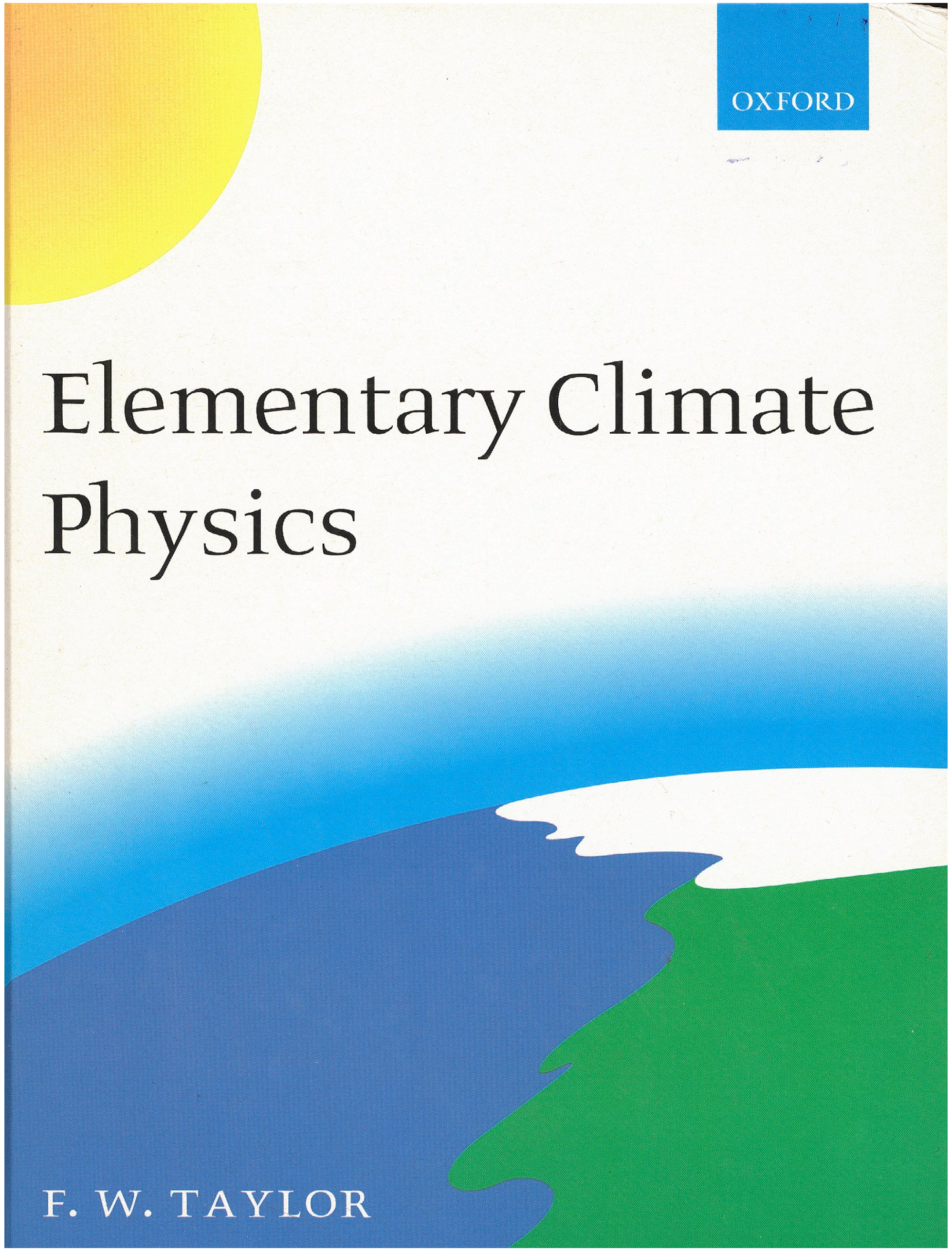
Planetary Atmospheres in the Solar System

Review and Tutorial

Challenges, Mysteries and Surprises

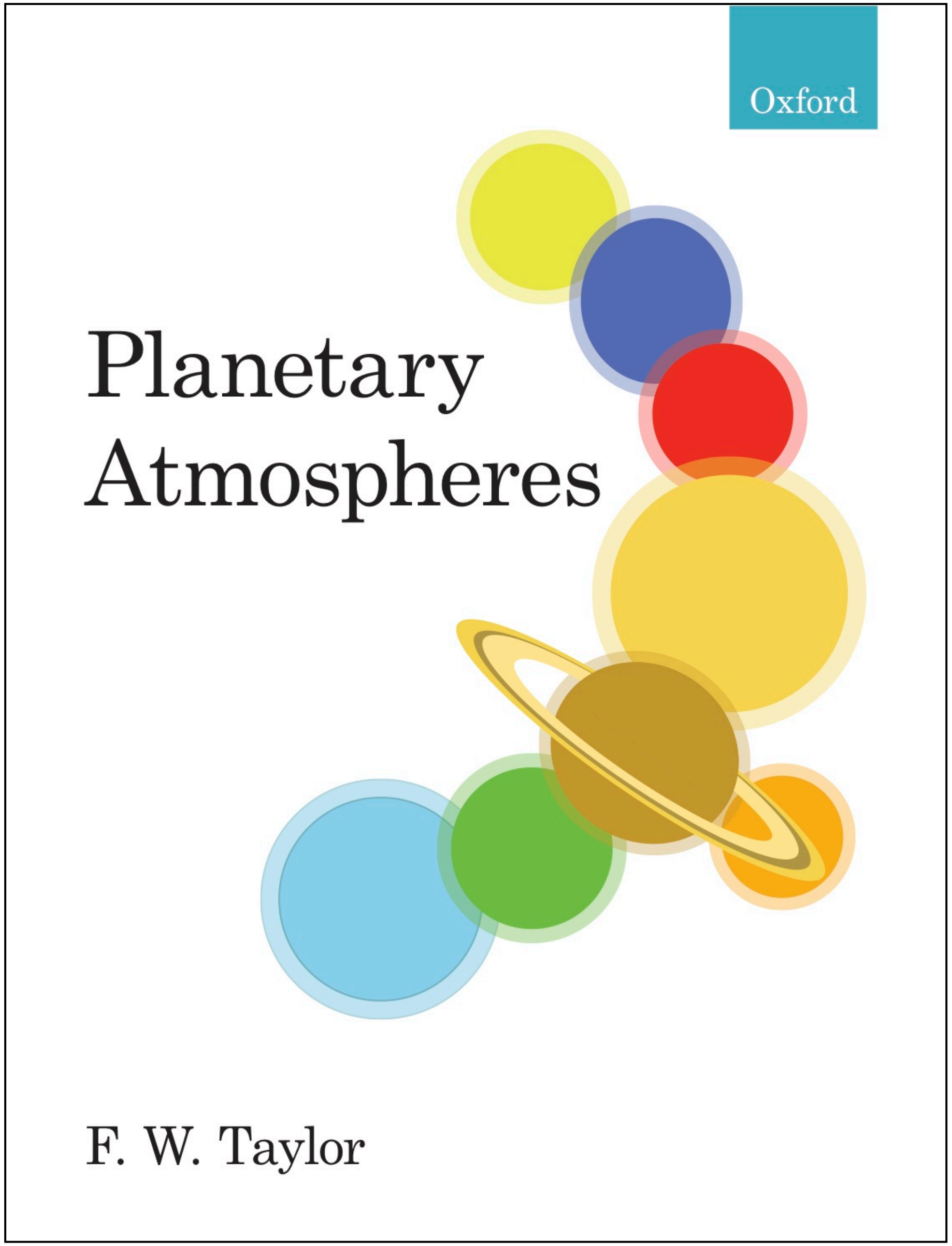
Fred Taylor ExoClimes Meeting, Exeter, Sept 2010



