Planetary Atmospheres

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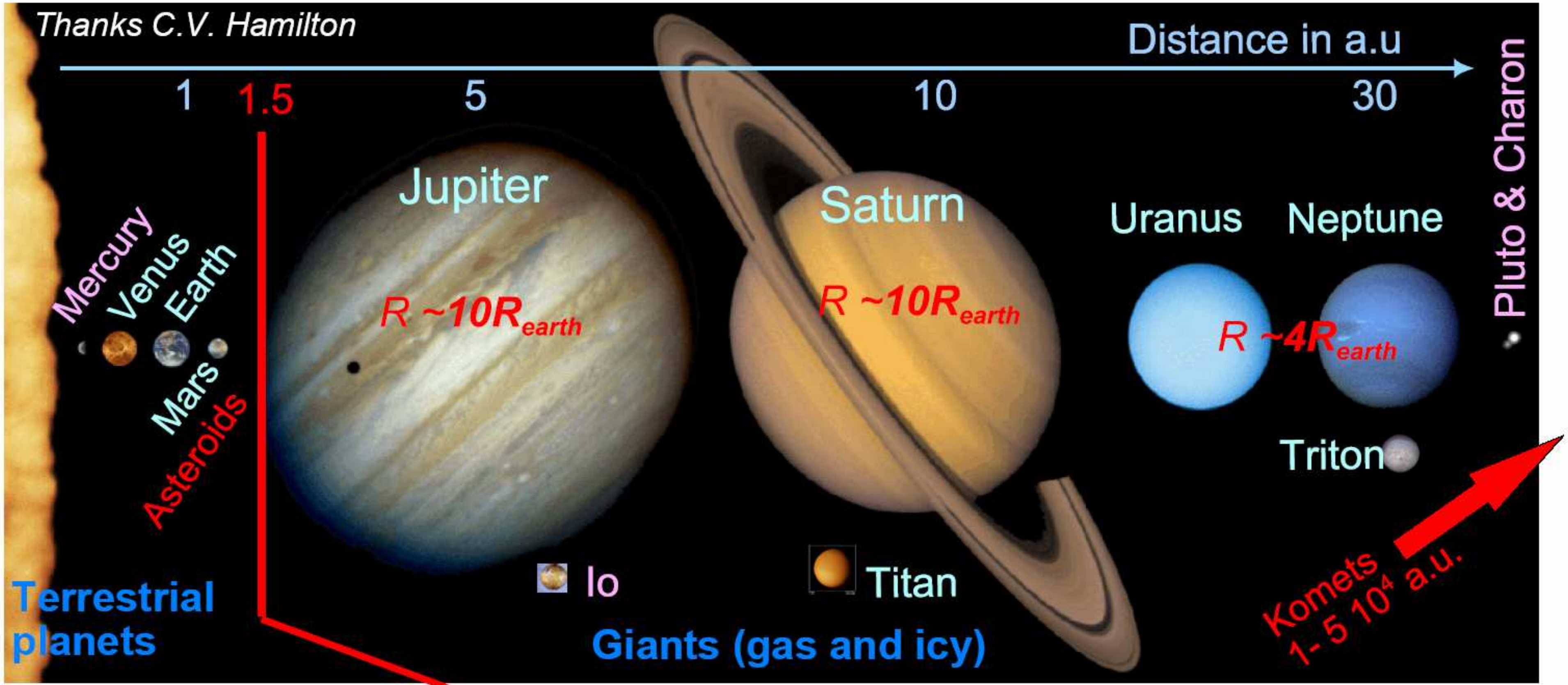
Content of the lecture

- **Introduction**
- **Structure of a planetary atmosphere**
- **Aerosols and clouds on the planets**
- **Energy balance**
- **Global circulation**
- **Atmospheres of planets**
  - *Venus*
  - *Mars*
  - *Giant planets*
- **Origin and evolution of planetary atmospheres**

Family of the Sun



- $M \sim M_{earth}$
- $\rho \sim 5\ g/cm^3$
- Solid bodies, heavy elements
- T > 1 day
- Interior flux << Solar flux

- $M > 20M_{earth}$
- $\rho \sim 1.5\ g/cm^3$
- Gas balls with heavy core
- Solar composition (H, He) and H_2O, NH_3, CH_4 ices
- T ~ 8 hours
- Interior flux ~ Solar flux

Types of planetary atmospheres

- **Fully developed atmosphers**
  - **Venus, Earth, Mars, Titan**
  - **Jupiter, Saturn, Uranus, Neptune**
- **Tenuous atmospheres (exospheres)**
  - **Mercury**
    - *O, Na, He, K, Ca at* $p < 10^{-12}$ *bar*
    - *Sputtering and capture of solar wind*
  - **Pluto & Triton**
    - N_2, CO, CH_4 *at* $p \sim 10^{-5}$ *bar*
    - *Sublimation of ices, freezing out in apohelium*
    - *Similar processes on icy satellites*
  - **Io**
    - SO_2 *at* $\sim 10^{-8}$ *bar*
    - *Volcanic activity*

Structure of a planetary atmosphere

Pressure in a planetary atmosphere

- **Hydrostatic equilibrium and gas law**

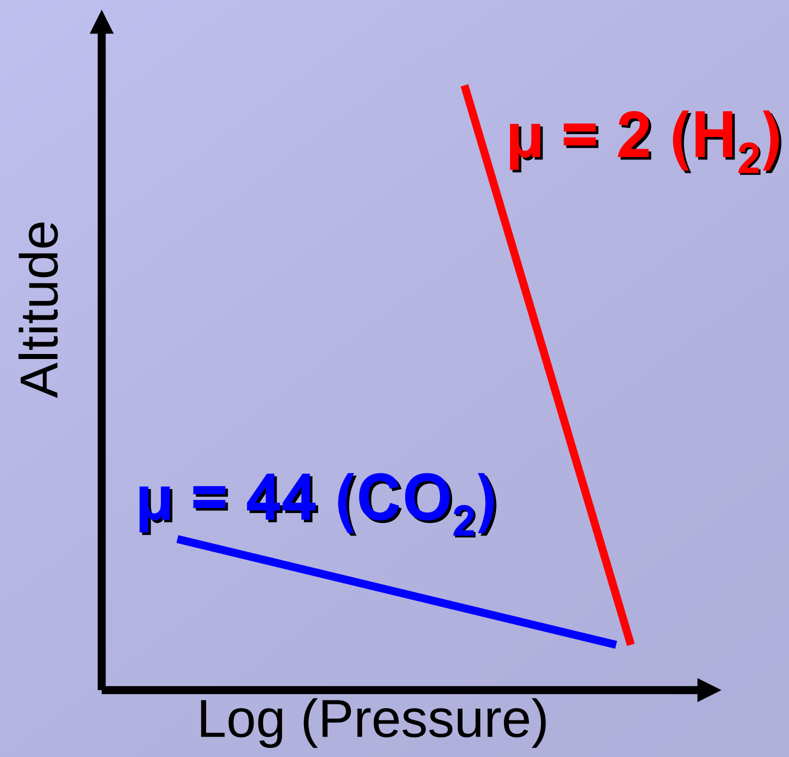
$$dP = -\rho g dz \ \& \ \rho = \frac{\mu P}{RT}$$

- **Barometric law**

$$P(z) = P_0 e^{-\int \frac{dz'}{H(z')}}$$

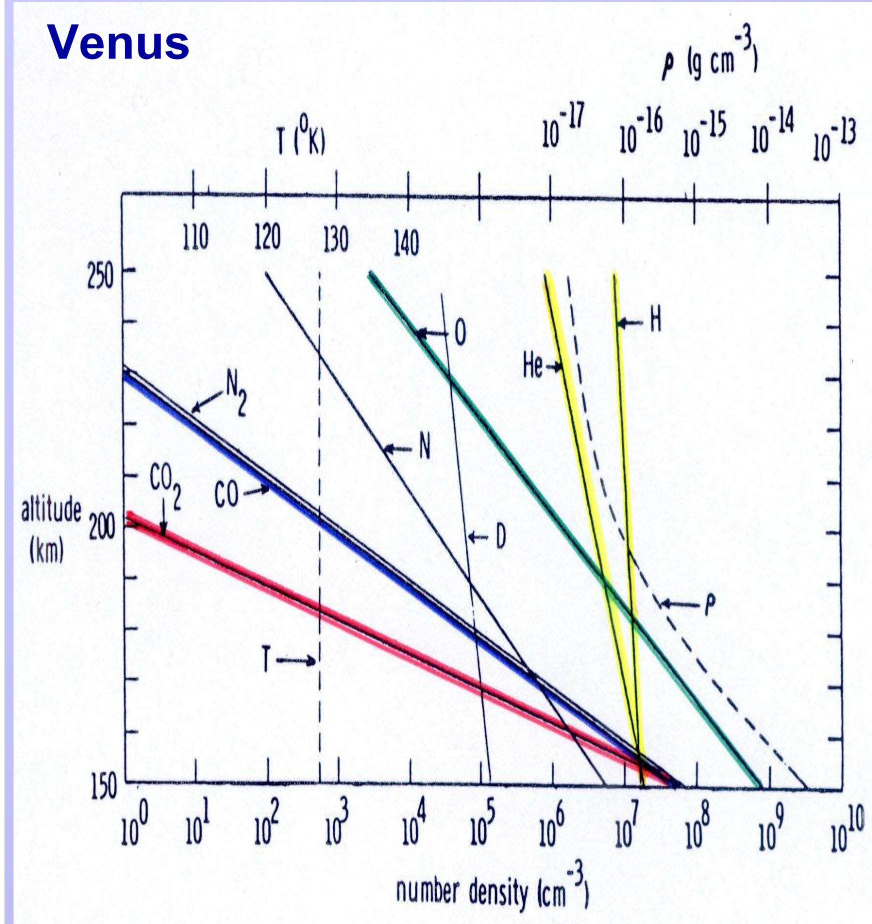
- **Scale height**

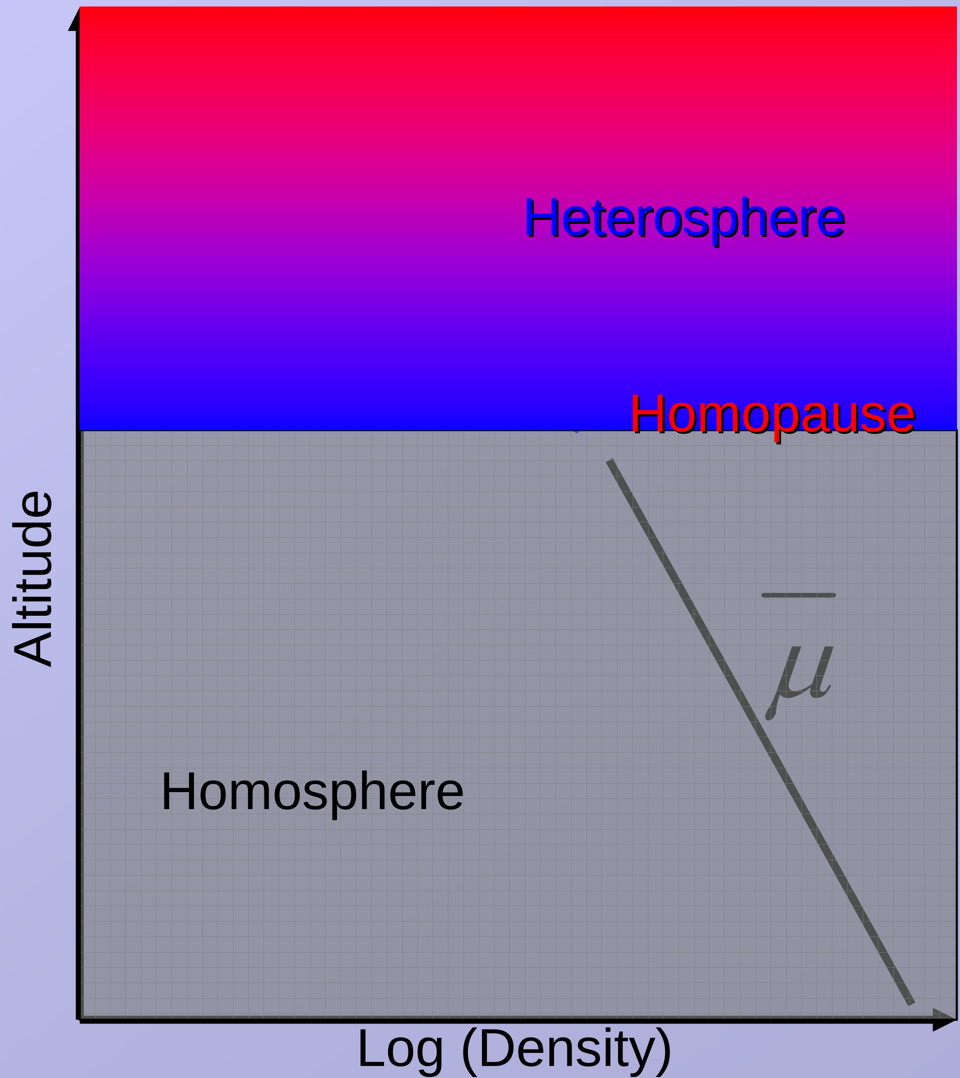
$$H(z) = \frac{RT(z)}{\mu g}$$



Density in a planetary atmosphere

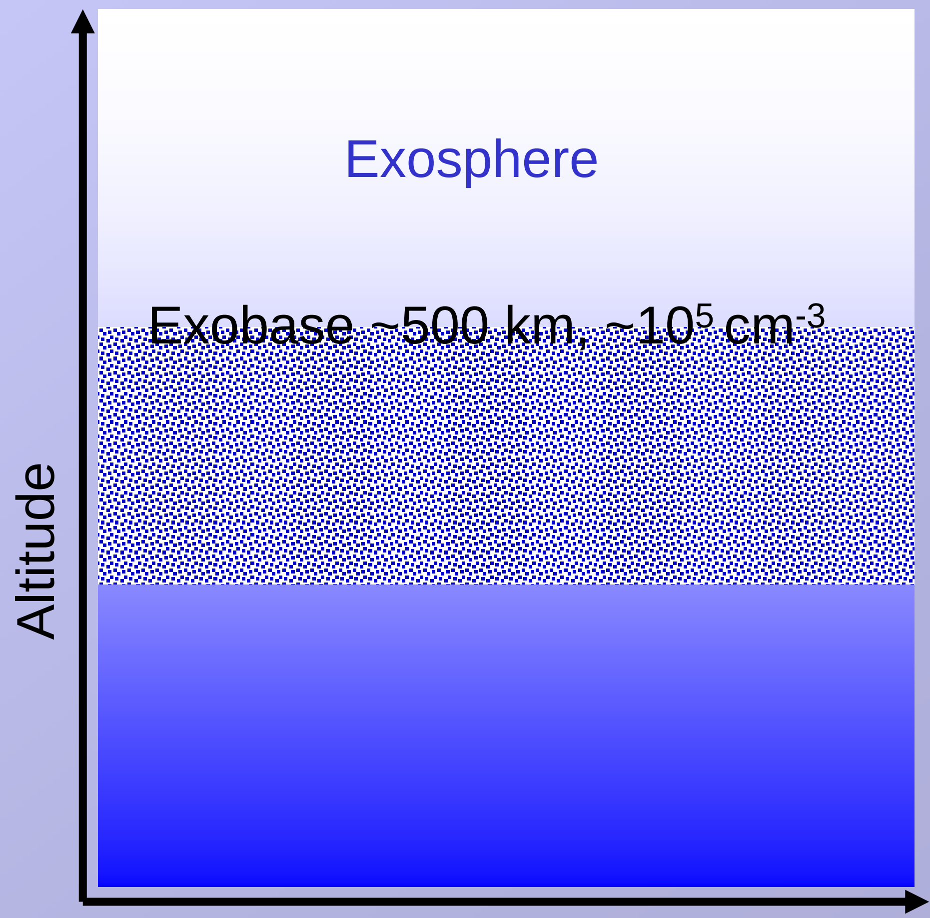
- Homopause: eddy mixing ~ molecular diffusion (z~ 130 km)
- Homo- and heterosphere
- Hydrogen-helium coronas



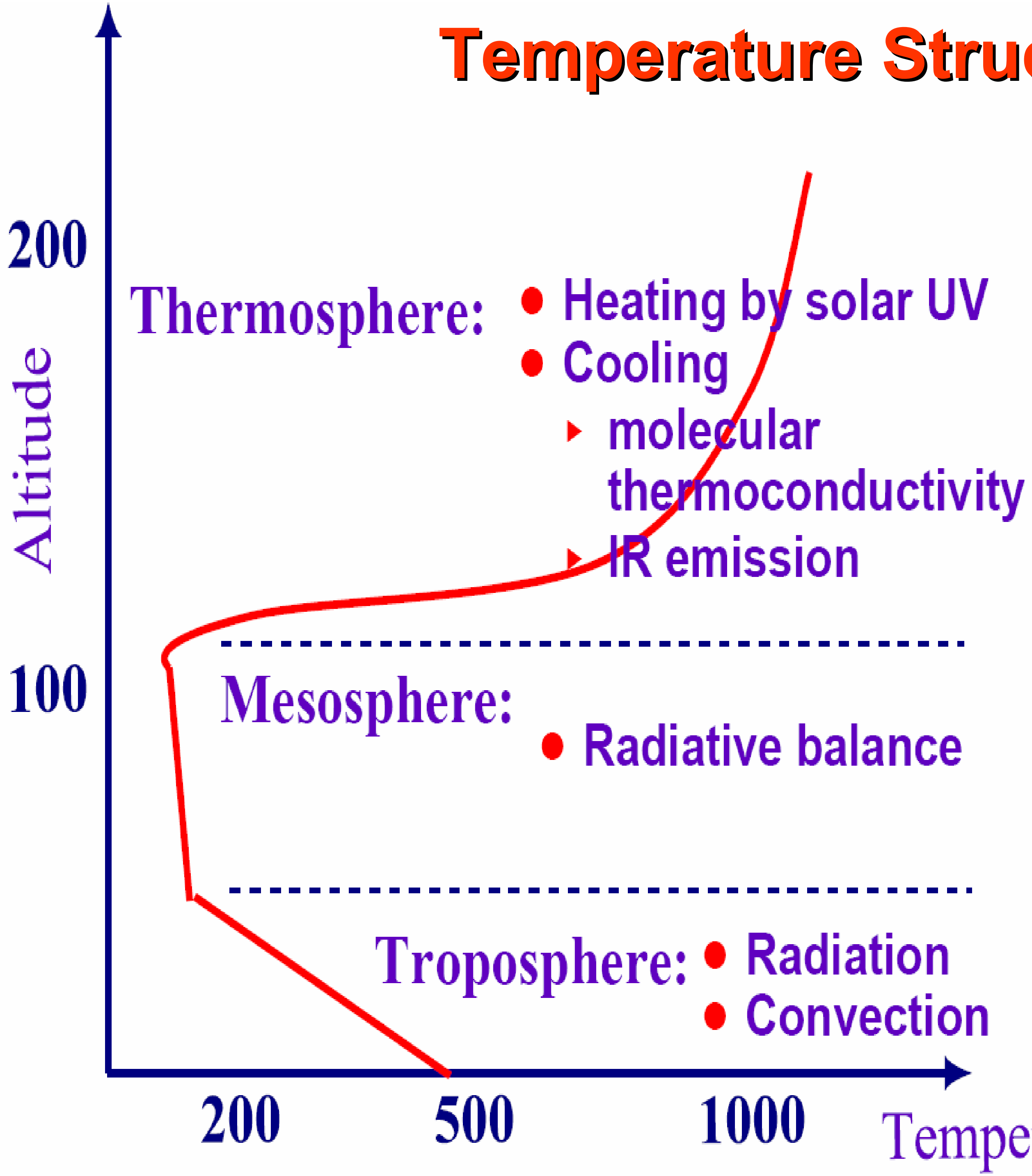


Exosphere and escape processes

- **Exosphere:** ***free path > scale height***
- **Thermal (Jeans) escape**
- **Non-thermal escape**
  - ***dissociation***
  - ***charge exchange***
  - ***sputtering***
  - ***acceleration by electric field***
  - ***sweeping by solar wind***
- **Hydrodynamic escape**
- **Impact escape**

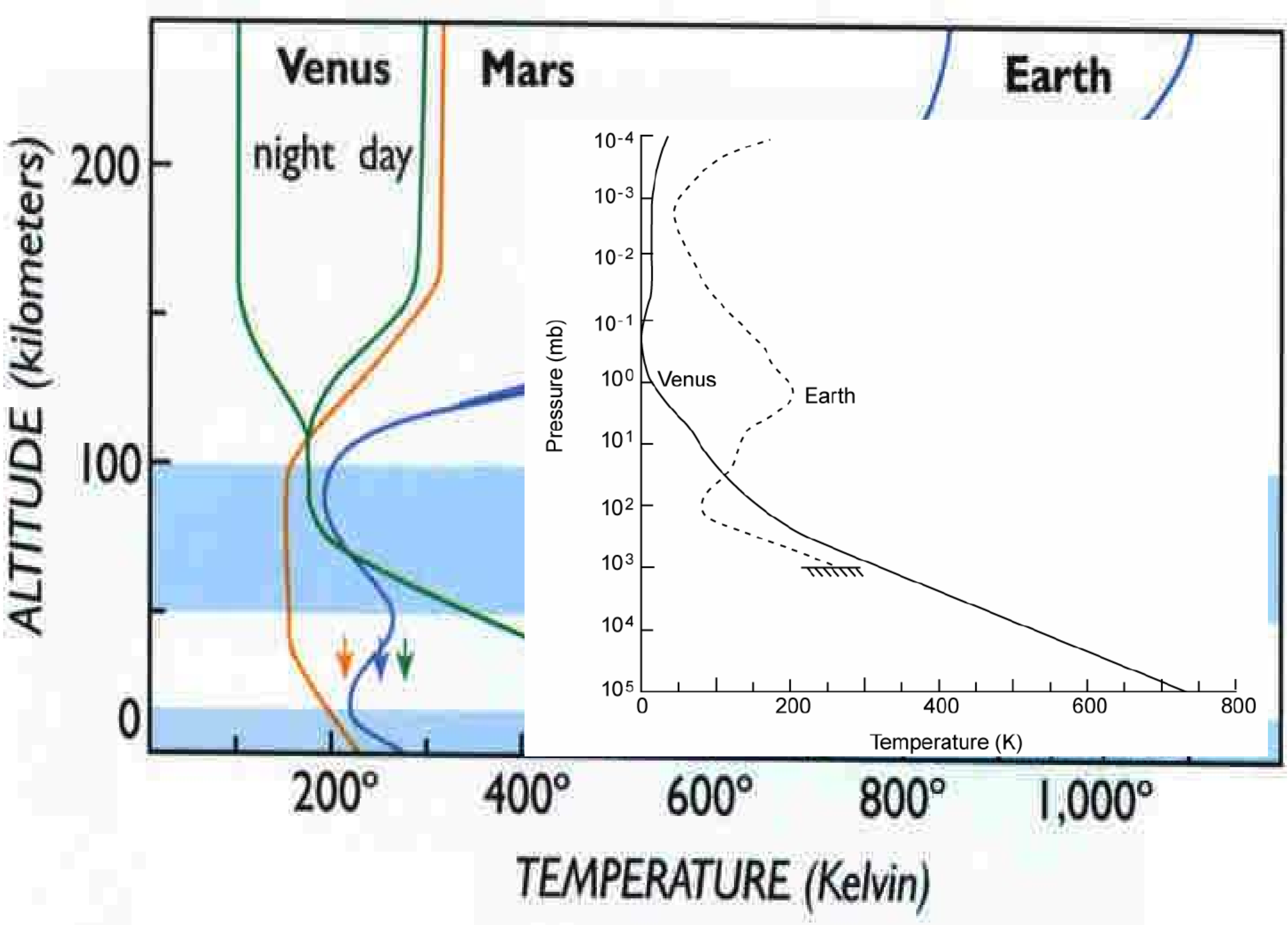


Temperature Structure

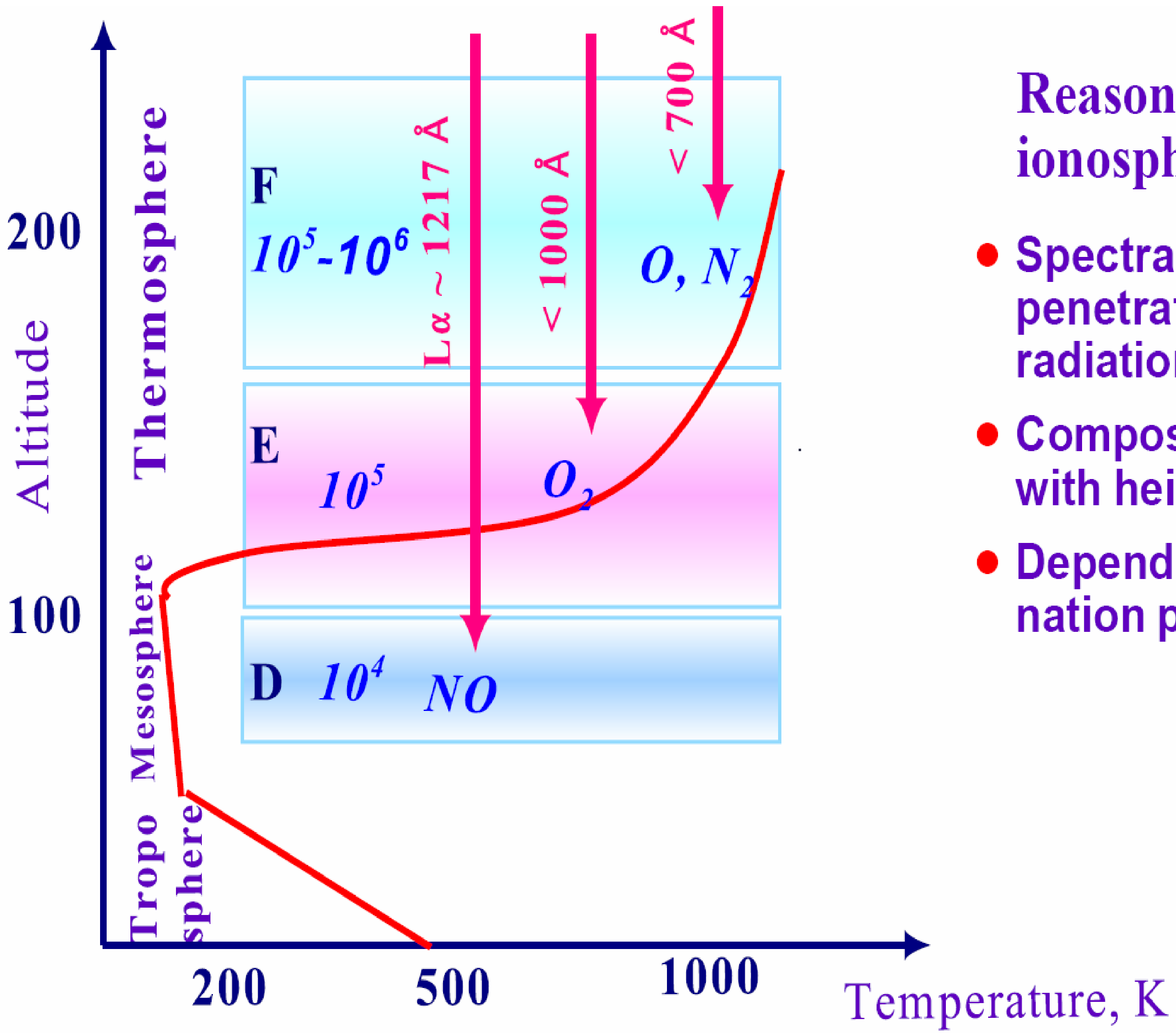


Adiabatic gradient:
$dT/dz = - g/C_p$

Temperatures on terrestrial planets



Formation of Ionospheres

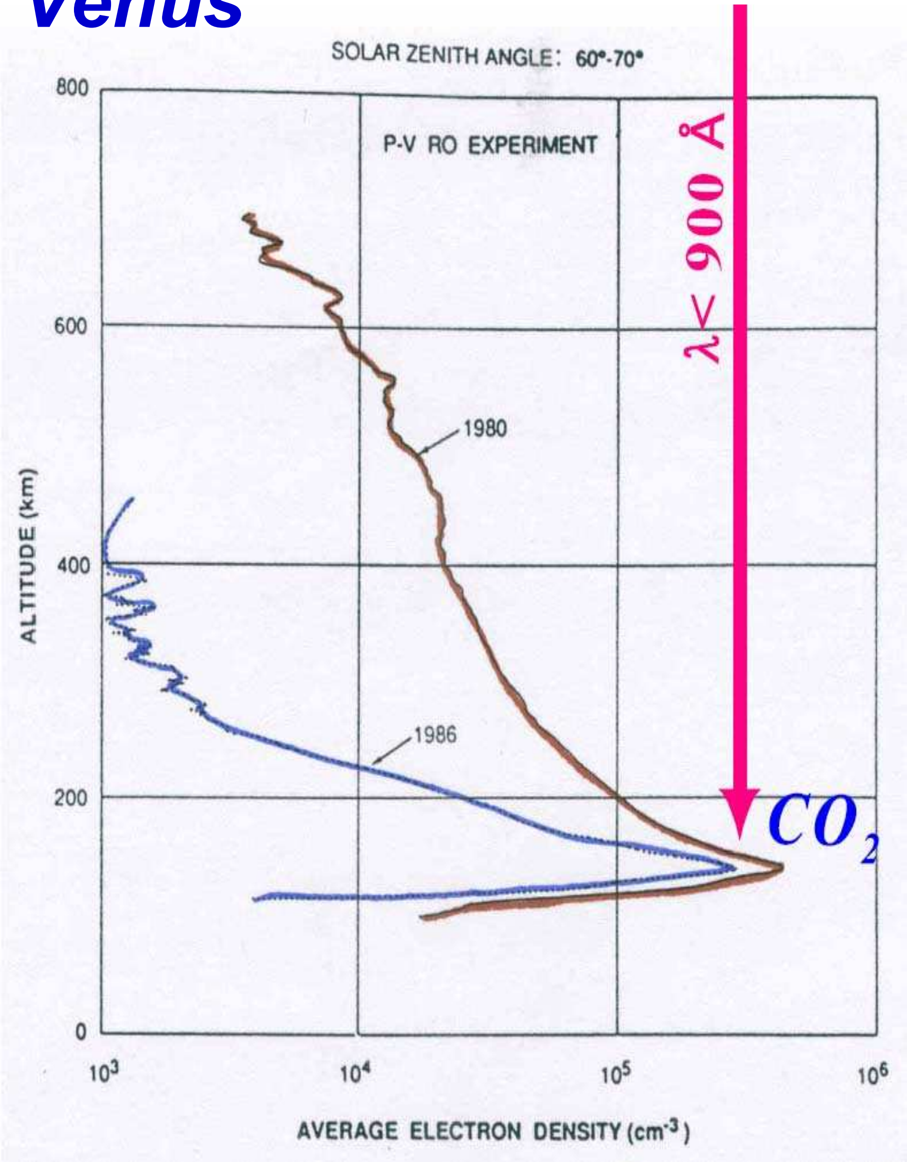


Reasons for distinct ionospheric regions

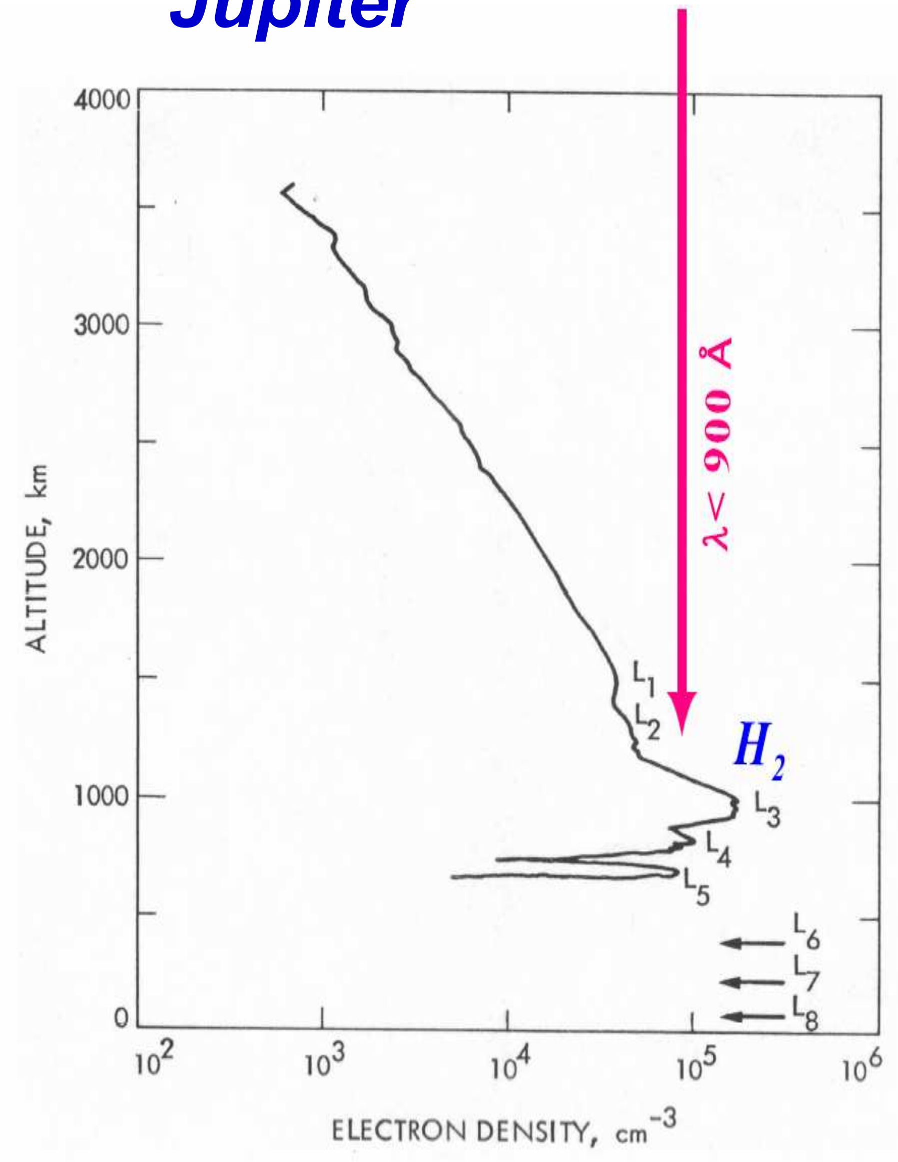
- Spectral dependence of penetration depth of solar radiation
- Composition changes with height
- Dependence of recombination physics on density

