Planetary Atmospheres

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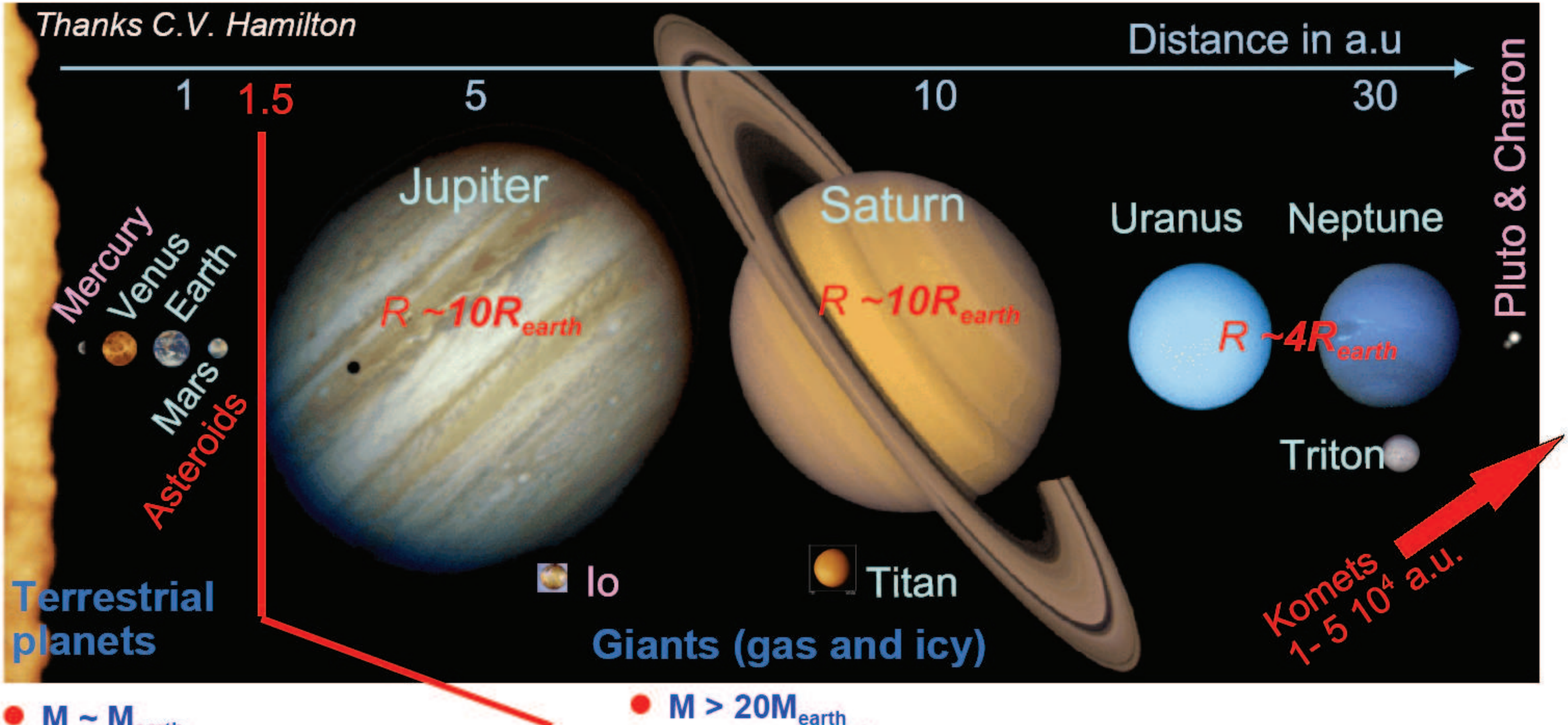
Content of the course

- **Introduction**
- **Structure of a planetary atmosphere**
- **Composition, chemistry and clouds**
- **Atmospheric dynamics**
- **Basics of radiative transfer**
- **Methods of investigation**
- **Origin and evolution of planetary atmospheres**
- **Radiative energy balance**
- **Atmospheres of planets**
  - *Venus*
  - *Mars*
  - *Giant planets*

Family of the Sun



Terrestrial planets

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

Giants (gas and icy)

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

Diversity of the Solar system bodies

- 8 Planets
- 67 moons
- 100s of comets
- 10,000 asteroids
- 10,000 Kuiper Belt Objects

Types of 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**

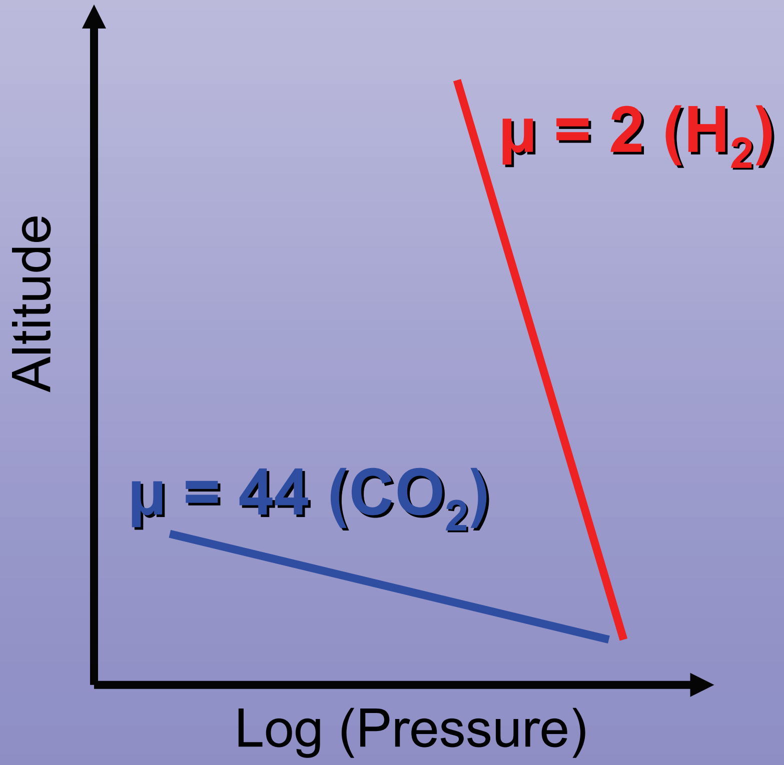
$$dP = -\rho g dz \;\&\; \rho = \frac{\mu P}{RT}$$

- **Barometric law**

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

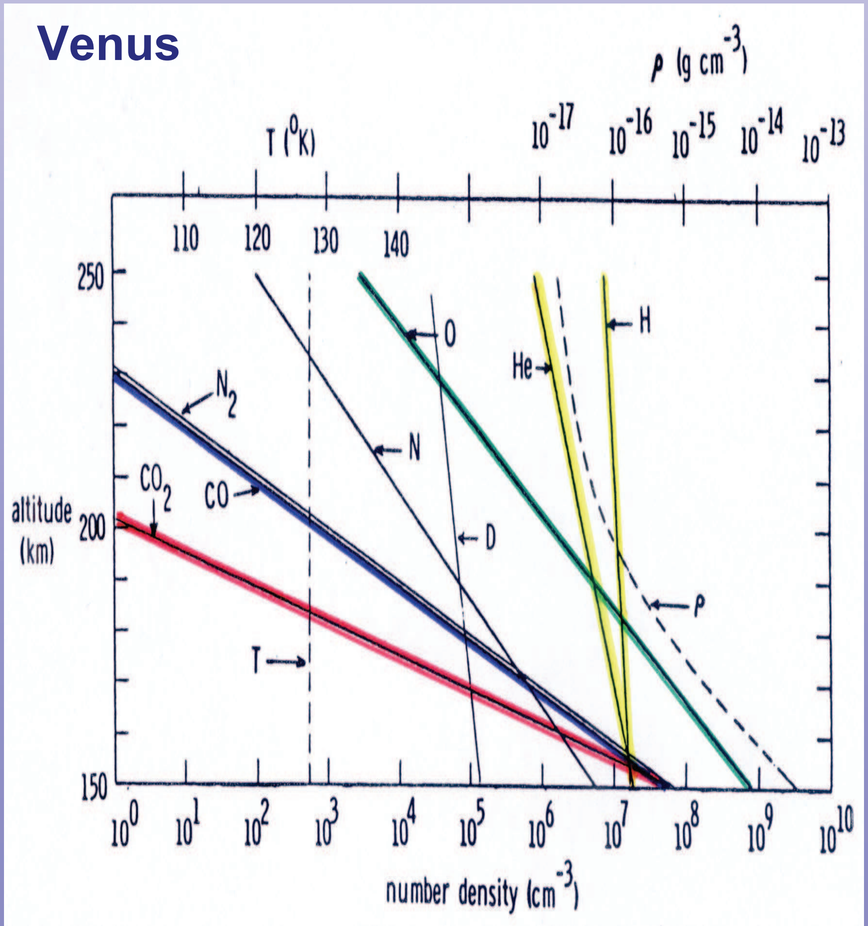
- **Scale height**

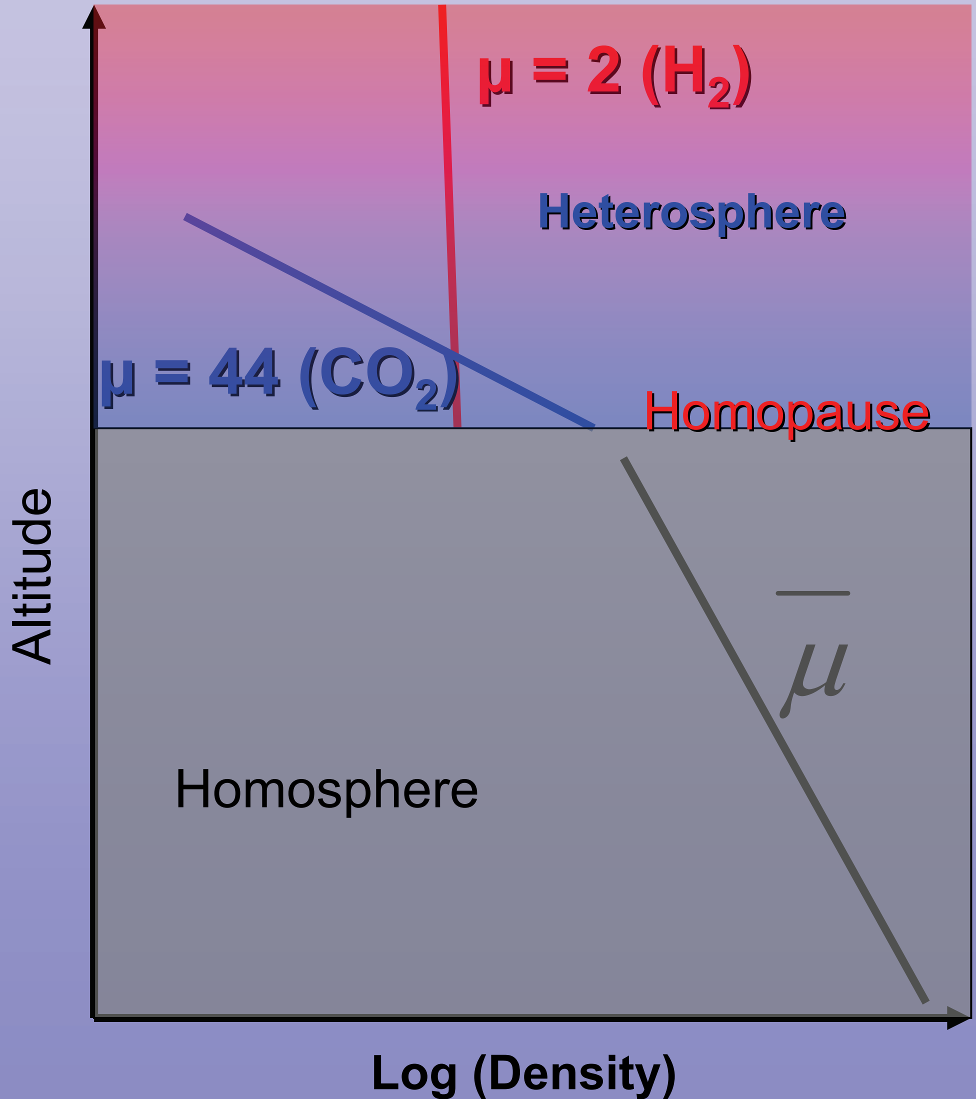
$$H(z) = \frac{RT(z)}{\mu g}$$



Density in a planetary atmosphere

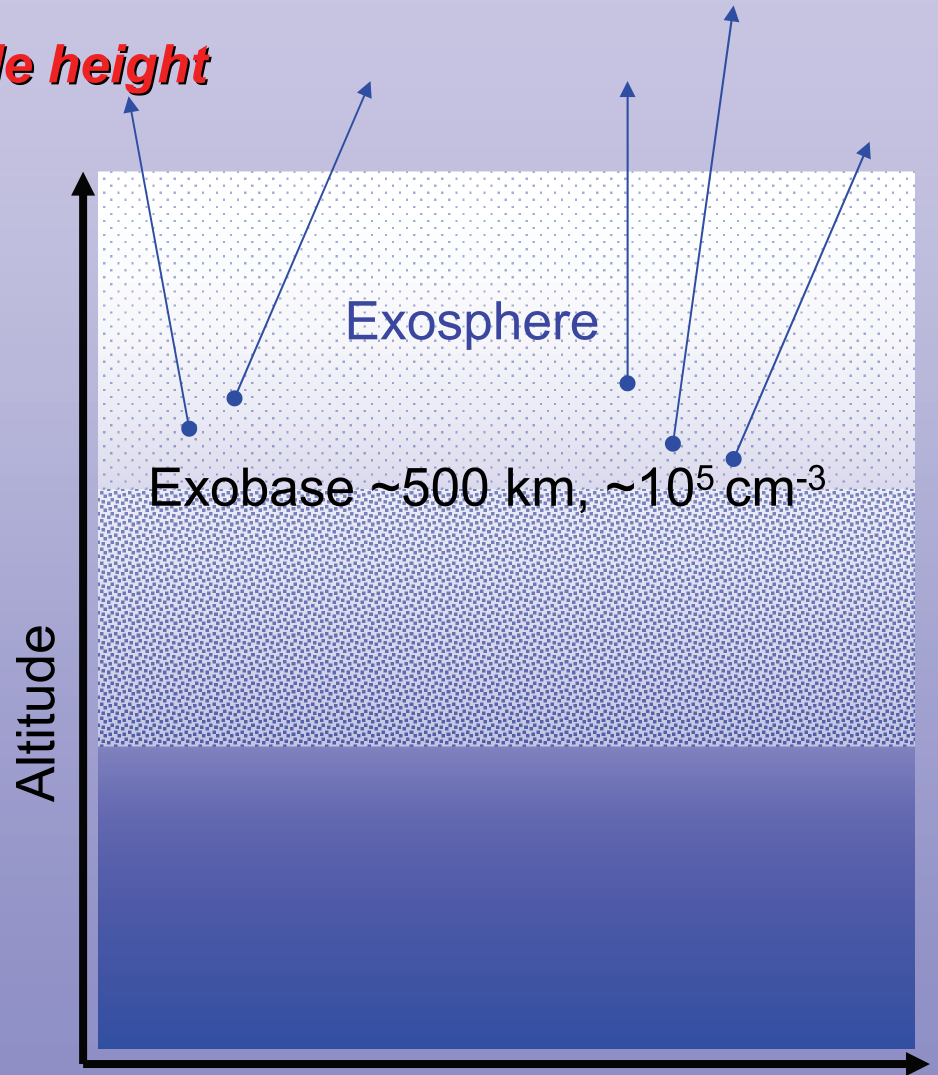
- Homopause: eddy mixing ~ molecular diffusion (z~ 130 km)
- Homo- and heterosphere
- Hydrogen-helium coronas



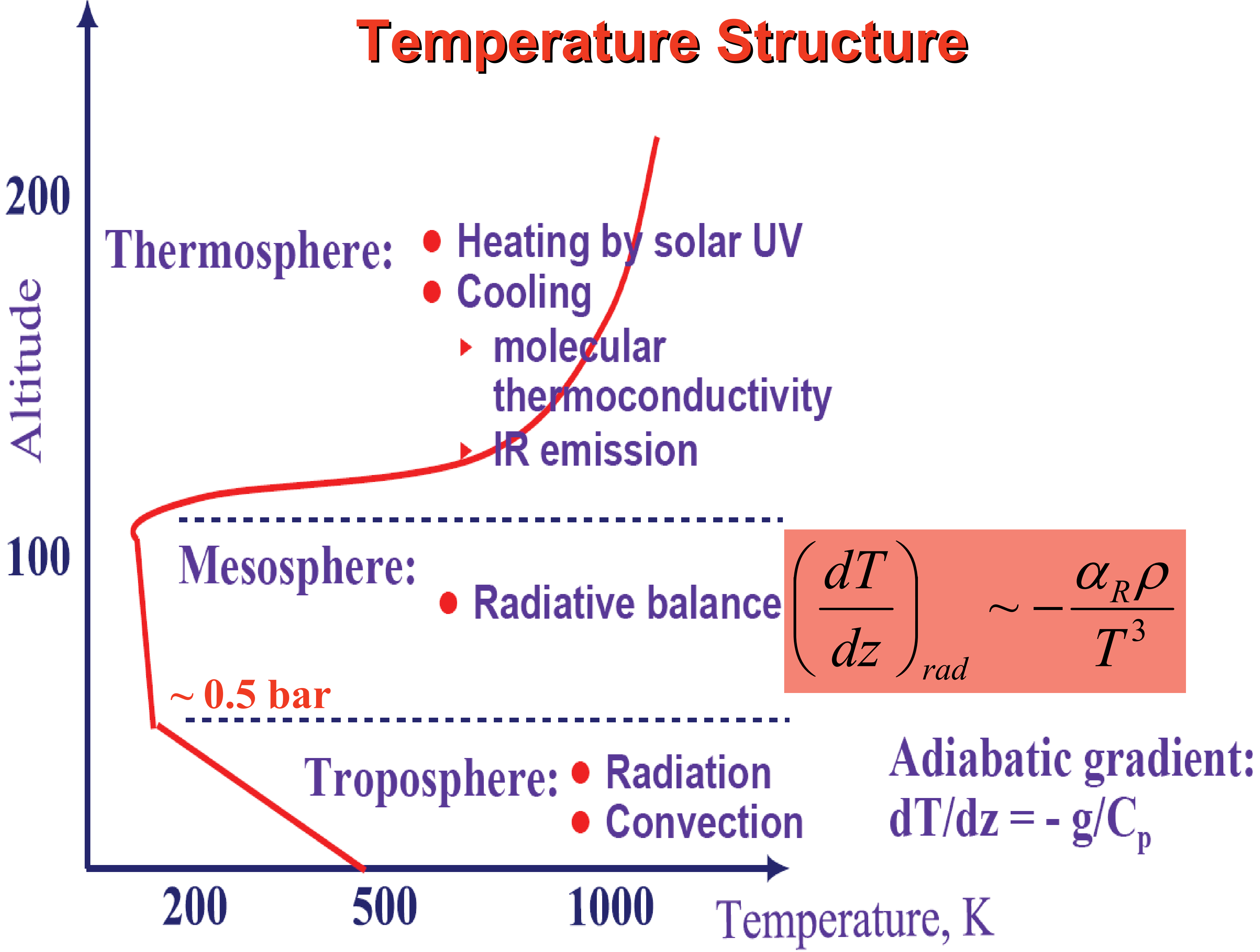


Exosphere and escape processes

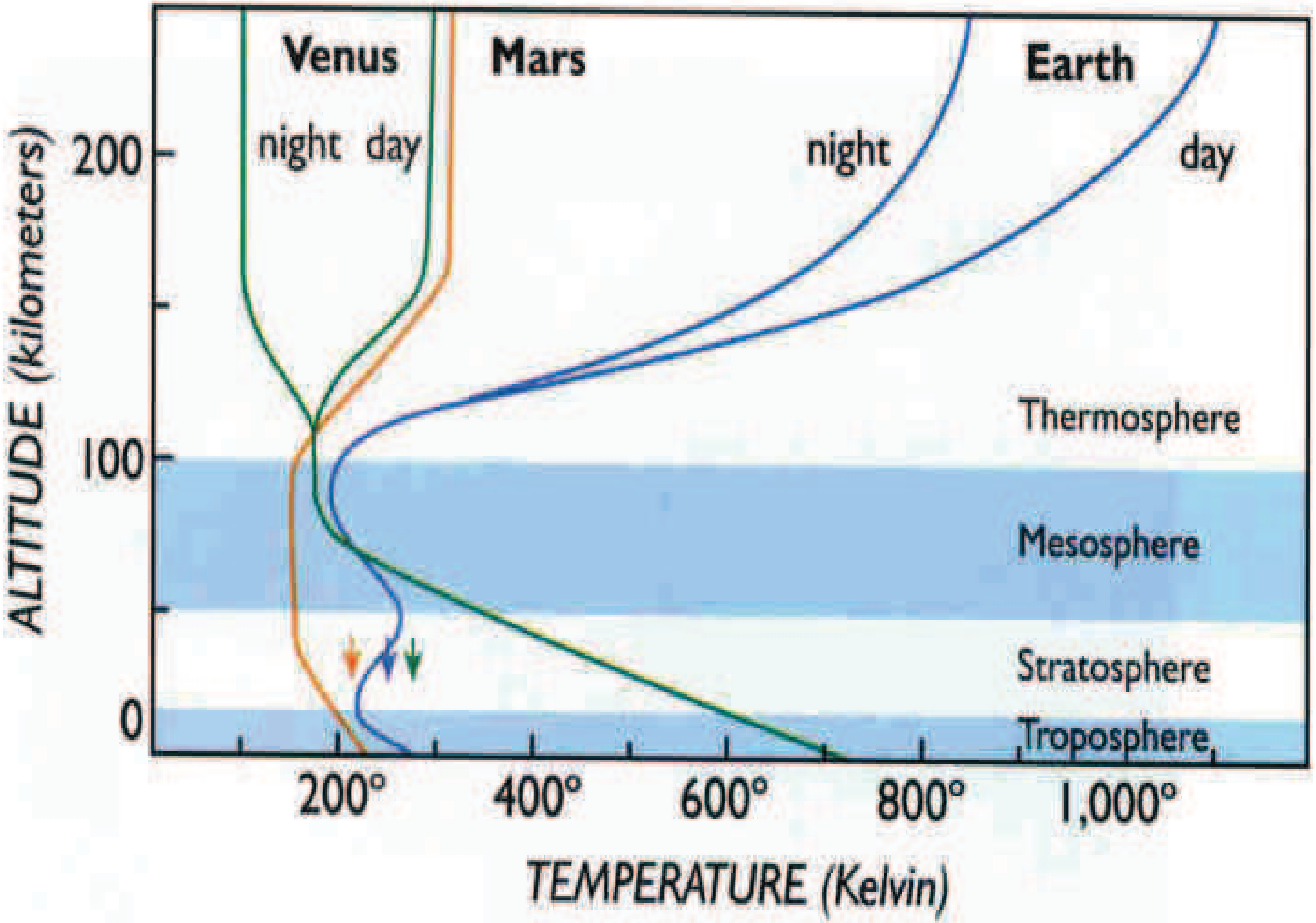
- **Exosphere:** ***free path > scale height***
- **Thermal (Jeans) escape**
- **Non-thermal escape**
  - ***dissociation***
  - ***charge exchange***
  - ***sputtering***
  - ***acceleration by electric field***
  - ***sweeping by solar wind***
- **Hydrodynamic escape**
- **Impact escape**



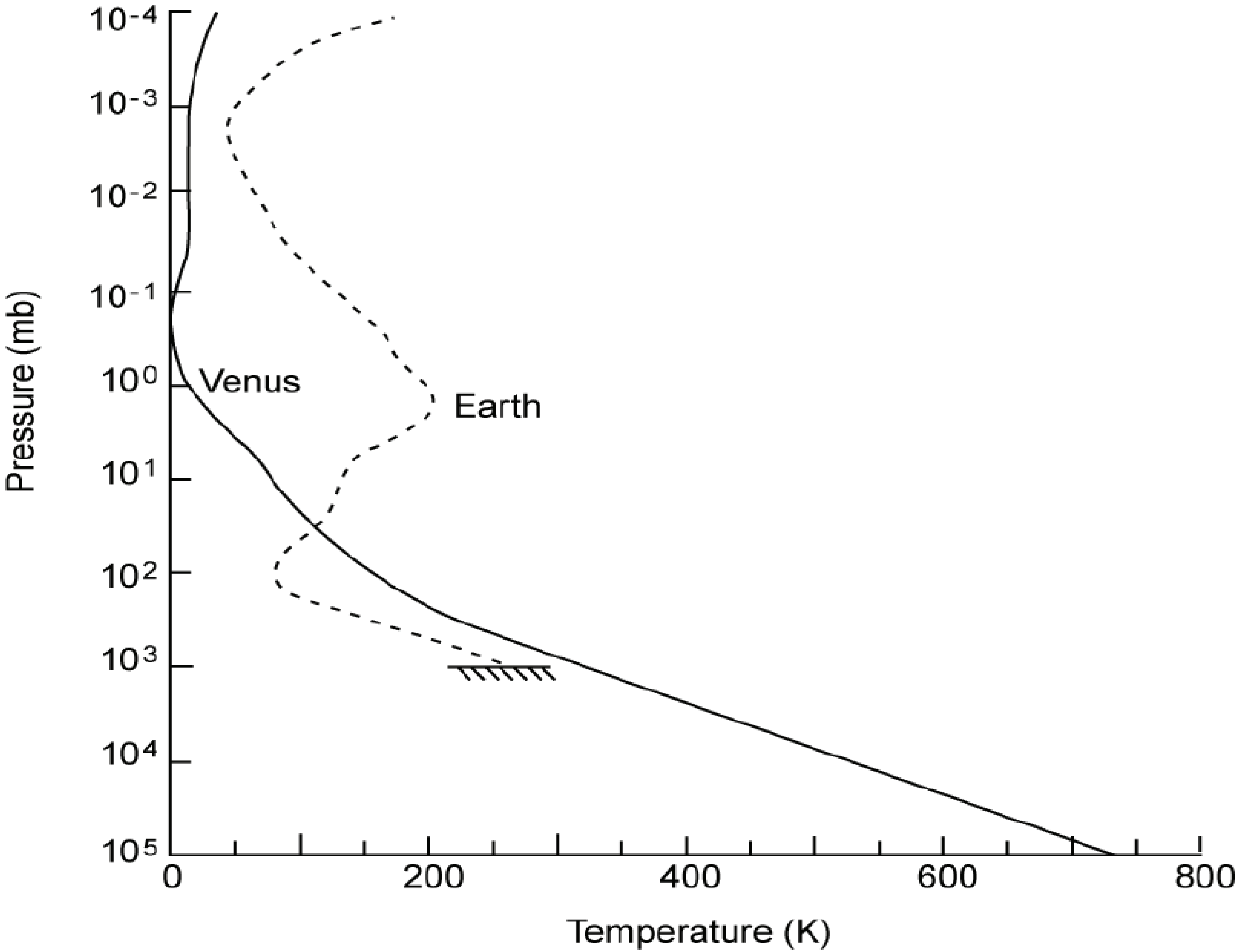
Temperature Structure



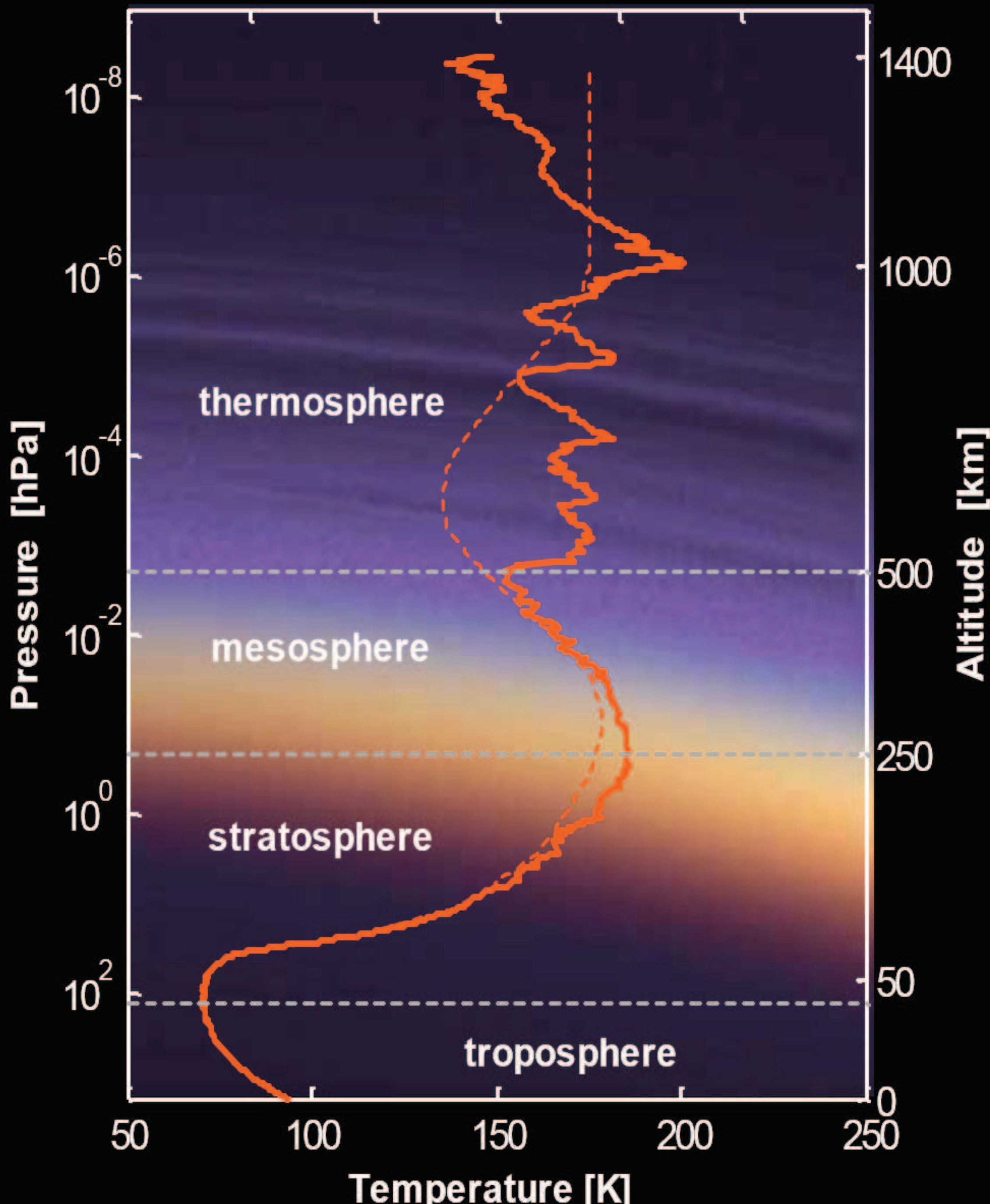
Temperatures on terrestrial planets



Temperatures on Earth and Venus

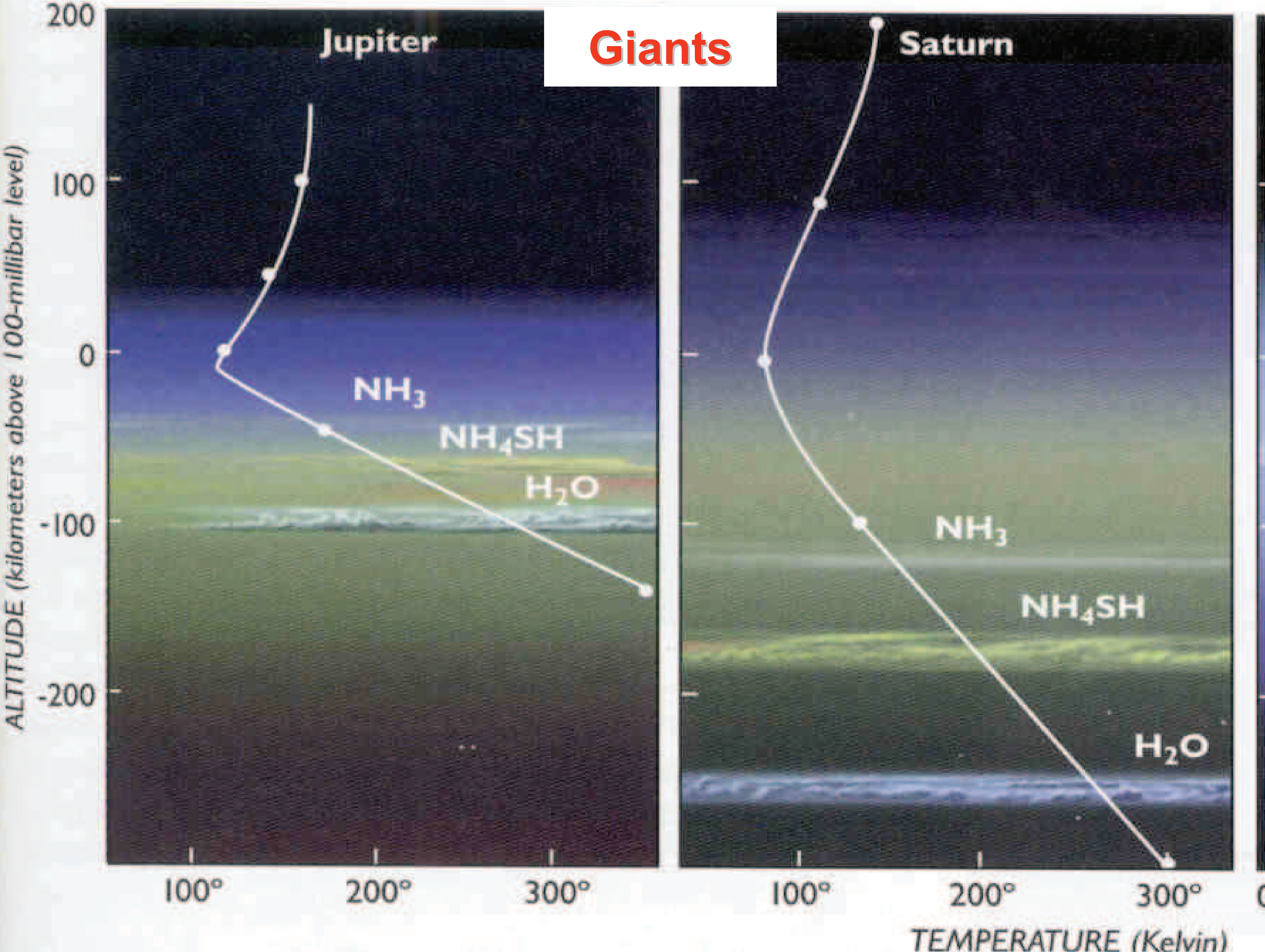


Titan



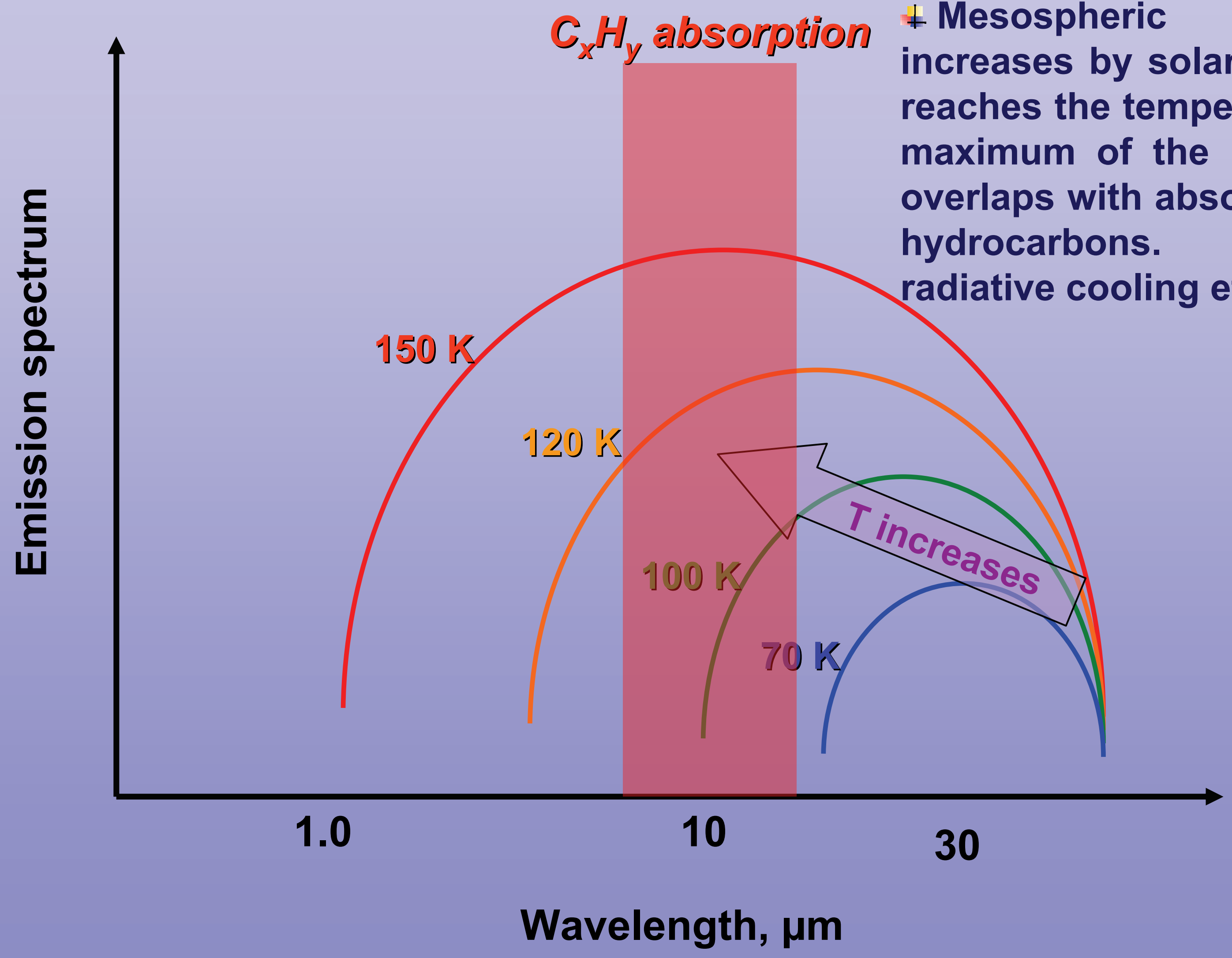
thermosphere
mesosphere
stratosphere
troposphere
Pressure [hPa]
10^-8
10^-6
10^-4
10^-2
10^0
10^2
Altitude [km]
1400
1000
500
250
50
0
50
100
150
200
250
Temperature [K]

Giants



Jupiter
Saturn
200
100
0
-100
-200
ALTITUDE (kilometers above 100-millibar level)
NH$_3$
NH$_4$SH
H$_2$O
NH$_3$
NH$_4$SH
H$_2$O
100°
200°
300°
100°
200°
300°
TEMPERATURE (Kelvin)

Mesospheric "thermostat" on Giants

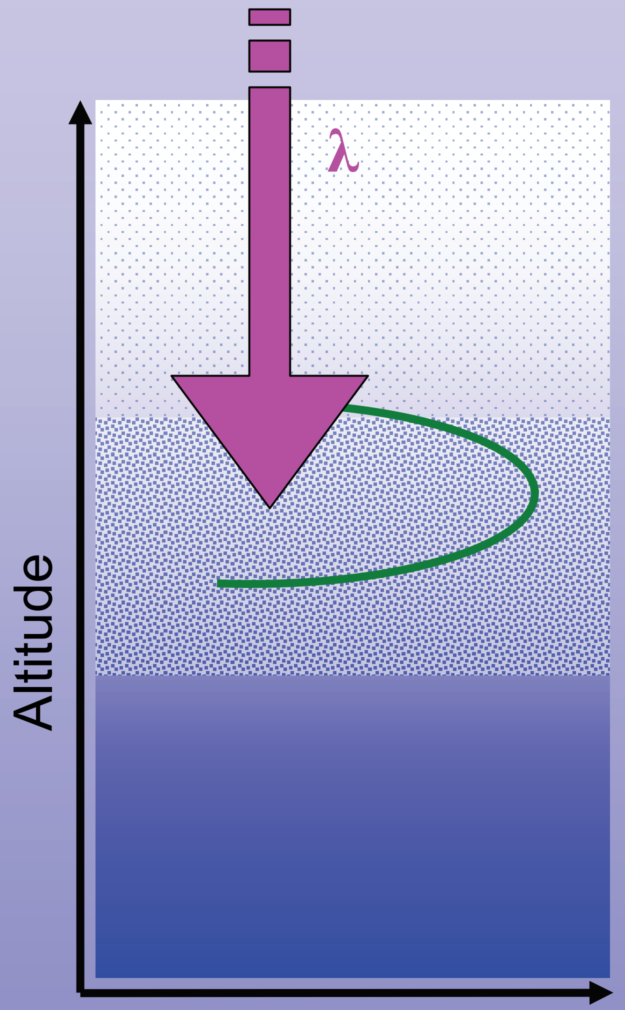


- Mesospheric temperature increases by solar heating until it reaches the temperature,for which maximum of the Planck function overlaps with absorption bands of hydrocarbons. This makes radiative cooling efficient.

Examples of structural parameters

	Venus	Earth	Titan	Jupiter	Saturn
g, m/s^2	8.87	9.78	1.35	~25	~10
μ	~44	29	28	~4	~4
Scale height, km	5-16	8.5	30-40	18	35
Lapse rate, K/km	8	8	~1	1.9	0.84

Formation of a planetary ionosphere



- Single gas
- Monochromatic radiation

Electron density $$\frac{\partial n}{\partial t} = Q - an^2$$

Chapman layer

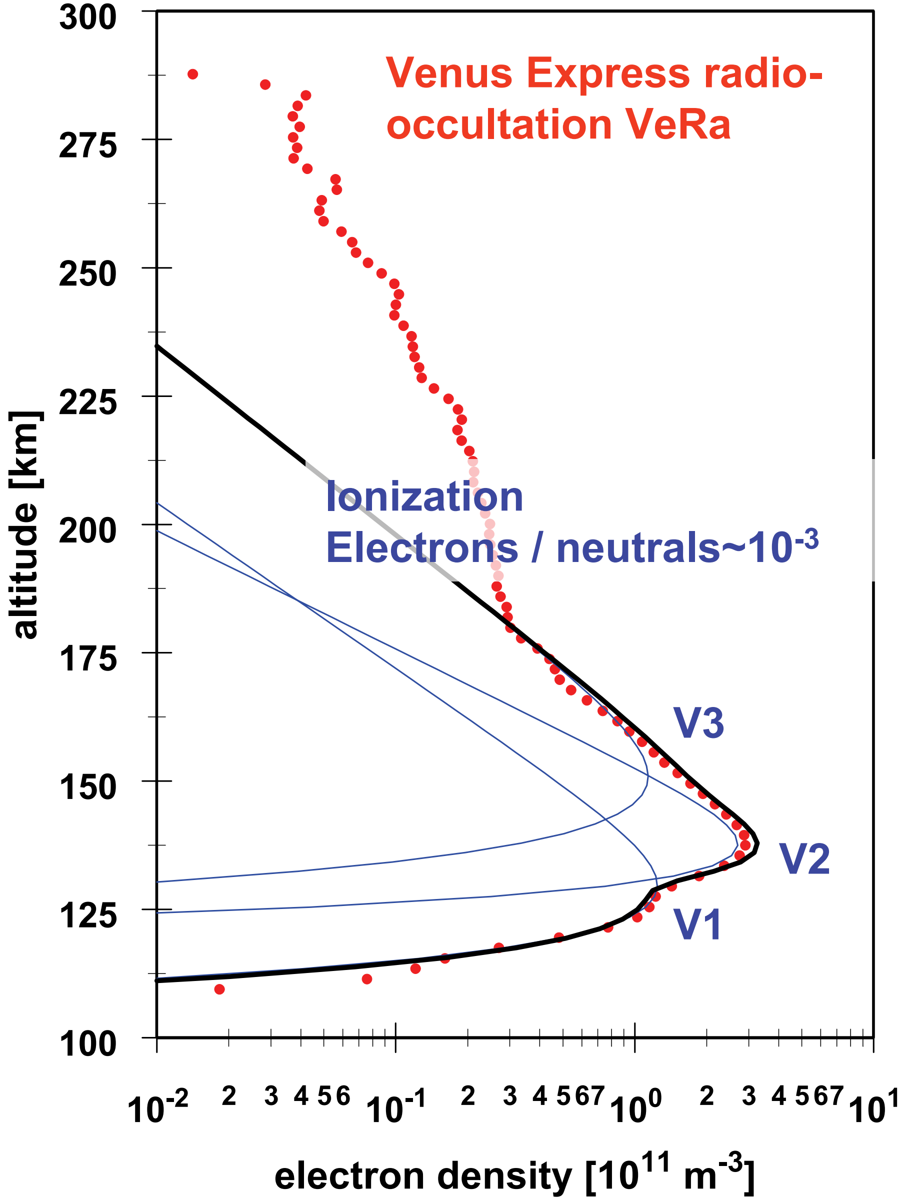
- Parabolic distribution of e⁻ density

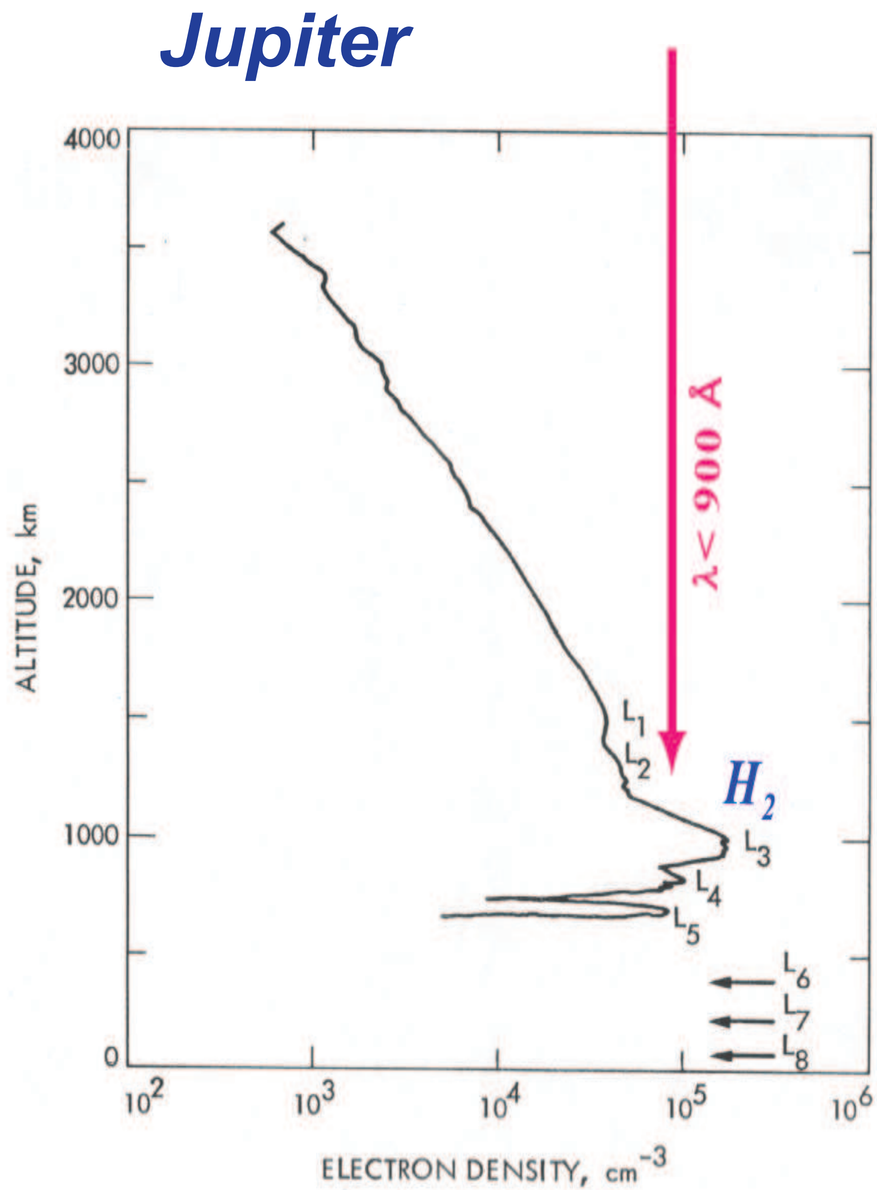
$$n \sim 1 - 0.25 \cdot (z - z_{\max})^2$$

- Variation with solar angle

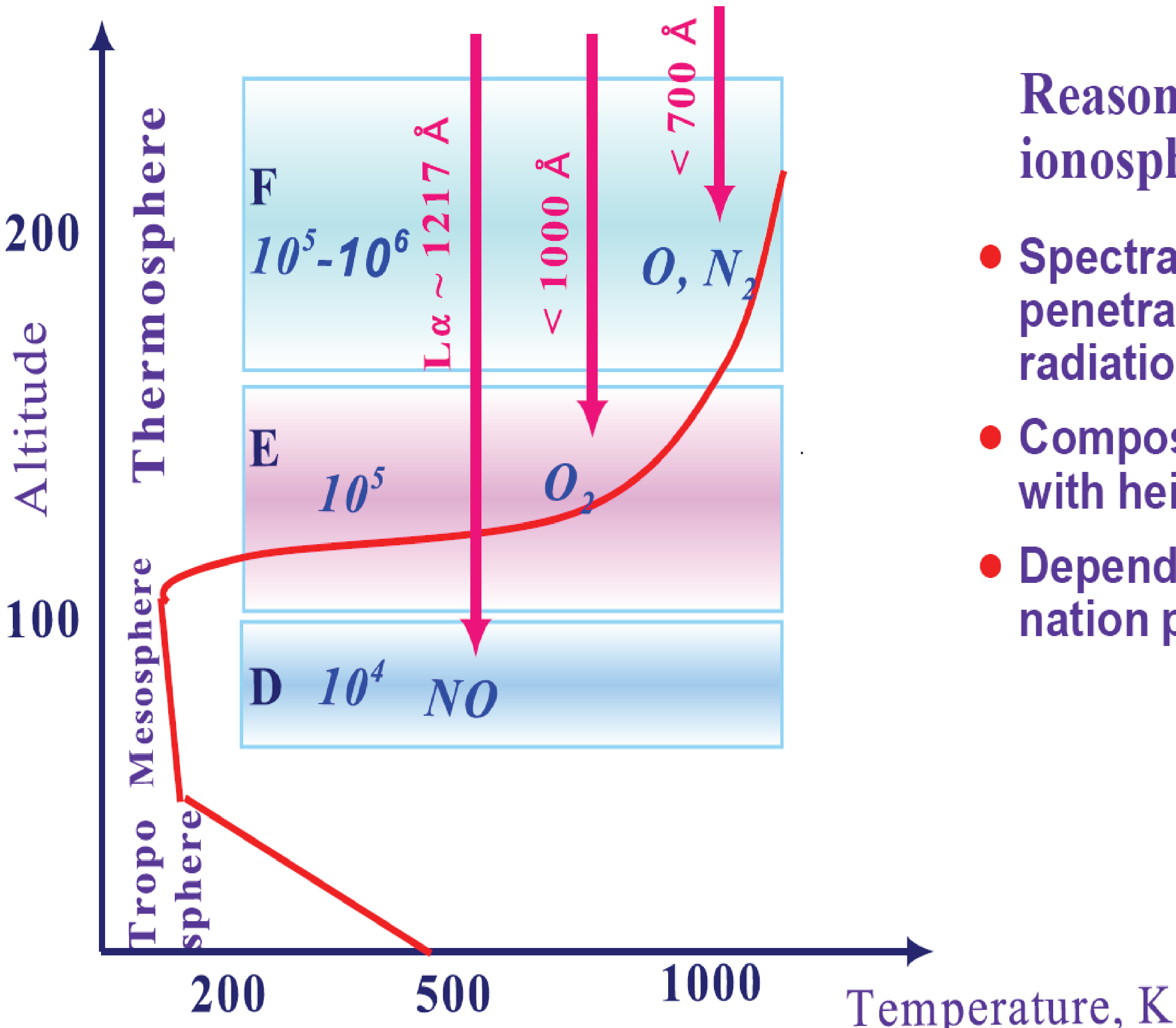
$$n_{\max} \sim \sqrt{\mu}$$

Structure of ionospheres





Ionosphere of the Earth



Reasons for distinct ionospheric regions

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

Composition, chemistry & clouds

Terrestrial planets

	Venus	Earth	Mars	Titan
N_2	3.5%	78%	2.7%	90-97%
O_2	0-20	21%	0.13	-
CO_2	96.5%	350	95.3%	10 ppb
CO	30-1000	0.2	700	10
H_2O	30	<3%	<100	0.4 ppb
SO_2	~200	-	-	
CH_4	-	3	10 ppb	4%
C_2H_2	-	~9 ppb		2
C_2H_6	-	~14	-	10

Giant planets

	Sun	Jupiter	Saturn	Uranus	Neptune
H_2	83.5%	86.4%	96.3%	85%	85%
He	19.5%	13.6%	3.2%	15%	15%
H_2O		600	?	?	?
CH_4		2000	4500	~2%	~3%
NH_3		~1000	500	<200	<200
H_2S		77	?	?	?