OXFORD

Elementary Climate Physics

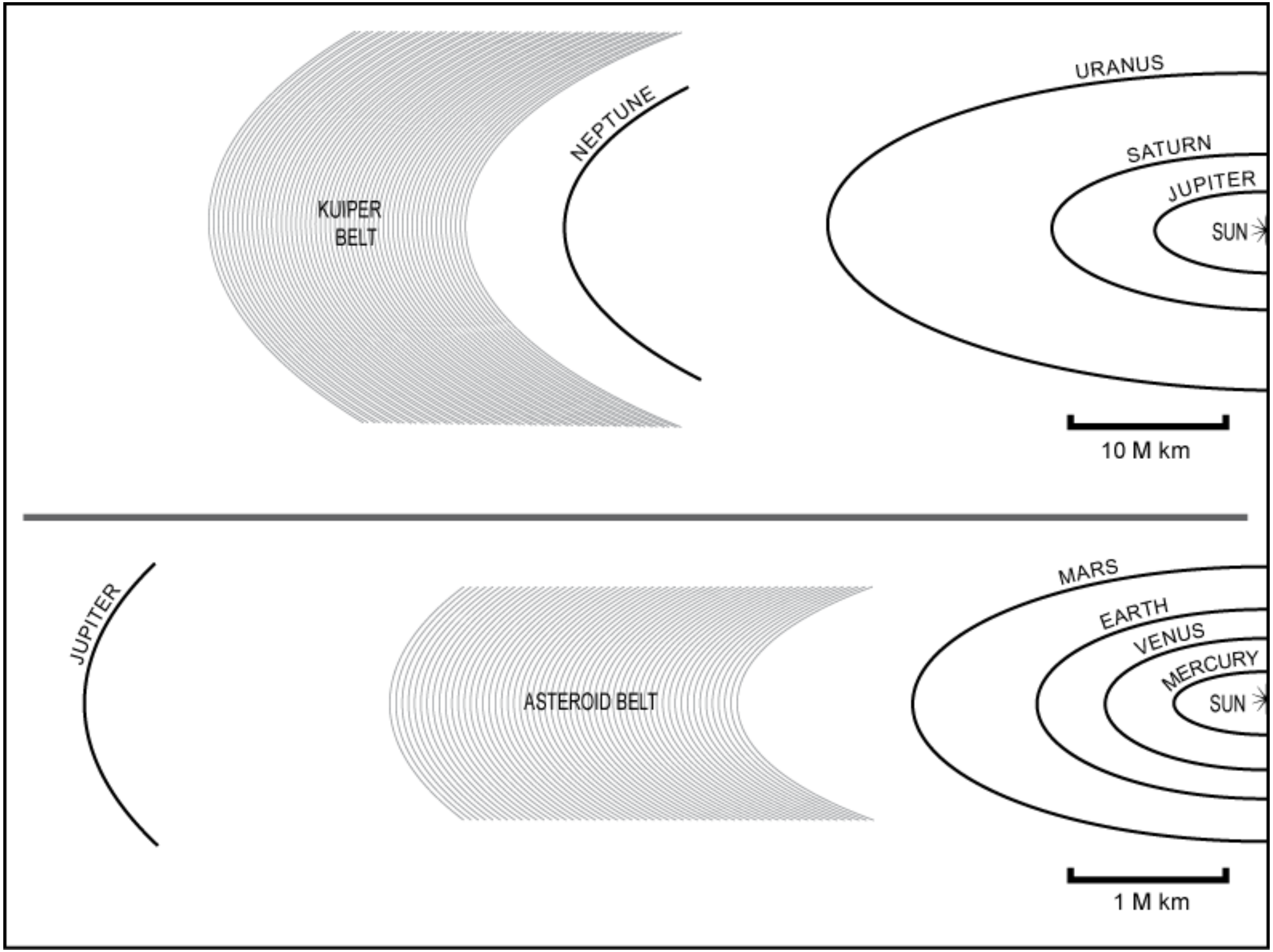
F. W. TAYLOR

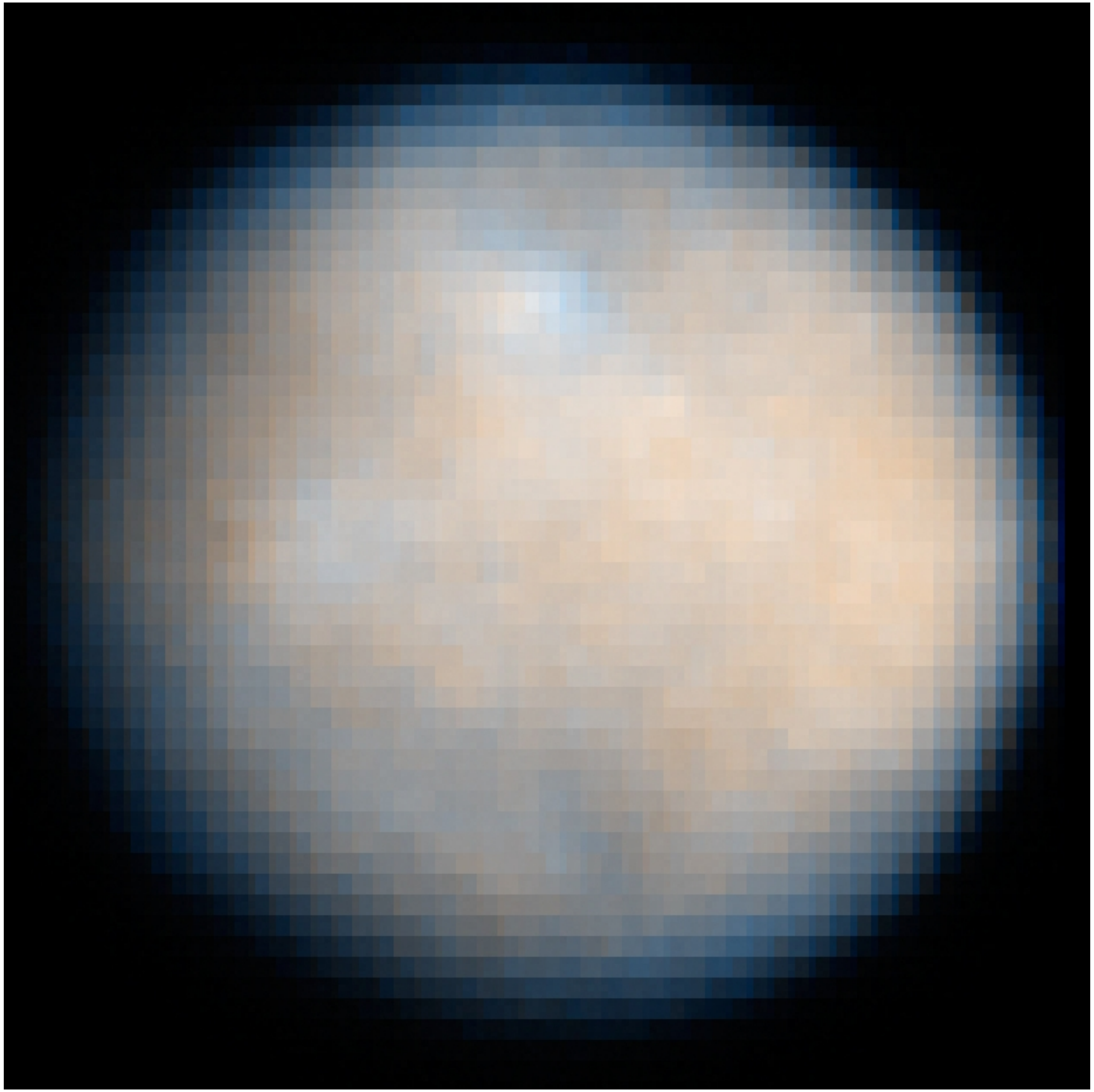


Oxford

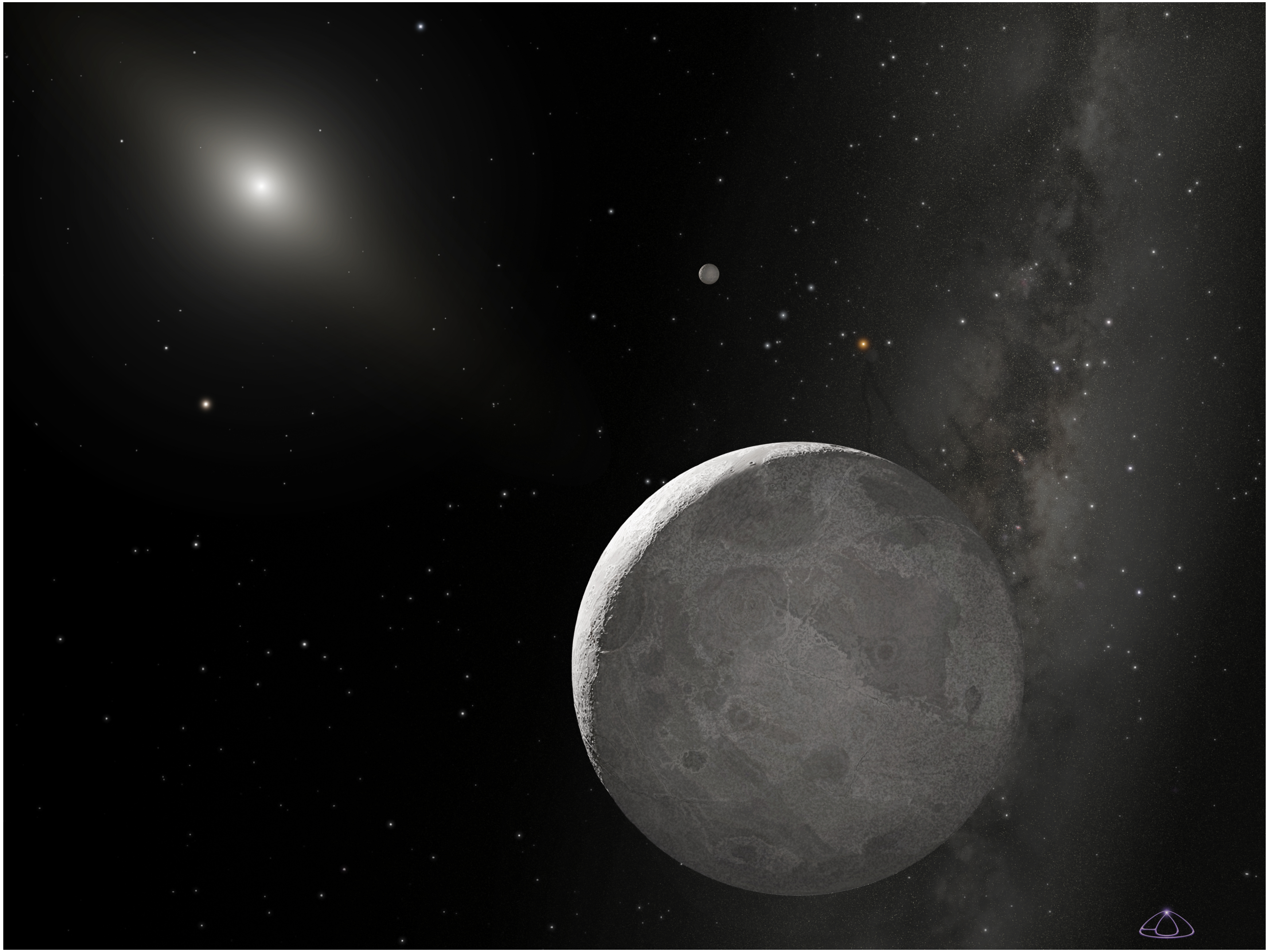
Planetary Atmospheres

F. W. Taylor

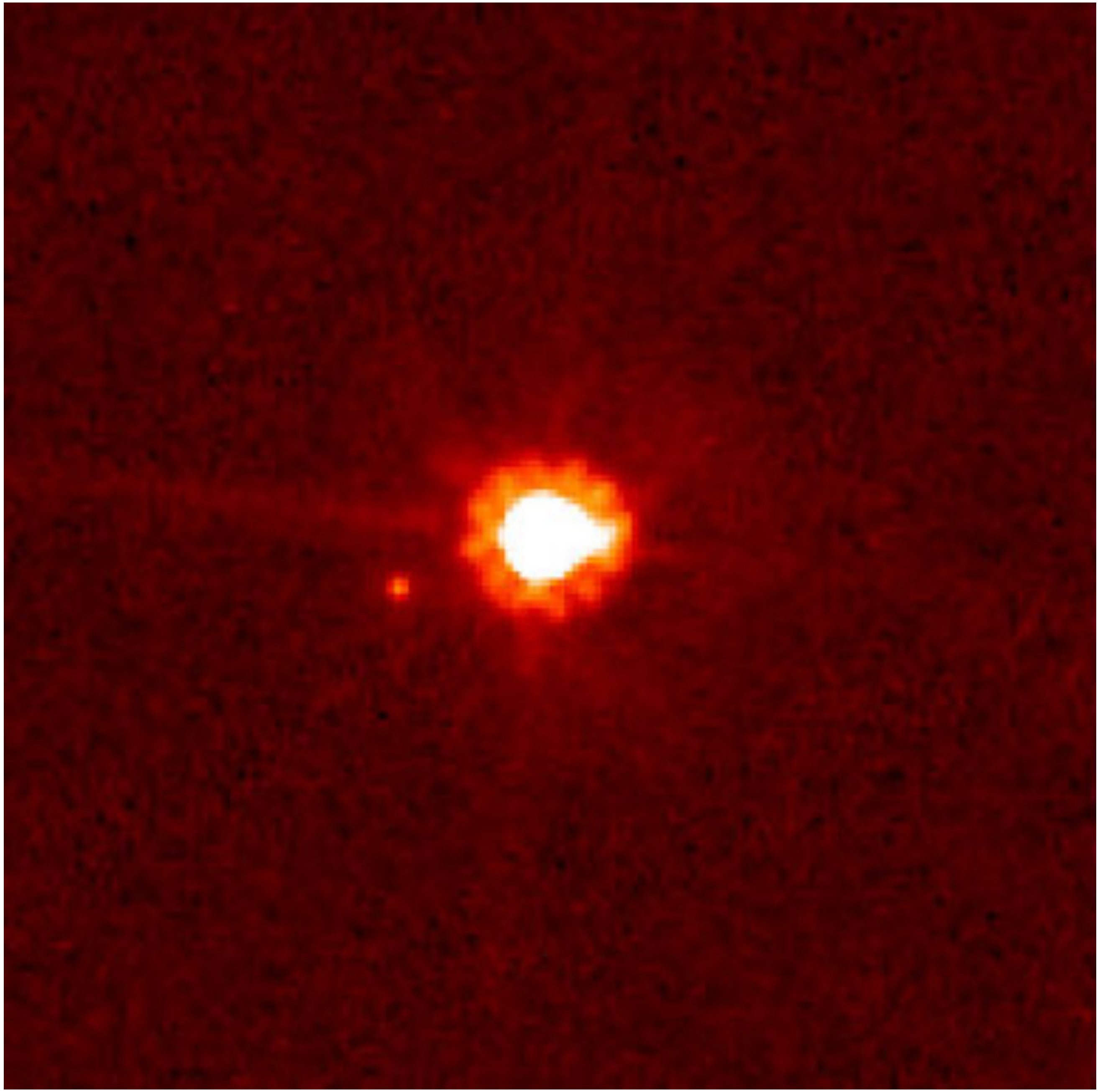

URANUS
NEPTUNE
SATURN
JUPITER
KUIPER BELT
SUN
10 M km
MARS
JUPITER
EARTH
VENUS
MERCURY
ASTEROID BELT
SUN
1 M km



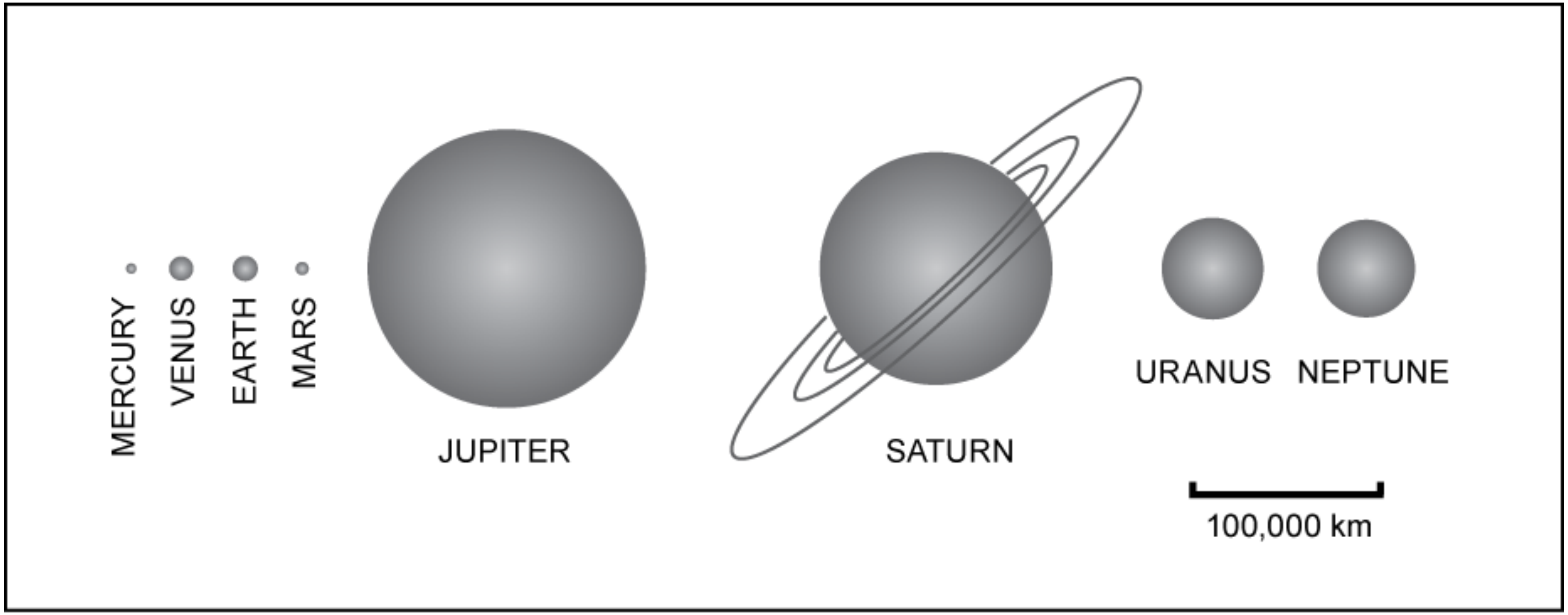
CERES

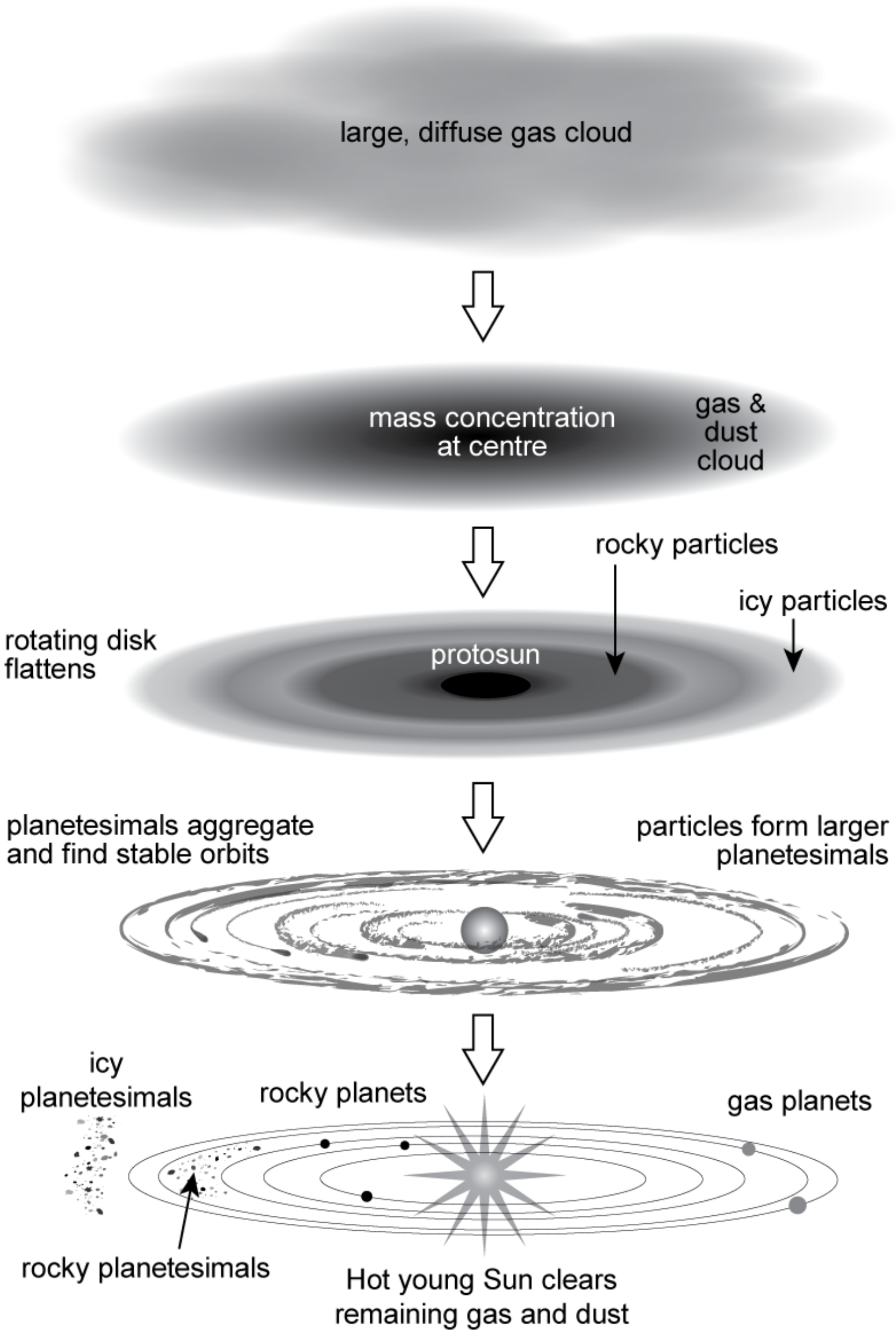


Eris and Dysnomia



Eris and Dysnomia


MERCURY
VENUS
EARTH
MARS
JUPITER
SATURN
URANUS
NEPTUNE
100,000 km

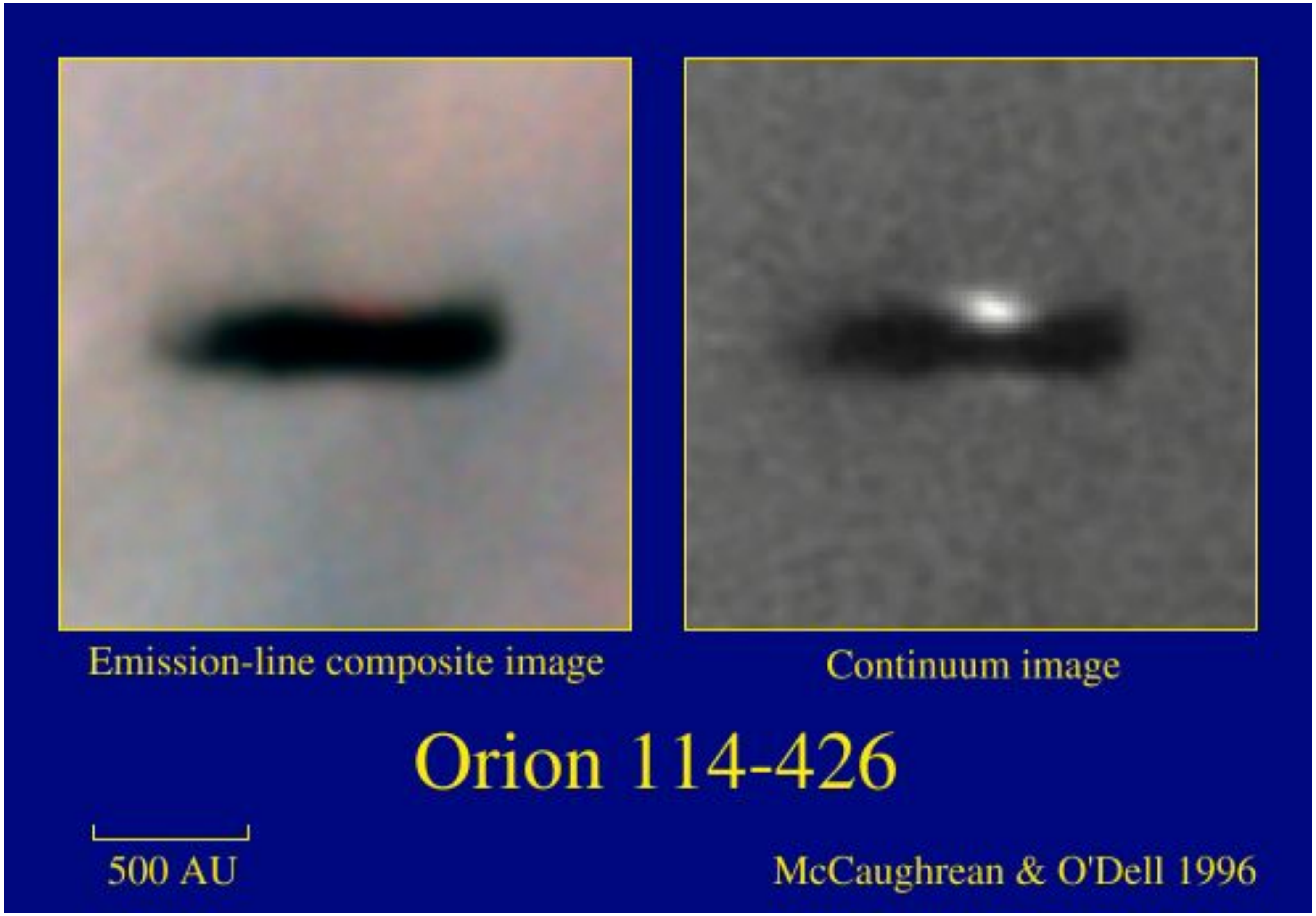

large, diffuse gas cloud
mass concentration at centre
gas & dust cloud
rocky particles
icy particles
rotating disk flattens
protosun
planetesimals aggregate and find stable orbits
particles form larger planetesimals
icy planetesimals
rocky planets
gas planets
rocky planetesimals
Hot young Sun clears remaining gas and dust

Molecular Clouds

- Molecular clouds are observed in the Universe
- Typical values for temperature and density are:
  - $T = 20\text{K}$,
  - $\rho \sim 10^{10}$ H atoms (10^{-17} kg) m^{-3}
- gives $M_J \approx 10^{31}$kg ≈ 10 solar masses.
- $R \approx$ 40,000 AU or about 1 light year.

Molecular Cloud Barnard 68 (VLT)

Circumstellar Discs



Formation of Protosolar Nebula

An isothermal cloud of mass *M* will collapse if its gravitational potential energy (binding energy) is greater then its internal thermal energy.

The thermal energy of the cloud is $E \approx NkT = \frac{M}{\mu m_H} kT$, where μ = mol wt of material in cloud, m_H = mass of H atom, M = mass of cloud, N = number of atoms in the cloud.

Stability/instability boundary where thermal energy = binding energy i.e. $\frac{MkT}{\mu m_H} = \frac{GM^2}{R}$

now $M = \frac{4}{3}\pi\rho R^3$, hence $R = \left(\frac{3M}{4\pi\rho}\right)^{\frac{1}{3}}$, giving $\frac{kT}{\mu m_H} = GM^{\frac{2}{3}}\left(\frac{4\pi\rho}{3}\right)^{\frac{1}{3}}$.

Thus the minimum mass of cloud of temperature *T* and radius *R* that will collapse is

$$M_J \approx \frac{1}{\sqrt{\rho}}\left(\frac{kT}{G\mu m_H}\right)^{\frac{3}{2}}$$

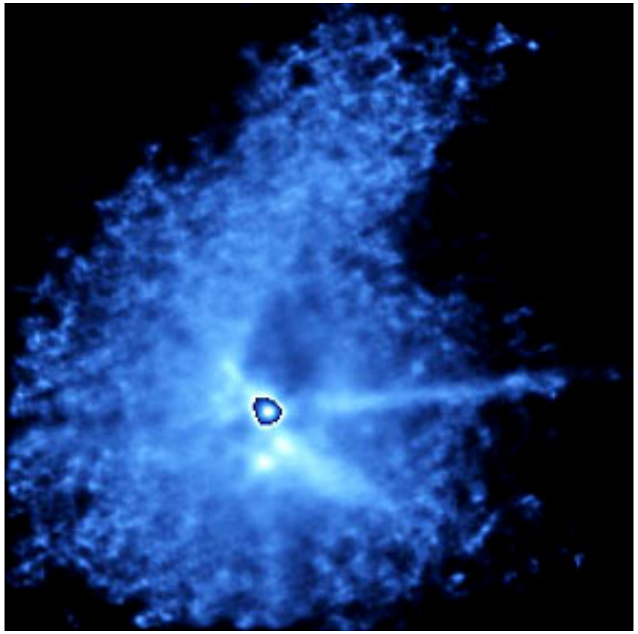
<u>Jeans' Criterion</u>

Formation of Circumstellar Disc

- The time scale for Jean's collapse is estimated by considering a particle in free fall at a distance *R* from the centre of a cloud of mass *M.*
- The acceleration of the particle is $\frac{GM}{R^2} \approx \frac{R}{t^2}$,
- where *t* is the time to collapse to the centre, $t \approx \frac{1}{\sqrt{G\rho}}$,
- Inserting typical values we find $t \sim 10^6$ years, so time is not a problem.
- Material falling along rotation axis can reach the centre, while material falling at right angles is balanced by centrifugal forces.
- Hence nebula forms a disc, with a protoSun at the centre which started fusing soon after collapse, heating the inner nebula.
- Early Sun should have been rotating very quickly; detailed models have trouble getting rid of the excess angular momentum.

Loss of mass and angular momentum in circumstellar discs:

The T-tauri phase of the Sun



- Problems:
  - M_J is >> present mass of Solar System.
  - Distribution of angular momentum between Sun and planets.
- Answer:
  - ☐ Soon after the Sun began to fuse hydrogen it entered its ‘T-tauri’ phase with ~ 3 x current luminosity and a very dense, high speed solar wind.
- Mass loss of 10^{-8} M_{Sun}/year over 10^7 years.
- Planets formed before the T-tauri phase.
- Remaining solar nebula was swept away.
- Angular momentum carried away by the solar wind, ‘despinning’ the Sun.

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, allowing that some of these are of radiogenic origin.
- For Venus, Earth and Mars it is found that:
  - i. the ratio of ^{20}Ne to ^{36}Ar is similar on all 3 planets, but different in the Sun: argues against (1) and (3)
  - ii. primordial argon decreases by several orders of magnitude from Venus to Earth and from Earth to Mars. Argues against (4).
- This leaves (2). Plus, outgassing is still observed (e.g. volcanoes).

Processes affecting the evolution of atmospheres to their present state

I. Thermal escape to space

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

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

IV. Regolith absorption/chemical combination, e.g $O_2 \rightarrow$ 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)

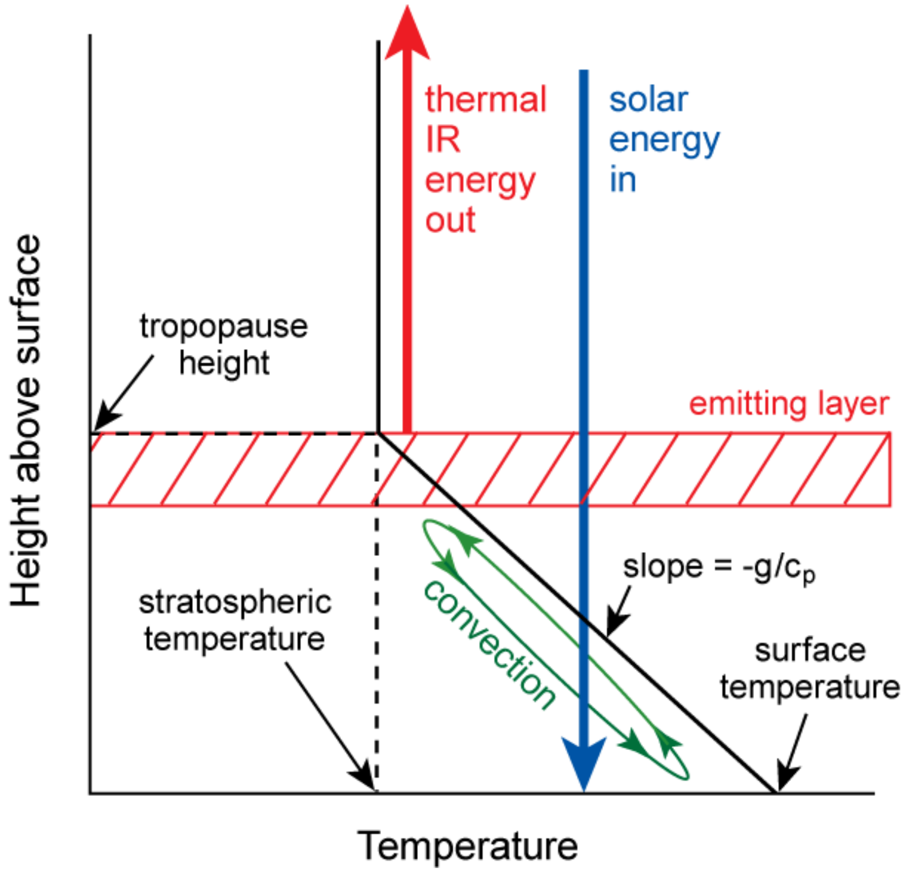
VIII. Sources (e.g. comets, volcanism)

Characteristic Jeans escape times for different gases on several planets.

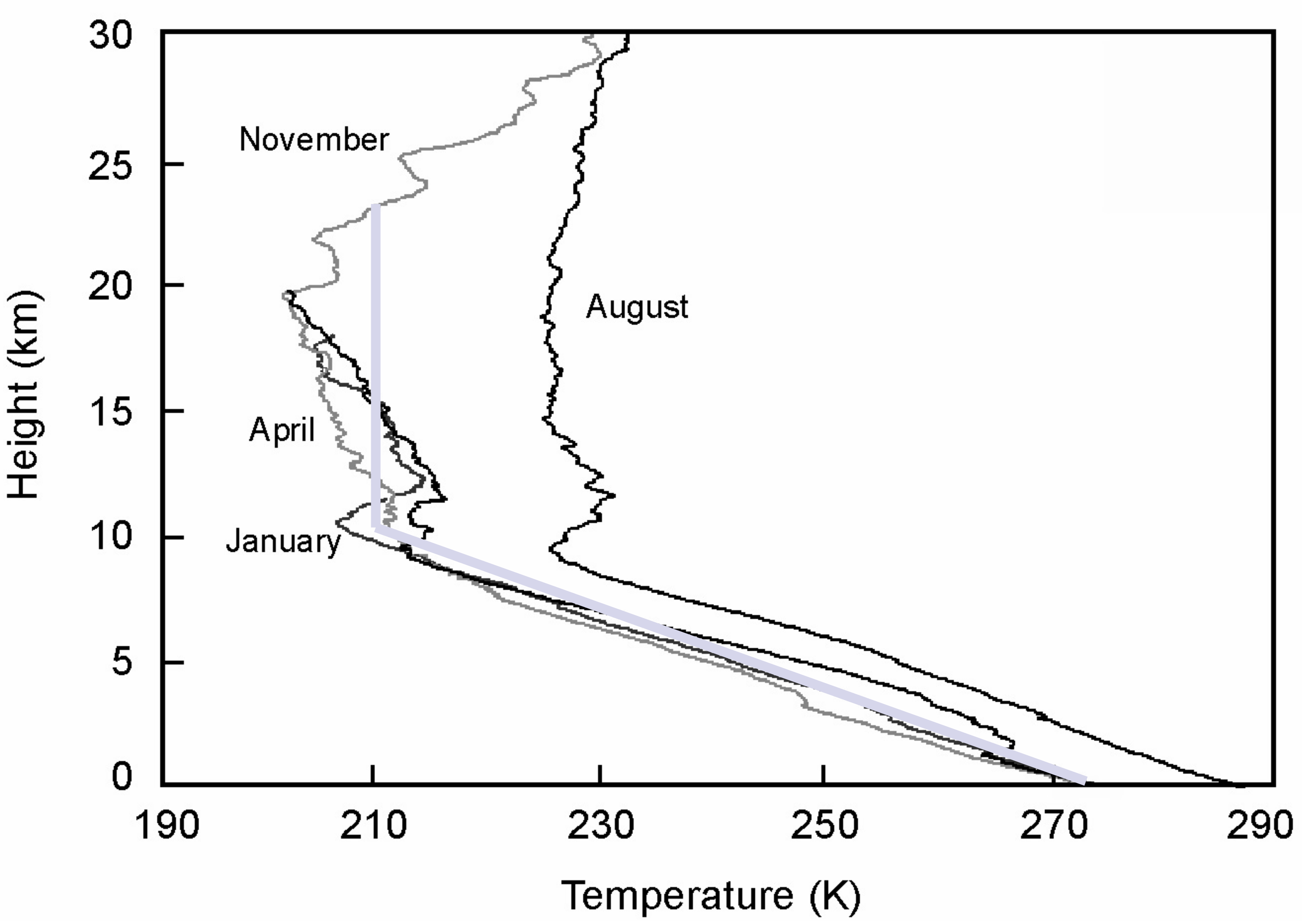
	Moon	Mercury	Mars	Venus	Jupiter
T (K)	300	600	365	700	155
R_e (km)	1738	2439	3590	6255	69500
g (ms^{-2})	1.62	3.76	3.32	8.27	26.2
τ_e(H) (s)	3.55×10^3	3.32×10^3	1.39×10^4	5.71×10^5	5.14×10^{617}
τ_e(He) (s)	2.03×10^4	1.40×10^5	2.66×10^8	2.85×10^{16}	1.18×10^{2455}
τ_e(O) (s)	2.25×10^9	7.37×10^{13}	1.04×10^{28}	7.87×10^{61}	1.03×10^{9820}
τ_e(Ar) (s)	3.29×10^{20}	2.57×10^{32}	1.97×10^{68}	6.20×10^{153}	6.61×10^{24522}
τ_e(Kr) (s)	3.53×10^{41}	9.09×10^{66}	4.45×10^{142}	4.67×10^{322}	3.72×10^{51445}

Calculating Model Vertical Temperature Profiles

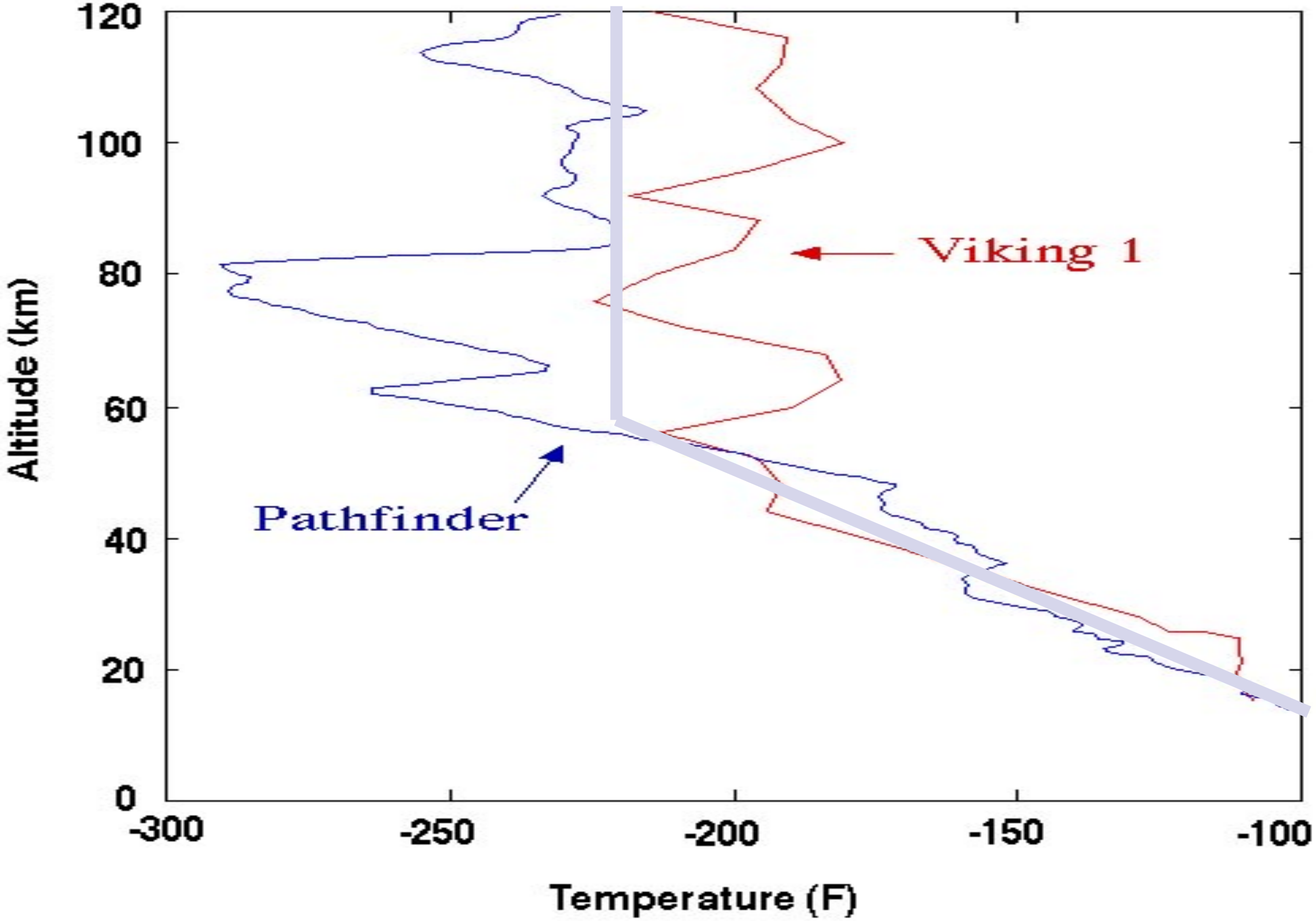
- Optically thick, convective troposphere
- lapse rate from simple thermodynamics
- Optically thin stratosphere in radiative balance
- Albedo determines T(strat)
- Solar energy deposition at surface
- ‘Greenhouse’ heating at surface
- Height of troposphere determines T(surface)