Structure of ionospheres

Venus



Jupiter

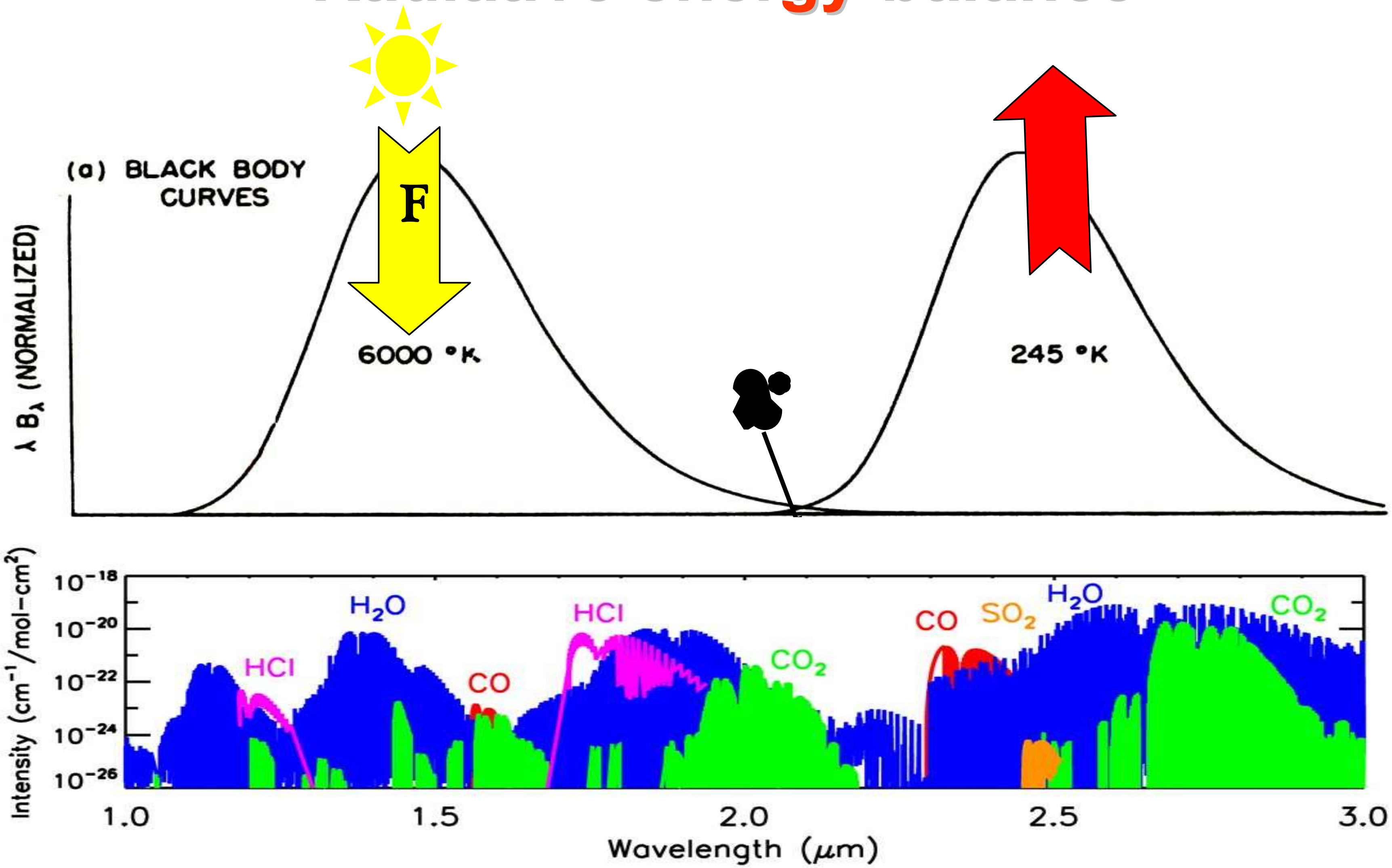


Aerosols and clouds on the planets

- *condensational (Earth, Mars, Jupiter)*
- *photochemical (Venus, Titan)*
- *gas phase reactions (Jupiter, Saturn)*

Radiative energy balance

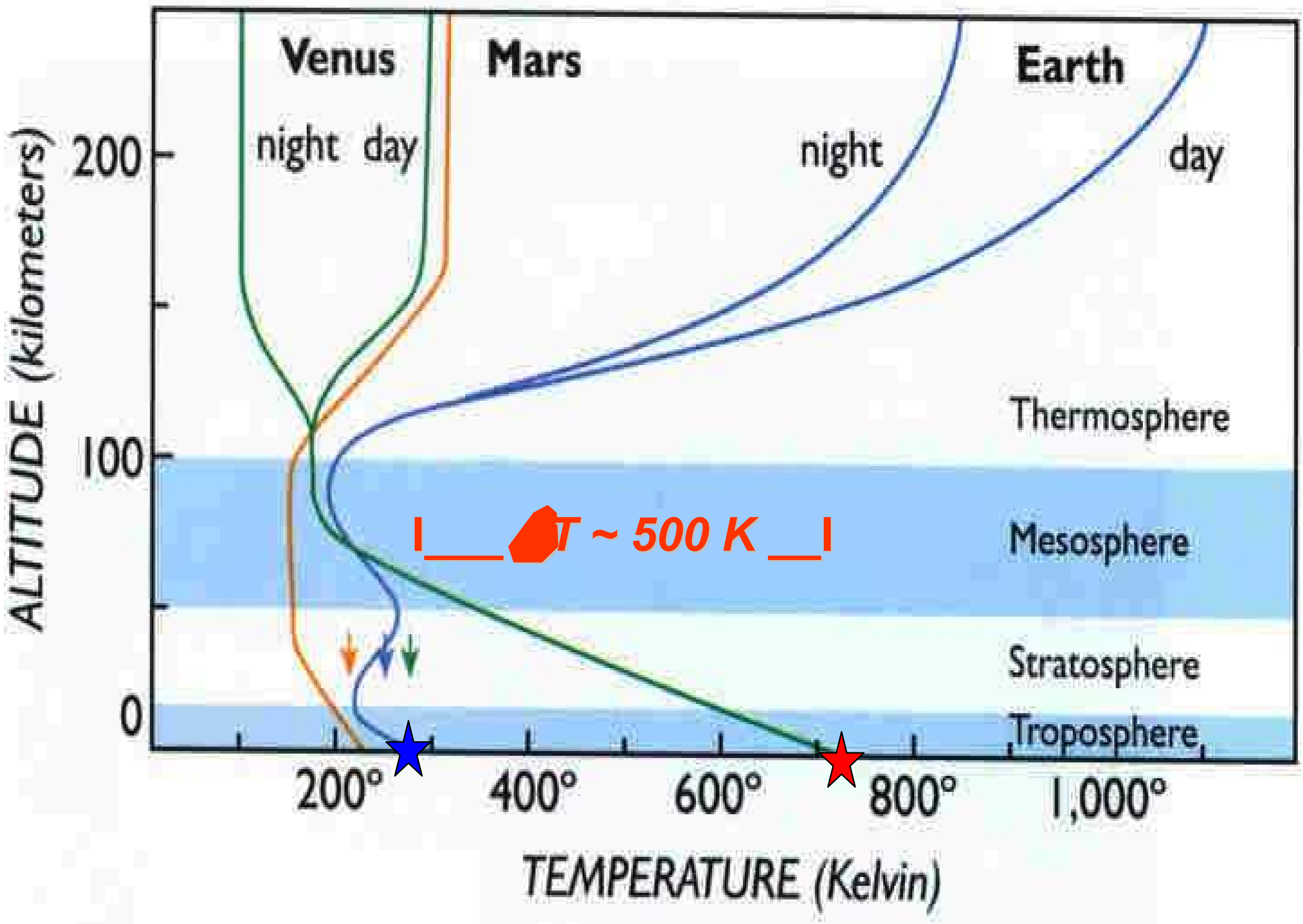
Radiative energy balance



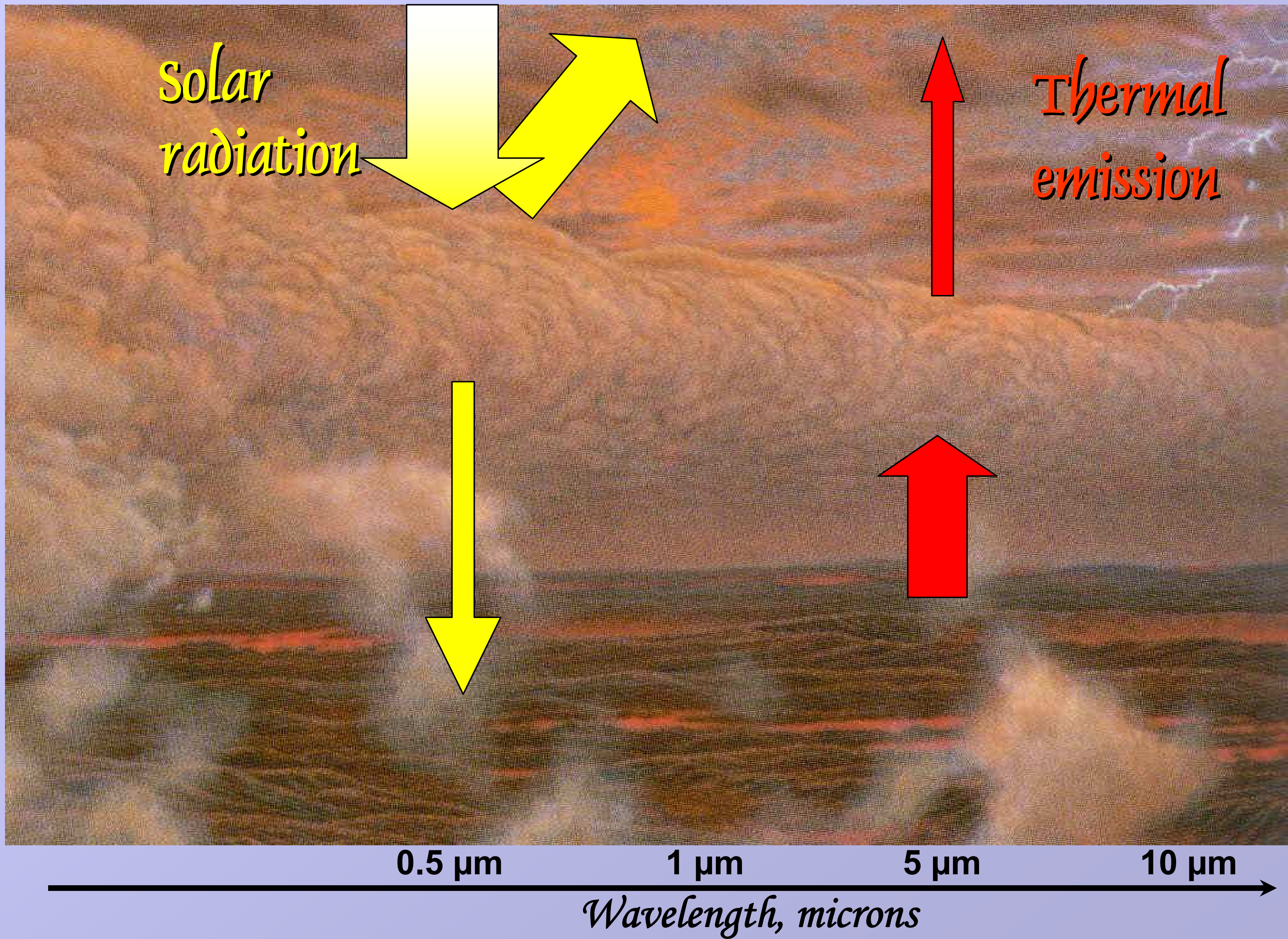
Effective temperature

$$F(1-A) = 4\sigma T_{eff}^{4}$$

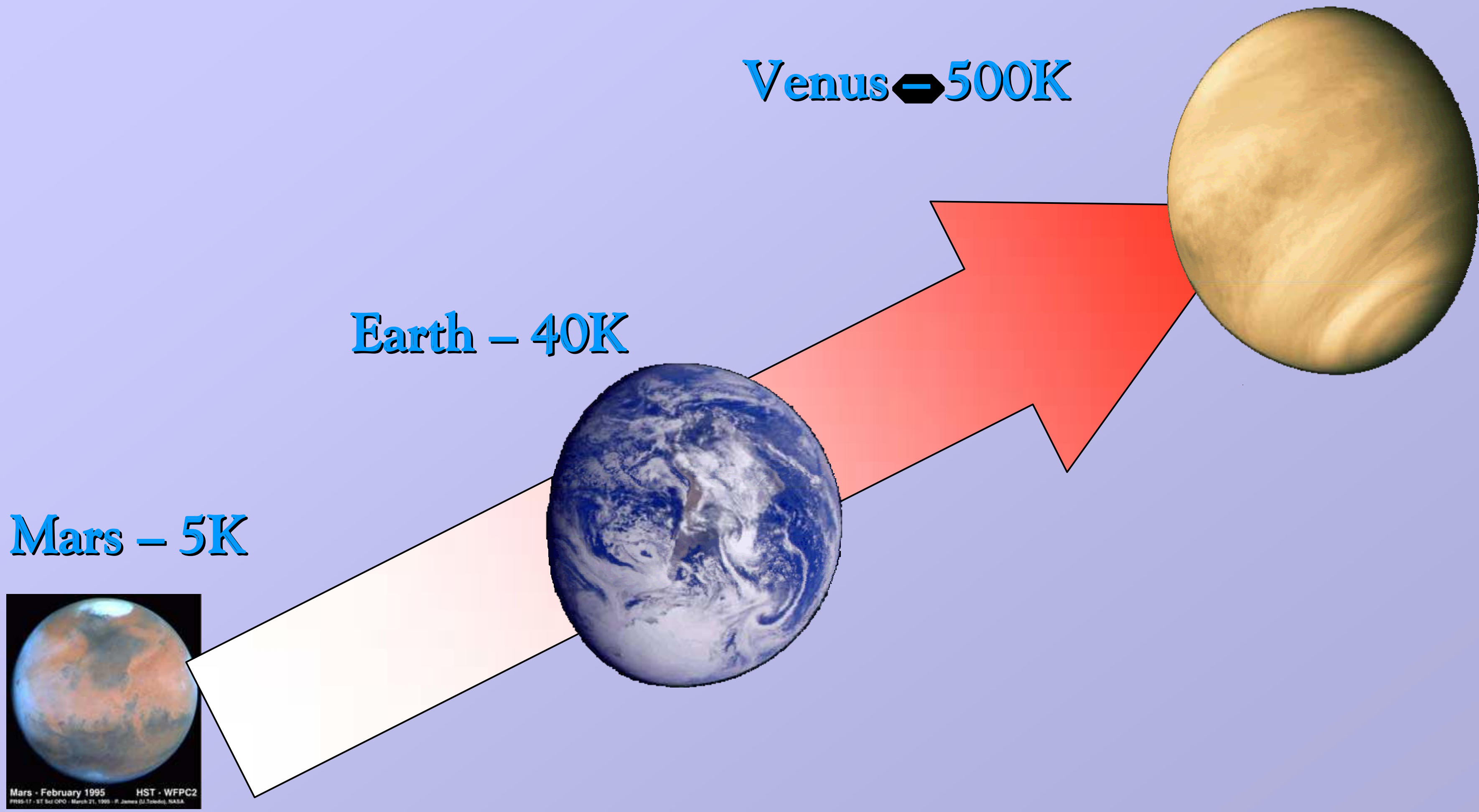
Temperatures on terrestrial planets



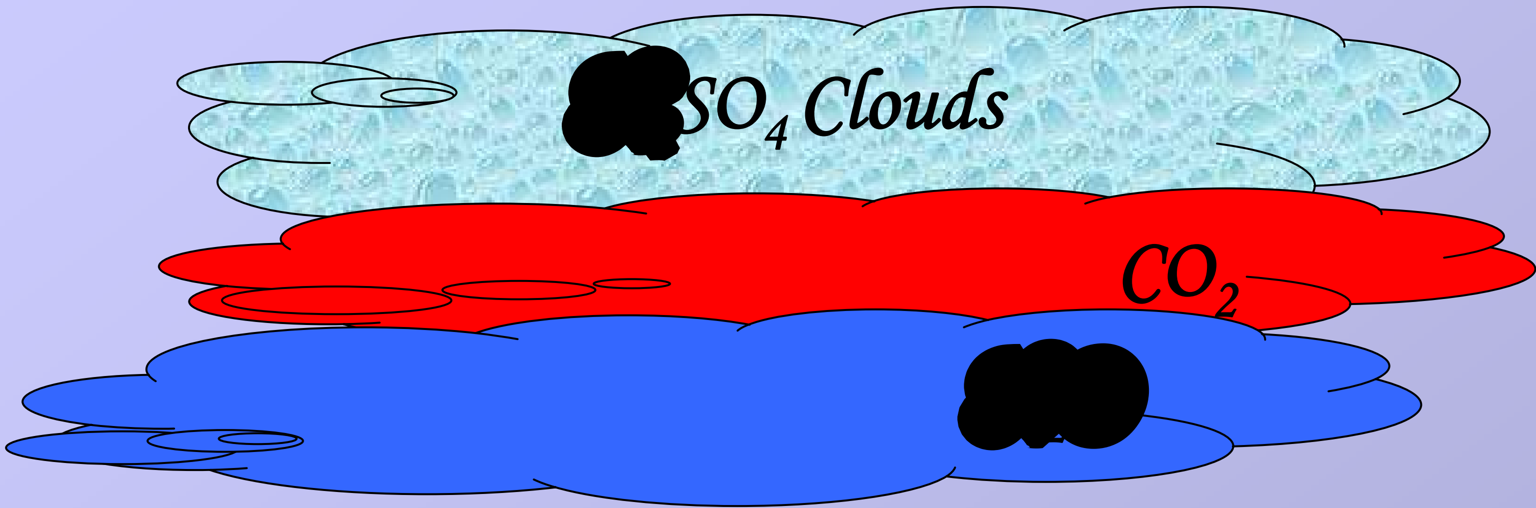
Basics of the greenhouse effect



Greenhouse effect on terrestrial planets



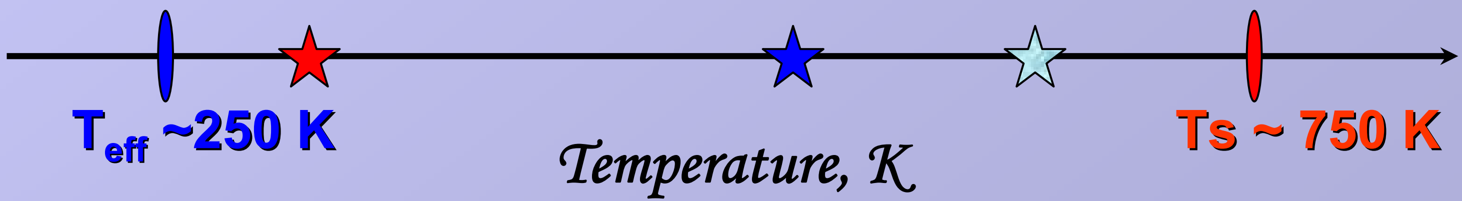
Contribution of the atmospheric components to the greenhouse effect on Venus



CO_2 – 460K

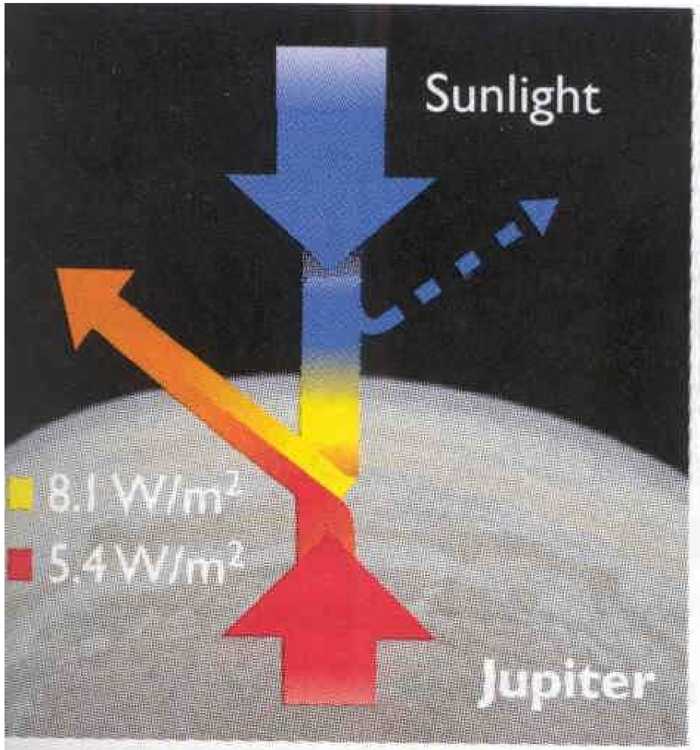
[illegible]$_2$O – 220K

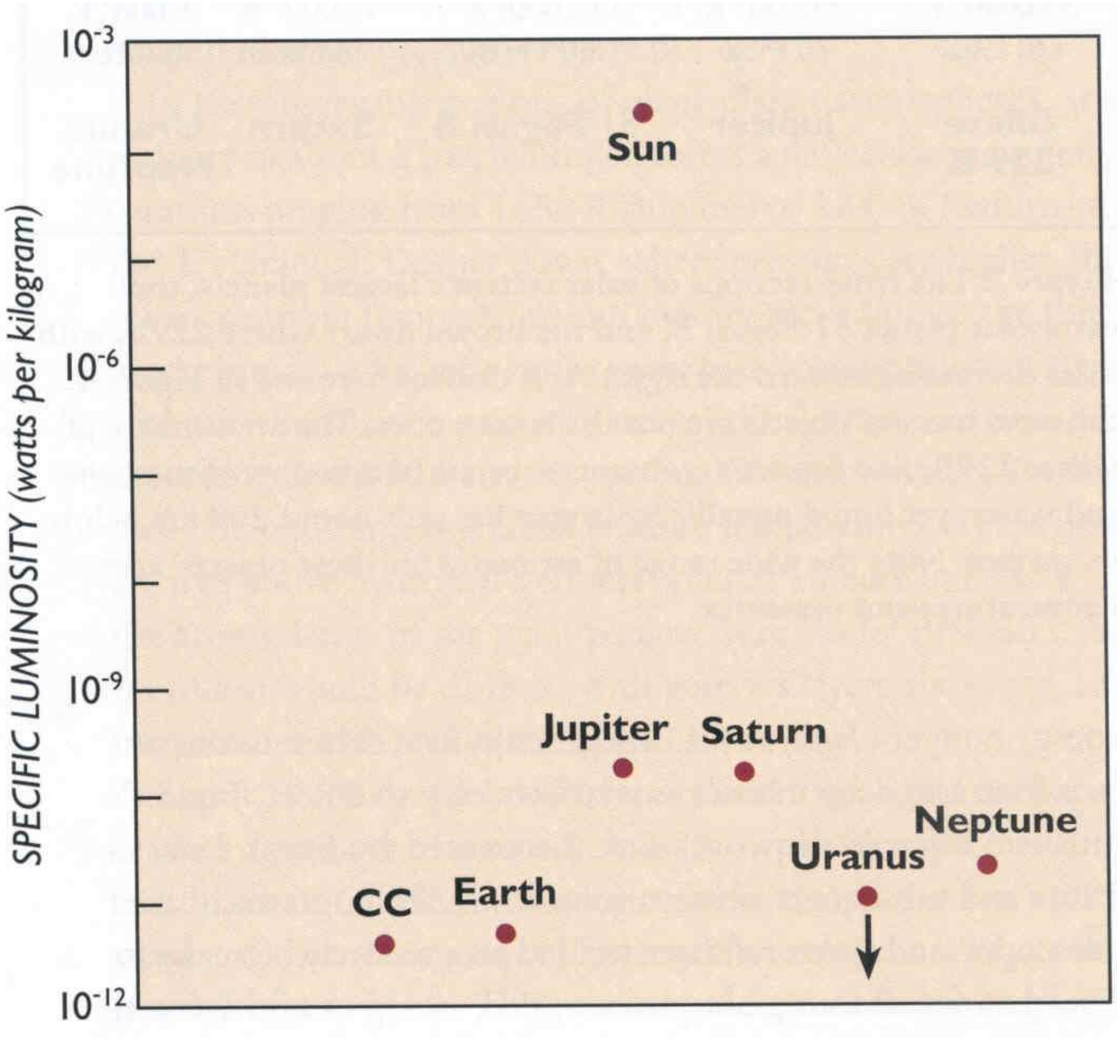
Clouds – 100K



Bullock, 2007

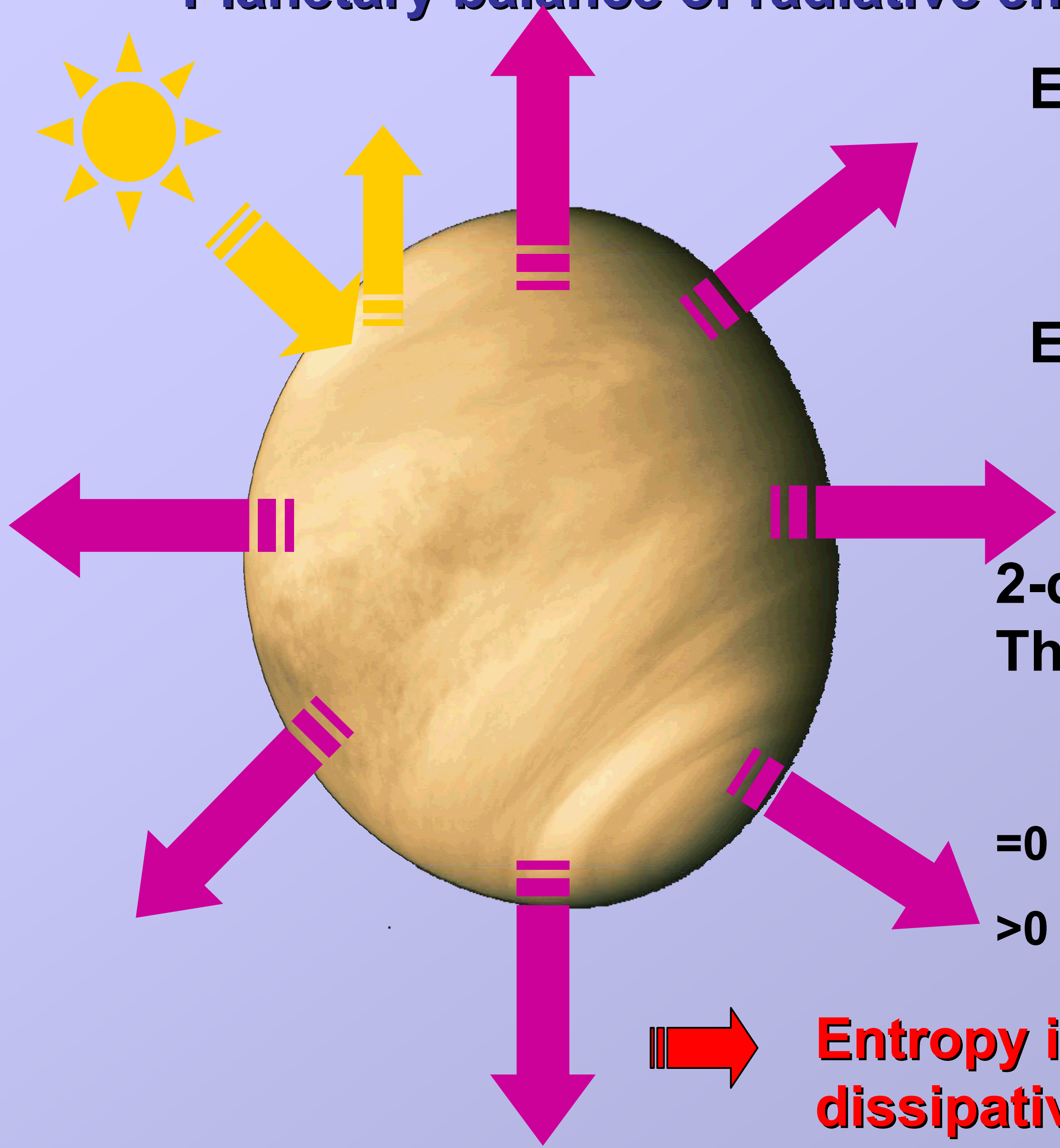
Internal sources of energy on giant planets





Entropy balance

Planetary balance of radiative energy and entropy



Energy balance:

$$E_{Solar} - E_{ThIR} = 0$$

Entropy:

$$\Delta S = E/T$$

2-d Law of Thermodynamics:

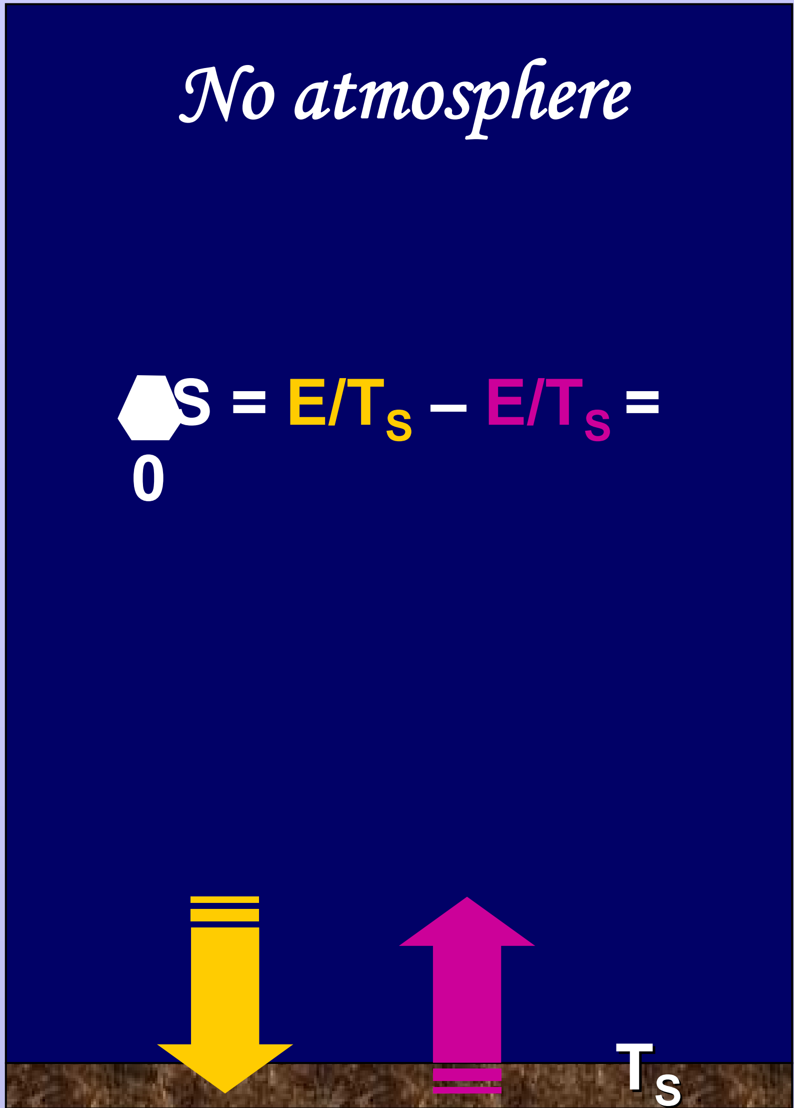
$$\Delta S \geq 0$$

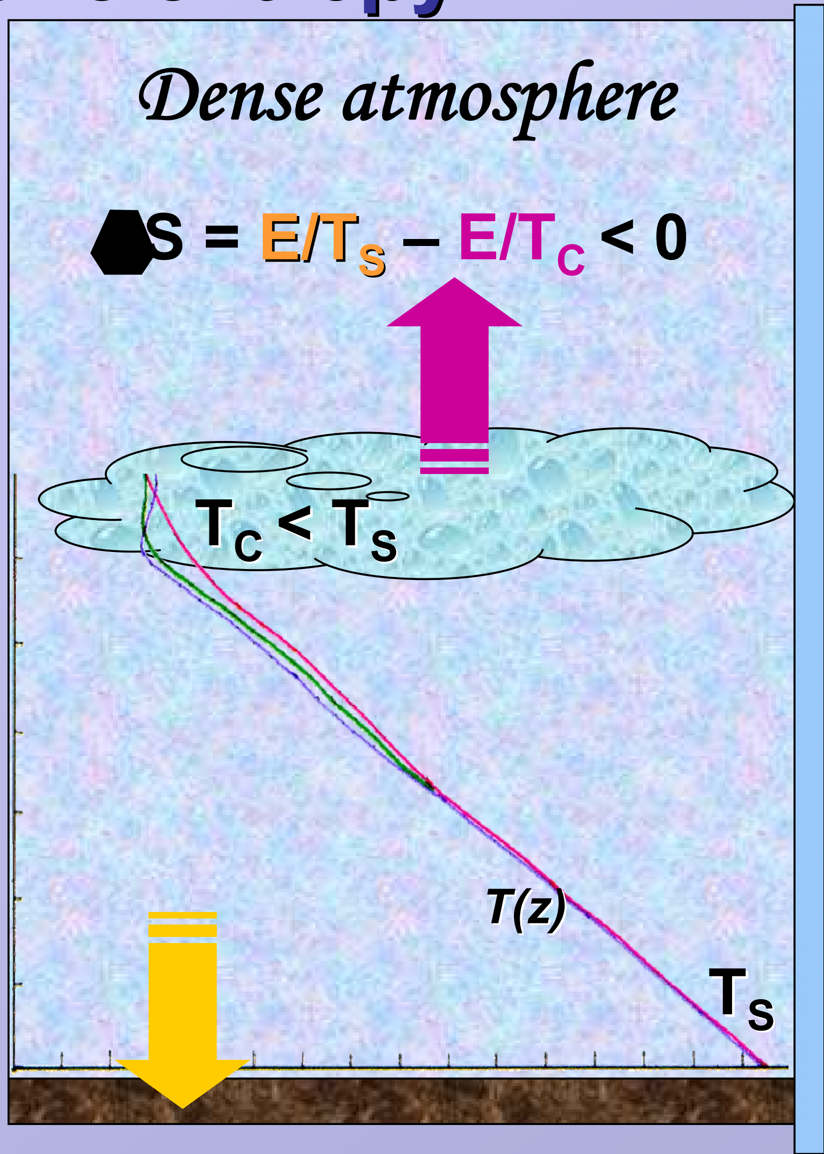
=0 - reversible processes

>0 – irreversible processes

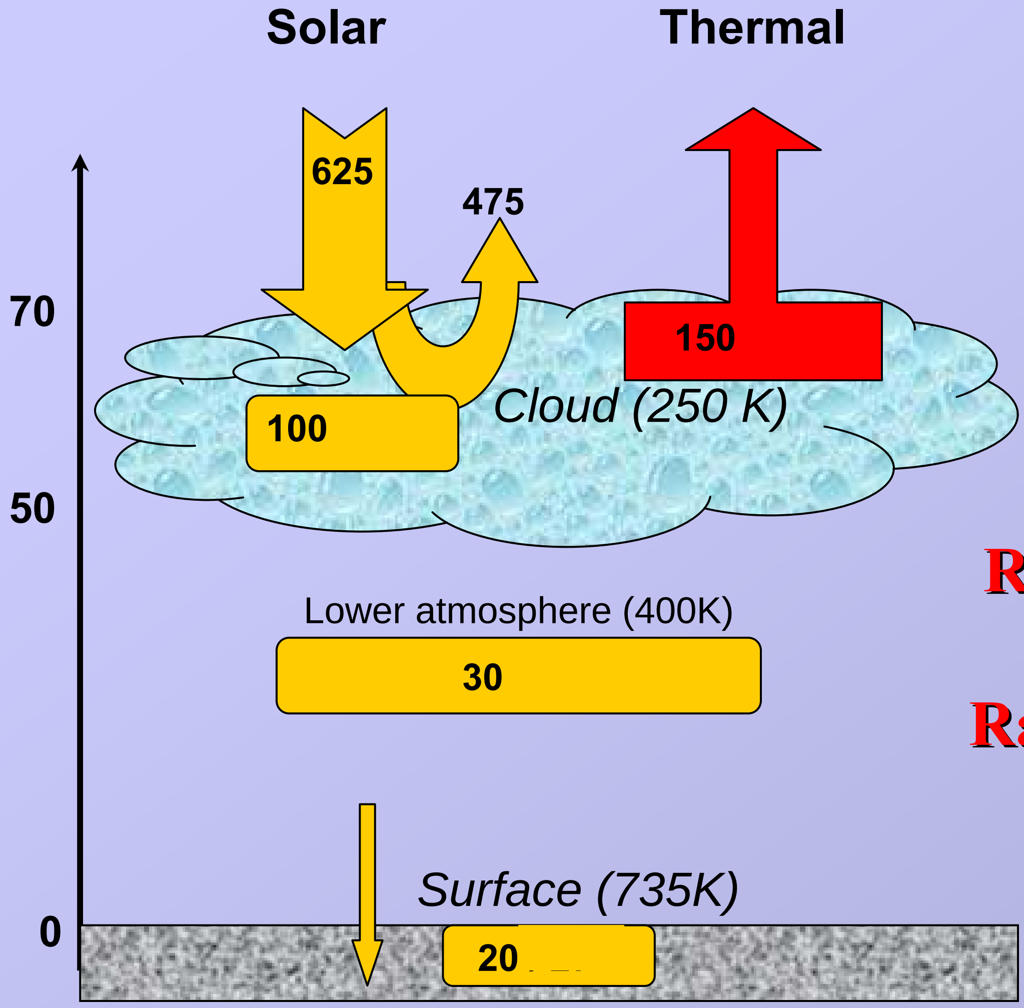
Entropy is a measure of dissipative processes

Flux of radiative entropy





Planet receives negative entropy from the Sun



Radiative Energy / Entropy balance on Venus

Radiative energy balance

$\Delta E \approx 0$

Radiative entropy balance

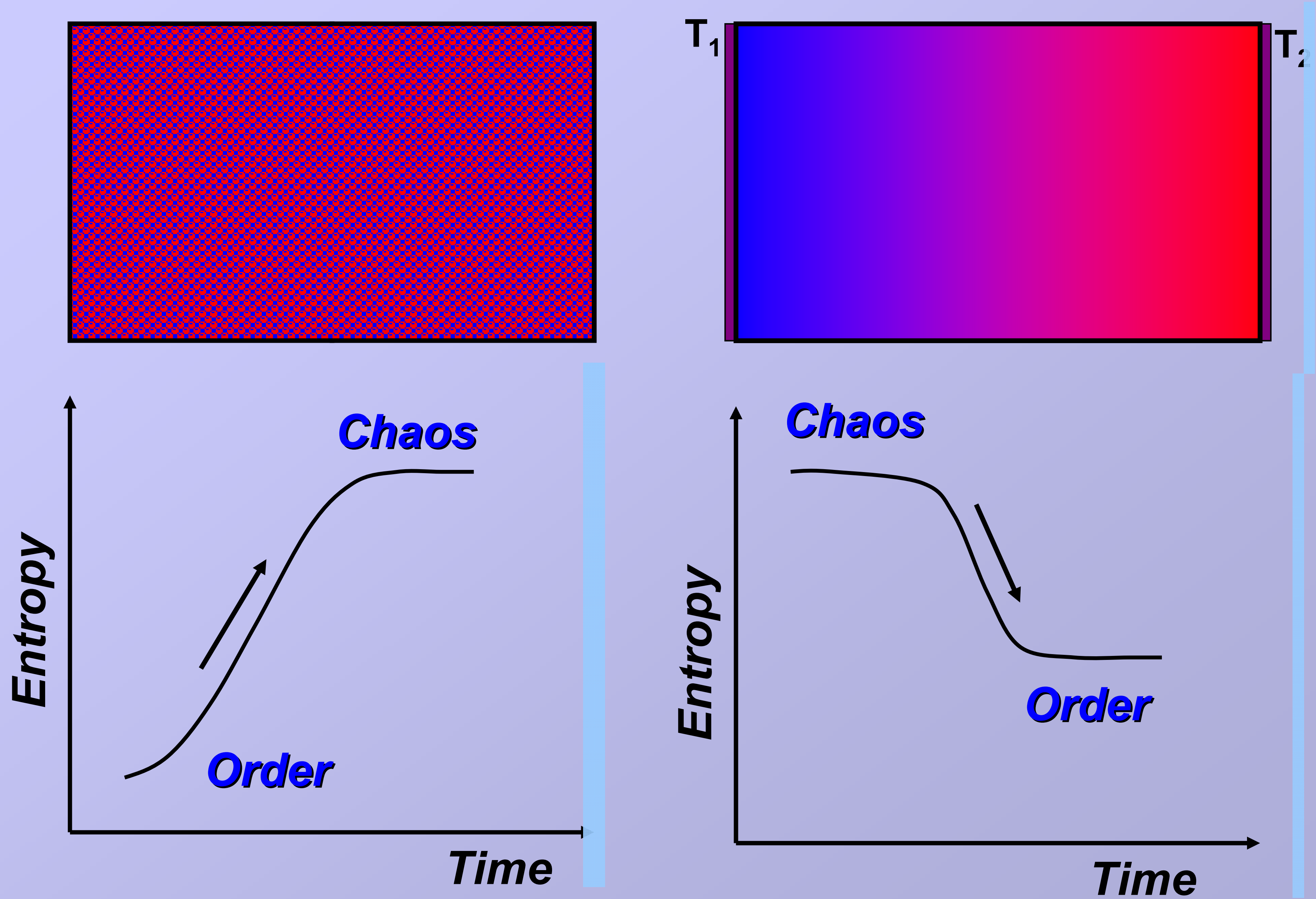
$\Delta S \approx -100\ mW/m^2/K$

Entropy balance on Earth and Venus

	Earth (Goody,2000)	Venus (this work)
Net radiative sink	-70	-100
Moist convection	+55	0
Mechanical dissipation	+12	~1
Net balance	-3	-100

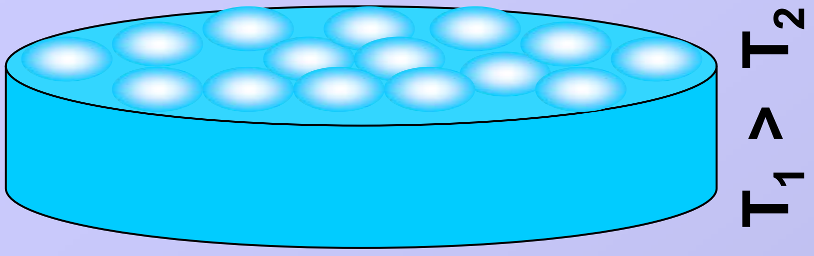
Dissipative processes in the Venus atmosphere - ????

Equilibrium and non-equilibrium thermodynamics

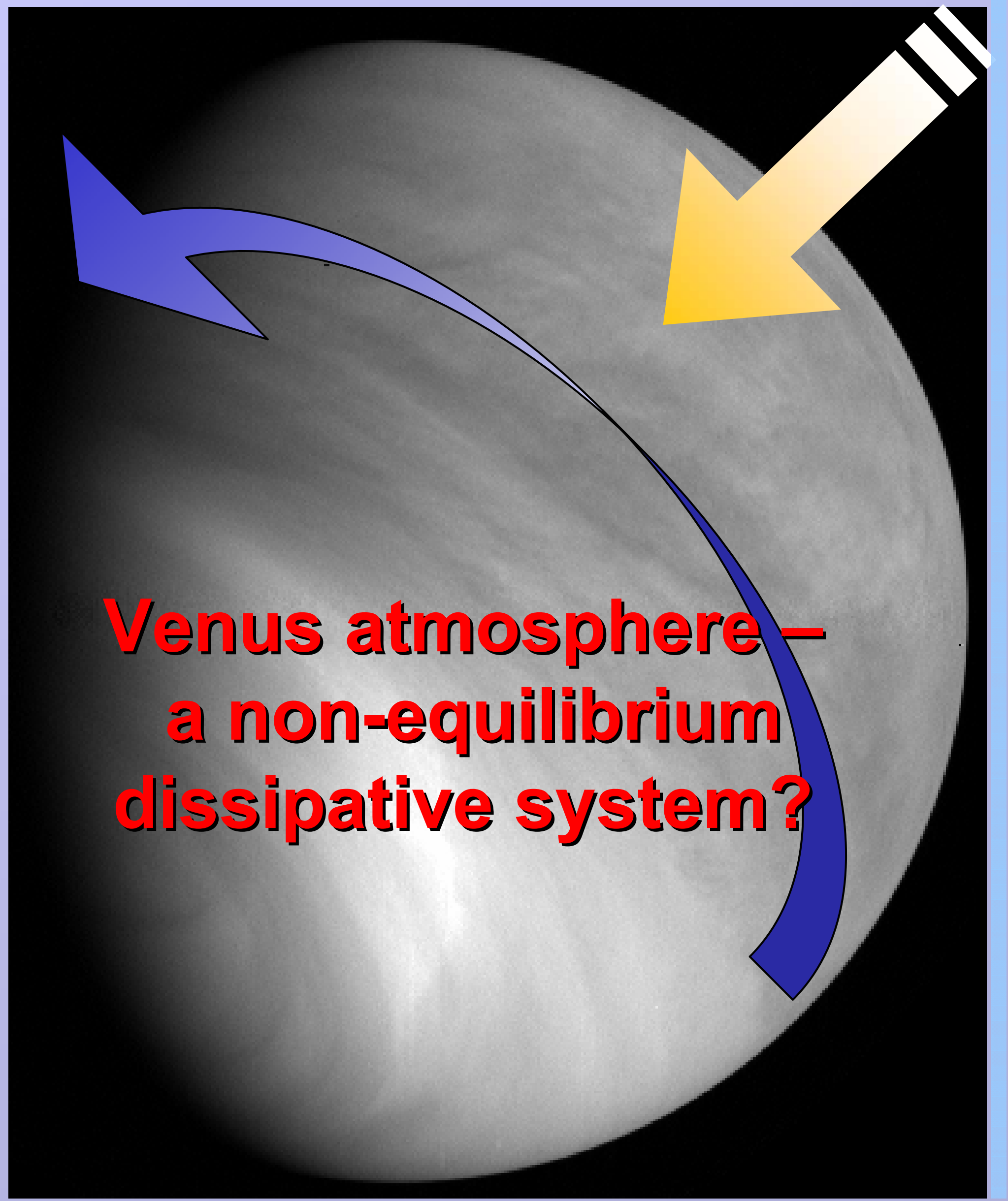


Non-equilibrium dissipative systems

Benard convection

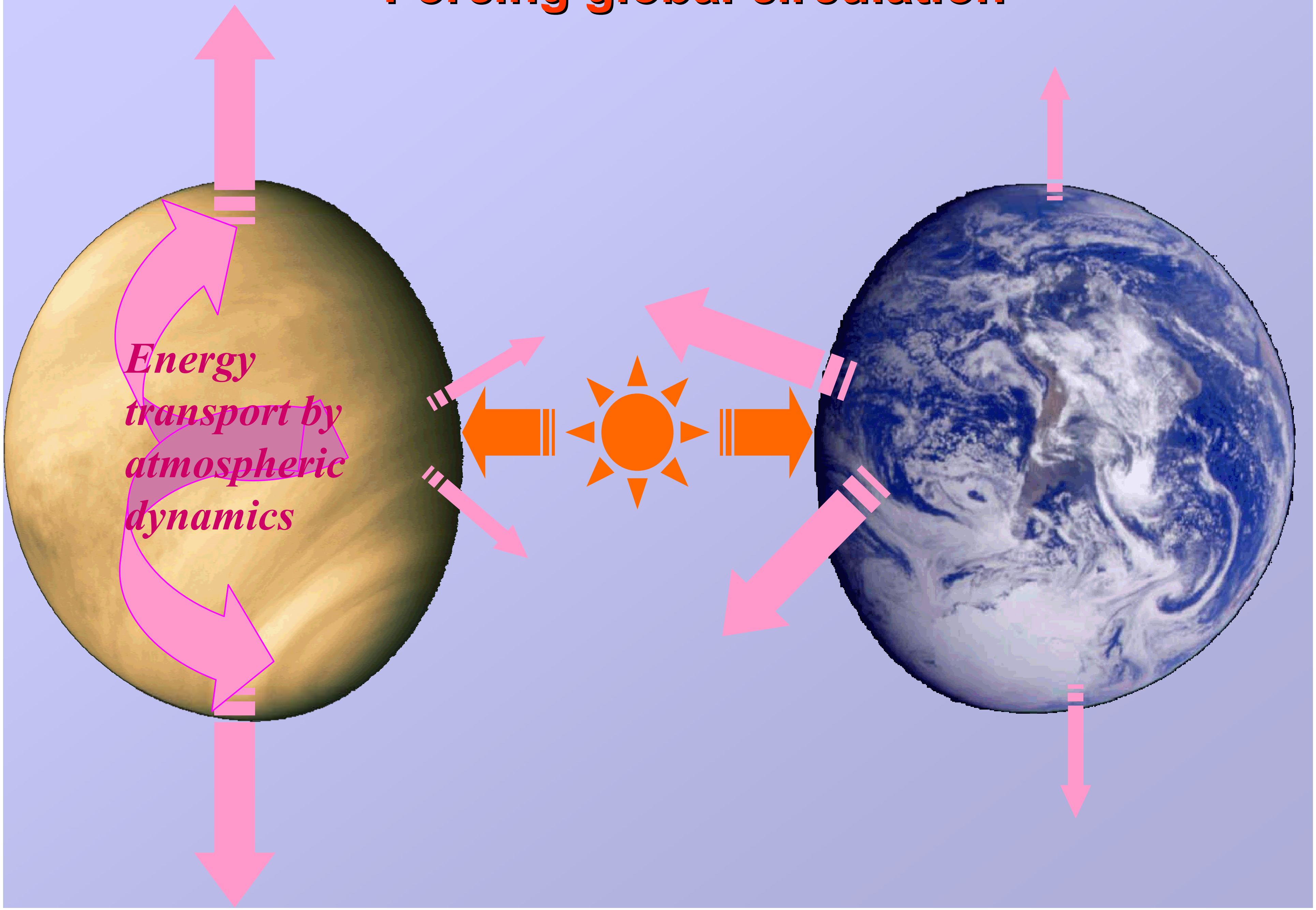


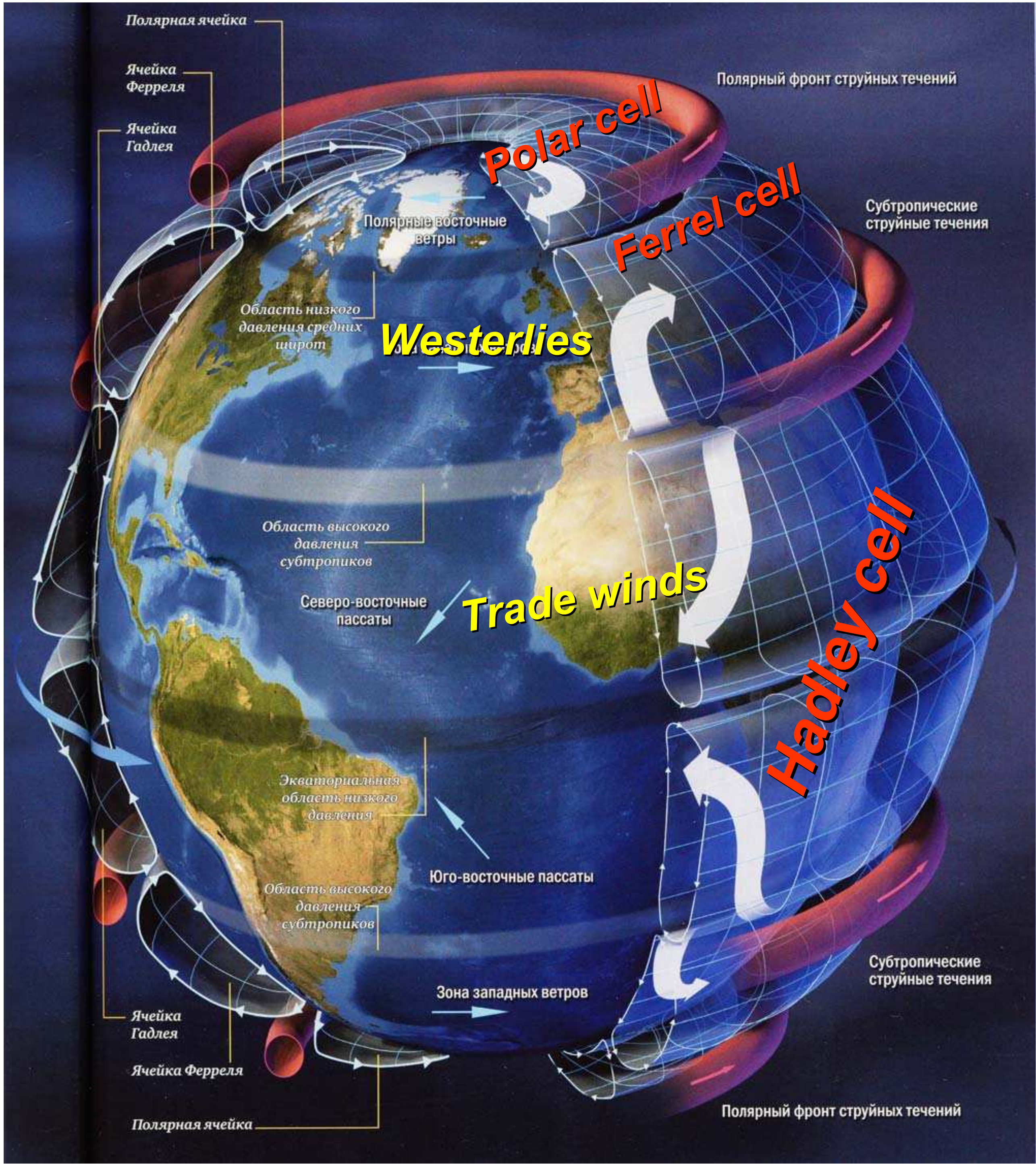
- critical temperature gradient
- high level of order
- high entropy production



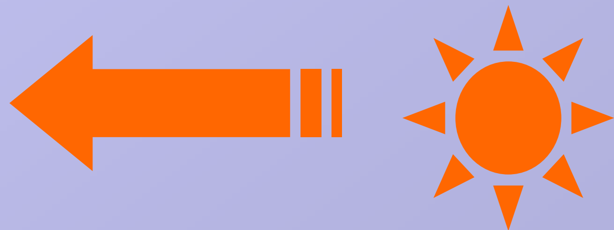
Dynamics of the planetary atmospheres

Forcing global circulation



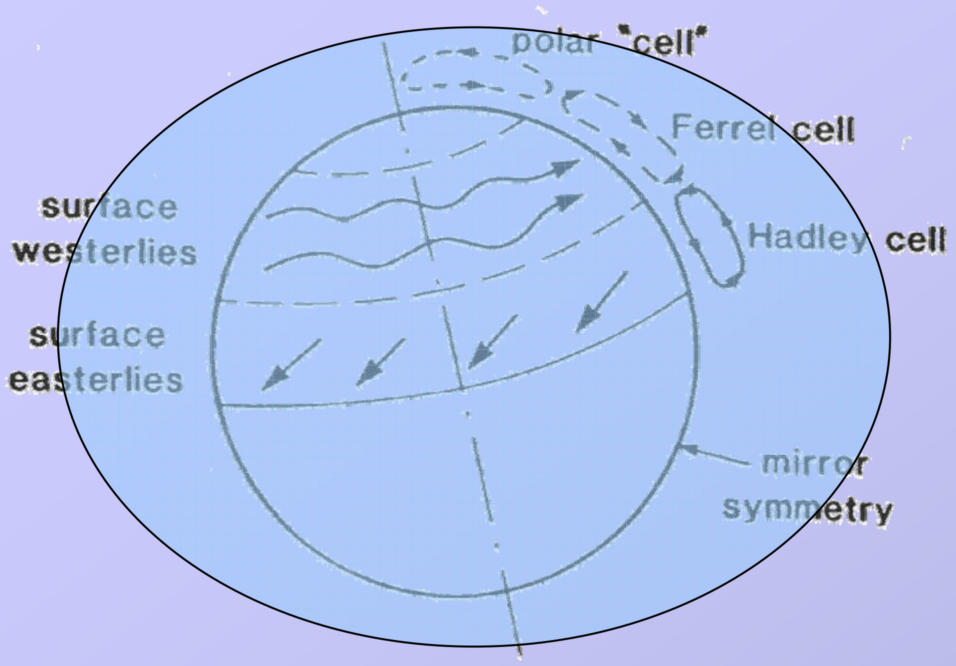


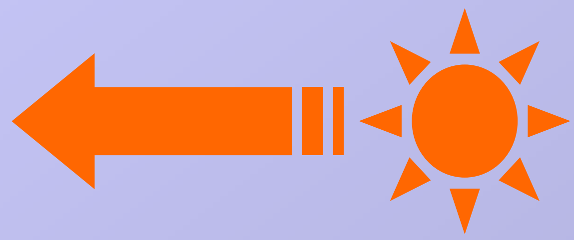
Circulation on Earth



- *Non-rotating planet – one cell per hemisphere*
- *Rotating planet – deflection of meridional winds and split of Hadley circulation into several cells*
- *If planet axis is not normal to ecliptic – Hadley pattern has seasonal behaviour*

Thermal tides

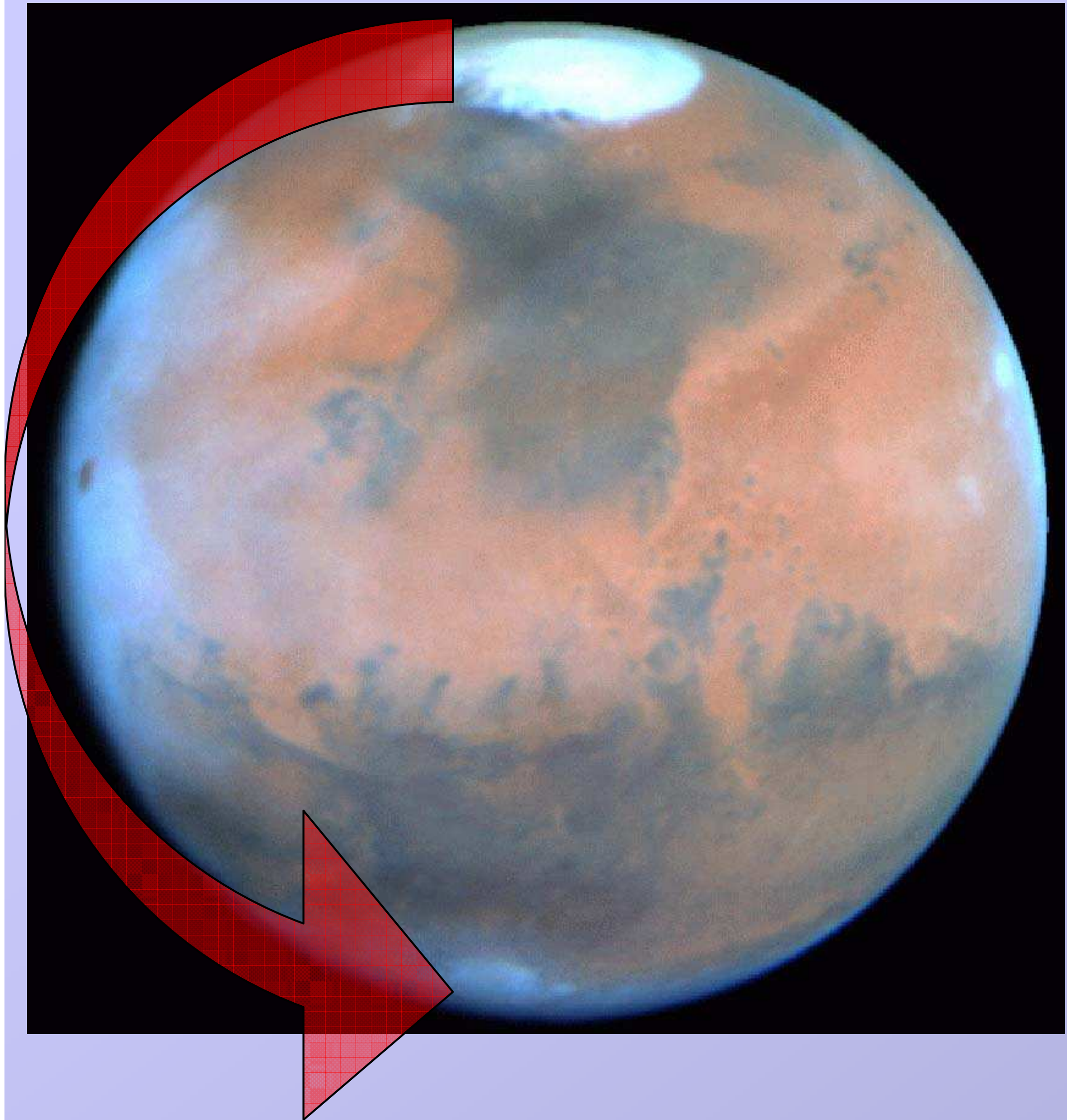




- *Global energy balance*

$$(1-A)Ft_{day} = C_p M \delta T$$

- *$\delta T / T \sim 0.4\%$ for Venus (tides in the thermosphere)*
- *$\delta T / T \sim 20\%$ for Mars (tides in the entire atmosphere)*



Condensation flows

- *Mars: ~20% of the atmosphere is involved (CO_2)*
- *Pluto and Triton : condensation of N_2 and CH_4*

Atmospheric dynamics equations

- *Navier-Stokes equation (inertial frame)*

$$\frac{D\mathrm{v}}{Dt} = -\frac{1}{\rho}\nabla P + g + \nu\nabla^2\mathrm{v}$$

- *Navier-Stokes equation (rotating frame)*

$$\frac{D\mathrm{v}'}{Dt} = -2\omega_{rot} \times \mathrm{v}' - \frac{1}{\rho}\nabla P + (g + \omega_{rot}^2 r) + \nu\nabla^2\mathrm{v}'$$

- *Advective derivative (observer in inertial frame)*

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \mathrm{v}\cdot\nabla$$

Simplified wind equations

- ***Simplifications***
  - ***incompressible and inviscid fluid***

$$\mathrm{v}\cdot\nabla = 0$$

  - ***centrifugal force << gravity***

$$\frac{D\mathrm{v}'}{Dt} = -2\omega_{rot}\times\mathrm{v}' - \frac{1}{\rho}\nabla P + (g + \omega_{rot}^2 r) + \nu\nabla^2\mathrm{v}'$$

$$\begin{cases} \dfrac{du}{dt} = 2\Omega\sin\varphi\cdot v - \dfrac{1}{\rho}\dfrac{dp}{dx} \\ \dfrac{dv}{dt} = 2\Omega\sin\varphi\cdot u - \dfrac{1}{\rho}\dfrac{dp}{dy} \\ \dfrac{dp}{dz} = -\rho g \end{cases}$$

- ***"shallow water" approximation***

$$\frac{\partial P}{\partial z} >> \frac{\partial P}{\partial x}, \frac{\partial P}{\partial y}$$

- ***hydrostatic equilibrium***

$$\frac{\partial P}{\partial z} = -\rho g$$

$$\frac{dV}{dt} = fV\times k - \frac{1}{\rho}\nabla p$$

$f = 2\Omega\sin\varphi$ - Coriolis parameter

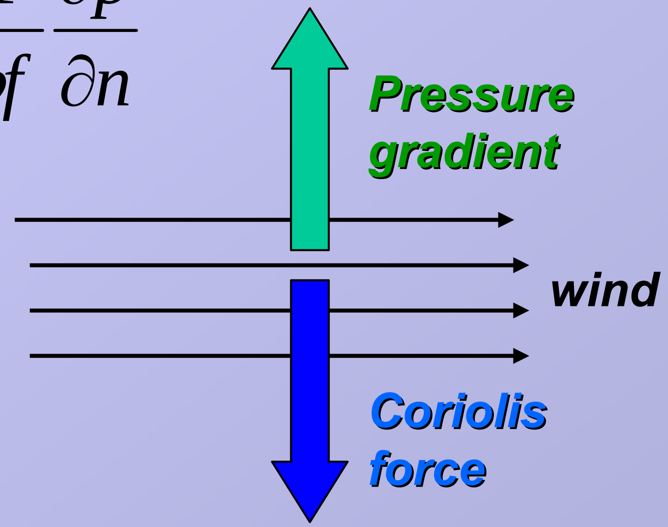
Geostrophic wind

$$\frac{dV}{dt} = fV \times k - \frac{1}{\rho}\nabla p \Rightarrow V = -\frac{1}{\rho f}\frac{\partial p}{\partial n}$$

(the $\frac{dV}{dt}$ term is struck out)

Rossby number

$$Ro = \frac{dV/dt}{fV} = \frac{V}{L\Omega}$$

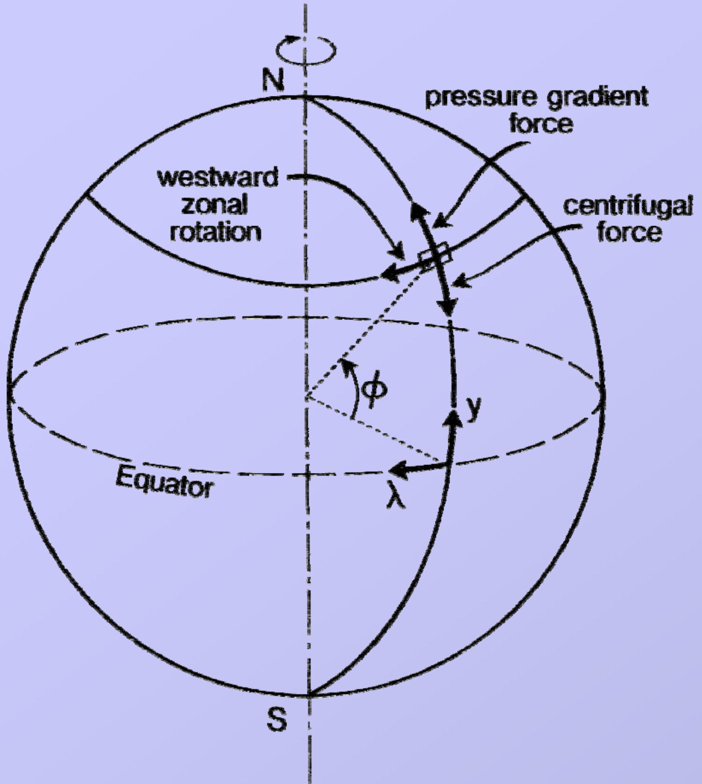


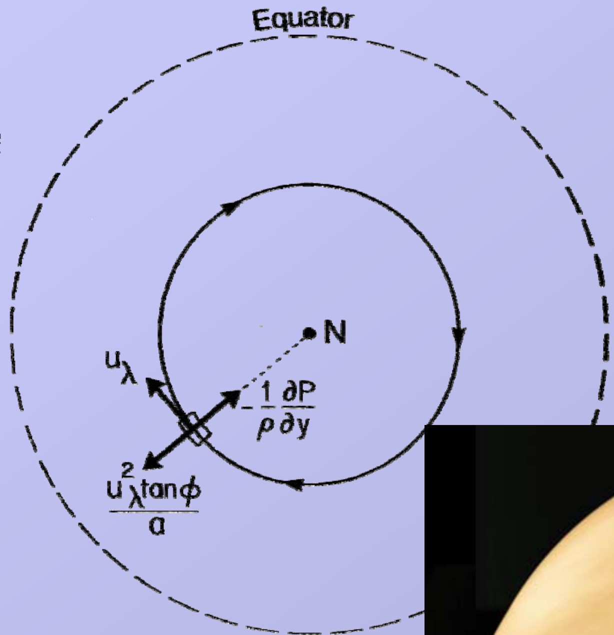
Cyclostrophic wind

$$\frac{dV}{dt} = fV \times k - \frac{1}{\rho}\nabla p \Rightarrow \frac{V^2}{R} = -\frac{1}{\rho}\frac{\partial p}{\partial n}$$