Other trace gases: PH_3, GeH_4, $AsH_{3,}$ C_xH_y

Tenuous atmospheres (in cm^{-3})

	Mercury	Moon	Pluto	Io
O	$4\ 10^4$			+
Na	$3\ 10^4$	70		+
He	$6\ 10^3$	$\sim 10^4$		
N_2			+	
Ar		$\sim 10^4$		
SO_2				10^{11}-10^{12}

Physical processes

- **Condensational equilibrium**
  - *Atmospheric H_2O on Earth and Mars*
  - *CO_2 on Mars*
  - *N_2 on Pluto and Triton*
- **Physical buffering by surface**
  - *Mars: regolith-atmosphere H_2O exchange*
- **Volcanic/ geiser activity**
  - *Io: SO_2 atmophere*
  - *Enceladus: H_2O supply by geisers*
- **Sputtering**
  - *Mercury: Na*
- **Capture from solar wind**
  - *Moon and Mercury: H, He*

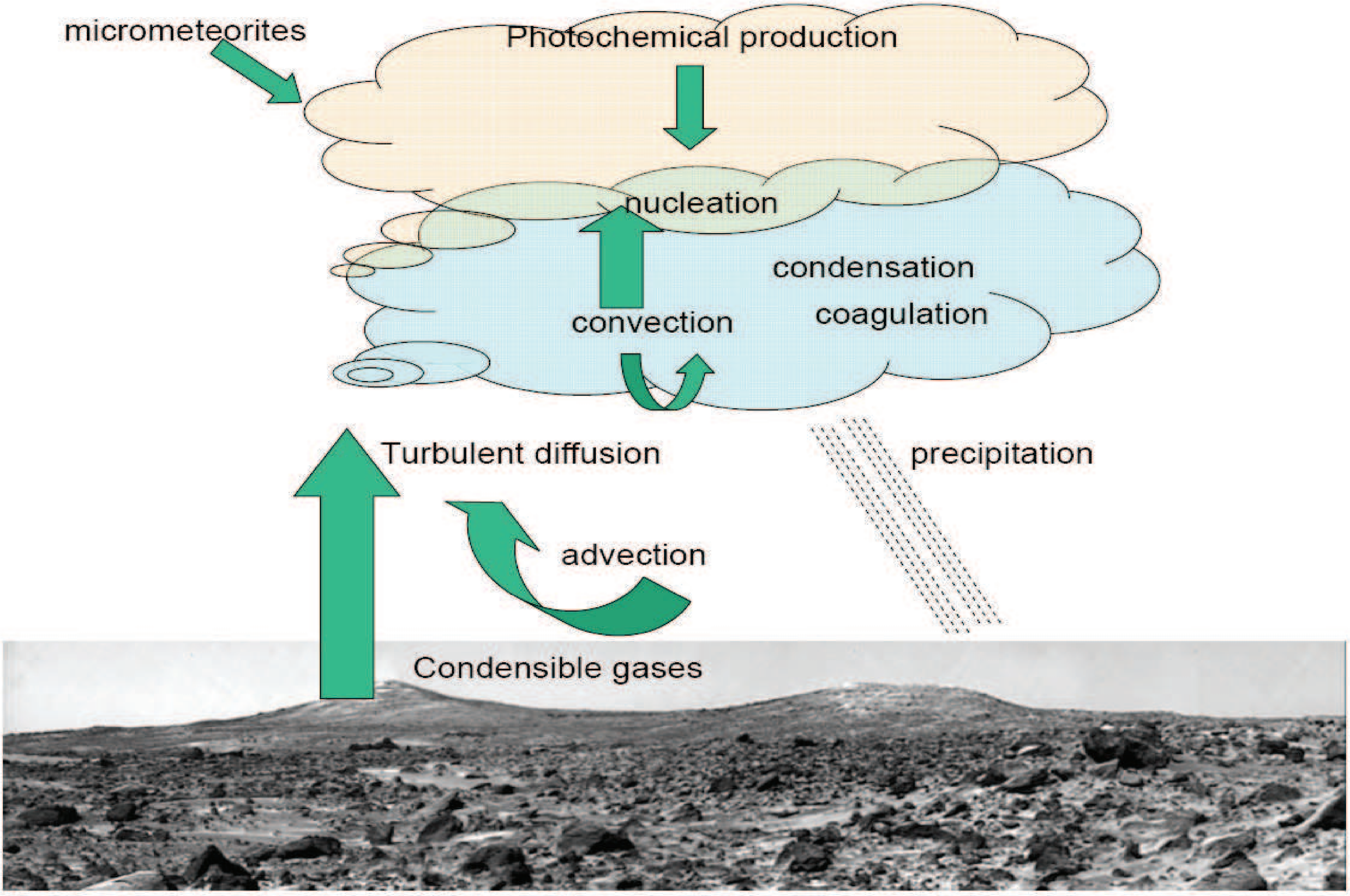
Chemical processes

- **Thermochemistry**
  - *Venus lower atmosphere*
- **Photochemistry**
  - *CO on Venus and Mars*
  - *Upper atmosphere of Titan*
- **Chemical buffering by surface minerals**
  - *Venus: atmospheric SO_2 and carbonates/ pyrites*
- **Heterogeneous chemistry on dust particles**
- **Biogenic / antropogenic influence**

Aerosols and clouds

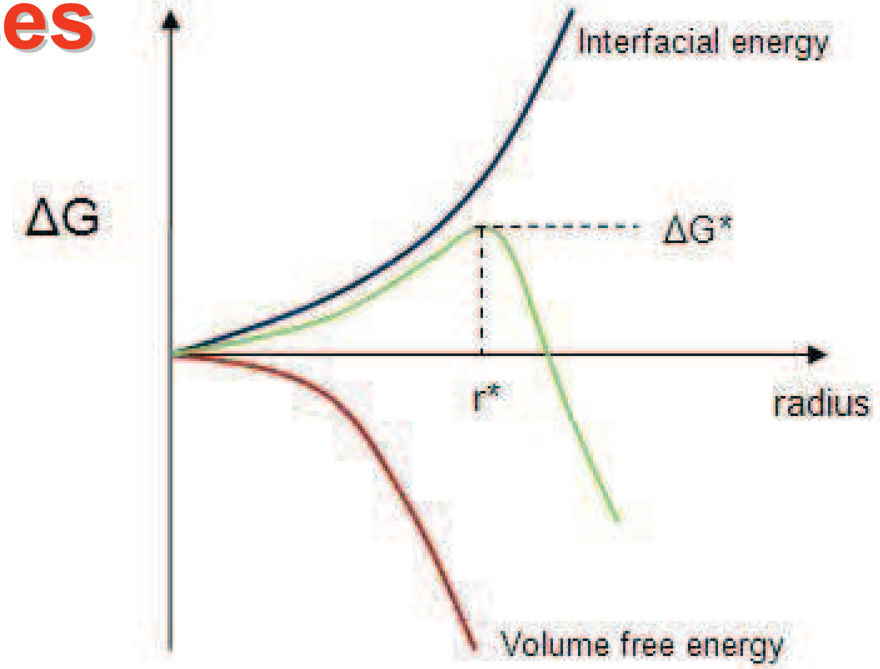
- **Condensational clouds**
  - *Earth: H_2O clouds*
  - *Mars: mesospheric CO_2 layers*
  - *Giants: NH_3 and H_2O ice clouds*
- **Chemical aerosols**
  - *Jupiter and Saturn: $NH_3 + H_2S \rightarrow NH_4SH$ (solid)*
- **Photo-chemical aerosols**
  - *Venus: $SO_2 + H_2O + h\nu \rightarrow H_2SO_4$ (liquid)*
  - *Titan: $CH_4 + h\nu \rightarrow C_xH_y$ (tholines)*
  - *Earth: photochemical smog*
- **Dust**
  - *Mars & Earth*

Microphysical processes



Microphysical processes

- **Homogeneous nucleation**



- **Heterogeneous nucleation**

- **Diffusional growth**

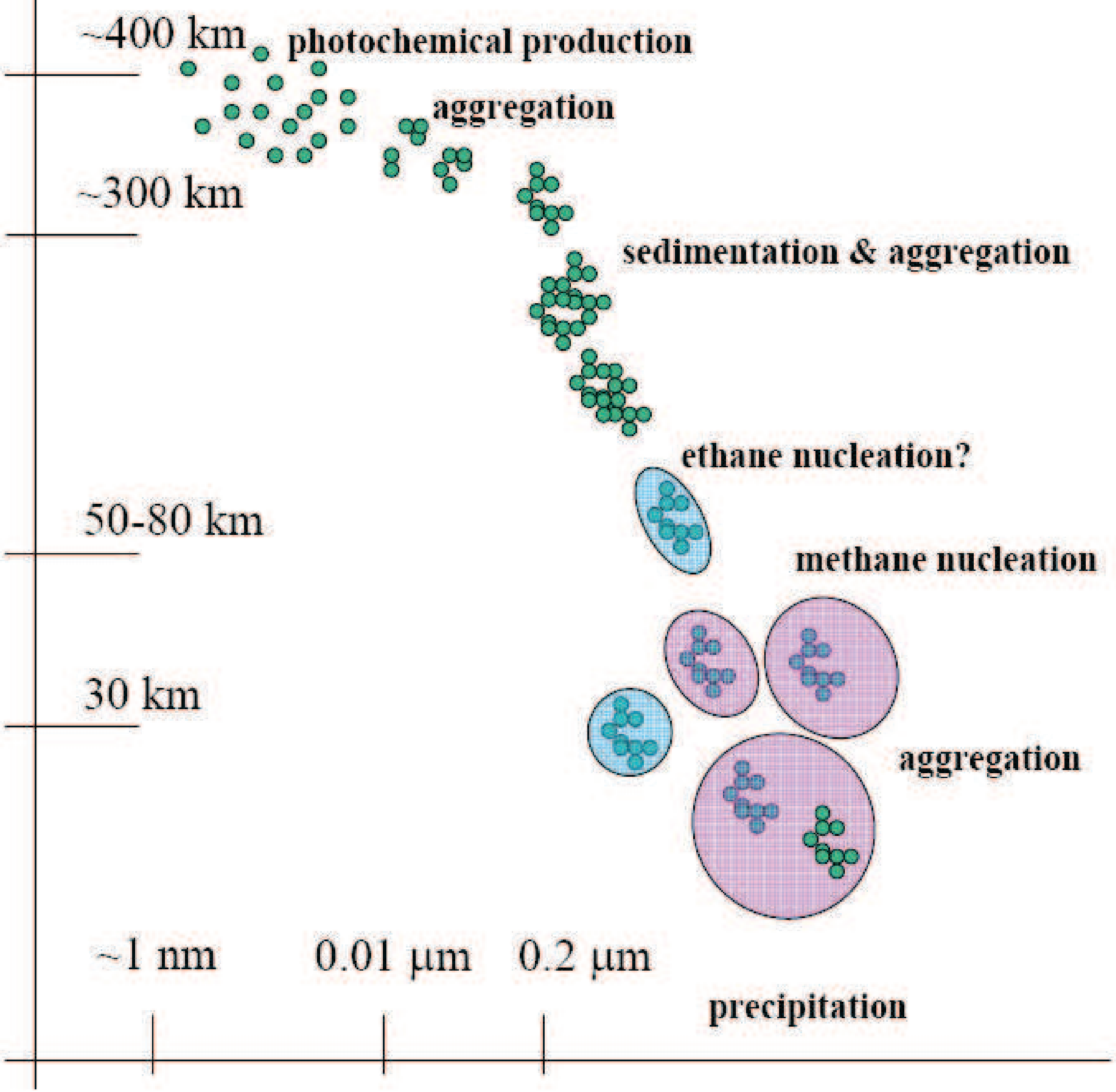
$$r\frac{dr}{dt} \sim S-1$$

  - *small droplets grow faster*
  - $r \sim \sqrt{t}$

- **Coagulation** $\frac{dn}{dt} \sim Kn^2$

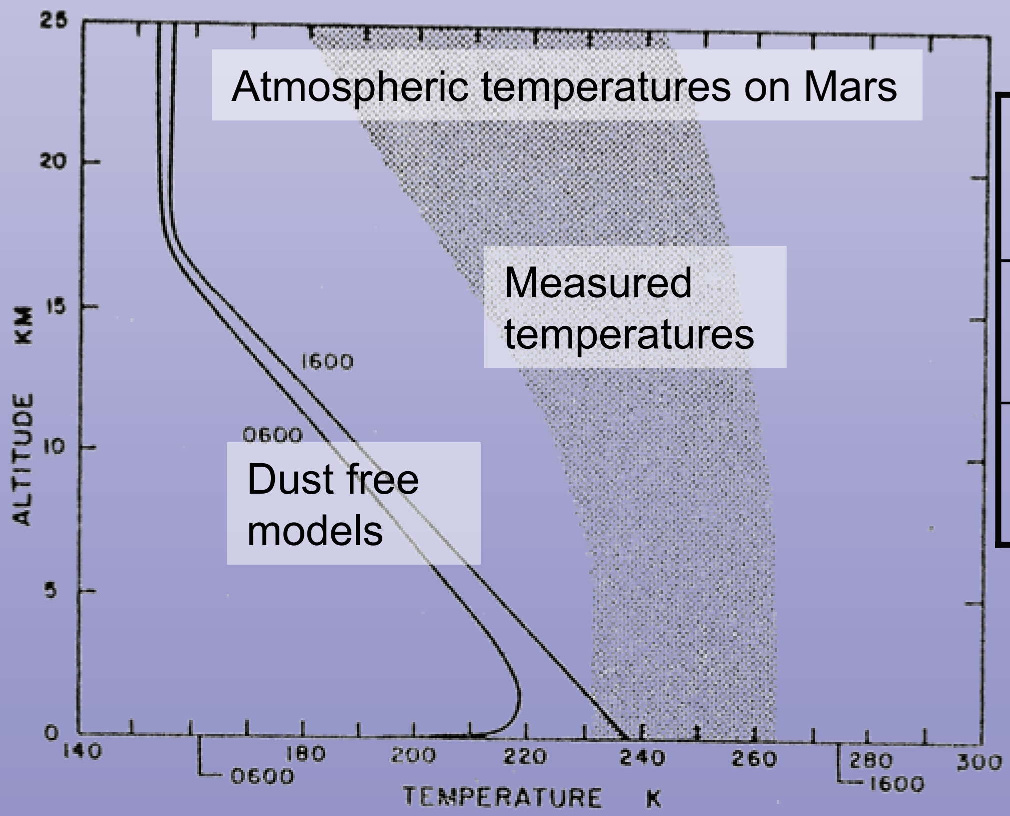
- **Sedimentation** $v \sim r^2$

Aerosols in Titan's atmosphere



Aerosol effects

- **Radiative effects**
  - *Deposited solar energy: Earth vs Venus*
  - *Greenhouse effect: Venus & Mars*

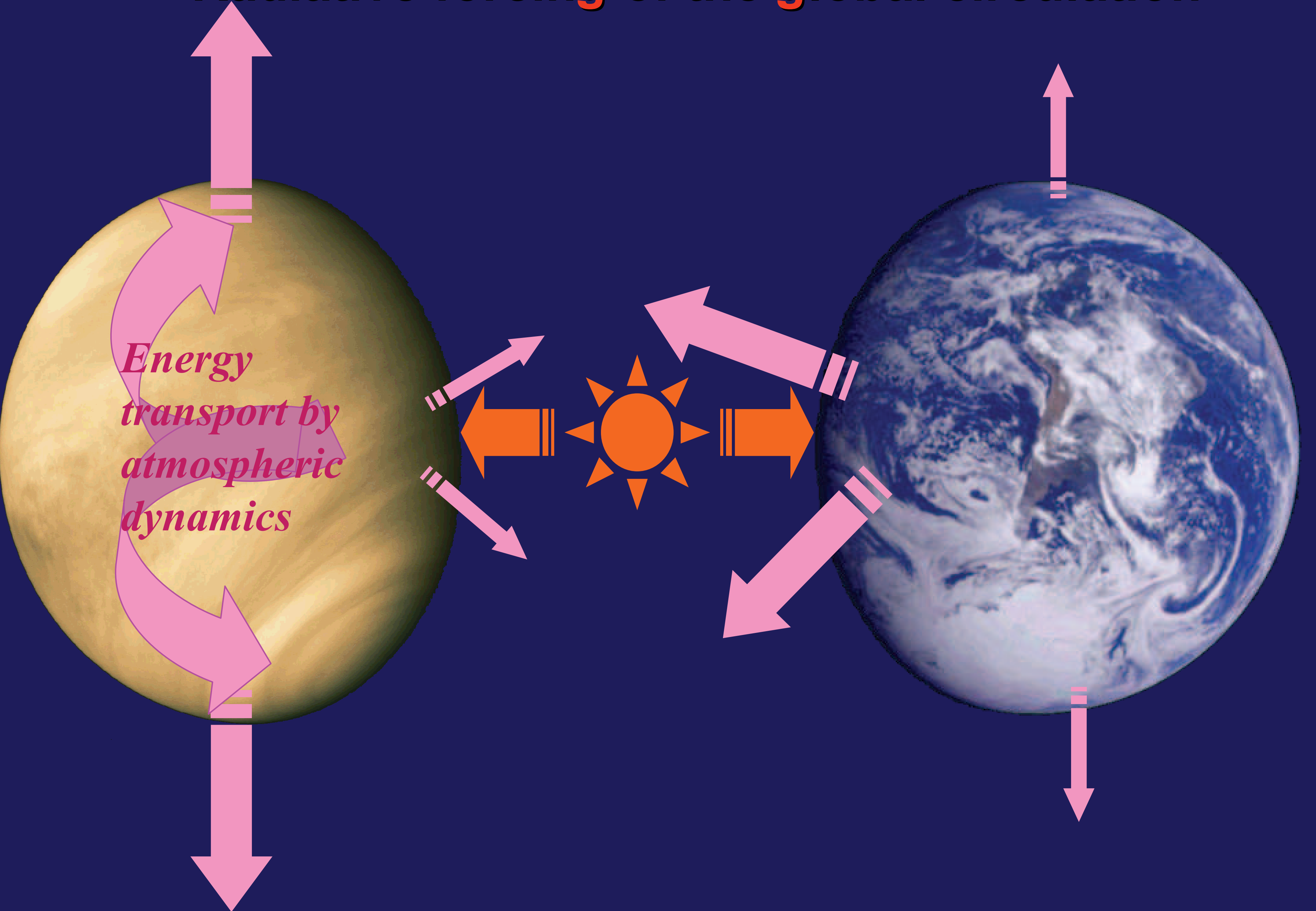


	Solar flux, W/m²	Albedo	Deposited Solar energy
Earth	~1300	0.4	780
Venus	~2600	0.75	650

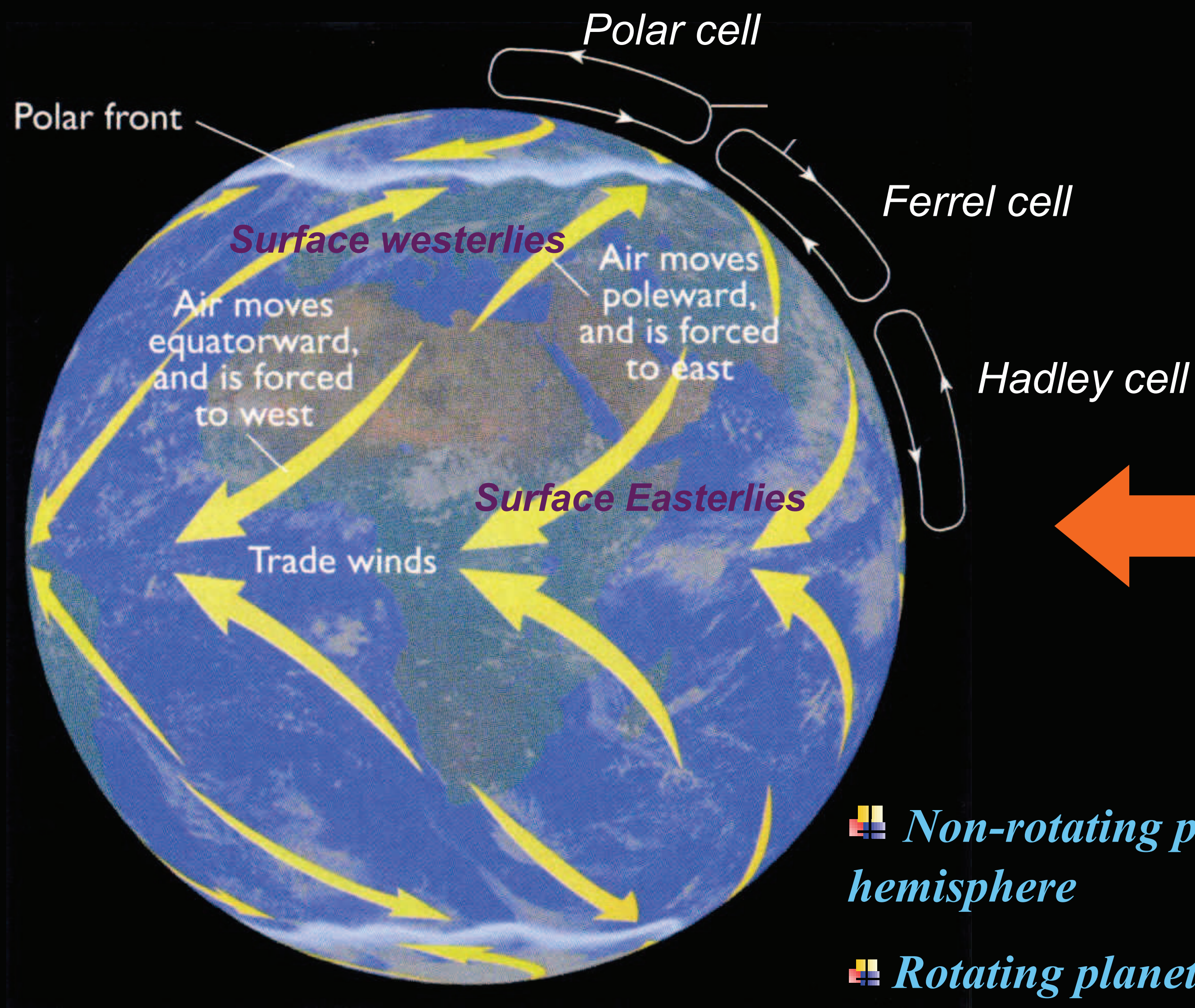
- **Cleaning of the atmosphere**

Dynamics of planetary atmospheres

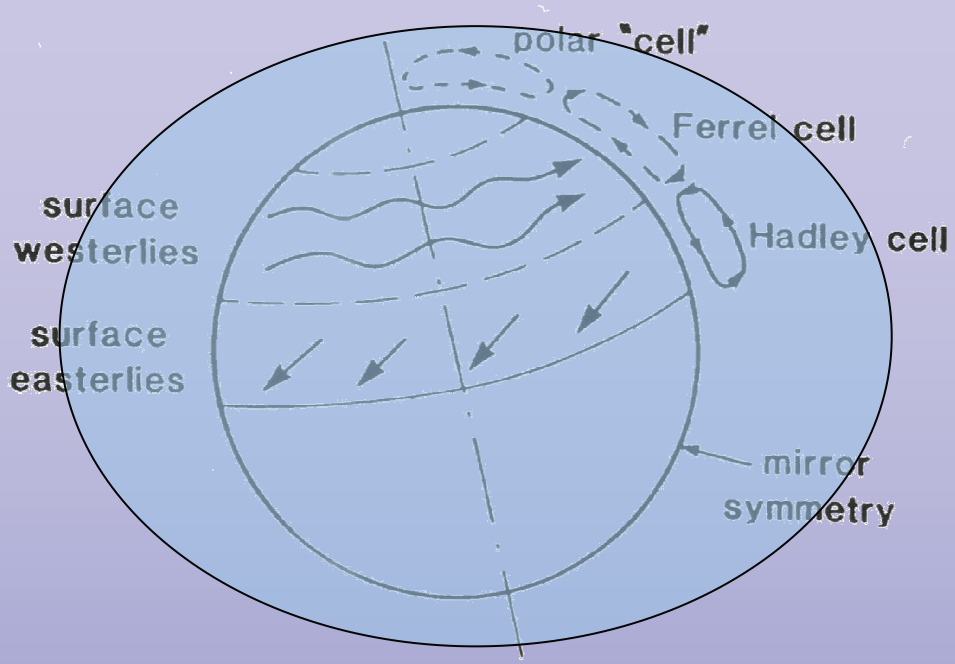
Radiative forcing of the global circulation



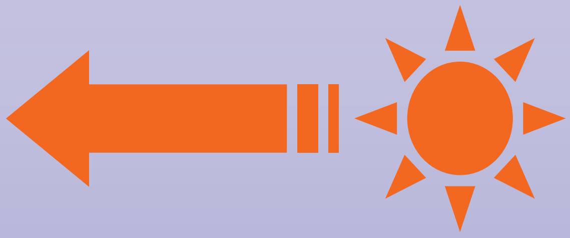
Hadley circulation



- *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

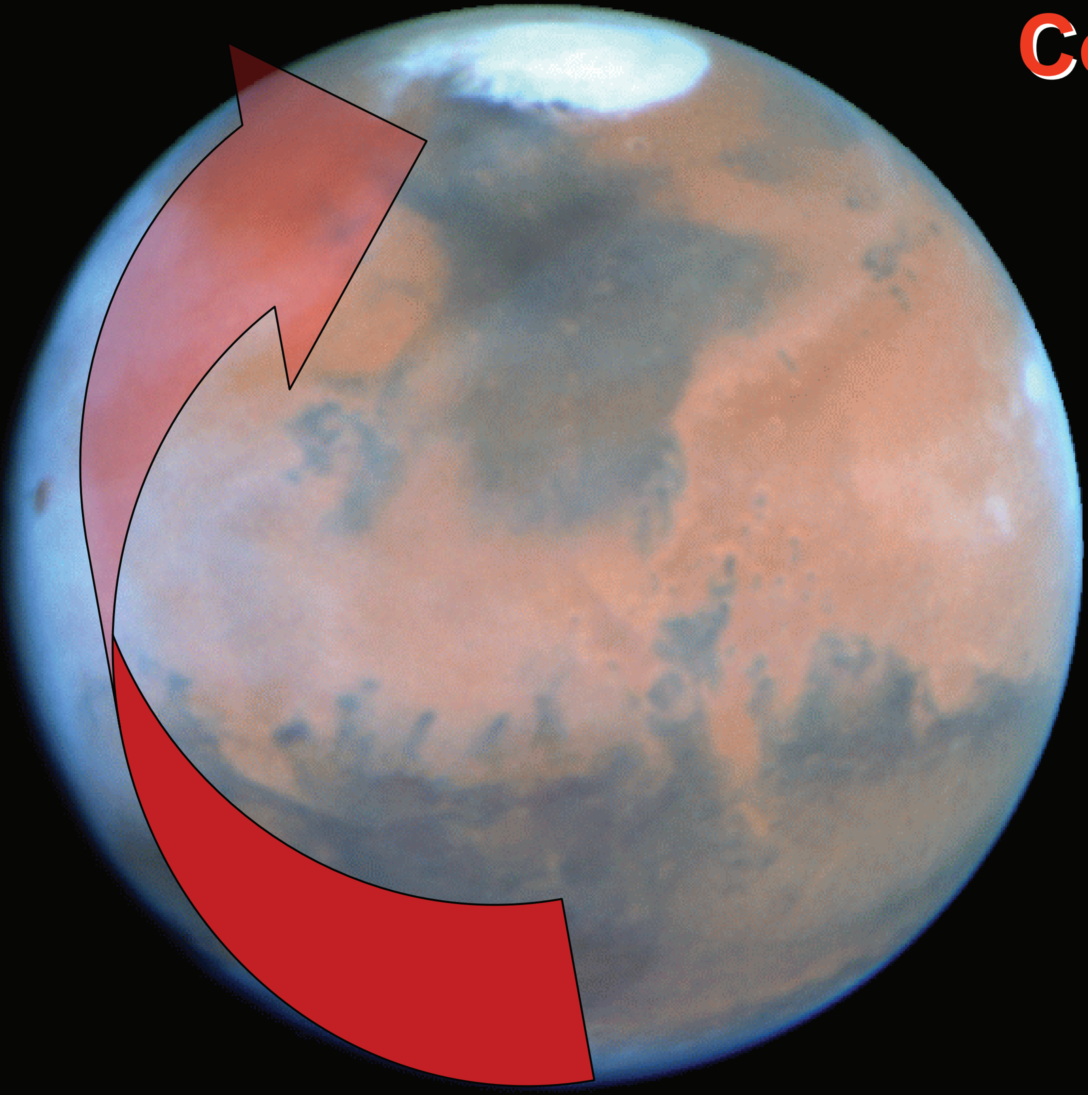


- *Global energy balance*

$$(1-A)Ft = C_p M \delta T$$

- *$\delta T/T$ ~ 0.4% for Venus (tides in the thermosphere)*
- *$\delta T/T$ ~ 20% for Mars (tides in the entire atmosphere)*
- *Maintenance of the Venus super-rotation*

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)*

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

Simplified wind equations

- *Simplifications*
  - *incompressible and inviscid fluid*
  - *centrifugal force << gravity*

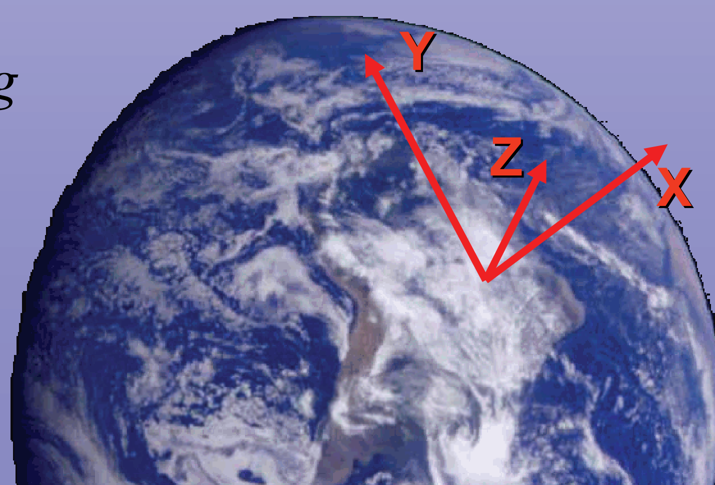
$$\frac{Dv'}{Dt} = -2\omega_{rot} \times v' - \frac{1}{\rho}\nabla P + (g + \omega_{rot}^2 r) + \nu\nabla^2 v'$$

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

- *"shallow water" approximation*
- *hydrostatic equilibrium*

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

f = 2Ωsin[illegible] - Coriolis parameter



Steady horizontal flow (1)

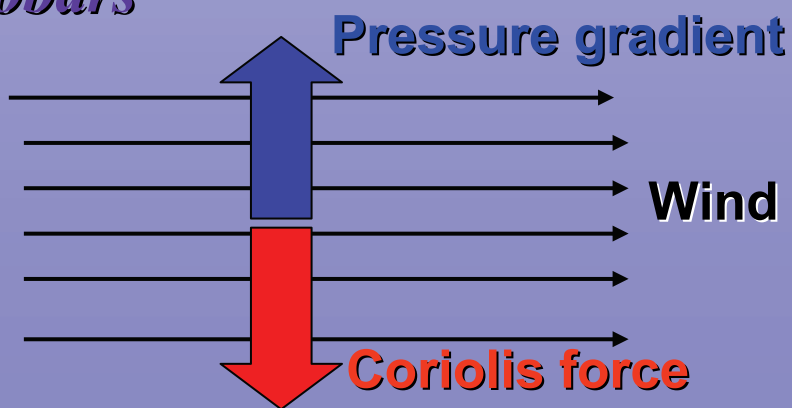
Geostrophic wind

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

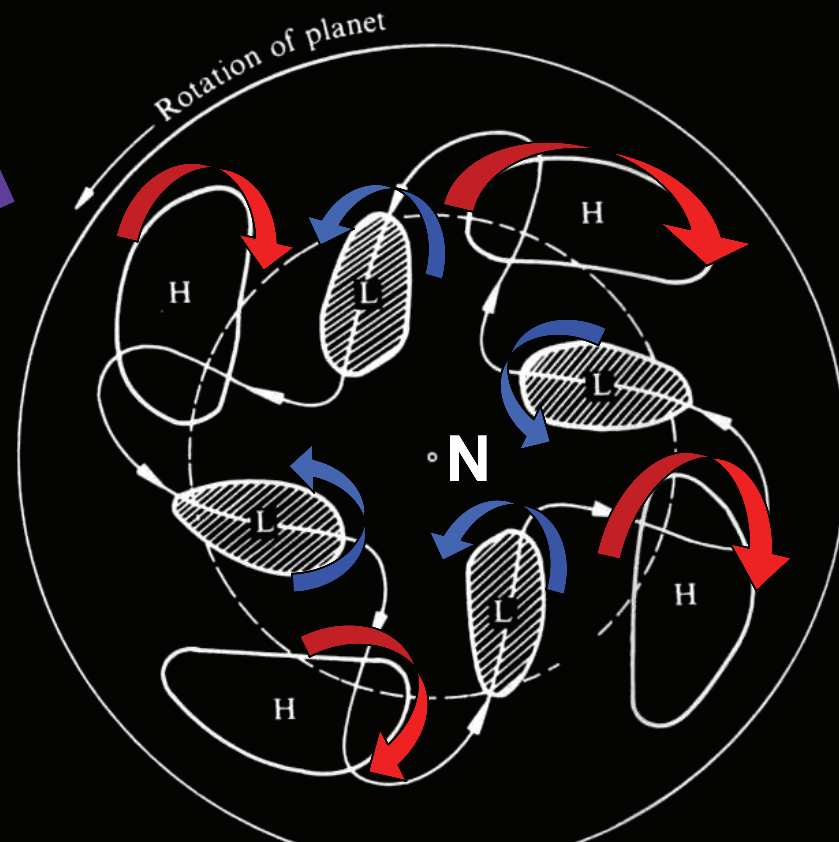
Rossby number :

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

- *Ro << 1 ⇒ importance of Coriolis force*
- *Geostrophic wind blows along isobars perpendicular to* ∇p



Global circulation on Earth



In the Northern hemisphere

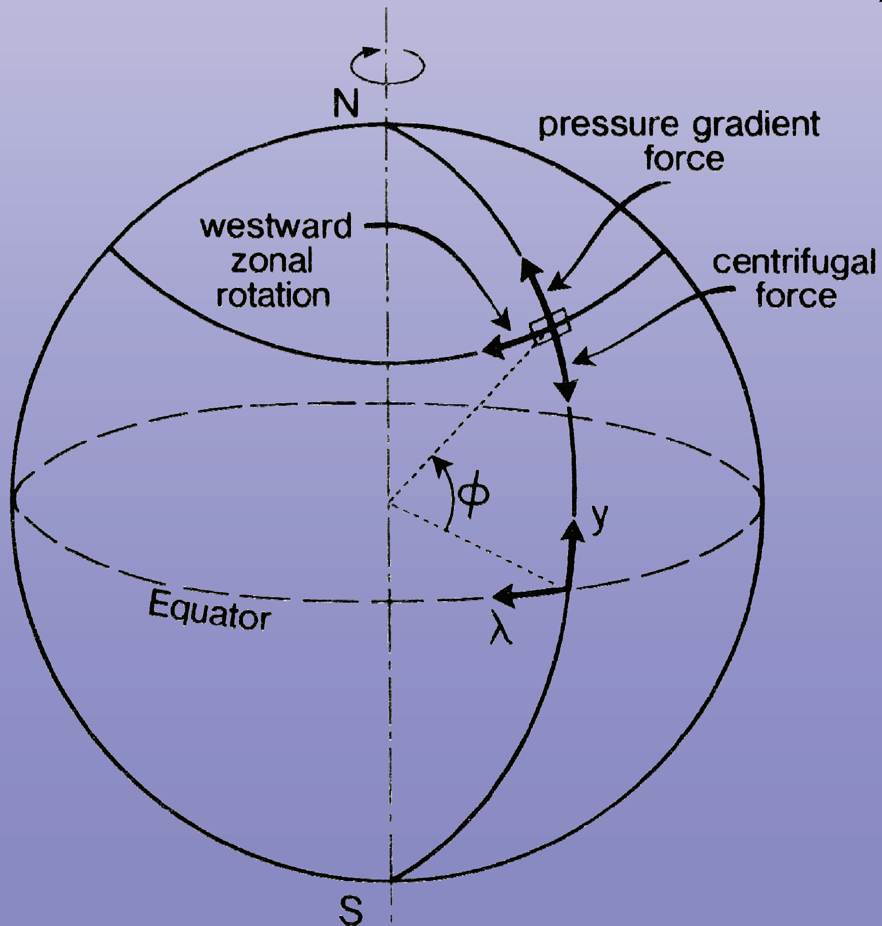
Cyclones – anticlockwise rotation

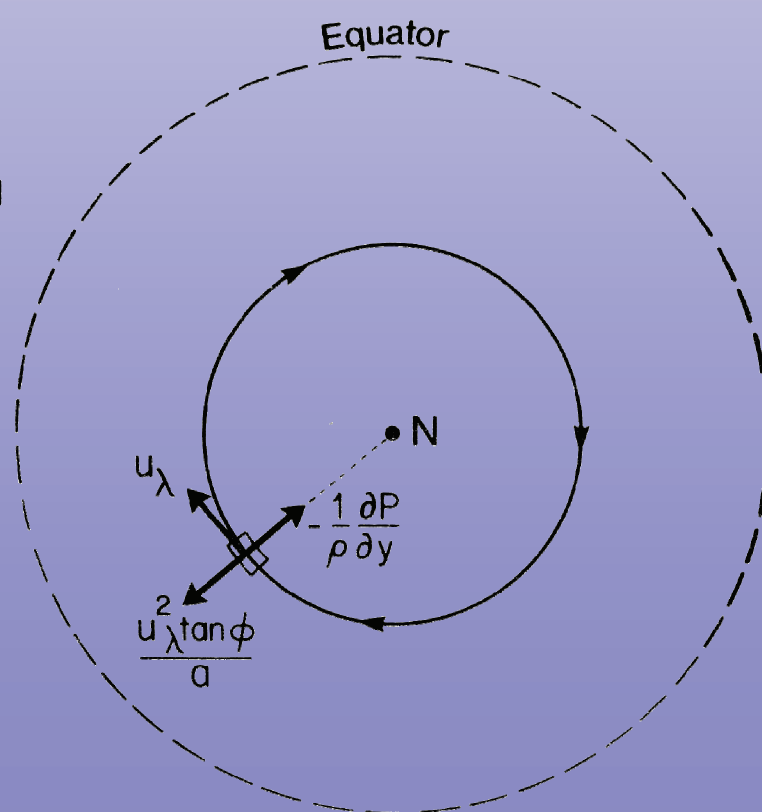
Anticyclones – clockwise rotation

Steady horizontal flow (2)

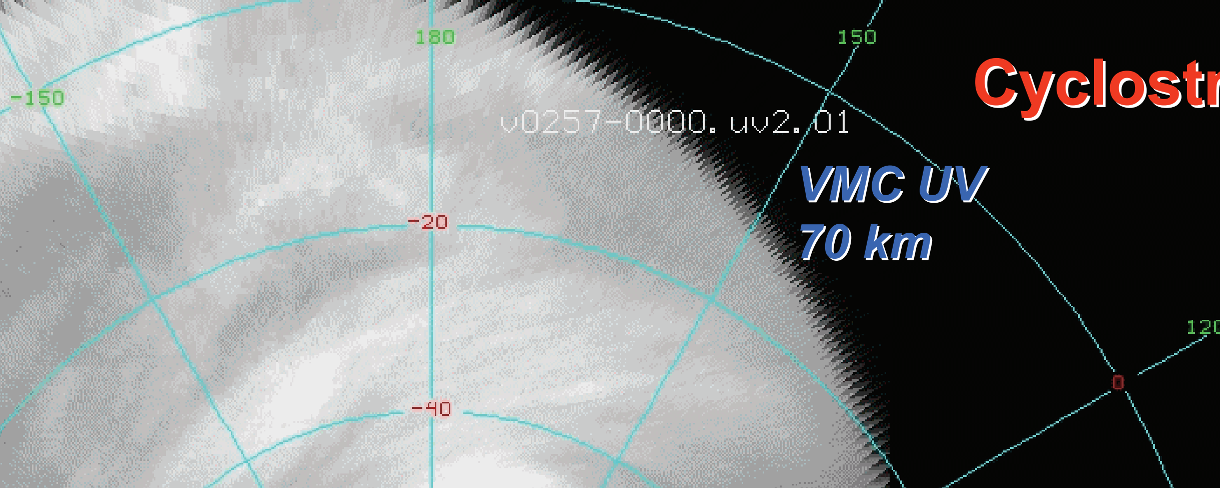
Cyclostrophic wind

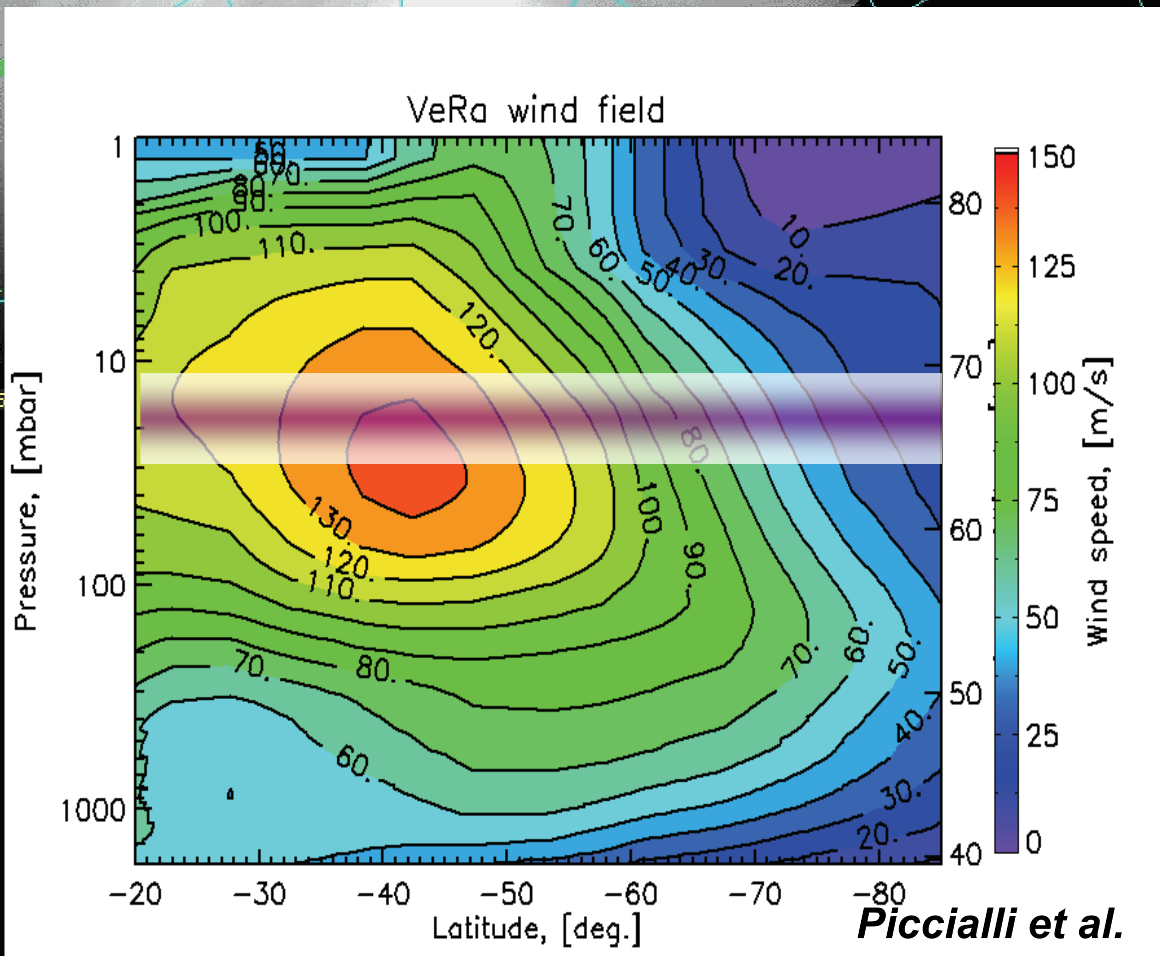
$$\frac{dV}{dt} = \cancel{fV \times k} - \frac{1}{\rho}\nabla p \;\Rightarrow\; \frac{V^2}{R} = -\frac{1}{\rho}\frac{\partial p}{\partial n} \;\Rightarrow\; \frac{\partial u^2}{\partial z} \approx -\frac{R}{\tan\varphi}\frac{\partial T}{\partial \varphi}$$