Measured Temperature Profiles: Earth

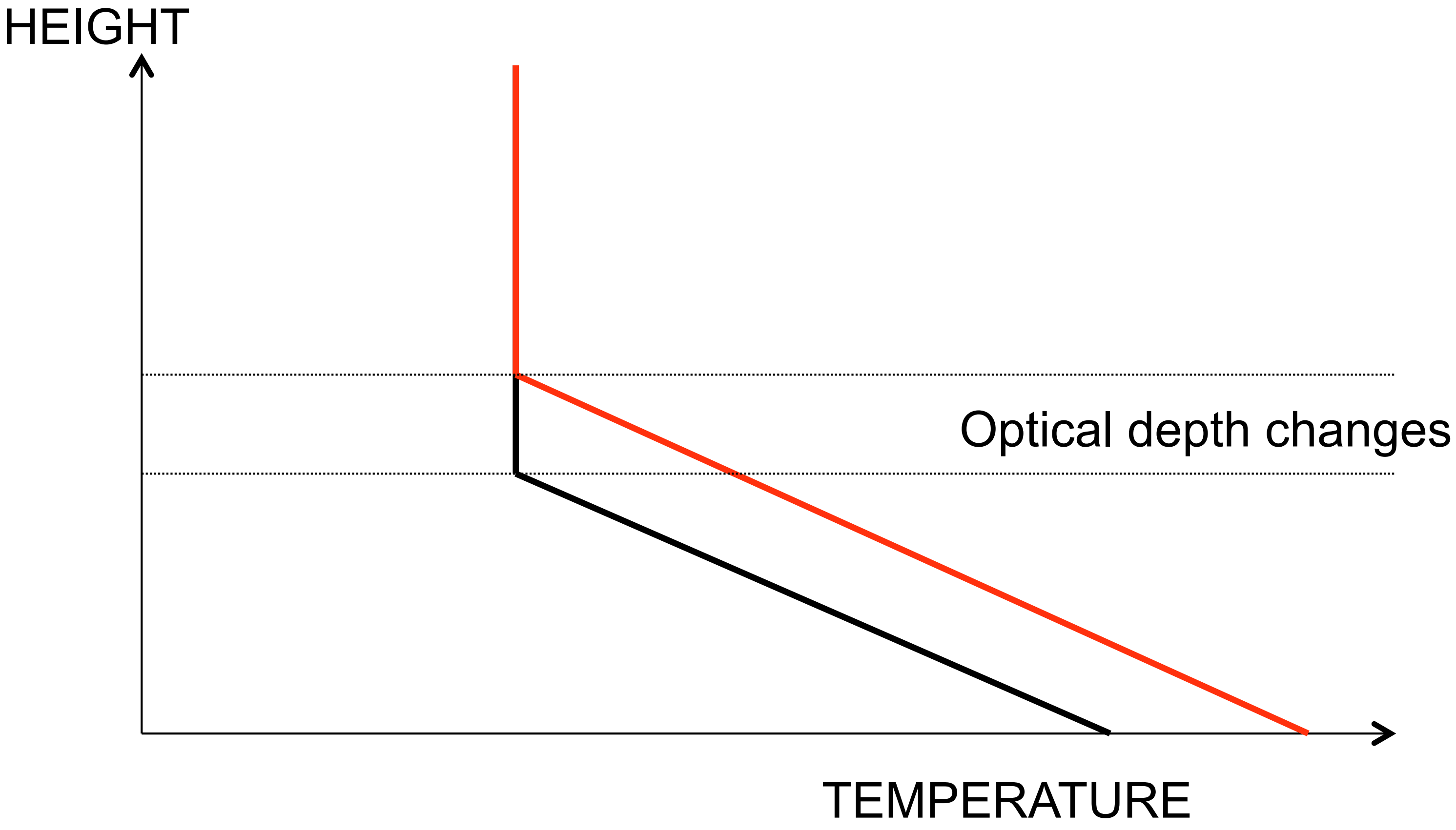


Measured Temperature Profiles: Mars

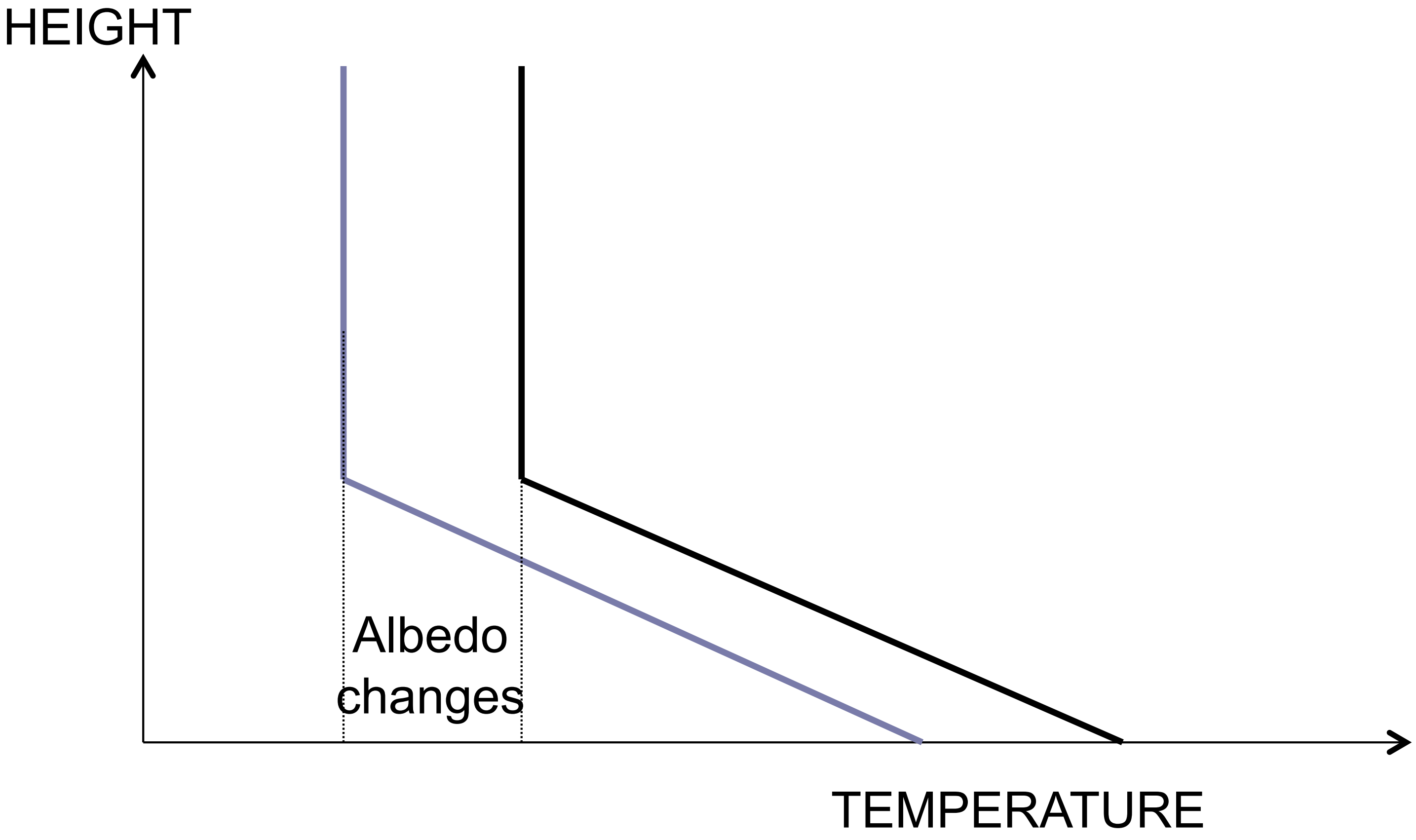


[NASA]

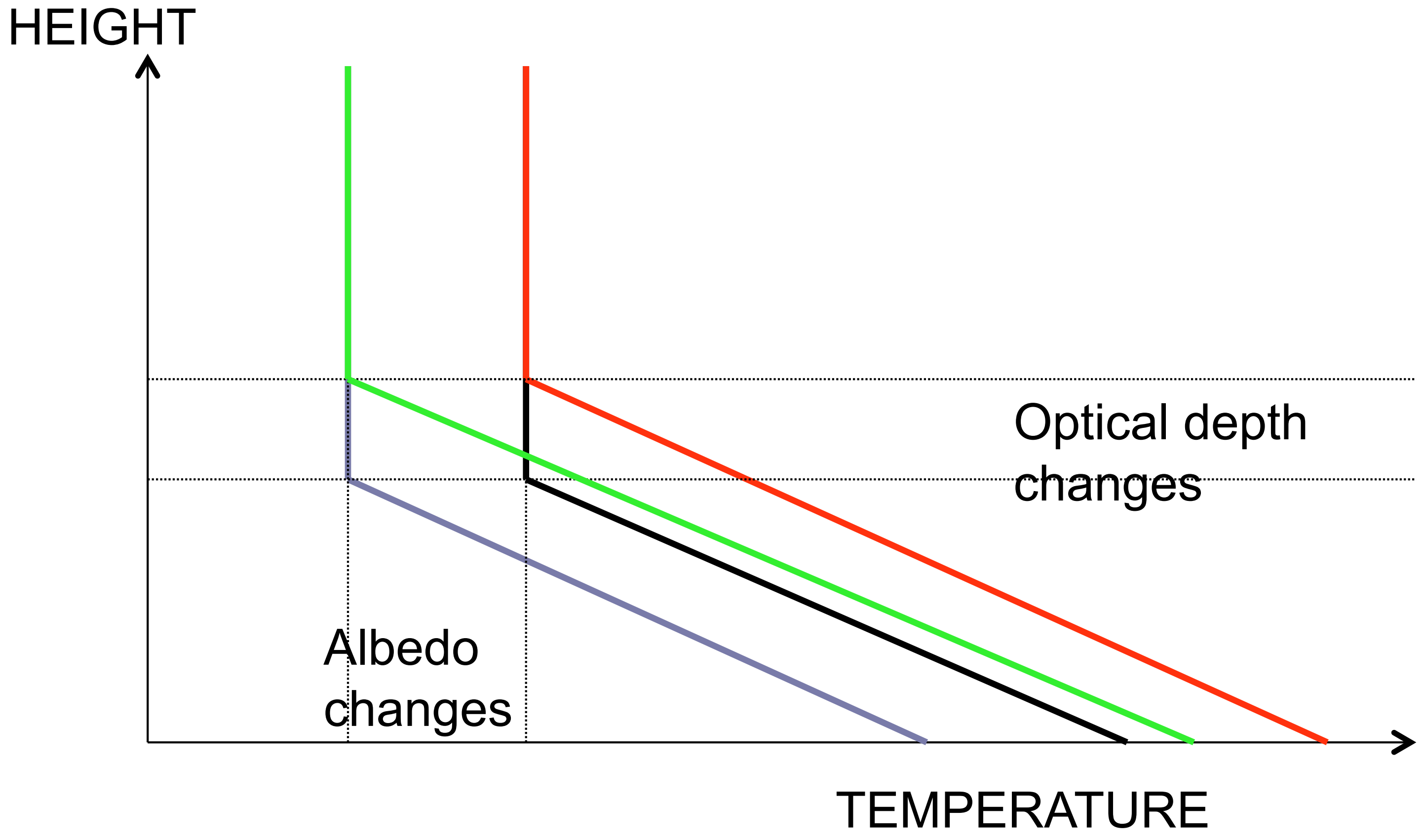
Radiative-Convective Model Temperature Profile

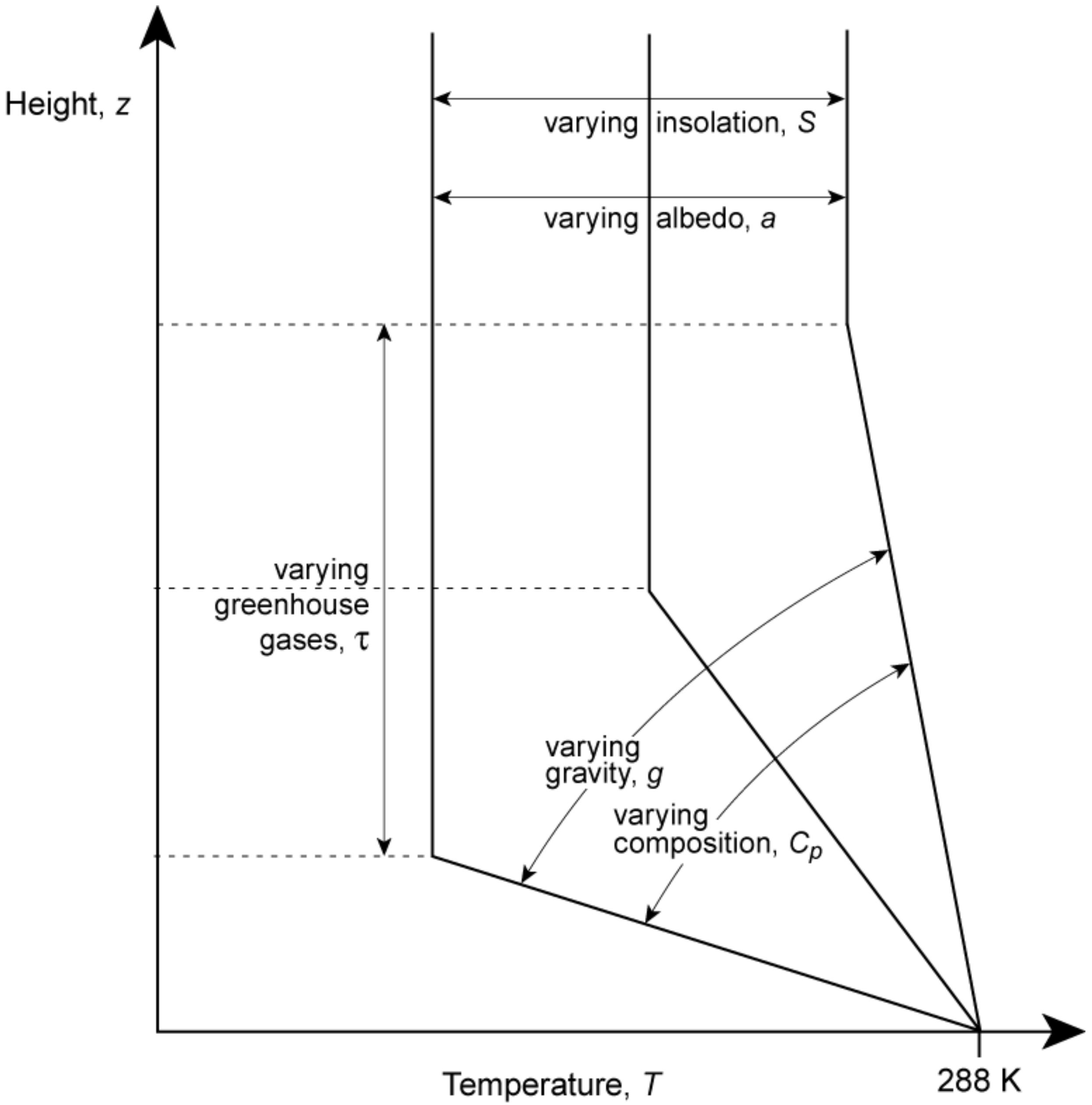


Radiative-Convective Model Temperature Profile

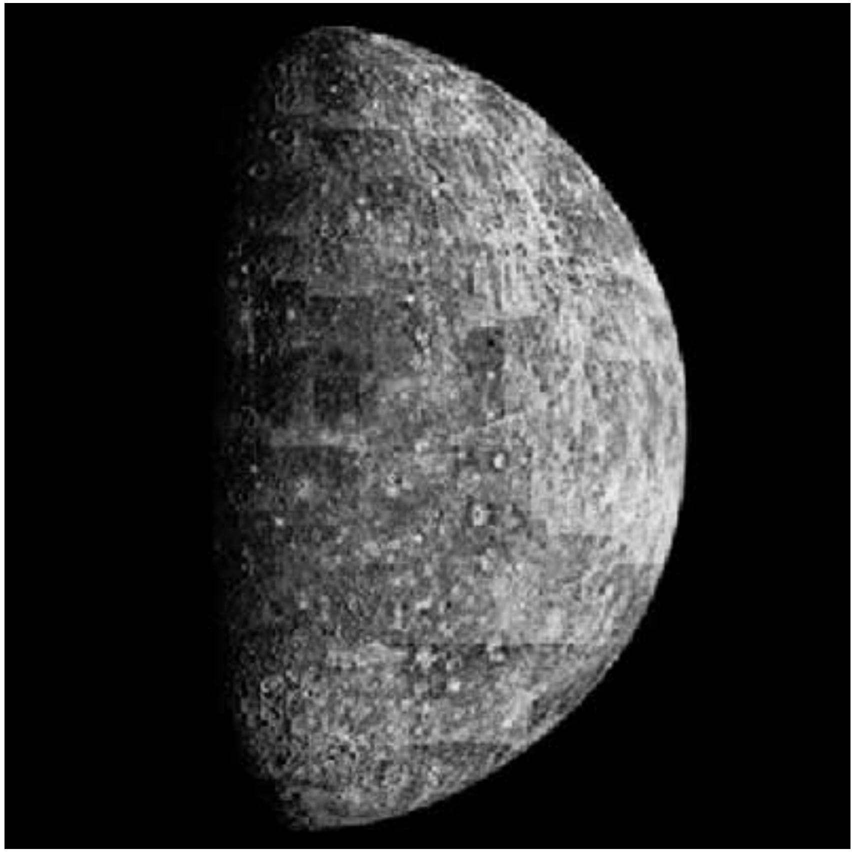


Radiative-Convective Model Temperature Profile

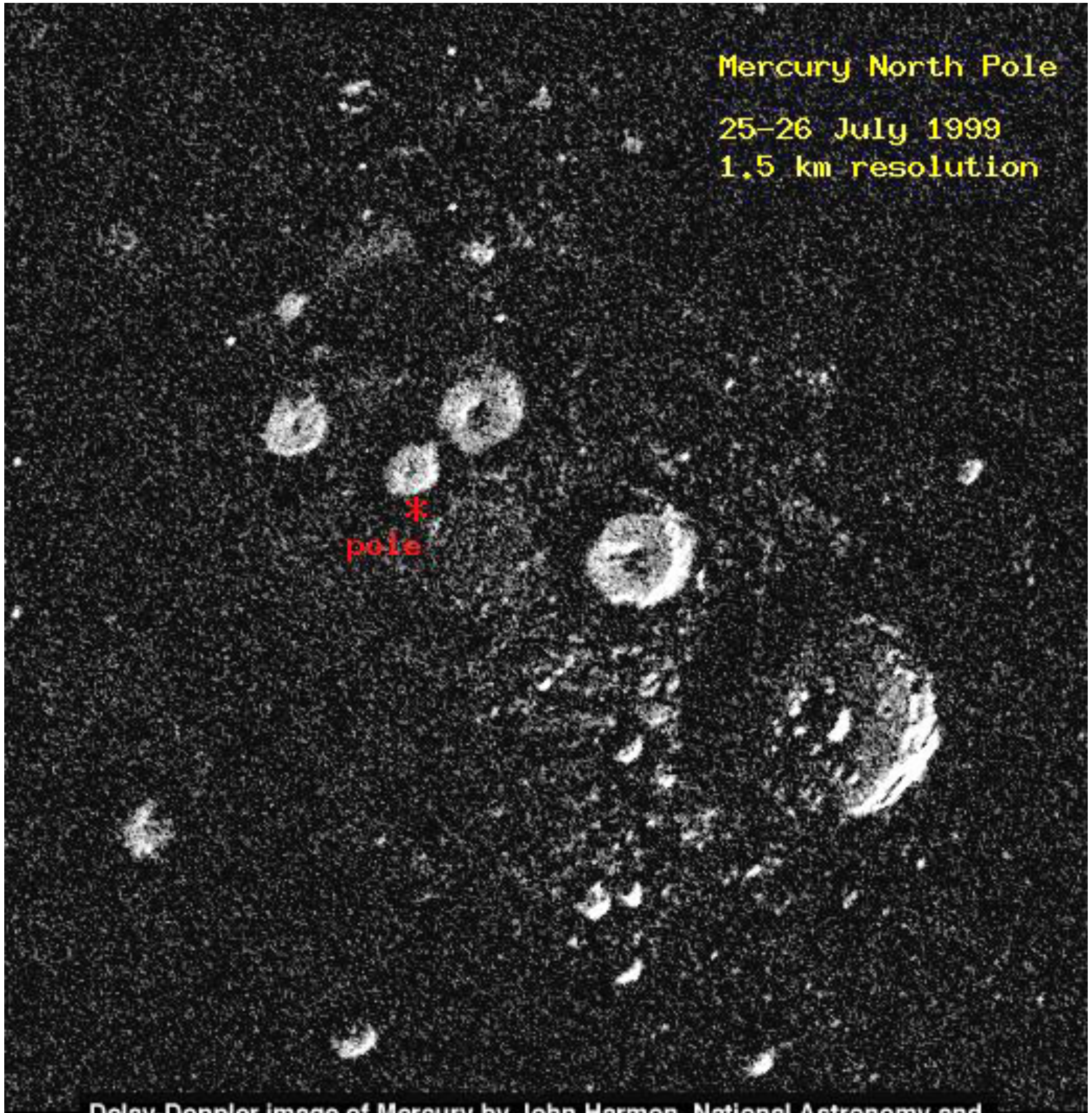



Height, z
varying insolation, S
varying albedo, a
varying greenhouse gases, τ
varying gravity, g
varying composition, Cp
Temperature, T
288 K

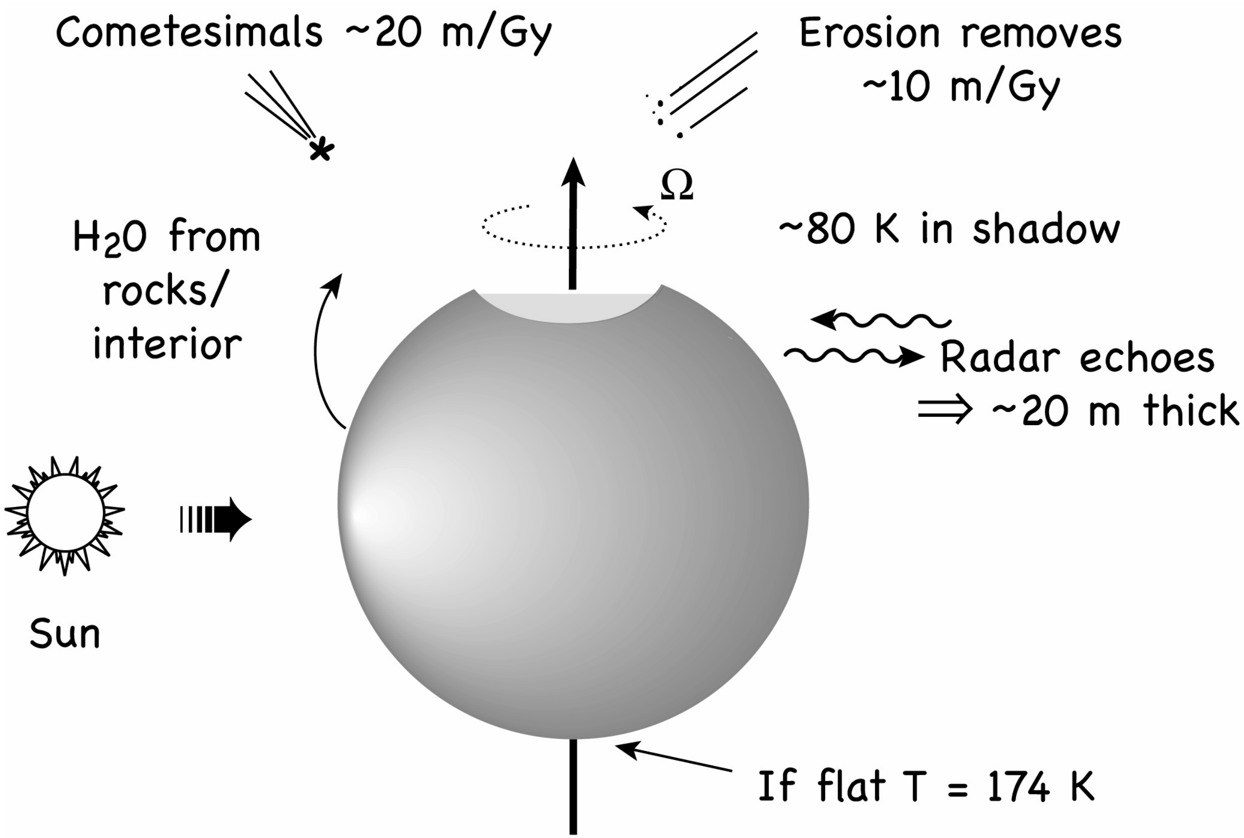
Mercury



- Diameter 1.4 times Moon
- Much denser than Moon: 5.43 vs. 3.34 g cm^{-3}
- Temperature range 70 to 700 K
- Thin atmosphere: surface pressure ~10^{-15} bar
- Icy polar deposits in shaded craters



Delay-Doppler image of Mercury by John Harmon, National Astronomy and Ionosphere Center, Arecibo Observatory, Puerto Rico.