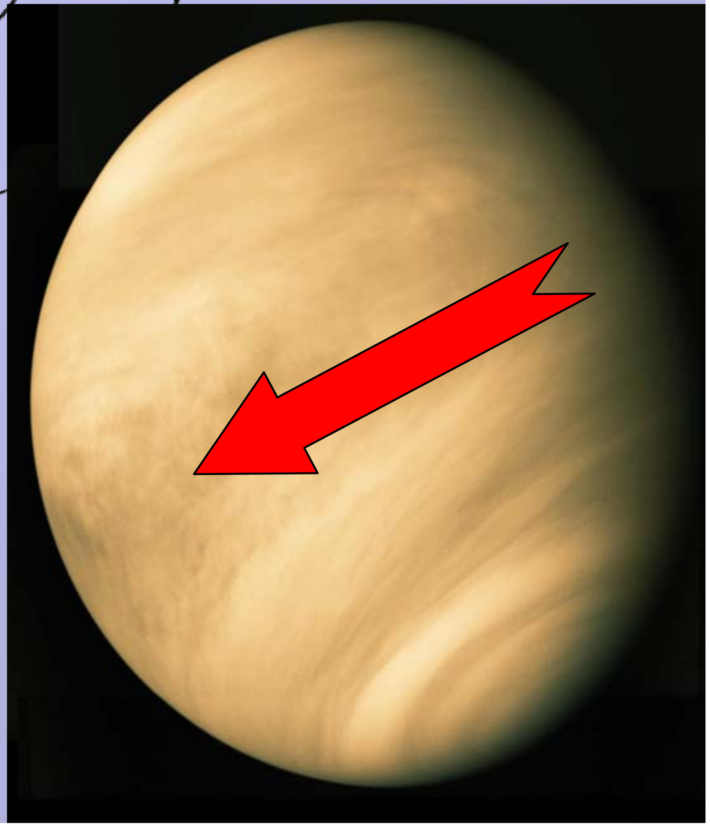
(the $fV \times k$ term is struck out)

Cyclostrophic balance on a slowly rotating planet



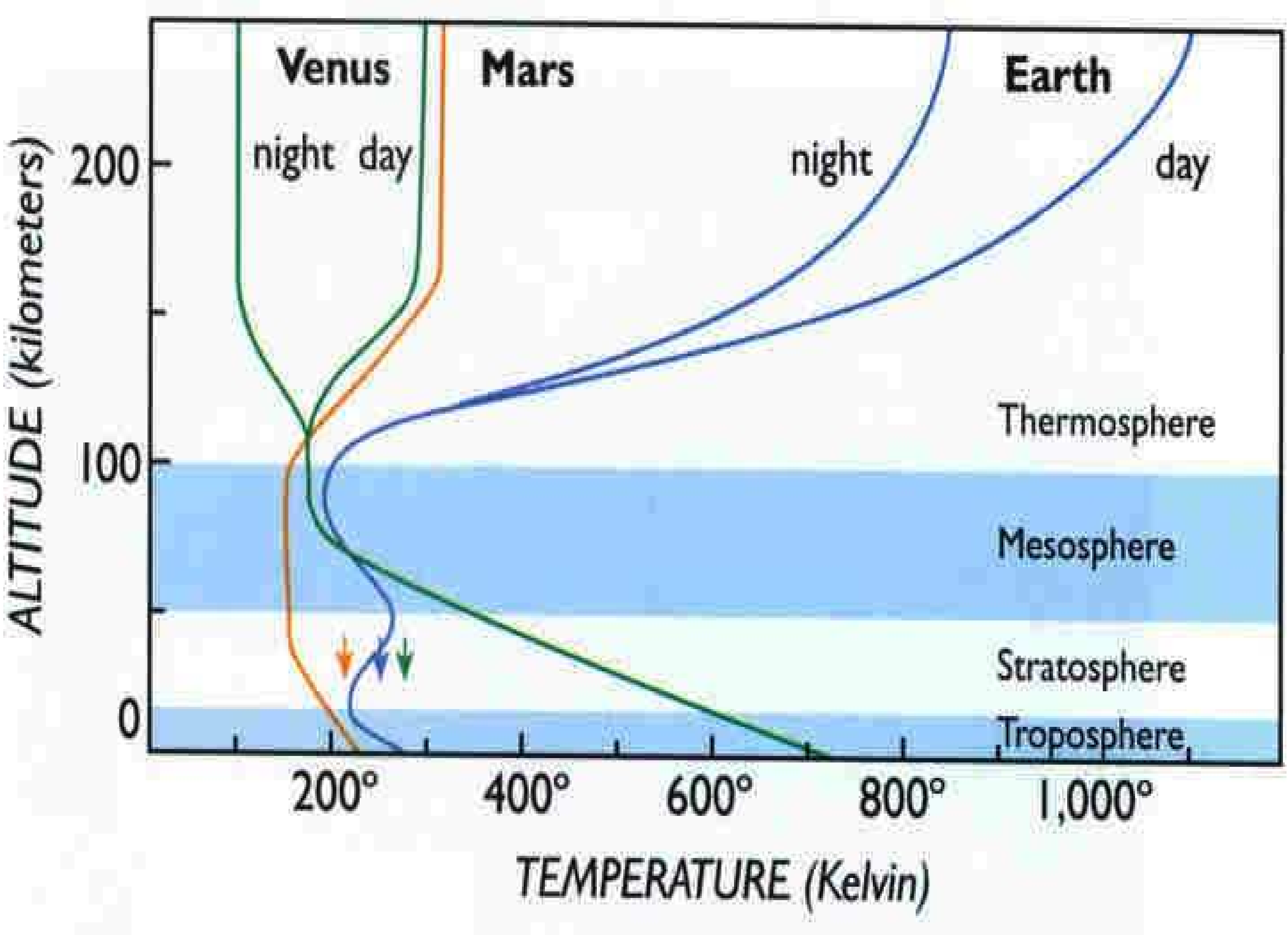


$$\frac{\partial u^2}{\partial z} \approx -\frac{R}{\tan\varphi}\frac{\partial T}{\partial \varphi}$$



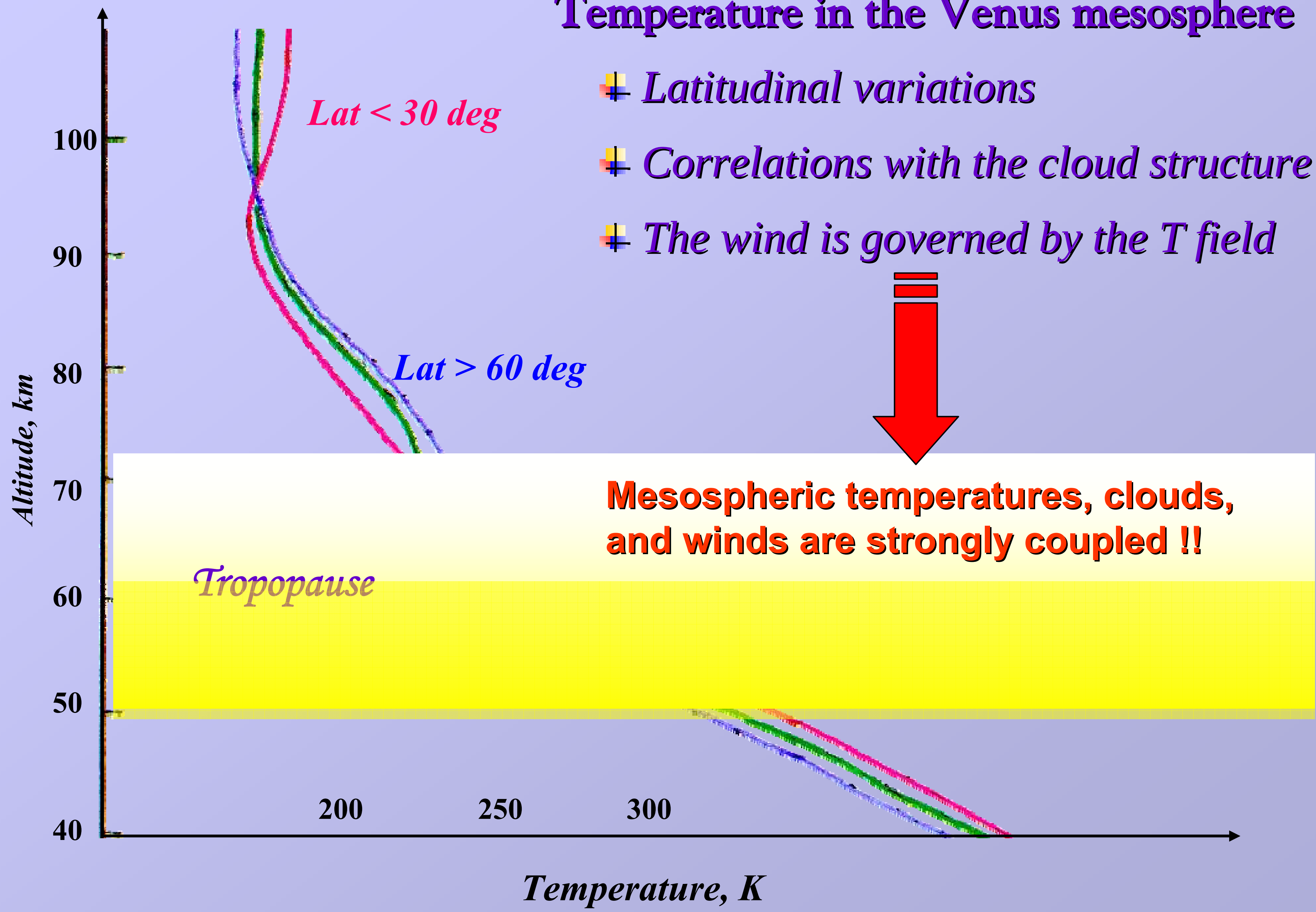
Venus

Temperatures on terrestrial planets



Temperature in the Venus mesosphere

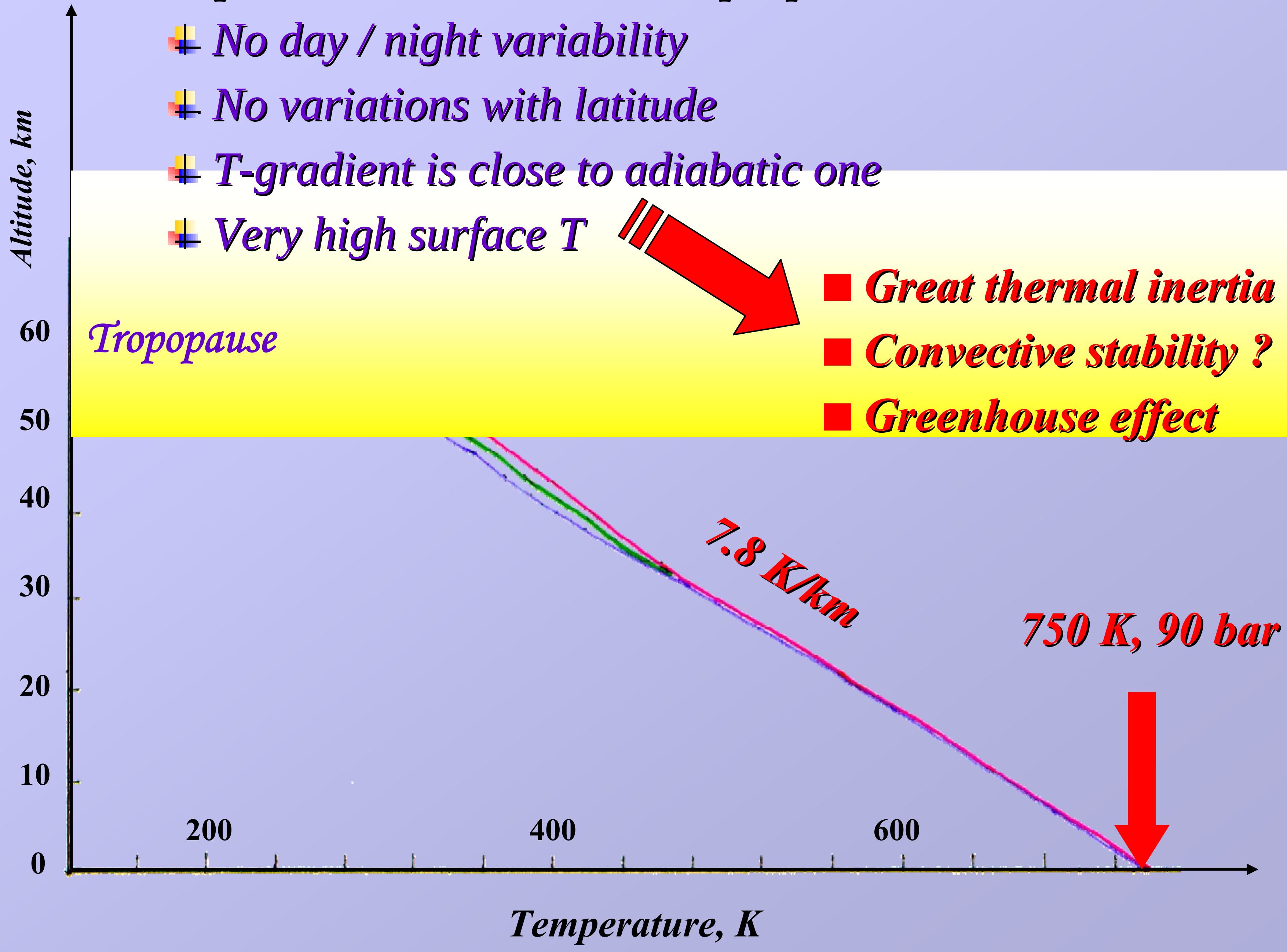
- *Latitudinal variations*
- *Correlations with the cloud structure*
- *The wind is governed by the T field*



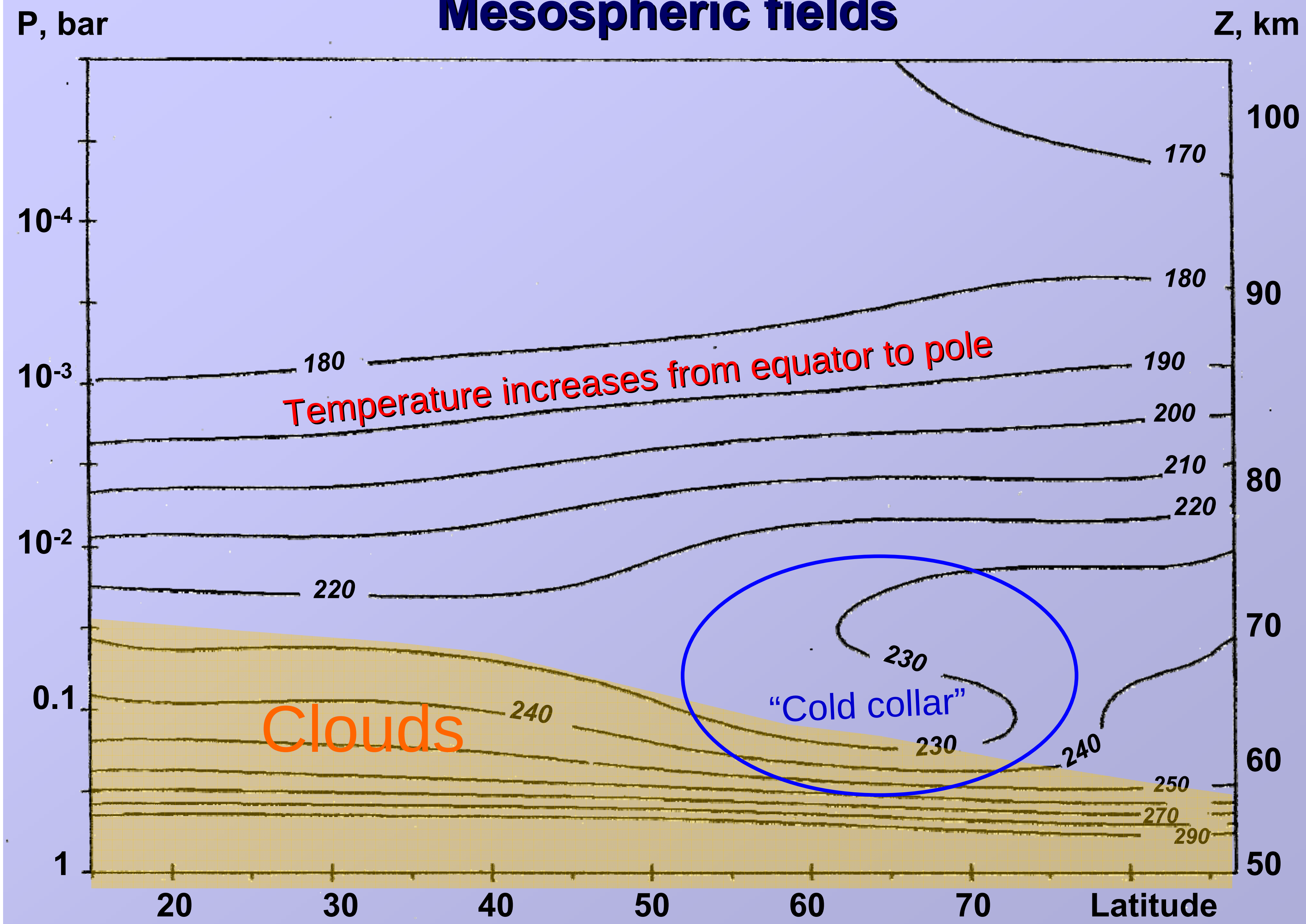
Mesospheric temperatures, clouds, and winds are strongly coupled !!

Temperature in the Venus troposphere

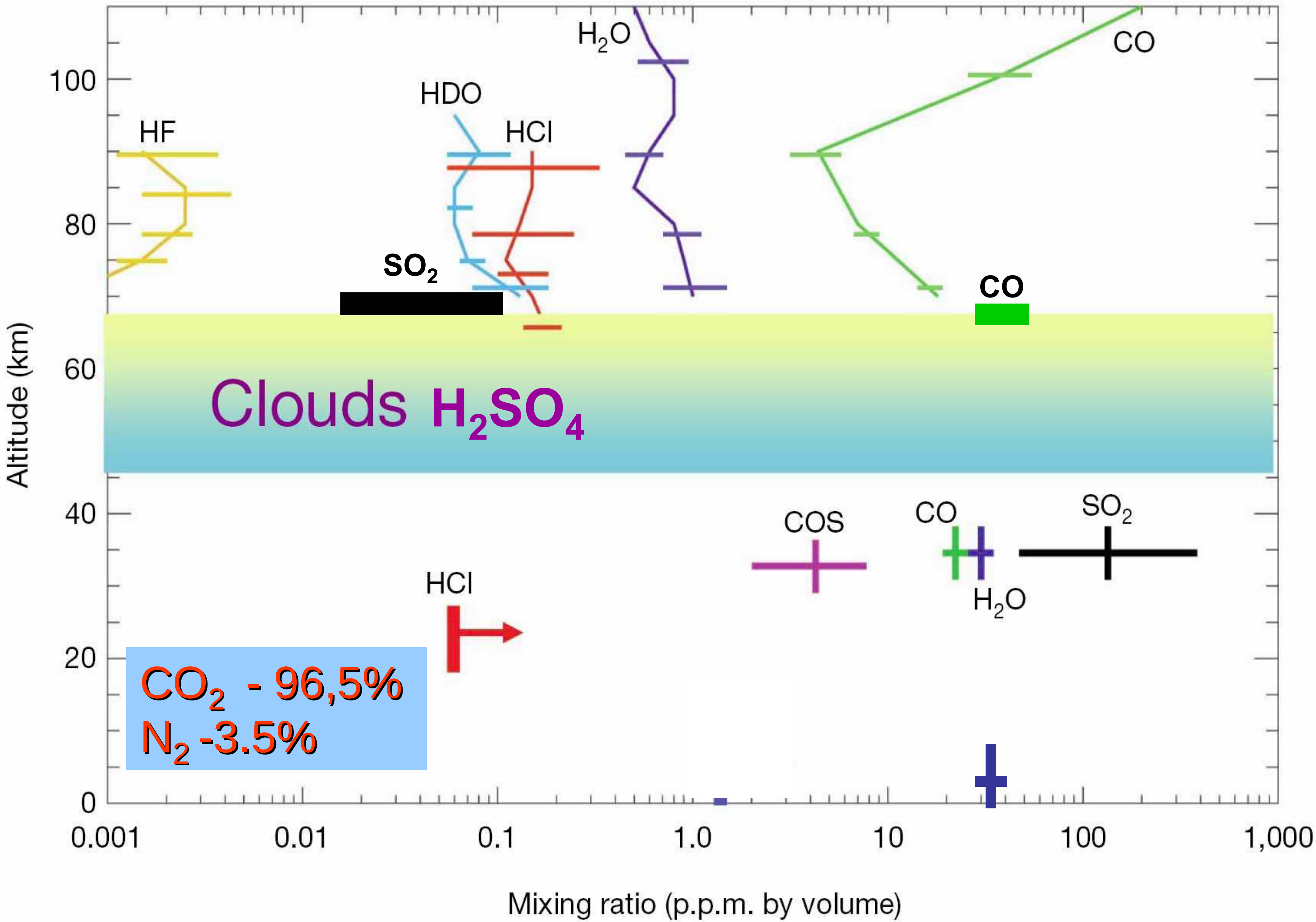
- *No day / night variability*
- *No variations with latitude*
- *T-gradient is close to adiabatic one*
- *Very high surface T*



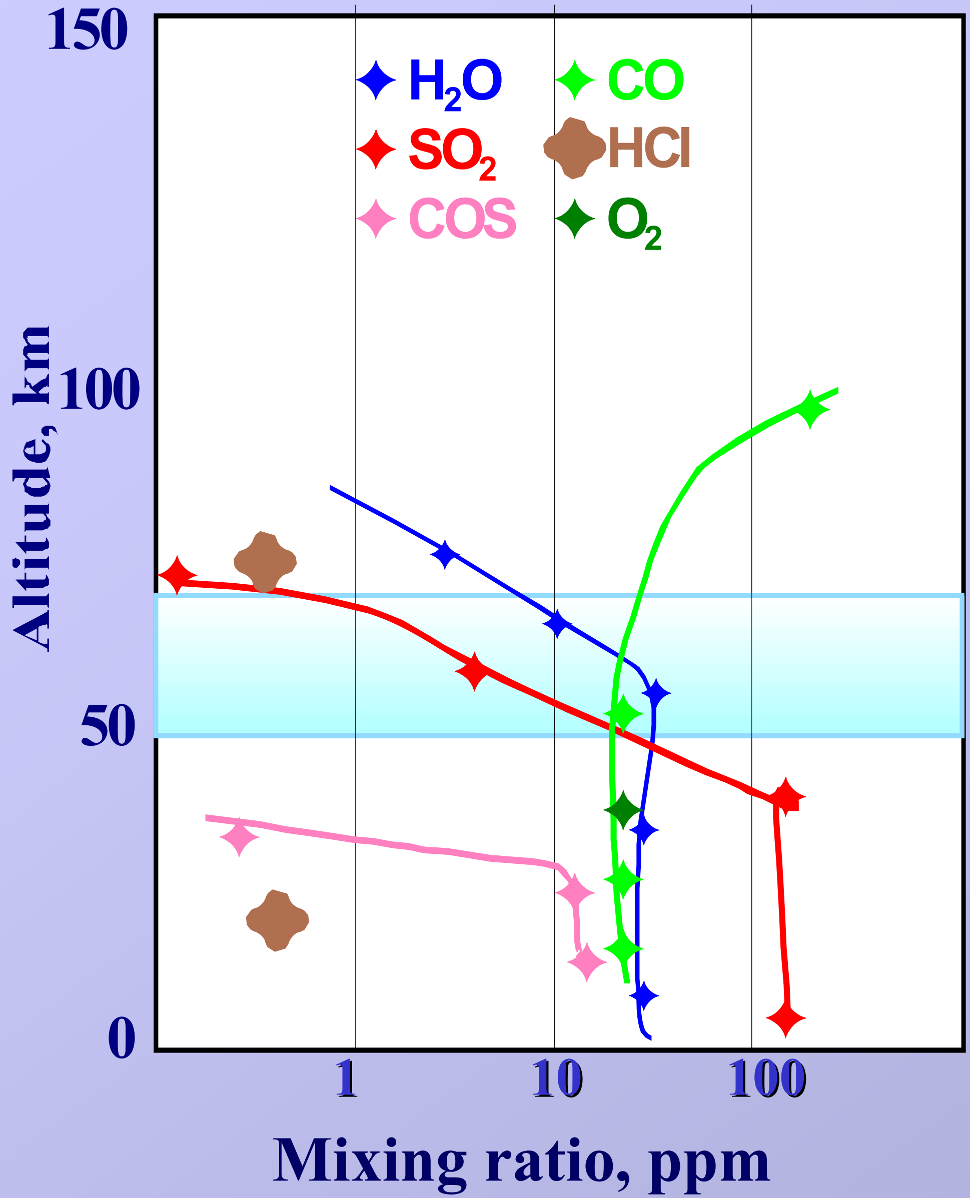
Mesospheric fields



Composition of the Venus atmosphere



Composition of the Venus atmosphere

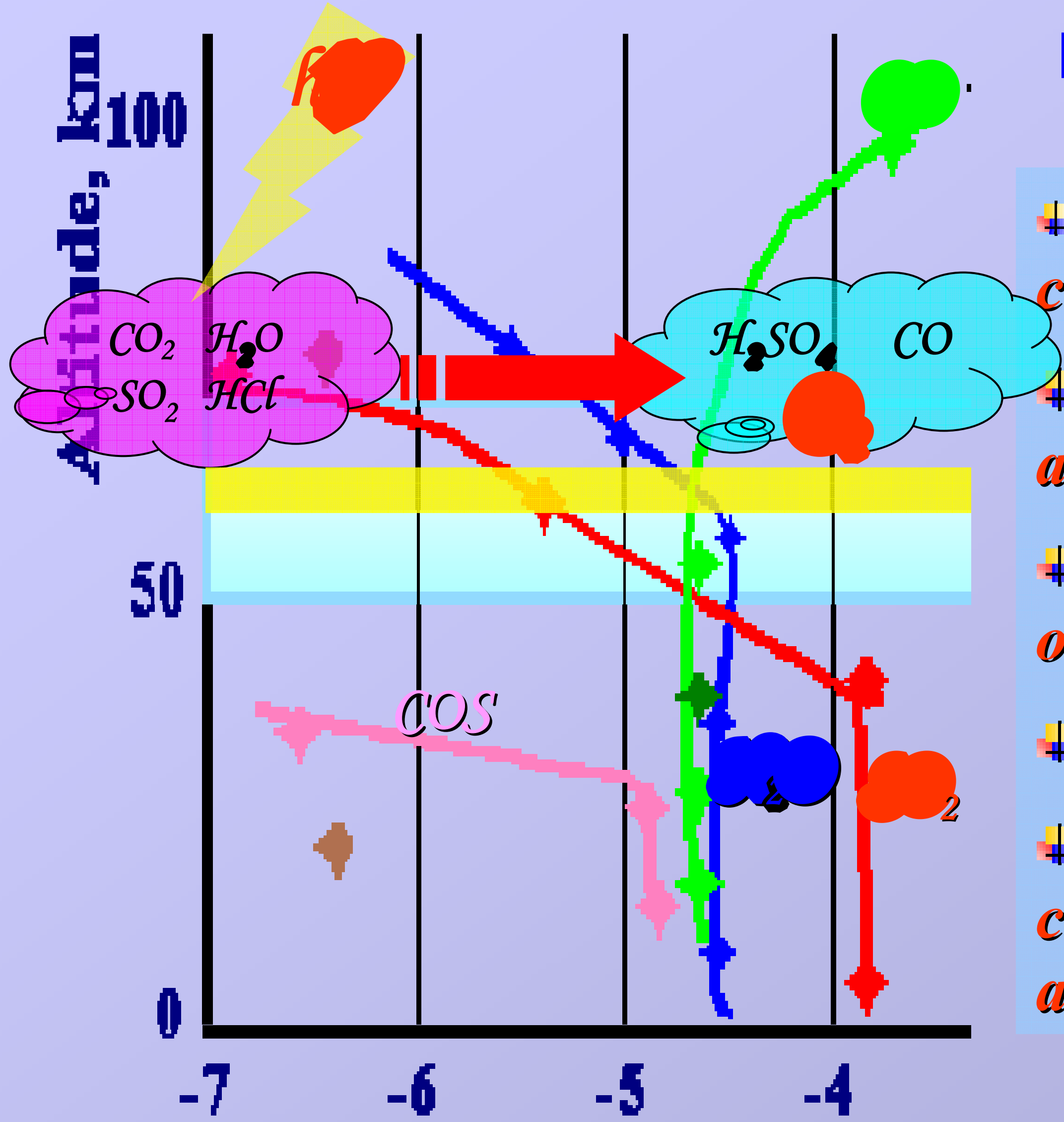


- **Main gases:**

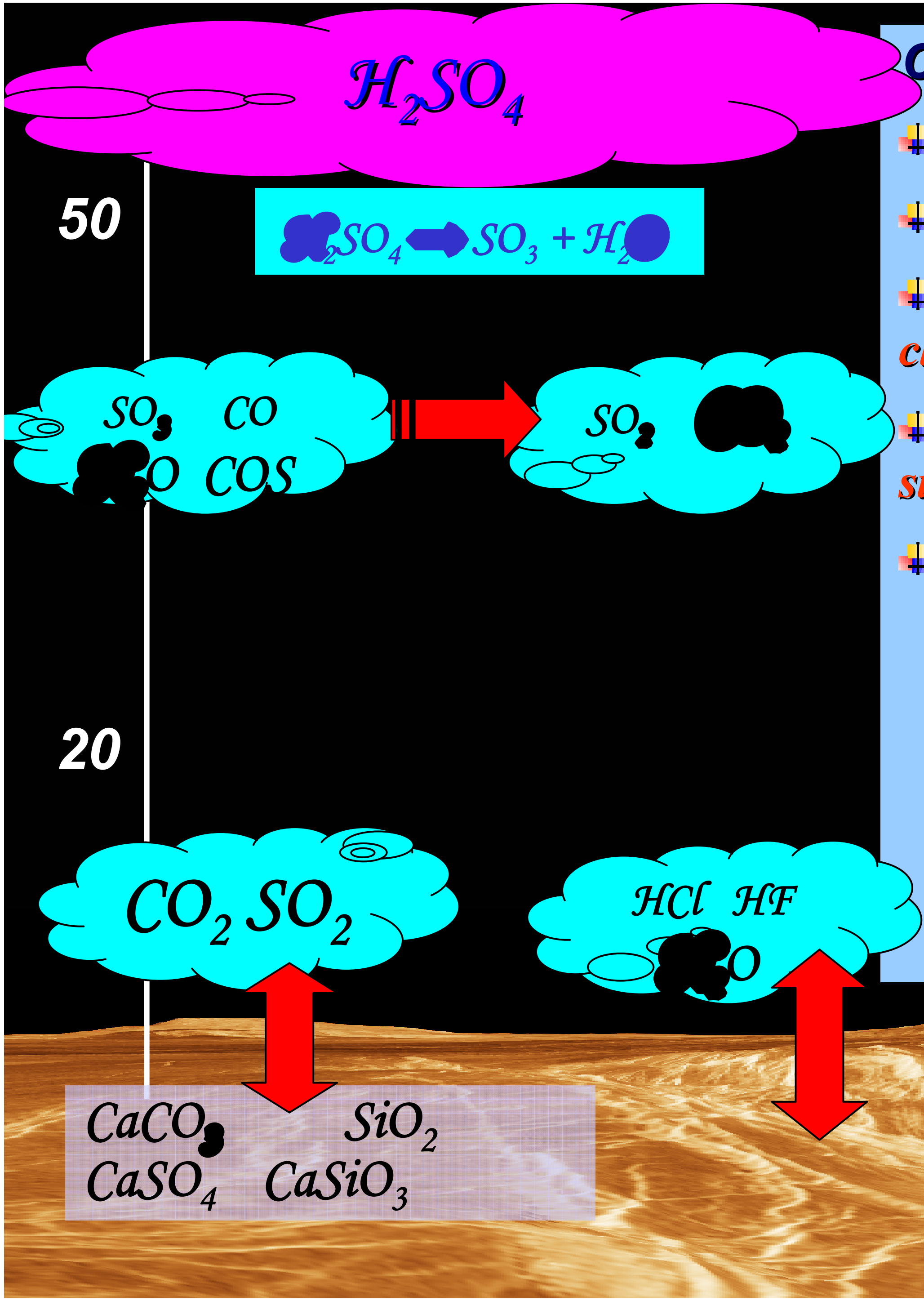
  CO_2 (96,5%), N_2 (3.5%)