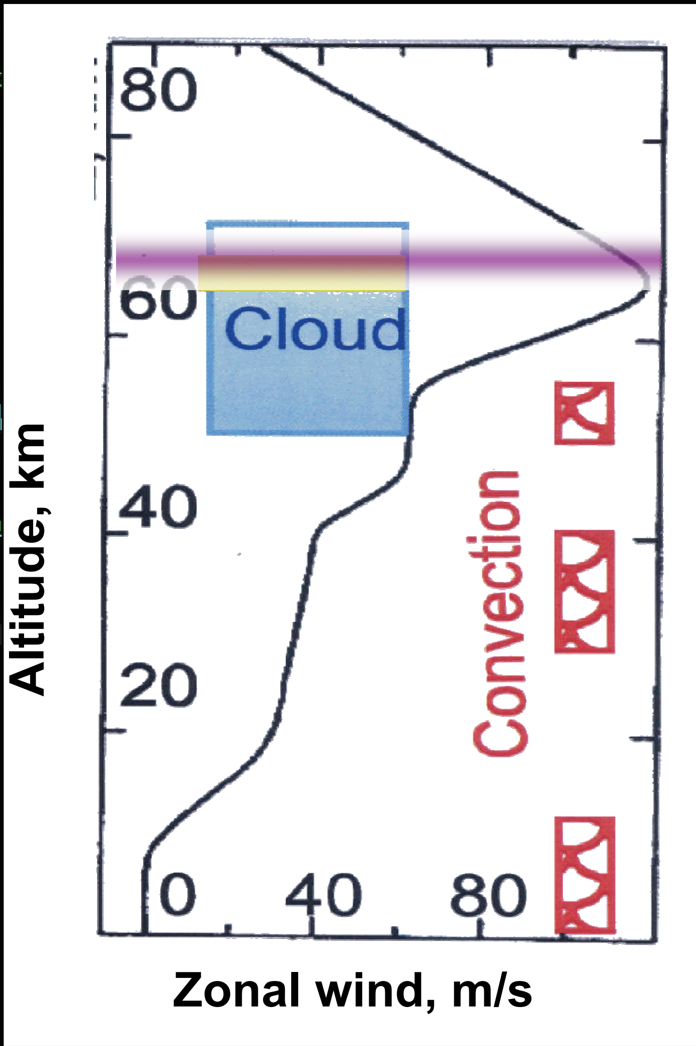




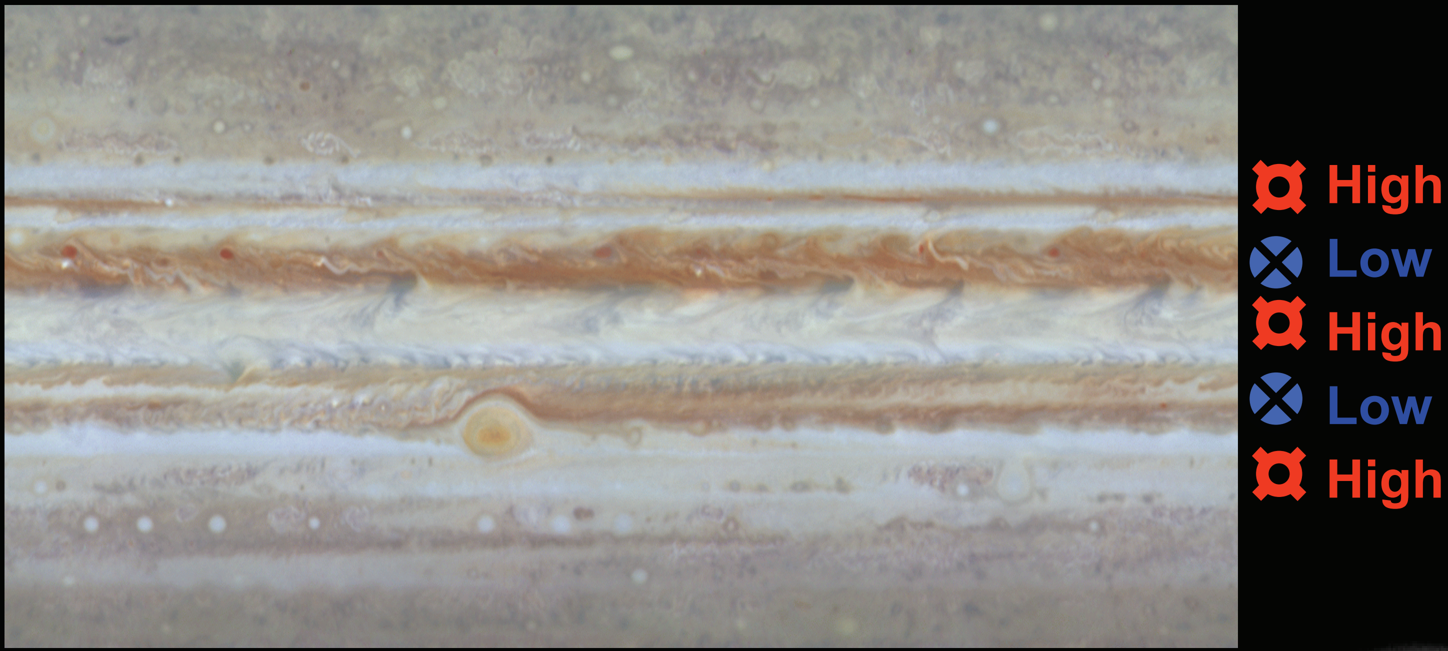
Cyclostrophic super-rotation on Venus







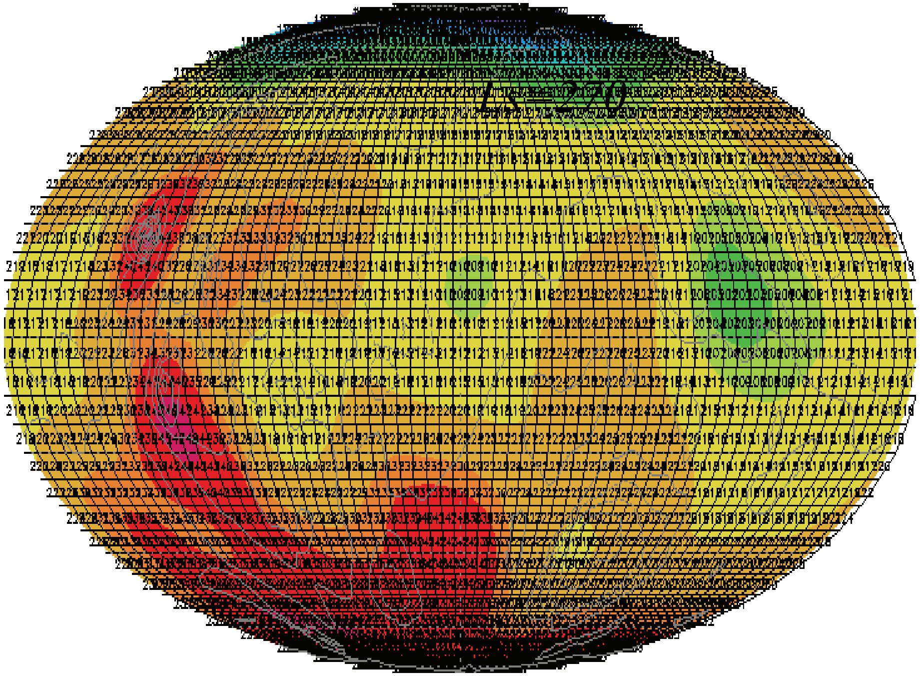
Mean circulation on Jupiter



- “Zebra” of cyclonic (low P) dark belts and anticyclonic (high P) bright zones
- *Equatorial super-rotating jet*

General Circulation Model: the MAOAM example

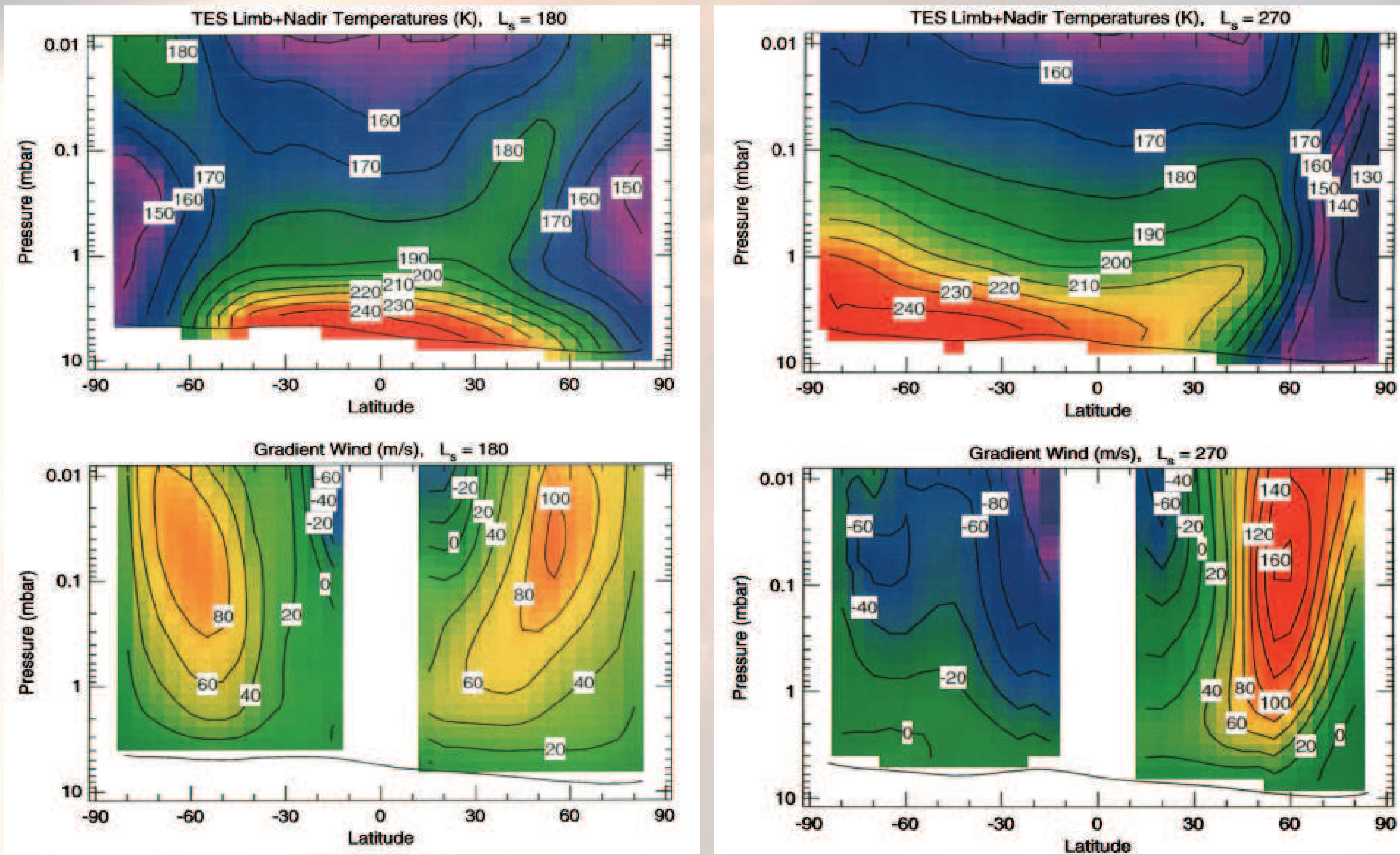
- Originate from Earth GCMs
- Grid point model from the surface to 120 km
- Variable vertical (~1 km) and horizontal (64x36) resolution
- Log-pressure coordinates (6 mb at z=0 km)
- Realistic topography and surface parameters: albedo and thermal inertia
- State-of-the-art physics package



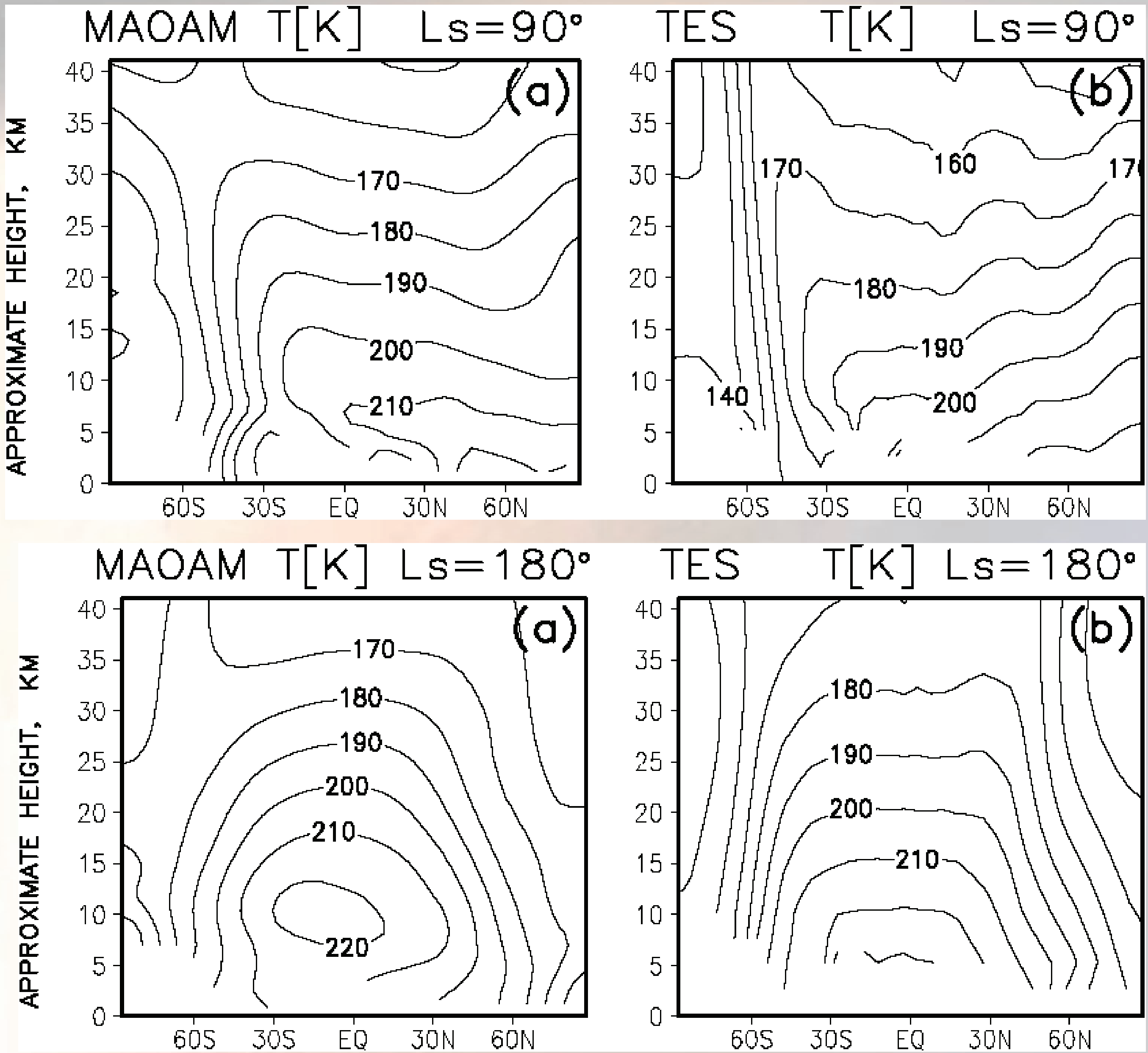
MAOAM atmospheric temperature

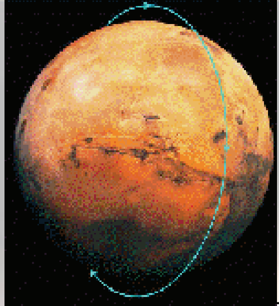
Hartogh, Medvedev, et al., JGR, 2005

Temperature and thermal winds on Mars from TES/ MGS observations

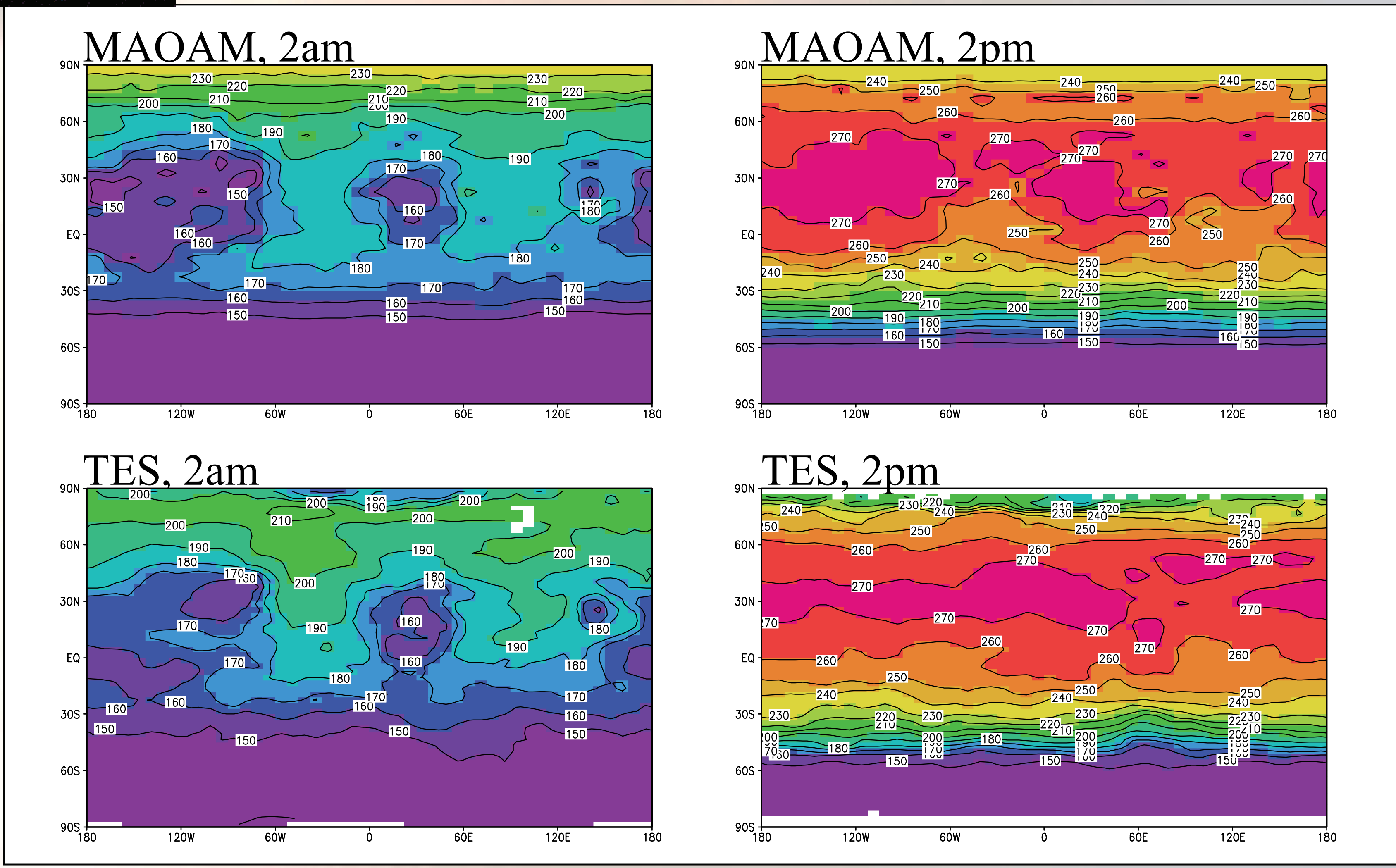


MAOAM-TES comparison

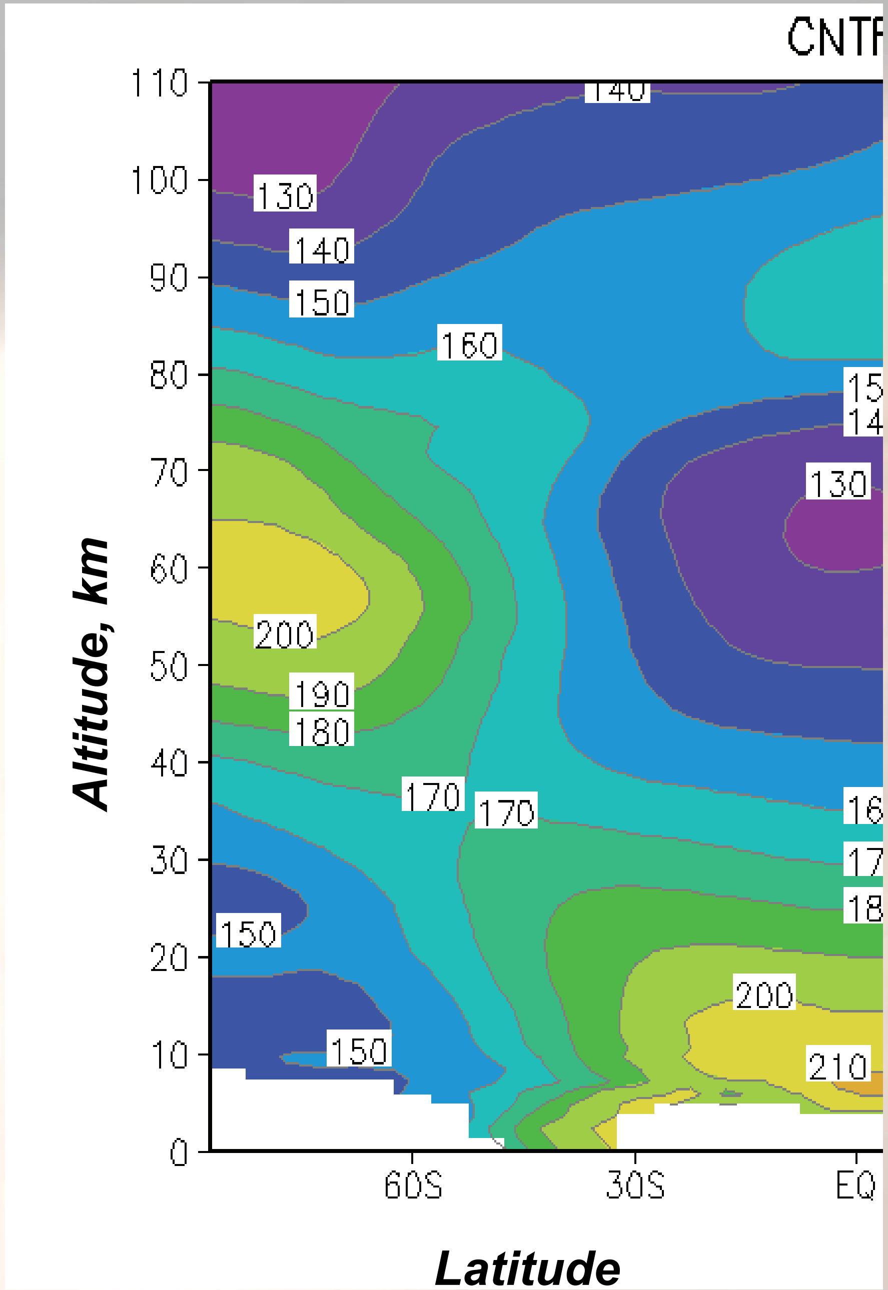




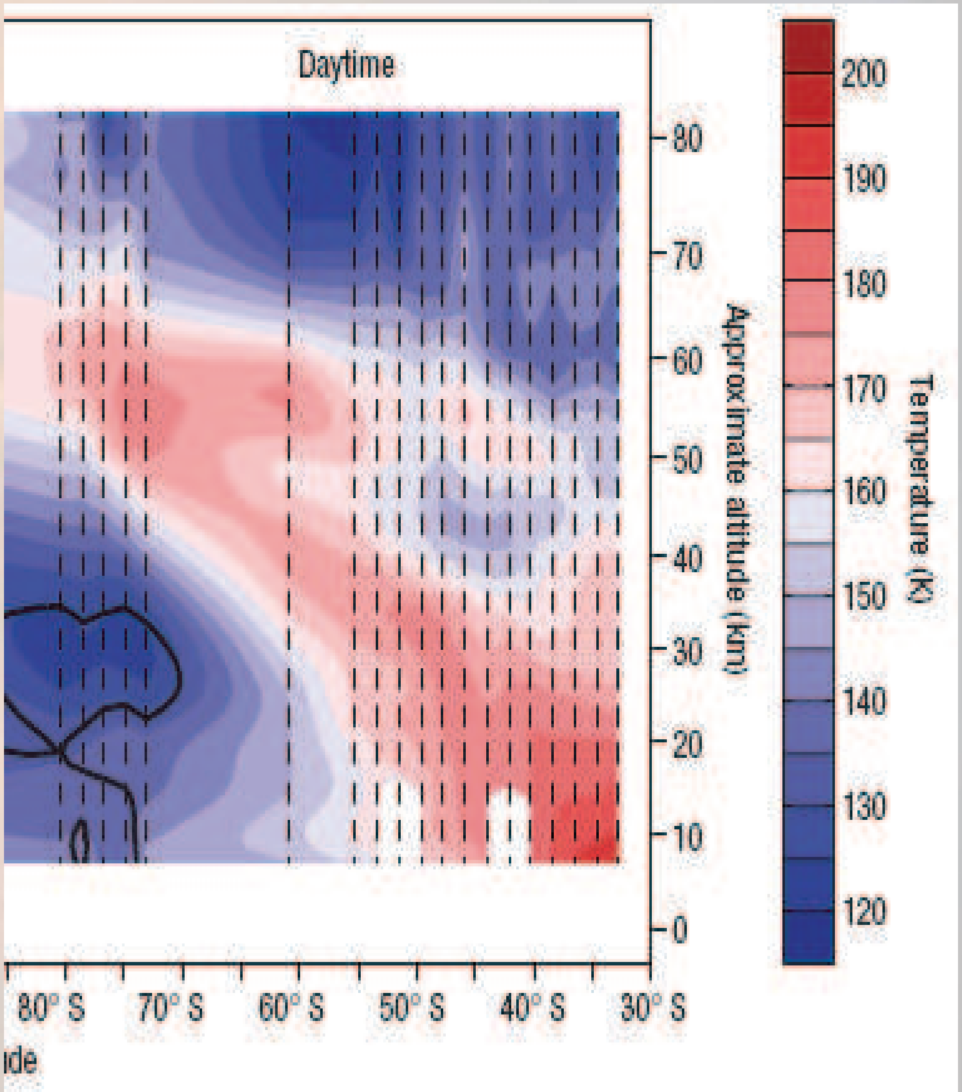
Mars surface temperature MAOAM vs. TES



MAOAM predictions and MCS observation

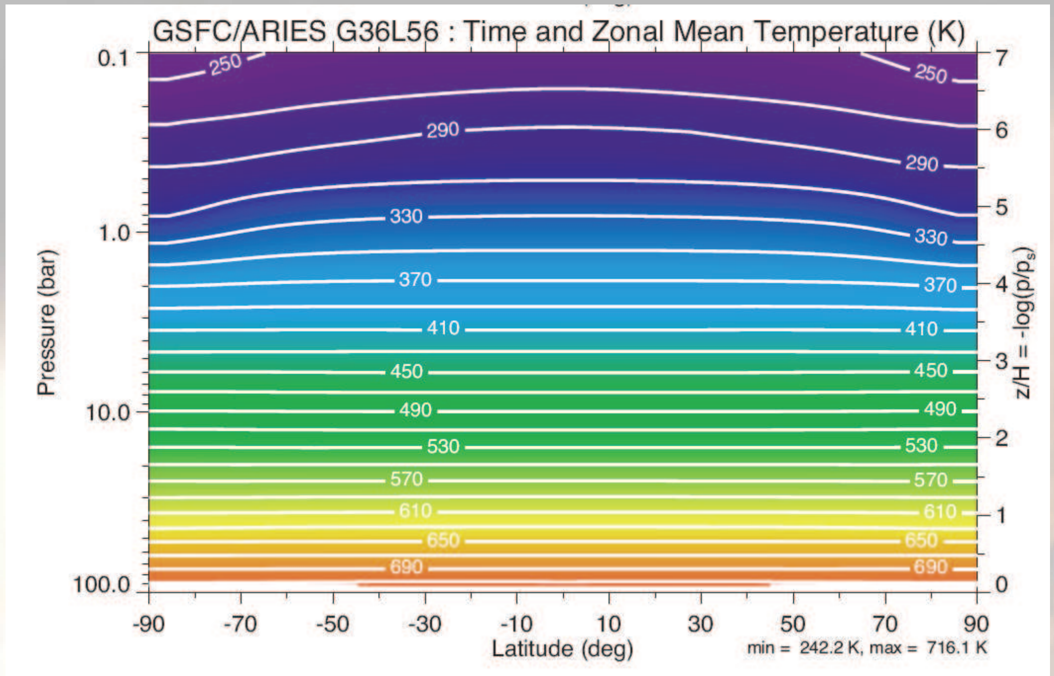


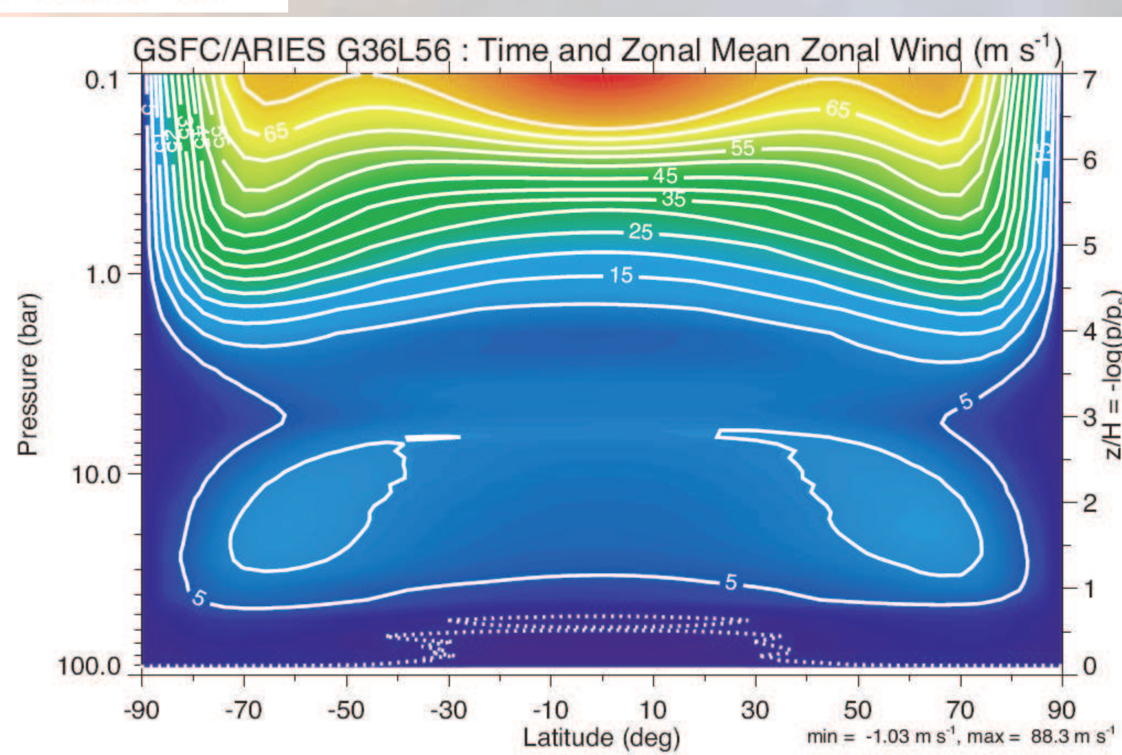
Hartogh et al, JGR, 2005



McCleese et al,
Nature Geoscience, 2008

Venus GCMs

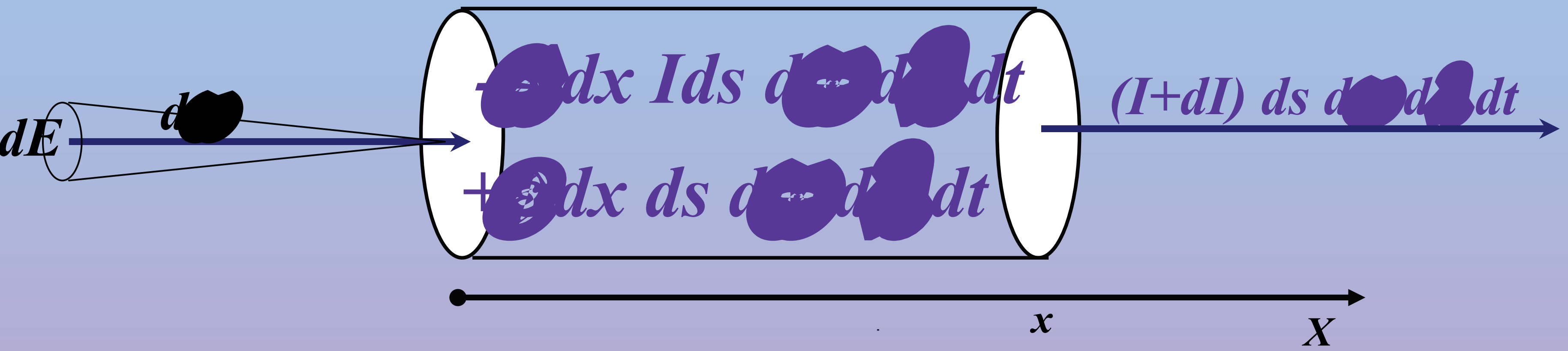

GSFC/ARIES G36L56 : Time and Zonal Mean Temperature (K)
Pressure (bar)
z/H = -log(p/p$_s$)
Latitude (deg)
min = 242.2 K, max = 716.1 K
0.1
1.0
10.0
100.0
250
290
330
370
410
450
490
530
570
610
650
690
-90 -70 -50 -30 -10 10 30 50 70 90
7 6 5 4 3 2 1 0


GSFC/ARIES G36L56 : Time and Zonal Mean Zonal Wind (m s^{-1})
Pressure (bar)
z/H = -log(p/p$_s$)
Latitude (deg)
min = -1.03 m s^{-1}, max = 88.3 m s^{-1}
0.1
1.0
10.0
100.0
65
55
45
35
25
15
5
-90 -70 -50 -30 -10 10 30 50 70 90
7 6 5 4 3 2 1 0

Basics of radiative transfer

Radiative transfer equation

$dE = I\, ds\, d\nu\, d\Omega\, dt$ – definition of intensity



$$dI / dx = -\alpha I + \varepsilon$$

or

$$dI / d\tau = -I + S$$

α - volume extinction coefficient

ε - volume emission coefficient

$d\tau = \alpha\, dx$ – optical depth

$S = \varepsilon / \alpha$ - source function

Basics of radiative transfer

1. **General solution**

   $$I(x) = I_0 e^{-\int_0^x \alpha(x')dx'} + \int_0^x \varepsilon(x') e^{-\int_{x'}^x \alpha(t)dt} dx'$$

2. **Empty space (α=0, ε=0)**

   I(x)=const

3. **Medium without sources ($\alpha \neq 0$, ε=0) (Beer's law)**

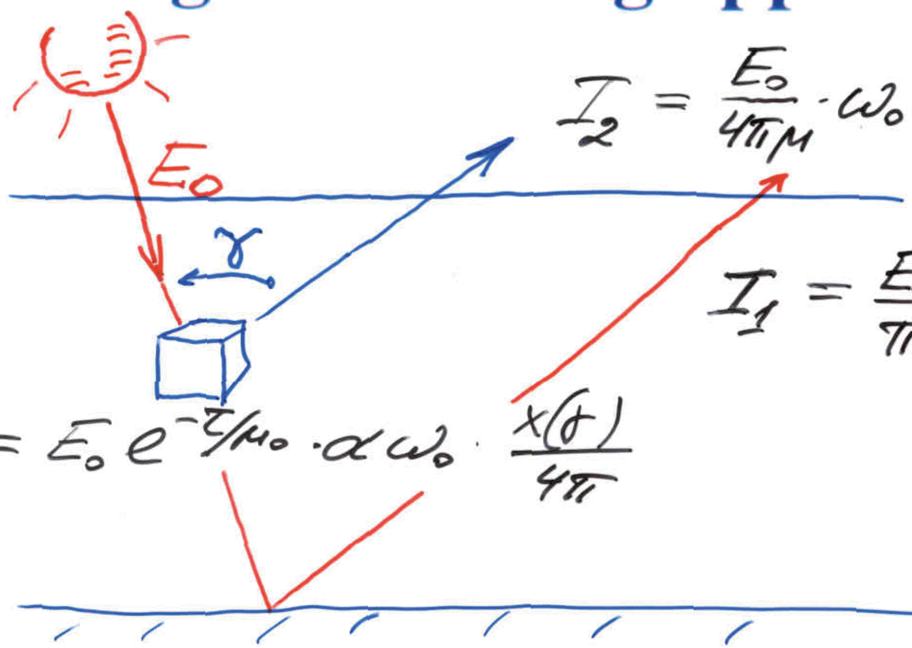
   $$I(x) = I_0 e^{-\int_0^x \alpha(t)dt}$$

Scattered solar light in the atmosphere

1. Radiative transfer equation

$$\mu \frac{dI}{dx} = -\alpha I + \mathcal{E}$$

2. Single scattering approximation ([illegible] << 1)

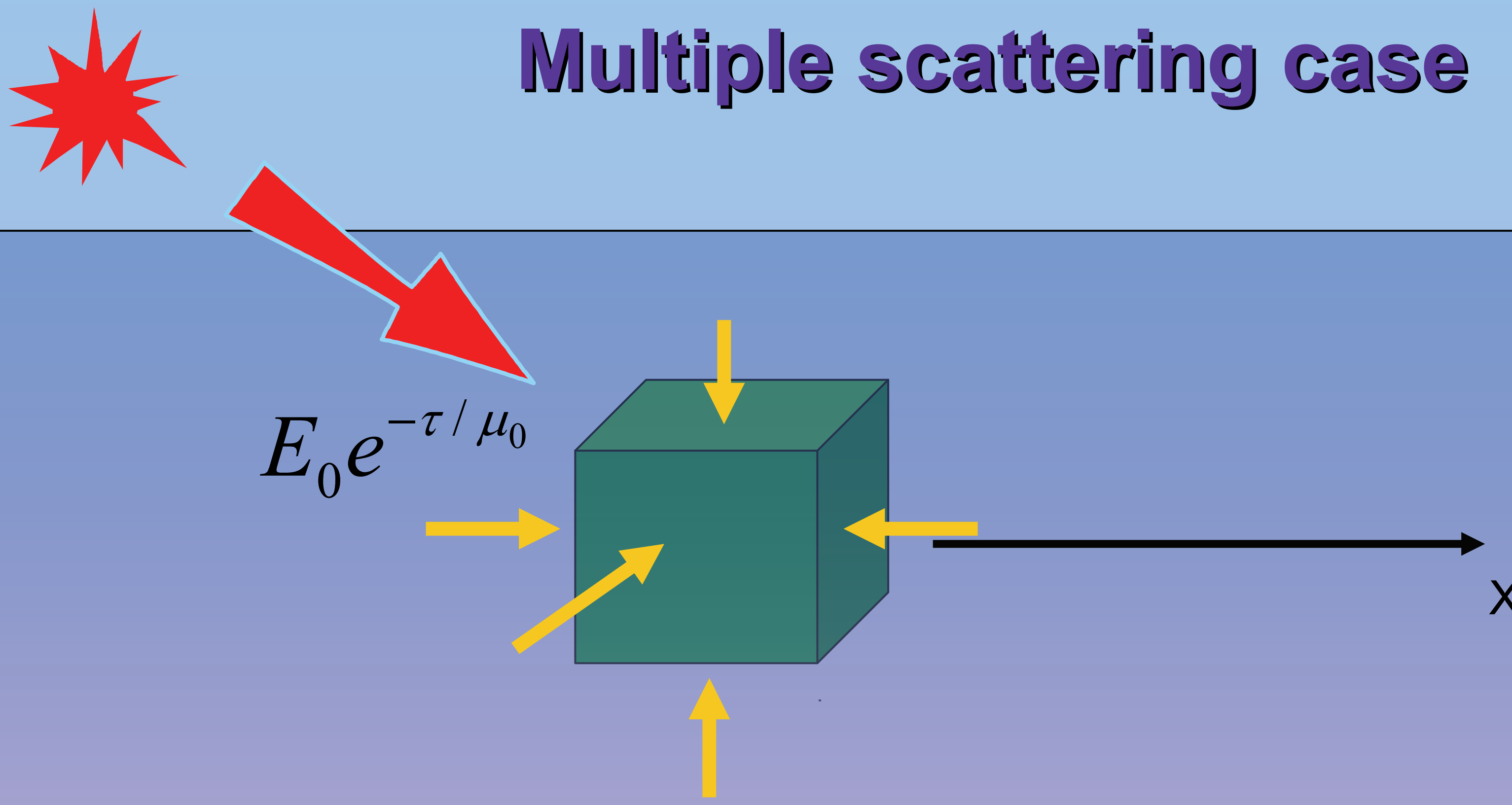


$$I_2 = \frac{E_0}{4\pi\mu} \cdot \omega_0 \, x(\gamma) \int_0^{\infty} \alpha(z) \cdot e^{-\tau(z)\left(\frac{1}{\mu_0} + \frac{1}{\mu}\right)} dz$$

$$I_1 = \frac{E_0}{\pi} A_S \mu_0 \, e^{-\tau_0\left(\frac{1}{\mu_0} + \frac{1}{\mu}\right)}$$

$$\mathcal{E} = E_0 \, e^{-\tau/\mu_0} \cdot \alpha \omega_0 \cdot \frac{x(\gamma)}{4\pi}$$

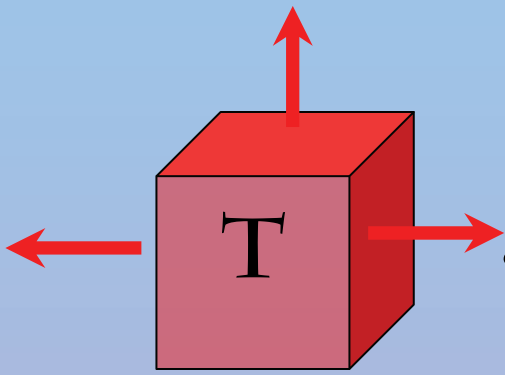
Multiple scattering case



$$\varepsilon = E_0 e^{-\tau/\mu_0} \omega_0 \alpha \frac{p(\gamma)}{4\pi} + \omega_0 \alpha \int_{\Omega} I(\omega') p(\gamma') \frac{d\omega'}{4\pi}$$

$$\frac{dI}{dx} = -\alpha I + \varepsilon$$

Thermal radiation

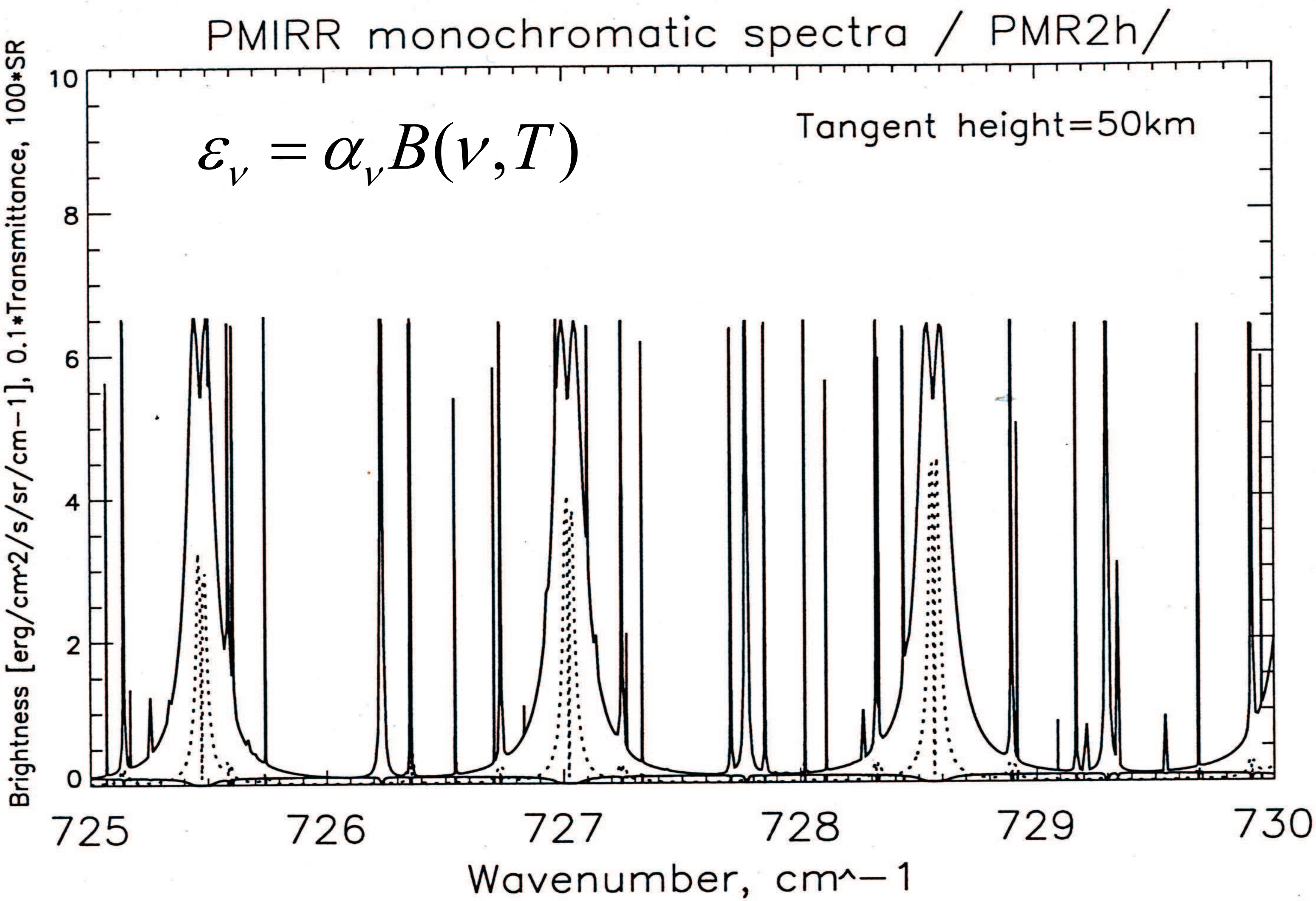


$$\varepsilon_\nu = \alpha_\nu B(\nu, T) = \alpha_\nu \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

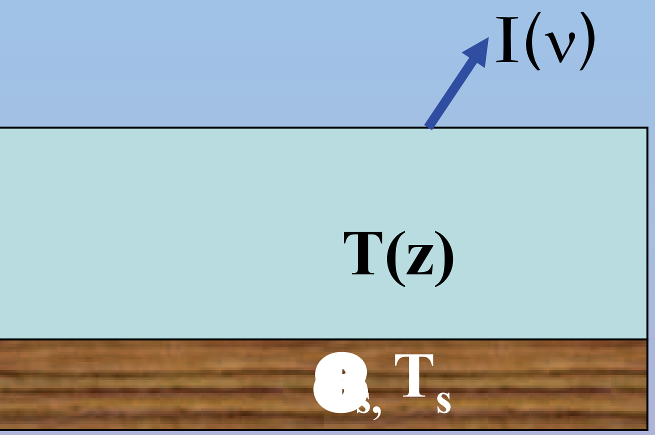
$$\Phi = \sigma T^4$$ **- full thermal flux**

- **Local thermodynamic equilibrium (LTE)**
- **LTE breakdown above relaxation level (n~10^{15} cm^{-3})**
- **Thermal radiation in gaseous atmosphere**

Atmospheric spectrum in CO_2 band



Radiative transfer equation for thermal radiation



$$\mathrm{I}(\nu) = \varepsilon_s B_\nu(T_s)t + \int\limits_{Surface}^{Space} B_\nu[T(z')]dt_\nu$$

Scattering is neglected

$$t_\nu(z') = \int\limits_{z'}^{space} e^{-\tau_\nu(z)}dz$$ **- transmittance**

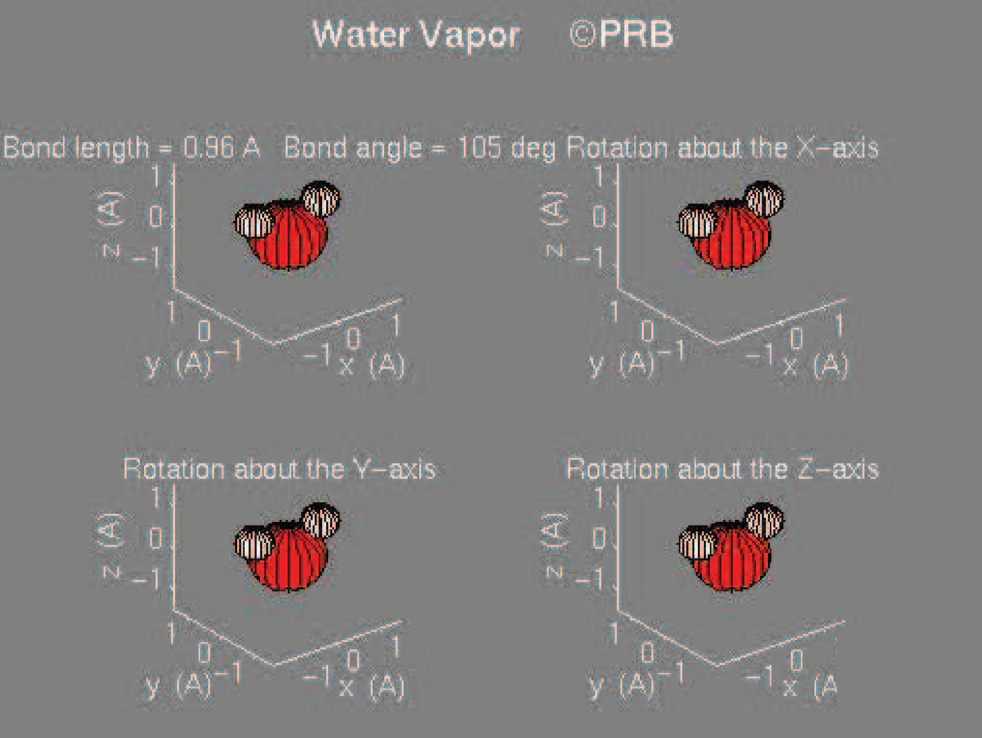
$$\mathrm{I}(\nu) = \varepsilon_s B_\nu(T_s)t_\nu + \int\limits_{Surface}^{Space} B_\nu[T(\xi)] \cdot K_\nu(\xi)d\xi$$