Cometesimals ~20 m/Gy

Erosion removes ~10 m/Gy

Ω

~80 K in shadow

H_2O from rocks/ interior

Radar echoes ⟹ ~20 m thick

Sun

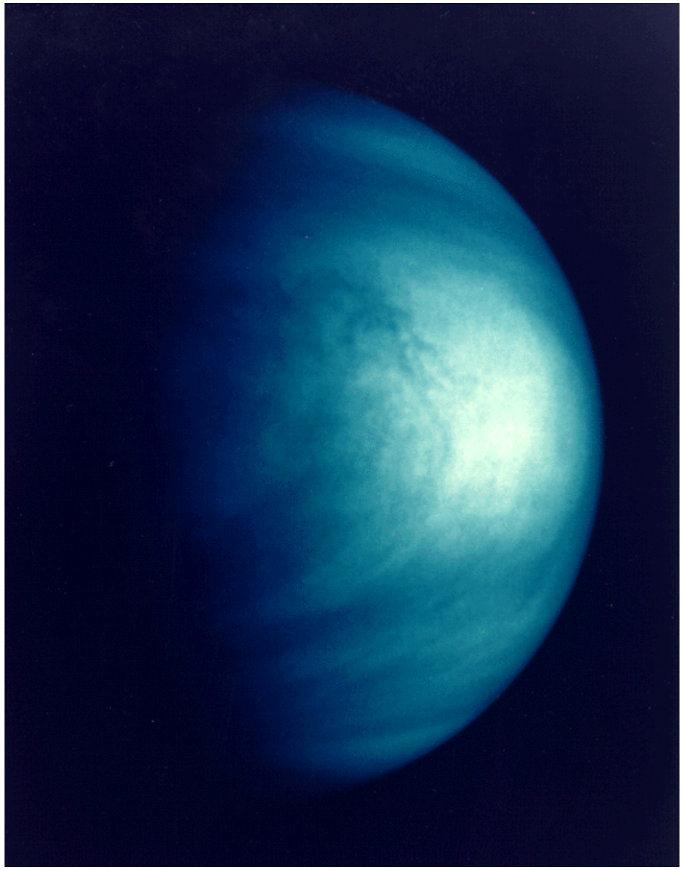
If flat T = 174 K

Must have T < 112 K or sublimation > 1m/Gy

Models suggest that some are > 150 K

⟹ water unstable

Venus

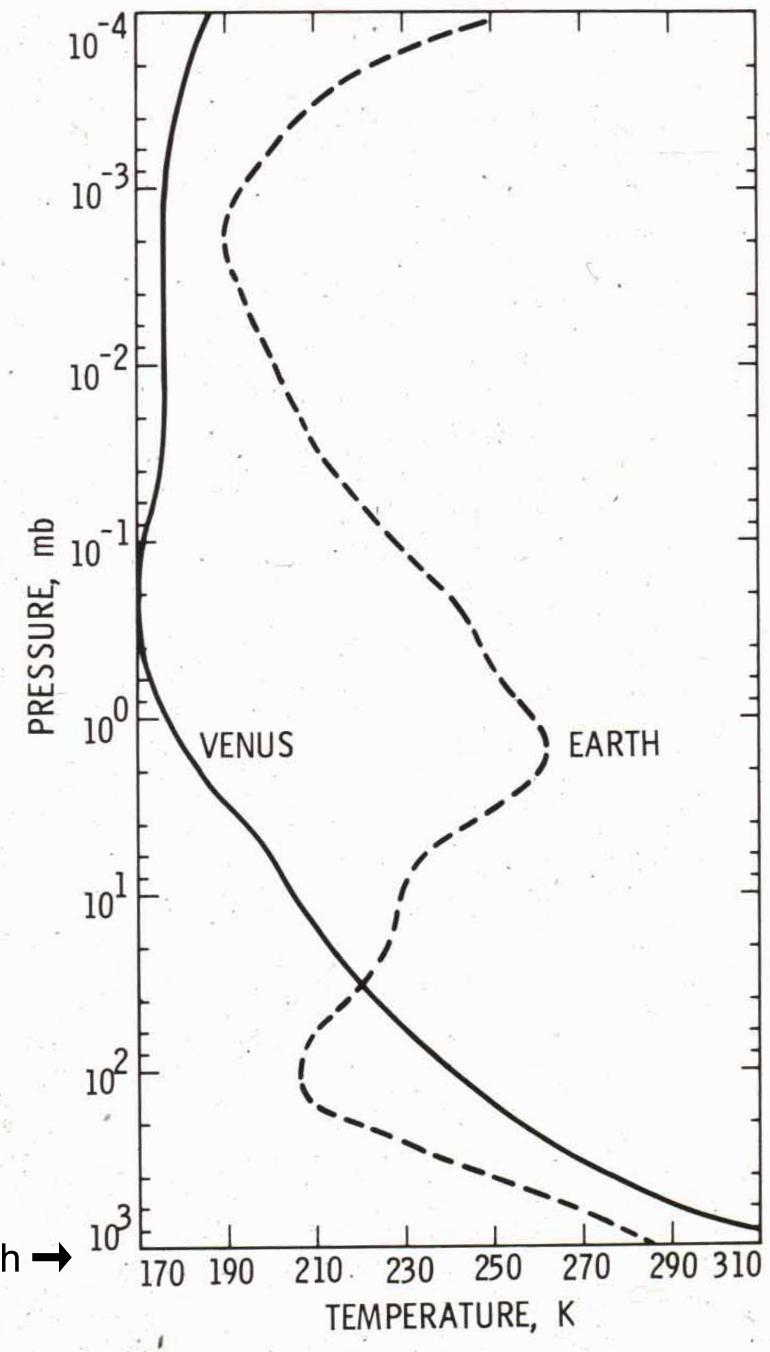


- Solid body resembles Earth
- Small inclination and eccentricity
- no seasons
- Complete cloud cover of mainly 75%H_2SO_4.25%H_2O.
- No liquid water & very little vapour
- Surface temperature ~ 730 K
- Net insolation < Earth!
- Equilibrium temperature ~ 240 K
- 500K greenhouse effect (Earth ~ 30K)
-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

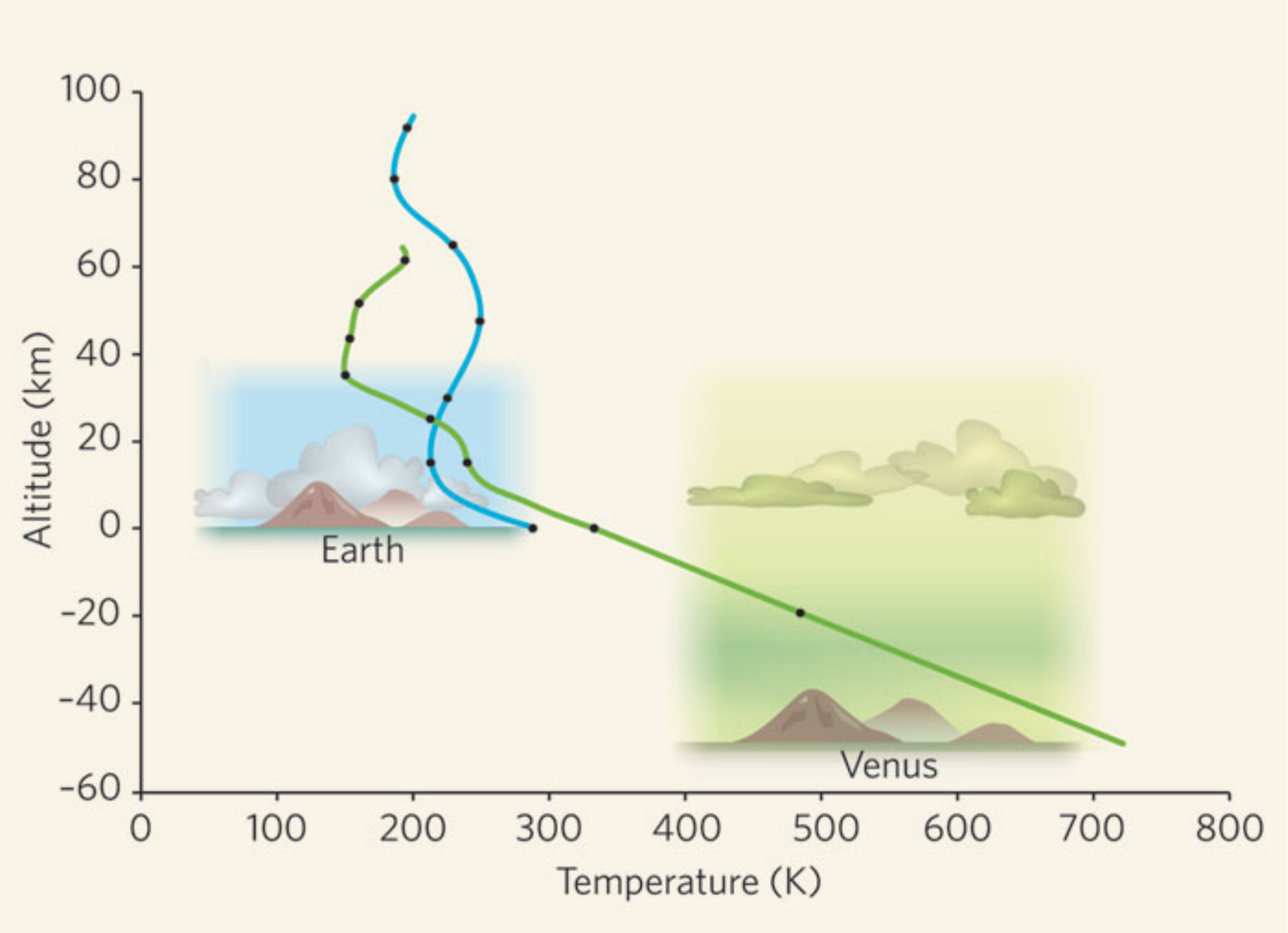
VENUS TEMPERATURE PROFILE MEASURED BY PIONEER VENUS ORBITER OIR,

EARTH TEMPERATURE PROFILE MEASURED BY NIMBUS 7 SAMS,

BOTH IN FEBRUARY 1980

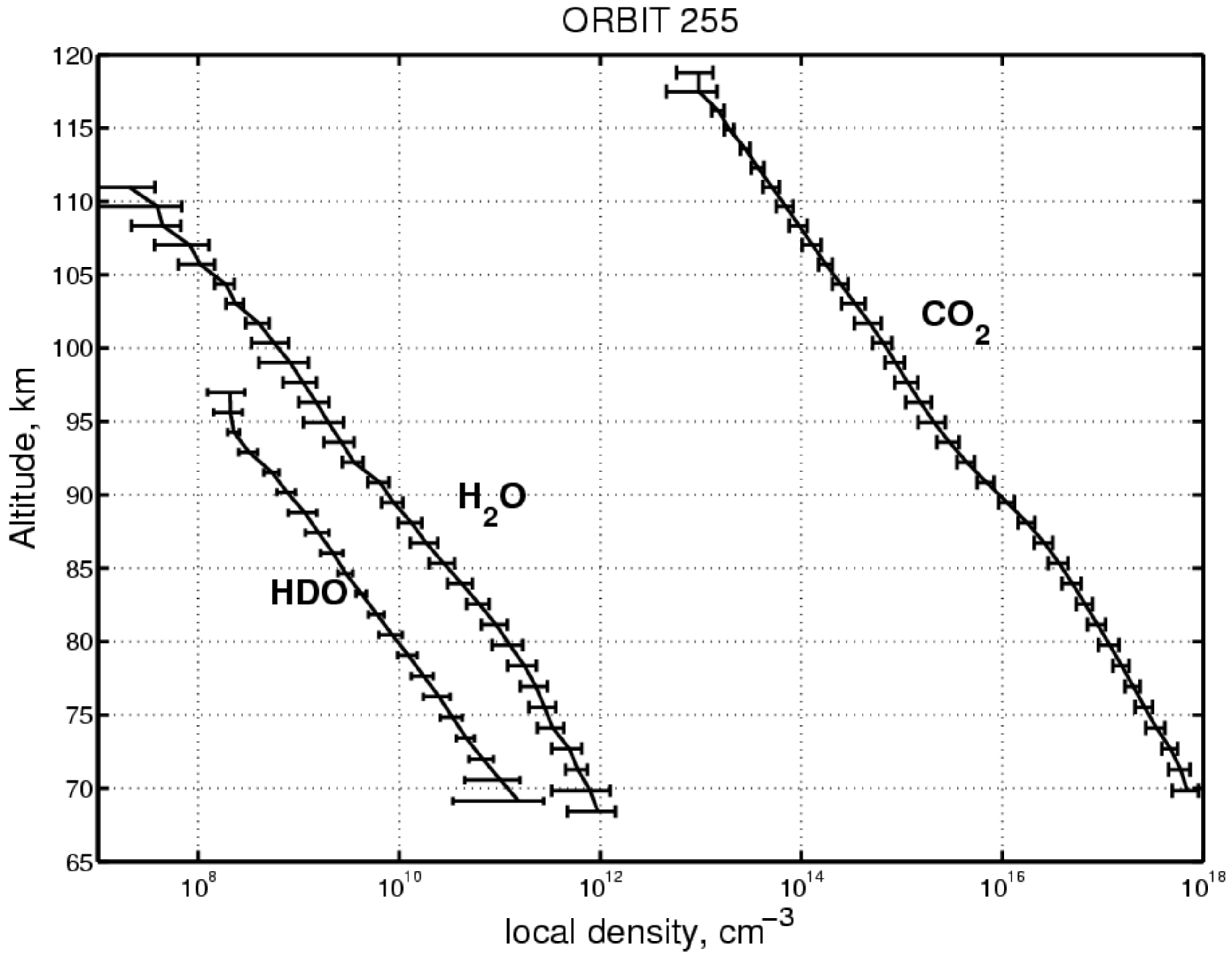


Pressure at the surface of the Earth ➞


Altitude (km)
100
80
60
40
20
0
-20
-40
-60
0
100
200
300
400
500
600
700
800
Temperature (K)
Earth
Venus

