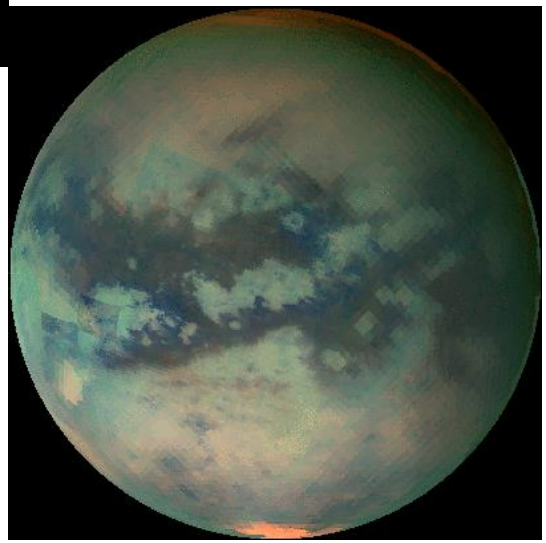
# Titan



*Voyager 1 Image of Titan (NASA)*



*Cassini VIMS surface image (NASA)*

- Handy Facts about Titan:
  - Saturn's largest moon (R=2575km, bigger than Mercury).
  - It is the **only moon in the Solar System known to have a substantial atmosphere** (1.5bar surface pressure, mostly Nitrogen with trace amounts of Hydrocarbons (mostly methane (about 2% at tropopause) and Nitriles.
  - These give rise to **complex photochemistry** (hence the 'Orange blob' look in the visible).
  - Cassini has found **evidence of weather** (clouds). There may be a methane 'hydrological cycle' with super-saturation and 'rain'.
  - Bizarrely seems to be the most Earth like 'planet' in the solar system.
  - Atmosphere is very primitive, often described as a frozen pre-biotic Earth.

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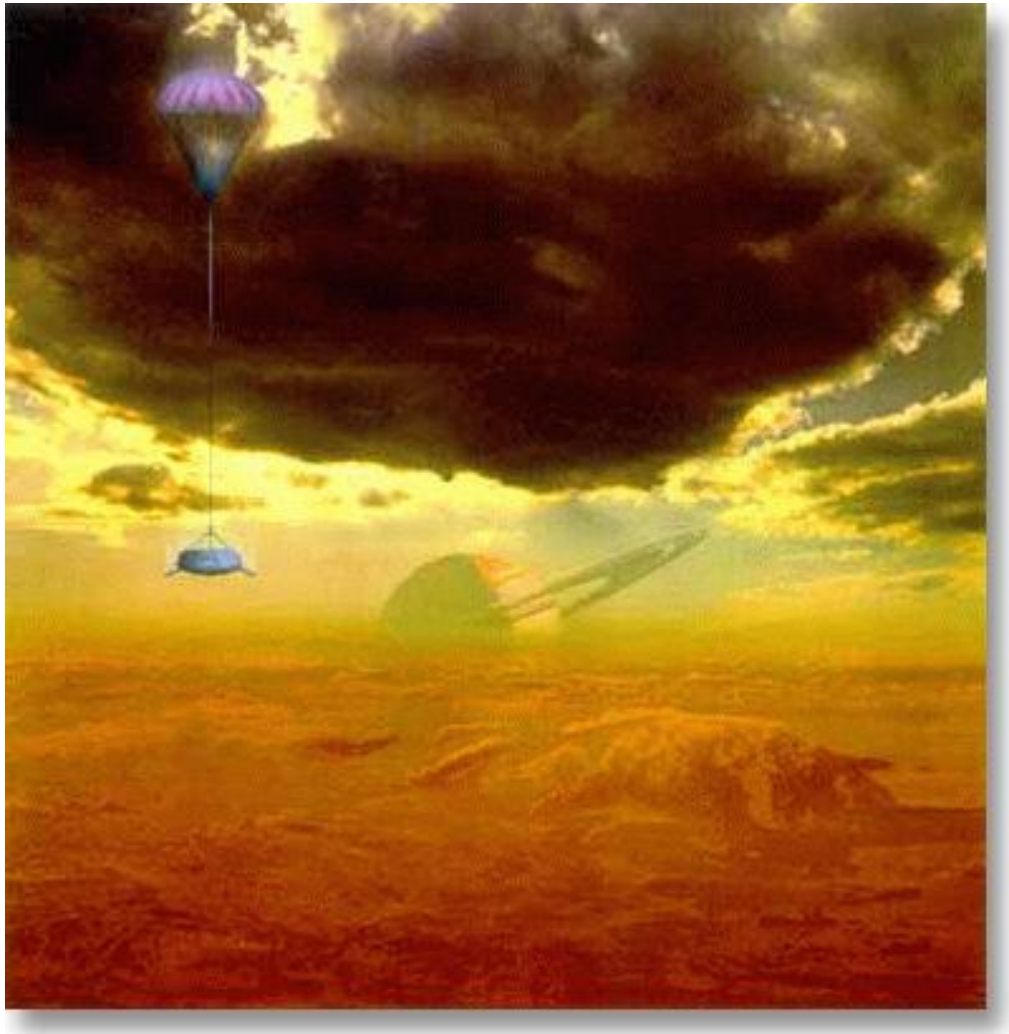
# 14 January 2005: Huygens lands on Titan