- ***Sulfur bearing gases***
  - ***SO_2 : 0.1 – 200 ppm***
  - ***COS: ~ 20 ppm < 30 km***
  - ***H_2S: ~2 ppm***
- ***CO: 300 – 30 ppm***
- ***H_2O: 1 – 20 ppm***
- ***HCl: ~ 0.4 ppm***

Mesospheric Photochemical Factory

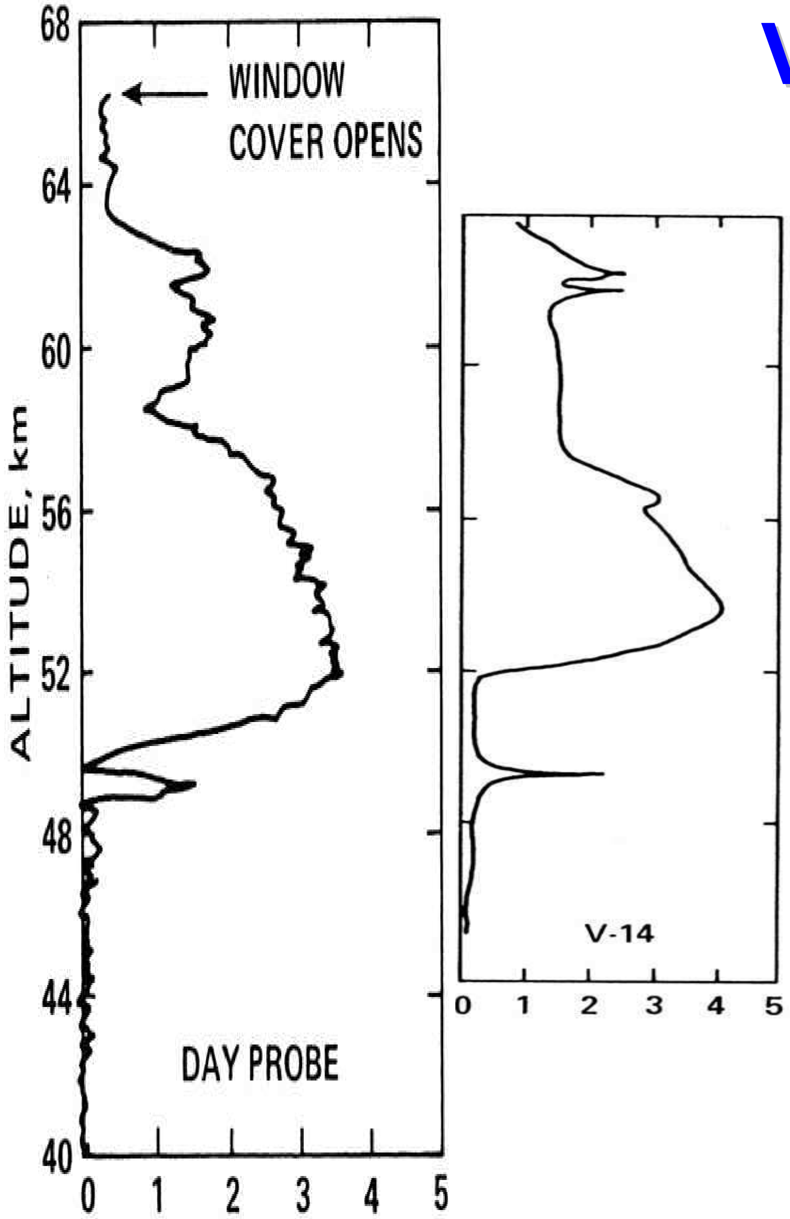


- SO_2 and H_2O profiles at the cloud tops
- Formation of the H_2SO_4 aerosols
- Models do not explain observed amount of O_2
- Unknown UV absorber
- Chlorine and sulfur chemistry in the Earth atmosphere



Chemistry of the lower Atmosphere

- *High temperatures and pressure*
- *No photochemistry*
- *Chemical disequilibrium except very close to the surface*
- *Buffering of the atmospheric composition by the surface*
- *Open questions*
  - *surface composition*
  - *CO and O_2 at the surface*
  - *too high SO_2 abundance*
  - *volcanism replenishes SO_2*

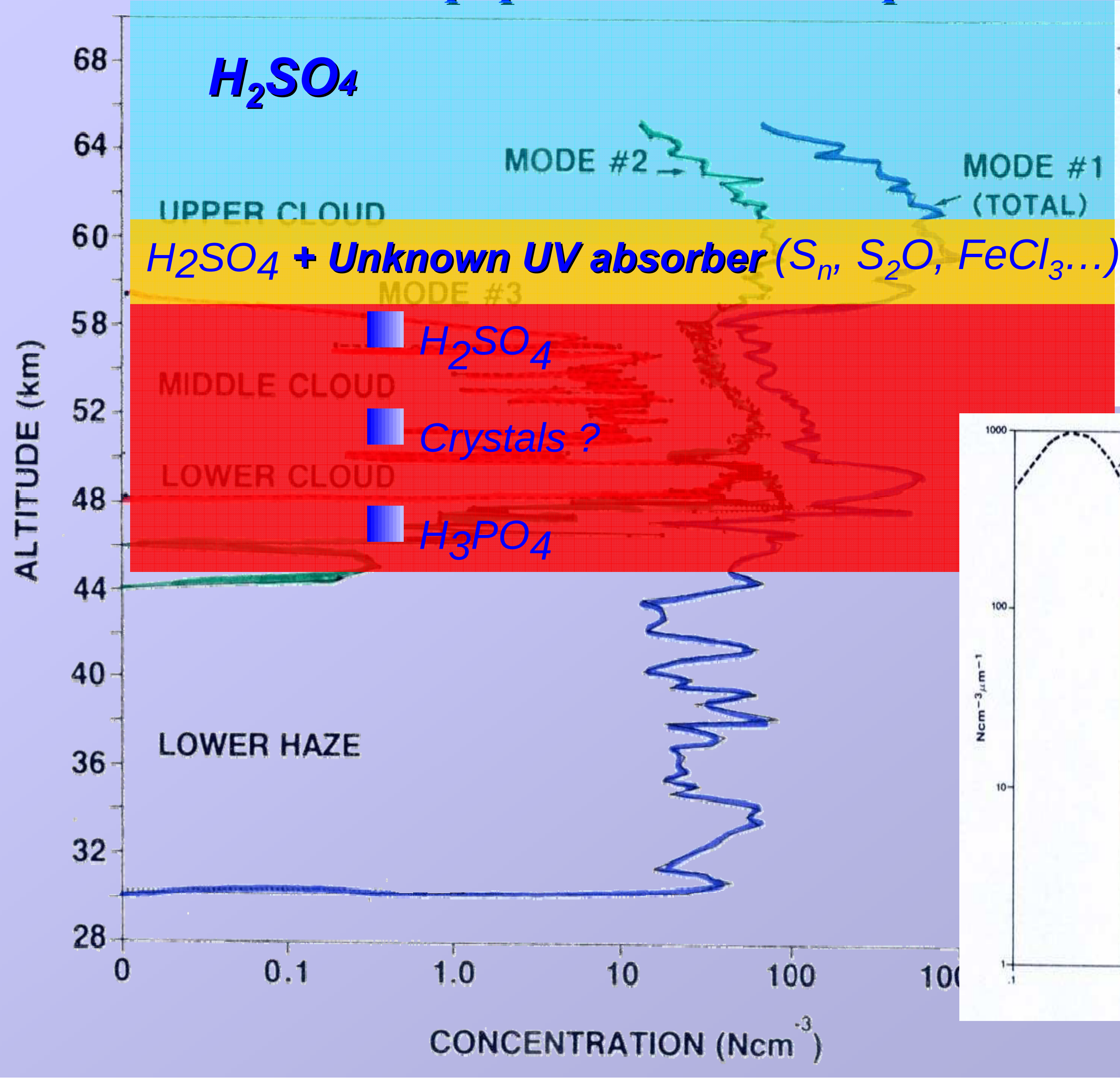


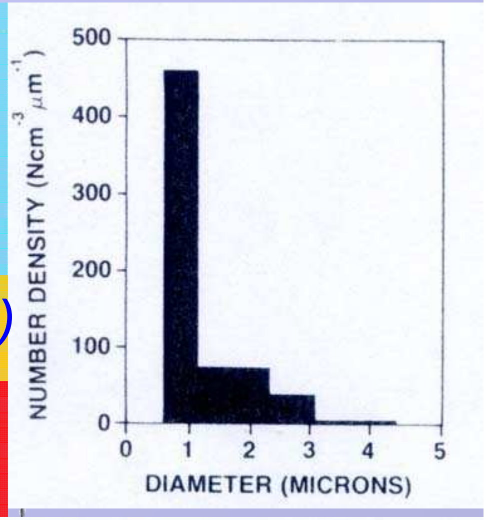
Aerosol extinction, km^{-1}

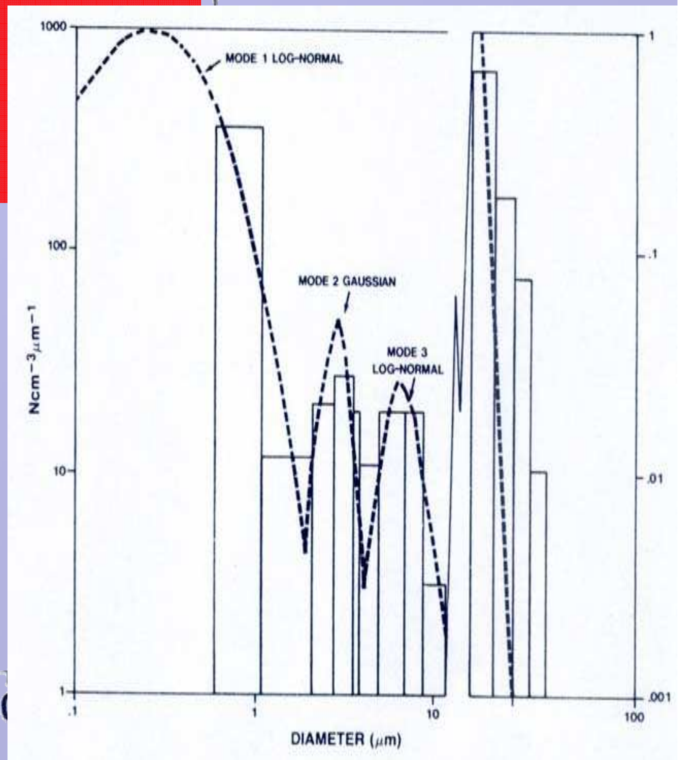
Venus Cloud Properties

- *Visibility > 300 m*
- *Altitude range 75 – 45 km*
- *Total opacity 20-40*
- *Particles:*
  - *R = 1-10 μm*
  - *N = 100-1000 cm^{-3}*
- *Composition:*
  - *H_2SO_4 + ? (S_n, $AlCl_3$, H_3PO_4, …,*

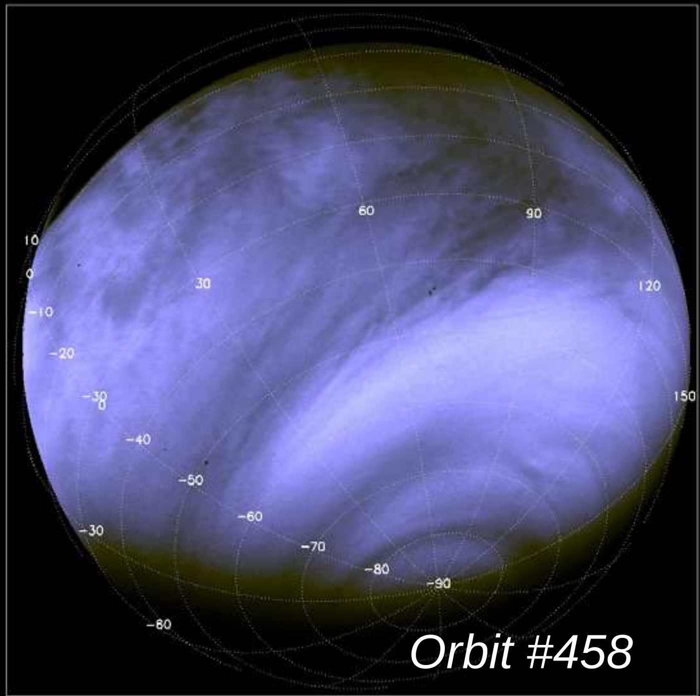
Aerosol population and composition



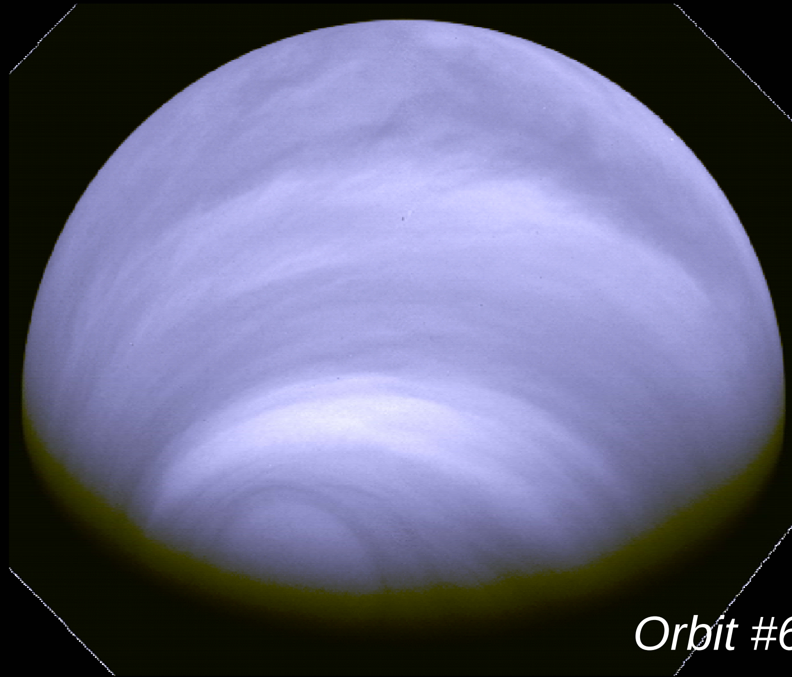




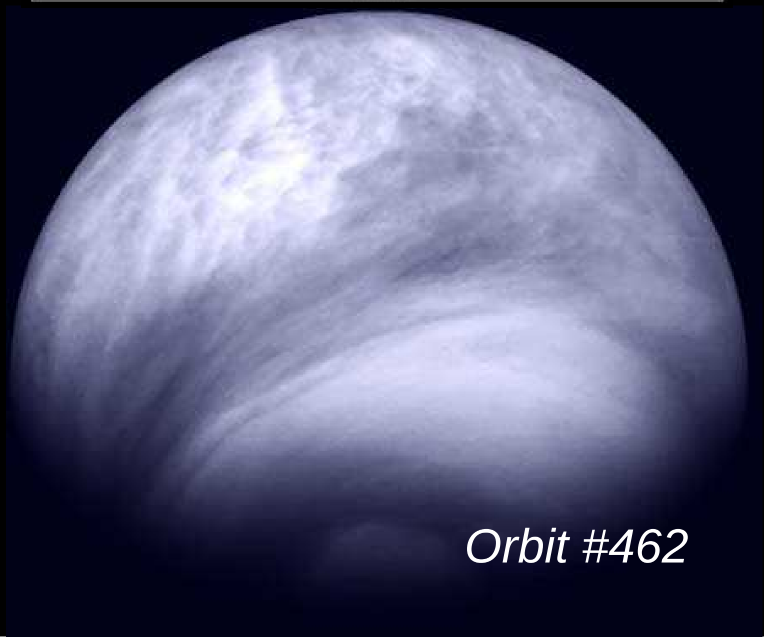
Cloud morphology: Global UV view



Orbit #458



Orbit #673



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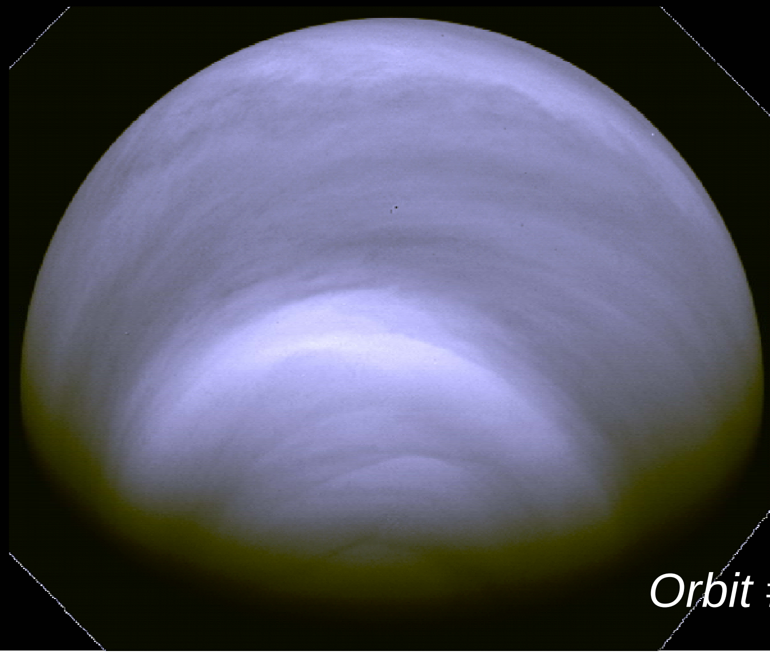
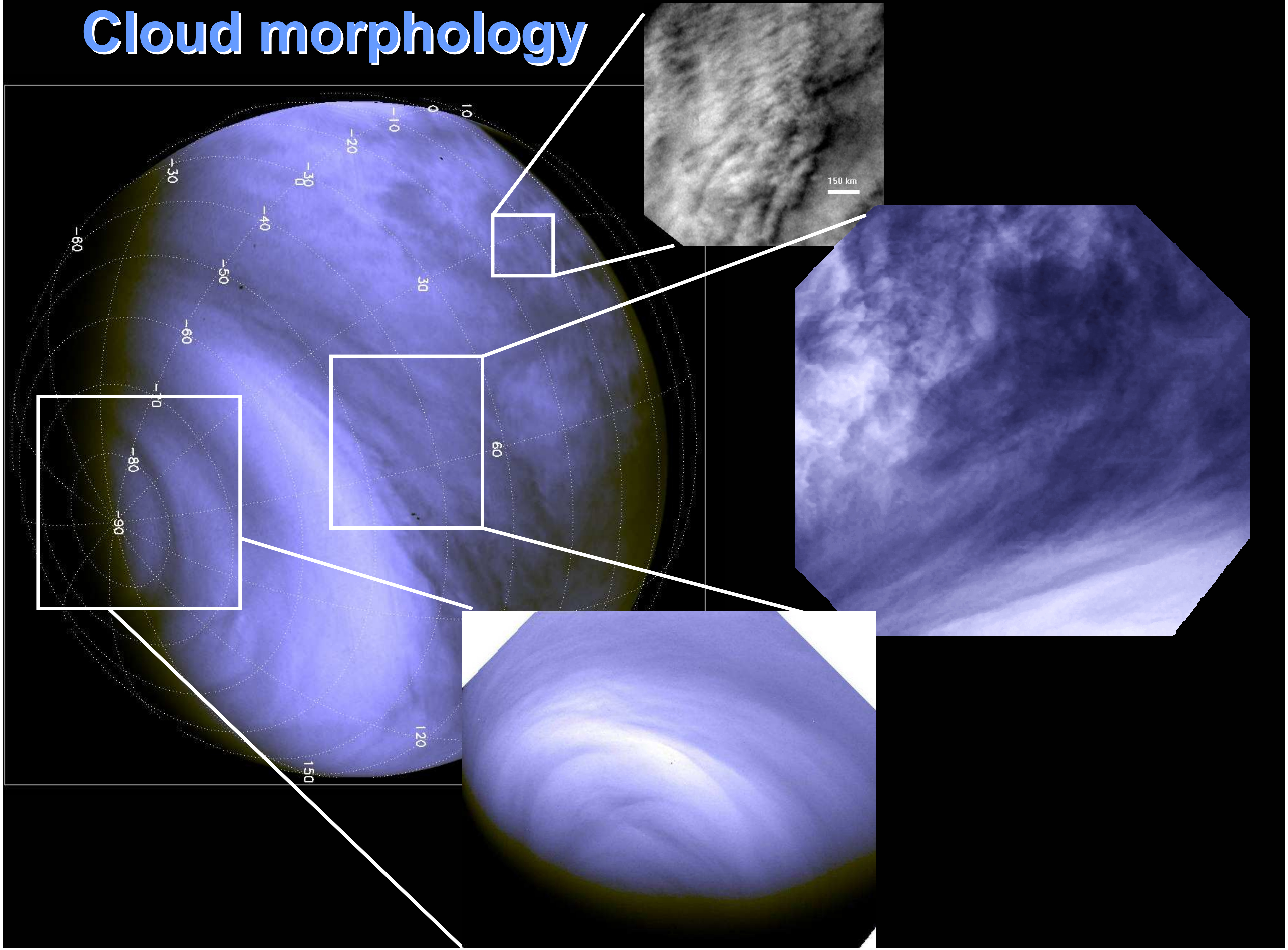
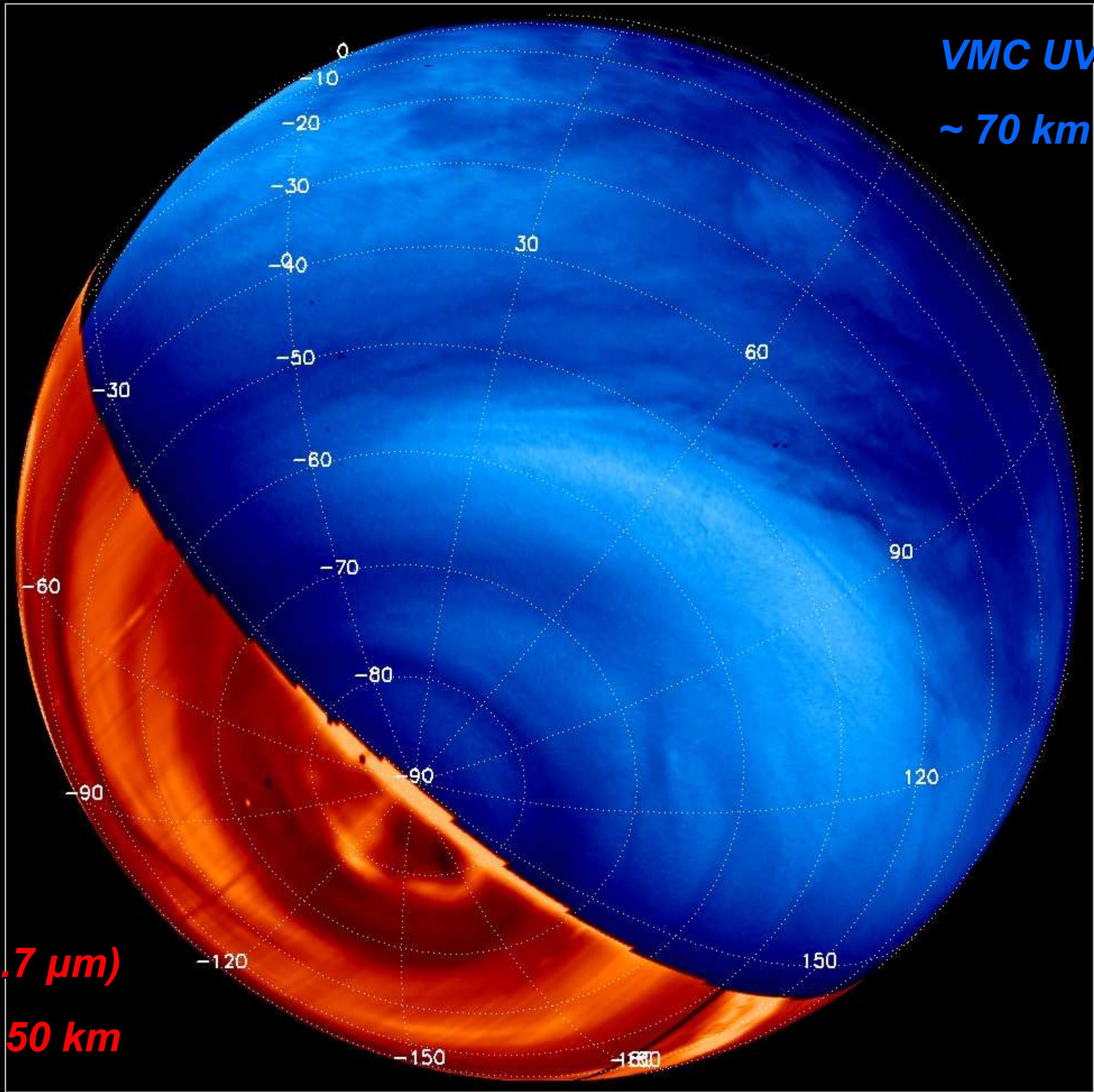


Orbit #679

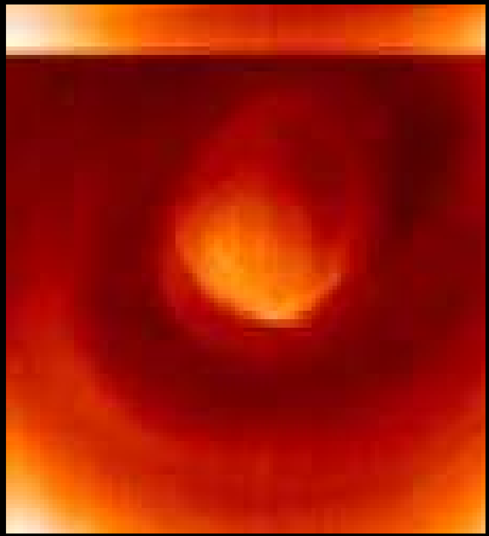
Cloud morphology



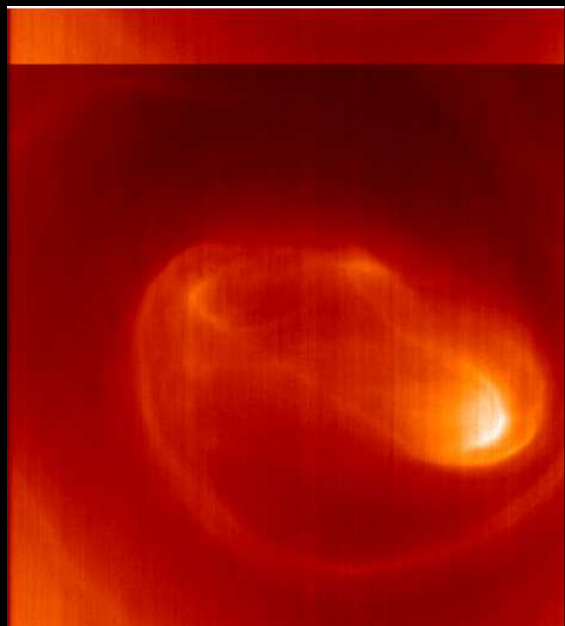
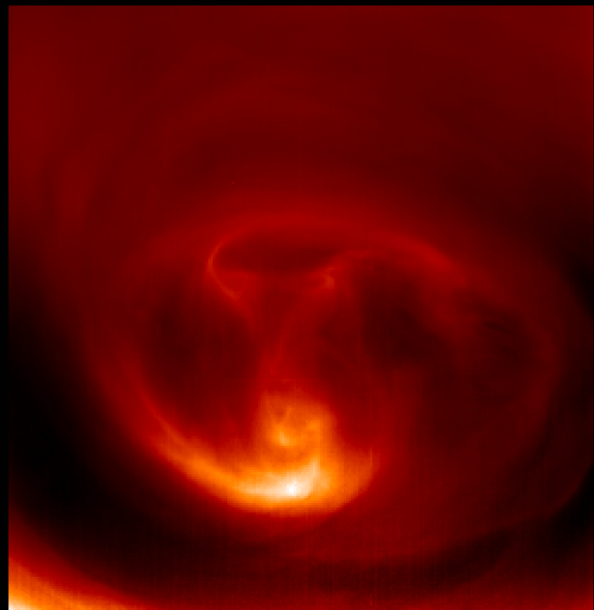
Global cloud morphology