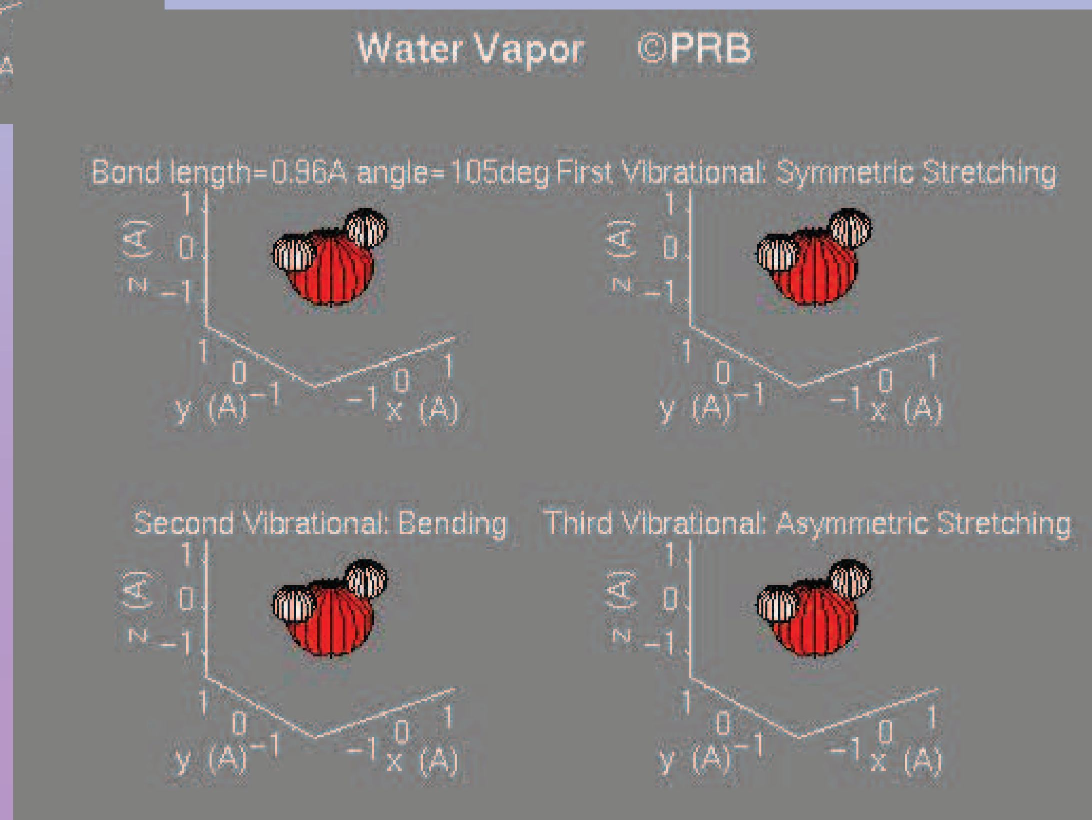
$$\xi = \lg p$$

$$\mathrm{K}_\nu(\xi) = -\frac{\partial t_\nu}{\partial \xi}$$ - weighting function

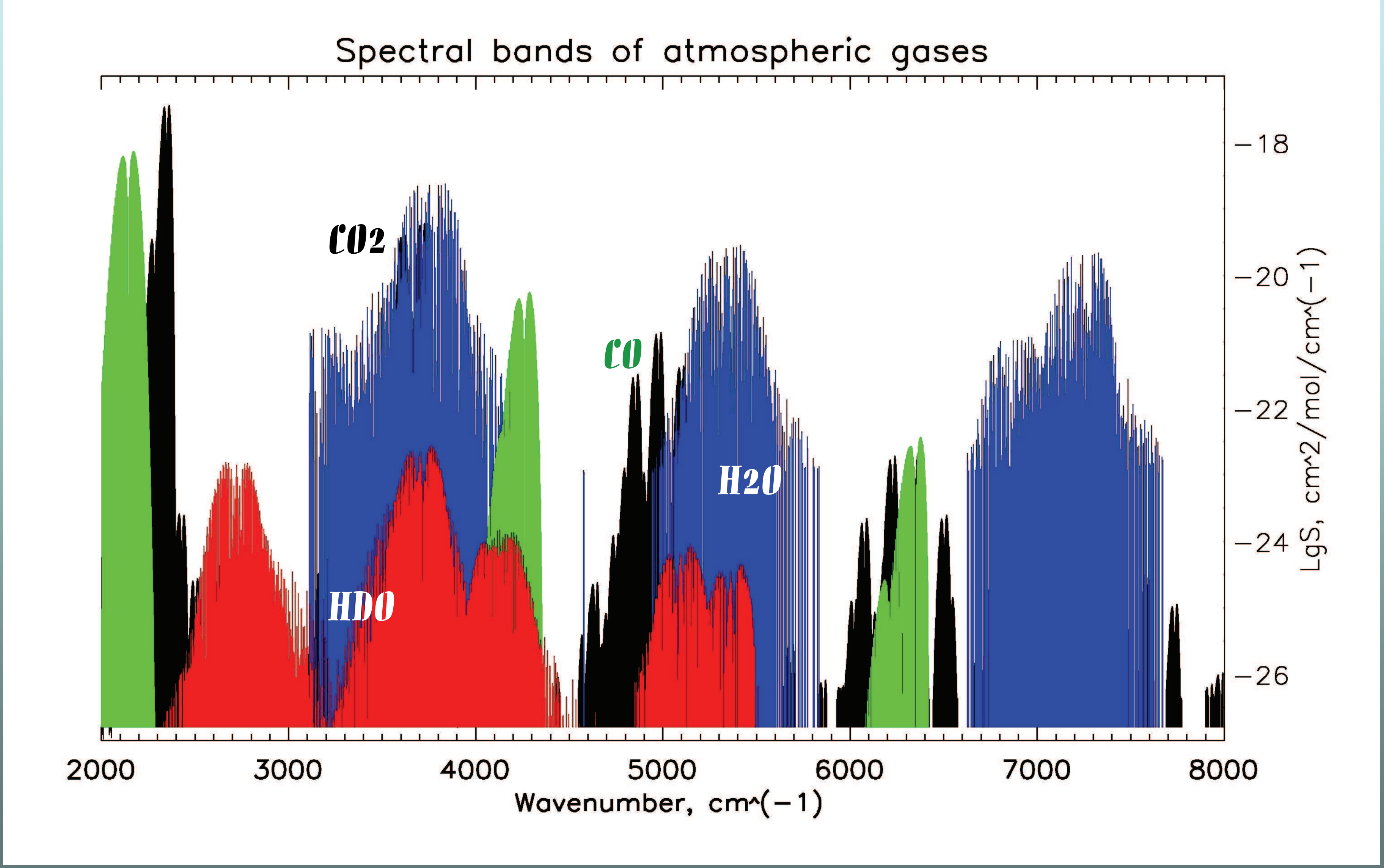
Basics of spectroscopy

Molecular “gymnastics”





Spectral bands of atmospheric gases



Spectral line shapes

1. Spectral line shape: k(ν) = S·L(ν - ν0)
2. Natural broadening: $\Delta\nu \sim 10^{-10}$ cm^{-1}
3. Doppler broadening

$$L_D = \frac{1}{\alpha_D\sqrt{\pi}} \cdot e^{-\left(\frac{\nu-\nu_0}{\alpha_D}\right)^2}$$

$$\alpha_D = \frac{\nu_0}{c}\sqrt{\frac{3kT}{m}} \simeq 10^{-2}-10^{-4}\,\mathrm{cm}^{-1}$$

4. Lorentz broadening

$$L_L = \frac{1}{\pi}\frac{\alpha_L}{(\nu-\nu_0)^2+\alpha_L^2} \qquad \alpha_L = \alpha_0 \frac{P}{P_0}\left(\frac{T_0}{T}\right)^n$$

5. Voigt line profile

$$L_V = \frac{\sqrt{\ln 2}\, a}{\pi^{3/2}\alpha_D}\int_{-\infty}^{\infty}\frac{e^{-y^2}dy}{(x-y)^2+a^2}$$

$$x = \frac{(\nu-\nu_0)\sqrt{\ln 2}}{\alpha_D} \qquad a = \frac{\alpha_L\sqrt{\ln 2}}{\alpha_D}$$

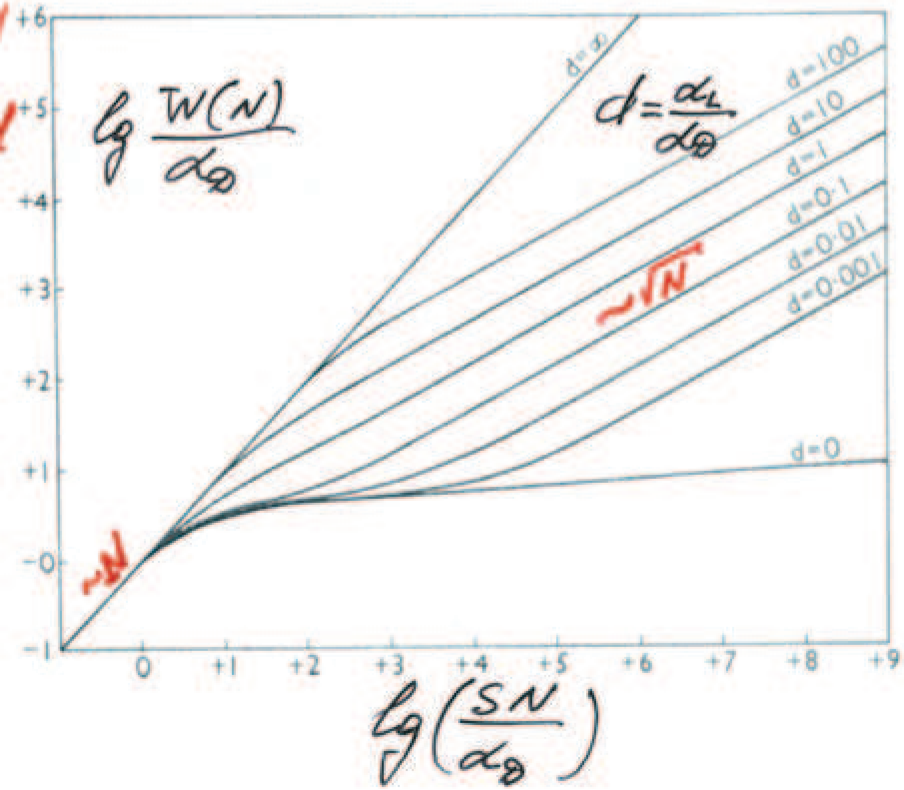
Solar range: Equivalent width and curve of grouth

1. Equivalent width
2. Absorption in isolated Lorentz line

$$W(N) = 2\pi\alpha_L \cdot L(u) \begin{cases} \sim u, & u \ll 1 \\ \sim\sqrt{u}; & u \gg 1 \end{cases}$$

$$u = \frac{SN}{2\pi\alpha_L}$$

3. Absorption in isolated Voght line



4. Elsasser band model

$$\tau(x) = 2\pi u y \frac{\operatorname{sh} 2\pi y}{\operatorname{ch} 2\pi y - \cos 2\pi x}$$

$$u = \frac{SN}{2\pi\alpha_L}, \quad x = \frac{\nu}{\delta}, \quad y = \frac{\alpha_L}{\delta}$$

Solar reflected spectrum depends mainly on gas amount and to a less extent on the temperature!

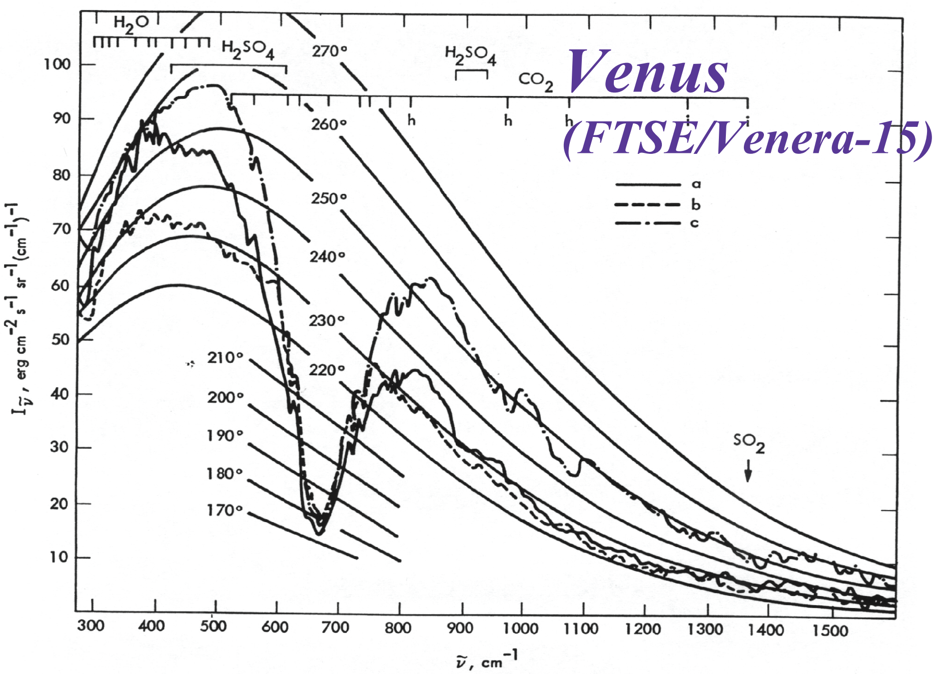
Spectra of thermal emission

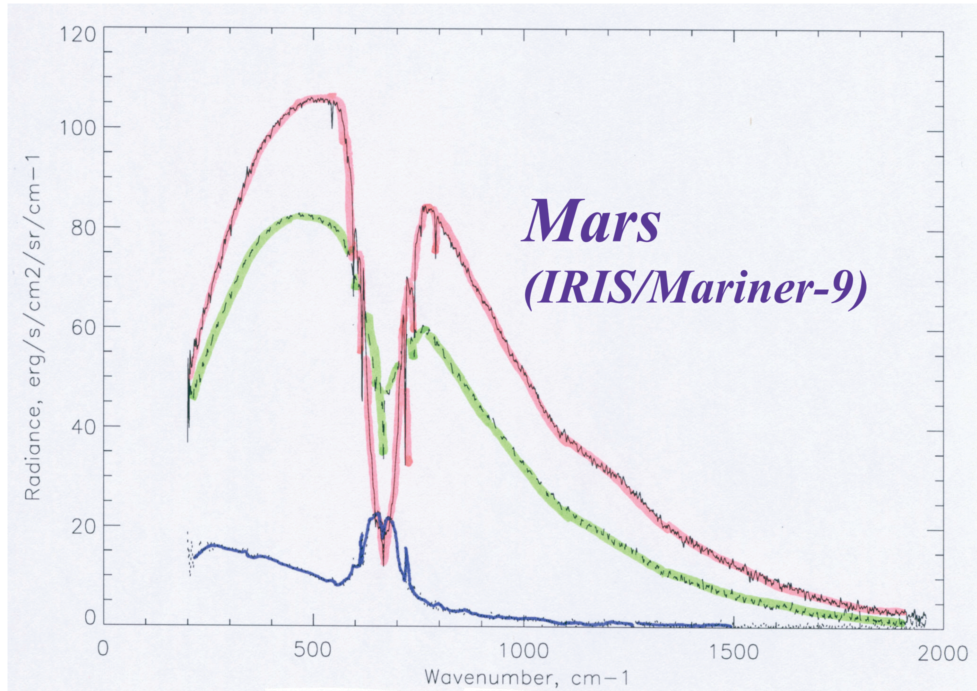
1. **Radiative transfer equation**

$$I = \varepsilon_s \cdot B(T_s) \cdot t + \int_{p_s}^{0} B[T(s')]\, dt$$

$$I = \varepsilon_s B(T_s)\, t + \int_{-\infty}^{\infty} B[T(\xi)]\, K(\xi)\, d\xi \qquad \xi = \lg p$$

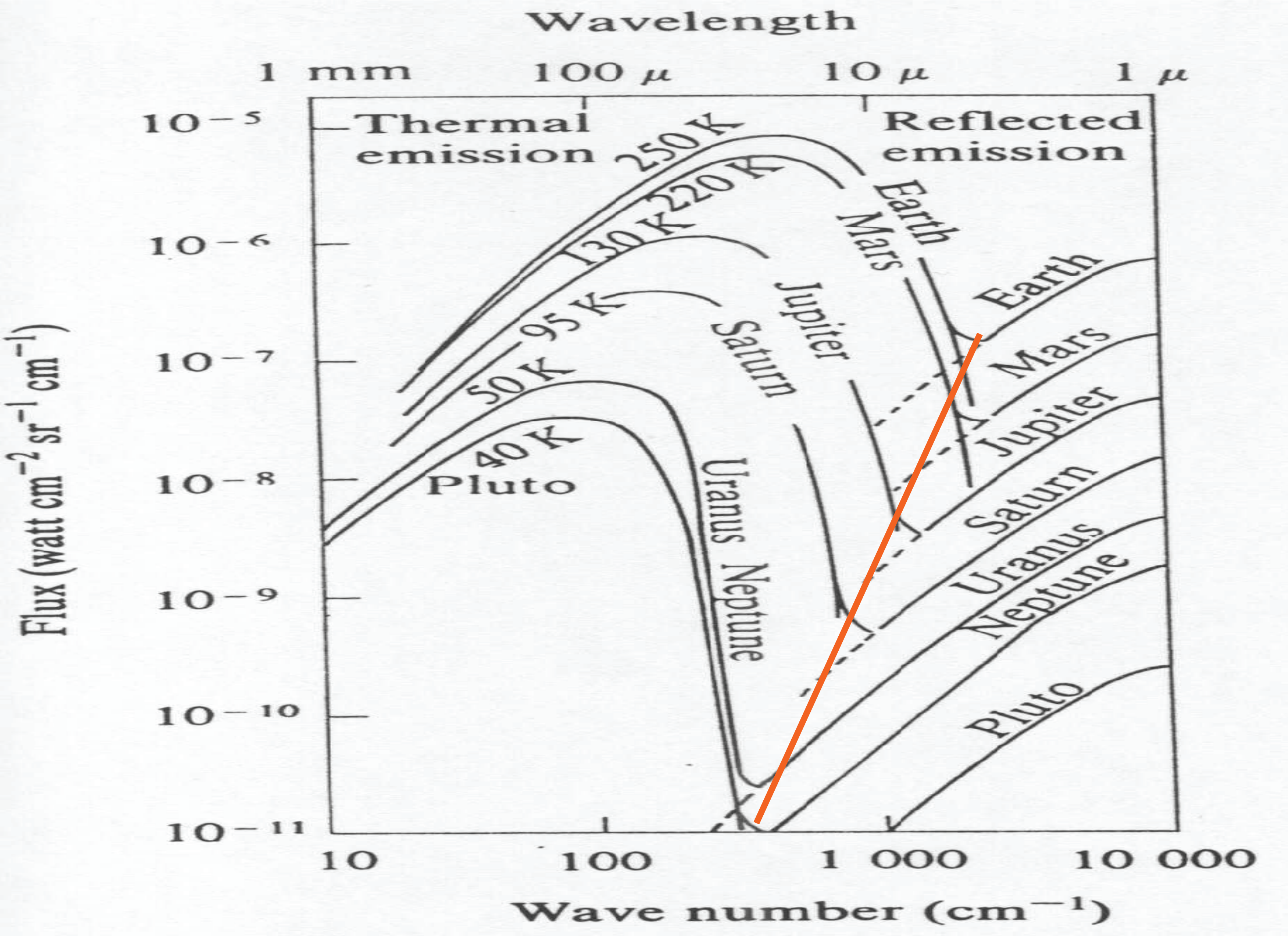
2. **Weighting function** $K(\xi) = -\frac{\partial t}{\partial \xi}$
3. **Examples of thermal spectra of planets**





Thermal spectrum depends temperature and gas abundance!

General shape of the planetary spectra

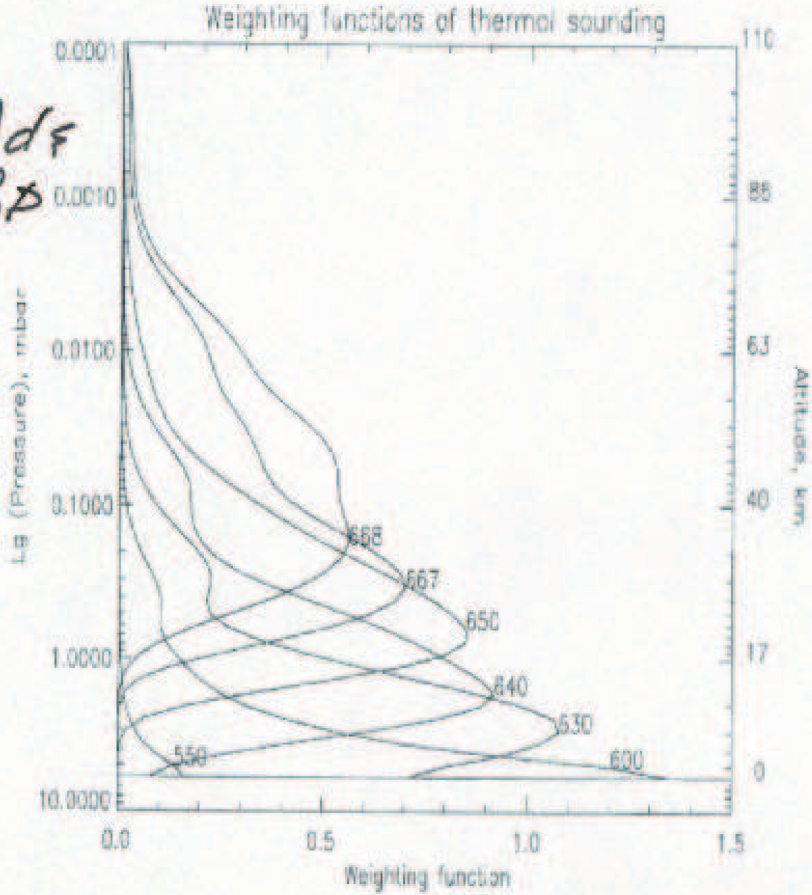


Additional slides to Basics of Radiative Transfer

Principles of temperature sounding

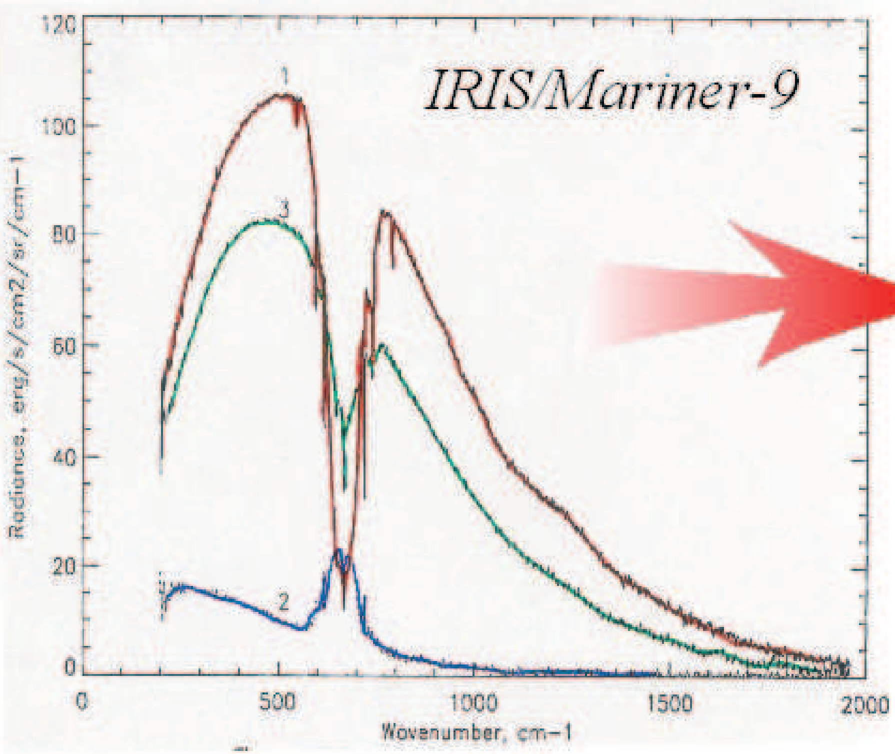
- In strong bands of atmospheric gases thermal radiation forms at different altitudes depending on wavelength
- $$I(\nu) = \varepsilon_s B(T_s) t_{ATM} + \int_{-\infty}^{\infty} B[T(\xi)] \cdot K(\xi) d\xi$$
  $$K(\xi) = -\frac{\partial t}{\partial \xi} \qquad \xi = \lg p$$
- Gas should be well mixed and its abundance known
- Local thermodynamic equilibrium
- Temperature retrieval is an ill-posed problem

Weighting functions of thermal sounding at Mars

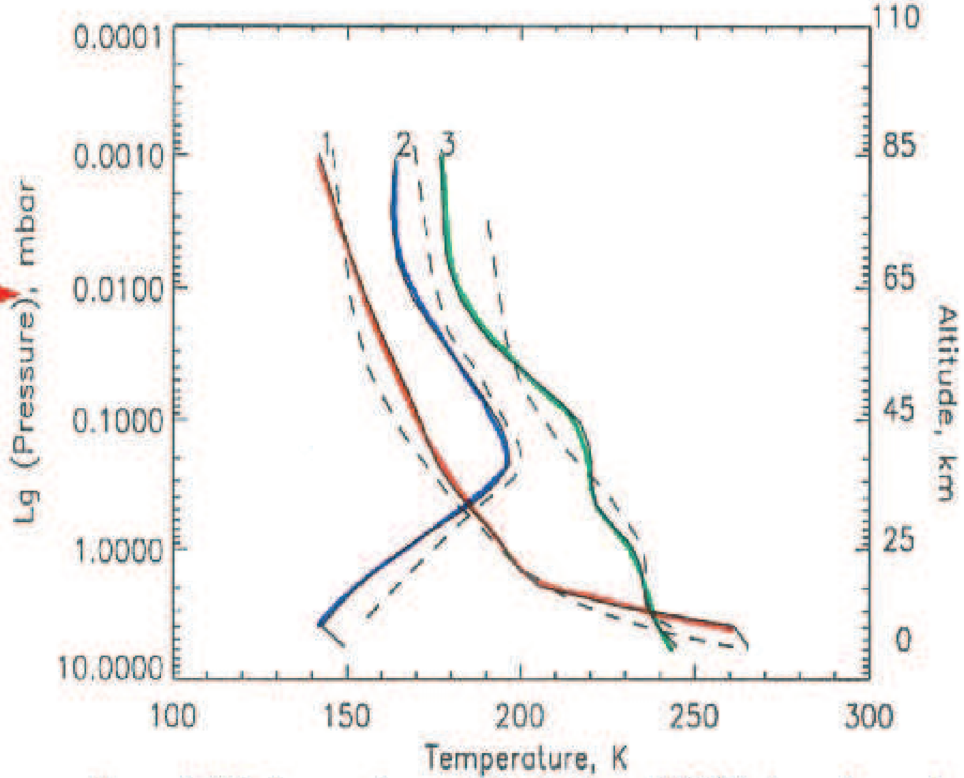


Example of temperature sounding

Measured spectra of Mars



Retrieved temperature profiles



Scattered solar light in the atmosphere (2)

5. Two stream approximation /Schwarzschild- Schuster/

$$I^{\uparrow}(\tau) = \int I(\tau) \sin\theta \, d\theta \qquad I^{\downarrow}(\tau) = \int I(\tau) \sin\theta \, d\theta$$

$$\begin{cases} \frac{1}{2} \frac{dI^{\uparrow}}{d\tau} = I^{\uparrow} - S \\ -\frac{1}{2} \frac{dI^{\downarrow}}{d\tau} = I^{\downarrow} - S \\ S(\tau) = \frac{1}{2}\left[I^{\uparrow} + I^{\downarrow} \right] \end{cases} \Rightarrow S(\tau) = F\left(\tau + \frac{1}{2}\right)$$

6. N-stream approximation

$$\mu_i \frac{dI(\tau,\mu_i)}{d\tau} = I(\tau,\mu_i) - \frac{1}{2} \sum a_j I(\tau,\mu_i) \qquad i = \pm 1 \ldots \pm N$$

Scattered solar light in the atmosphere (3)

3. Spherical phase function X(γ)=1 /Hvolson/

$$\begin{cases} \mu \dfrac{dI}{d\tau} = I - S \\ S = \dfrac{\omega_0}{2} \displaystyle\int_{-1}^{1} I(\mu)\, d\mu + \dfrac{\omega_0}{4\pi} E_0 e^{-\tau/\mu_0} \end{cases}$$

$$\Rightarrow S(\tau) = \frac{\omega_0}{2} \int_0^\infty Ei_1(|\tau - t|) S(t)\, dt + \frac{\omega_0}{4\pi} E_0 e^{-\tau/\mu_0}; \quad Ei_1(x) = \int_1^\infty \frac{e^{-xy}}{y} dy$$

4. Reflection from semi-infinite atmosphere /Ambartsumjan/

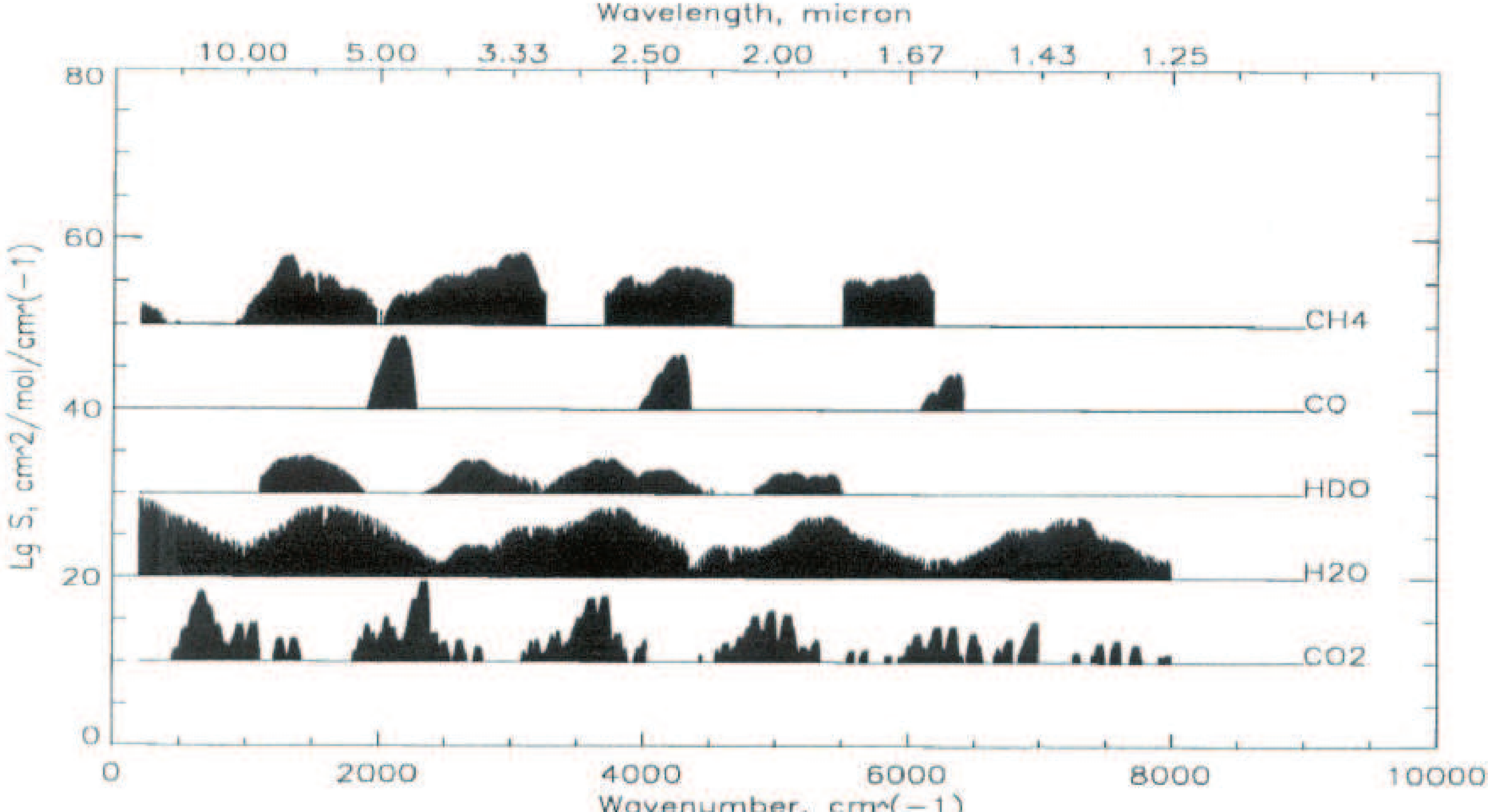
τ

$$\rho(\mu, \mu_0) = \frac{\omega_0}{4} \frac{\varphi(\mu) \cdot \varphi(\mu_0)}{\mu + \mu_0}$$

$$\varphi(\mu) = 1 + \frac{\omega_0}{2} \varphi(\mu) \int_0^1 \frac{\varphi(\mu')}{\mu + \mu'} d\mu'$$

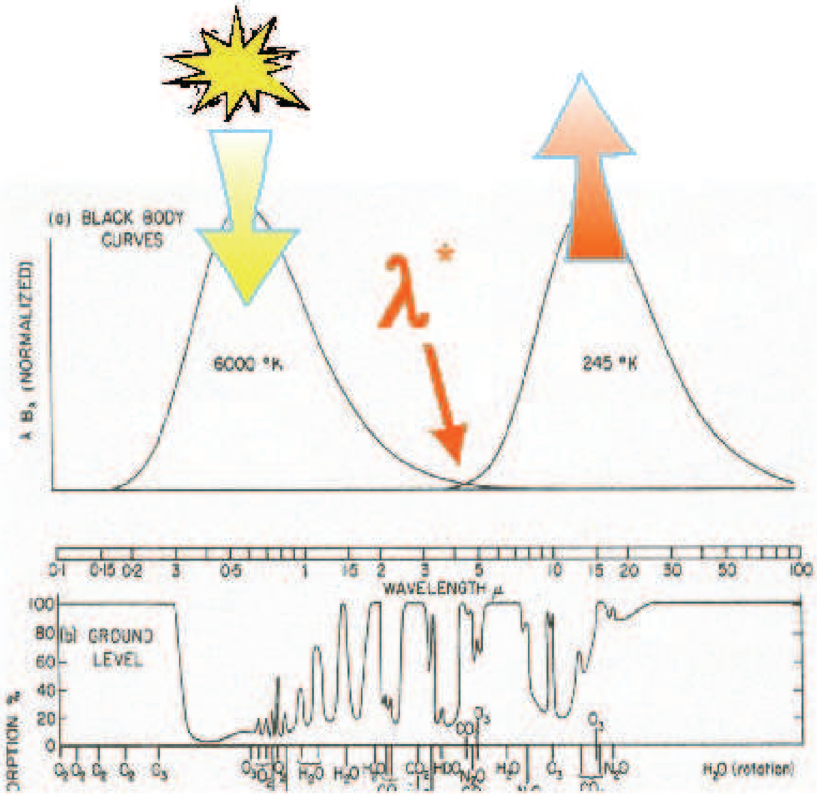
Basics of spectroscopy (3)

Absorption bands of atmospheric gases

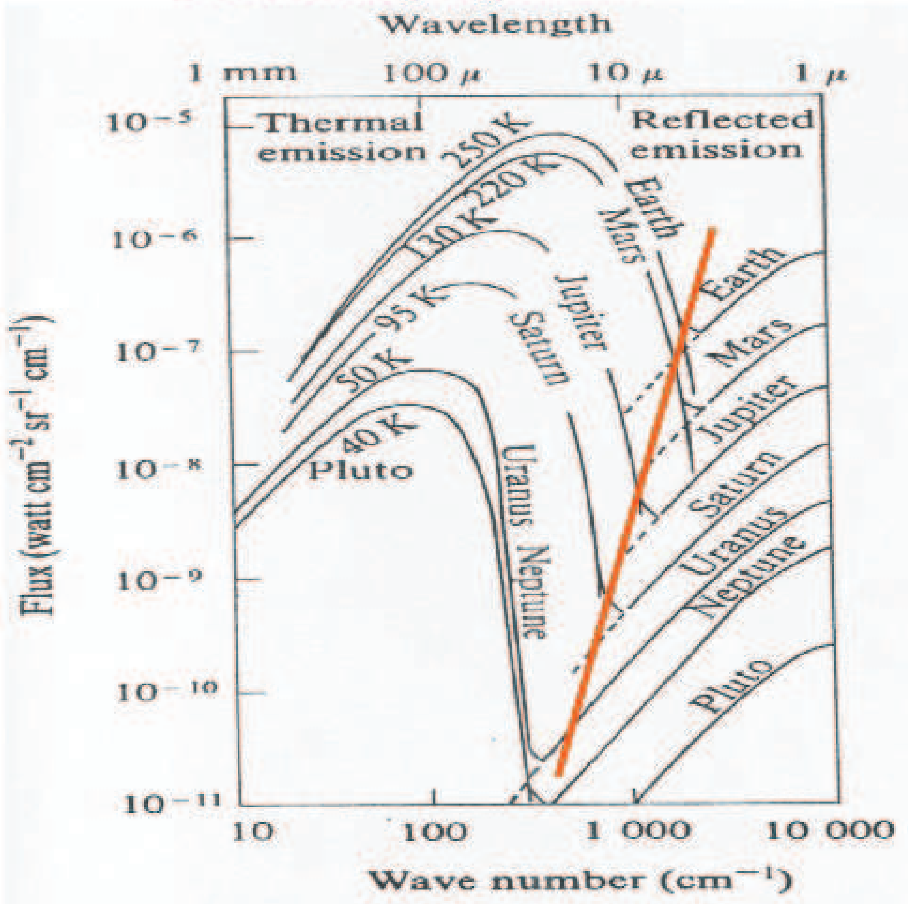


Absorption bands of the atmospheric gases

Energy balance of planets



Planetary spectra



Effective temperature

$$E(1-A) = 4\sigma T^4_{eff}$$

Solar constant

$E_\oplus = 1370\ W/m^2$

Investigations of planetary atmospheres: methods and results

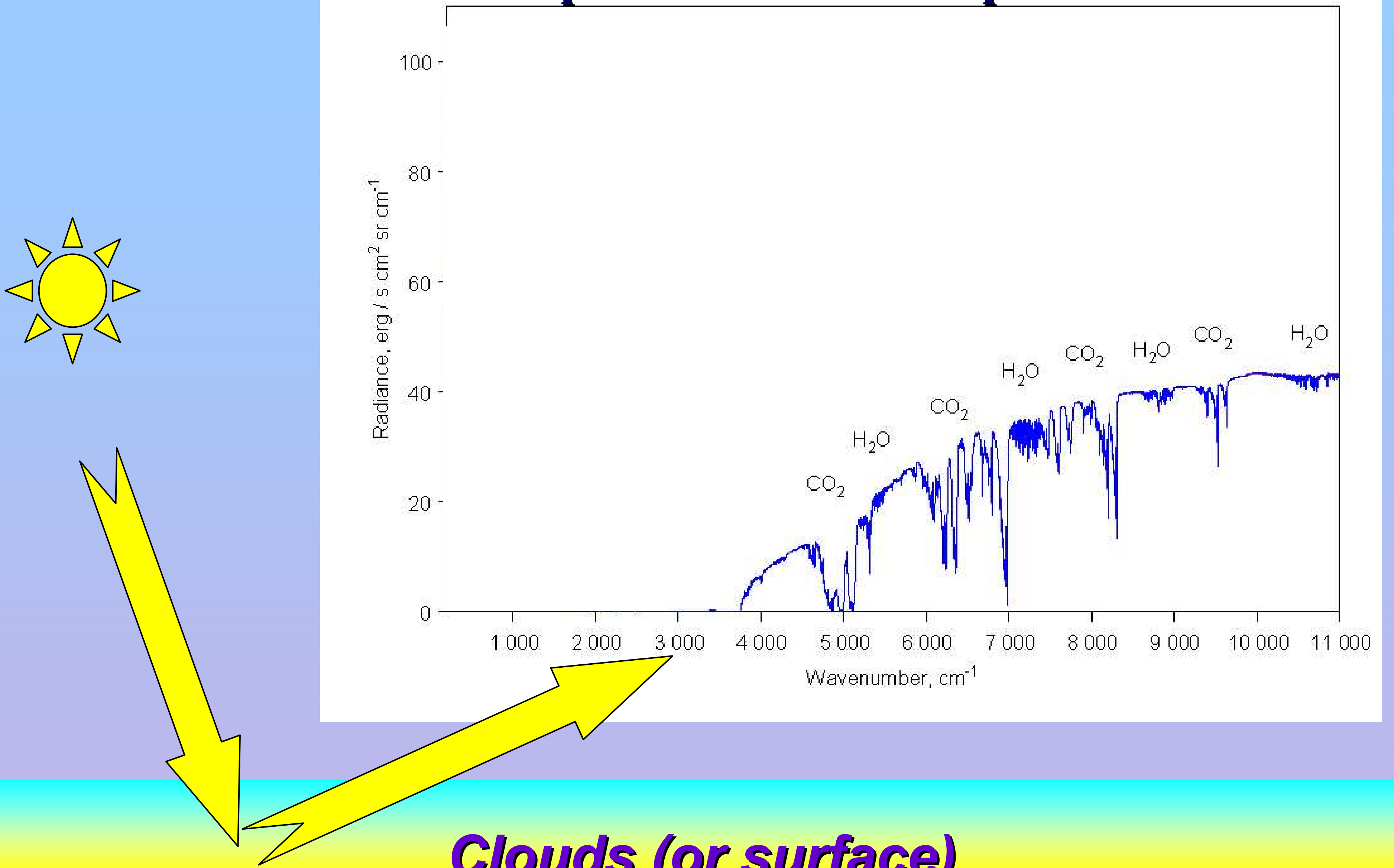
Remote sensing

- Imaging
- Spectrometry
- Polarimetry
- Limb sounding
- Occultation methods
- Radar sounding
- Thermal sounding
- Microwave investigations

Spectrometry of reflected solar radiation

- Wavelength range UV – Near-IR ***(0.3 … ~ 3 μm)***
- Good sensitivity to the ***total number of molecules*** on the line of sight
- Low sensitivity to the atmospheric temperature
- Day side observations
- Multiple scattering needs to be taken into account

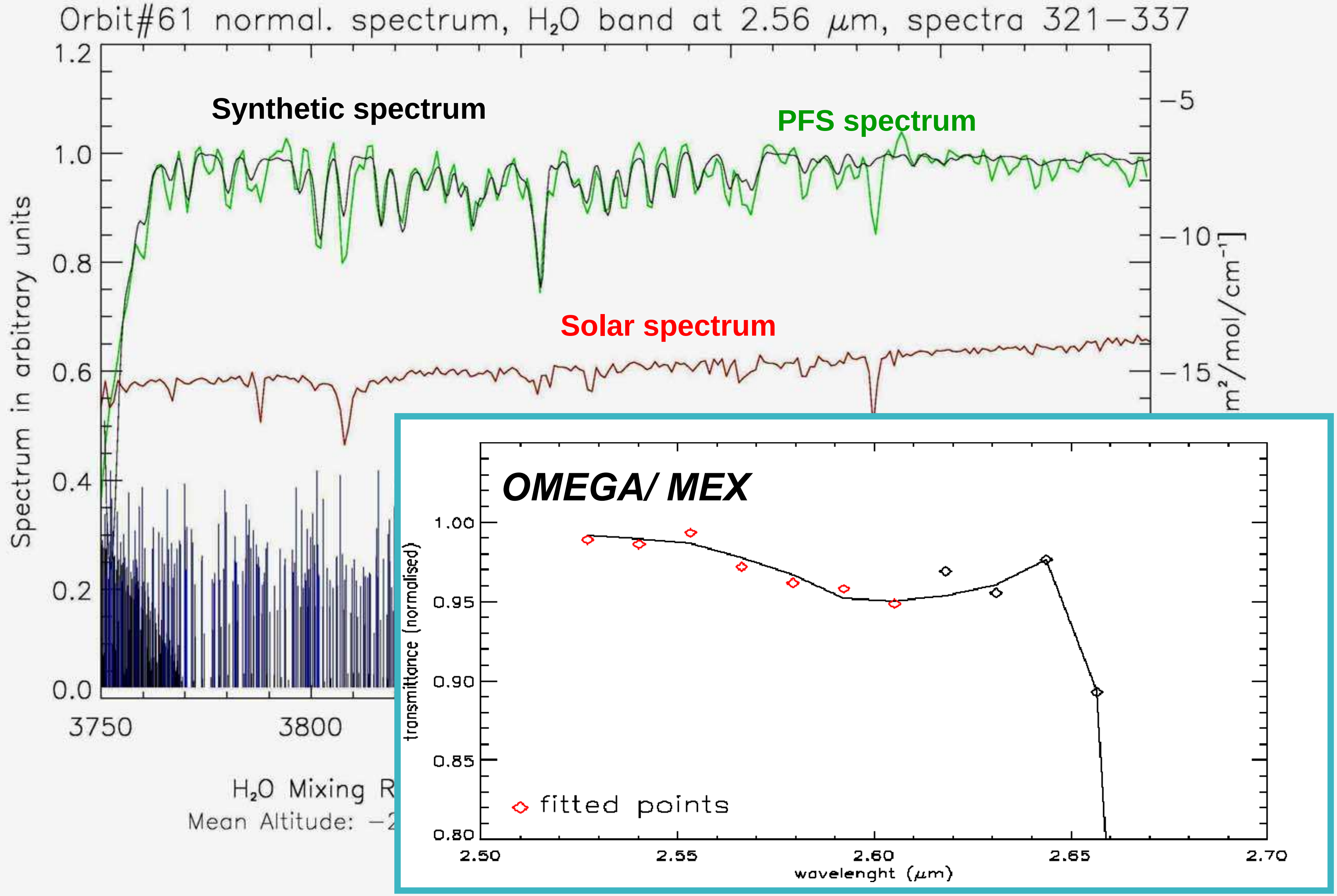
Composition of the atmosphere



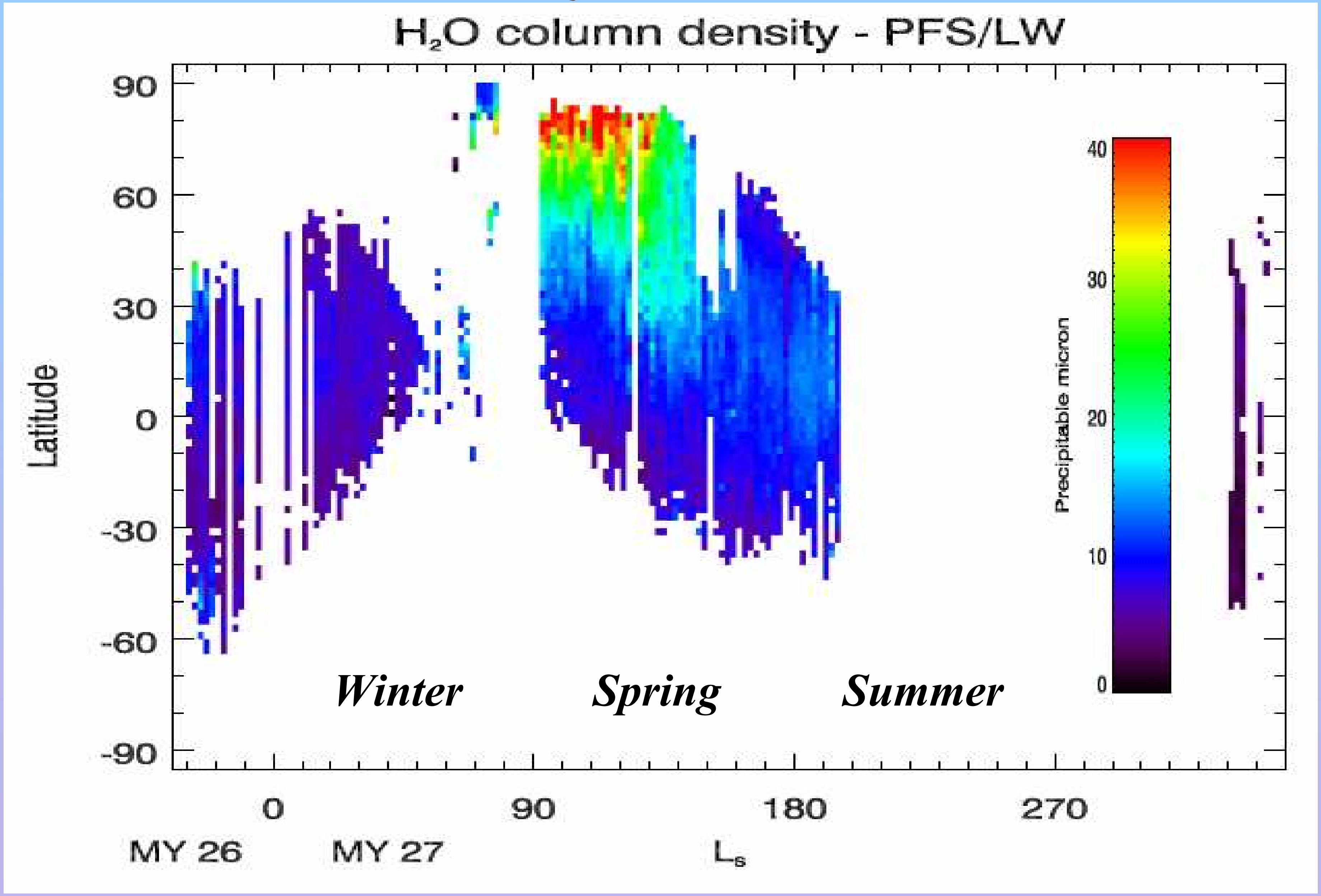
Clouds (or surface)