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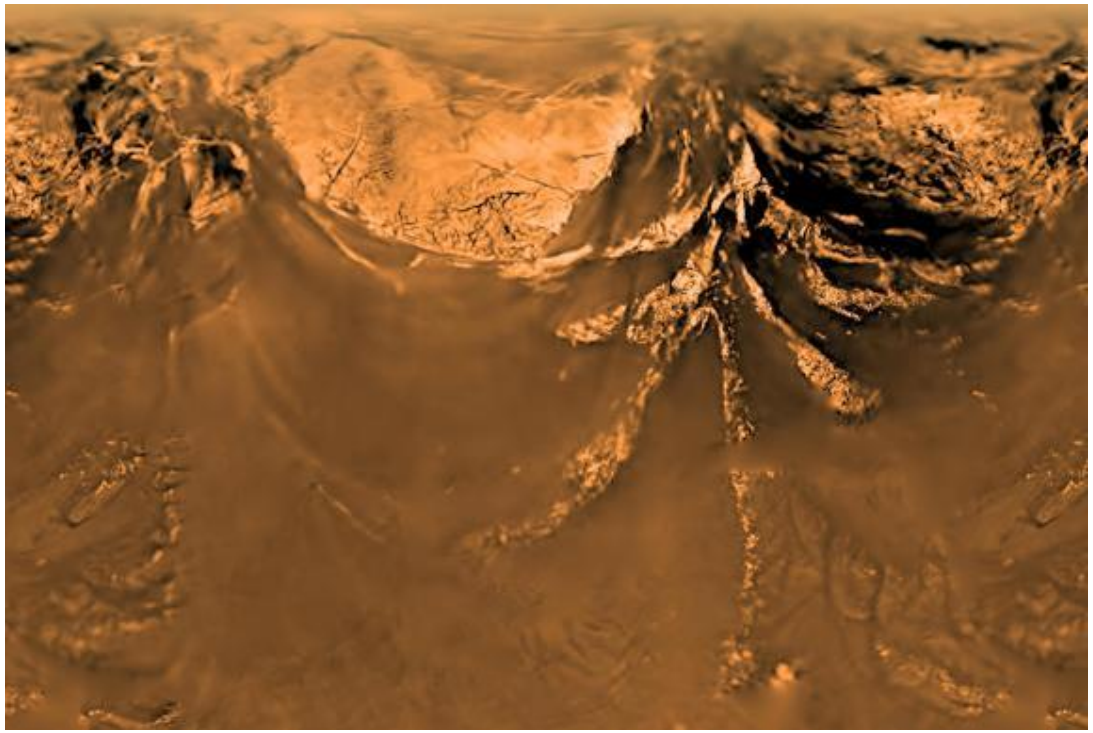