Eye of the polar vortex

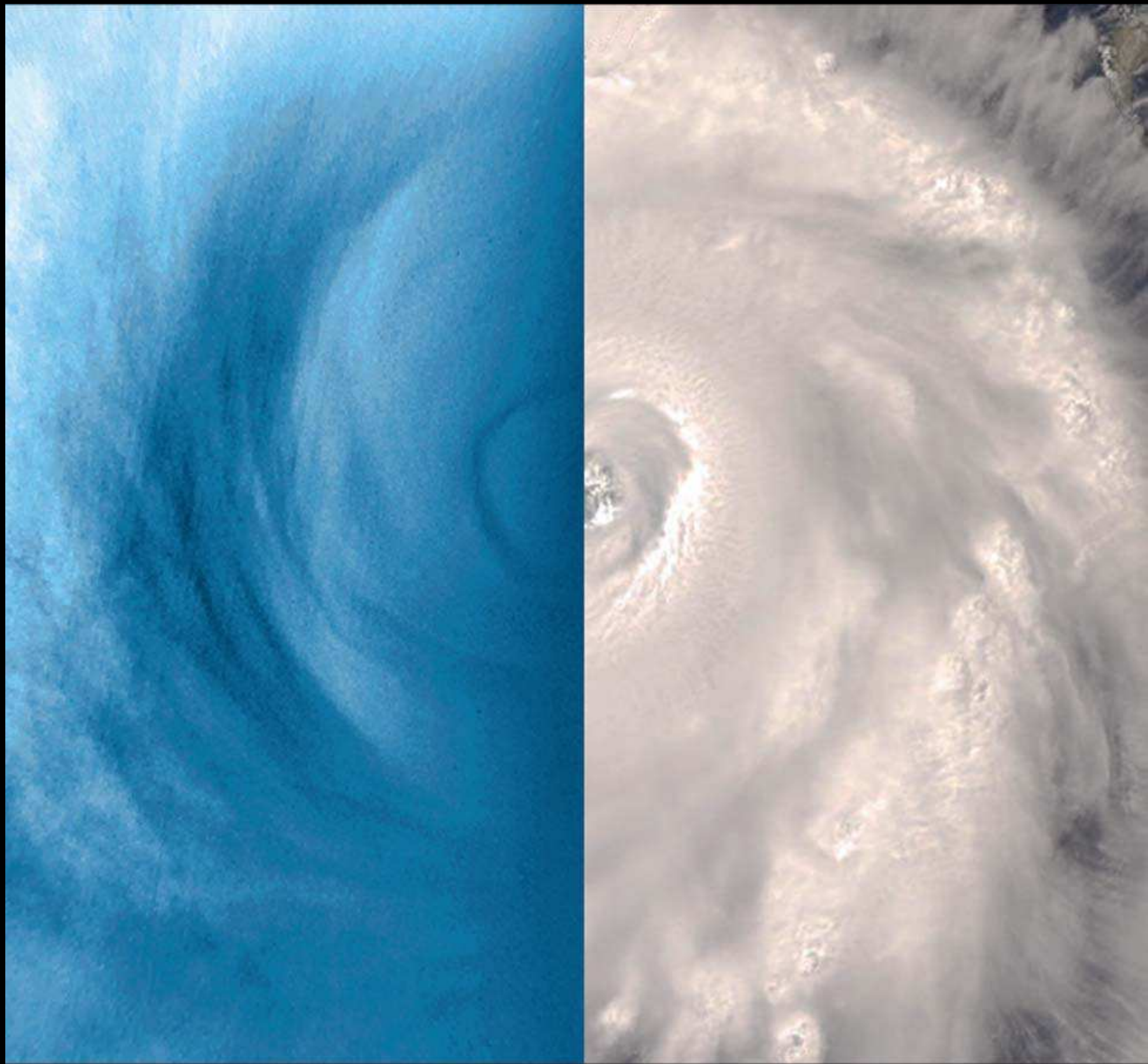




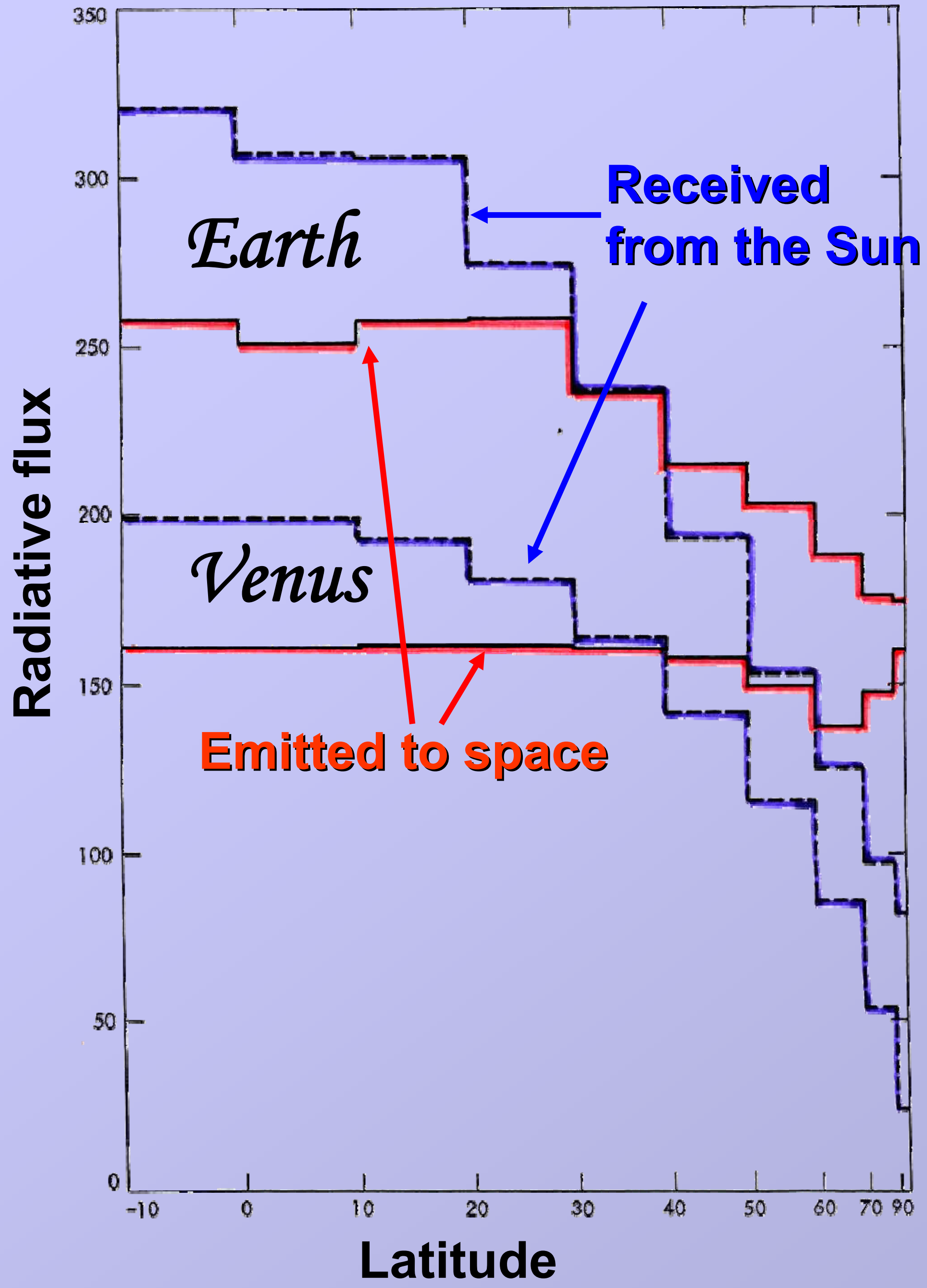
VIRTIS

Venus polar vortex and hurricane Frances



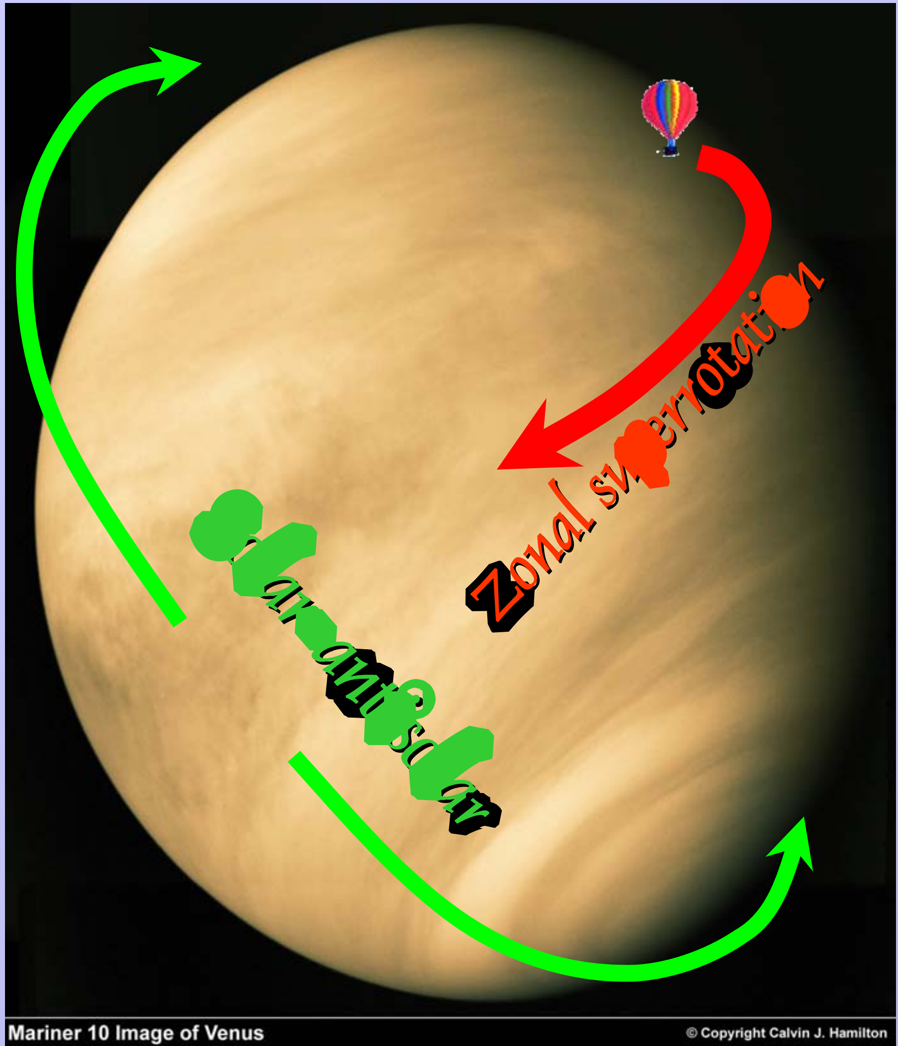
S. Limaye et al., GRL 2009

Venus energy balance

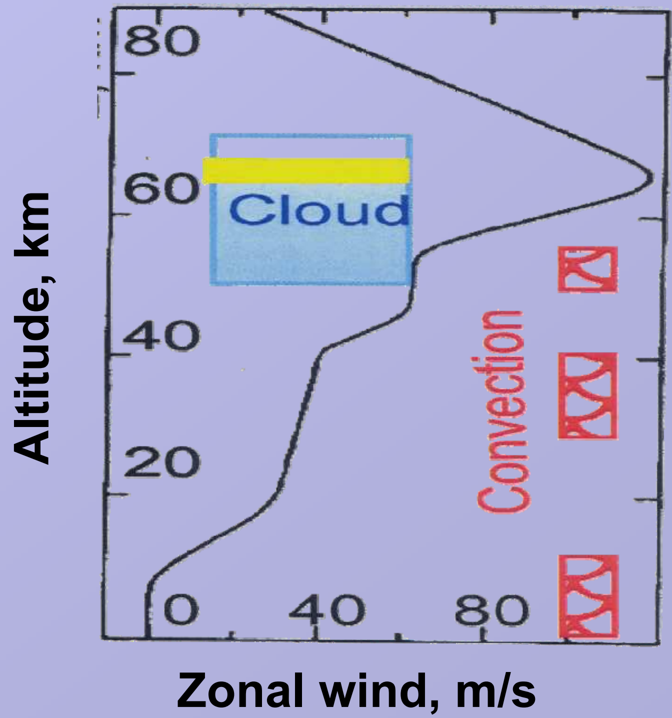


- *Venus gets less energy than the Earth !*
- *Latitudinal distribution of radiative balance implies dynamic energy transport*

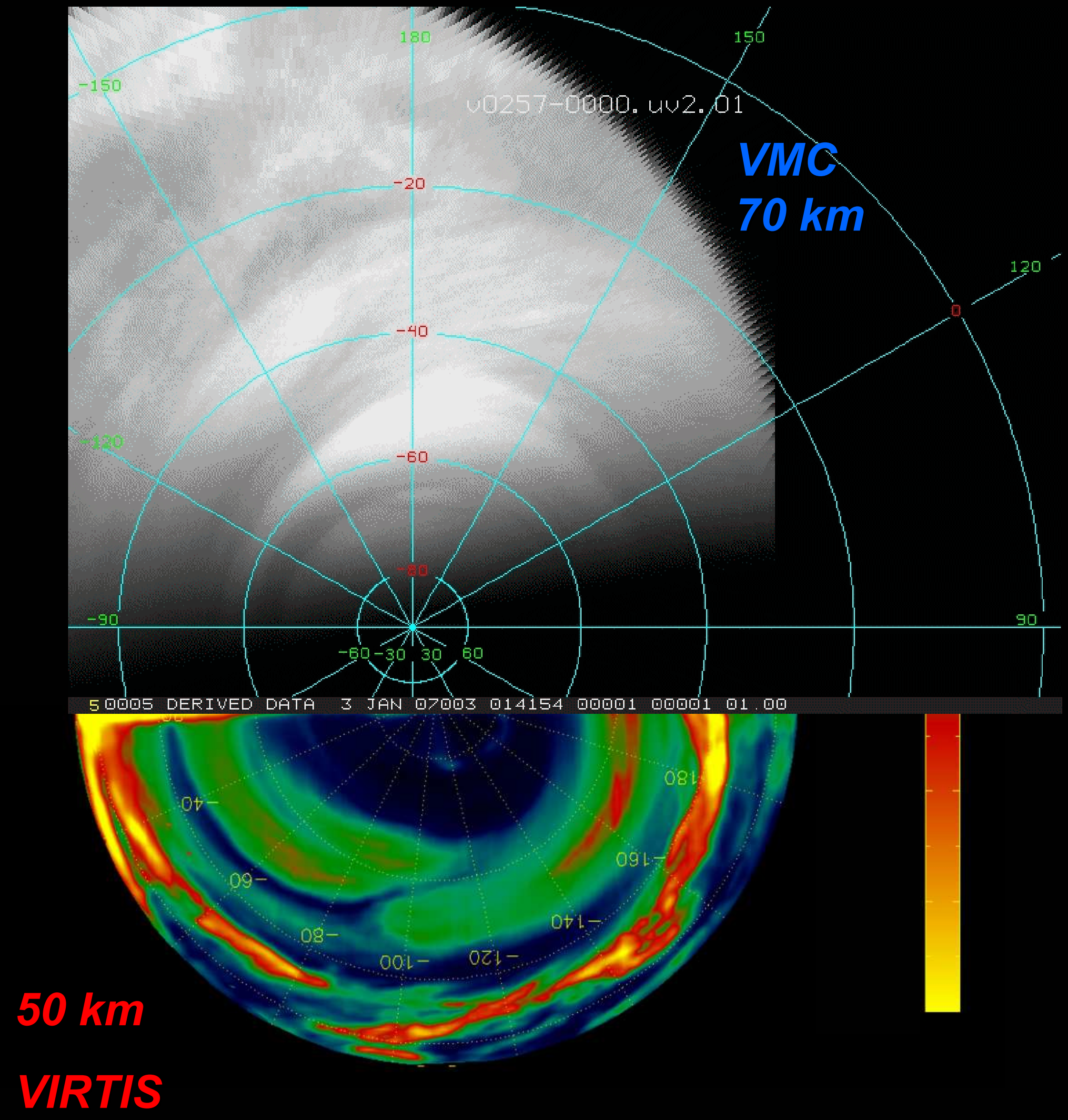
Venus global circulation



- *Troposphere and mesosphere*
  - *Zonal superrotation (>100 m/s)*
  - *Poleward winds v ~ 10 m/s*
  - *Cyclostrophic balance*
- *Thermosphere (> 120 km)*
  - *Zonal superrotation (~100 m/s)*
  - *Solar-antisolar circulation (~200 m/s)*

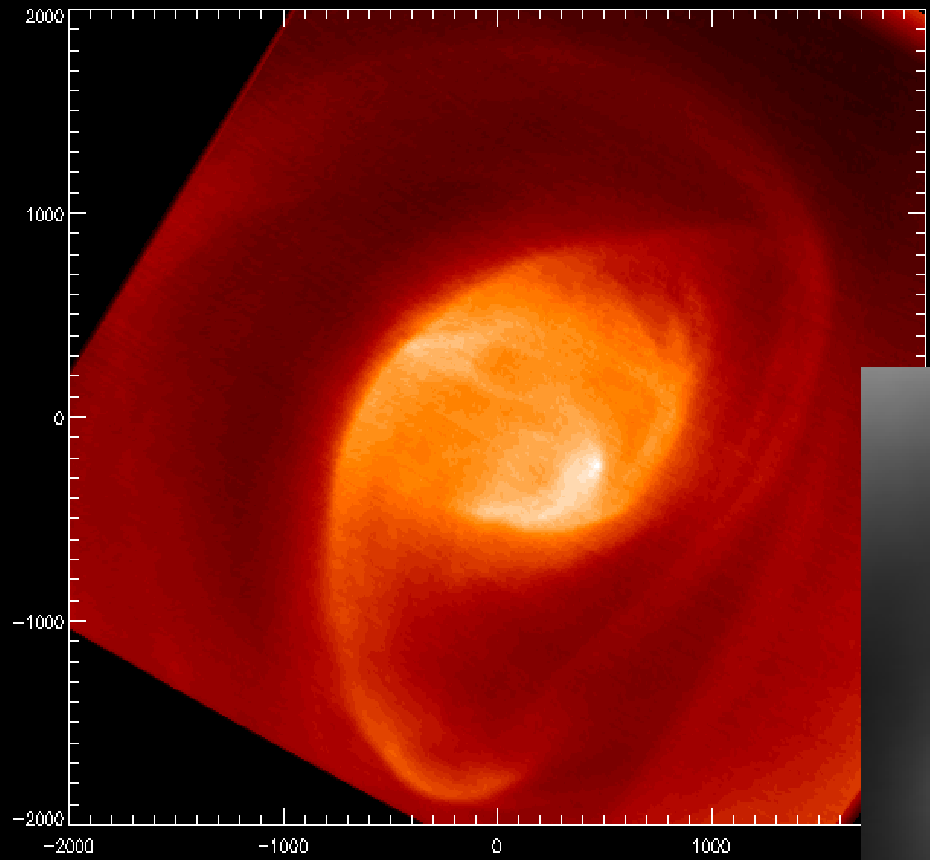


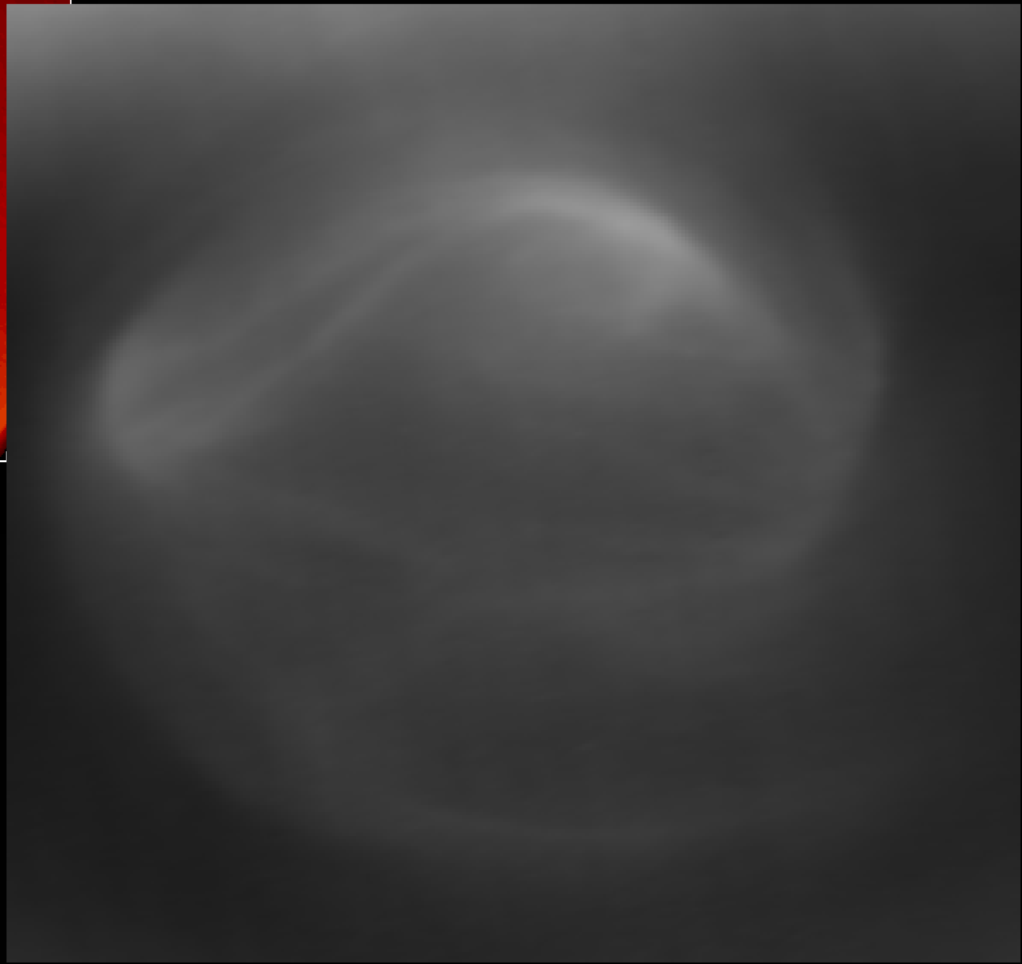
Global super-rotation at the cloud level



Credit S. Limaye

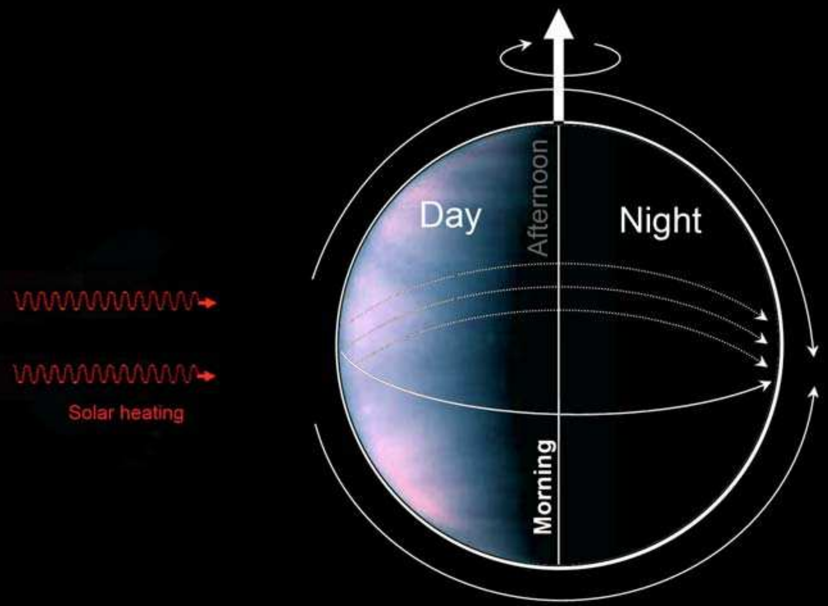
Dance of the Vortex eye





VIRTIS

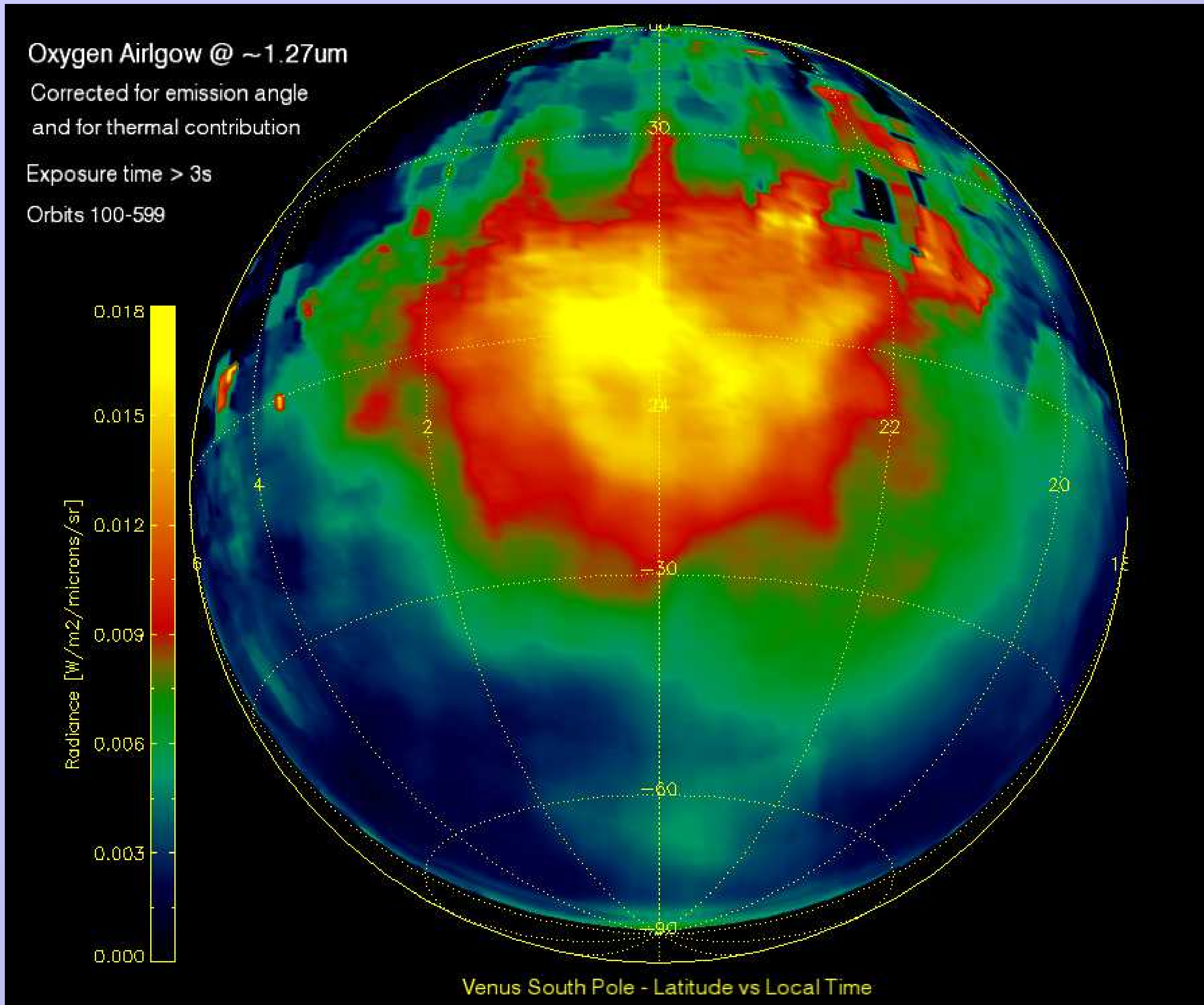
Venus night airglow



Recombination	$O + N \text{-->} NO^*$
3-body recombination	$O + N + CO_2 \text{-->} NO + CO_2$
Emission	$NO^* \text{-->} NO + h\nu$
Loss	$N + NO \text{-->} N_2 + O$

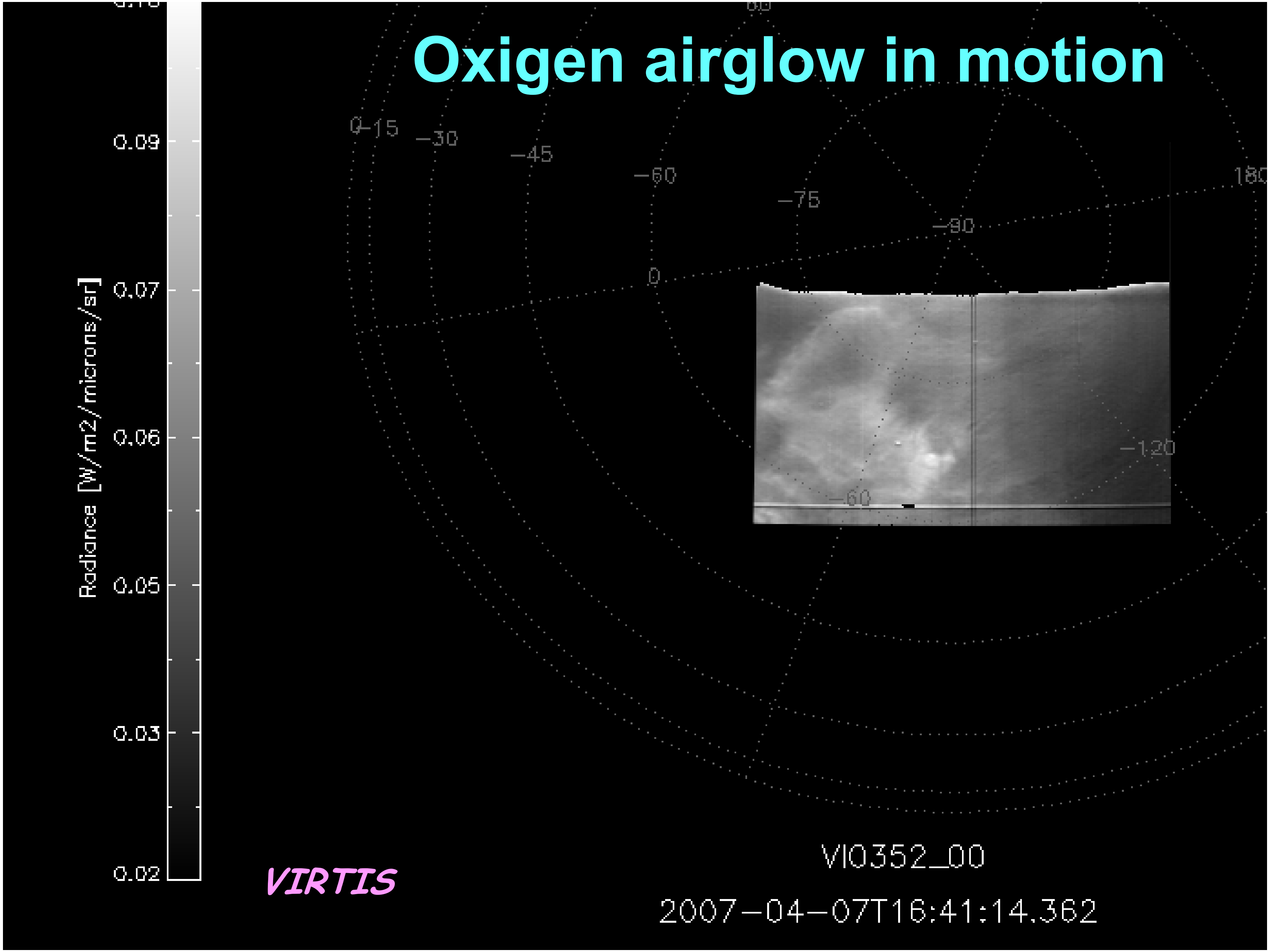
Recombination	$O + O + CO_2 \text{-->} O_2^* + CO_2 + 5.17\ eV$
De-excitation	$O_2^* \text{-->} O_2 + h\nu$
Quenching	$O_2^* + M \text{-->} O_2 + M$

O_2 airglow global average (500 orbits)



27 micron

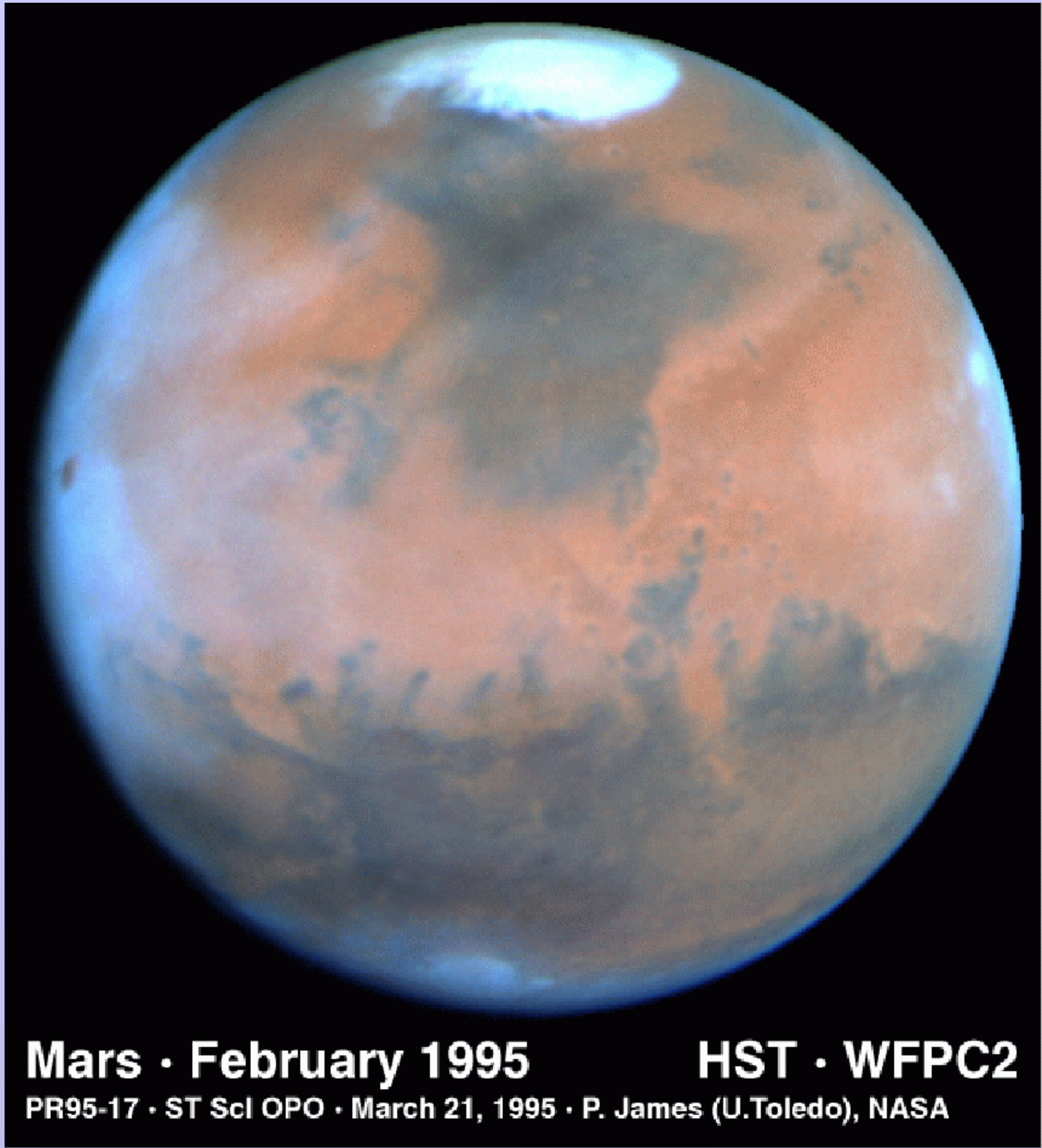
n airglow
rrected by clouds
ck scattering and
nergence angle



Oxigen airglow in motion
Radiance [W/m2/microns/sr]
0.09
0.07
0.06
0.05
0.03
0.02
0
−15
−30
−45
−60
−75
−90
180
−120
−60
VIRTIS
VI0352_00
2007−04−07T16:41:14.362