Monitoring the atmospheric water on Mars

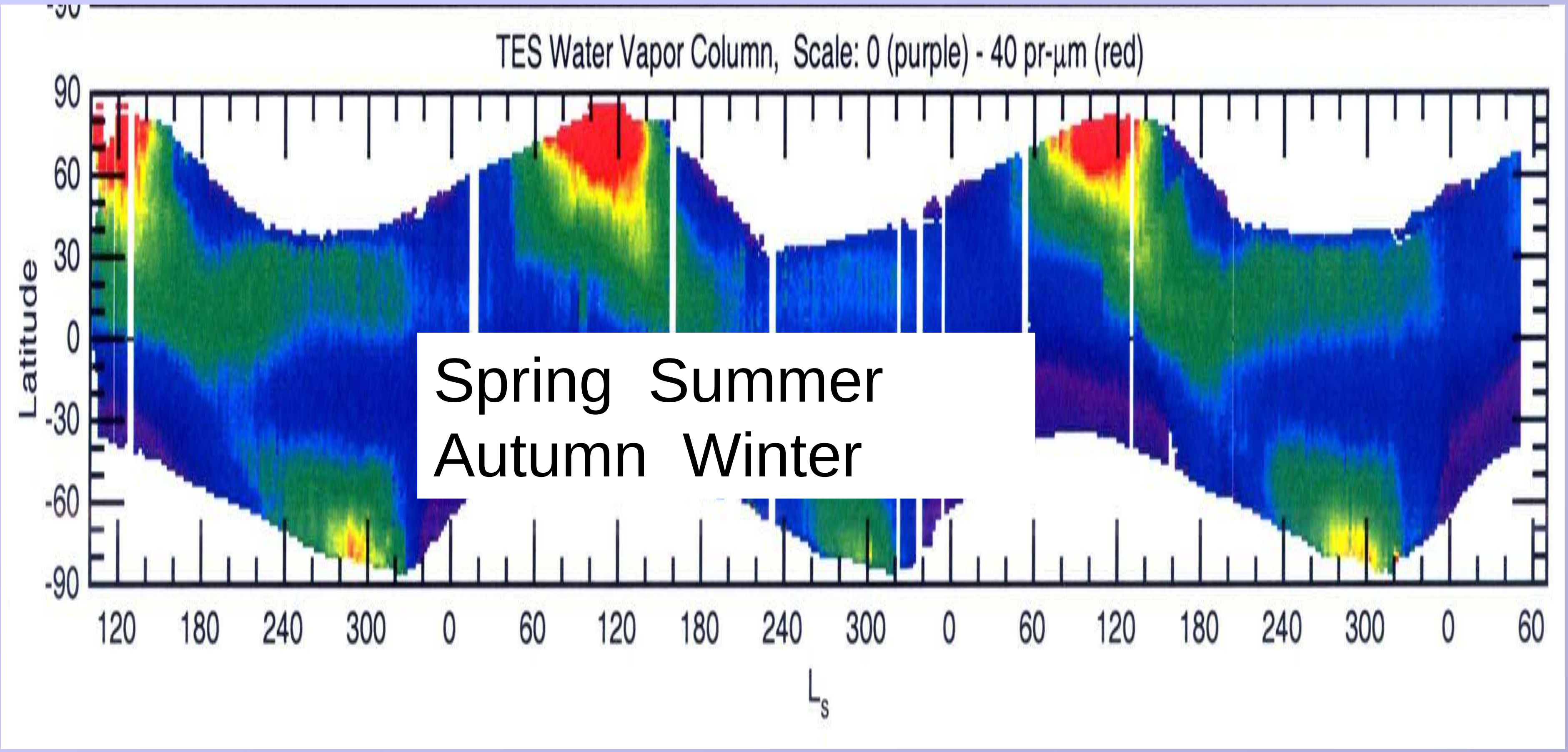
PFS/MEX spectrum in the 2.56 [redacted]m H_2O band



Seasonal cycle of water on Mars

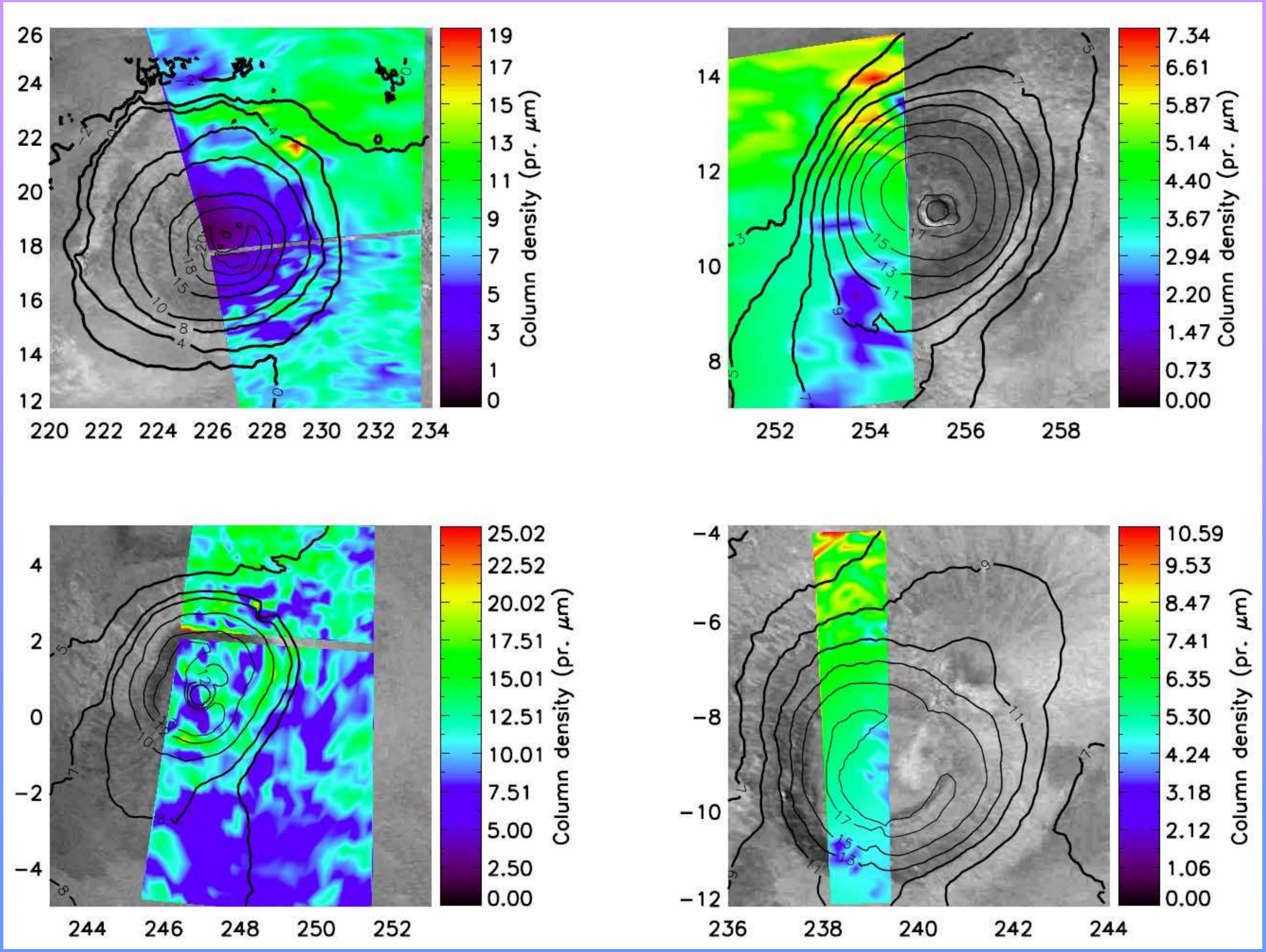


Seasonal water cycle on Mars



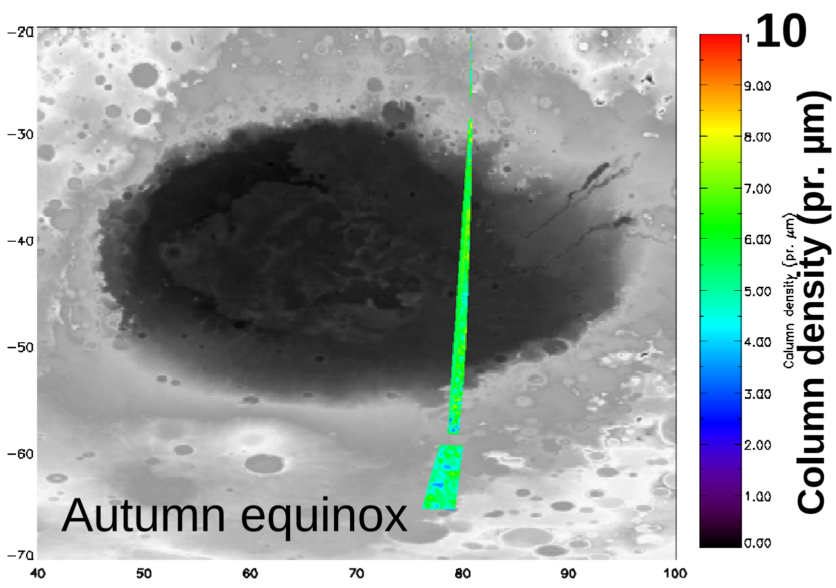
- **Seasonal variability 100 – 1000 ppm**
- **Advective transport**
- **Non-atmospheric reservoirs (polar caps, regolith)**

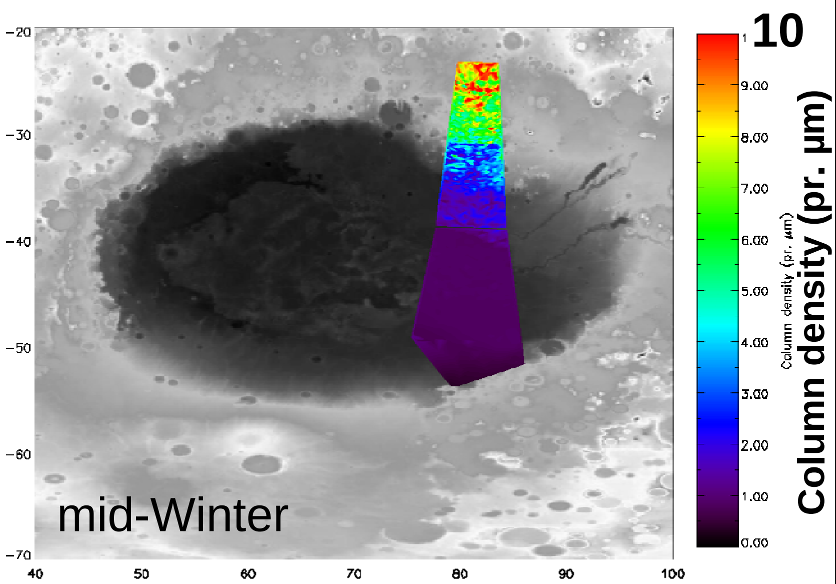
Atmospheric water above Tharsis volcanoes

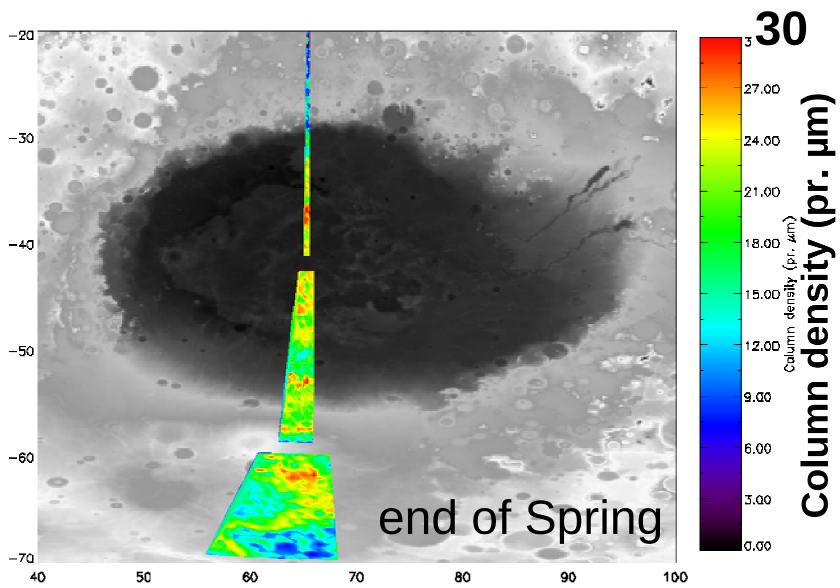


Maltagliati, Titov & OMEGA Team

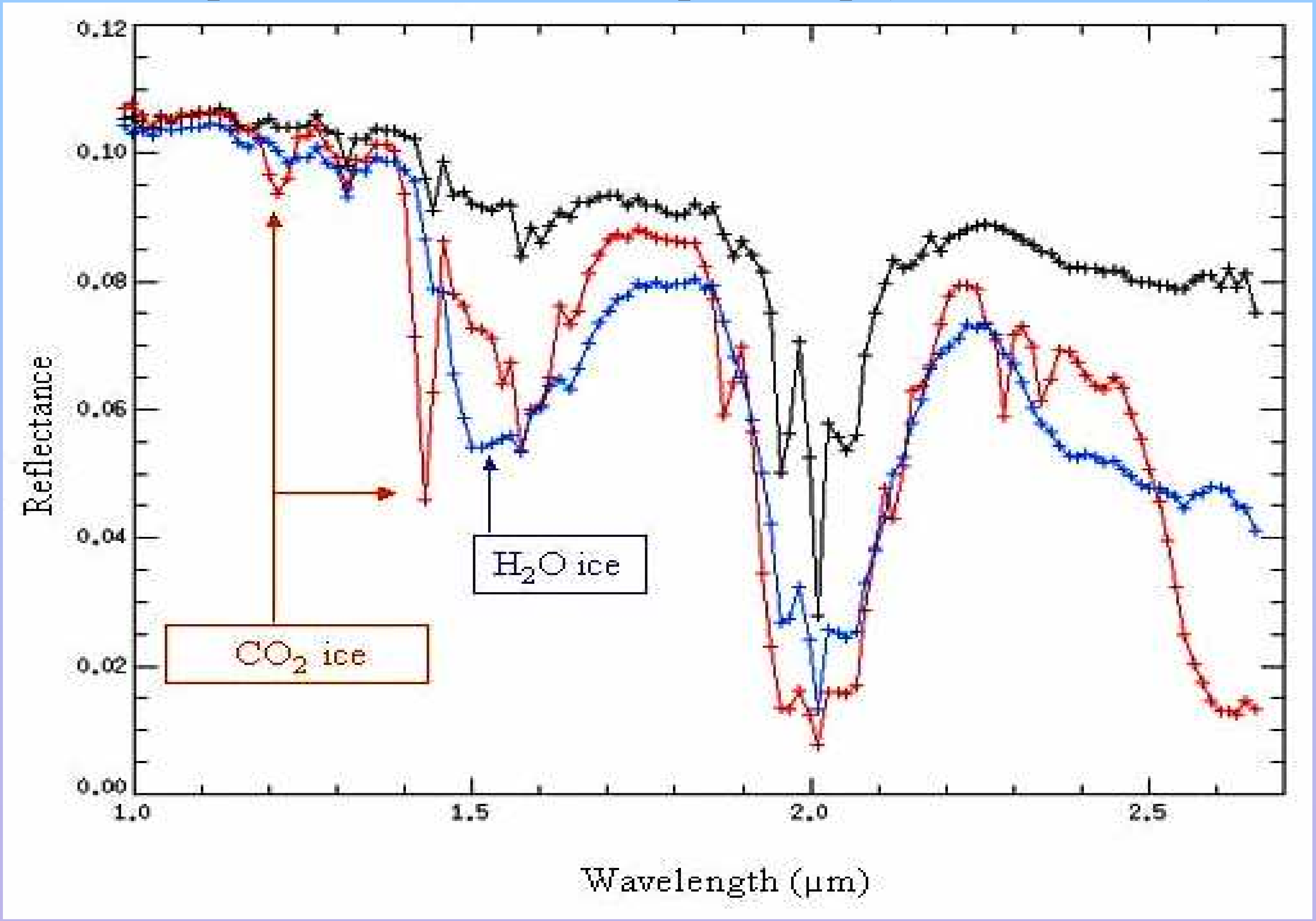
Atmospheric water above Hellas Basin



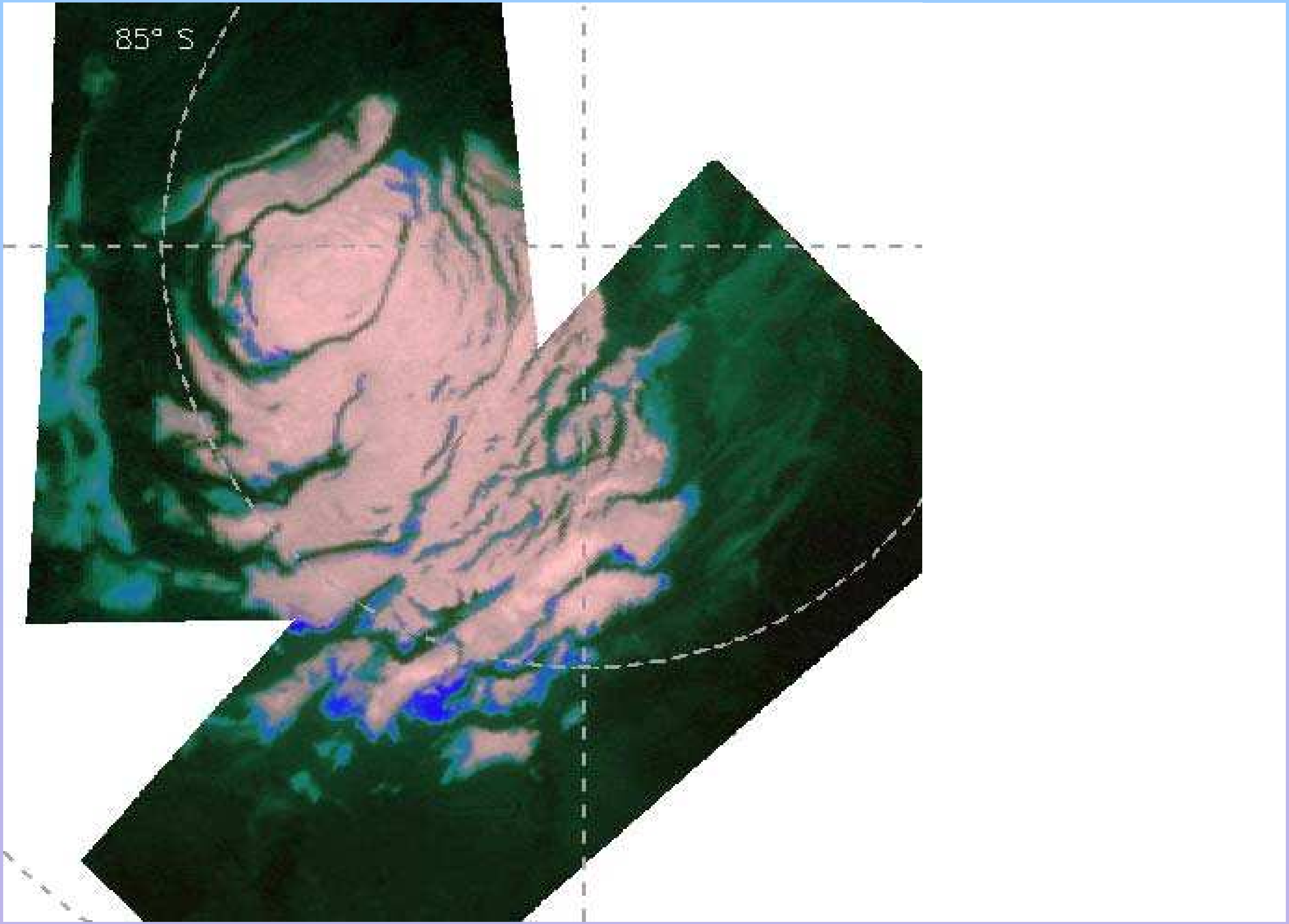




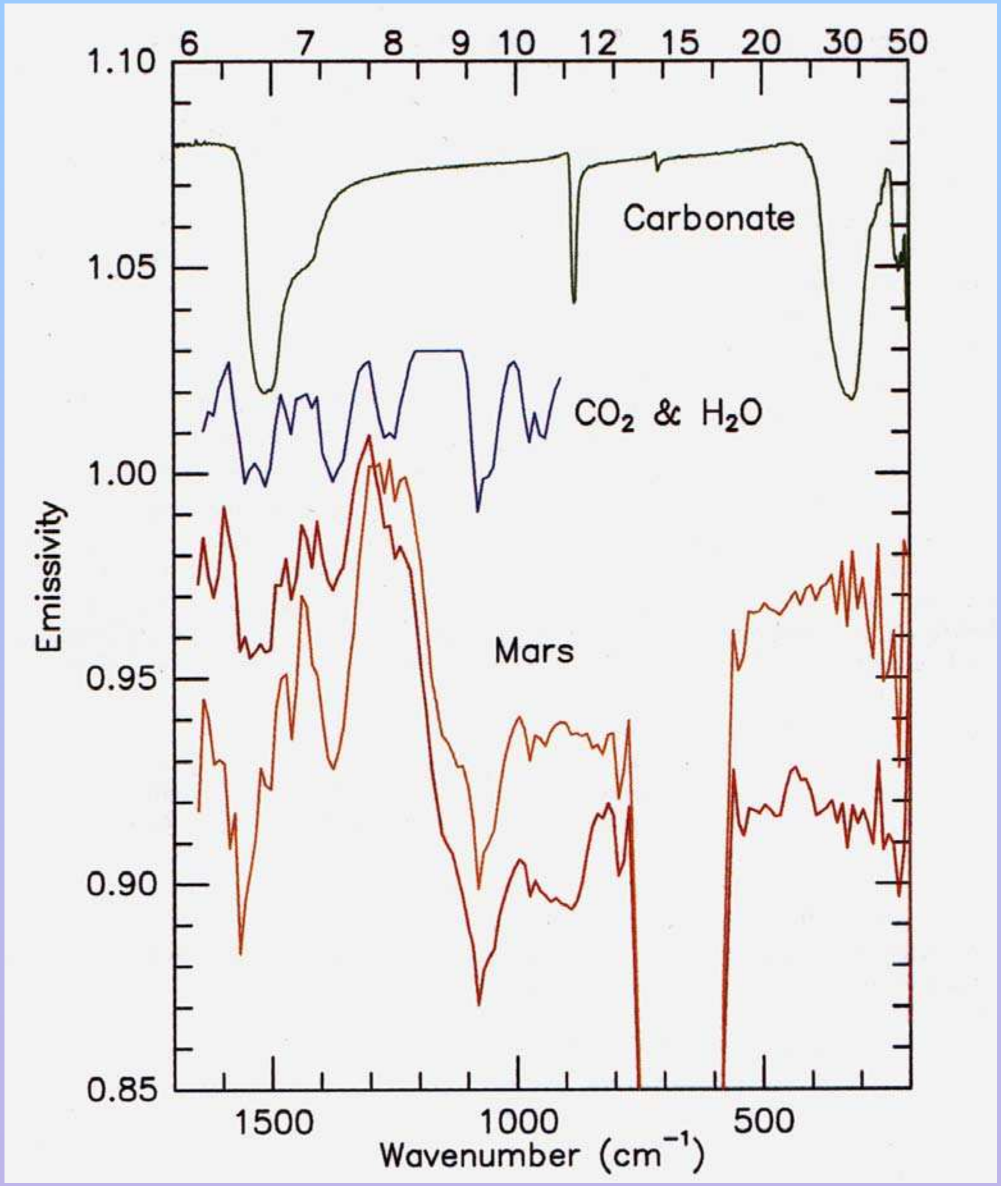
Composition of the Martian polar cap (OMEGA/ MEX)



Detection of perennial water ice on the South pole of Mars (OMEGA/ MEX)



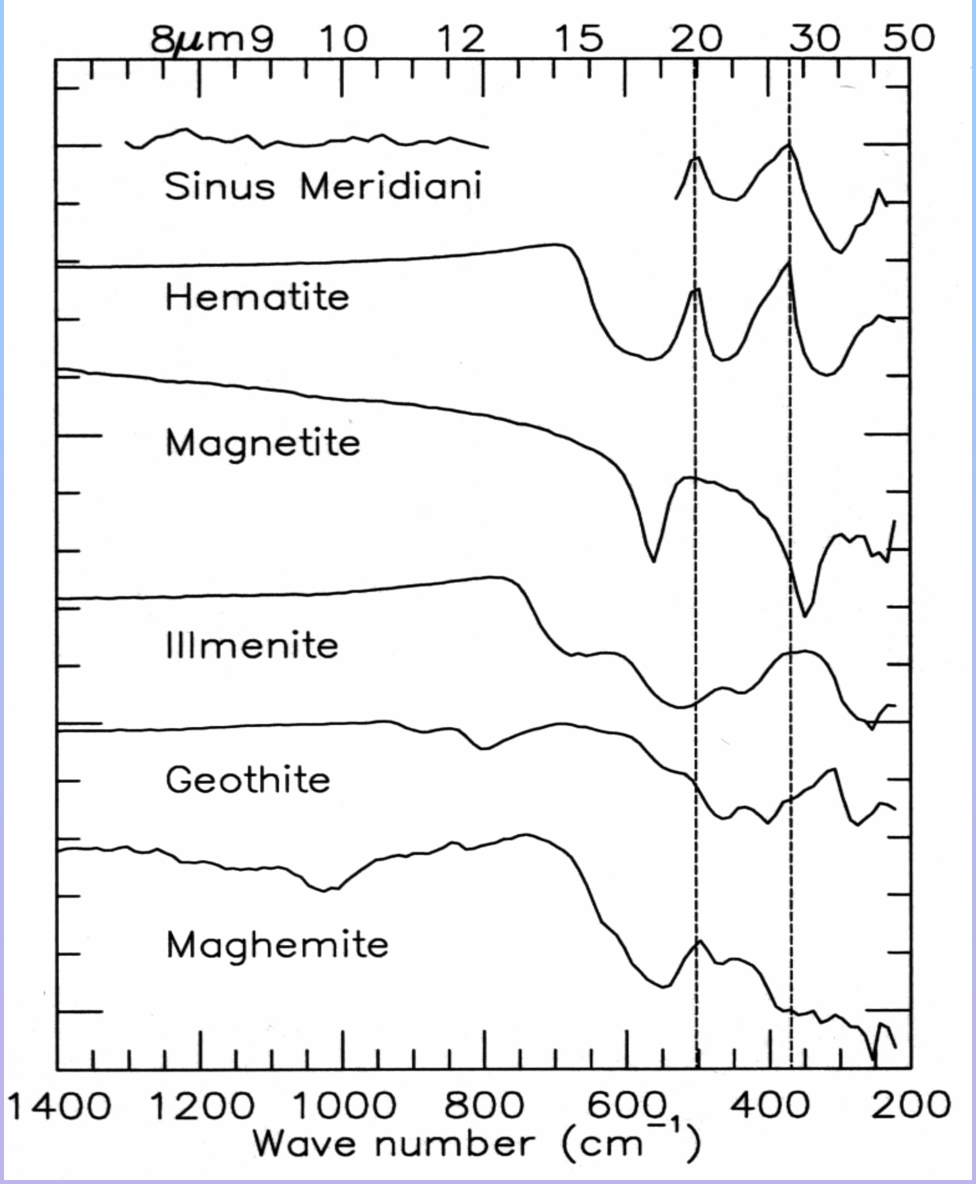
TES: Surface mineralogy
Carbonates and weathering products

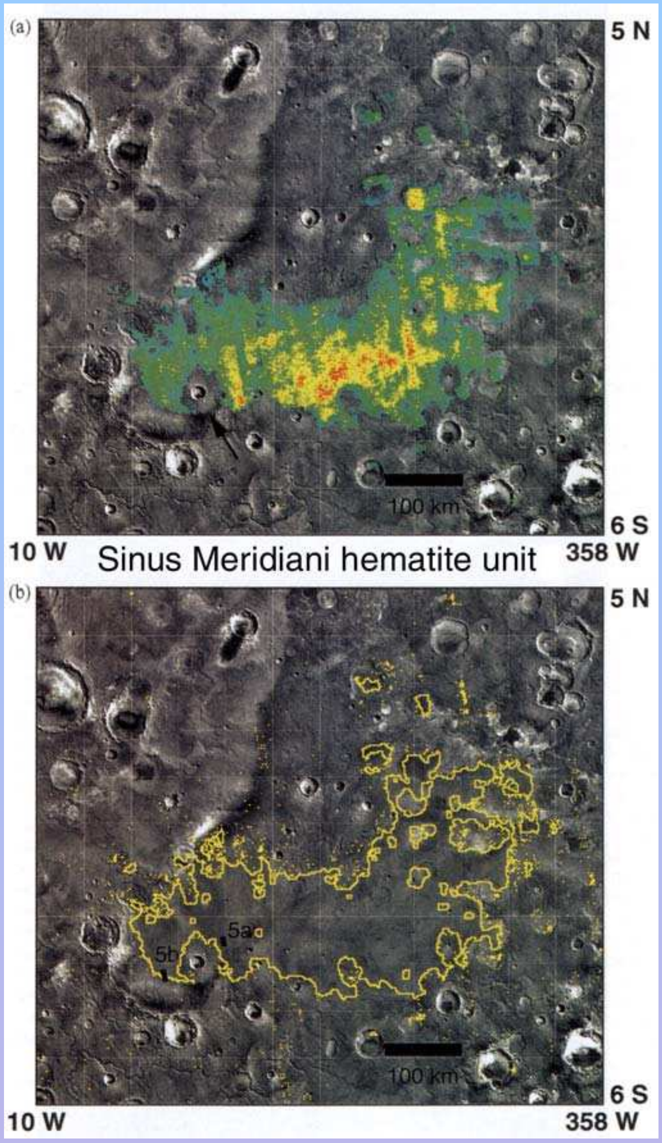


Carbonates, quartz and sulfates have not been identified at detection limit of 5, 5, and 10% respectively and 3 km spatial resolution.

Christiansen et al., 2000, 2001

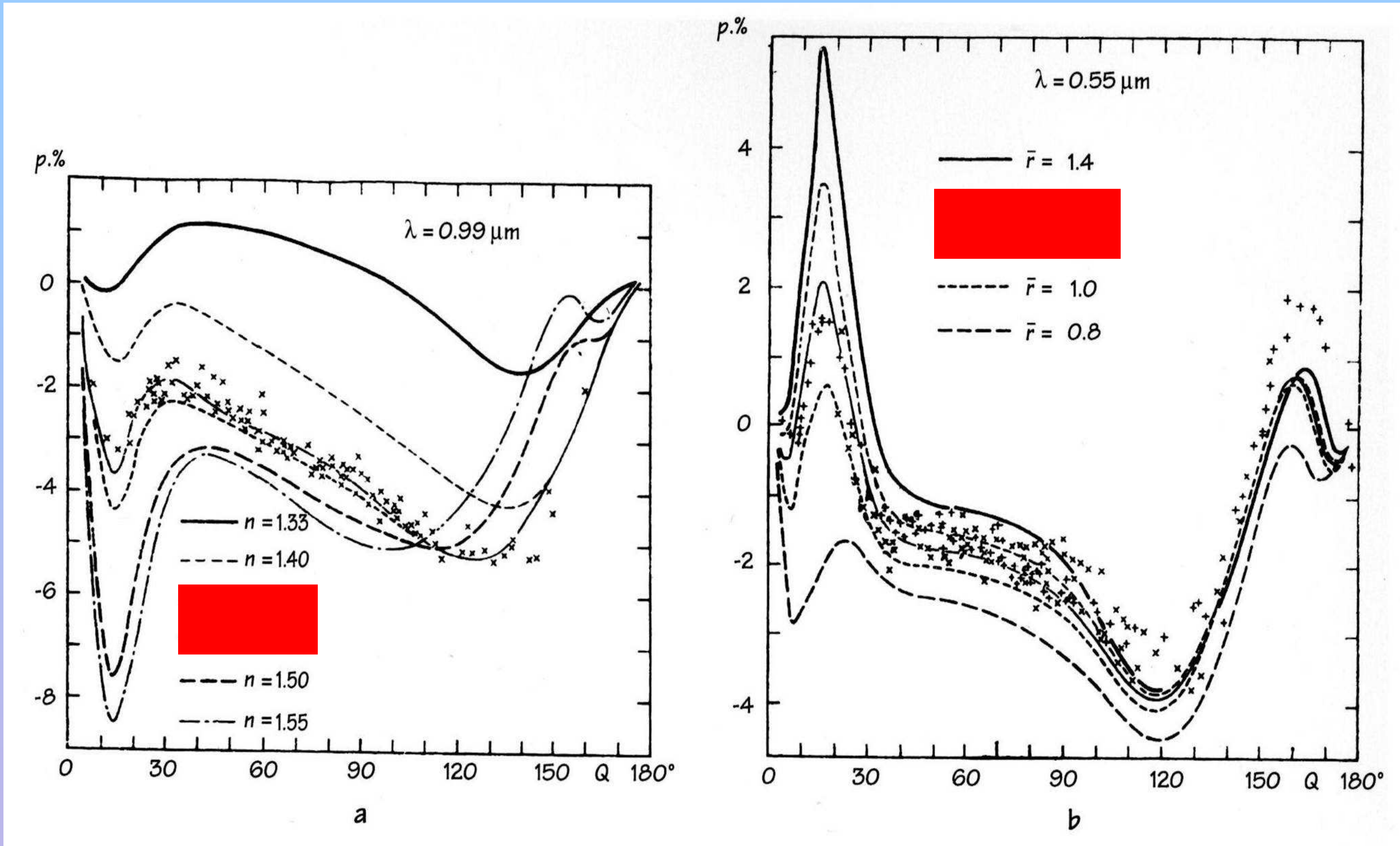
TES: detection of hematite





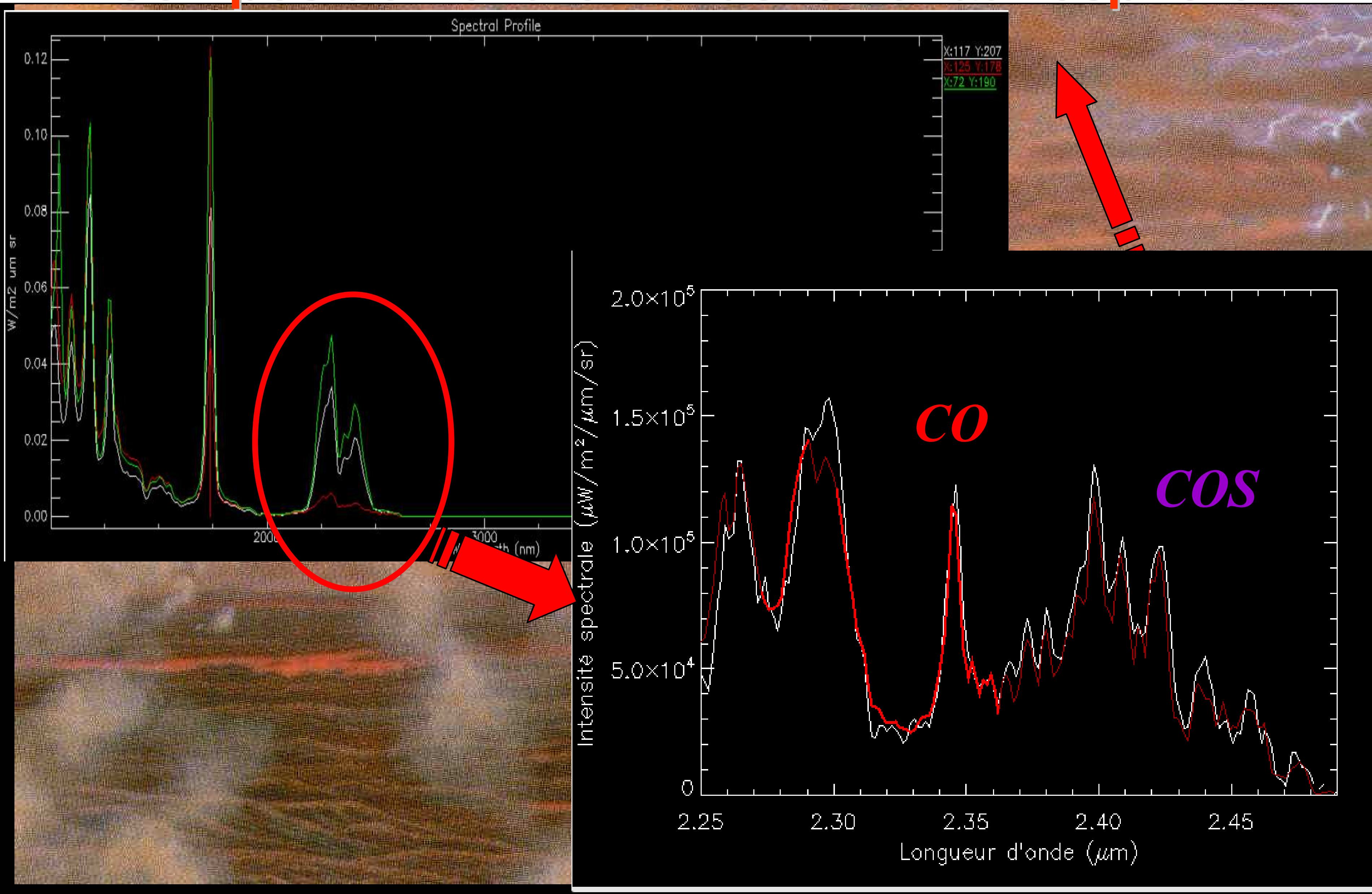
Three localities of crystalline gray hematite: Sinus Meridiani, Aram Chaos, Ophir/Candor small deposits.

Polarimetry of Venus: discovery of sulfuric acid clouds

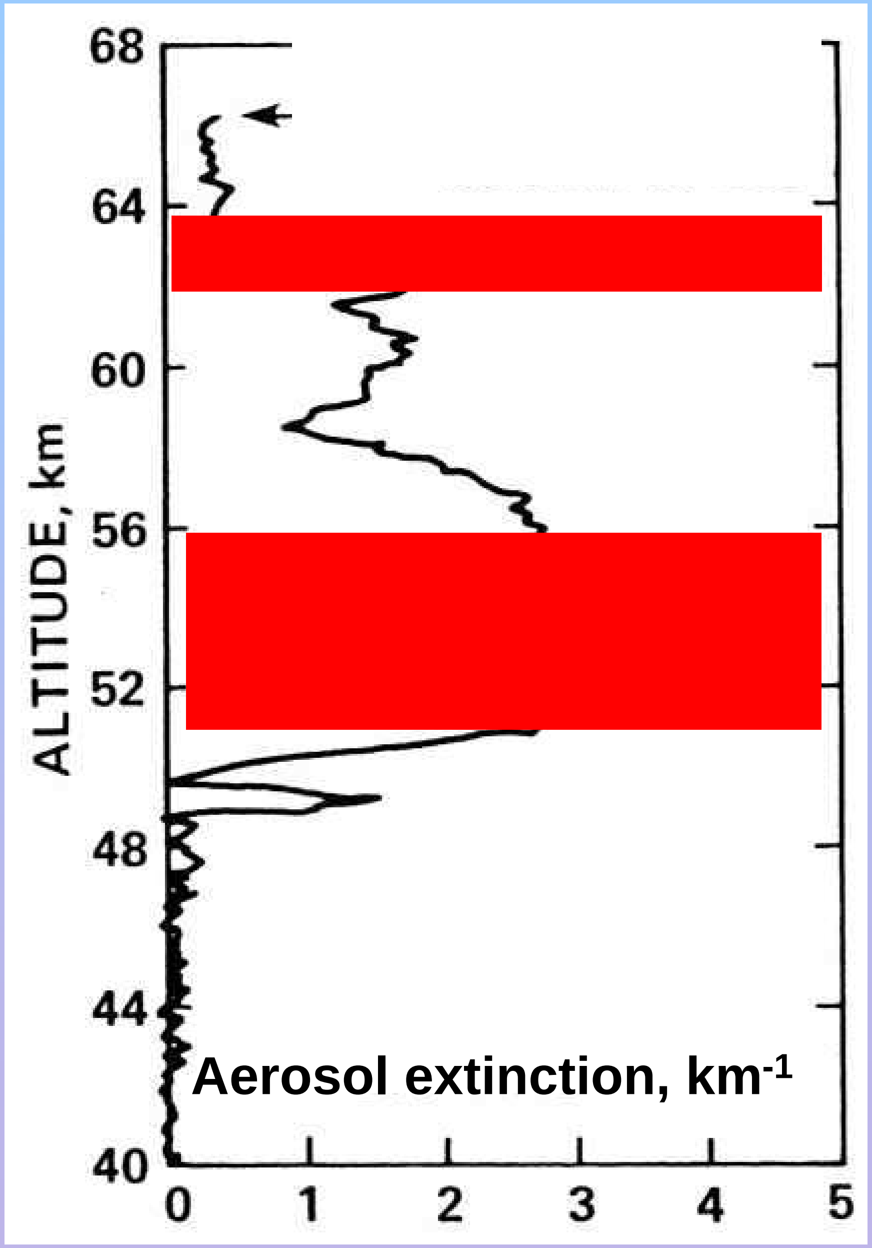


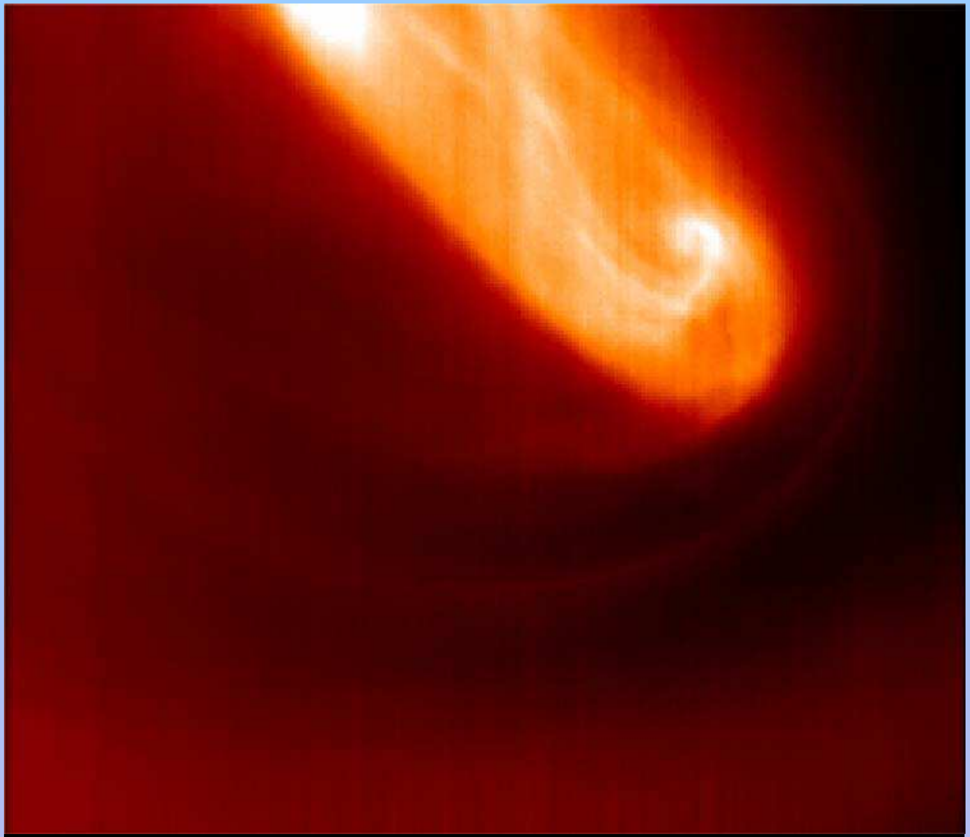
- Sensitivity to aerosol optical properties and size distribution

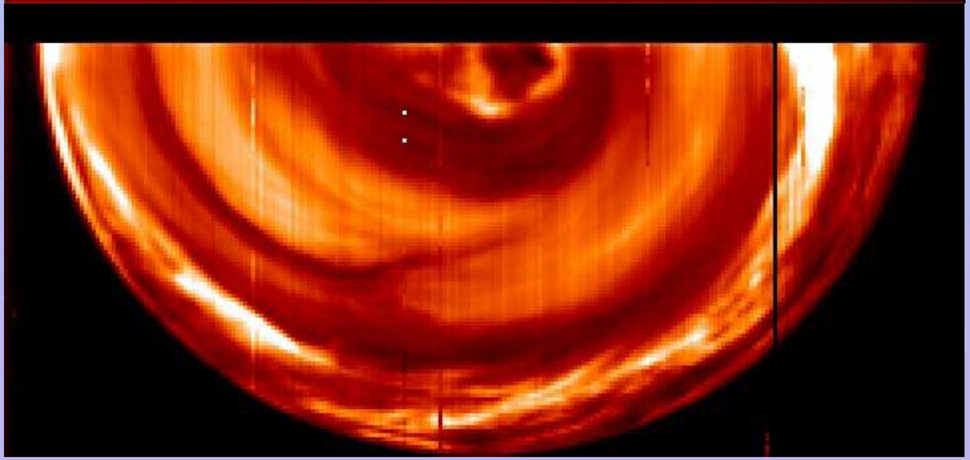
Spectroscopy in transparency "windows": Composition of the Venus lower atmosphere