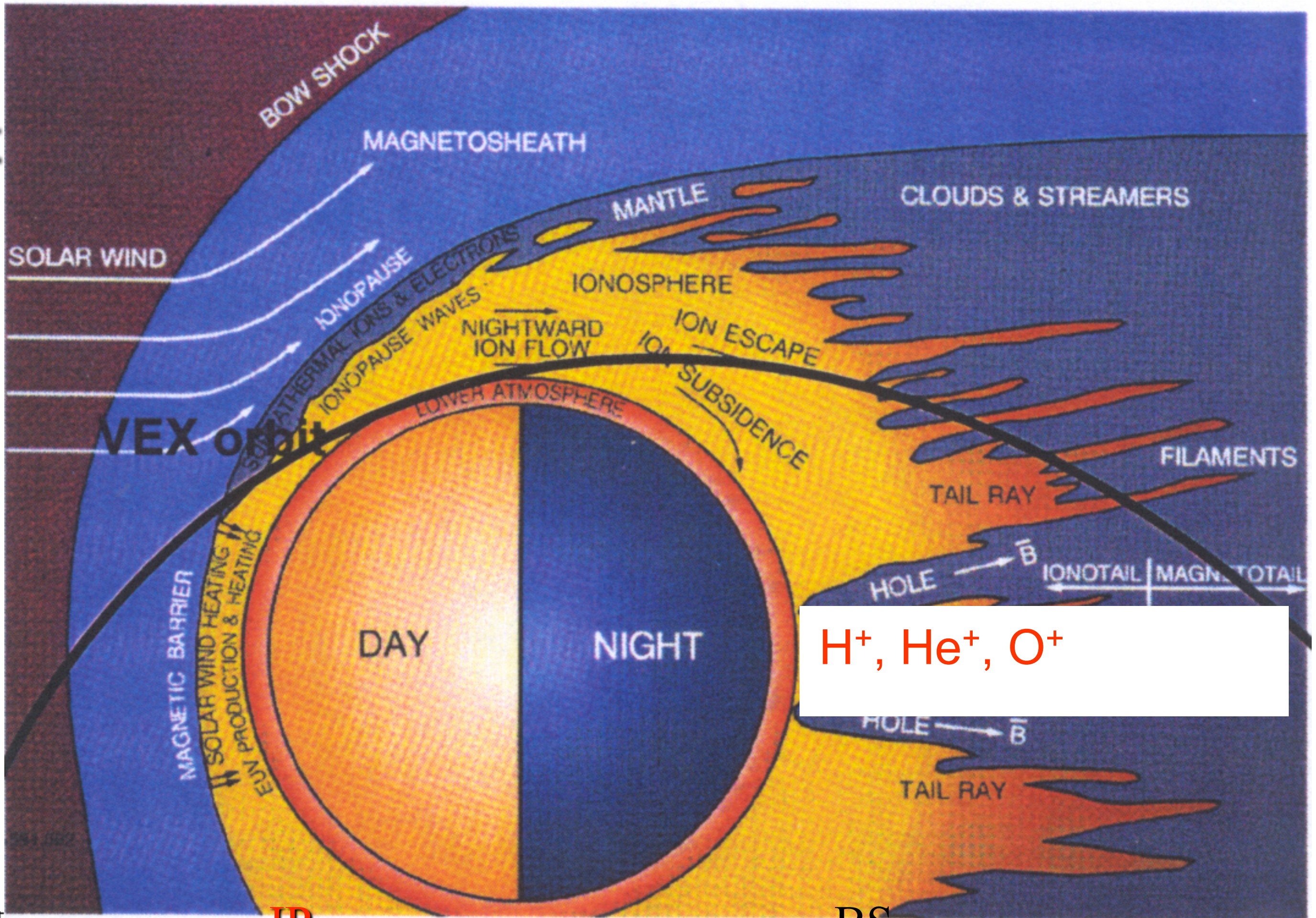
(C) AG Hoyle

VEx SOIR: D/H on Venus is 240±25 times that on Earth

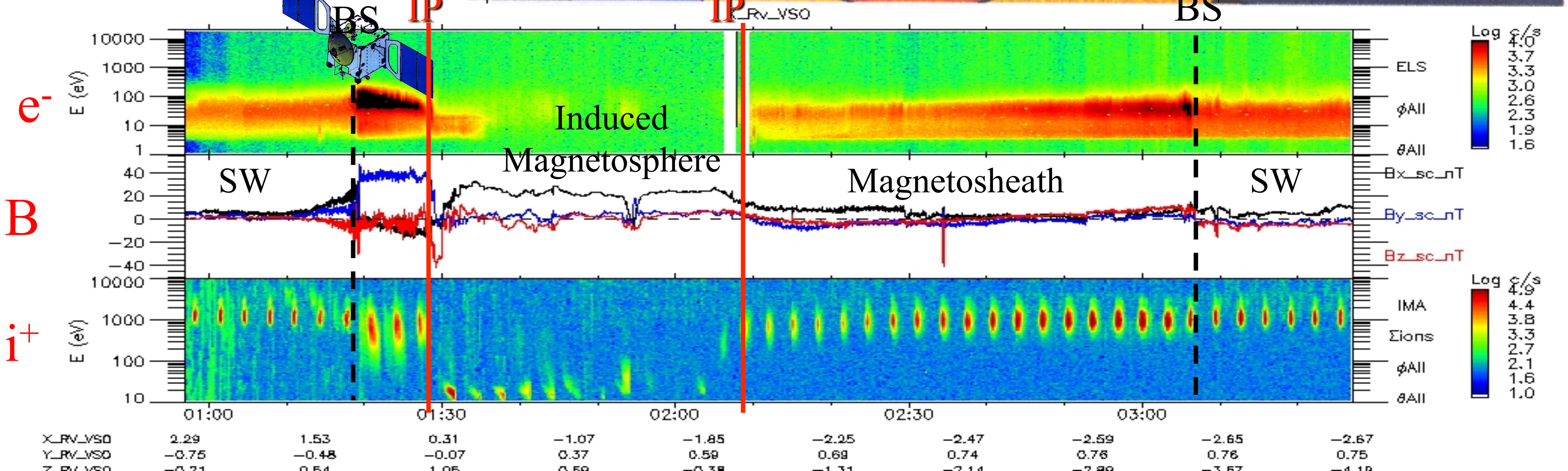


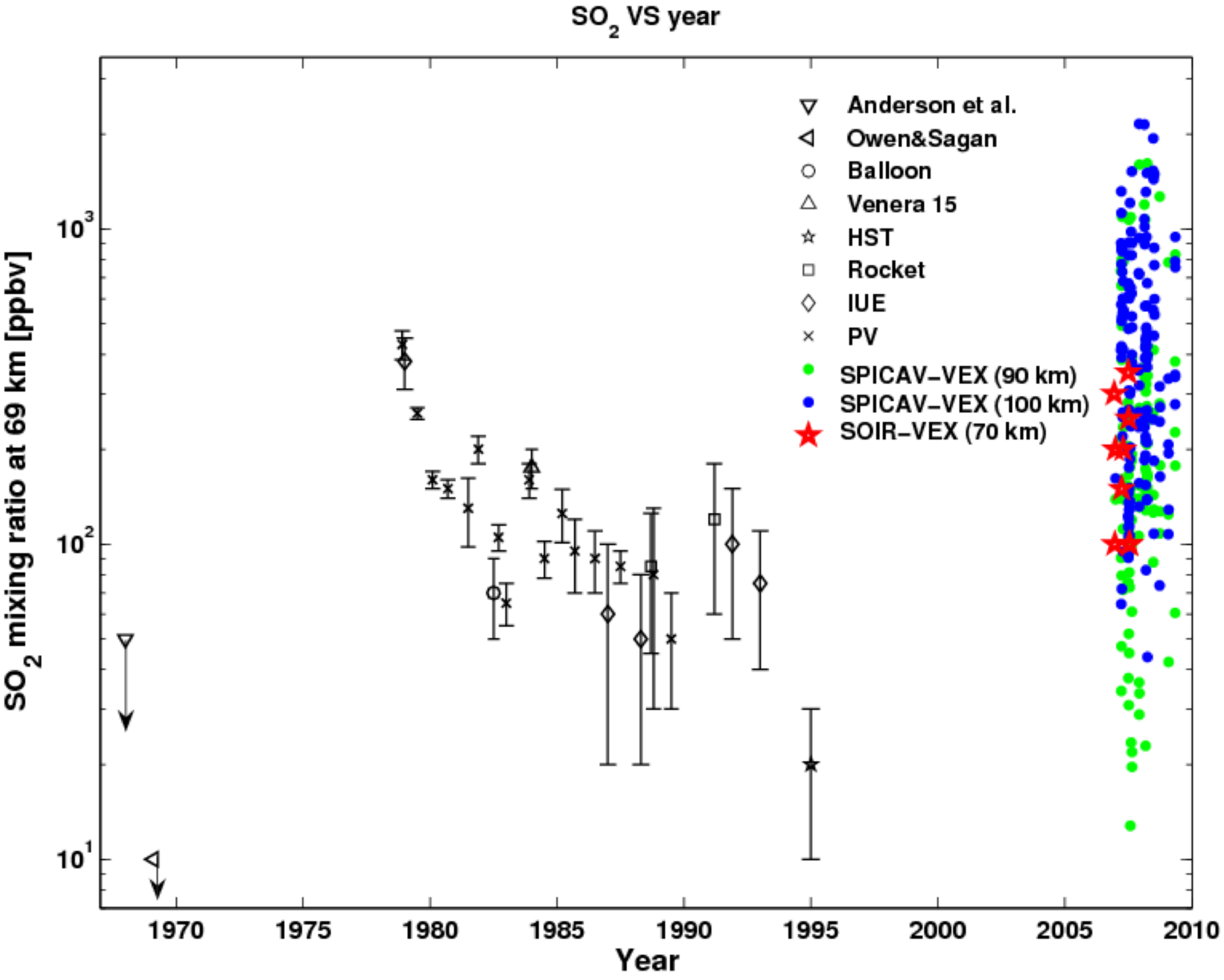
Plasma environment

Barabash, Zhang &
ASPERA, MAG Teams

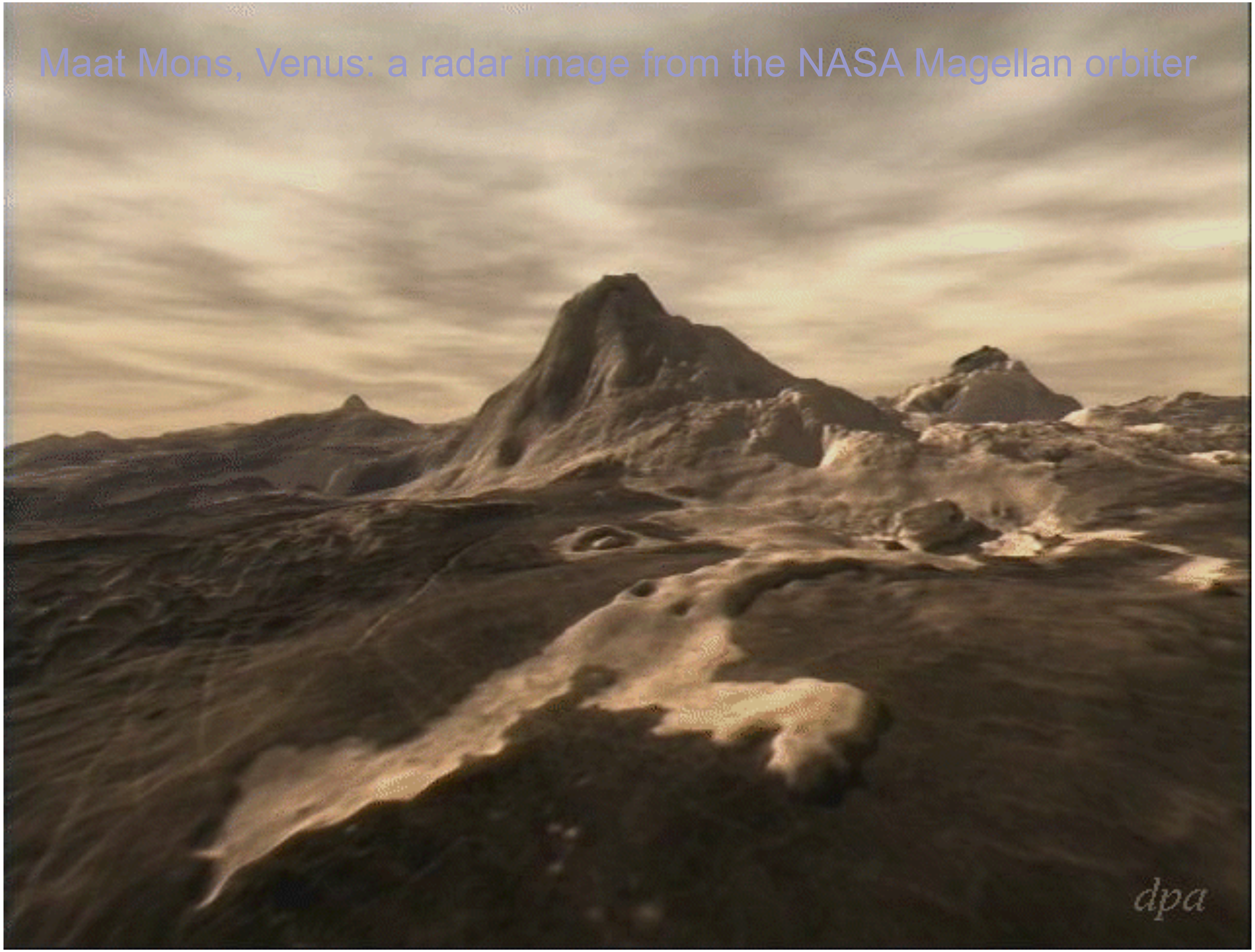


H^+, He^+, O^+

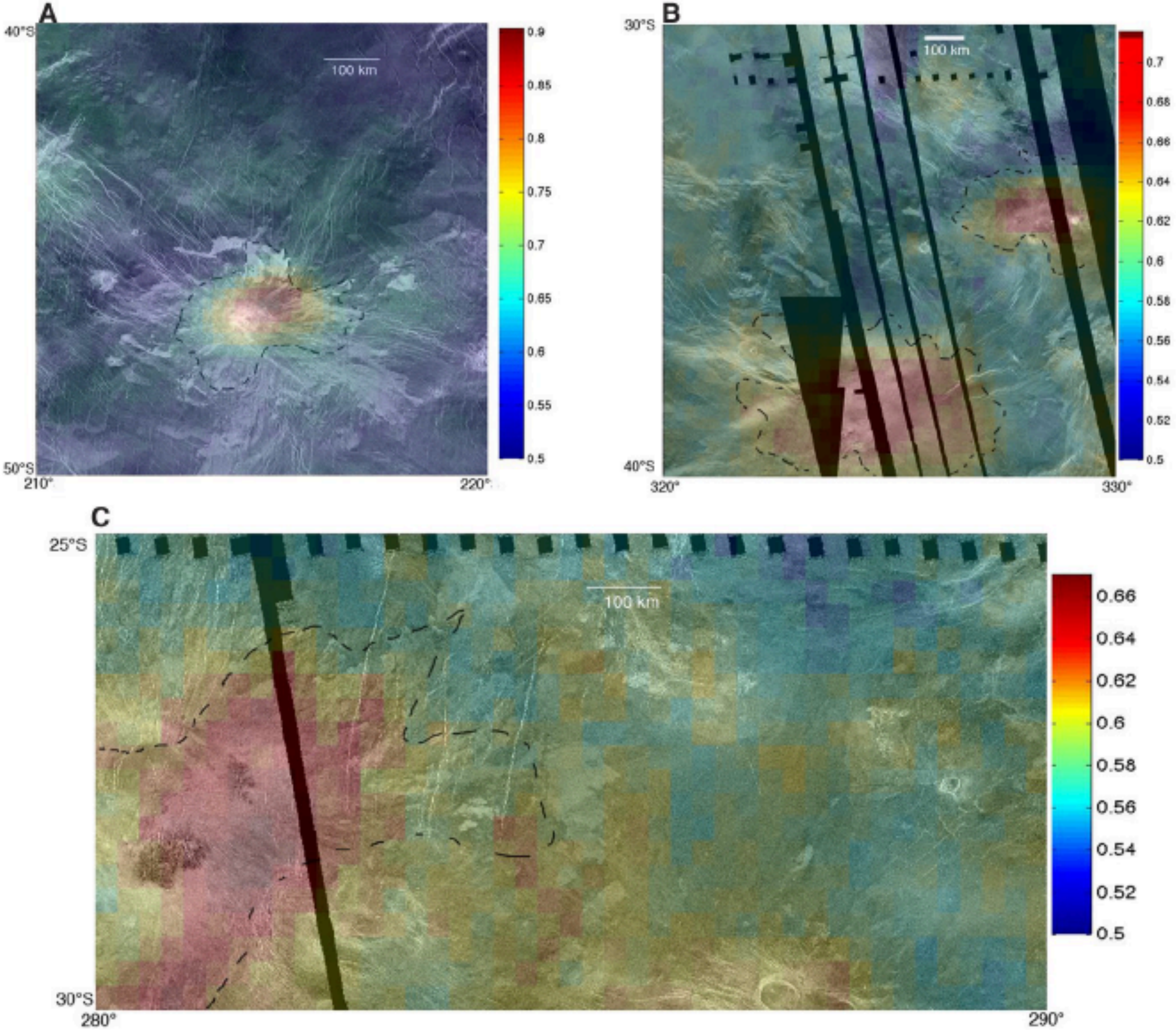



SO$_2$ VS year
SO$_2$ mixing ratio at 69 km [ppbv]
Year
10^3
10^2
10^1
1970
1975
1980
1985
1990
1995
2000
2005
2010
Anderson et al.
Owen&Sagan
Balloon
Venera 15
HST
Rocket
IUE
PV
SPICAV−VEX (90 km)
SPICAV−VEX (100 km)
SOIR−VEX (70 km)

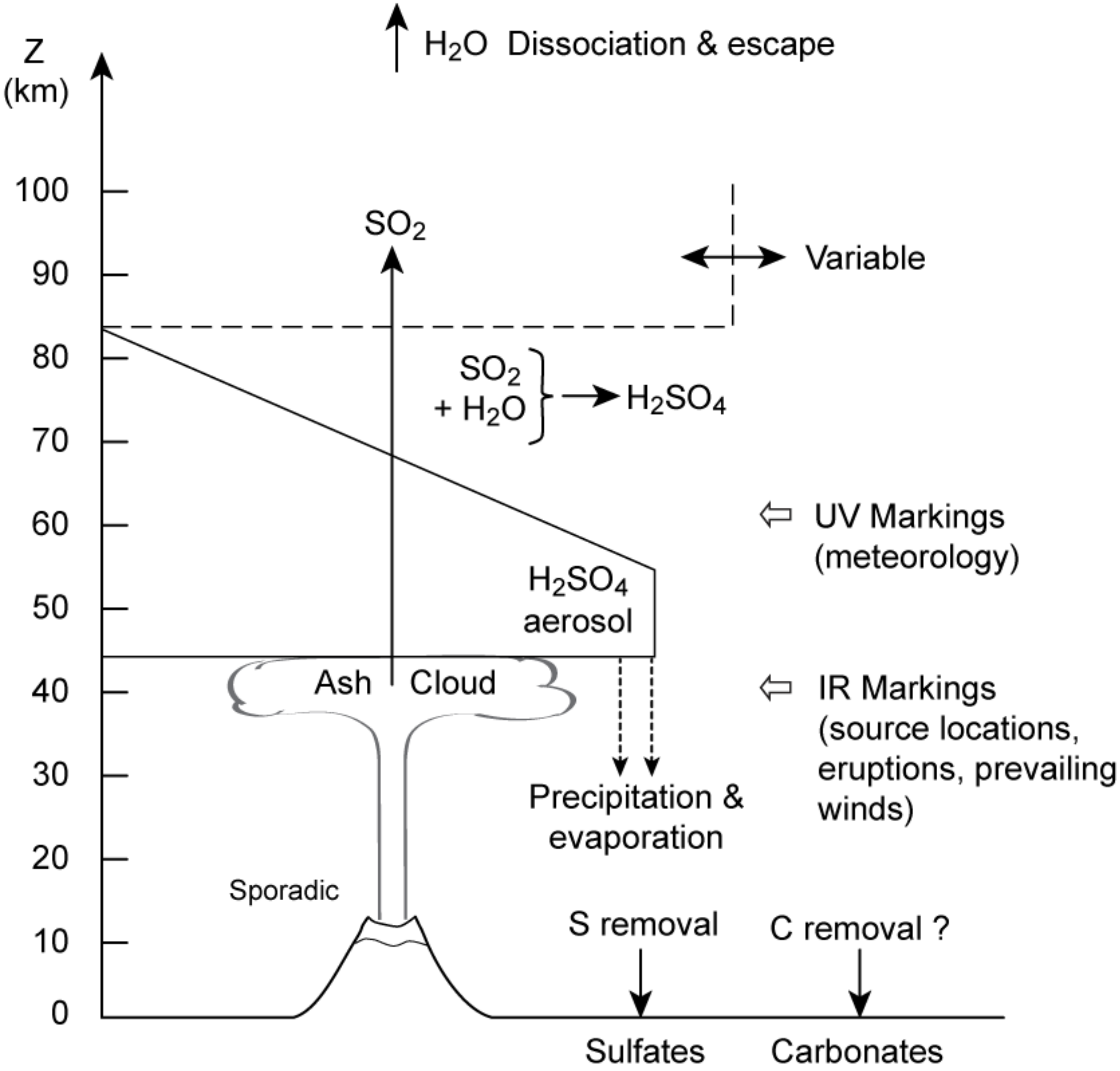
Maat Mons, Venus: a radar image from the NASA Magellan orbiter



The Surface of Venus seen from Orbit (Venus Express & Magellan)

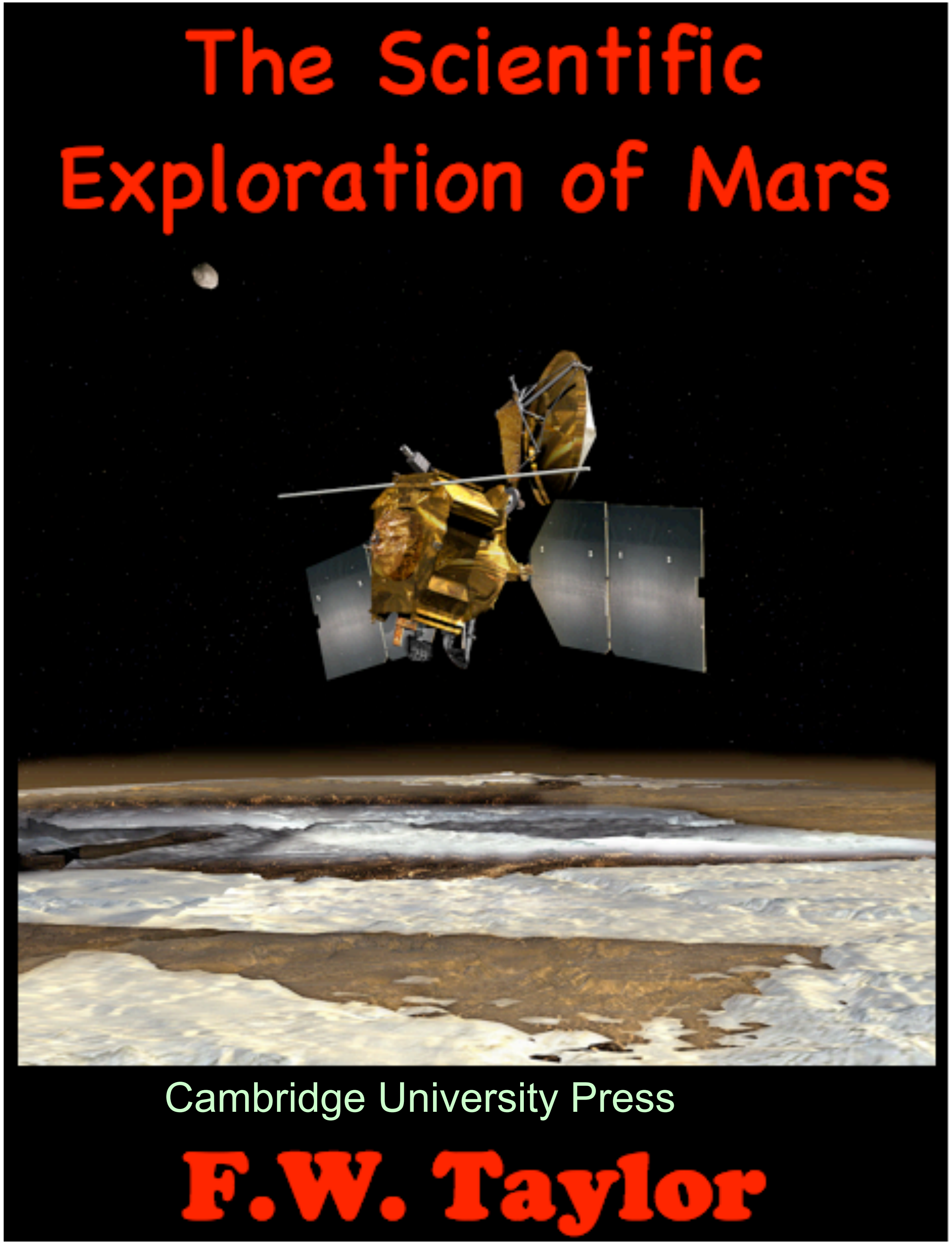


[Smrekar et al., 2010]


H2O Dissociation & escape
Z
(km)
100
90
80
70
60
50
40
30
20
10
0
SO2
Variable
SO2
+ H2O
H2SO4
UV Markings
(meteorology)
H2SO4
aerosol
Ash Cloud
IR Markings
(source locations,
eruptions, prevailing
winds)
Precipitation &
evaporation
Sporadic
S removal
C removal ?
Sulfates
Carbonates

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
- Uniqueness?
- Stability?

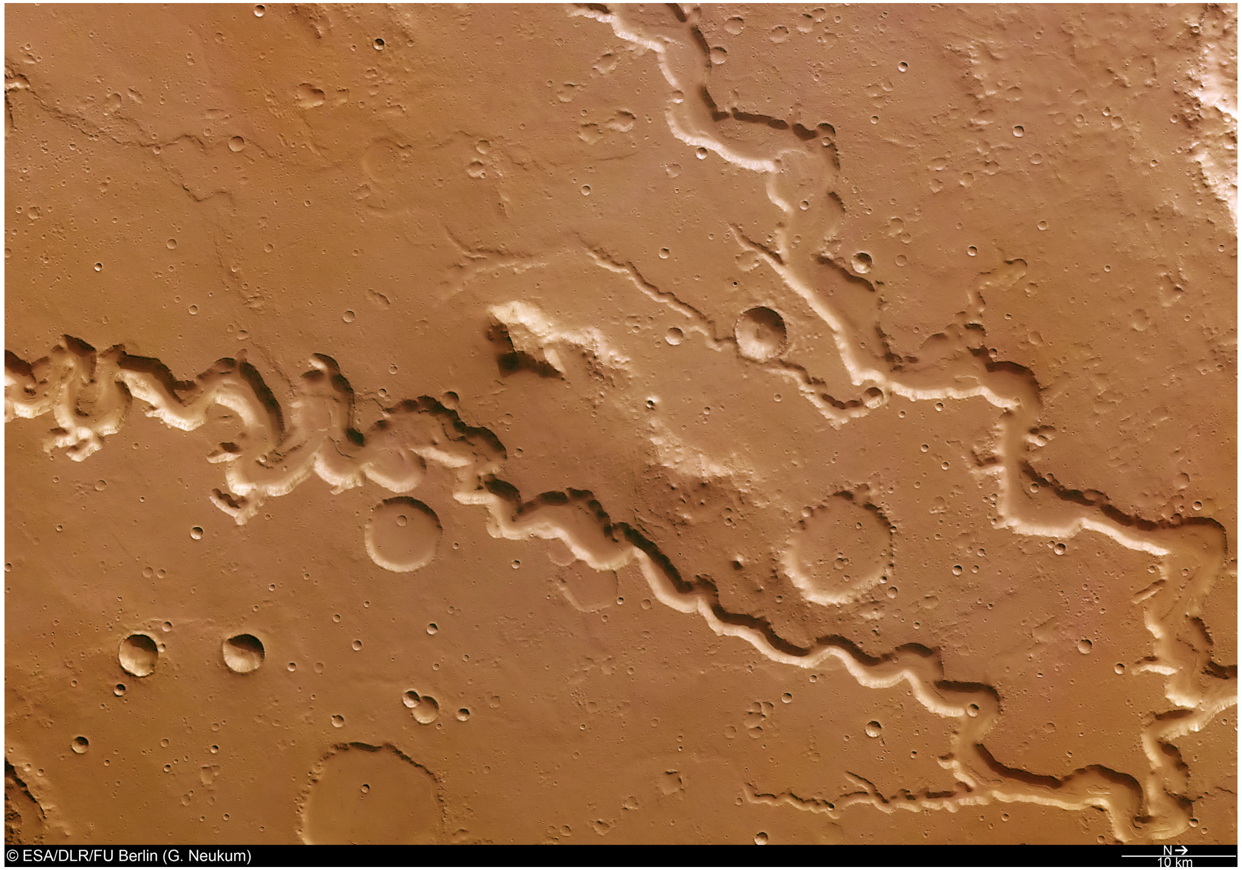


The Scientific Exploration of Mars

Cambridge University Press

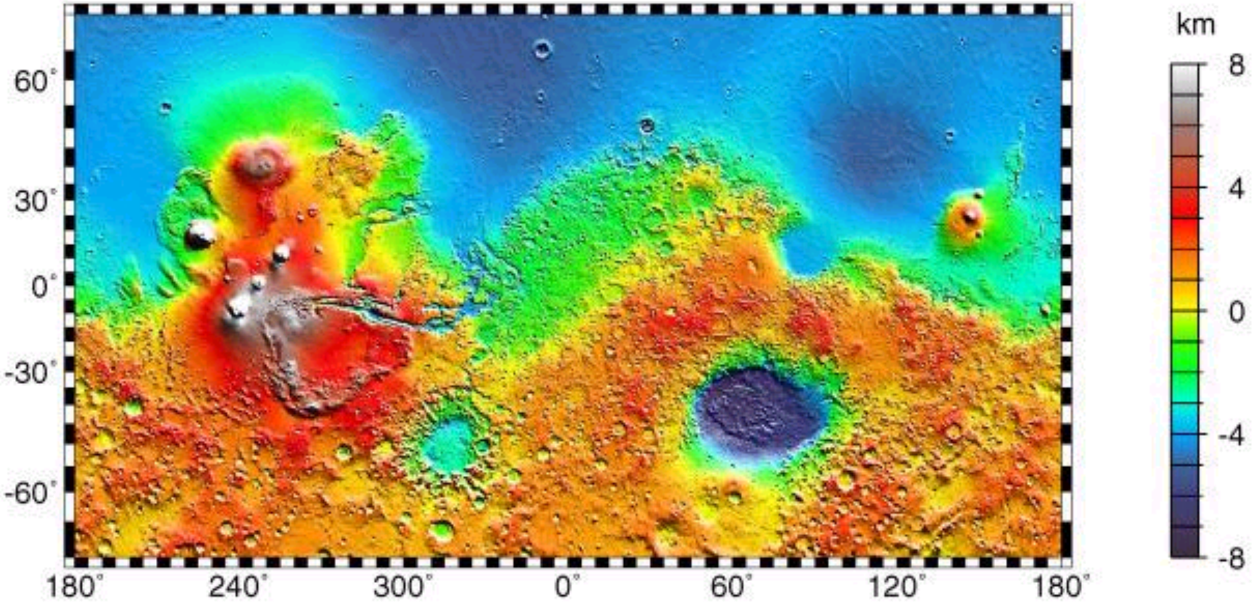
F.W. Taylor

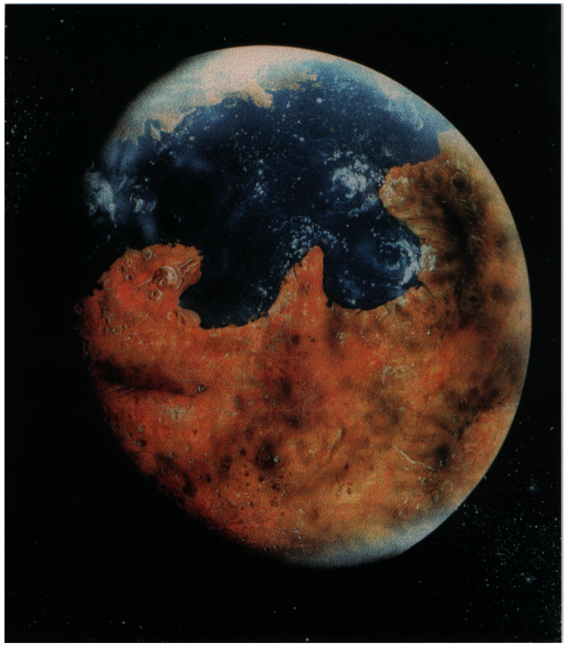
Evidence for liquid water - fluvial features (Nanedi Valles)



© ESA/DLR/FU Berlin (G. Neukum)

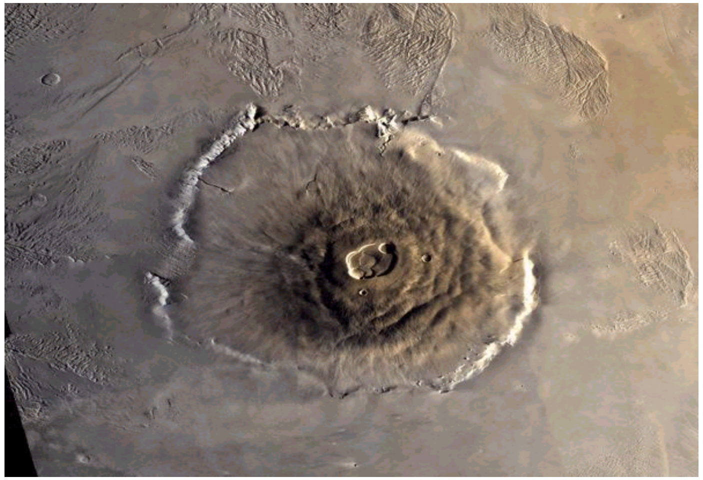
Evidence for liquid water - coastlines of paleo-ocean?