Huygens views of the surface of Titan

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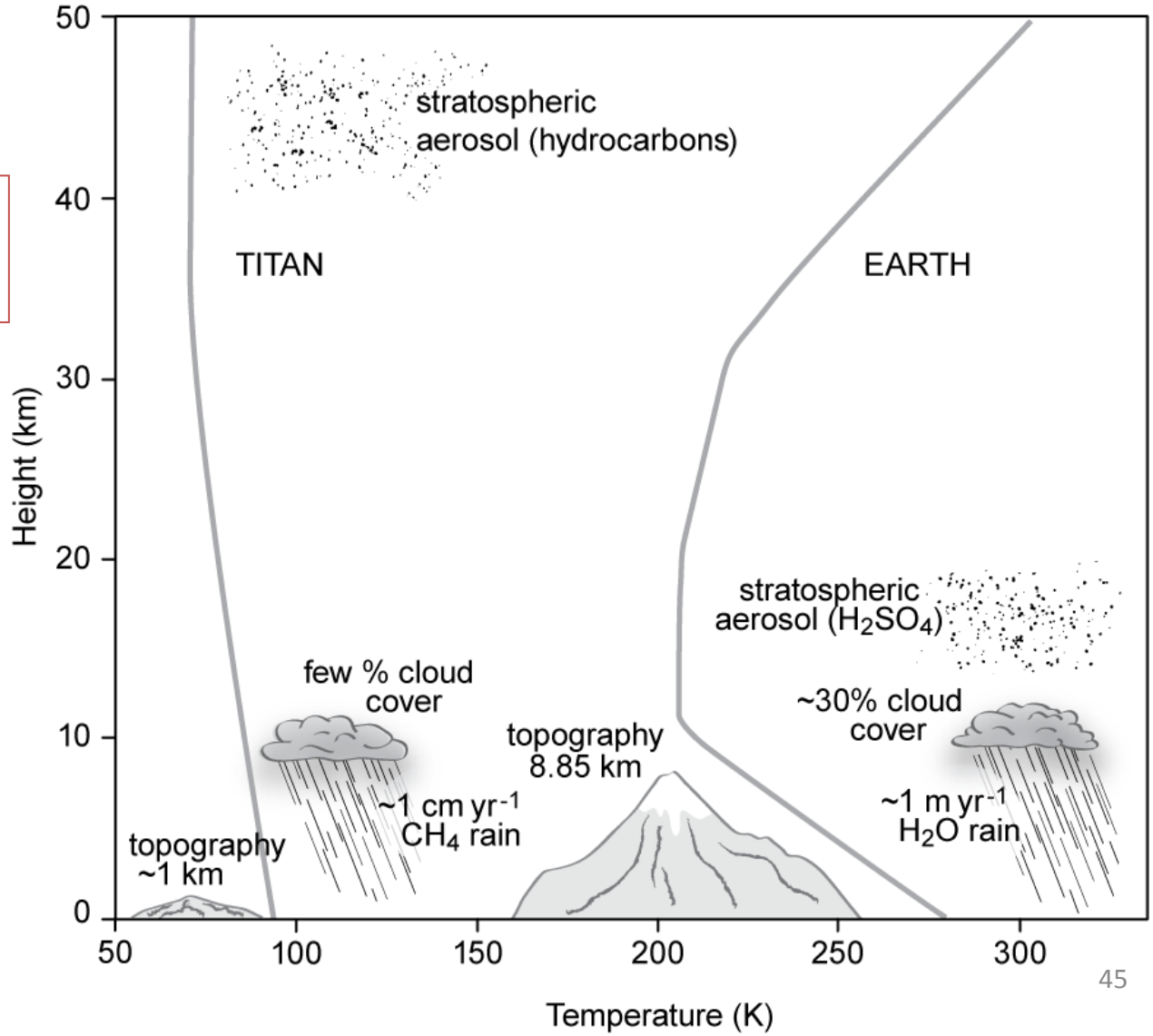
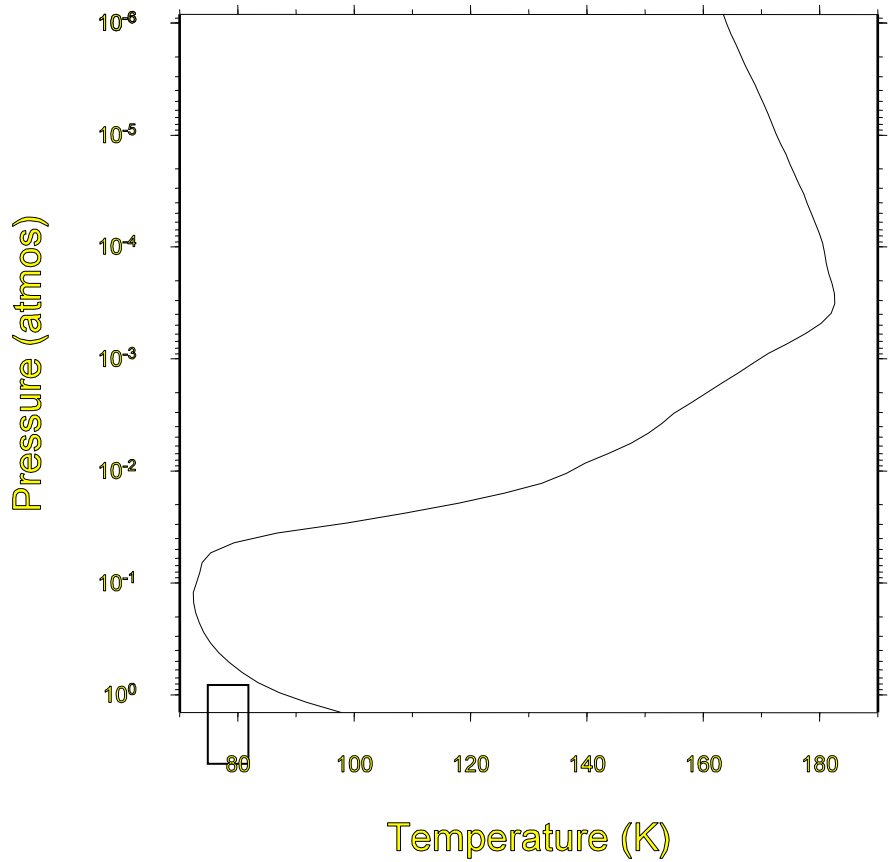
# Titan's atmosphere