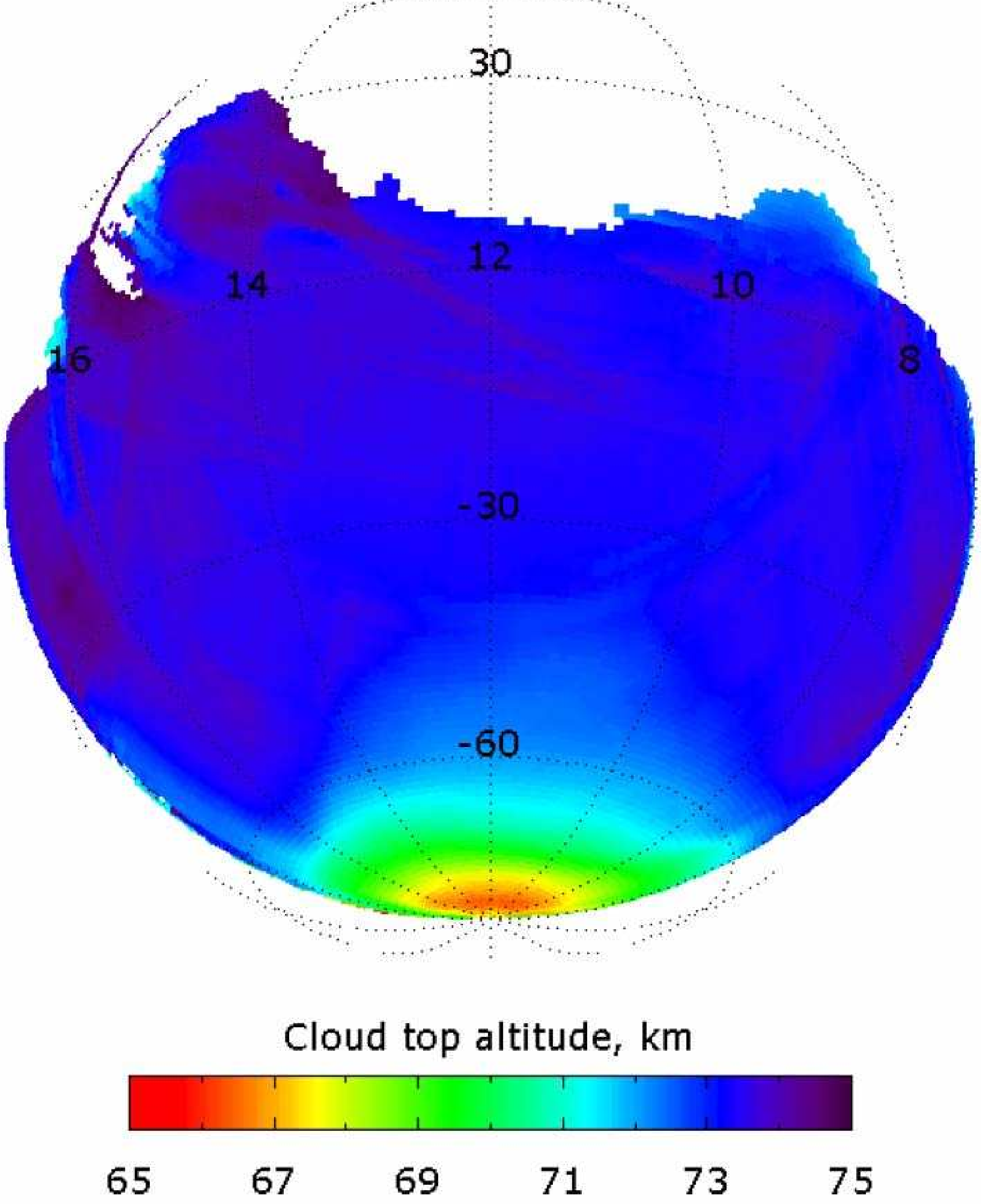
Imaging at different wavelengths

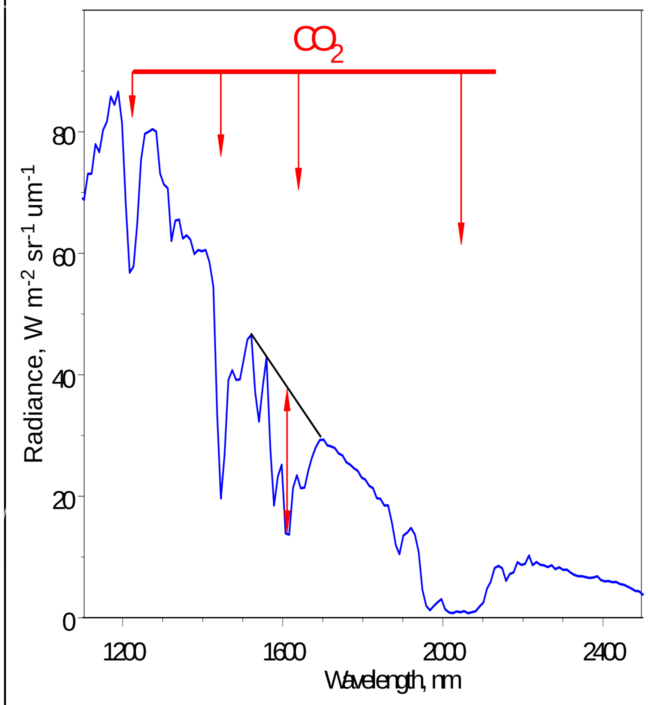






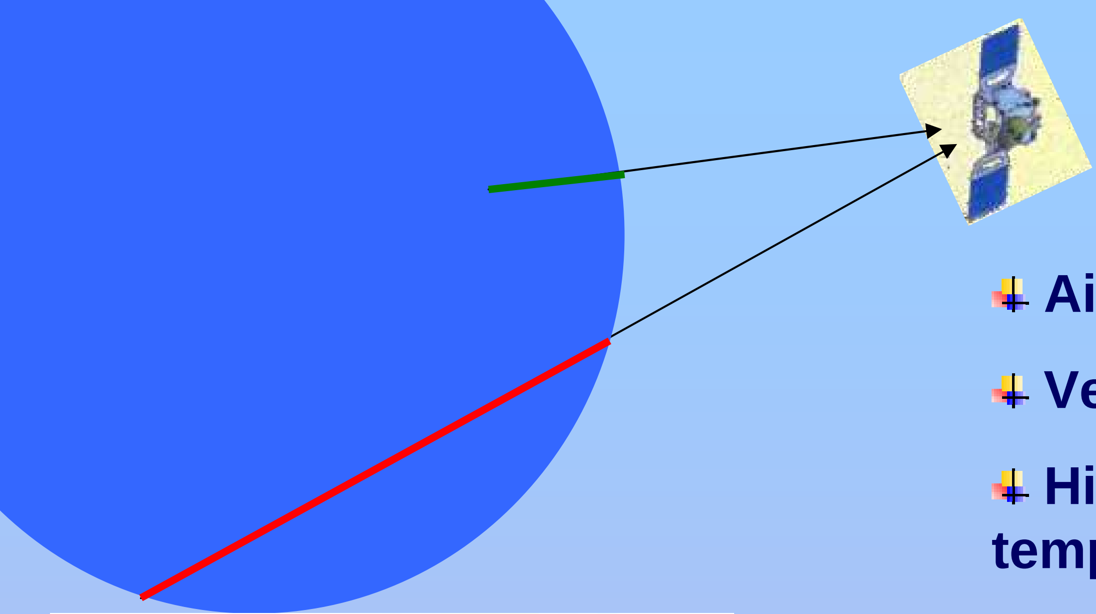
Cloud top altitude



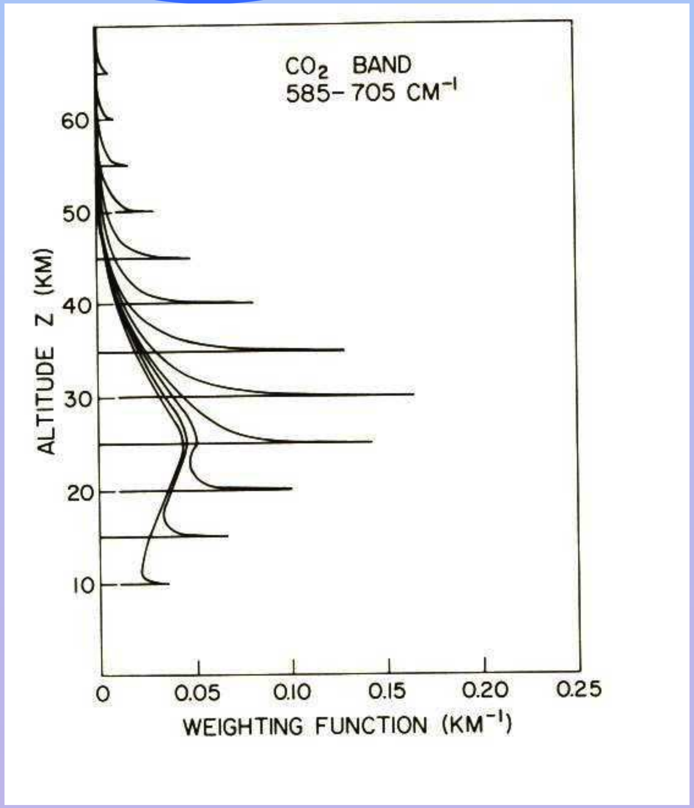


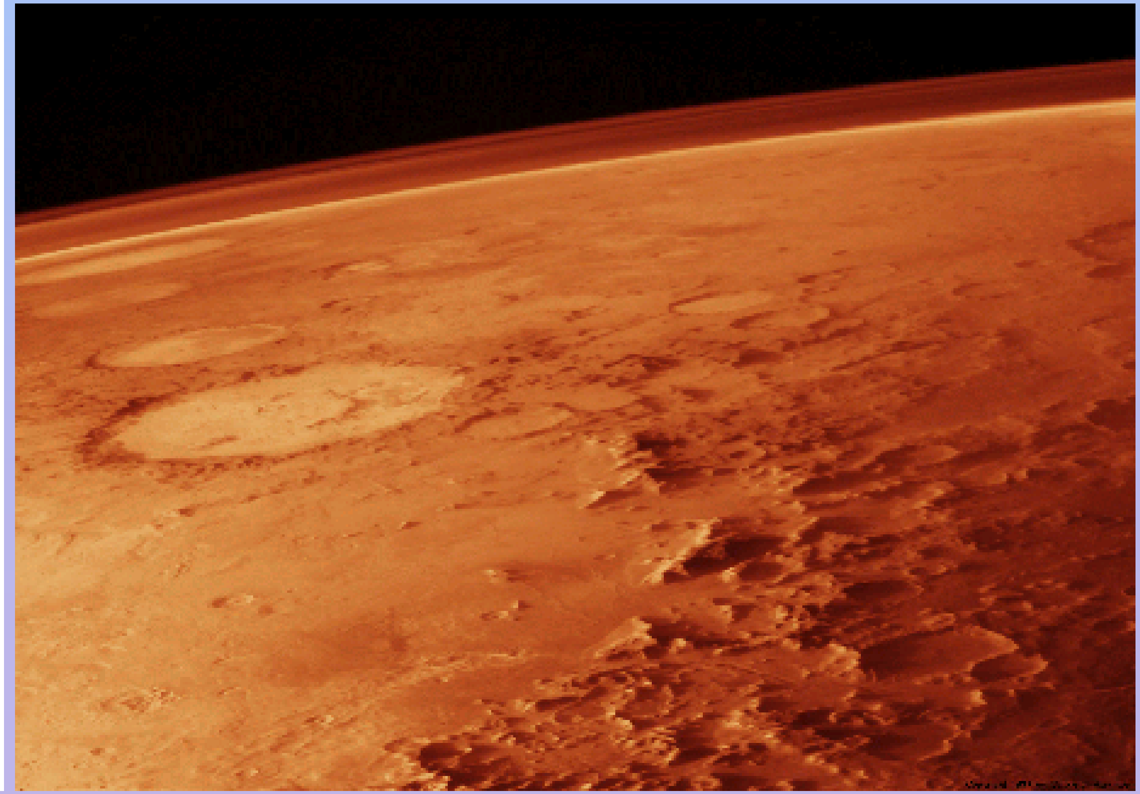
Ignatiev et al.

Limb sounding

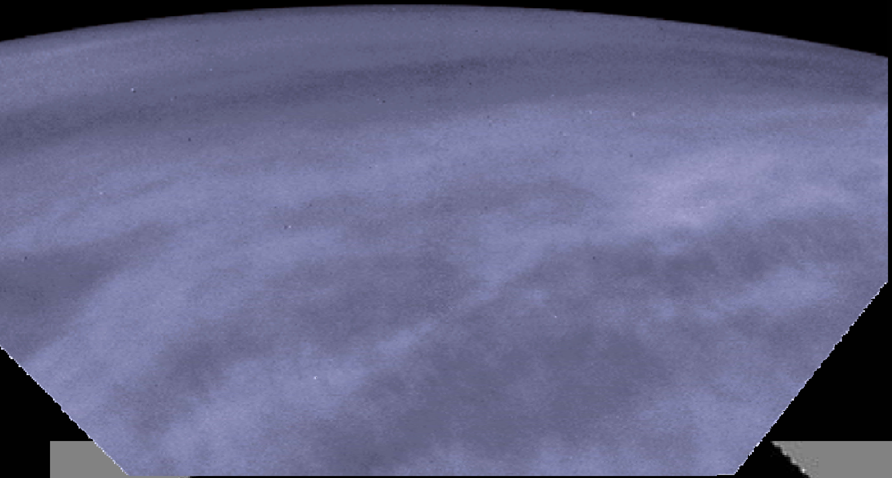


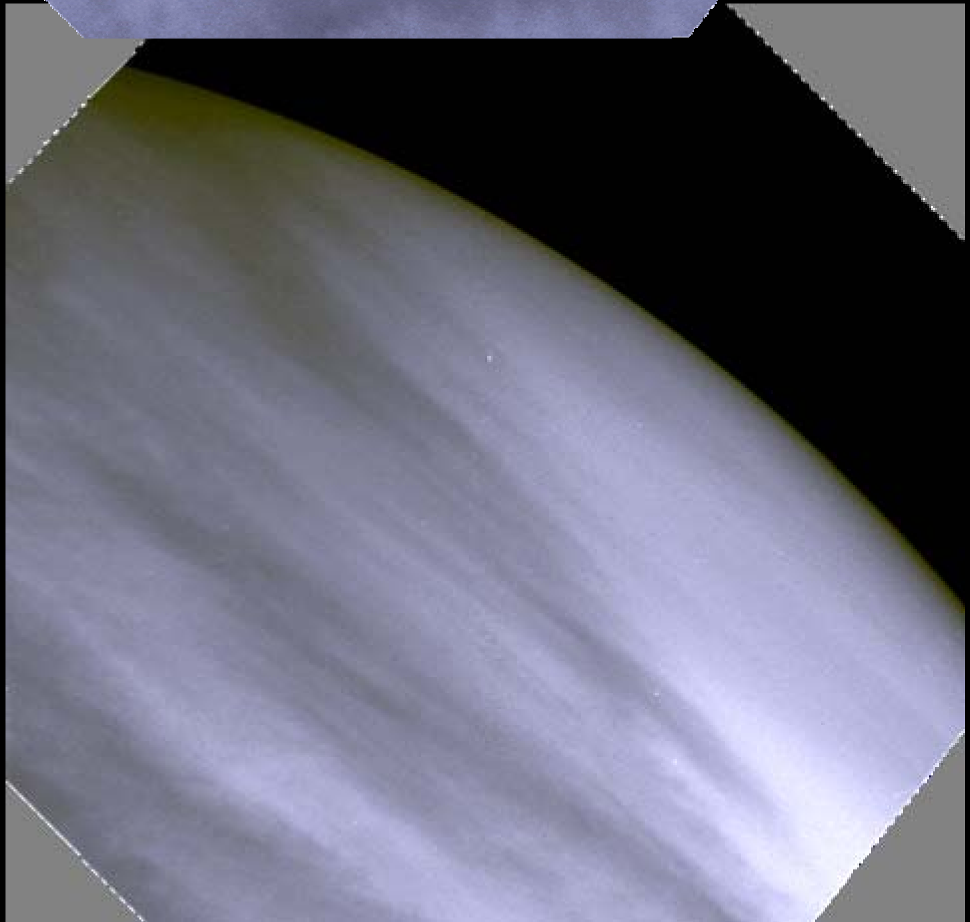
- Air mass advantage
- Vertical sounding
- Higher altitude resolution in temperature sounding

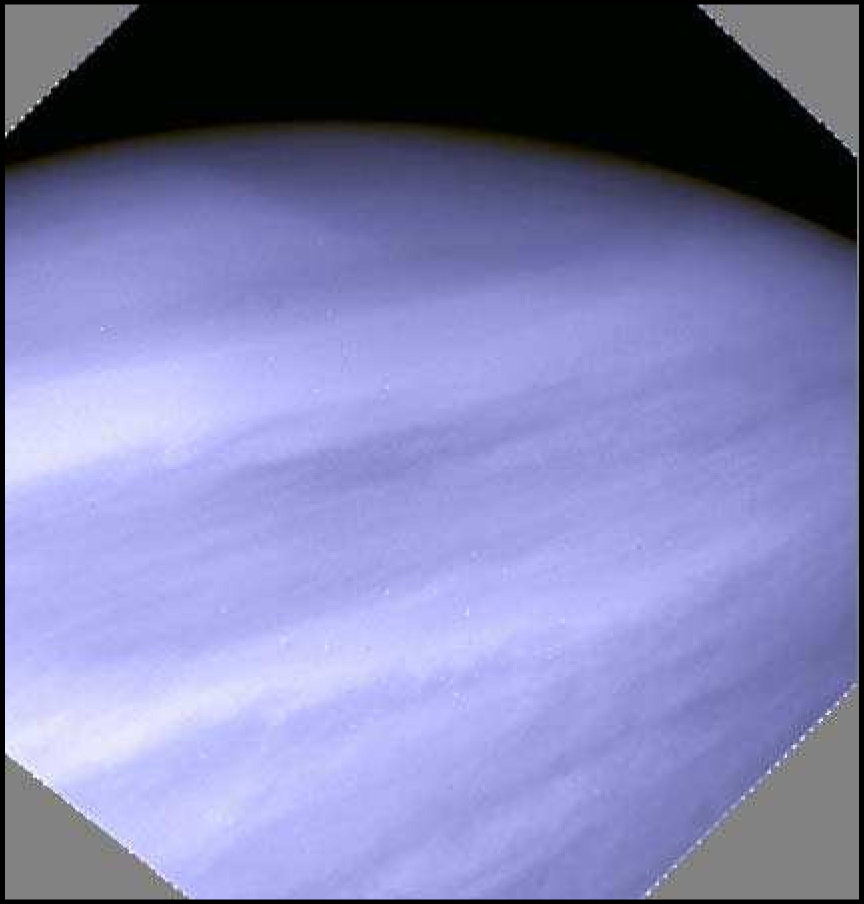




Venus limbs by Venus Express Monitoring Camera

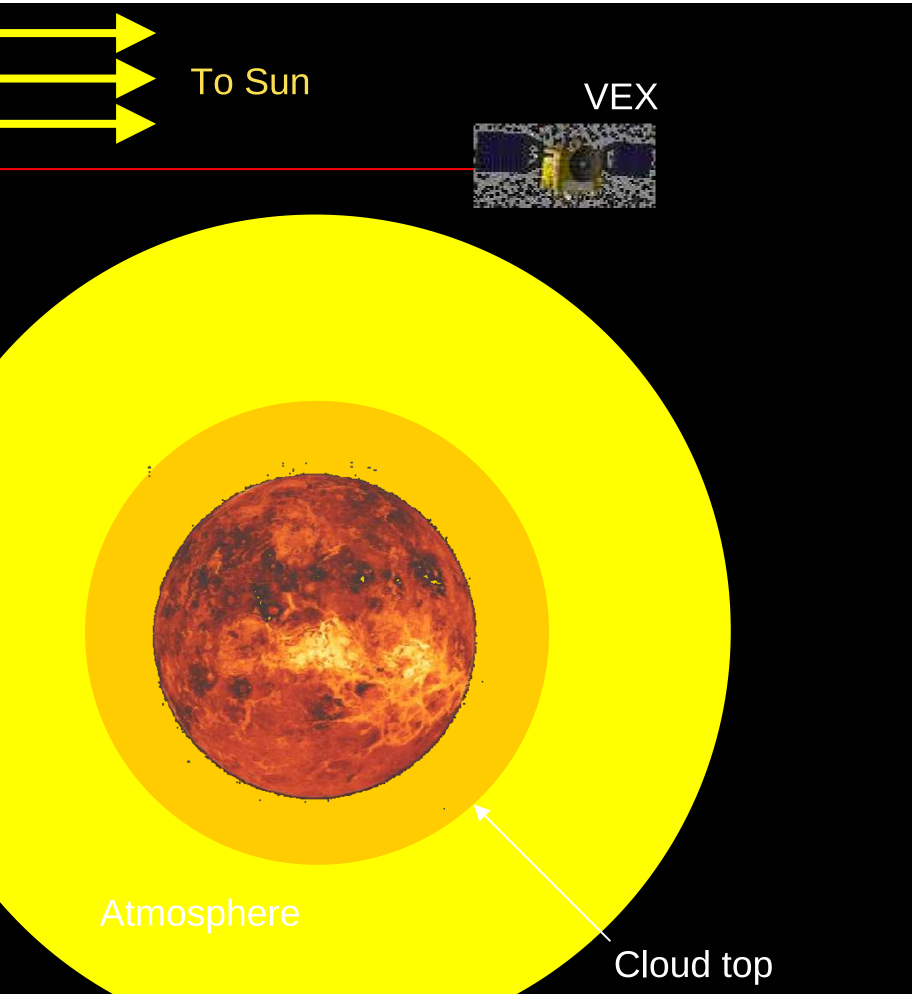




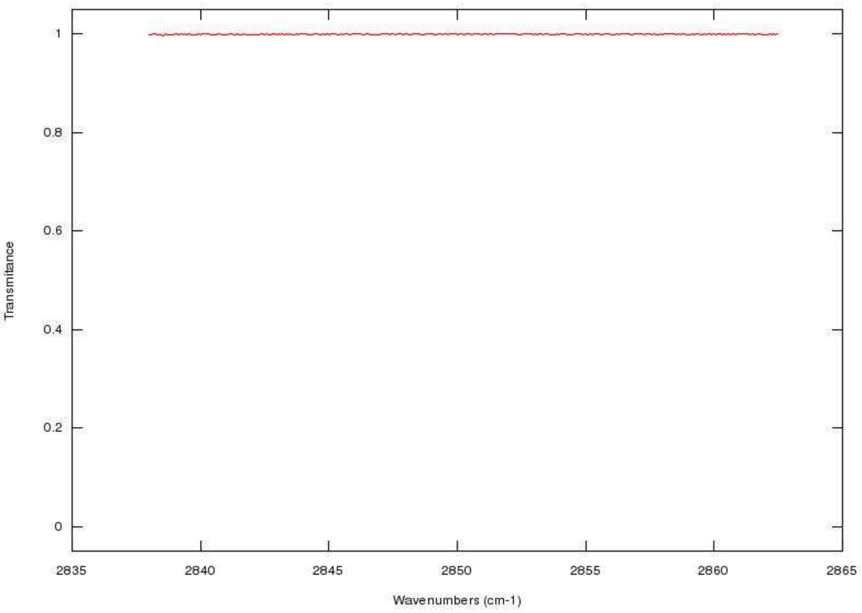


Solar occultation sounding

SPICAV/SOIR solar occultation



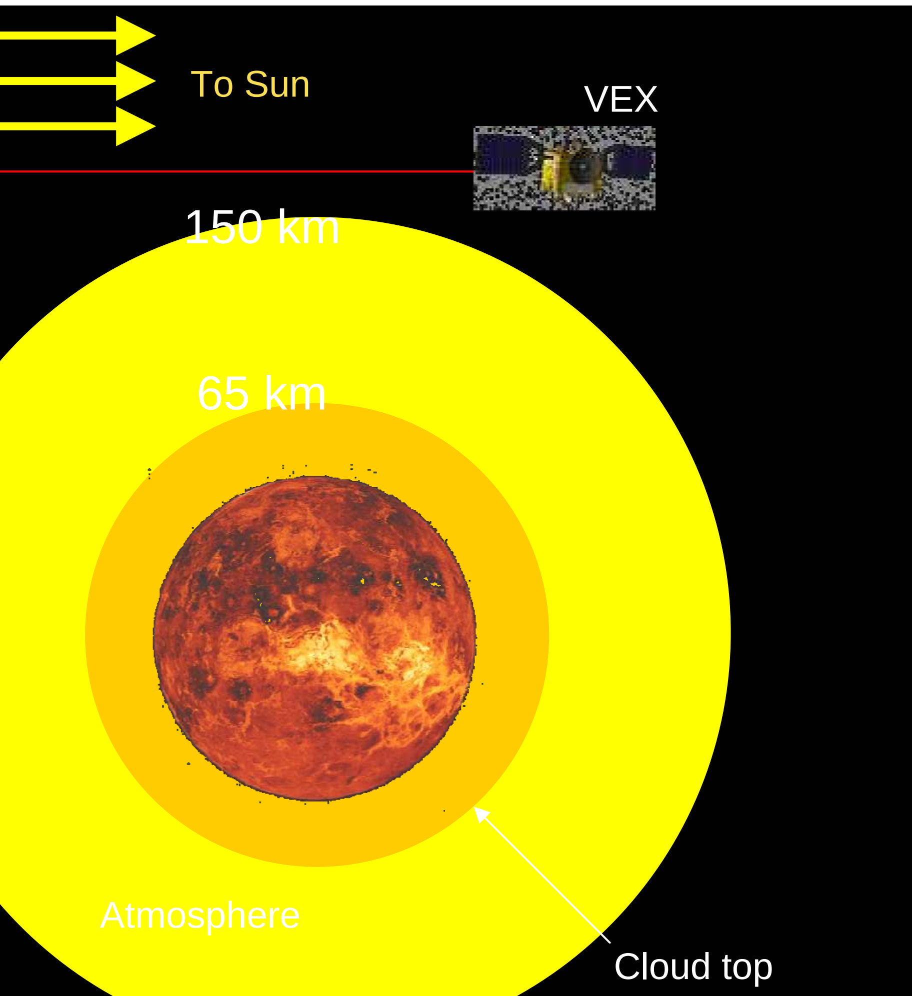
Orbit 232 – Order 129

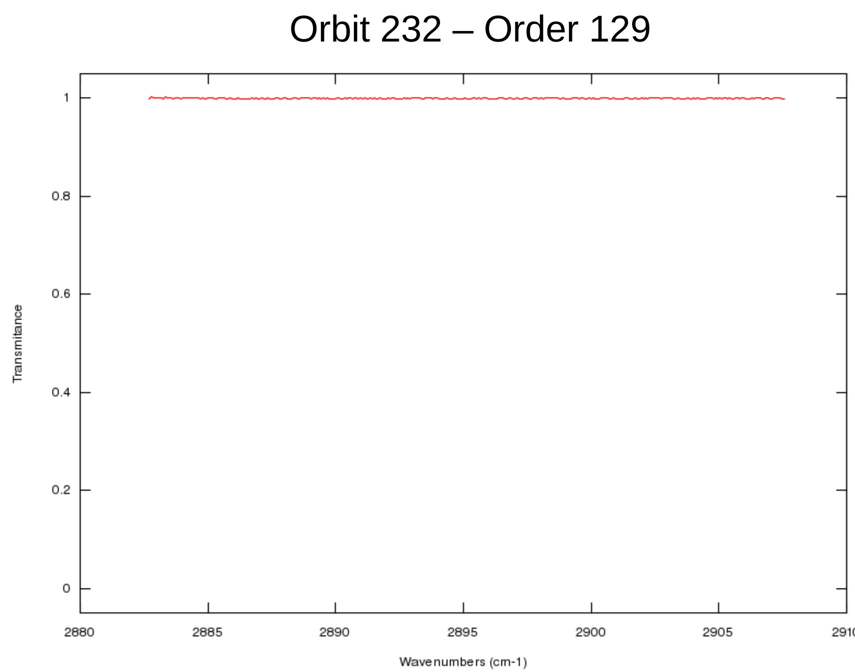


SPICAV/SOIR solar occultation

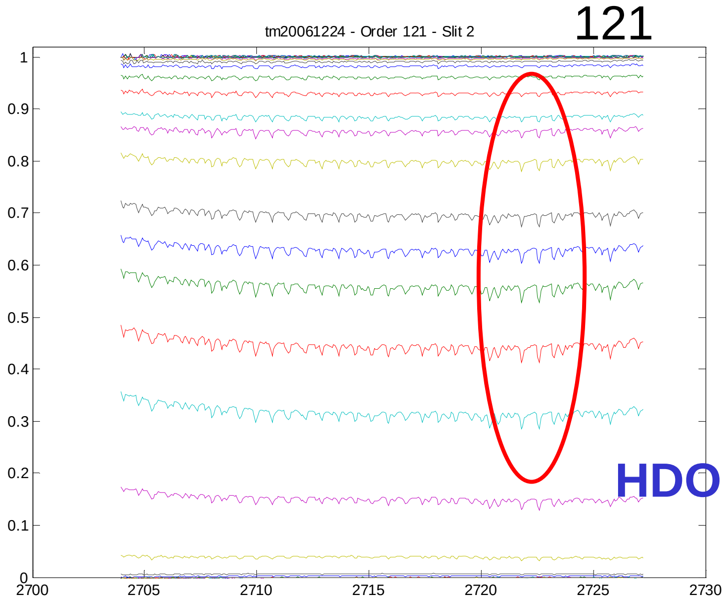
Detected molecules:

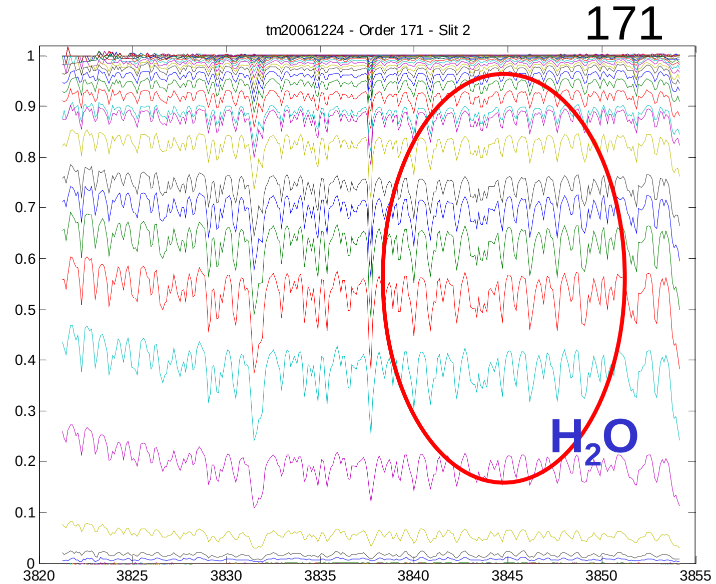
CO_2, H_2O, HDO, CO, HCl, SO_2

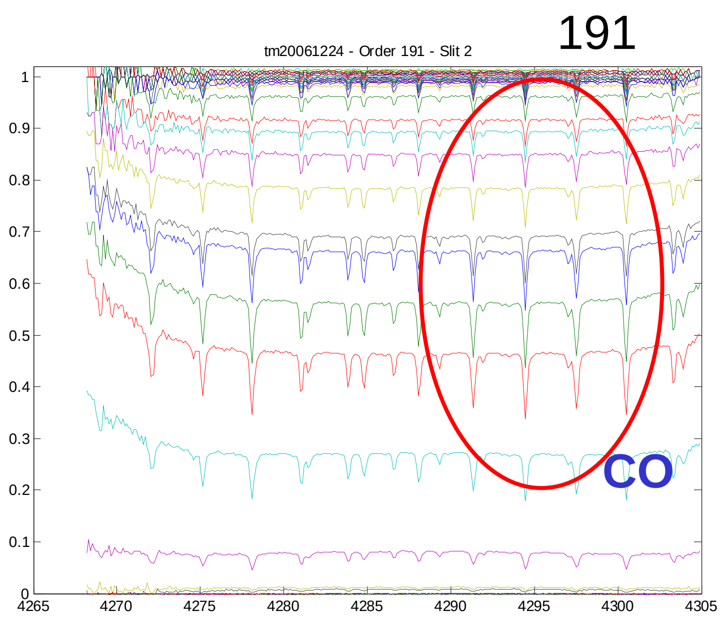


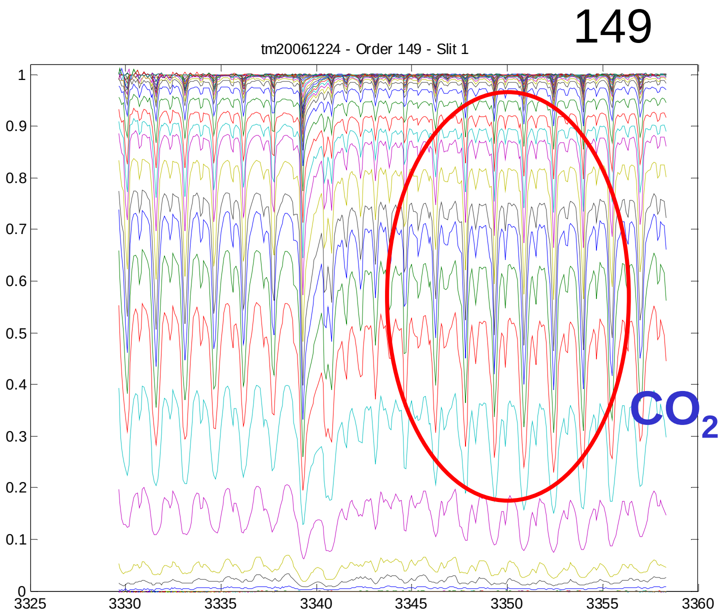


Examples of SOIR Venus Express spectra

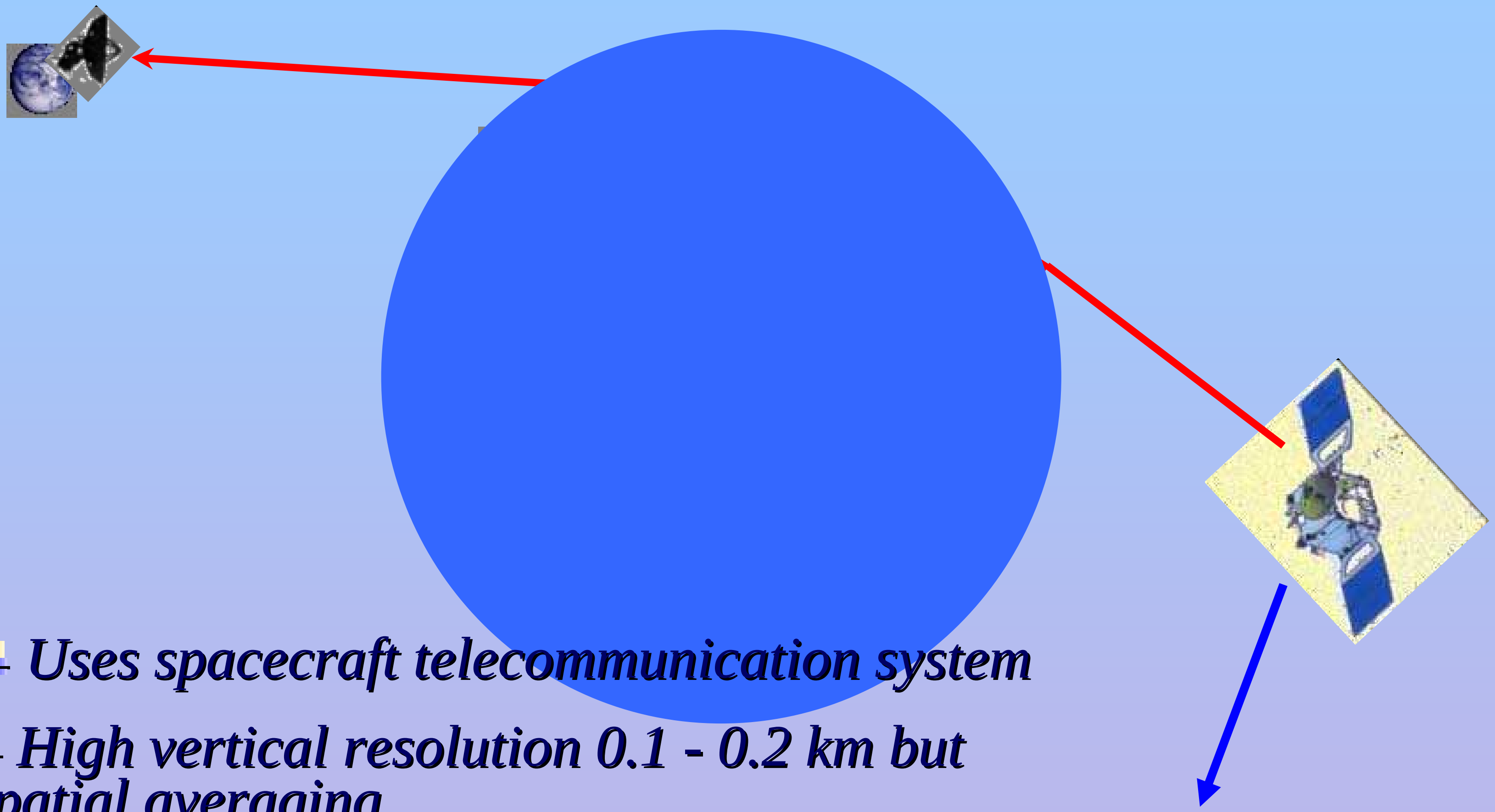






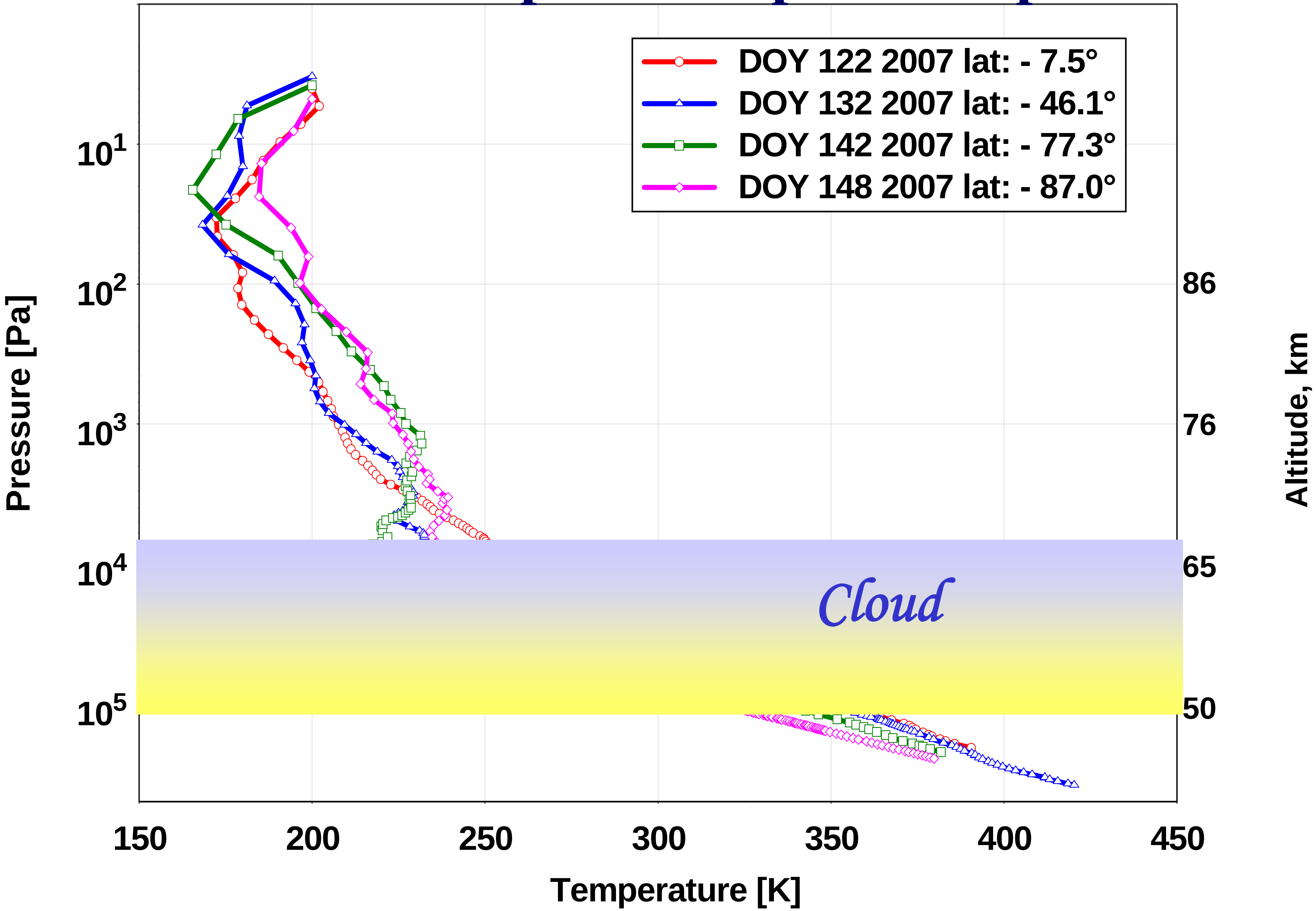


Earth radio occultation



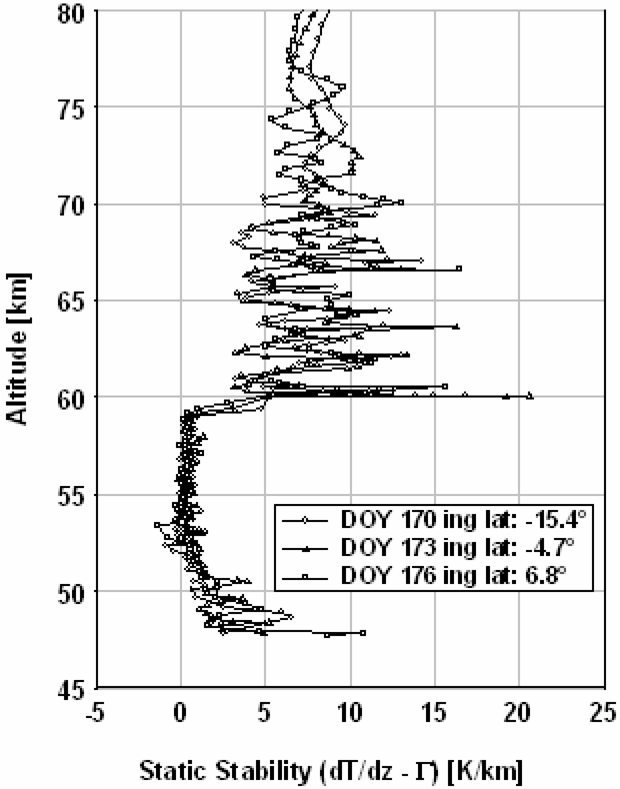
- Uses spacecraft telecommunication system
- High vertical resolution 0.1 - 0.2 km but spatial averaging
- Deep penetration in the atmosphere
- Complete latitude coverage
- Occultations occur in seasons

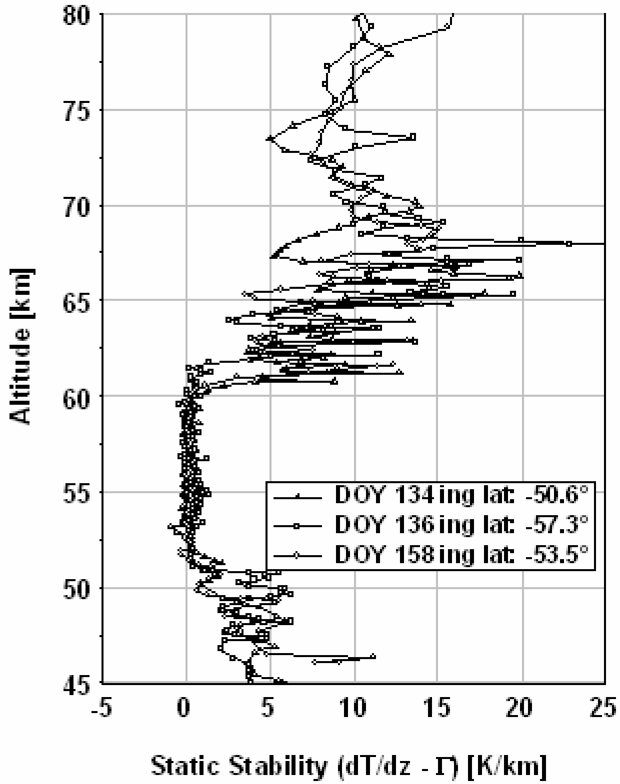
VeRa/Venus Express temperature profiles

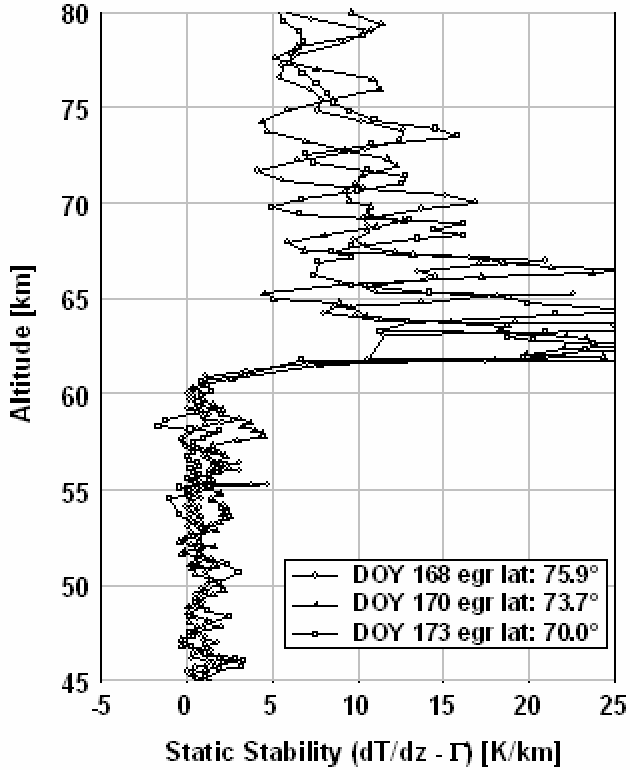


Atmosphere static stability from radio-occultations by Venus Express

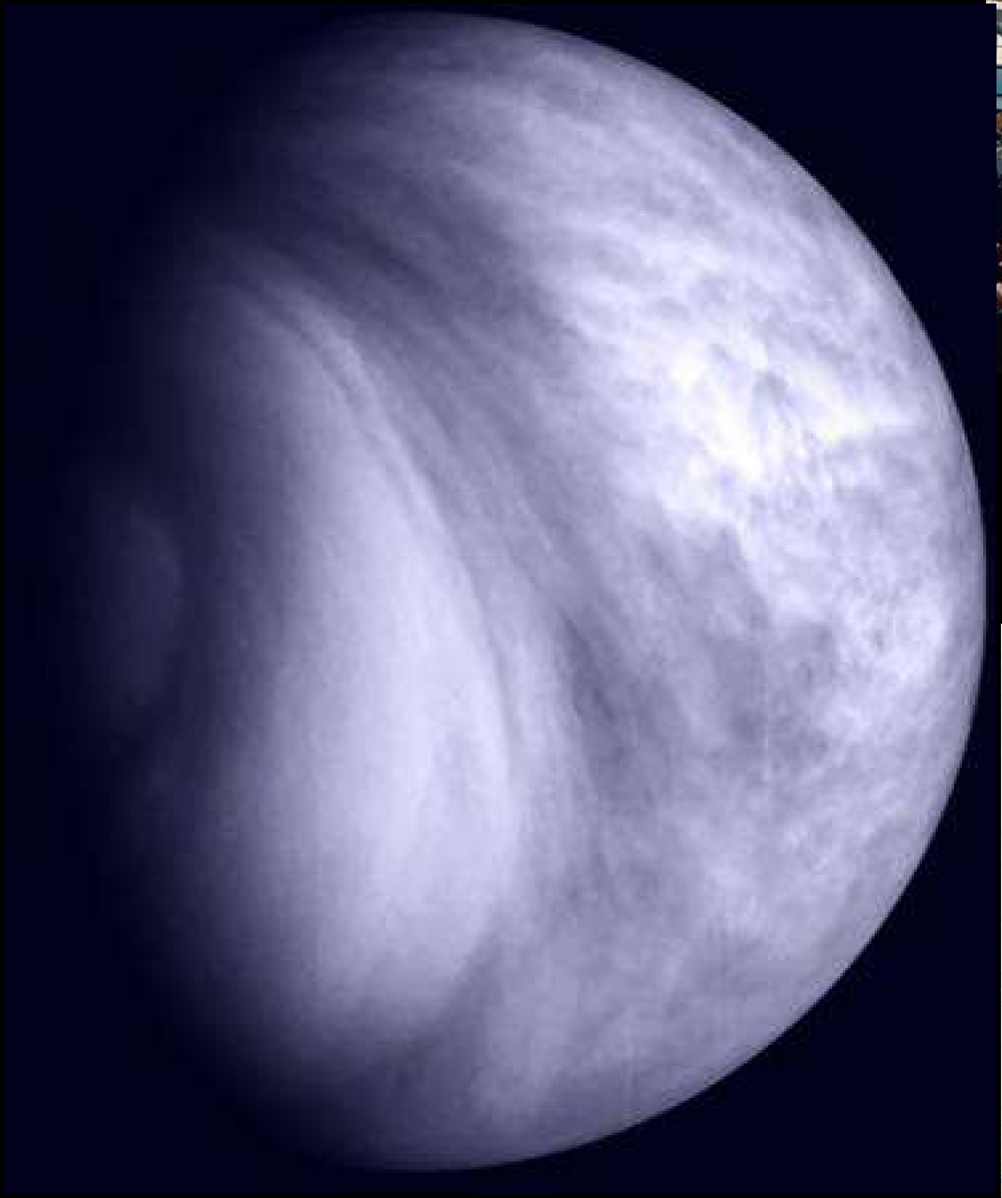
low latitudes | middle latitudes | high latitudes

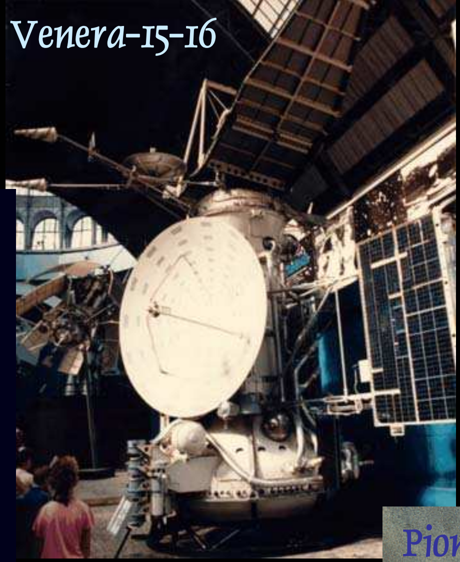


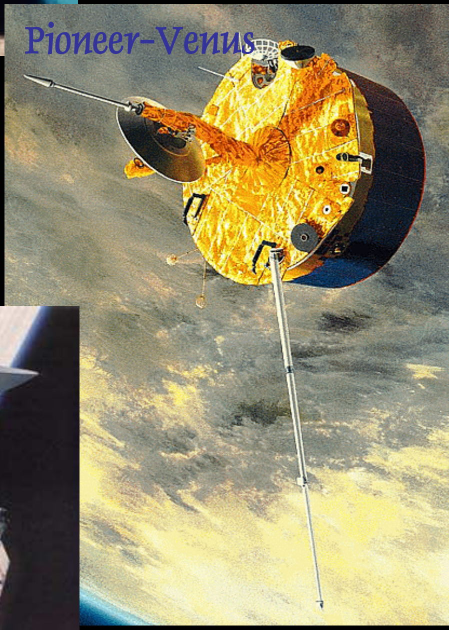




Venus unveiled…







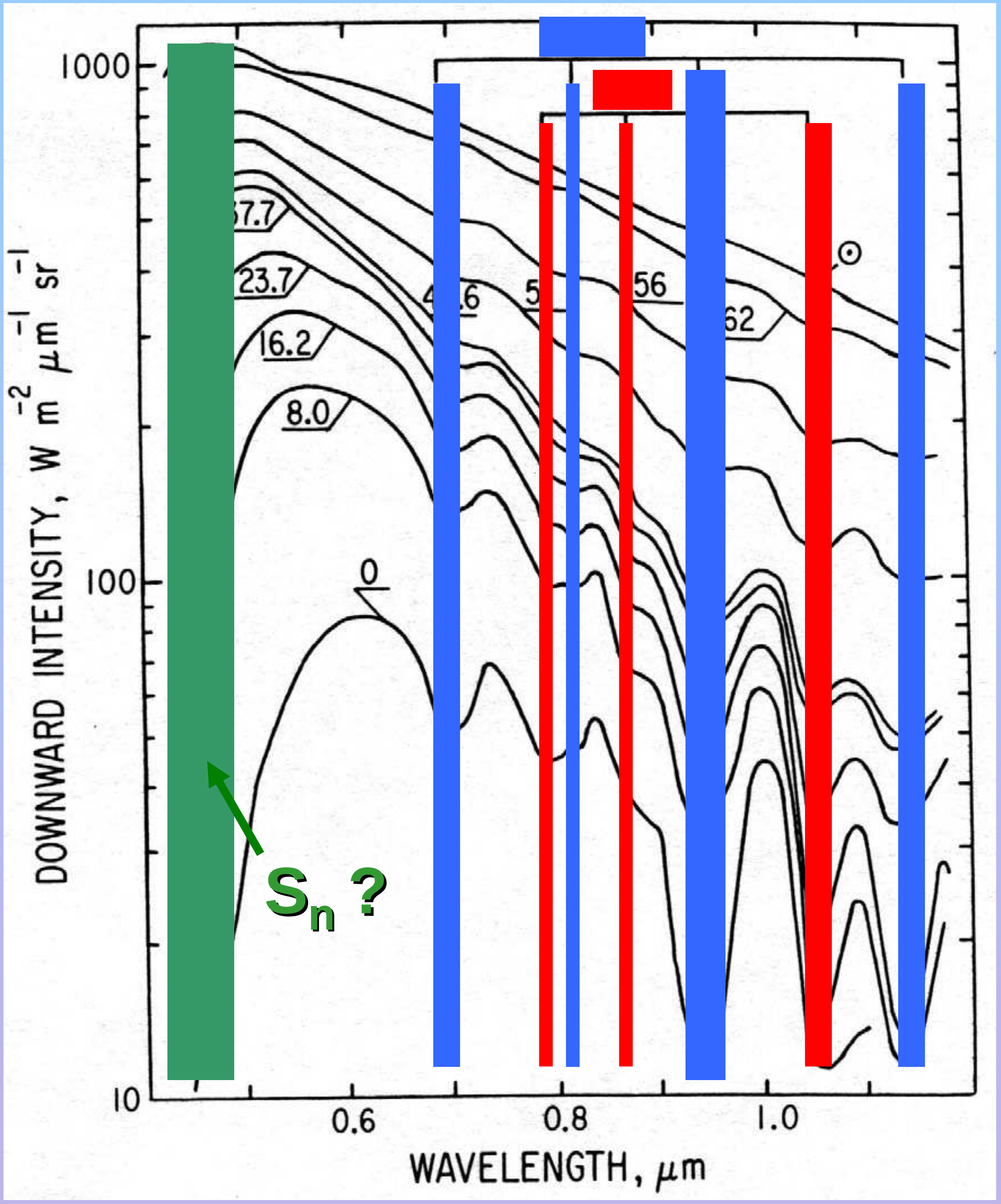
Magellan, US, 1990, SAR images (100-200 m), radioph. properties, gravity