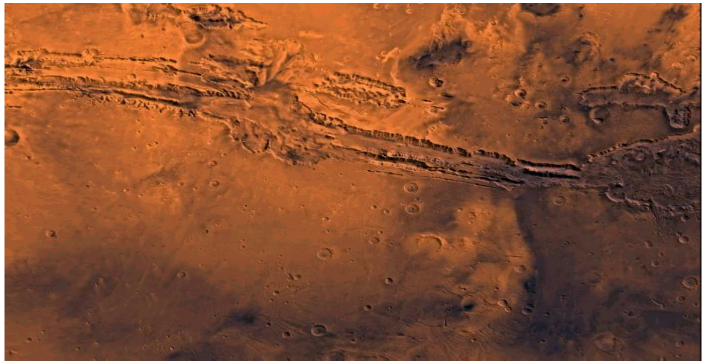




Global altitude map of surface by laser altimeter on orbiter

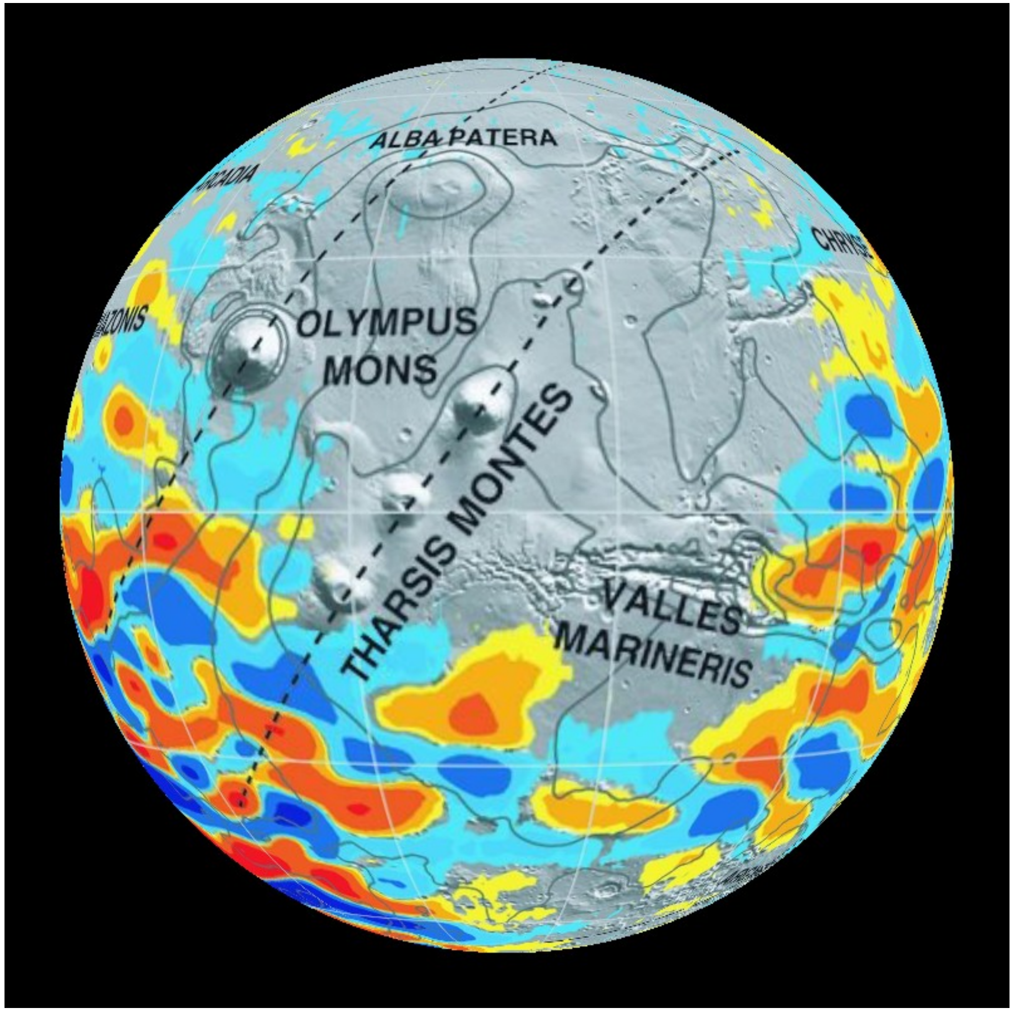
What changed? 1. Massive volcanic and tectonic features suggest early geophysical activity, now dormant



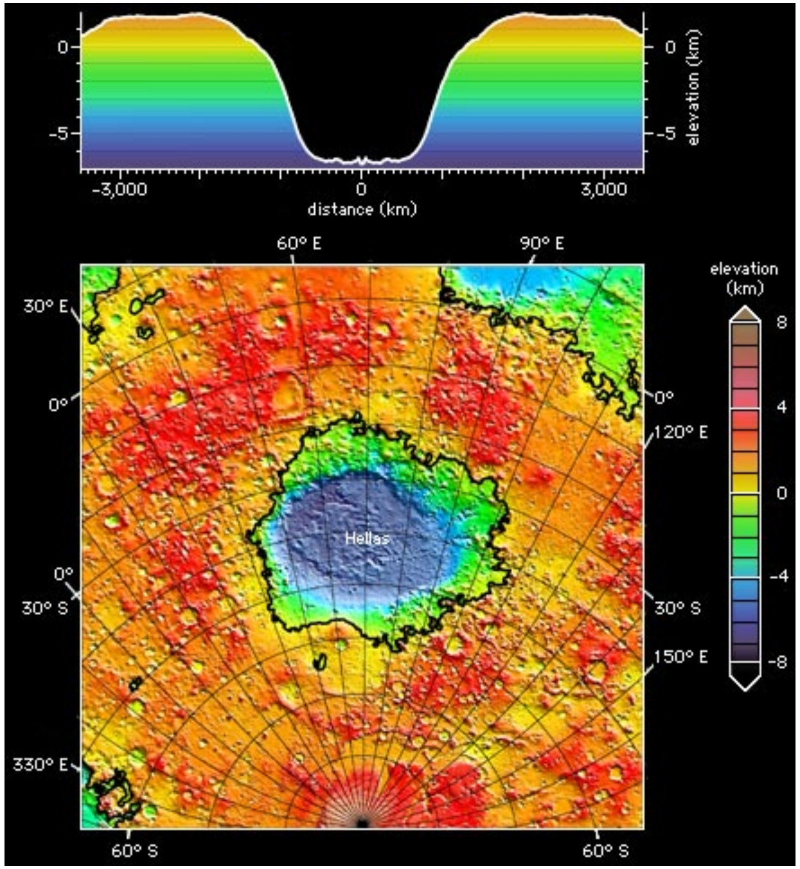


- Olympus Mons
  - 27 km high (c.f. 11km for Everest)
- Mariner Valley
  - 100km wide, 10km deep, 4800 km long

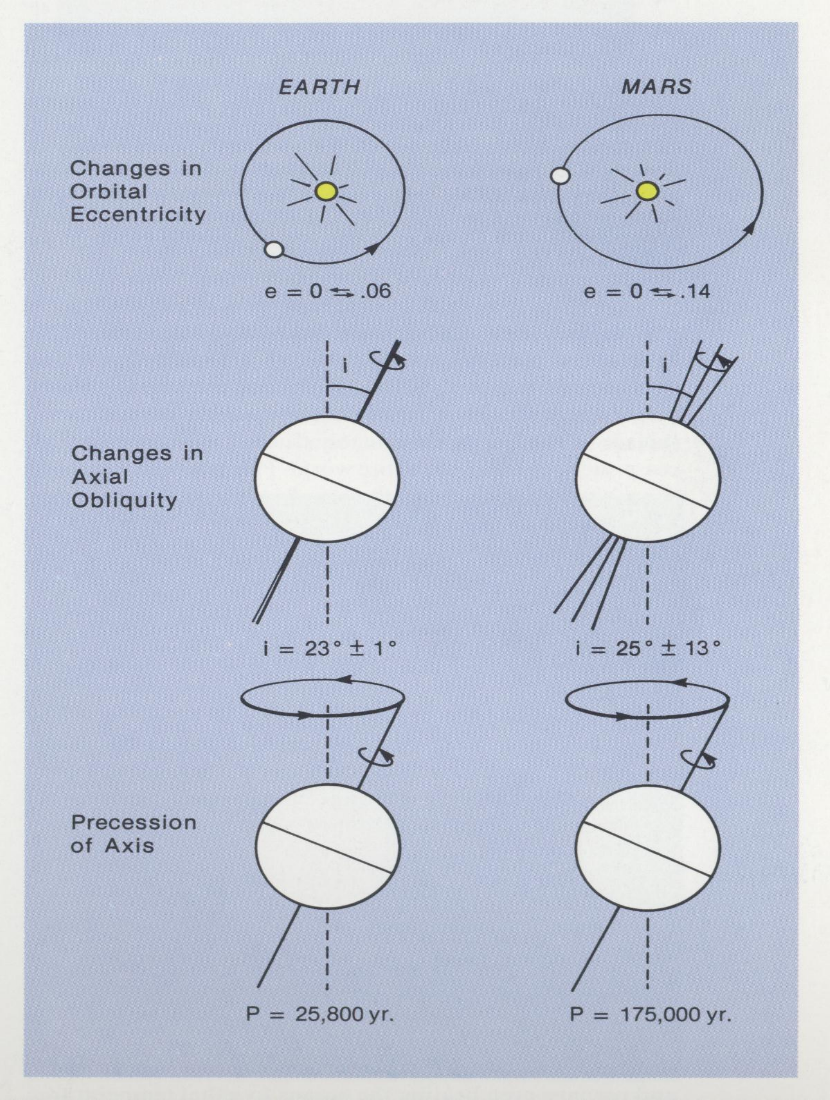
What changed? 2. Mars’ residual magnetic field measured from orbit shows it once had a global field, but not now



What changed? 3. Collisions stripped away >95% of atmosphere. Solid debris reached Earth. Very large impact features still visible on surface e.g. Hellas.

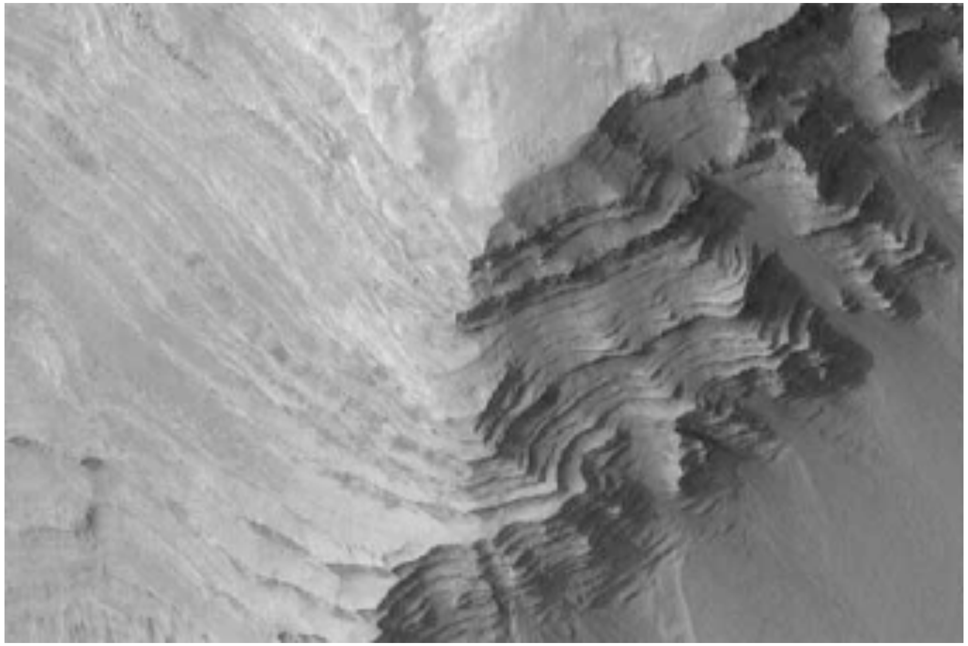


What changed? 4. Milankovitch Cycles are large for Mars

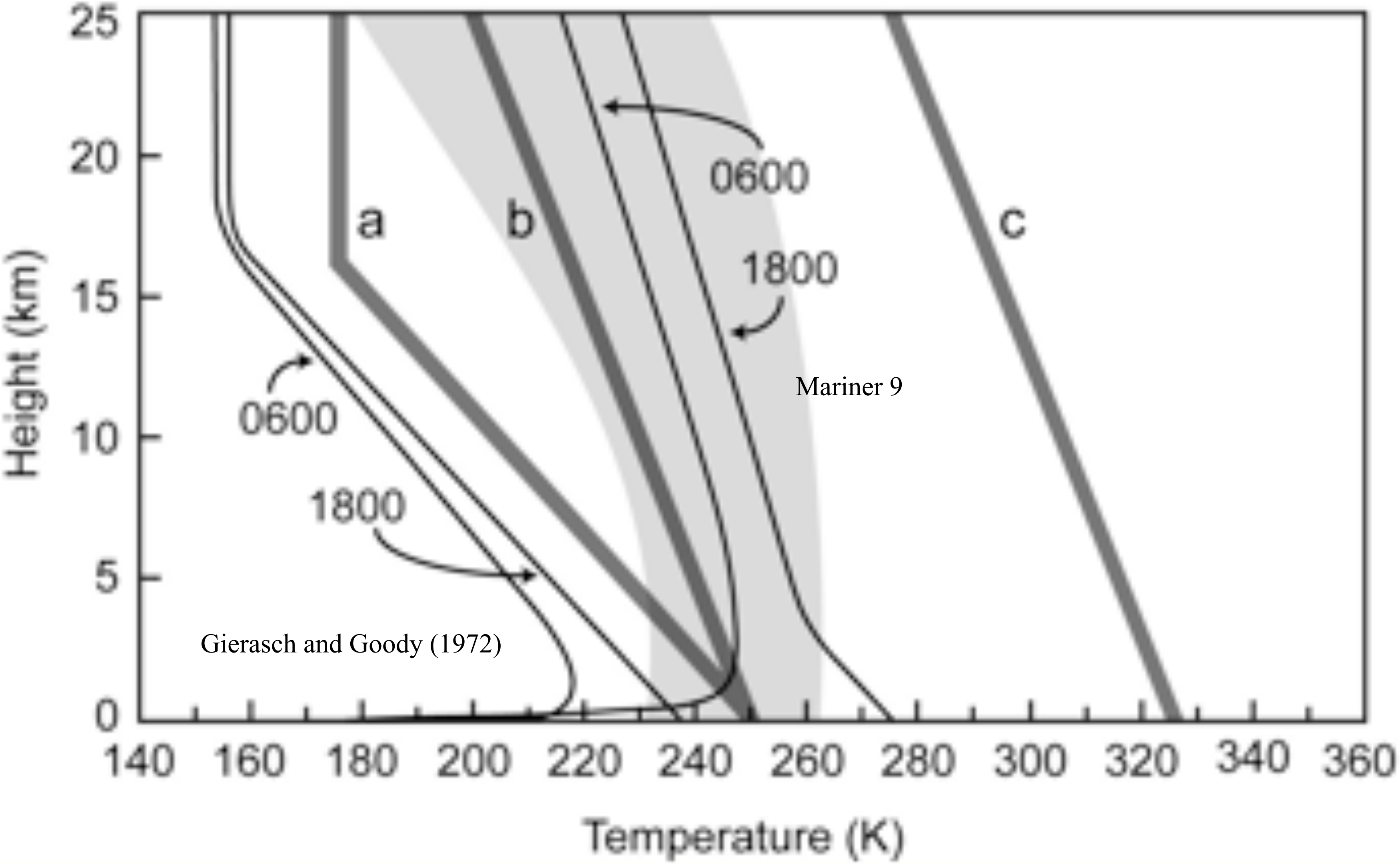


- large eccentricity and obliquity, together with precessions, cause variations in solar forcing
- layers everywhere indicate period