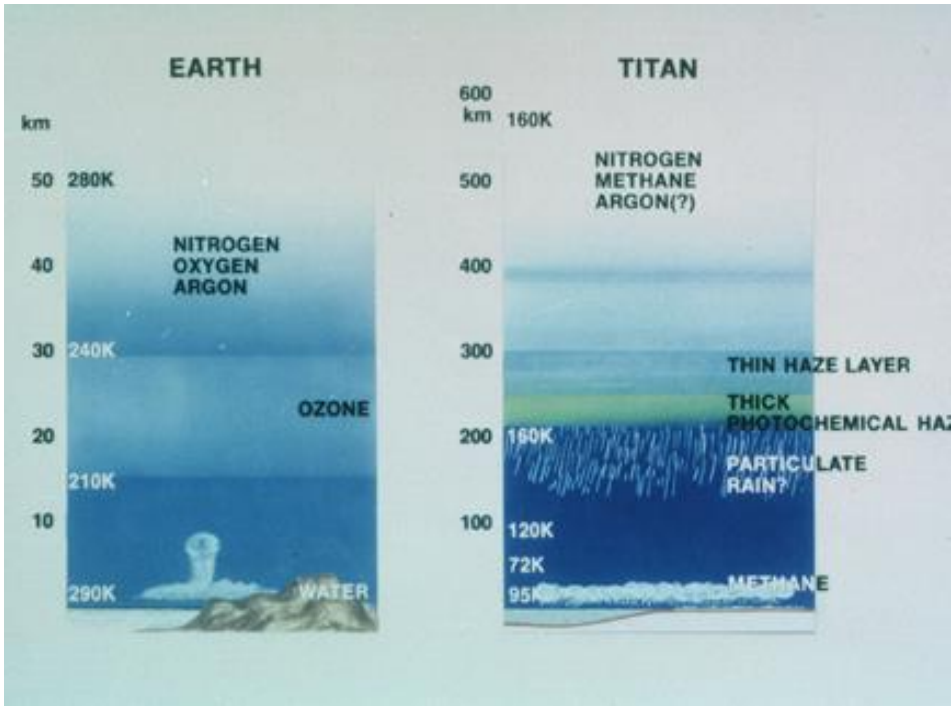
Nitrogen $N_2$: 95.1%

Methane $CH_4$ 4.9%



# A methane ‘Hydrological’ cycle?




The temperature in Titan’s atmosphere is low enough for methane to exist in super-saturation, possible methane rain!

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# Big Questions in Planetary Science

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  - The scientific search for life in the solar system and galaxy
  - Concepts of habitability driven by fundamental physical processes
- The diversity of planets across multiple solar systems
- The evolution of solar systems
  - Where did the Earth's oceans come from?
  - How do terrestrial planetary surfaces form and evolve?
- Comparative planetology
  - Internal structure of planets (Earth/Mars/Titan/Mercury/Moon)
  - From GCMs of giant planet atmospheres to extra-terrestrial sand-dunes on Mars and Titan.

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# Conclusions

- This was a taste of planetary atmospheres in our solar system
- A wide variety of atmospheres share common physical processes – comparative approach
- A revolution is ongoing … the discovery of exoplanetary systems means we need to evolve our thinking about the Solar System
- Recommended further reading – from which many of the unreferenced figures here were taken:
  - Planetary Science (de Pater and Lissauer)
  - Planetary Atmospheres (Taylor)
  - An Introduction to Planetary Atmospheres (Sanchez-Lavega)
  - Electrifying Atmospheres (Aplin) and Planetary Atmospheric Electricity (Leblanc et al)

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