In-situ investigations

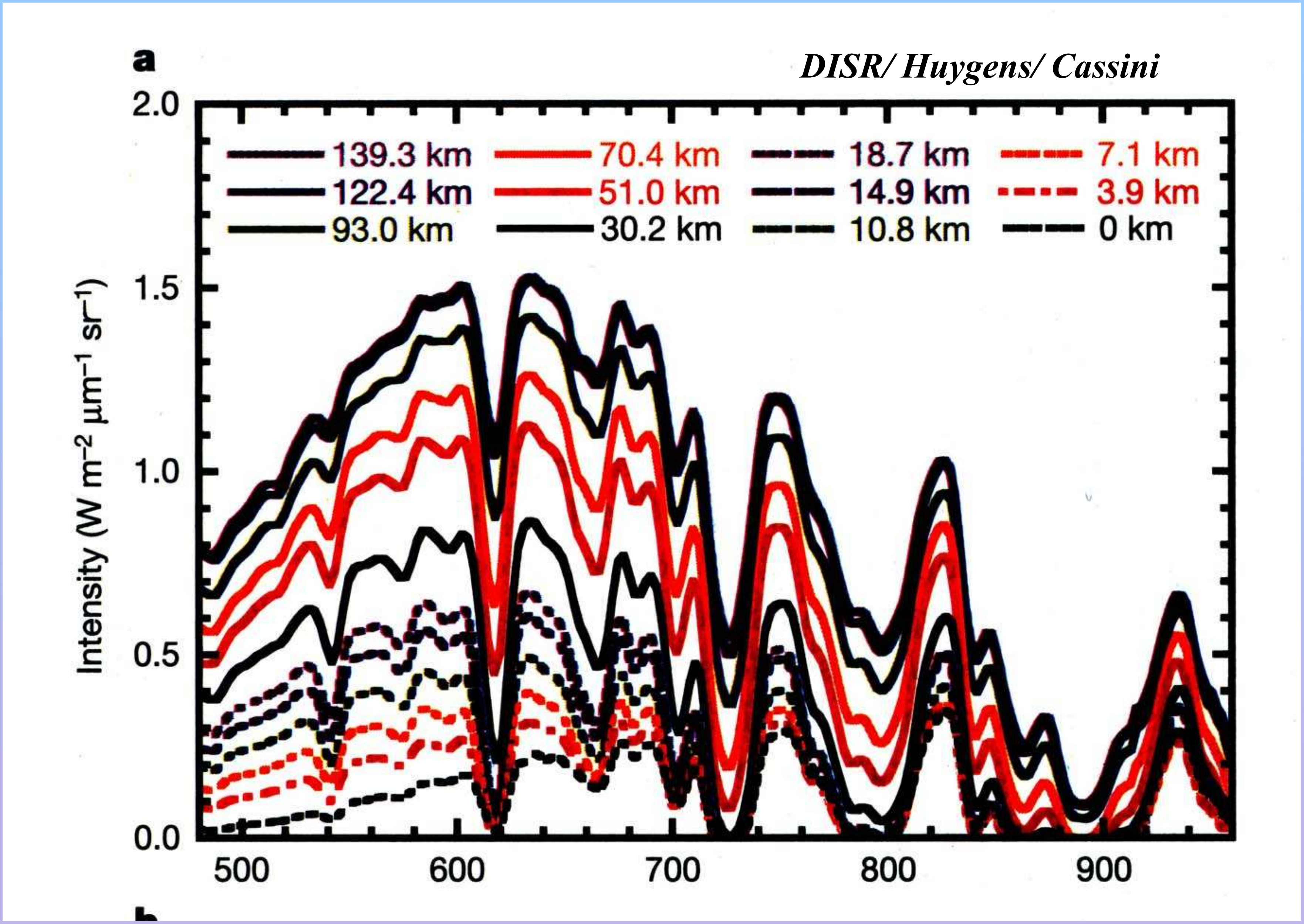
- Descent probes
  - *Pressure/ temperature sensors*
  - *Optical studies*
  - *In-situ analysis of gases, aerosols, and rocks*
- Balloons
- Rovers

Spectrophotometry on descent probes

Venera-11



Spectra of the Titan atmosphere

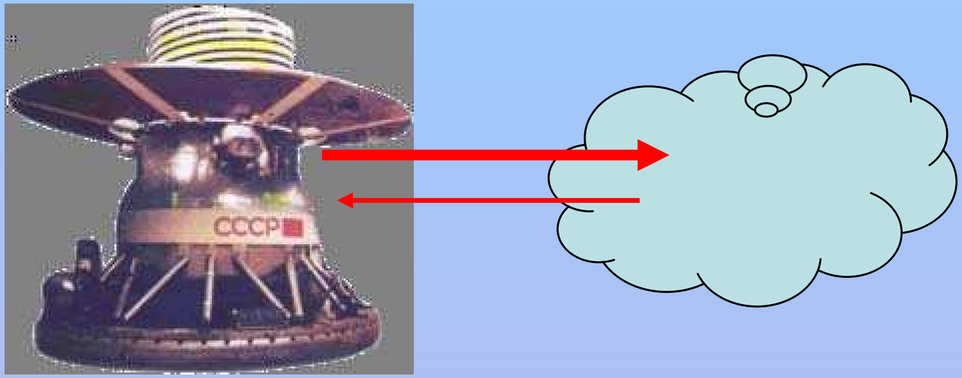


Titan atmosphere: Let´s dive in !

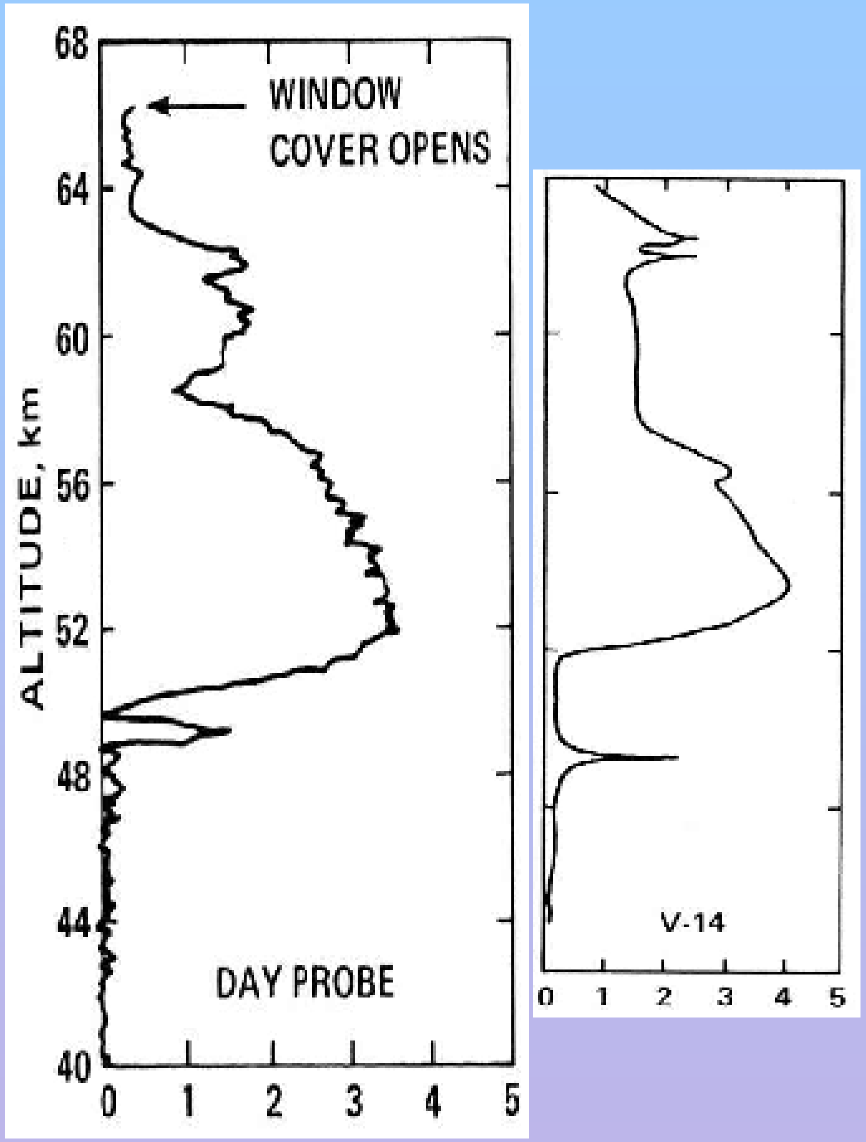
Descent on Titan.mpeg

Huygens descent on Titan
Simulations by B. Grieger

Nephelometry on descent probes



- Vertical profile of aerosol extinction
- Optical properties of cloud particles



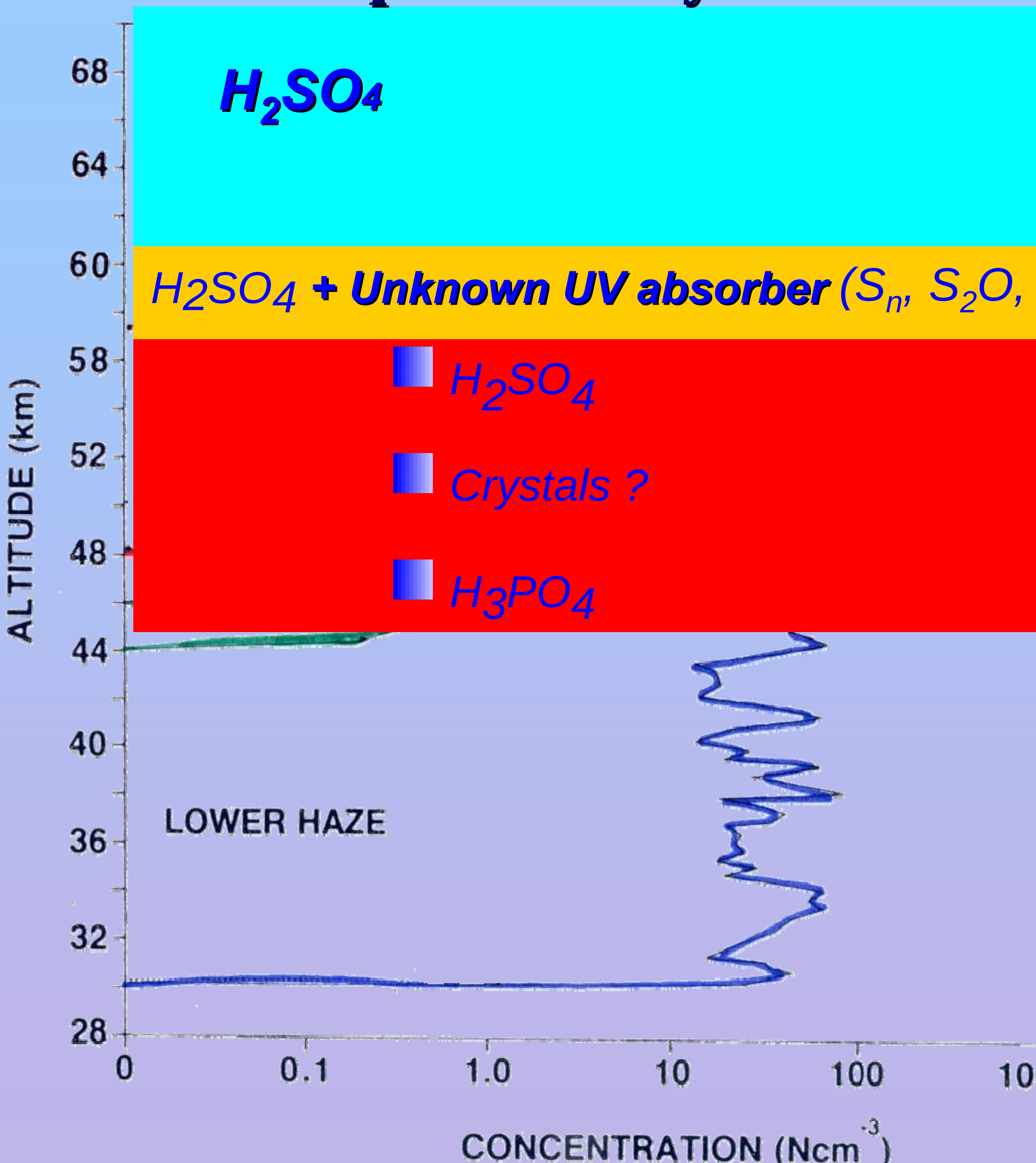
Extinction coefficient, km^{-1}

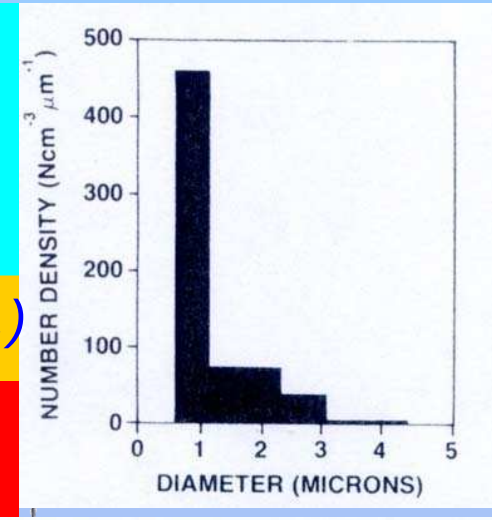
Spectrometry of the aerosol particle sizes

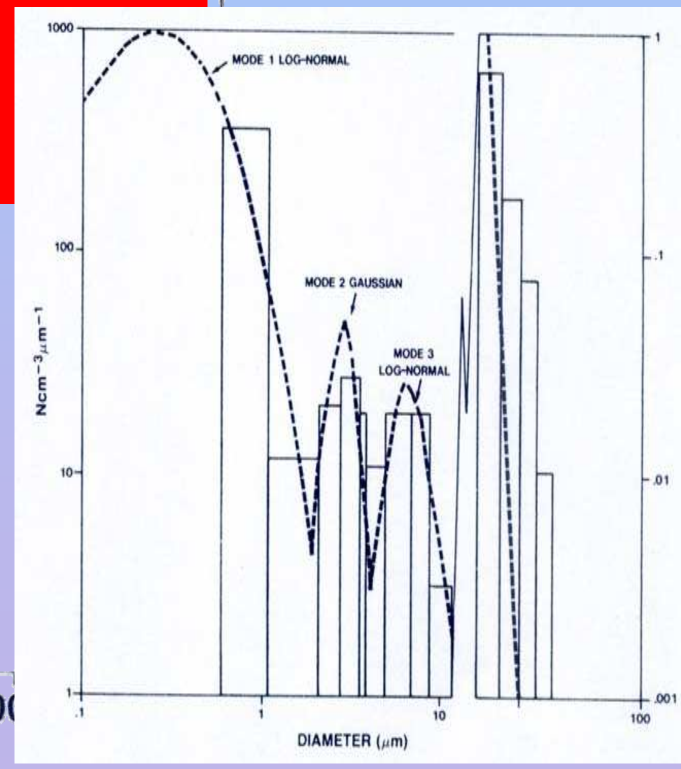
H_2SO_4

H_2SO_4 ***+ Unknown UV absorber*** *(S_n, S_2O, $FeCl_3$…)*

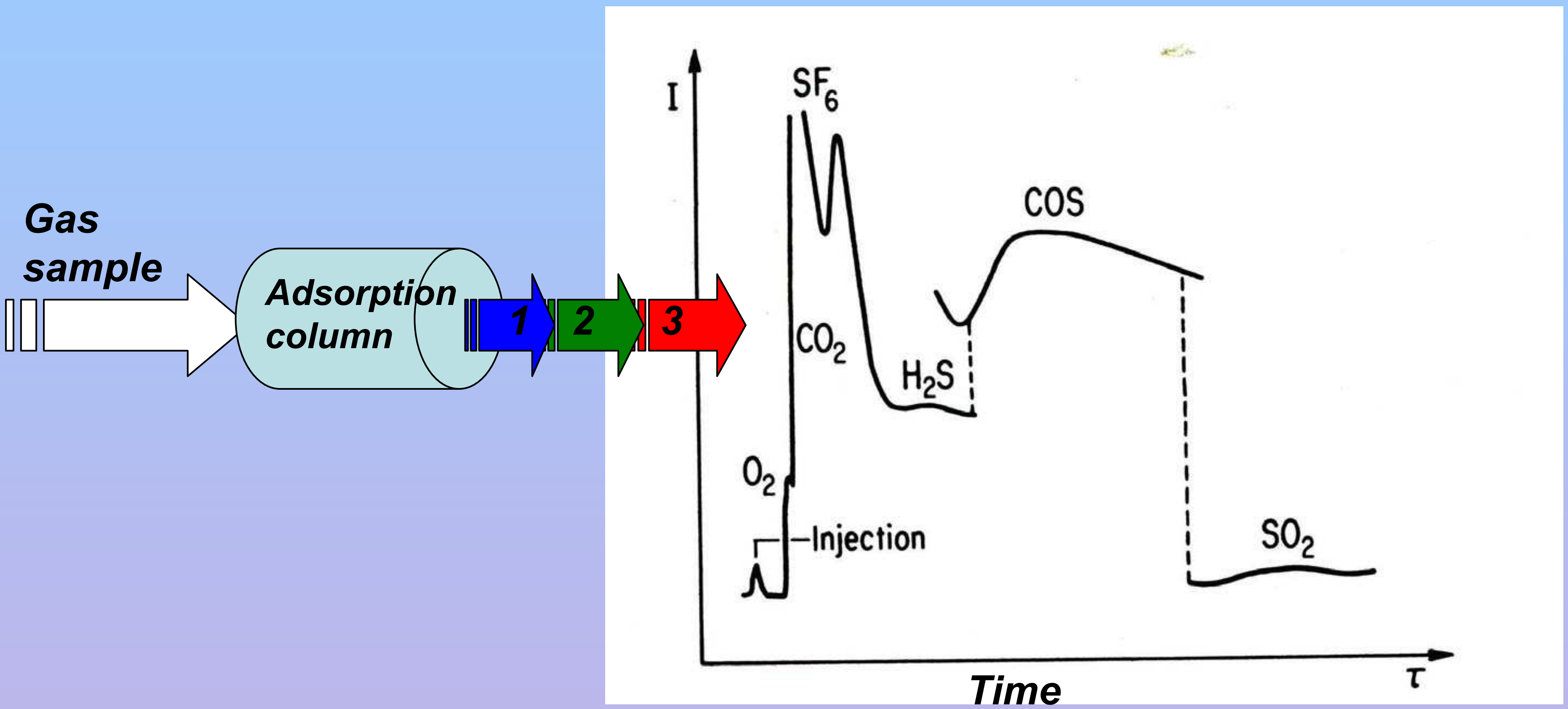
- *H_2SO_4*
- *Crystals ?*
- *H_3PO_4*



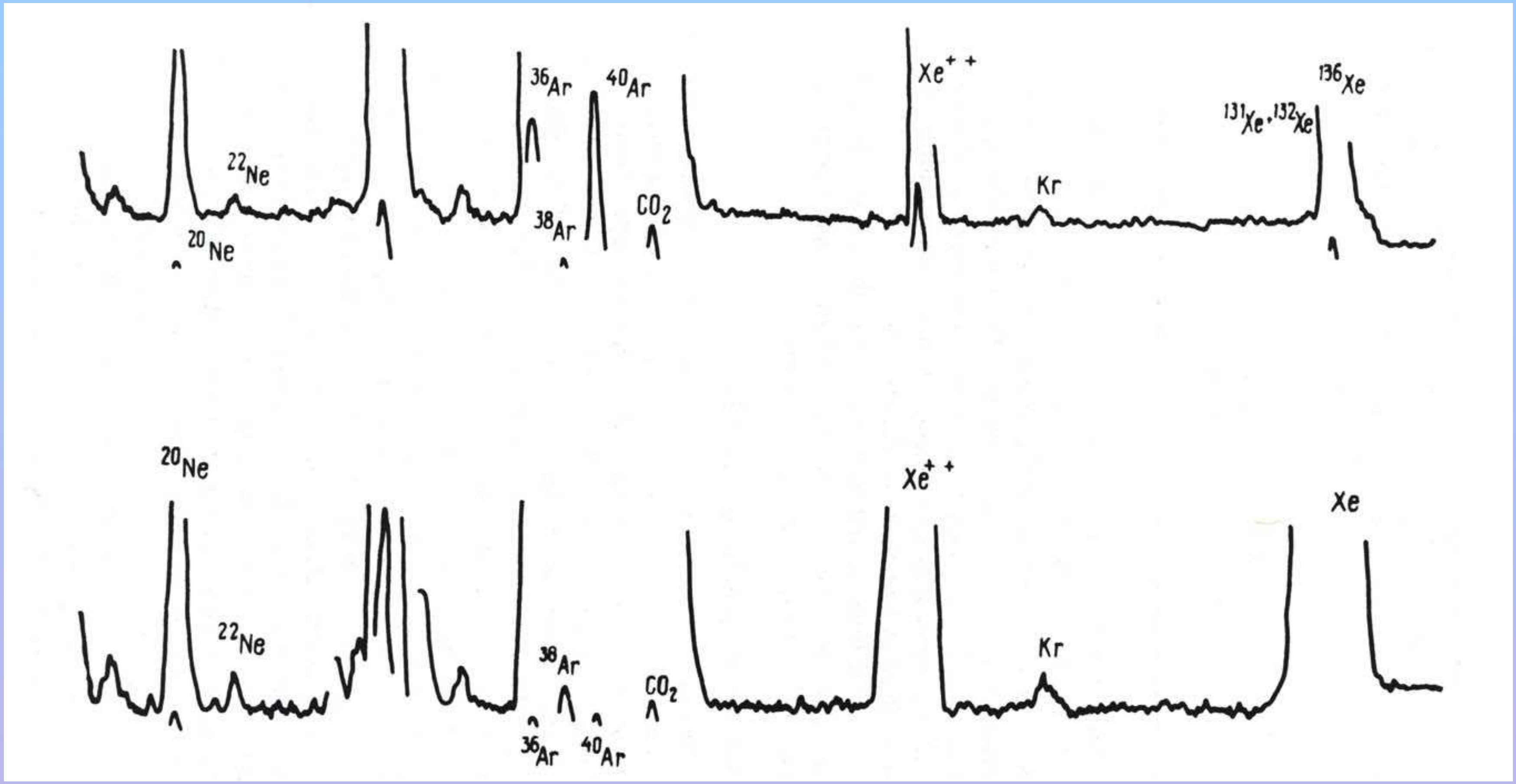




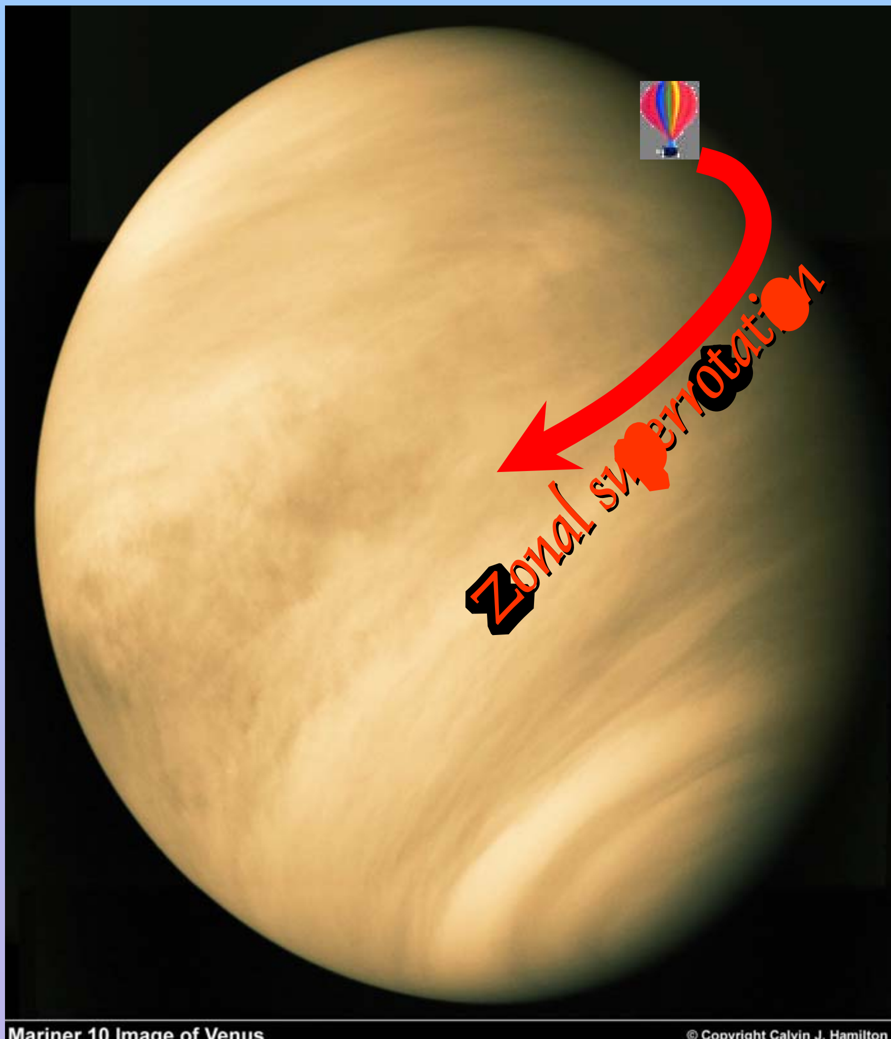
In-situ composition analysis: gas chromatography



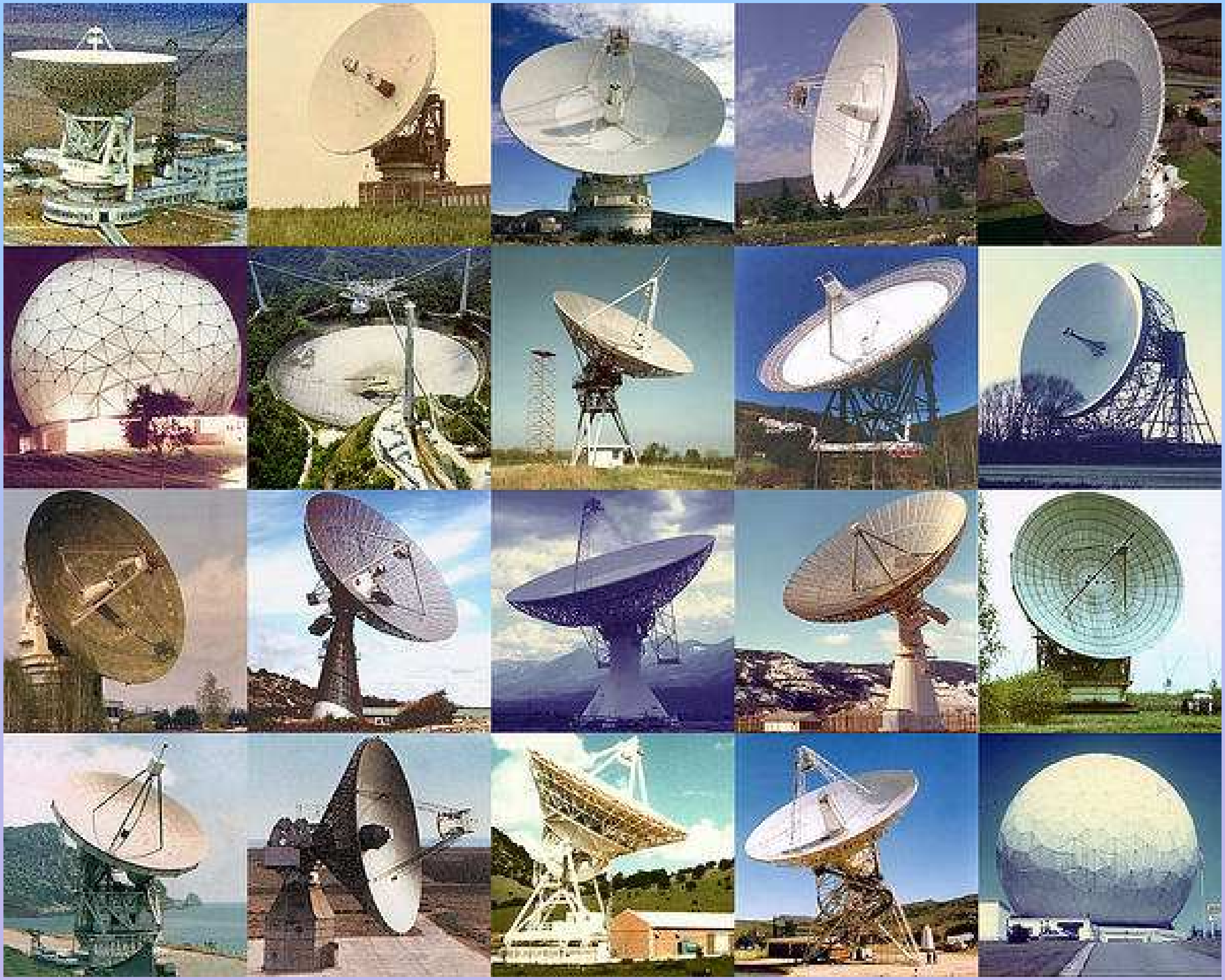
In-situ composition analysis: mass-spectrometry



VEGA-1, -2 Balloon Experiment (1984)



Global network of tracking stations

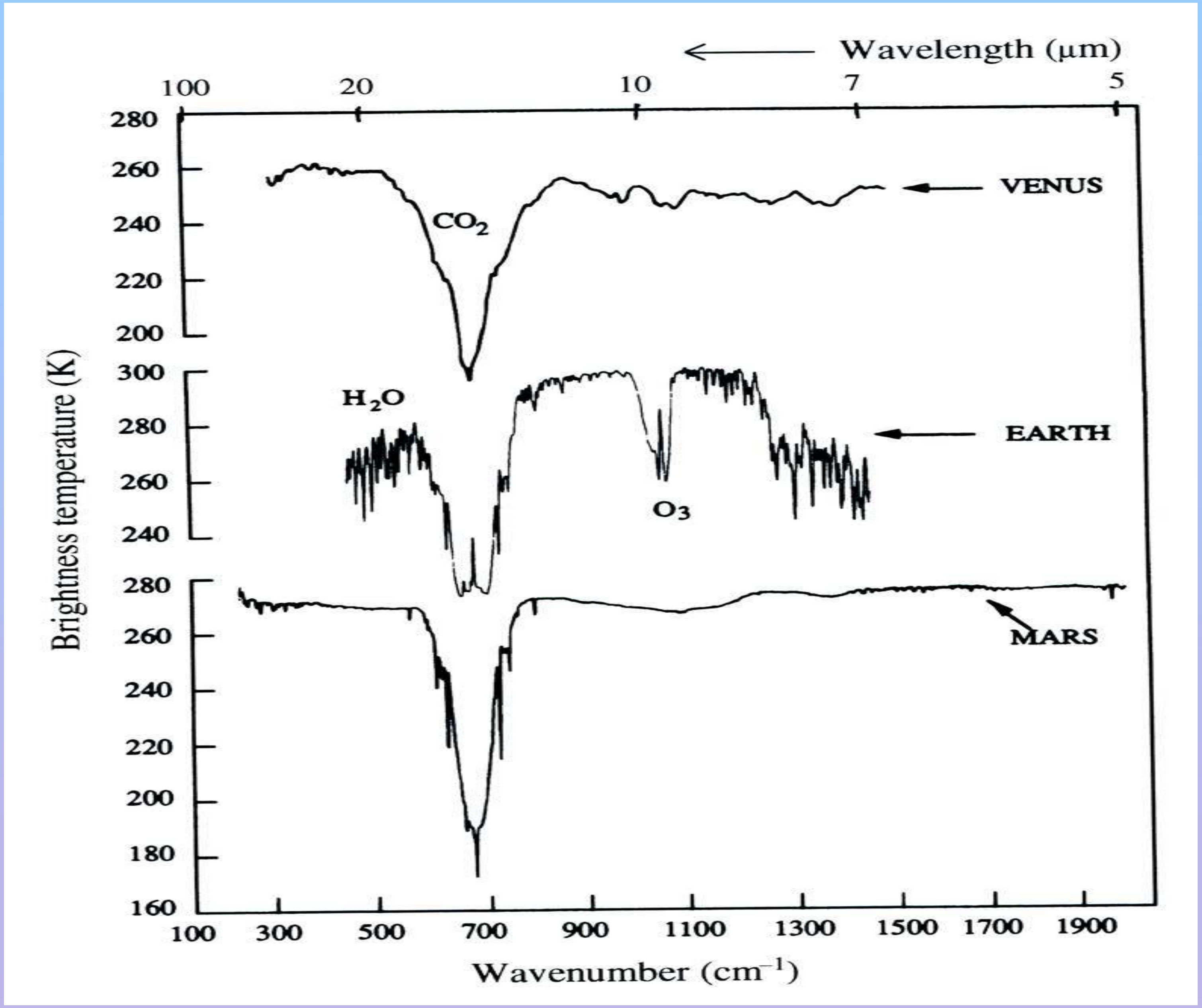


Spectrometry of thermal radiation

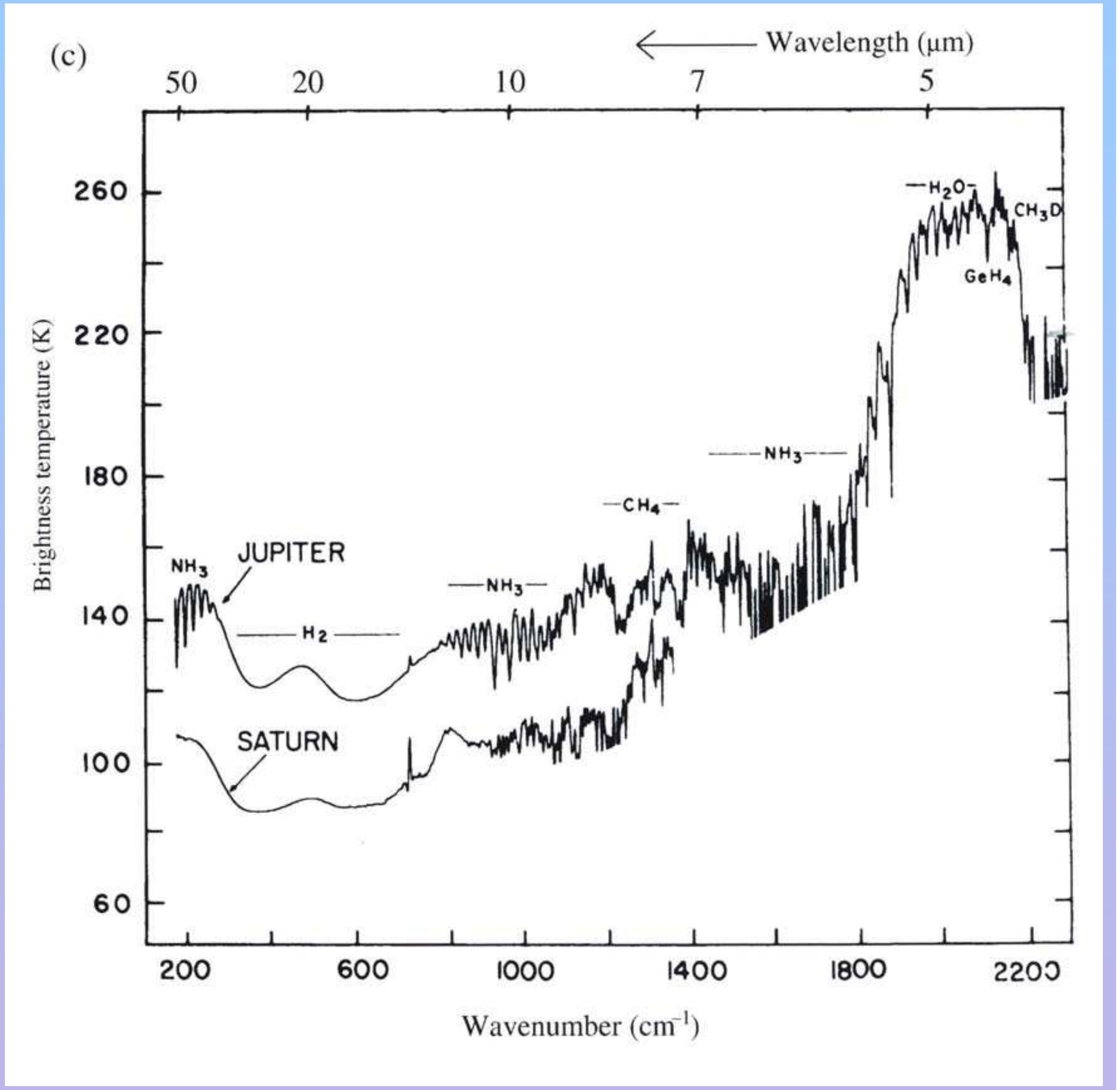
Spectrometry of thermal radiation

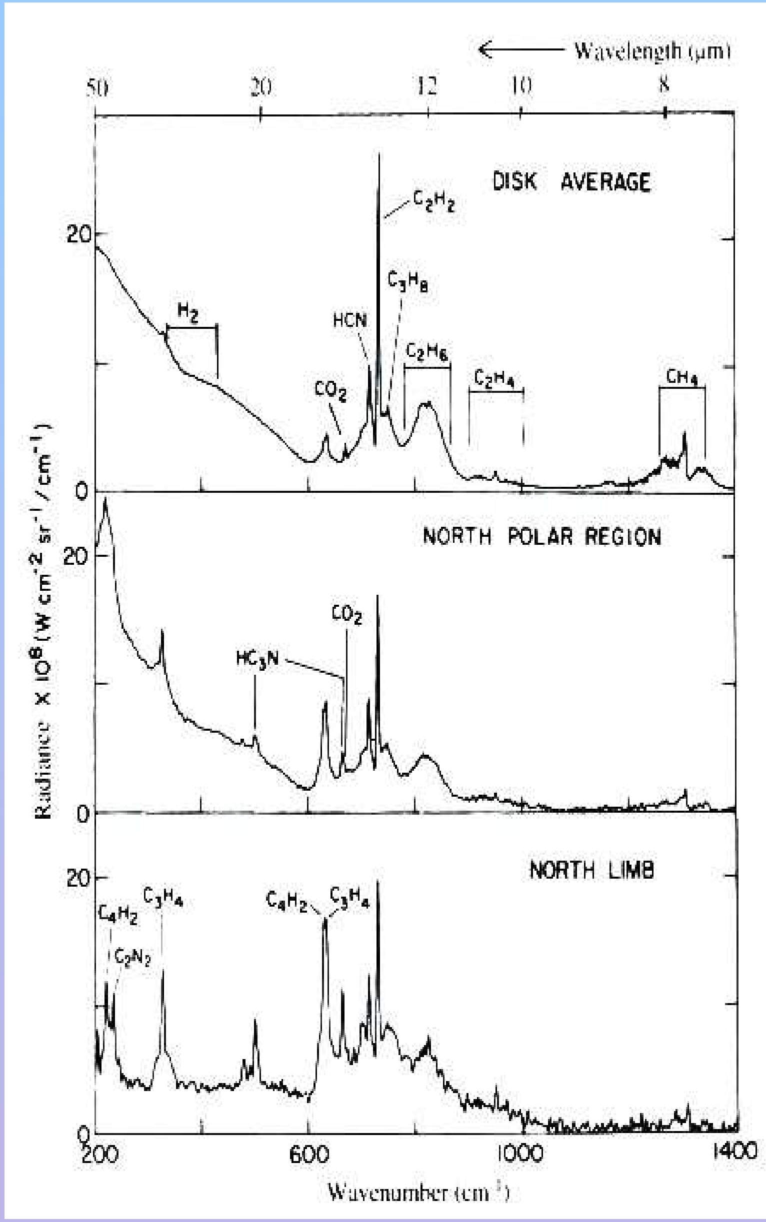
- Wavelength range mid – far-IR *(3 – 1000 μm)*
- Good sensitivity to
  - *1. atmospheric temperature and*
  - *2. total number of molecules*
- Both day and night side observations
- Multiple scattering is usually of minor importance

Thermal emissions spectra of terrestrial planets



Thermal emission spectra of Giants and Titan





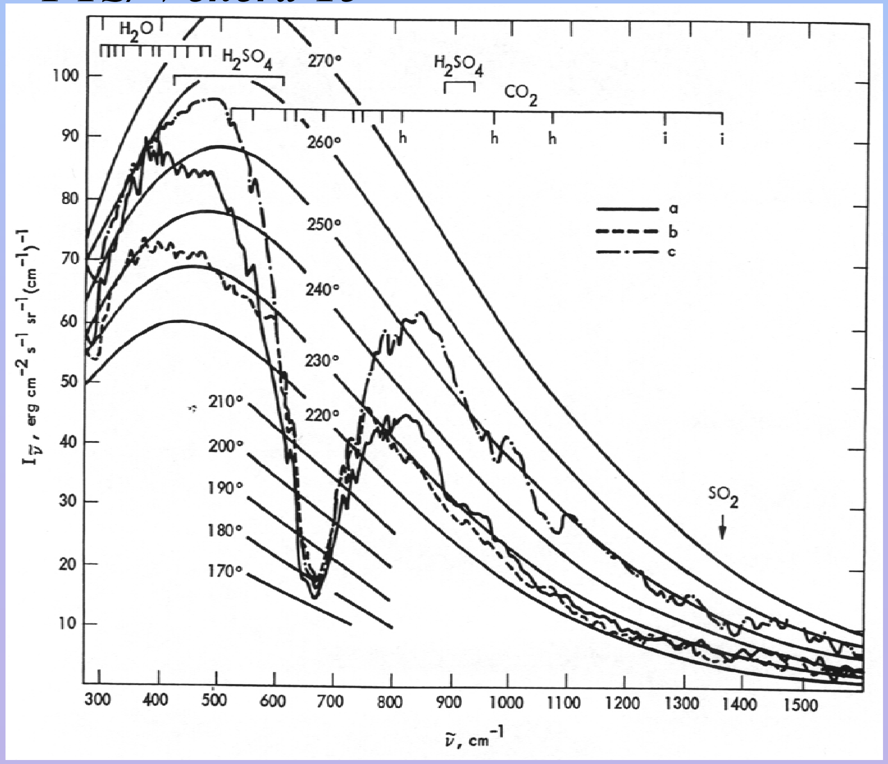
Temperature sounding

$$I(\nu) = \varepsilon_s B_\nu(T_s)t + \int_{Surface}^{Space} B_\nu[T(\xi)]\cdot K_\nu(\xi)d\xi \qquad \xi = \lg p$$

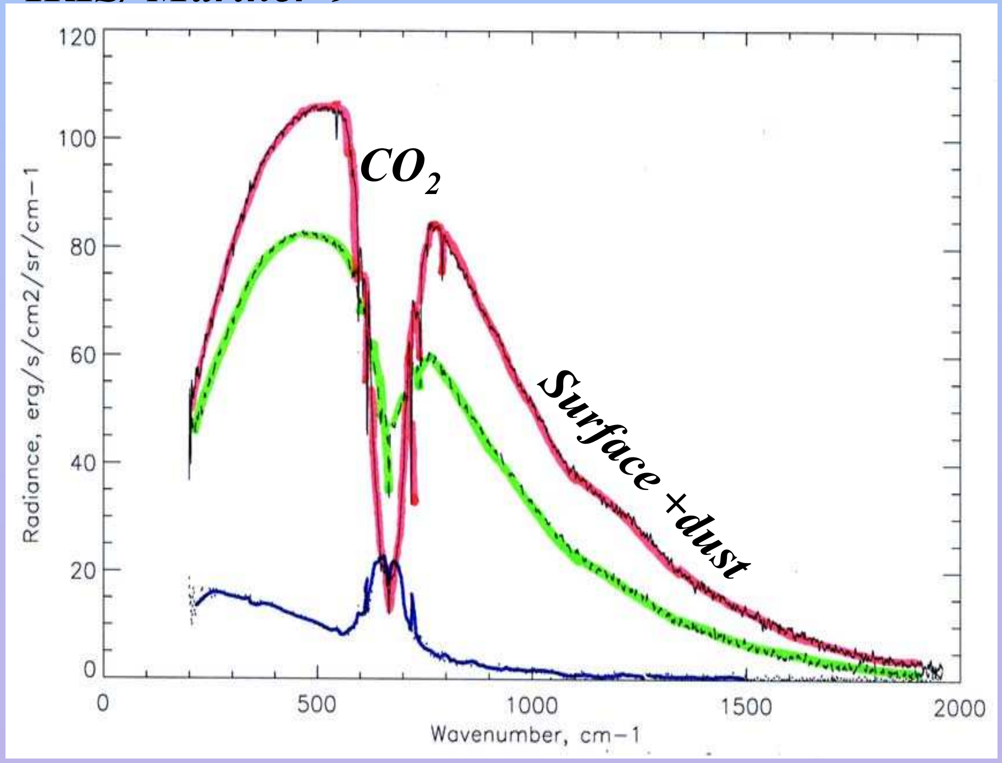
$$K_\nu(\xi) = -\frac{\partial t_\nu}{\partial \xi}$$ - weighting function

No scattering!