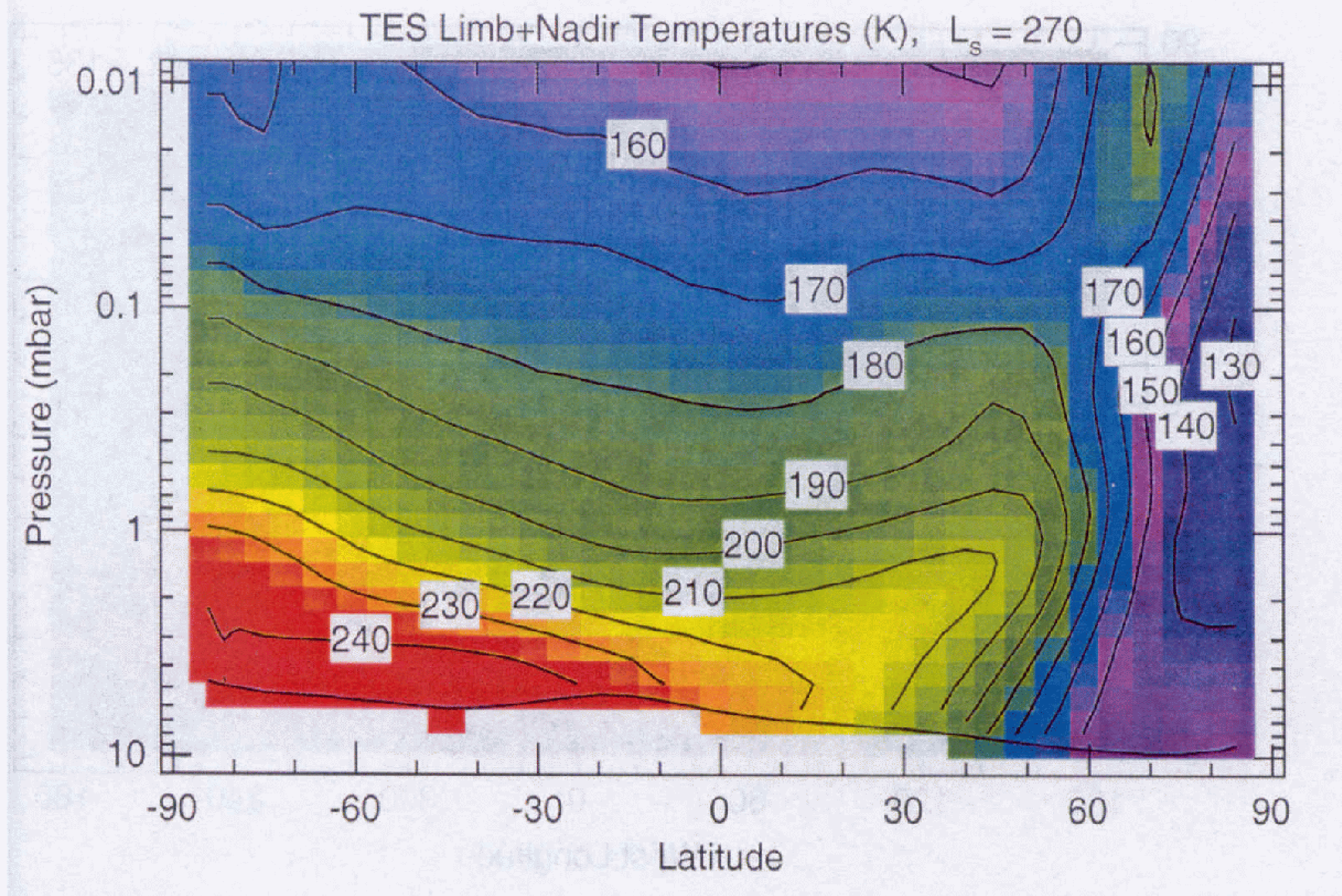
Mars

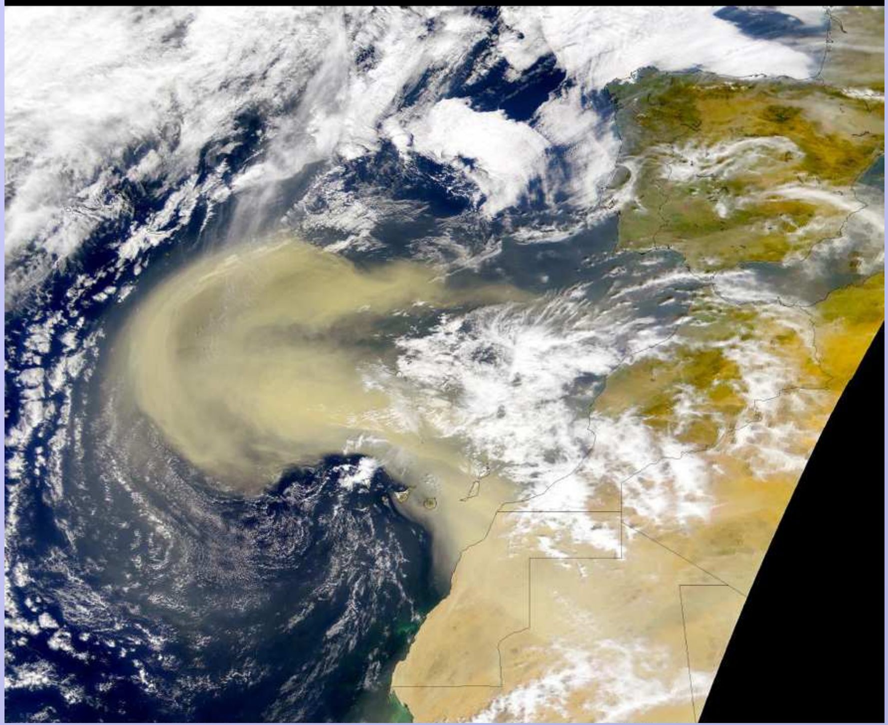
Basic facts about Mars



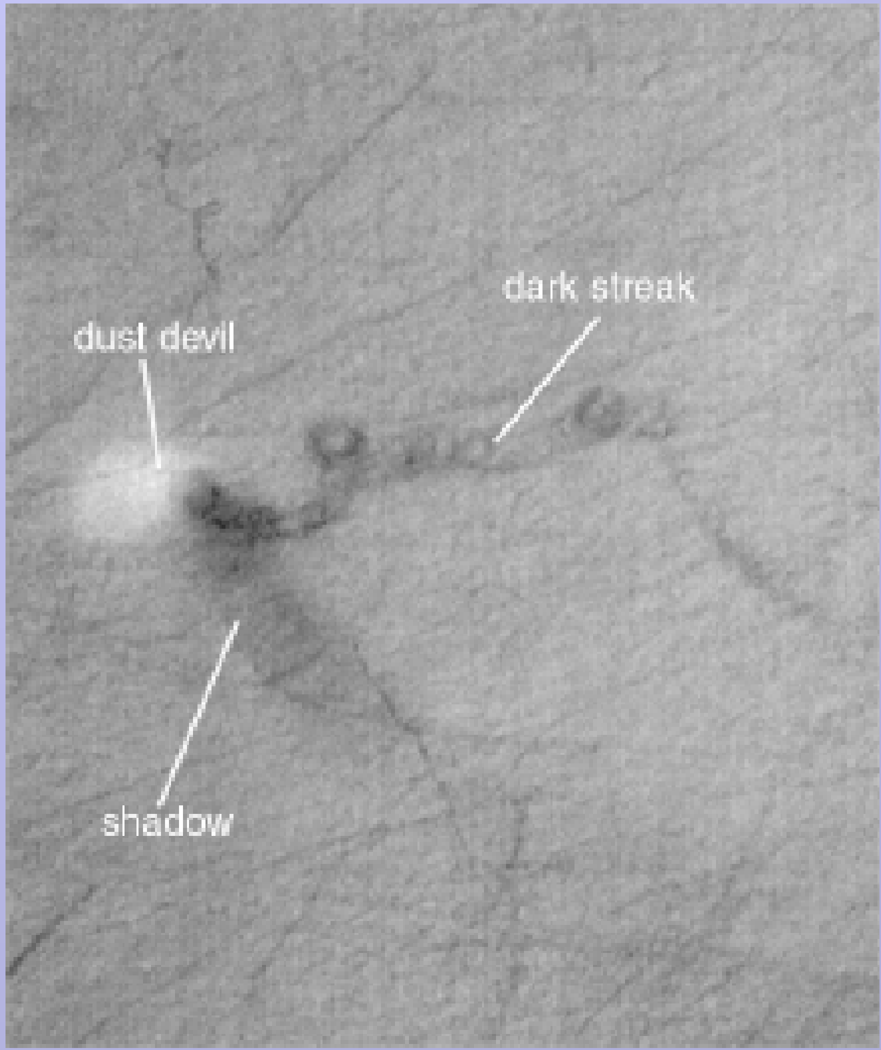
- Orbital radius - 1.52 a.u.
- Eccentricity ~0.09
- Obliquity 25 deg
- Sidereal day 24h 37 min
- Orbital period 687 days
- R ~ 3400 km
- Surface P ~ 6 mbar
- Surface T=120-280K
- Atmospheric composition
  - 95.3% CO_2
  - 2.7% N_2
  - 0.13% O_2
  - 100-1000 ppm H_2O
  - 700 ppm CO

Mars atmospheric temperatures

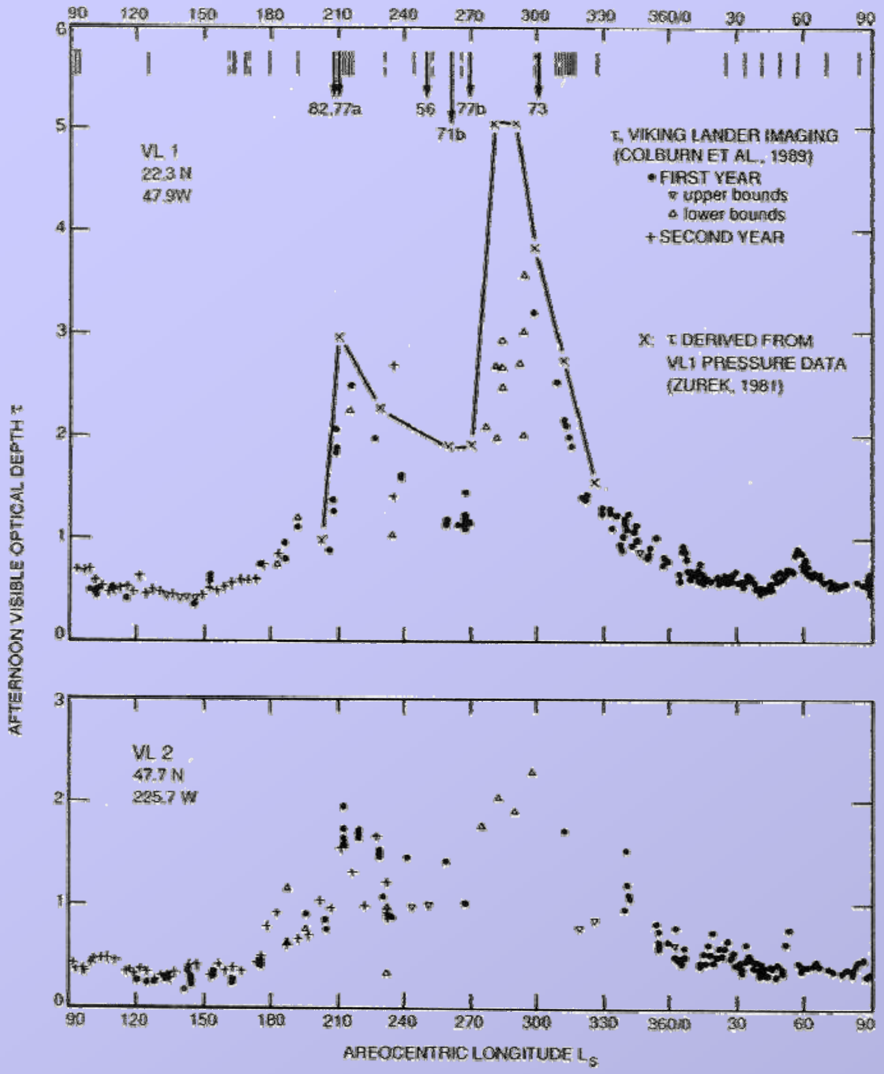




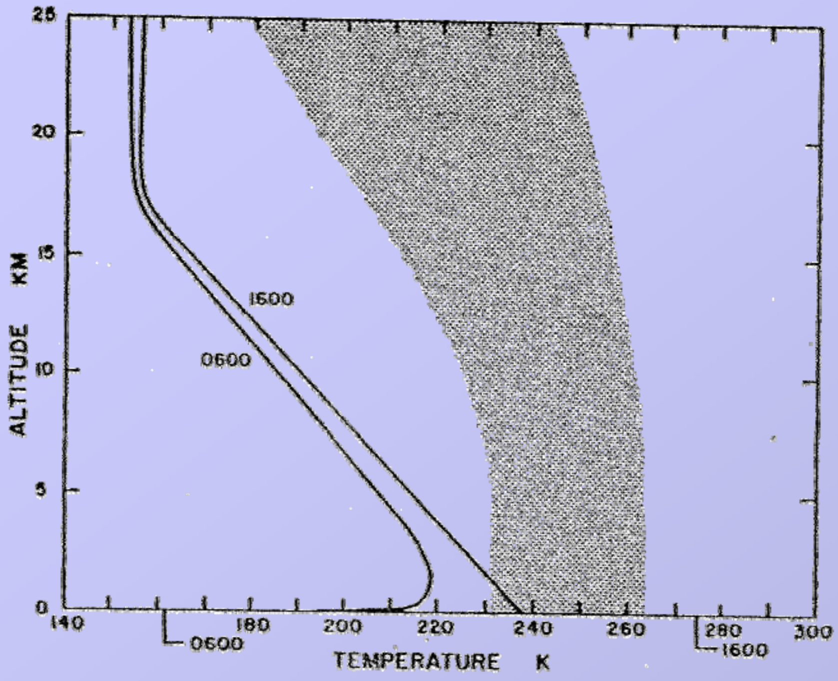
Dust storms and dust devils

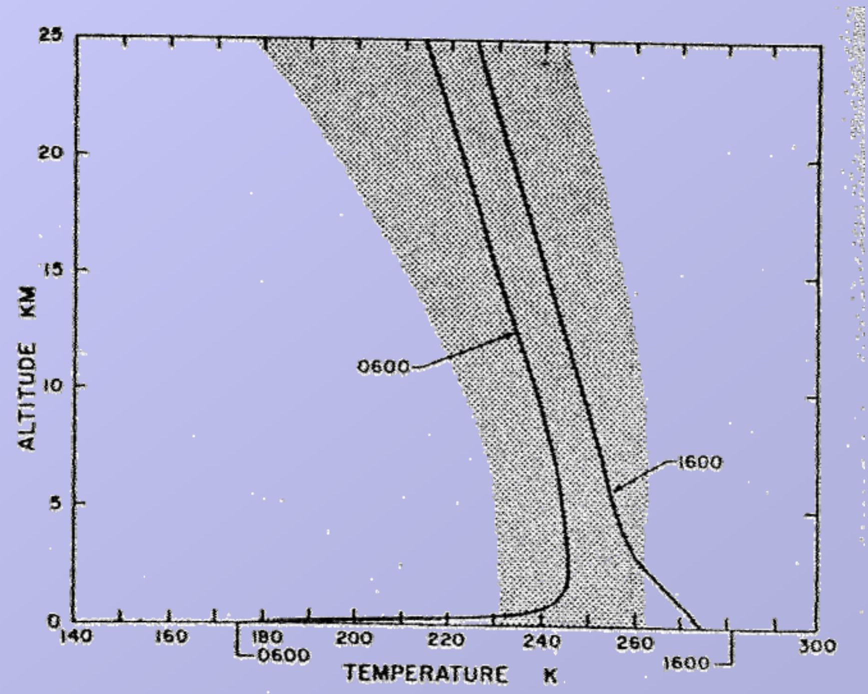


Global dust storms

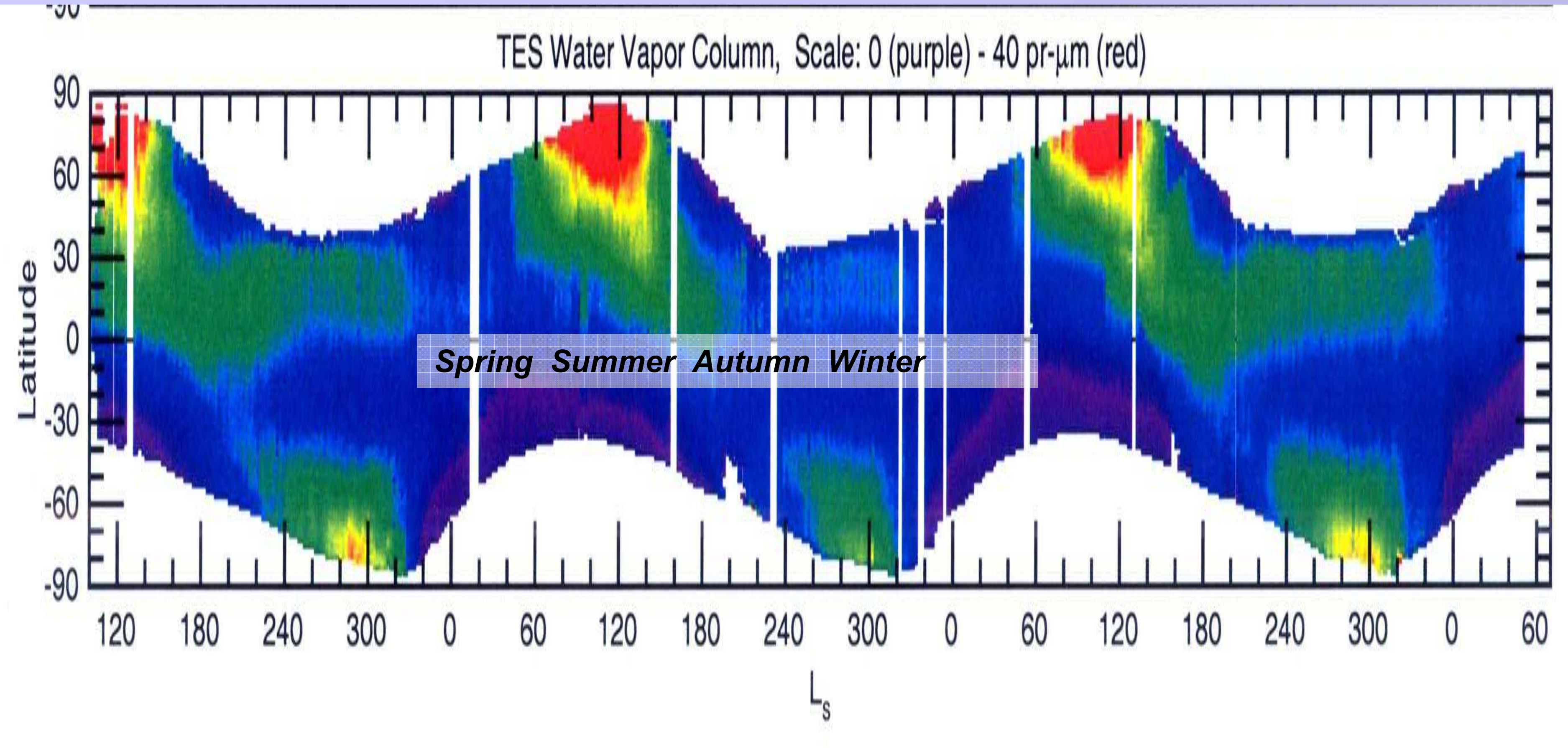


Dust and atmospheric temperature





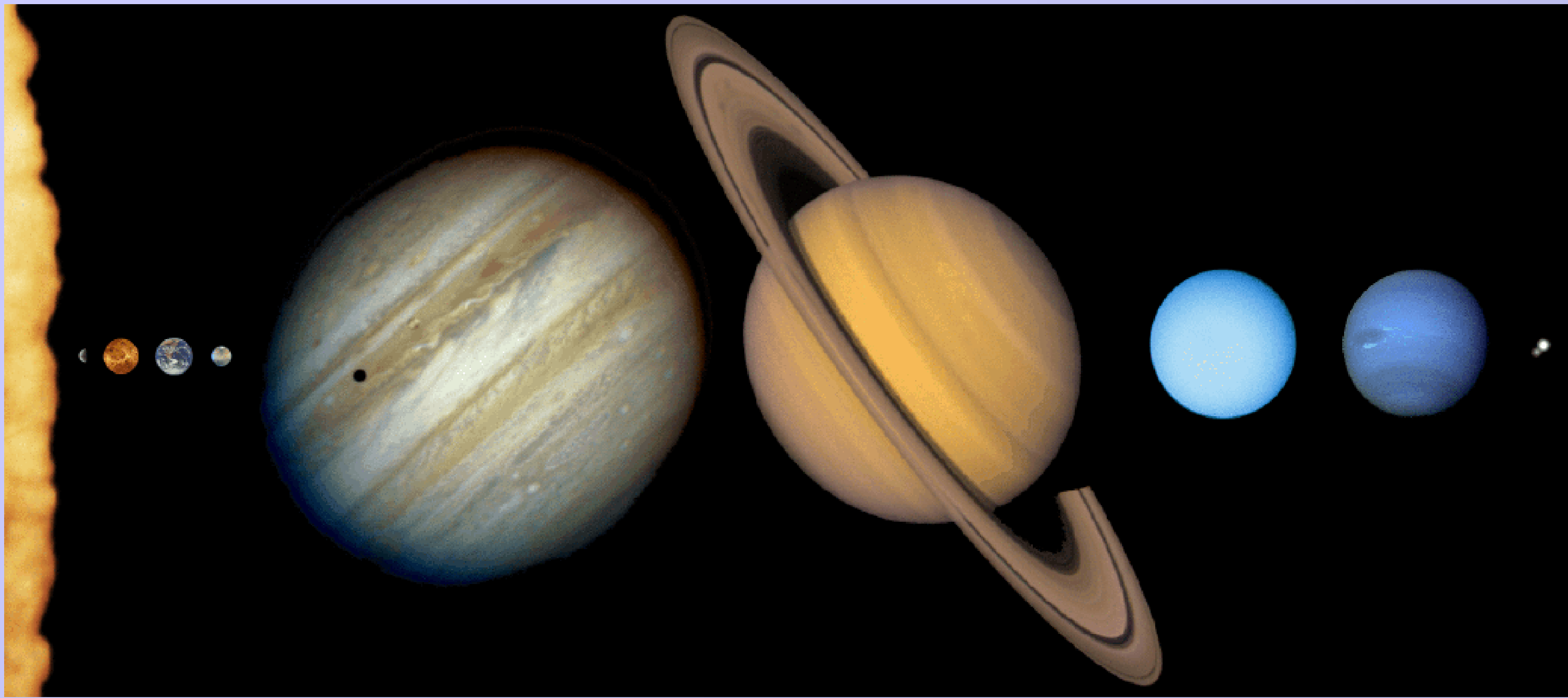
Seasonal water cycle on Mars



- **Seasonal variability 100 – 1000 ppm**
- **Advective transport**
- **Non-atmospheric reservoirs (polar caps, regolith)**

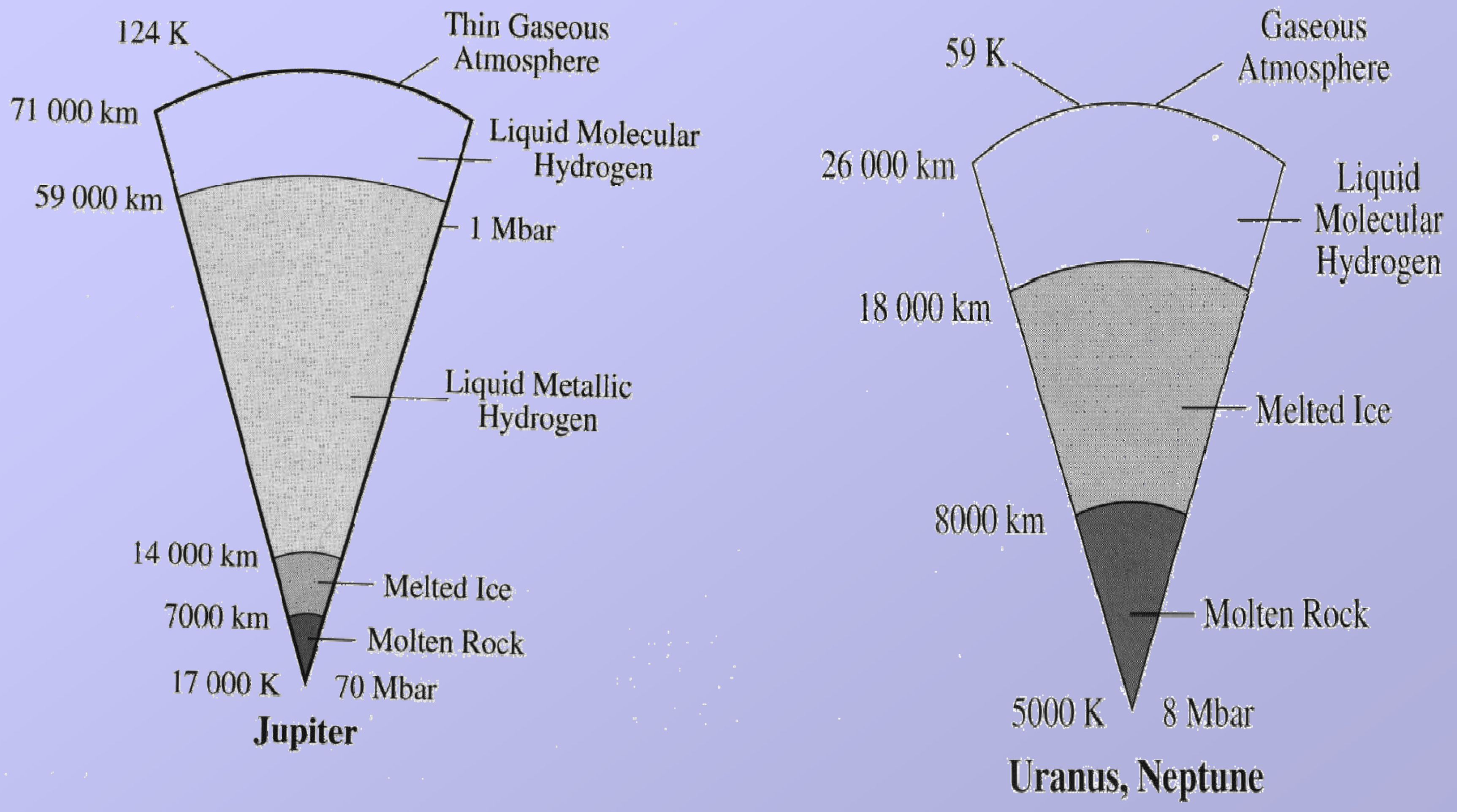
Giant planets

Basic Features

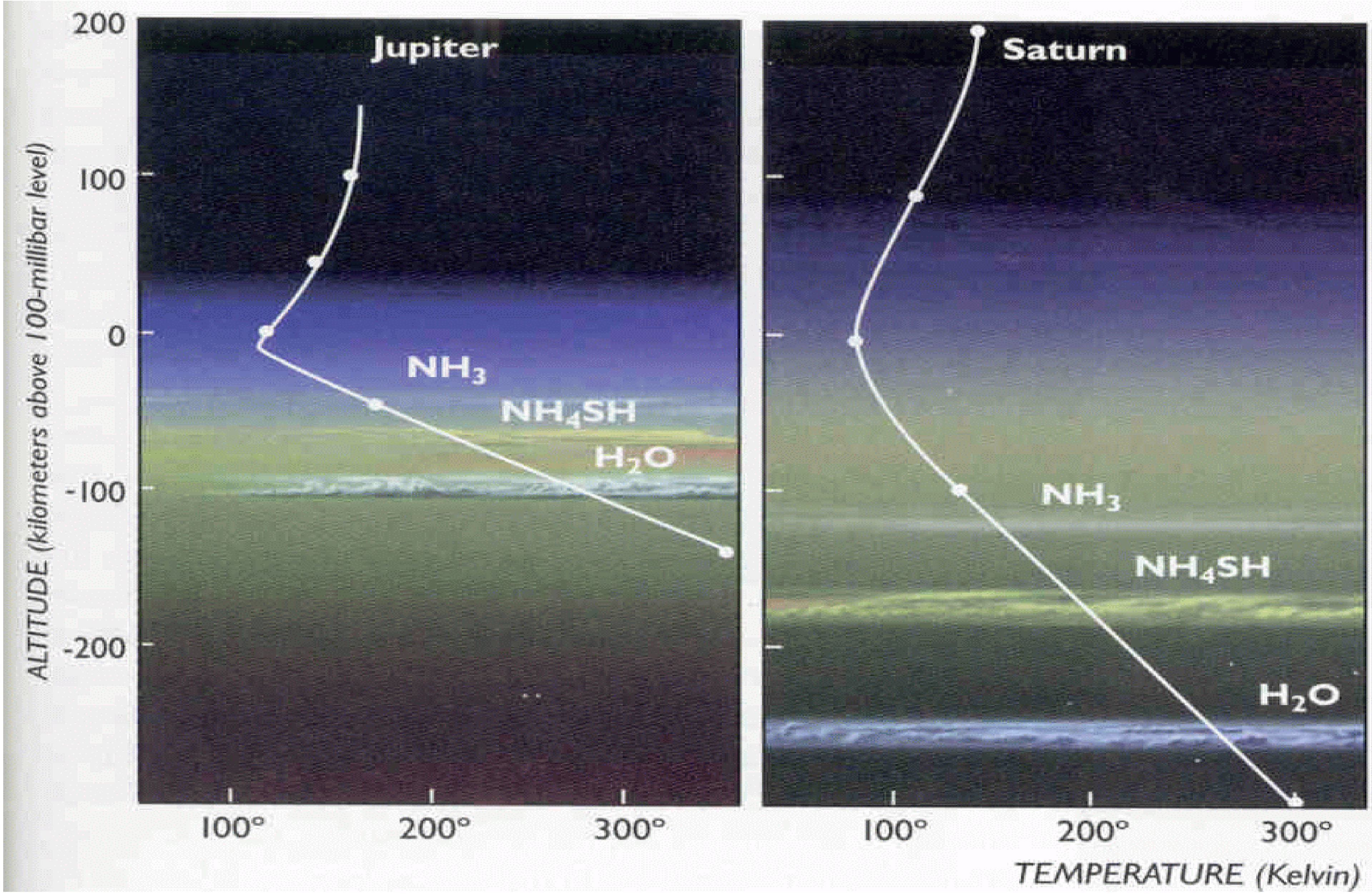


- Distance to the Sun > 5 a.u.
- R = 10-4 R_{Earth}
- Composition: H_2, He, ices H_2O, NH_3, CO_2, H_2S, Ne, Ar, Kr, Xe
- Mean density ~1.3-1.6 g/cm^3
- Rotation periods ~10 -17 hours, non spherical shape
- Effective temperature 170 – 60 K