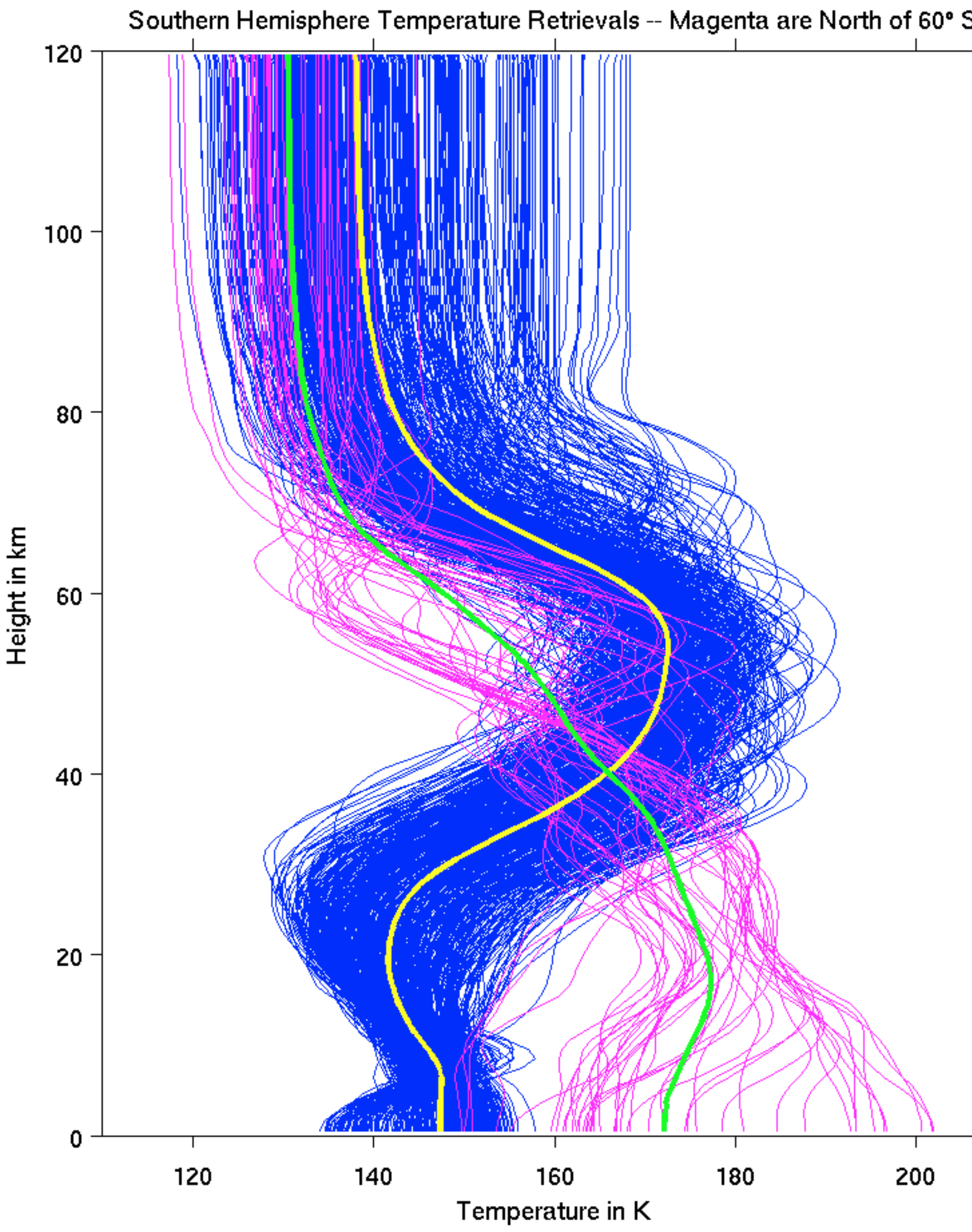
climate change in response

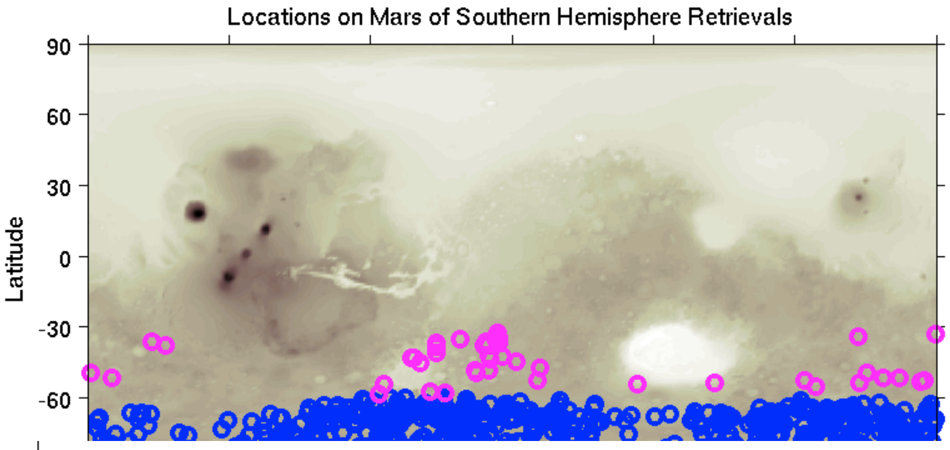


Mars model temperature profiles

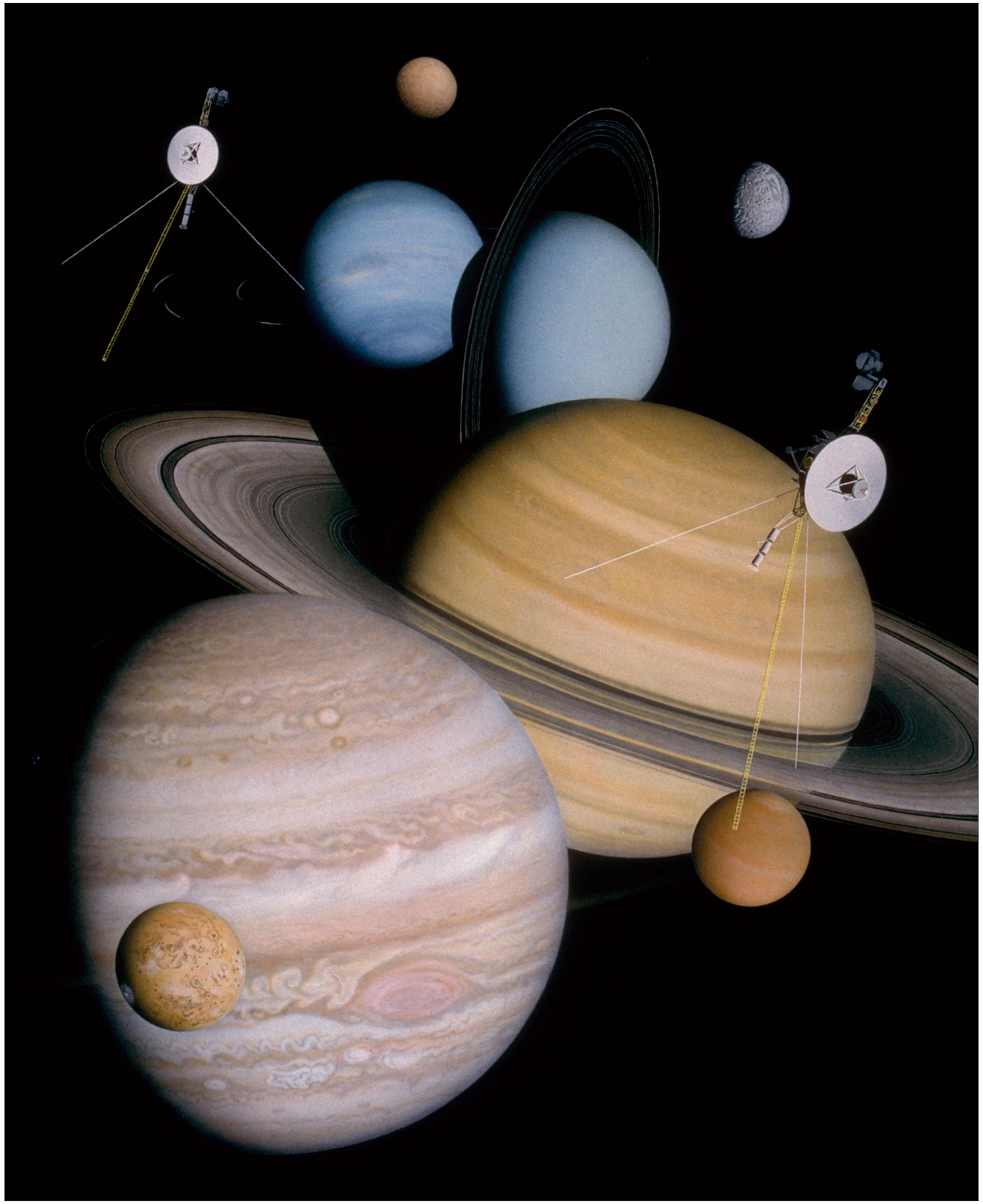


MCS temperature profile retrievals from limb radiances

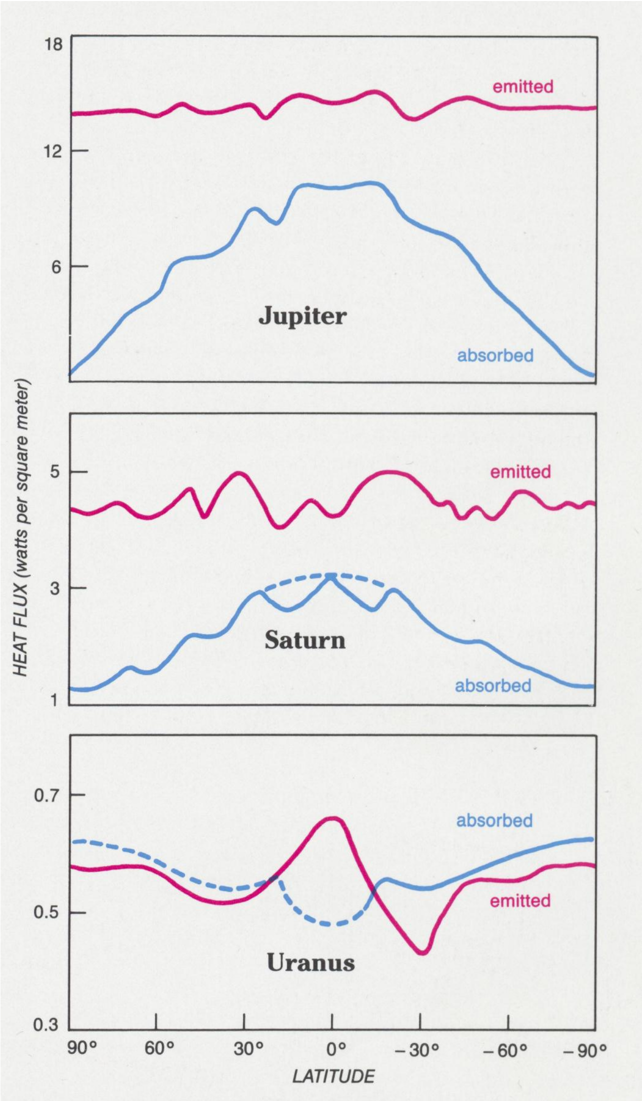




The atmospheres of the Outer (gas giant, or Jovian) Planets

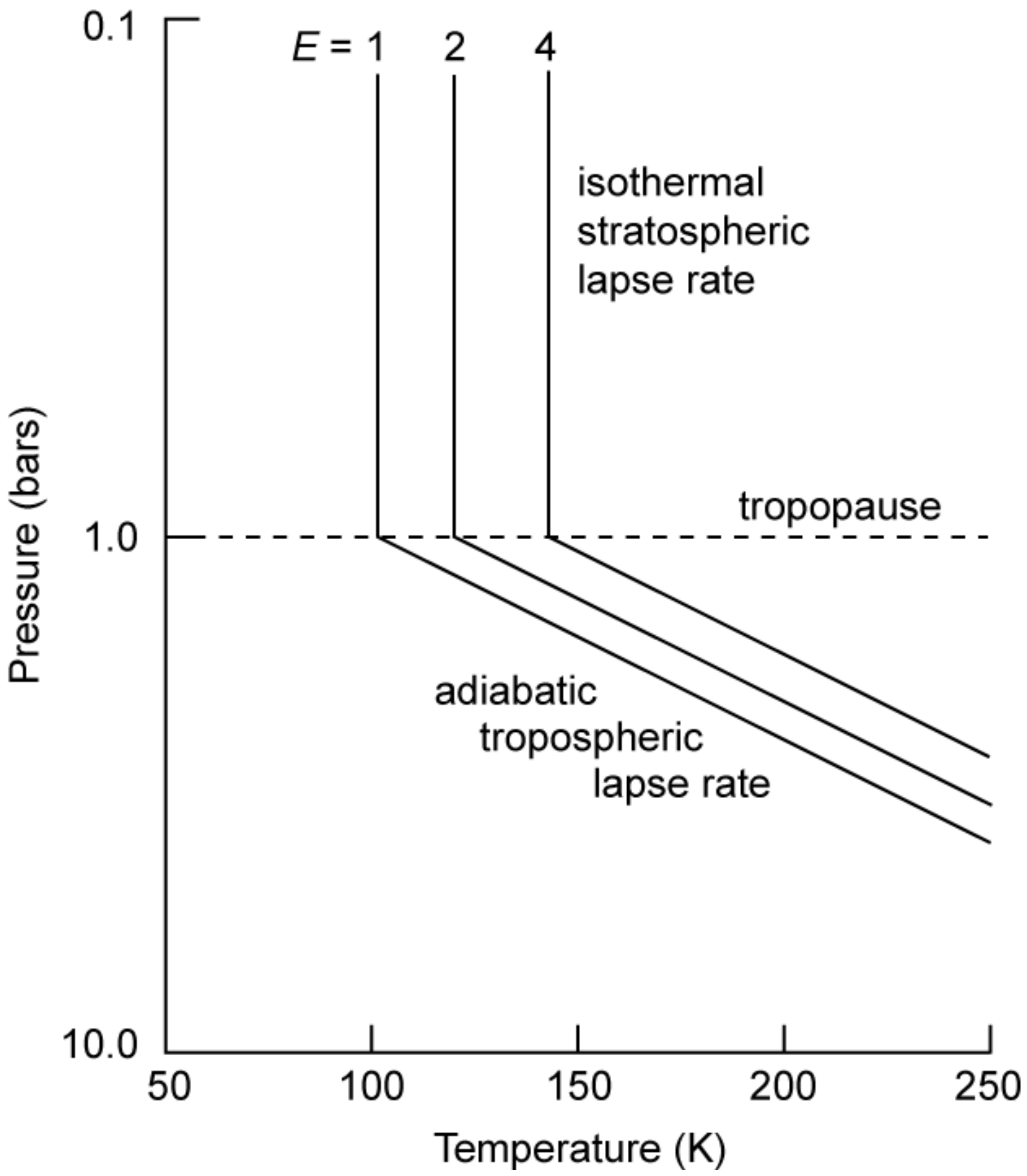


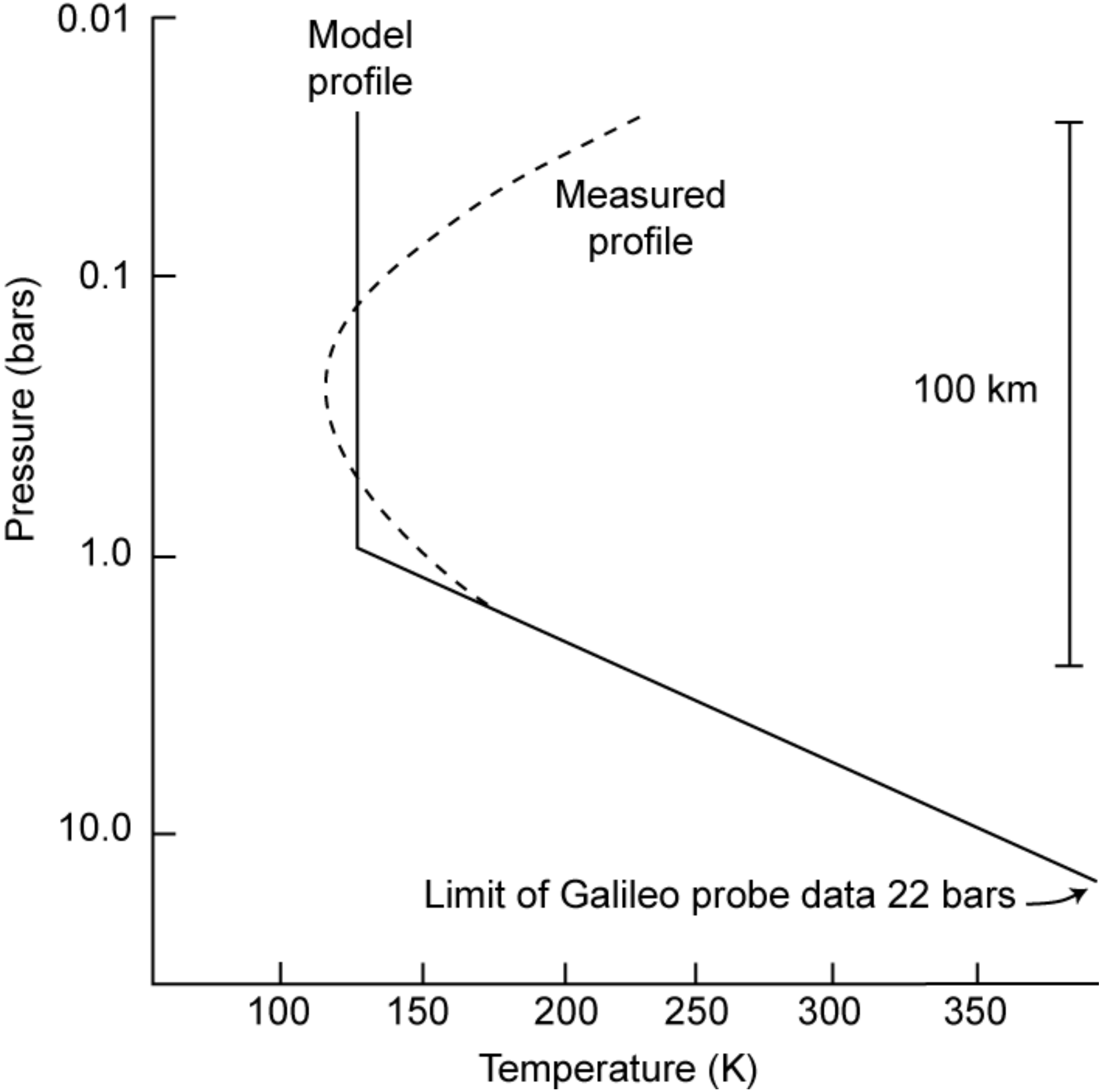
Heat Balance of Giant Planets



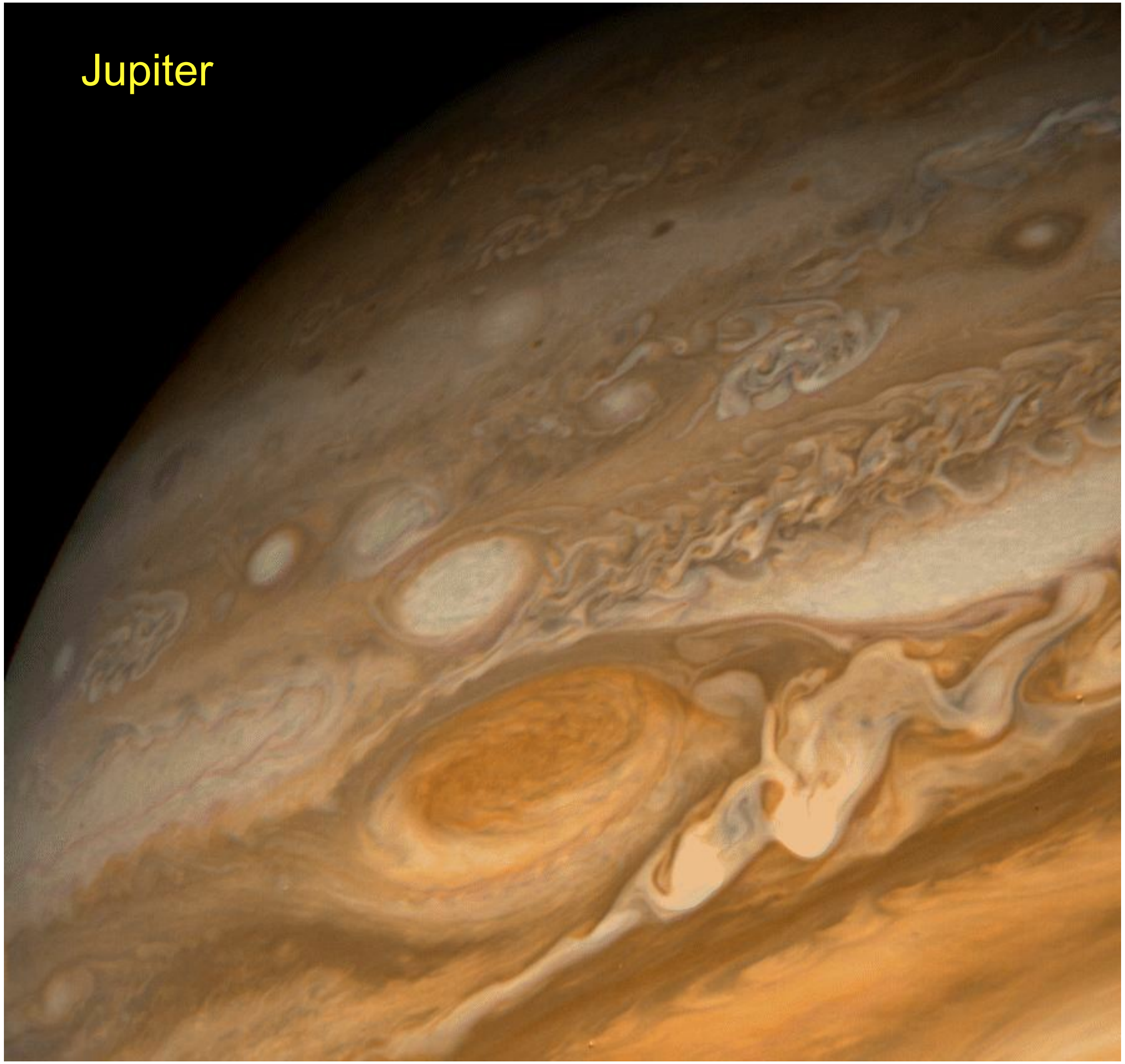
- Solar heating varies approximately as cosine of latitude.
- Thermal emission shows almost no latitudinal variation.
- Interior dynamics effectively redistribute heat.
- All giant planets (except Uranus) emit more (~2x) energy as radiation than they receive from the Sun, indicating internal sources of heat.
- Mean vertical velocity required to carry observed flux of heat is ~ 1 ms^{-1} at 1 bar.

Effect of internal heat on model temperature profile

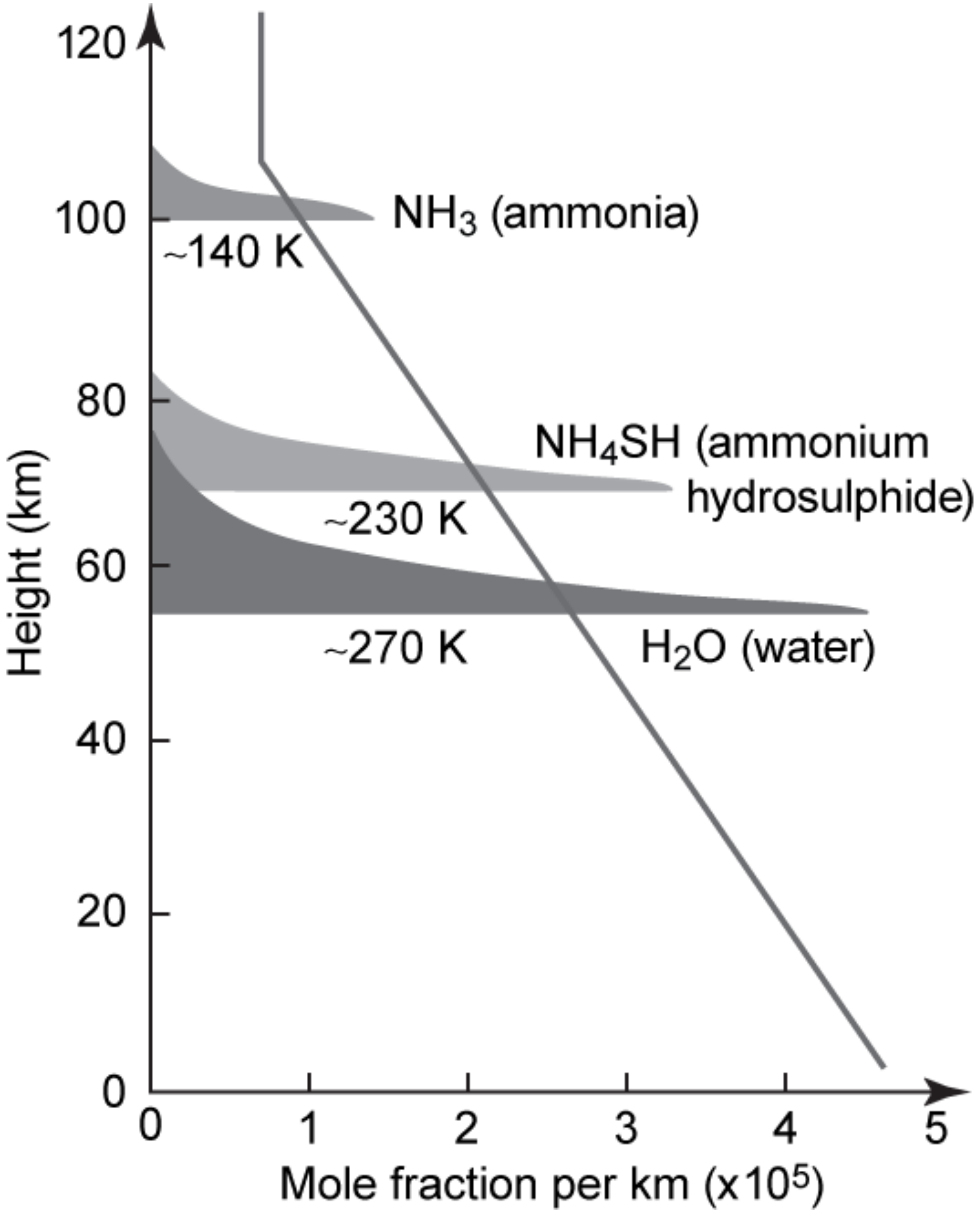



0.01
0.1
1.0
10.0
Pressure (bars)
Model profile
Measured profile
100 km
Limit of Galileo probe data 22 bars
100
150
200
250
300
350
Temperature (K)

Jupiter

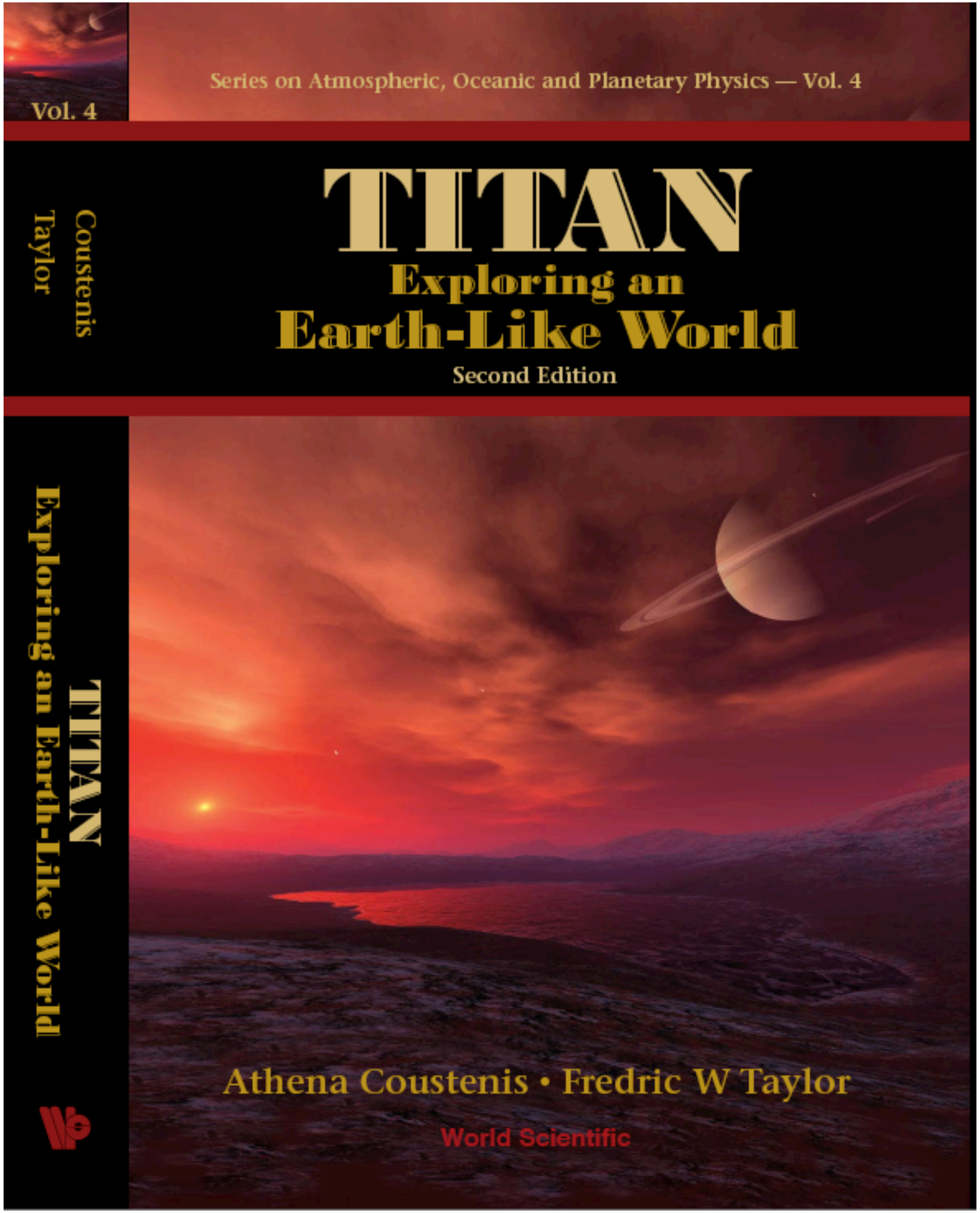


Vertical Cloud Structure on Jupiter



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

	Solar	**Jupiter**		**Saturn**		**Uranus**		**Neptune**	
		fraction *f*	*f*/solar	fraction *f*	*f*/solar	fraction *f*	*f*/solar	fraction *f*	*f*/solar
H_2	1	1	1	1	1	1	1	1	1
He	0.1954	0.157	0.8	0.13	0.67	0.18	0.92	0.18	0.92
H_2O	1.3×10^{-3}	**?**	~0.44	2×10^{-7}	0.00	?	?	?	?
CH_4	6.6×10^{-4}	2.1×10^{-3}	3.17	4.5×10^{-3}	6.8	0.019	29	0.027	40
Ne	2.4×10^{-4}	2.5×10^{-5}	0.1	?	?	?	?	?	?
NH_3	1.6×10^{-4}	7.1×10^{-4}	4.27	$>1.1 \times 10^{-4}$	> 0.66	?	?	?	?
H_2S	3.1×10^{-5}	8.1×10^{-5}	2.56	?	?	?	?	?	?
Ar	5.0×10^{-6}	1.81×10^{-5}	3.6	?	?	?	?	?	?
PH_3	7.2×10^{-7}	6.9×10^{-7}	0.96	7.9×10^{-6}	10.9	?	?	?	?
GeH_4	8.5×10^{-9}	8.1×10^{-10}	0.1	2×10^{-9}	0.23	?	?	?	?
Kr	4.0×10^{-9}	8.7×10^{-9}	2.13	?	?	?	?	?	?
Xe	2.9×10^{-10}	8.7×10^{-10}	2.95	?	?	?	?	?	?
AsH_3	4.6×10^{-10}	8.1×10^{-10}	1.73	2.3×10^{-9}	4.27	?	?	?	?