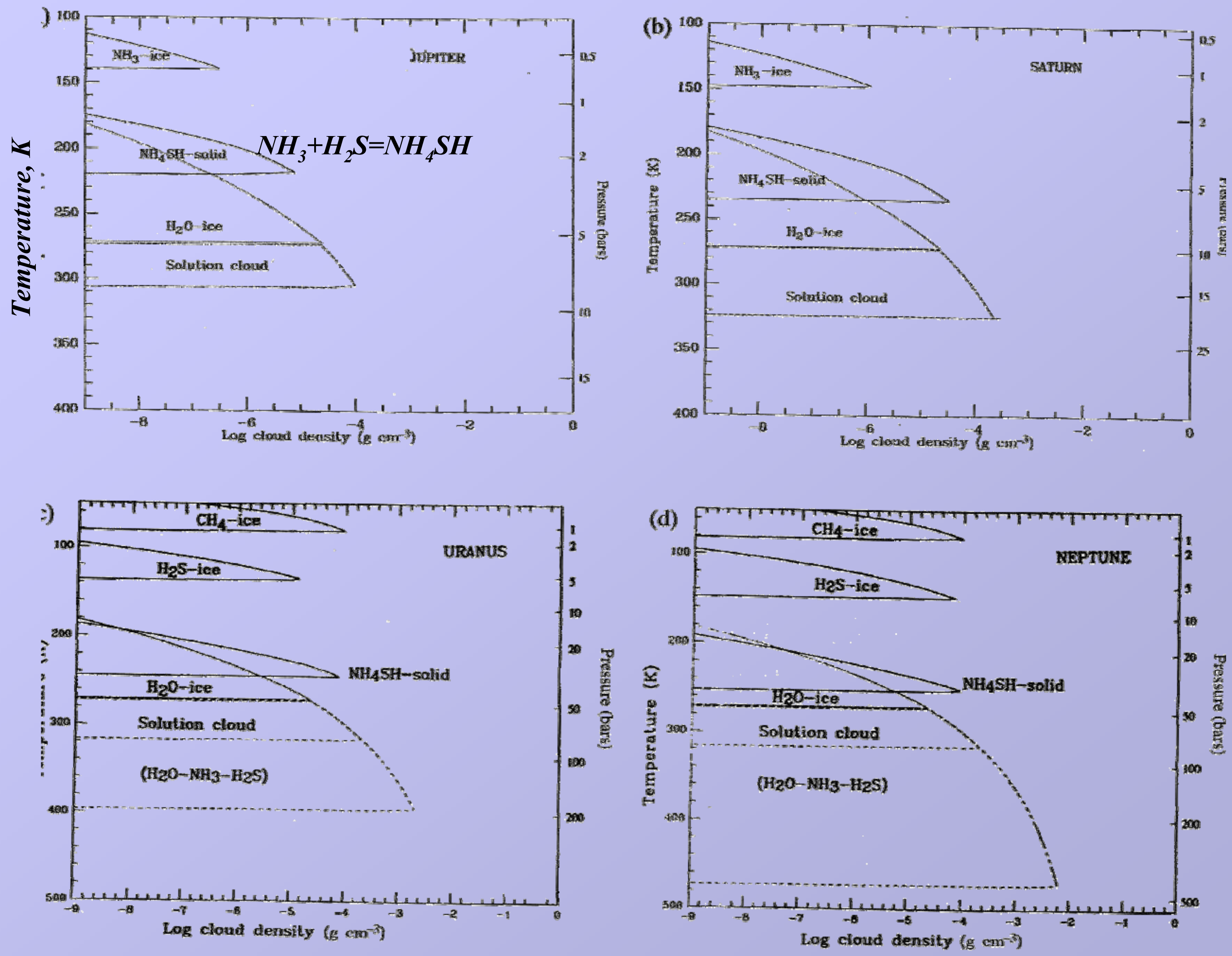
Inner structure of the Giants



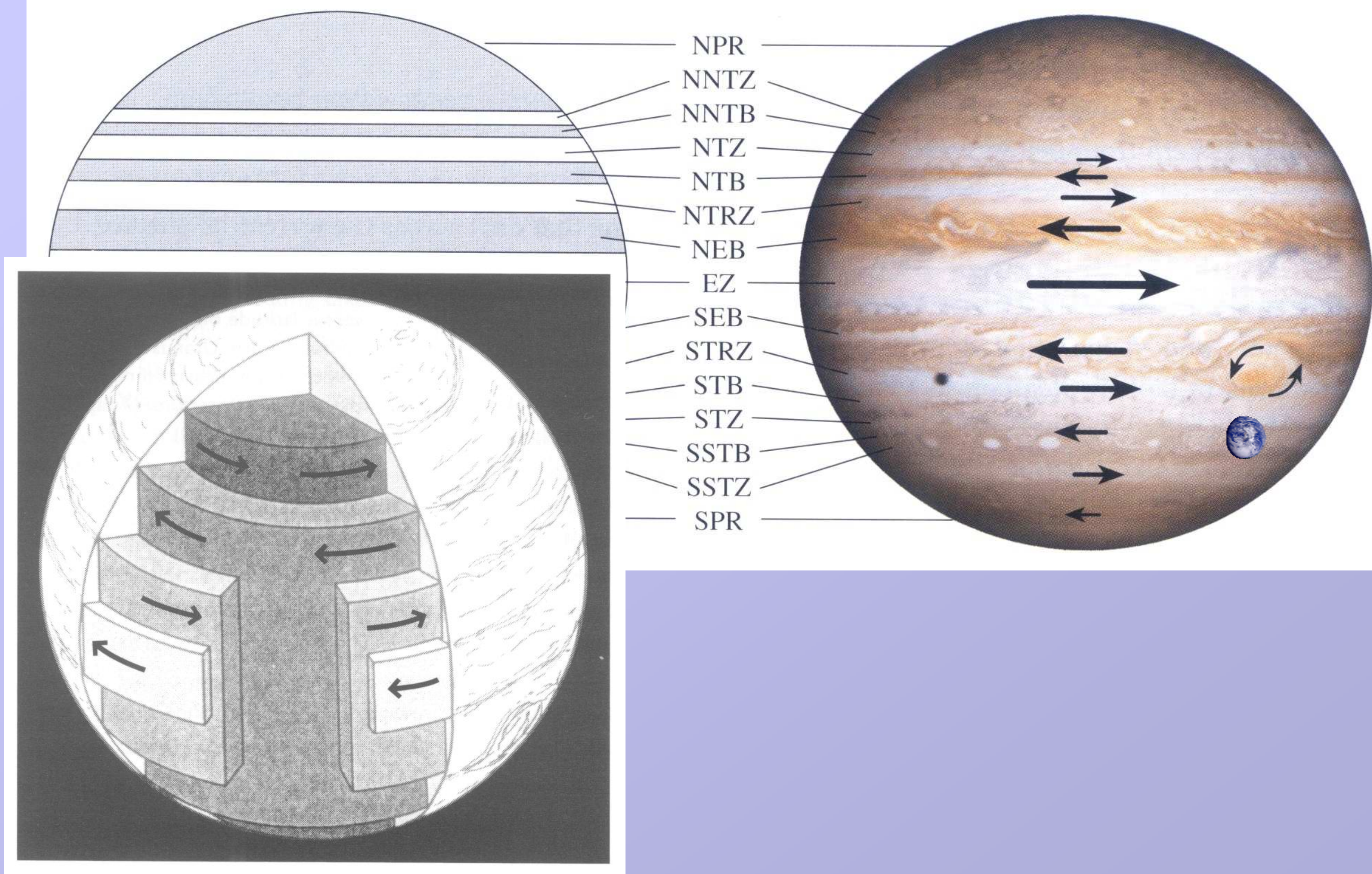
Atmospheric structure



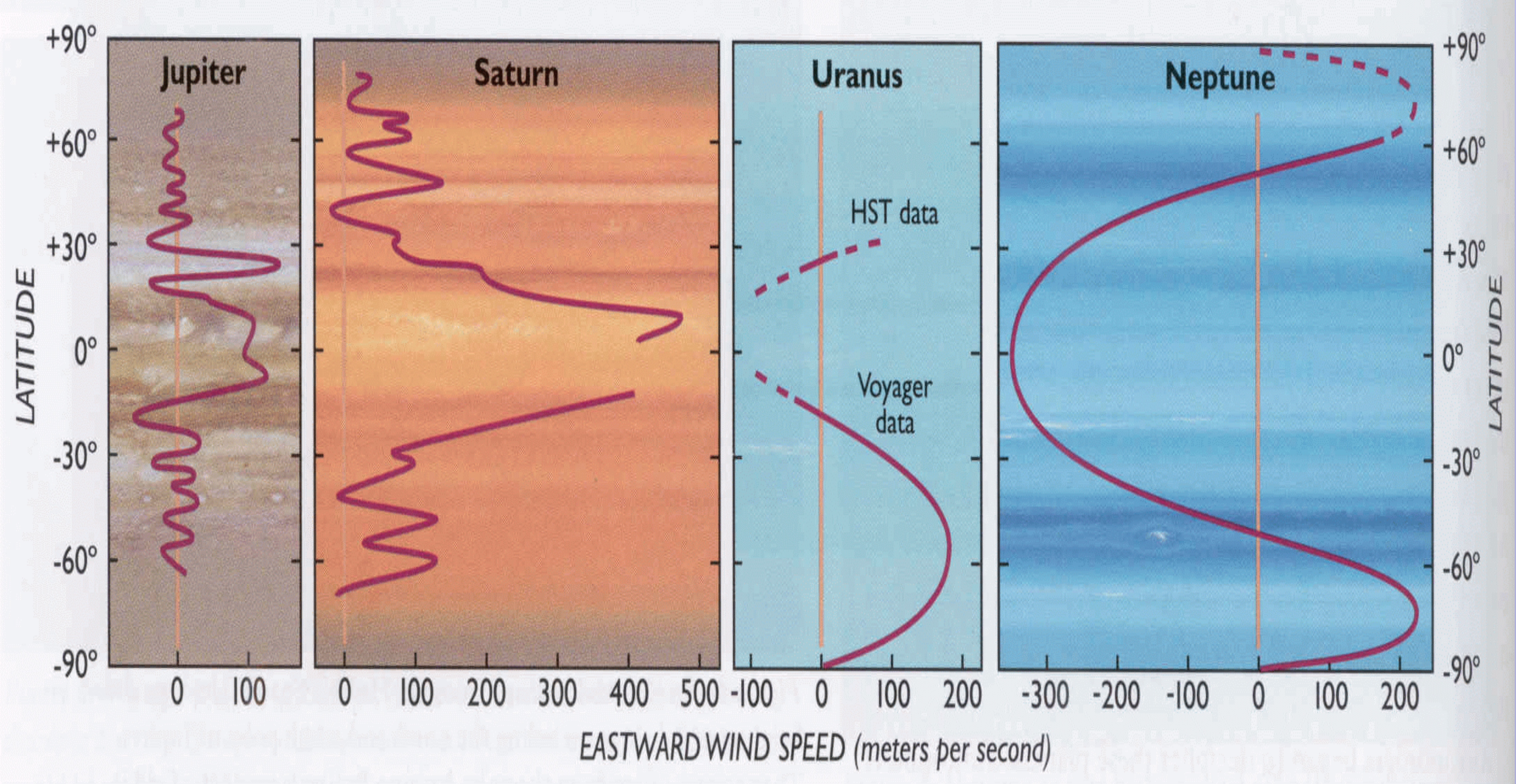
Clouds on the Giants



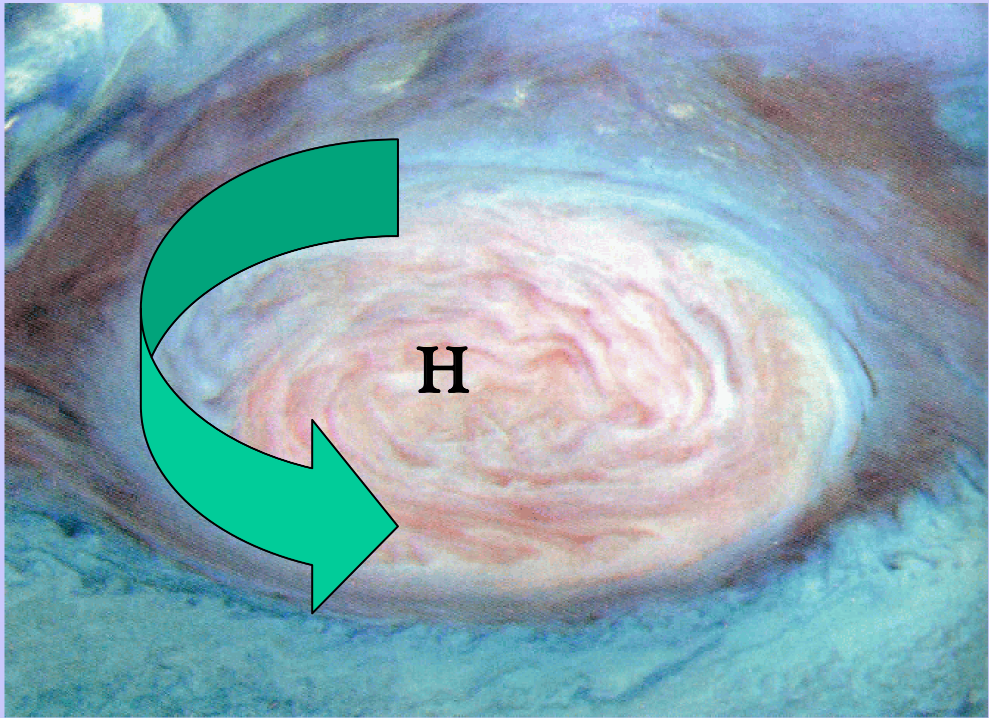
Jupiter band structure

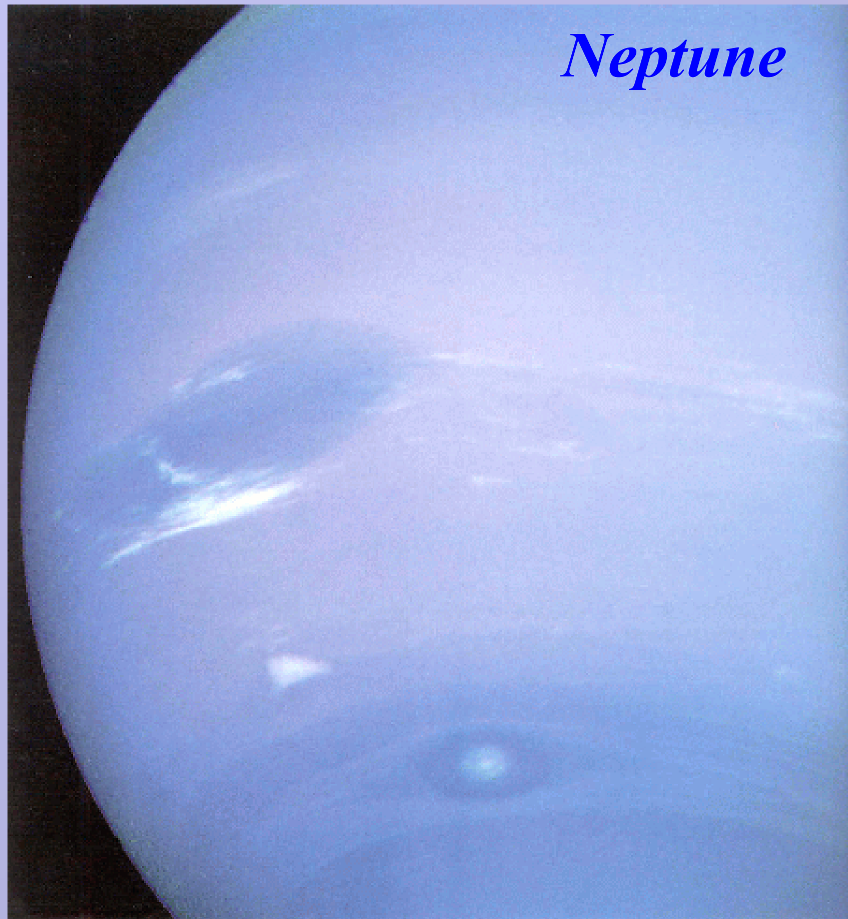


Atmospheric dynamics (1)



Atmospheric dynamics (2)





- GRS is variable
- GRS looks cold in the IR
- anti-clockwise rotation
- GRS – long-living anticyclon

Origin and Evolution of planetary atmospheres

Accumulation of planetary atmospheres

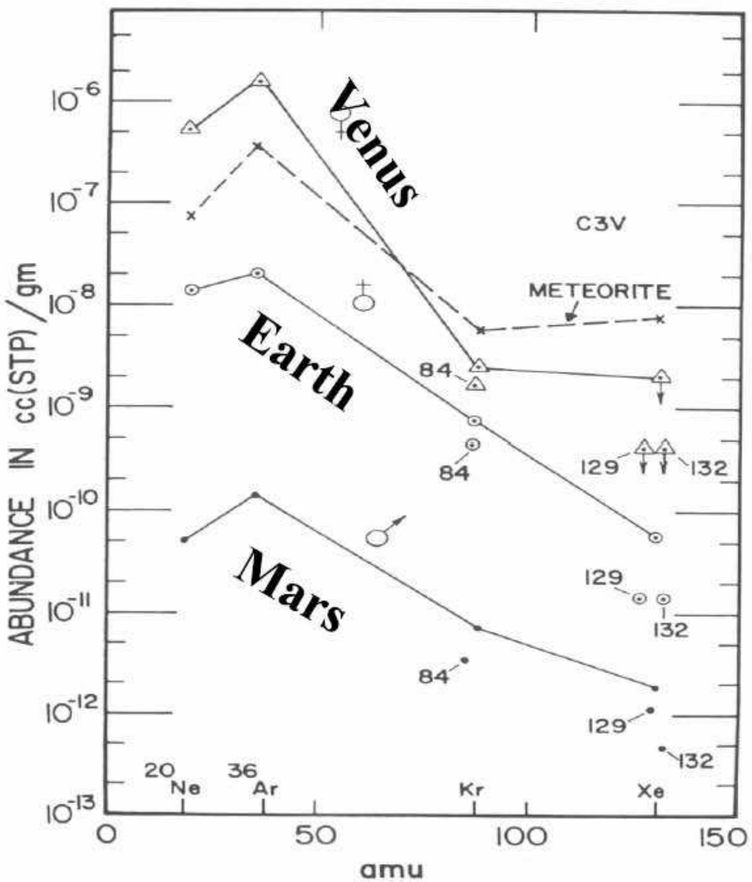
- Outgassing during accretion phase
  - $M \sim 0.1\ M_{earth}$
  - $T \sim 1600$ K
  - Melting of the solid body, differentiation, and outgassing
- Volcanic erruptions
- Cometary supply

Erosion of planetary atmospheres

- **Thermal or Jeans escape**
  - Exobase: free path~scale height
  - Simple estimate: $V_{th} > V_{esc}$
  - Maxwellian velocity distribution
  - Escape parameter: $\lambda=(V_{esc}/V_{th})^2$
  - Jeans flux: $\Phi \sim NV_{th}(1+\lambda)\exp(-\lambda) \sim$
  $\sim 10^7$ cm^{-2} s^{-1} H atoms from Earth
  - Isotopic fractionation
- **Non-thermal escape**
  - Dissociation and recombination
  - Charge exchange
  - Sputtering
  - Solar wind sweeping
-
- **Hydrodynamic escape (blow off)**
  - Planets during accretion period
- **Impact erosion (d>H)**
  - $M_e/M \sim d^2$

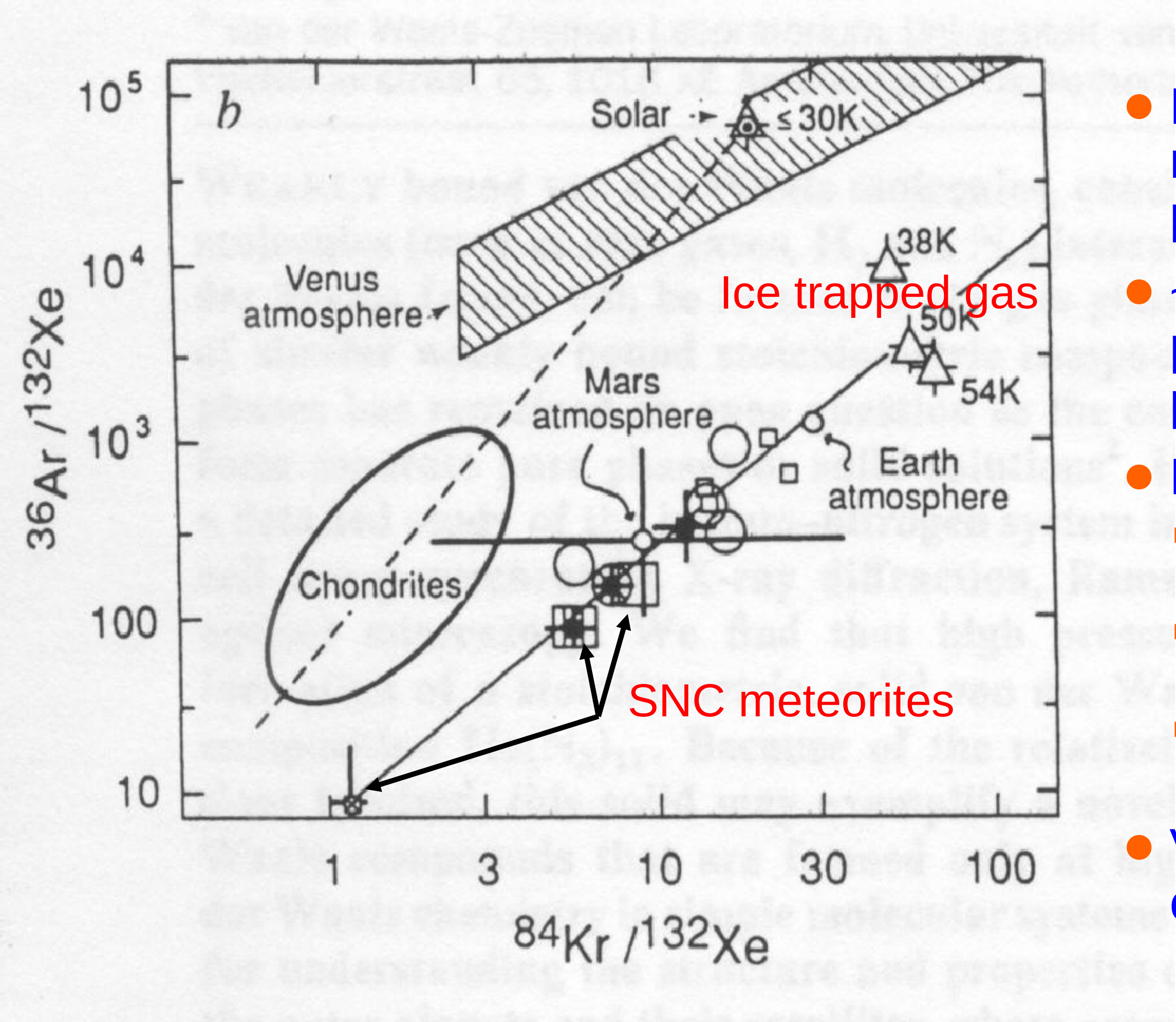
Records of atmospheric evolution

Noble gases on terrestrial planets



- Terrestrial atmospheres were degassed from planetesimals, not accreted from nebula
- Gases (except Ne) were trapped in the planetesimals at ~30K
- Venus atmosphere is more primordial
- Mars and Earth has possibly survived severe impact erosion
- Possibly two reservoirs - planetesimals and comets - fed Mars and Earth
- $\mathbf{(D/H)_V}$ ~150 $\mathbf{(D/H)_E}$; $\mathbf{(D/H)_M}$ **~ 6** $\mathbf{(D/H)_E}$
  ⇒ much greater amonts of water existed on Venus and Mars

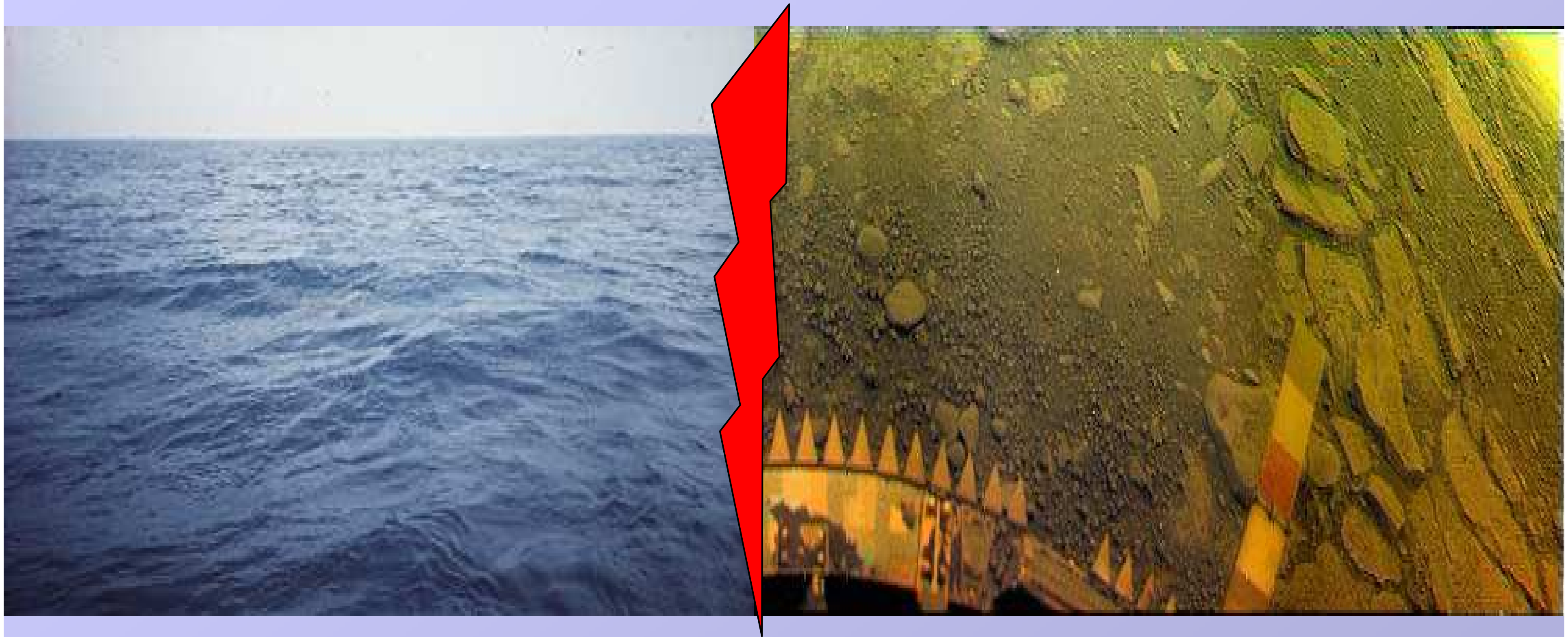
Two reservoirs of atmospheric material



- Earth and Mars received material from two reservoirs: planetesimals and comets
- ~100 km object is enough to produce observed noble gas pattern
- Ne abundance
  - *Ne is not trapped in the ice and is expected to be primordial*
  - *Hydrodynamic escape on Earth ai Mars can explain depletion of Ne*
  - *On Venus - isotope escape differentiation*
- Venus is closer to solar composition

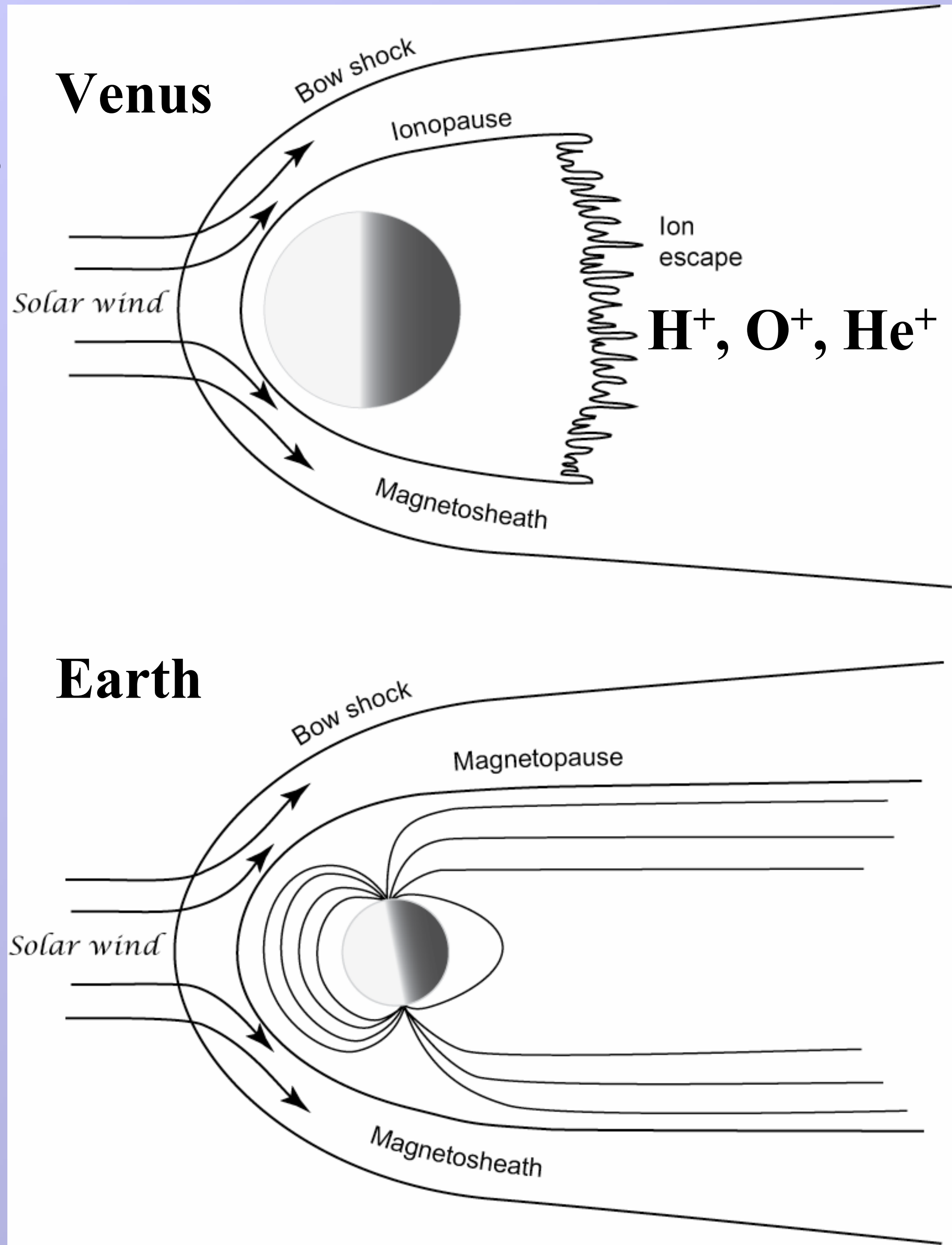
Water on Venus

Greenhouse effect and water loss (1)

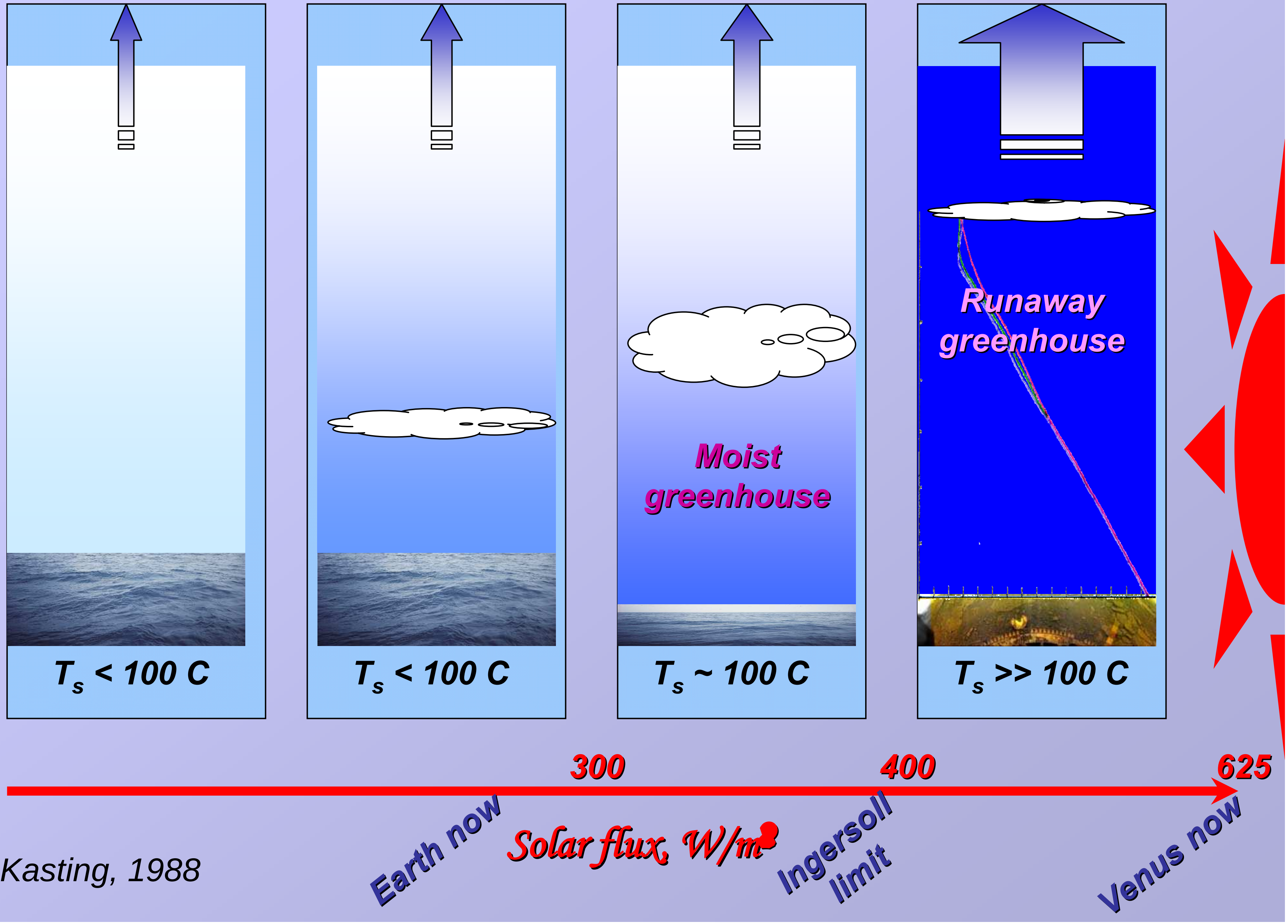


- Similar volatile inventories at origin
- Present water amount: $H_2O_{VENUS} \sim 10^{-5}\ H_2O_{EARTH}$
- Deuterium enrichment: $(D/H)_{VENUS} \sim 150\ (D/H)_{EARTH}$

Plasma environment and escape processes

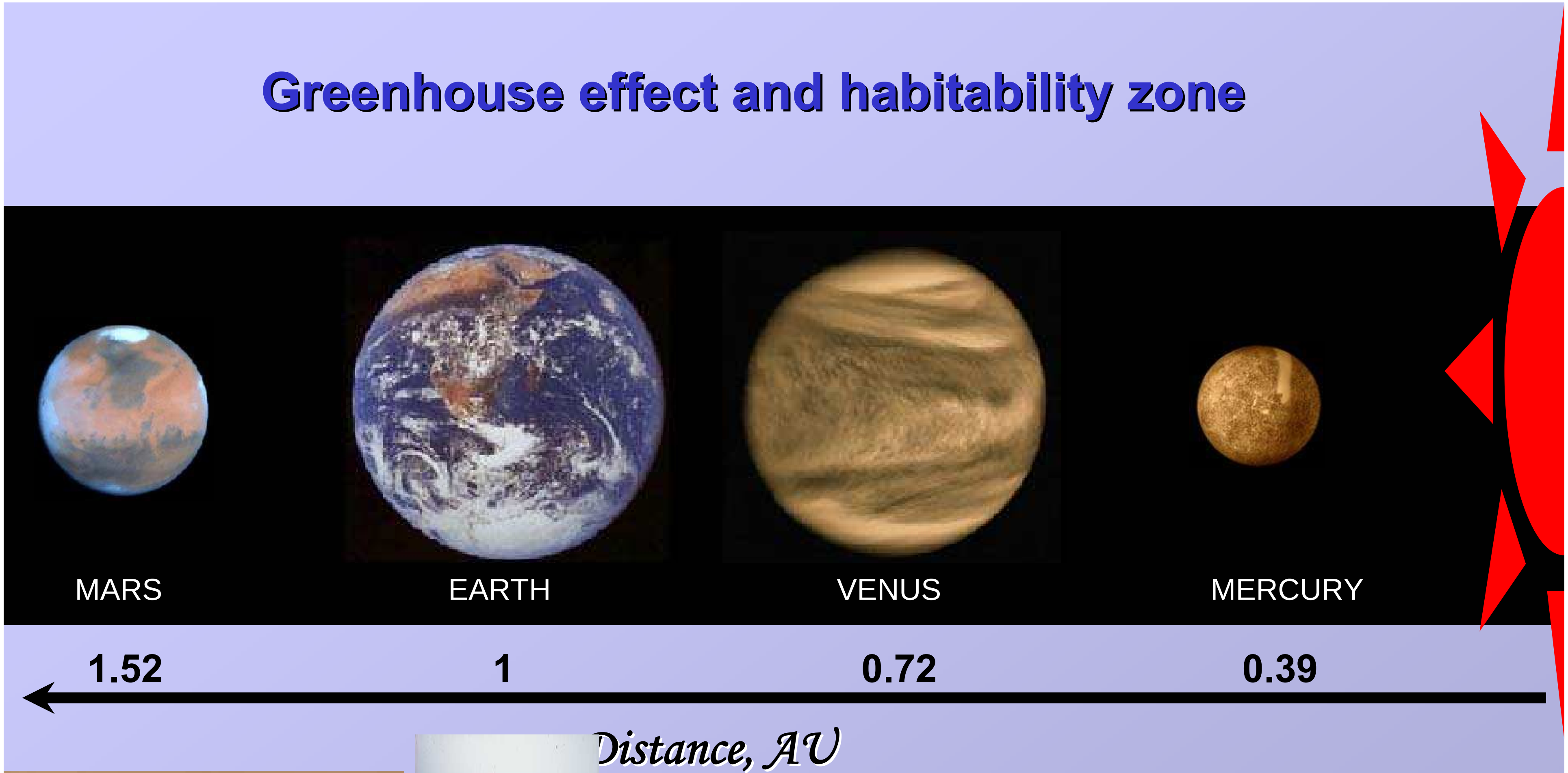


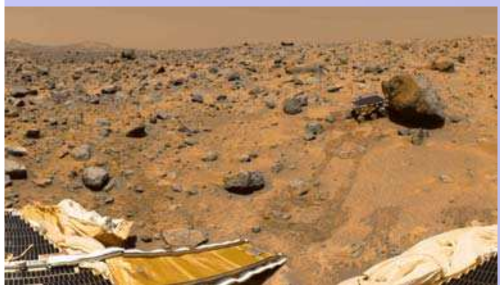
Earth-like planet: greenhouse effect and water loss (2)



Kasting, 1988

Greenhouse effect and habitability zone





Global fridge

Paradise

Greenhouse bath

Runaway greenhouse