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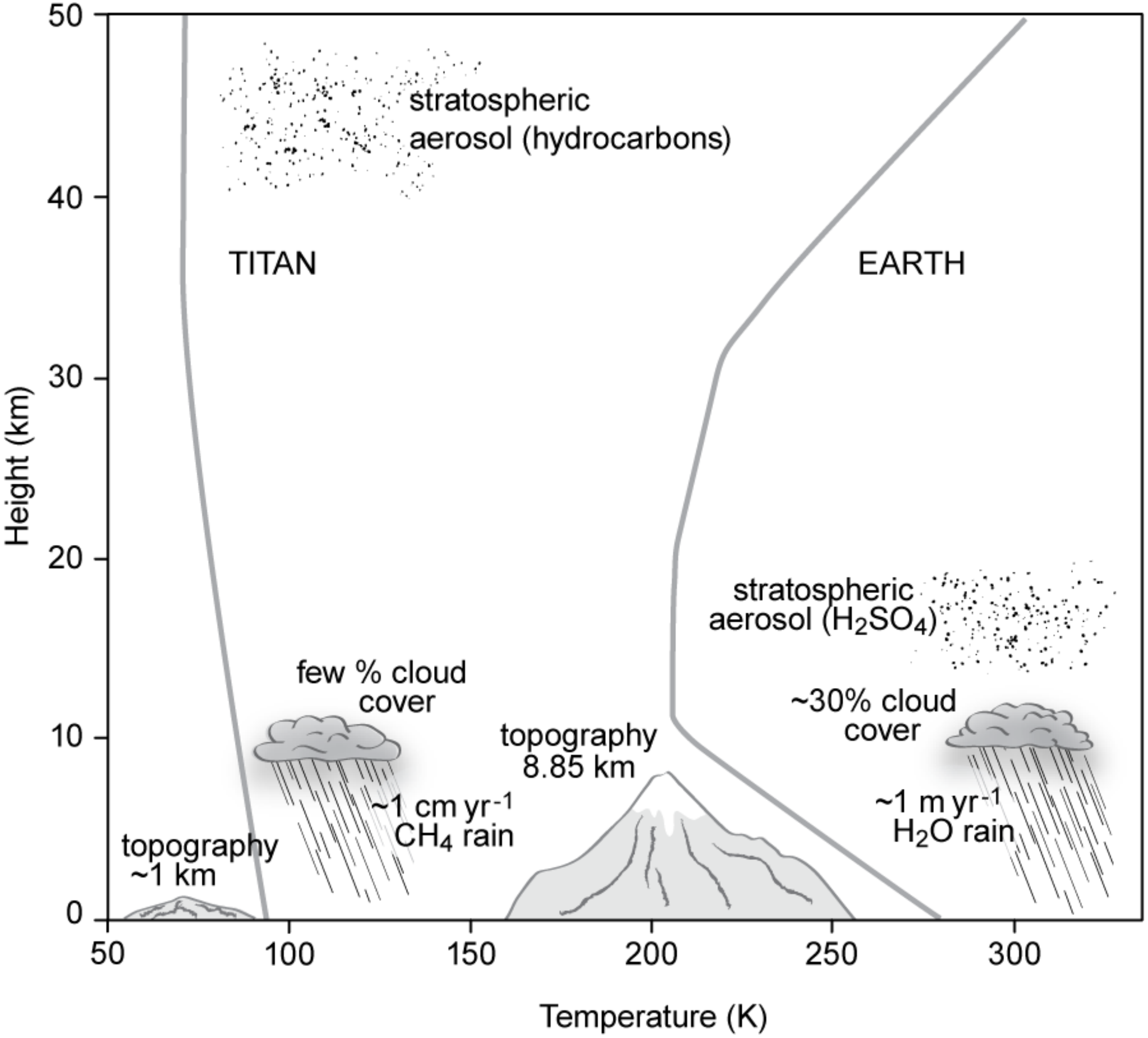
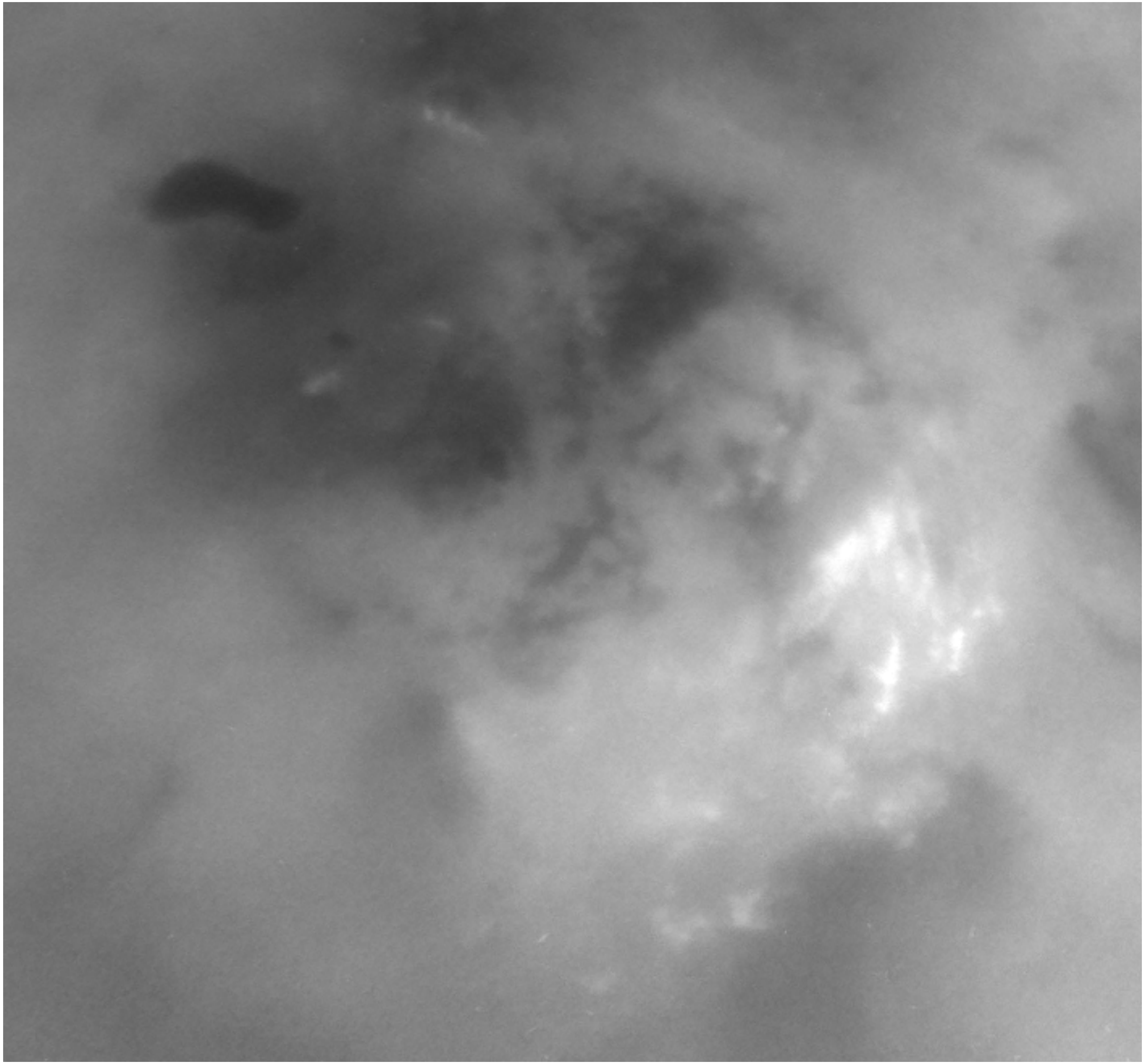
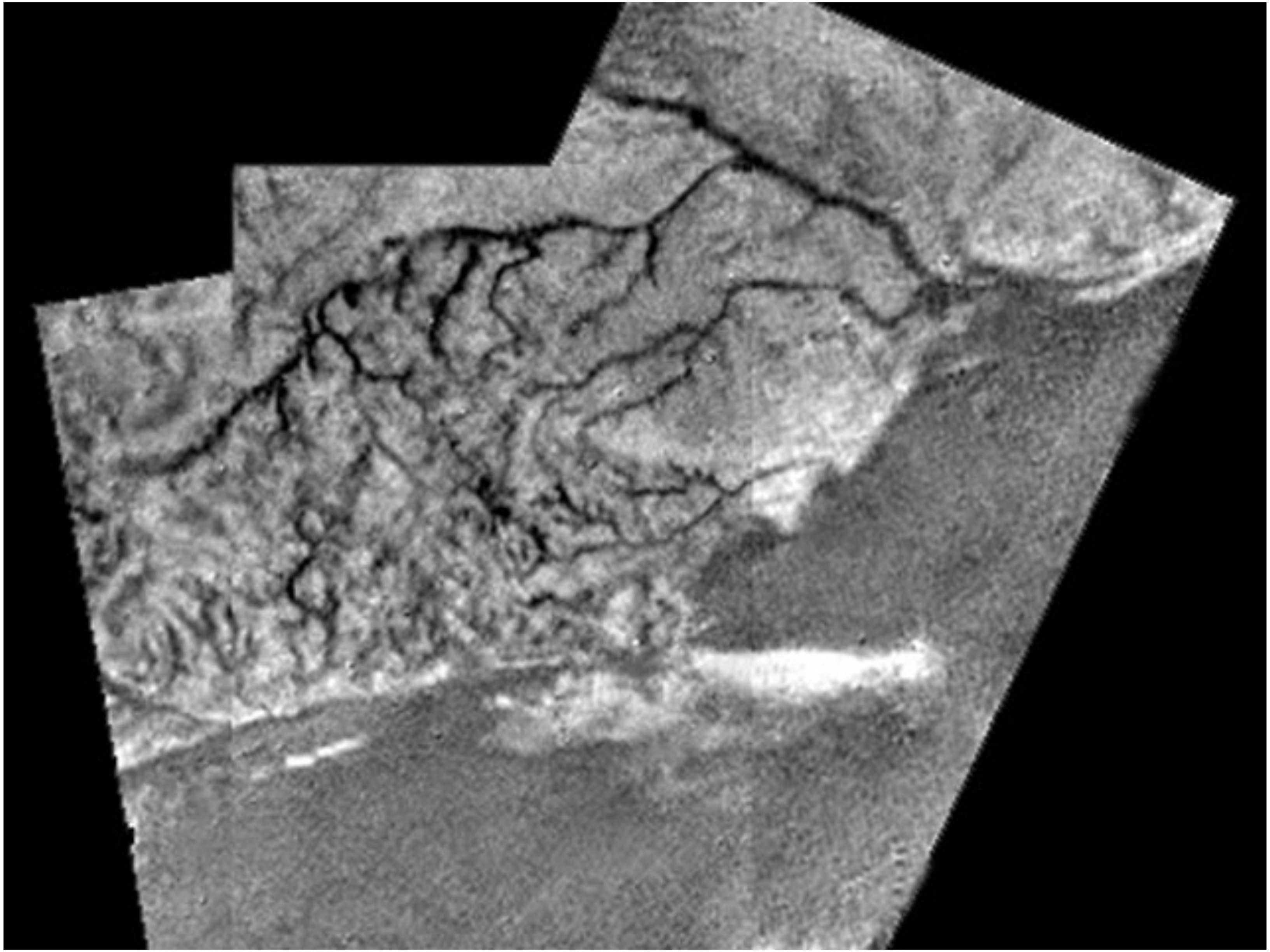
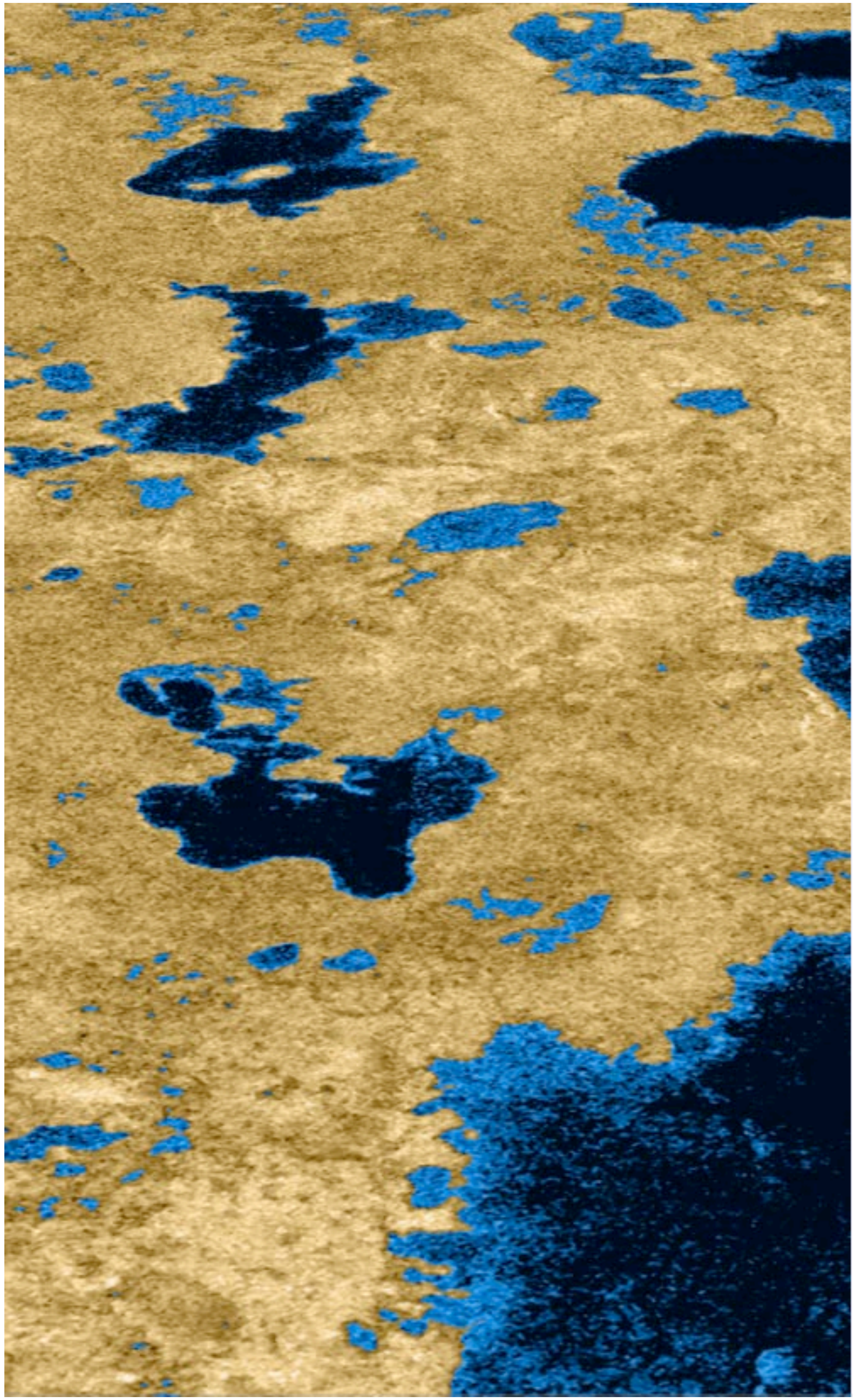






Cassini Radar Image of ‘Lakes’ on Titan

- Acquired by the Cassini radar instrument in synthetic aperture mode on July 22, 2006.
- Centred near 80°N, 35°W
- About 140 kilometres (84 miles) across.
- Smallest details in this image are about 500 metres (1,640 feet) across. (NASA/JPL)



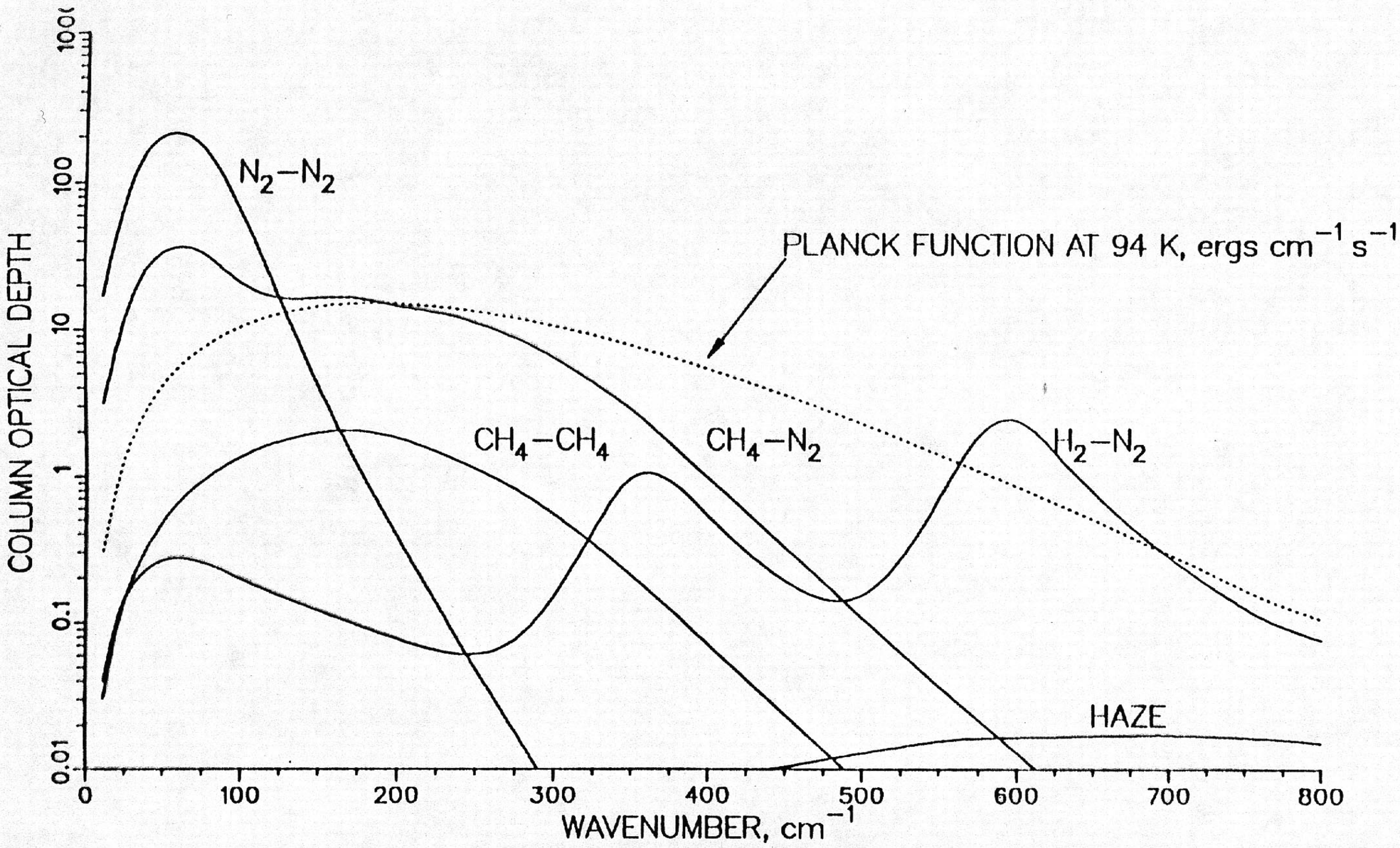
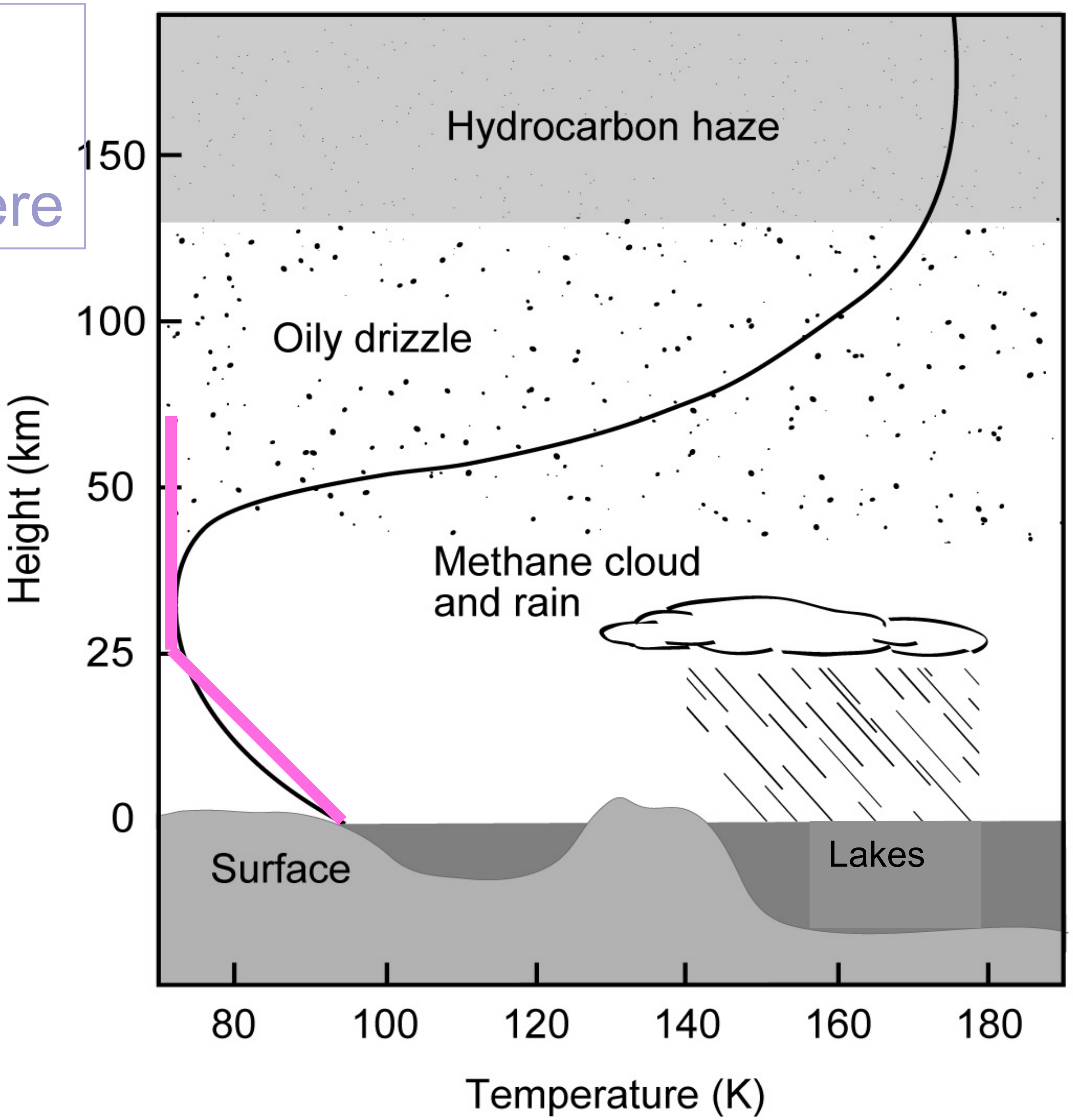
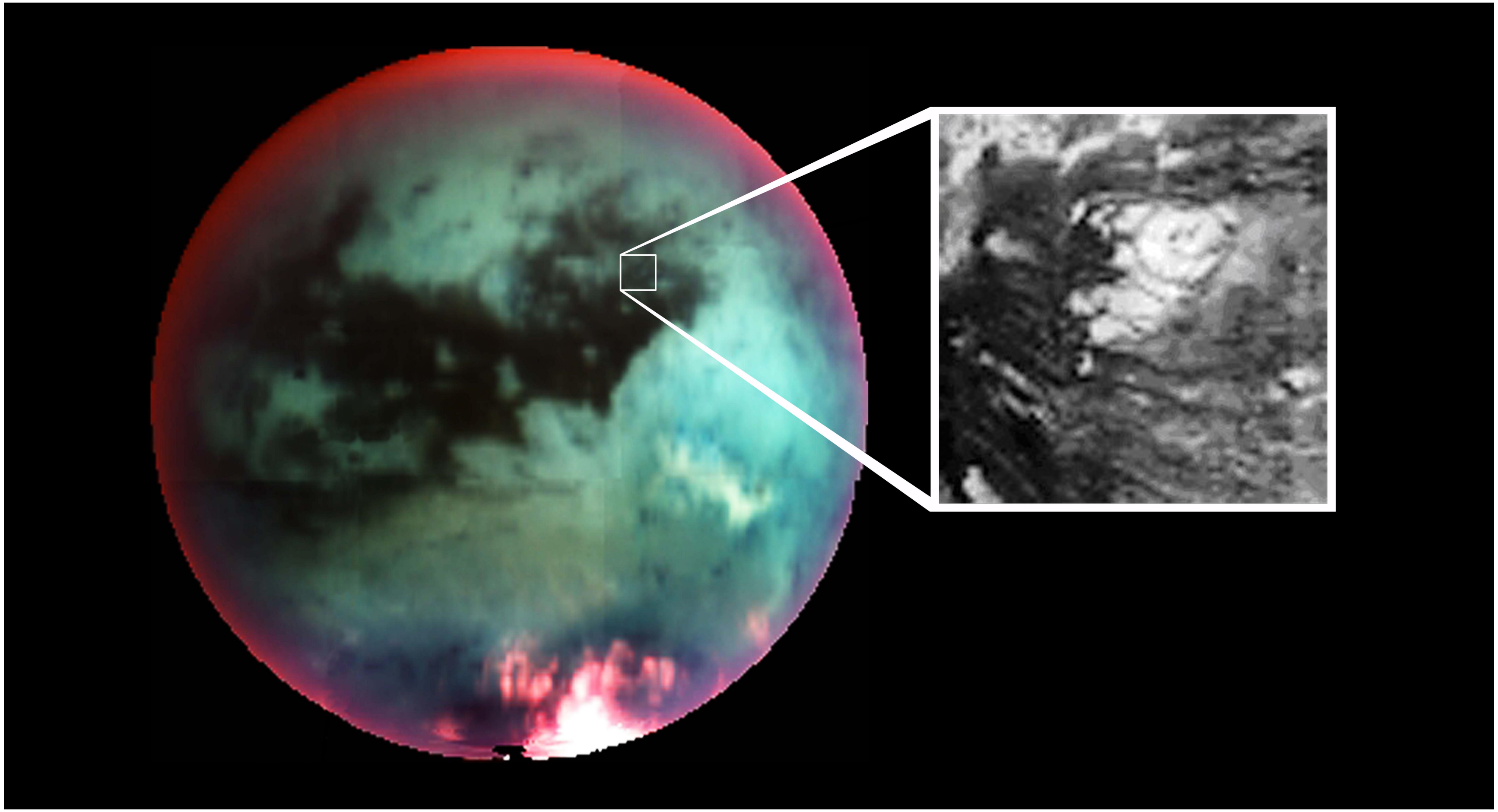


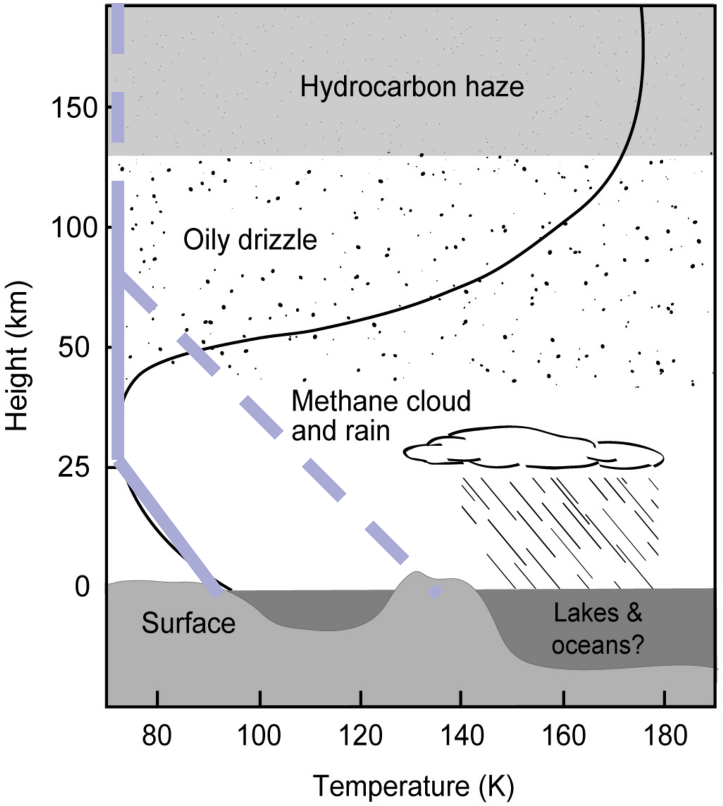
Fig. 1. Total column optical depth in the thermal infrared for Titan's atmosphere. Absorption is due to collision induced transitions. Also shown is the total column opacity of the haze layer. The dotted line is the blackbody flux emitted from the surface at a temperature of 94 K. Figure adapted from McKay *et al.* [Refs. 6, 9].

TITAN model atmosphere

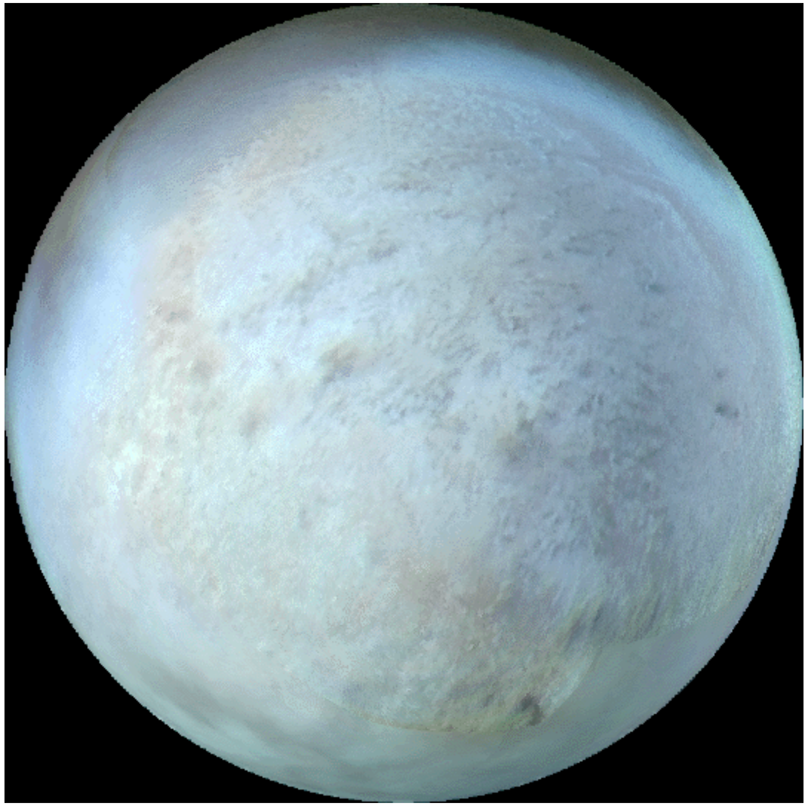




Climate change on TITAN



- If methane remains abundant, a runaway greenhouse is possible (Lorenz et al. 1999)
- Upper limit on surface temperature and pressure depends on solar brightness and atmospheric composition (greenhouse gases & albedo)



Triton

- Titan’s climate depends on the methane inventory
- If the methane runs out, the N_2 will freeze,
- the atmosphere will collapse in < 10 My and
- Titan will resemble Neptune’s giant satellite Triton

The End