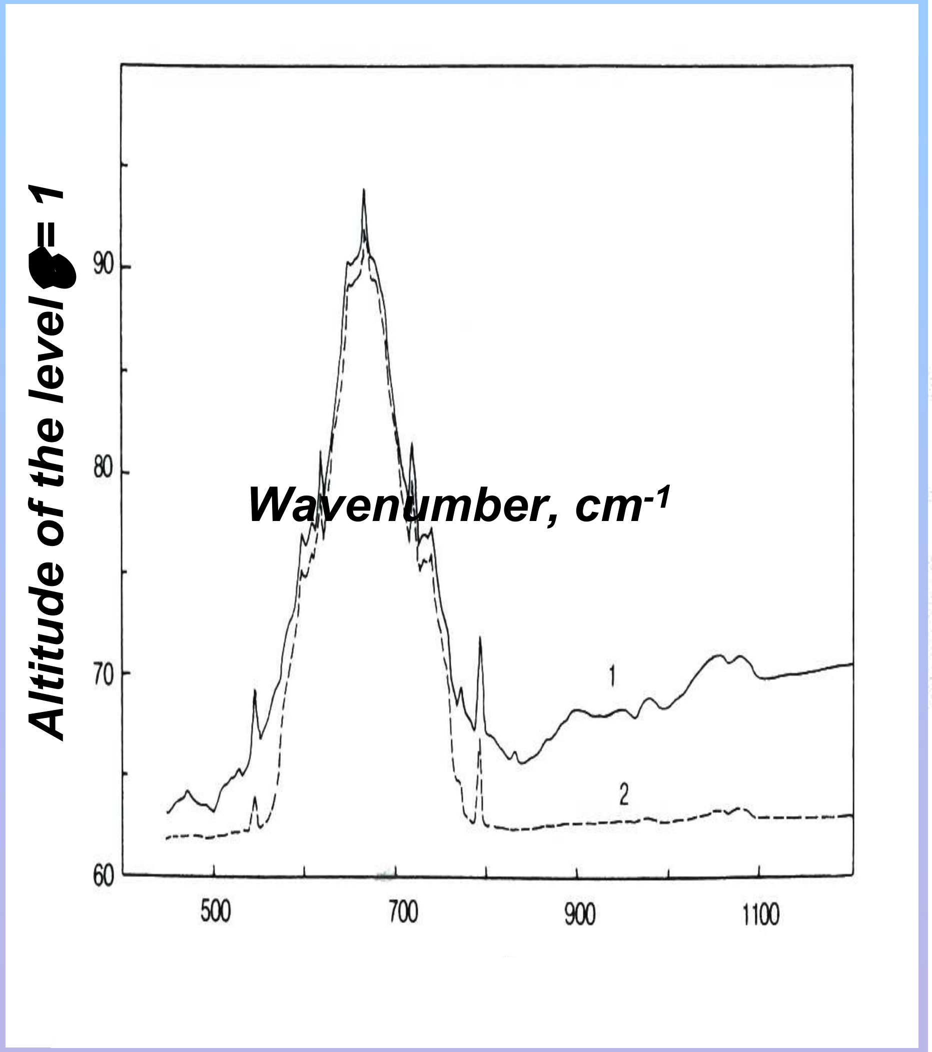
FTS/ Venera-15

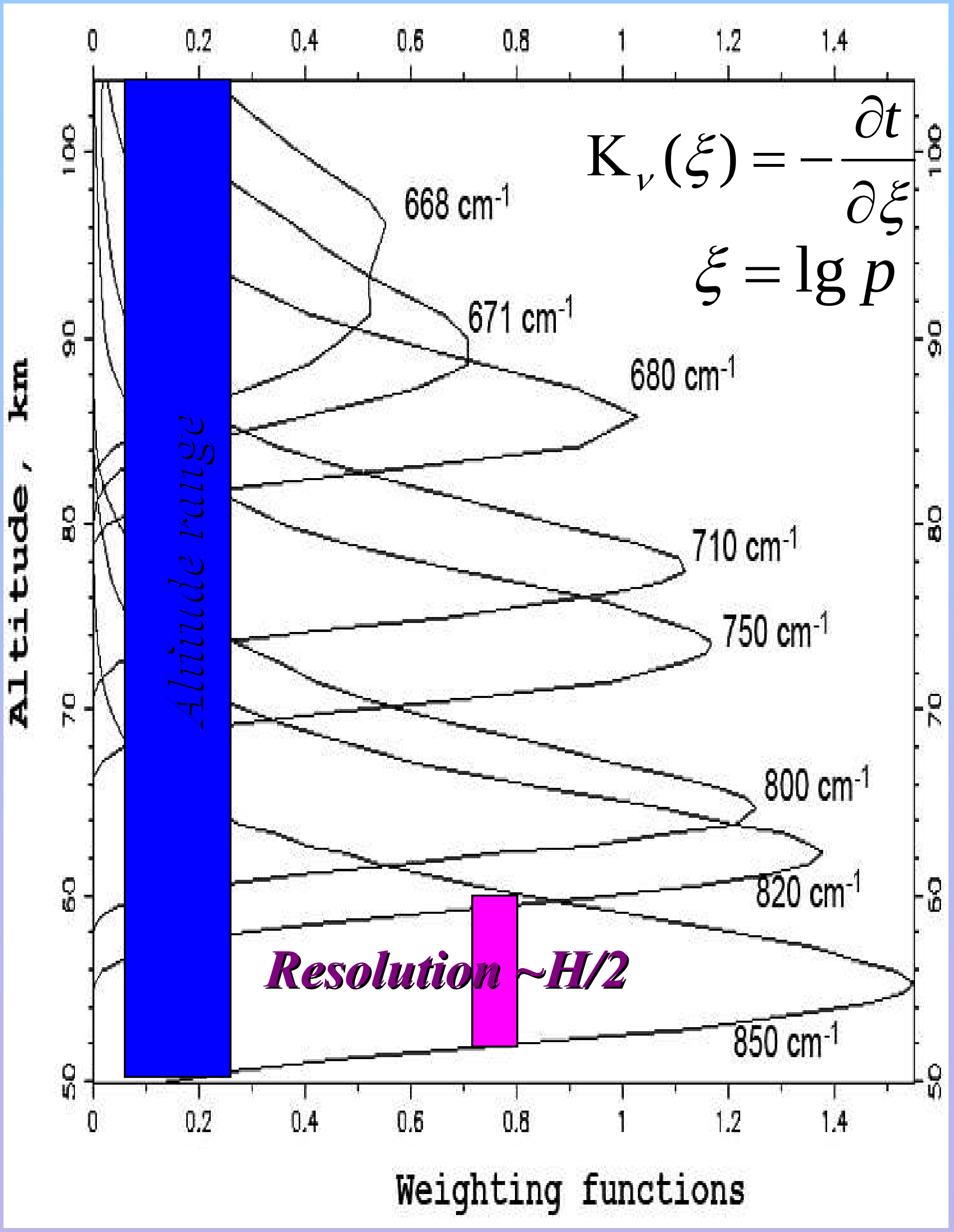


IRIS/ Mariner-9



Vertical sounding of the temperature structure





τ ~ 1 rule

Principles of the temperature remote sensing

- **In strong bands thermal radiation forms at different altitudes depending on wavelength (*τ ~ 1 rule*)**
- **Gas should be well mixed, not variable, with known abundance**
- **Local thermodynamic equilibrium (LTE)**
- **Vertical resolution ~ half a scale height**

$$\int_{+\infty}^{-\infty} B_\nu[T(\xi)] \cdot K_\nu(\xi)\, d\xi = \mathrm{I}(\nu)$$

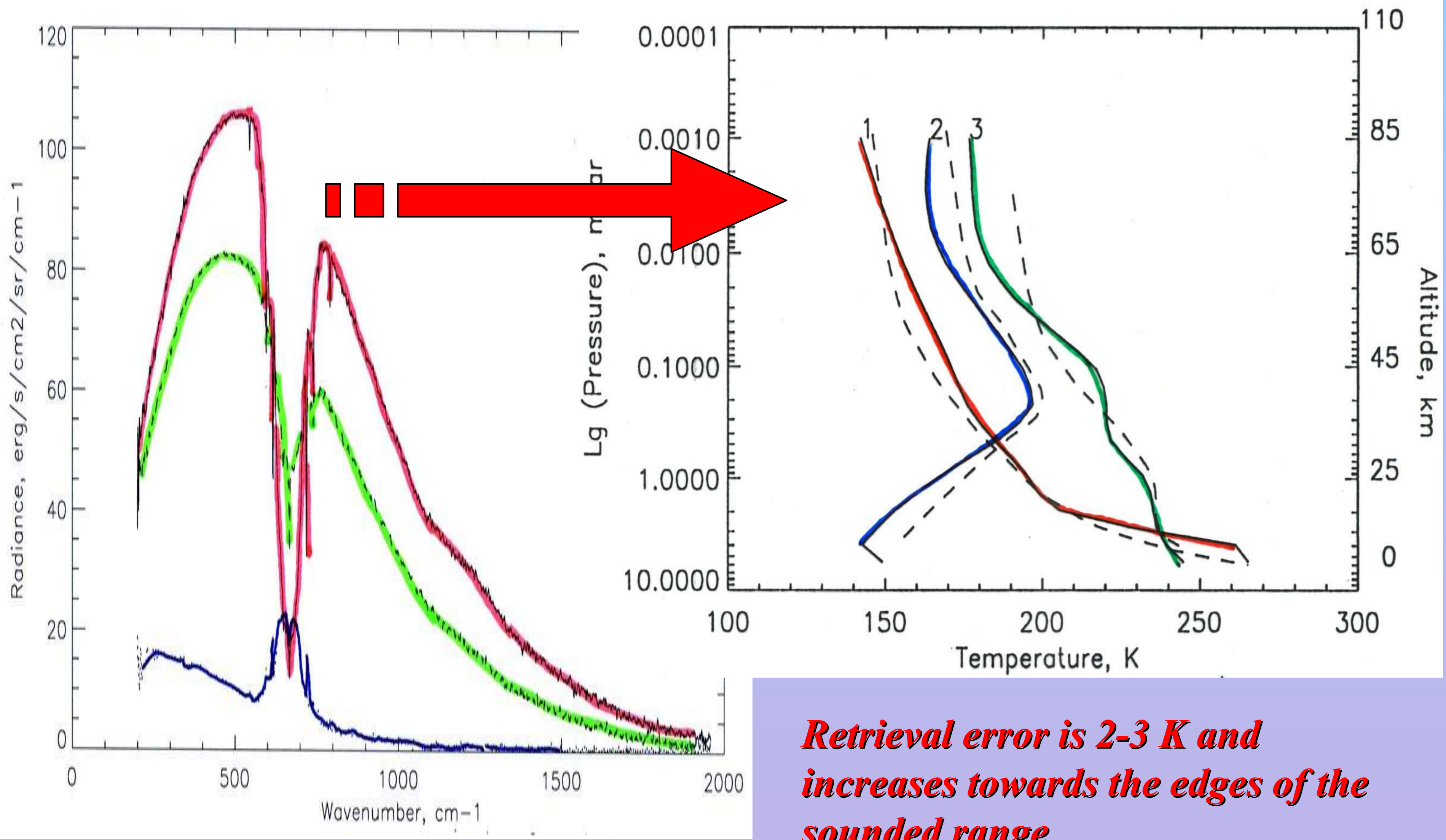
$$B_\nu[T] = B_\nu[T_0] + \frac{\partial B}{\partial T} \Delta T(\xi)$$

$$\int_{+\infty}^{-\infty} \ldots d\xi = \ldots$$

Temperature retrieval is an ill-posed problem.

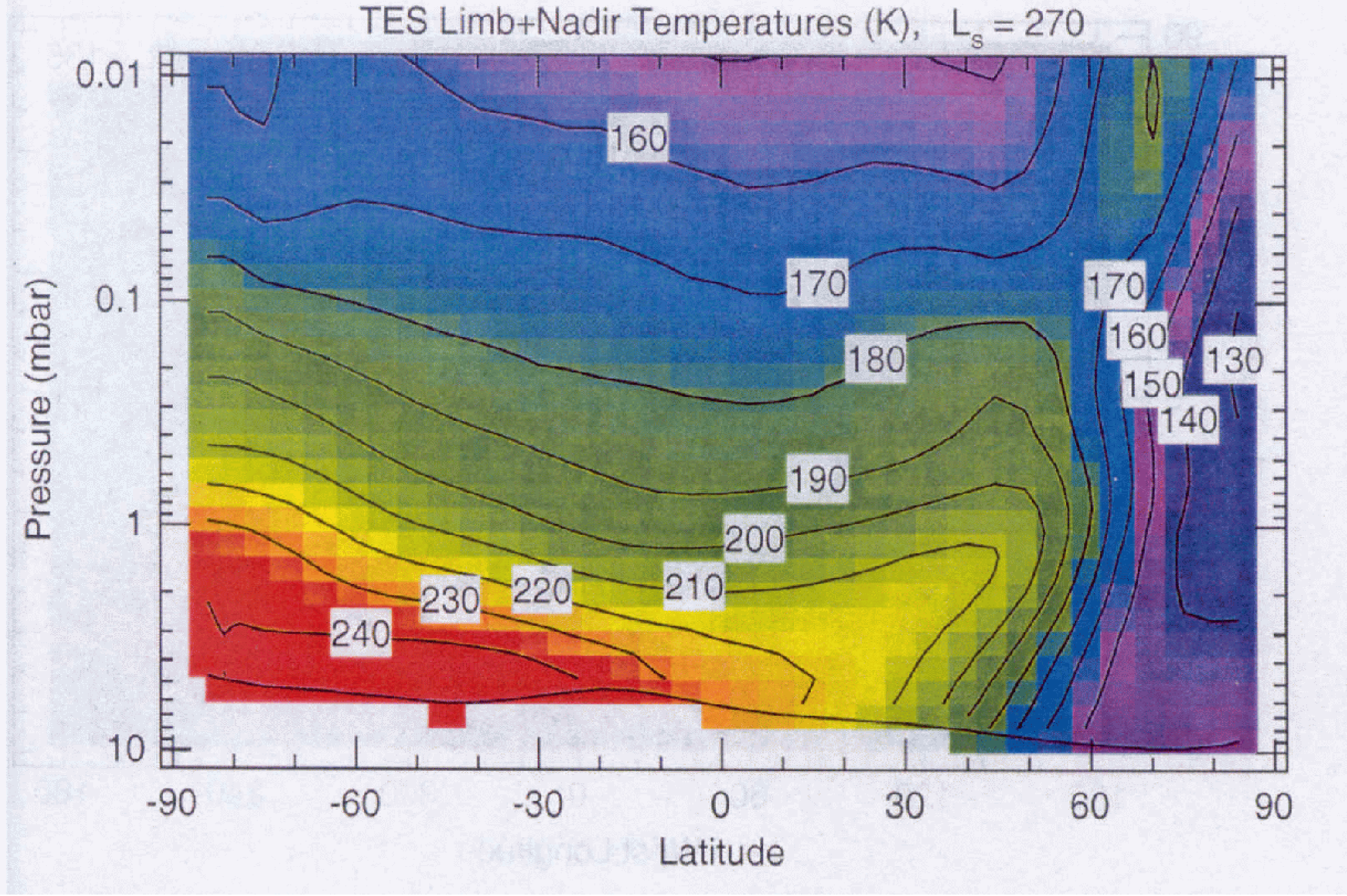
Special stabilization (regularization) methods are required

Temperature sounding of the Martian atmosphere

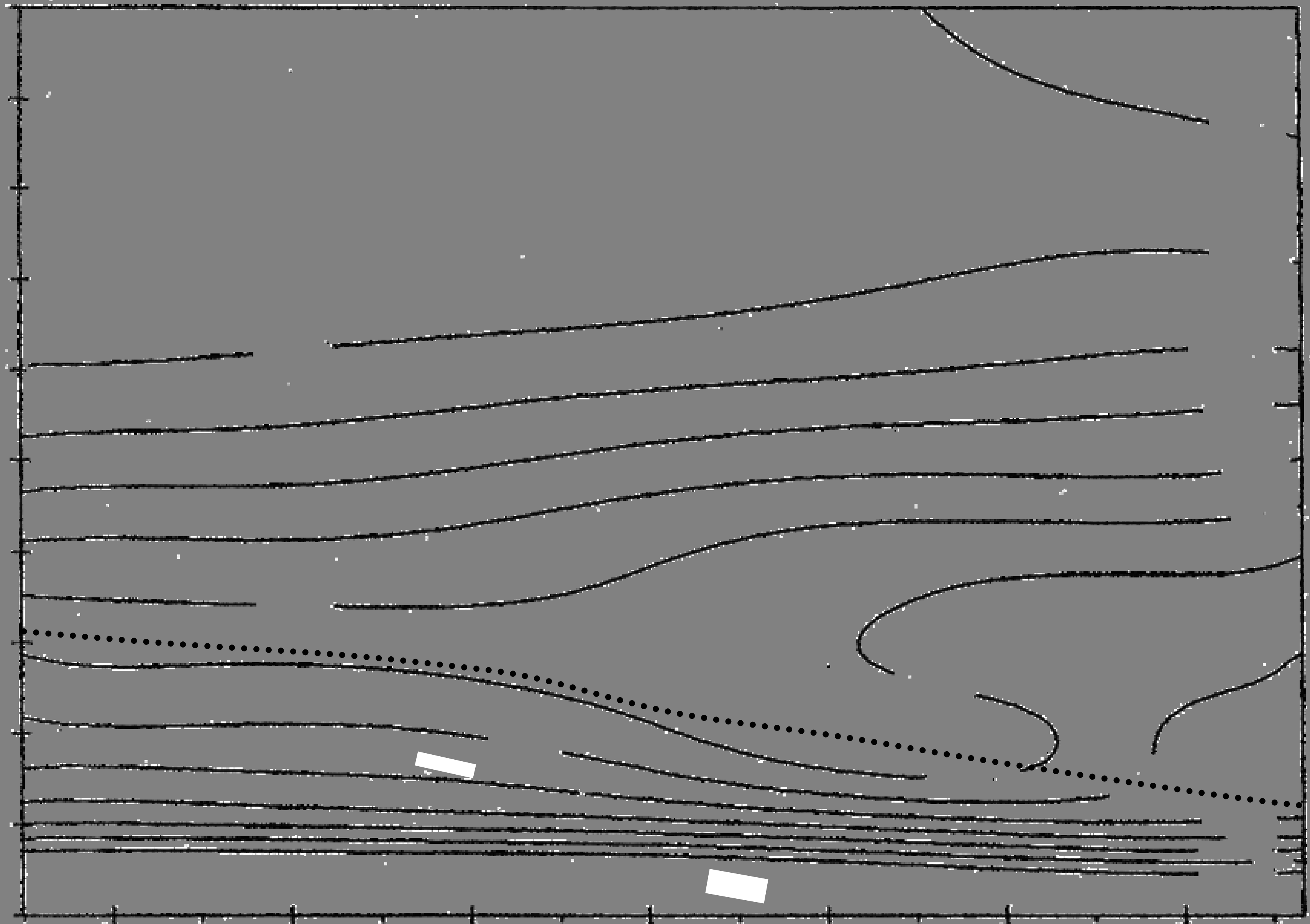


Retrieval error is 2-3 K and increases towards the edges of the sounded range

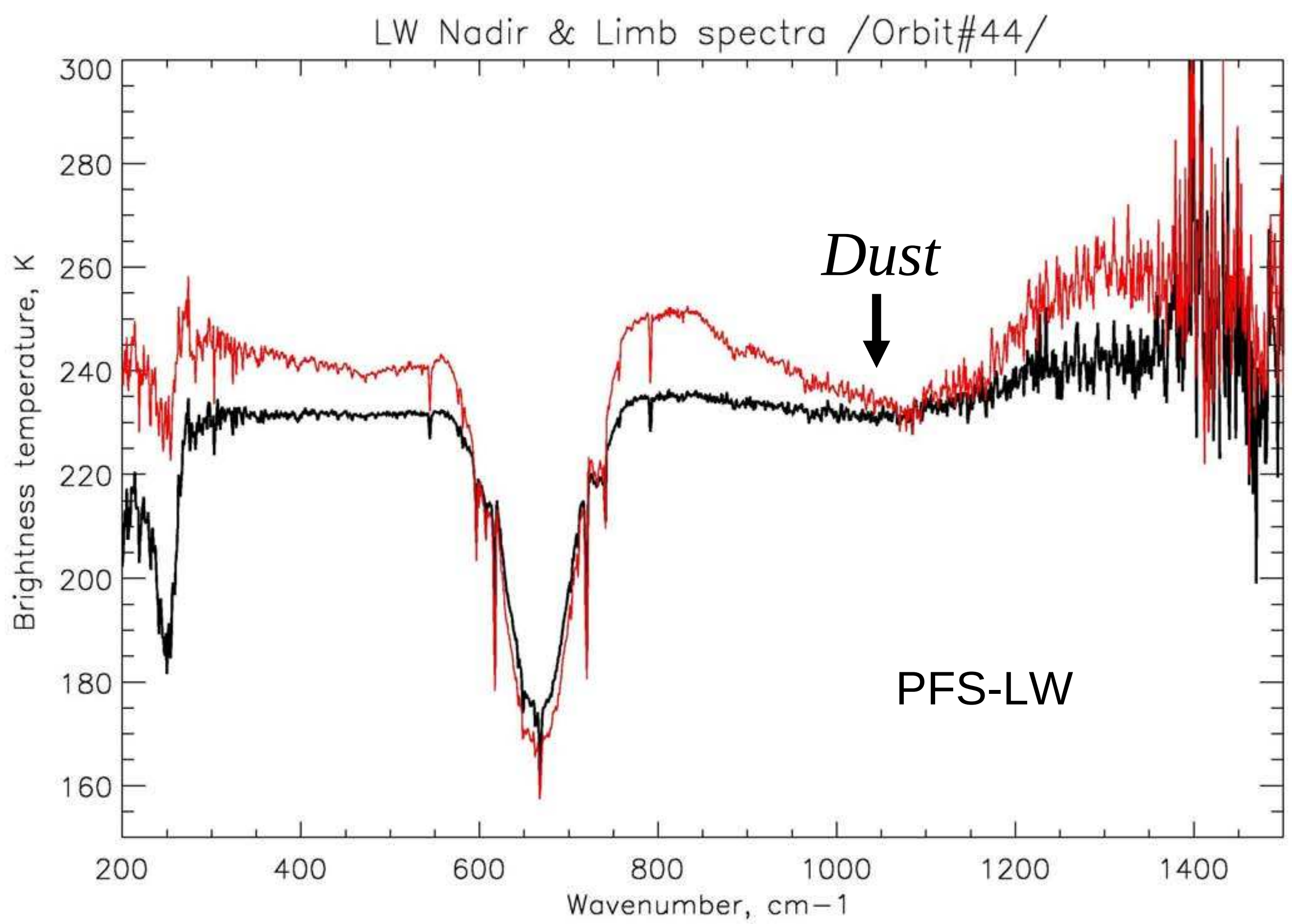
Mars atmospheric temperatures



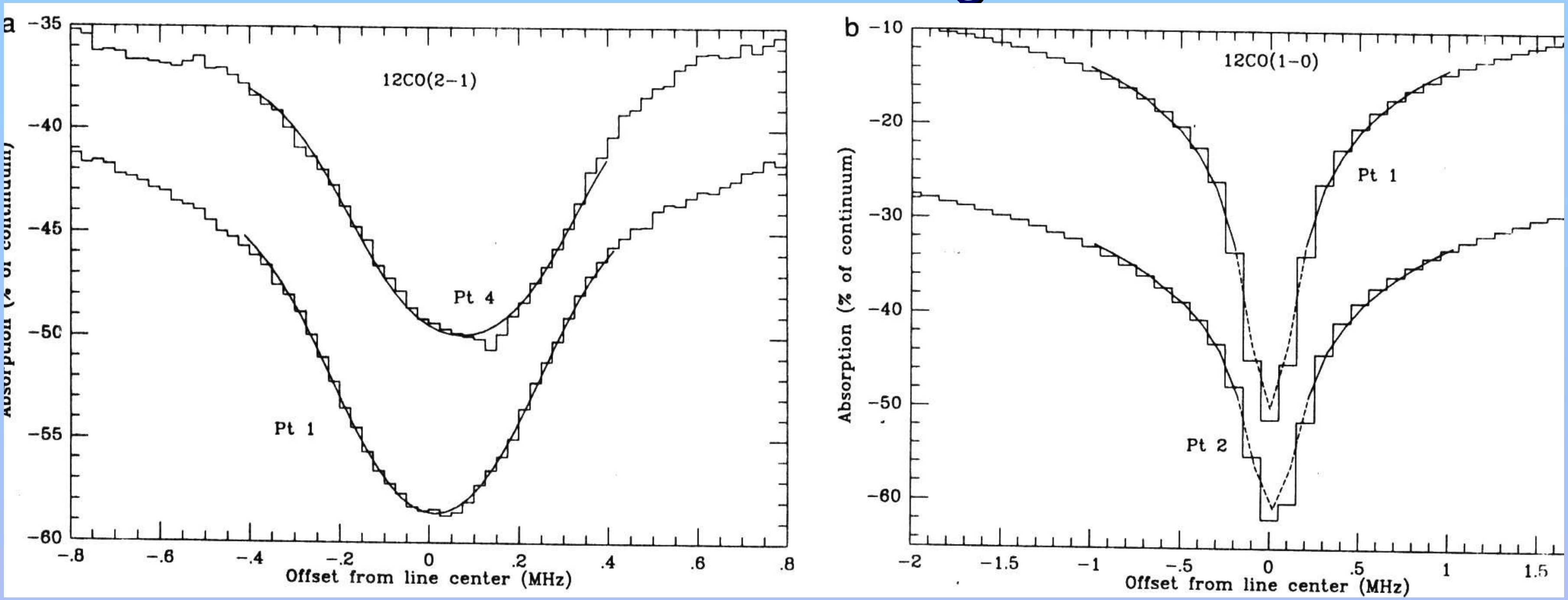
Temperature sounding of the Venus mesosphere



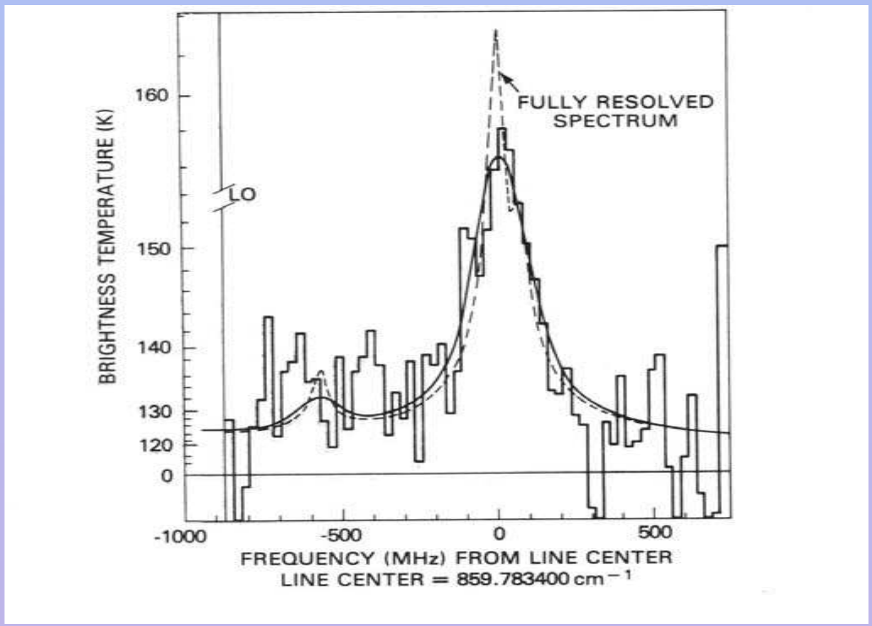
Sounding of the Martian atmospheric dust



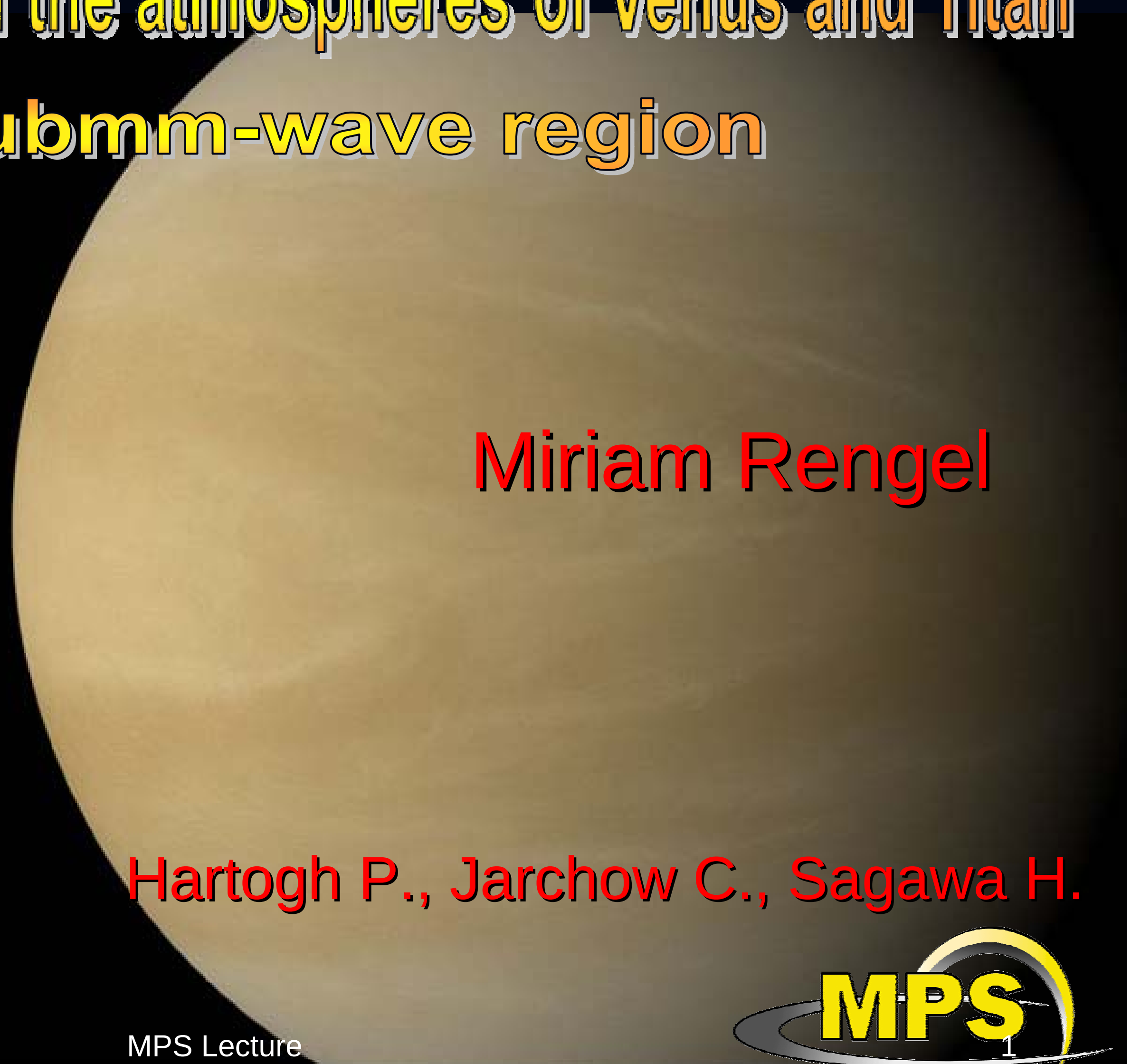
Microwave investigations



- ***Very high spectral resolution $10^{-3} – 10^{-4}$ cm^{-1}***
- ***Temperature sounding***
- ***Trace gases sounding***
  - ***Very high sensitivity***
  - ***Vertical profile***
- ***Doppler wind measurements***



Remote Sounding of the atmospheres of Venus and Titan
in the submm-wave region



Miriam Rengel

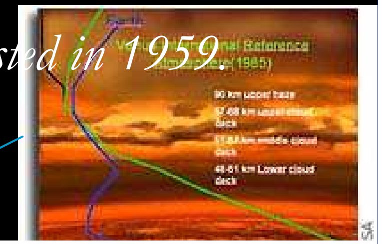
Hartogh P., Jarchow C., Sagawa H.

Outlook

- Introduction
- Principles of remote sensing – Approach to retrieve parameters
- Applications- Examples
  - 1st Example : Mesospheric Winds, Thermal Structure, and CO Distribution on Venus
    - Spectral Line Observations of Venus
    - Approach to retrieve thermal structure and CO distribution
    - Results: Thermal structure and Winds
    - Conclusion and Outlook for the future
  - 2nd Example: Atmospheric Gases of Titan. APEX observations
    - Spectral Line Observations of Titan
    - Approach
    - Results: CO and HCN
    - Conclusion and Outlook for the future
  - 3rd Example: Atmospheric Gases of Titan. Predictions for Herschel
    - Planned observations
    - Approach
    - Results: Synthetic spectra of Titan
    - Results: water CO, HCN, CH4
    - Conclusion
- Future of planetary observations in the mm/submm
- Where to consult?

Planetary atmosphere Science:

Remote sounding of the atmosphere temperature profile and composition was first suggested in 1959.



Constraints on

Thermal structure

T profiles

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 49, NUMBER 10 OCTOBER 1959

Inference of Atmospheric Structure from Remote Radiation Measurements*

LEWIS D. KAPLAN
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received April 27, 1959)

A detailed analysis of the structure of the atmosphere, including the three-dimensional distribution of temperature and water vapor, can be obtained from the spectral variation of its thermal radiation as viewed from a reconnaissance aircraft or earth satellite. In order that the measurements be capable of unambiguous interpretation, however, it is essential that the selection of spectral intervals to be used are based on a carefully planned interpretation scheme.

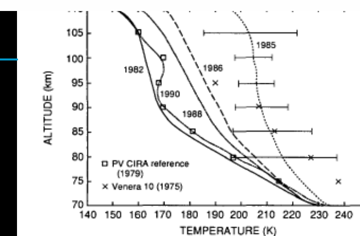
A possible program is outlined, in which the temperature distribution is obtained by measurements in the 15-μ CO_2 band and the water vapor distribution obtained by simultaneous measurements in the rotational band. The temperature-and-pressure dependence of the absorption coefficients must be taken into account.

The instrument should be a multiple-slit or multiple-detector grating spectrometer, capable of resolving 10 cm^{-1} at 15 μ.

Spectral models and methods of analysis of the spectra are discussed briefly.

3D mapping and monitoring

Seasonal variations



Constraints on the origin and evolution of planets and the formation of the solar system

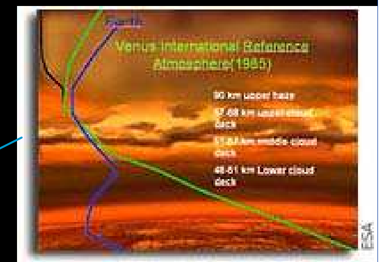
Clancy and M. 1991

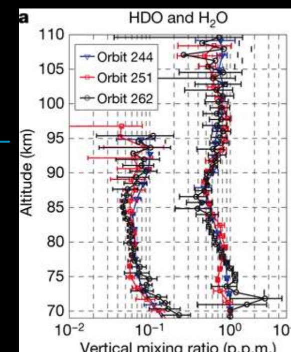
Planetary atmosphere Science:

Constraints on

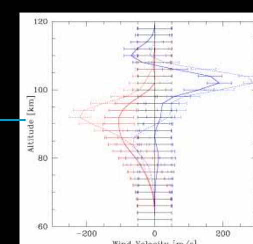
- Remote sounding and in situ observations
- Observations of vertical cloud structure

Thermal structure	T profiles
Composition	**Vertical distribution of species**
	New species
Dynamics	Winds
3D mapping and monitoring	Seasonal variations

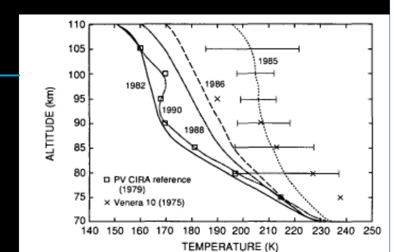




Bertaux et al. 2007



Rengel et al. 2008



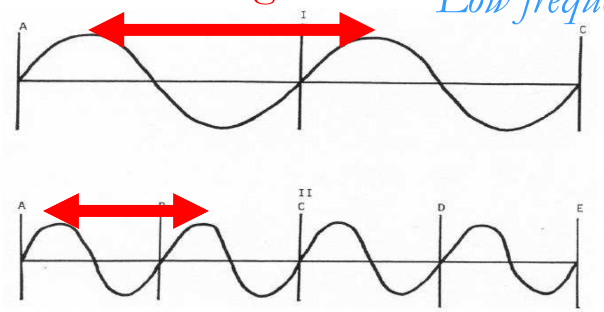
Clancy and M. 1991

Constraints on the origin and evolution of planets and the formation of the solar system

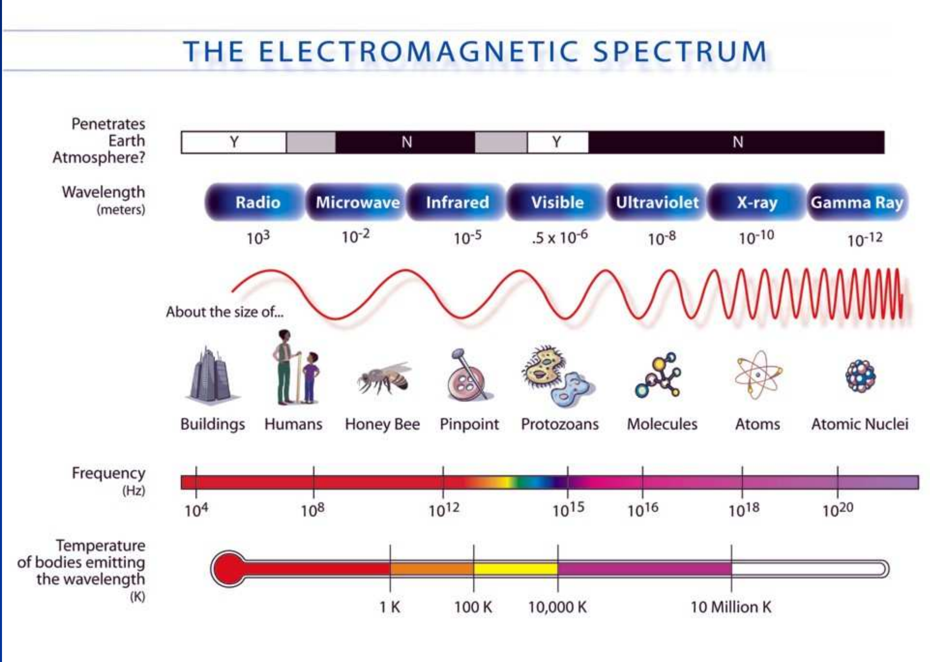
What is the sub-mm/mm region?

wavelenght

Long wavelenght
Low frequency



Short wavelenght
High frequency



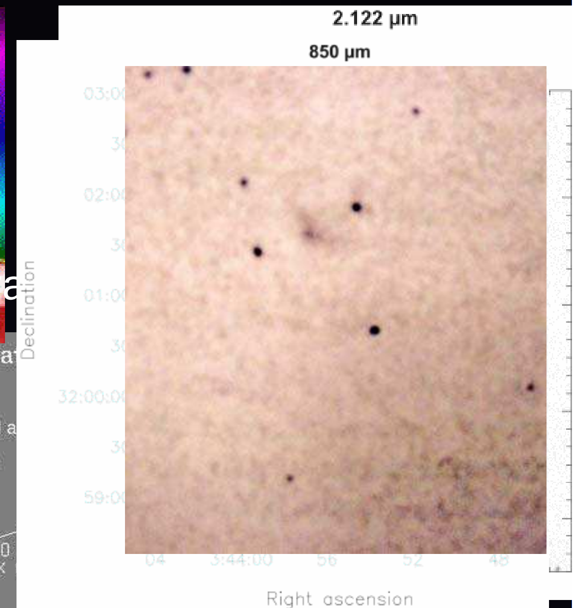
Microwaves

Sub-mm:	0.1mm – 1mm	300GHz-3 THz
mm:	1mm – 10mm	30 GHz -300 GHz
Cm	1cm - 10cm	3 GHz - 30 GHz

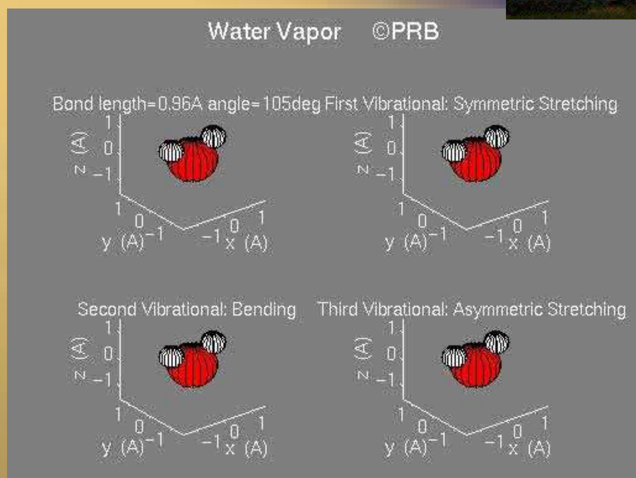
$$f = c / \lambda$$

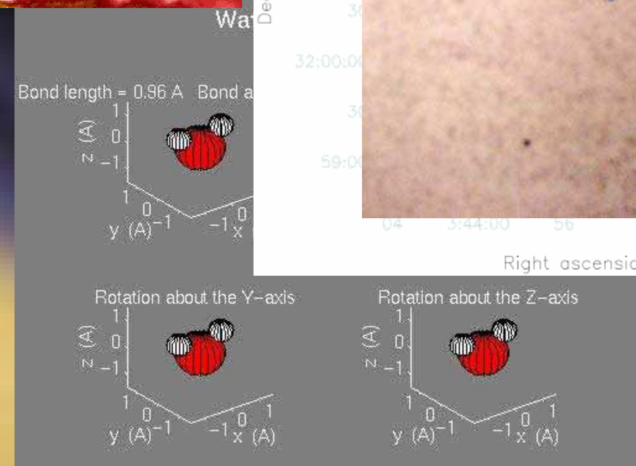
What do we detect in the sub-mm and FIR region?

thermal radiation!!!!

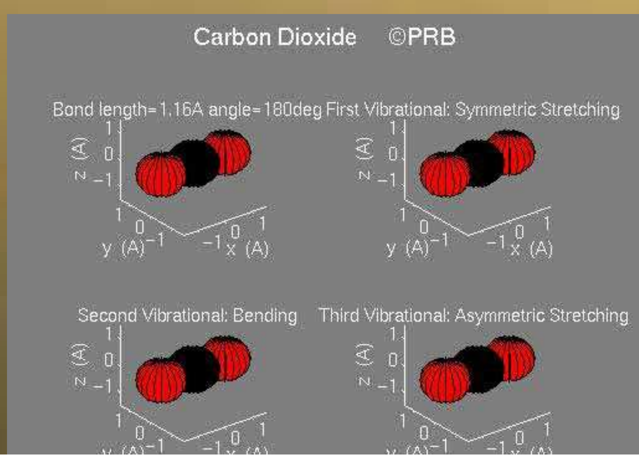


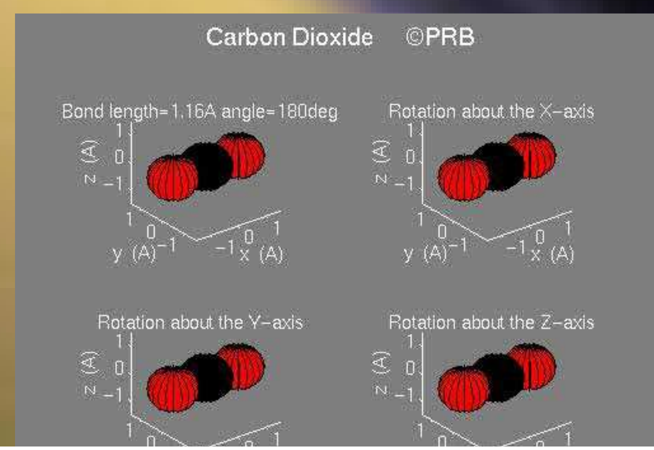
IR radiation interacts with molecular vibrations, sub-mm intera





http://www.ems.psu.edu/~bannon/moledyn.html

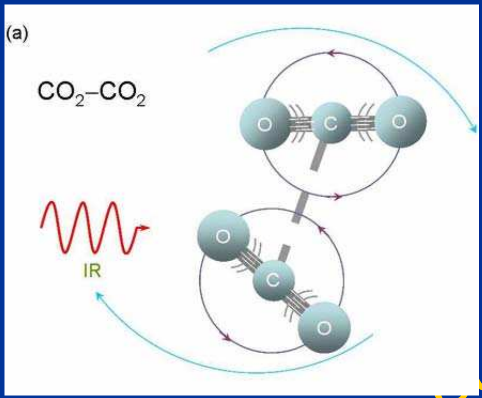




But, how the spectrum is formed?

The absorption of gases is due to both vibration-rotational bands and collision induced absorptions.

Two vibrating CO2 molecules as they intercept IR radiation (red wavy line) during a collision.



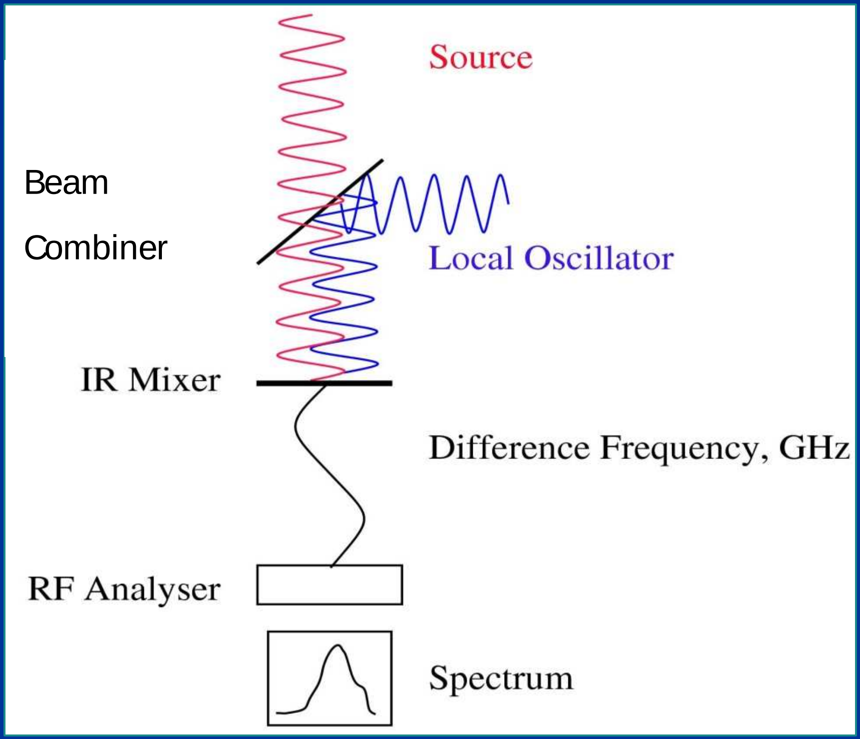
Radiation is absorbed; half is transferred to the rotation of the molecules, and half goes toward translation making the two molecules move faster relative to each other (blue arrows).

But, how to detect so extremately week emission?

We need:

- For deriving the temperature profile: **resolve the spectral shape**
- For detecting weak and narrow lines of molecular species: **very high spectral resolution**

Heterodyne Technique



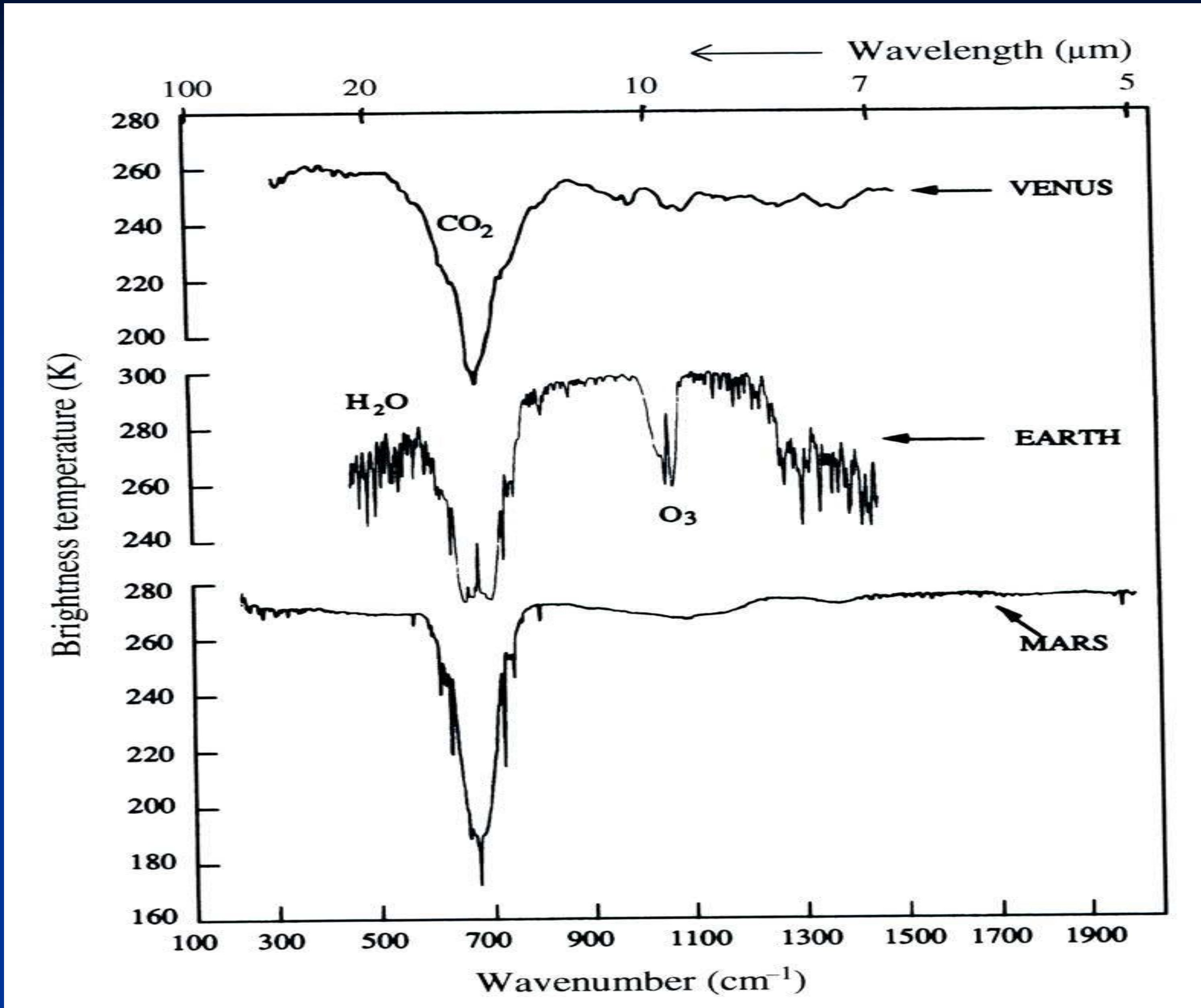
The source signal is combined with the signal of the LO .

Mixing shifts signal (preserving spectroscopic information)

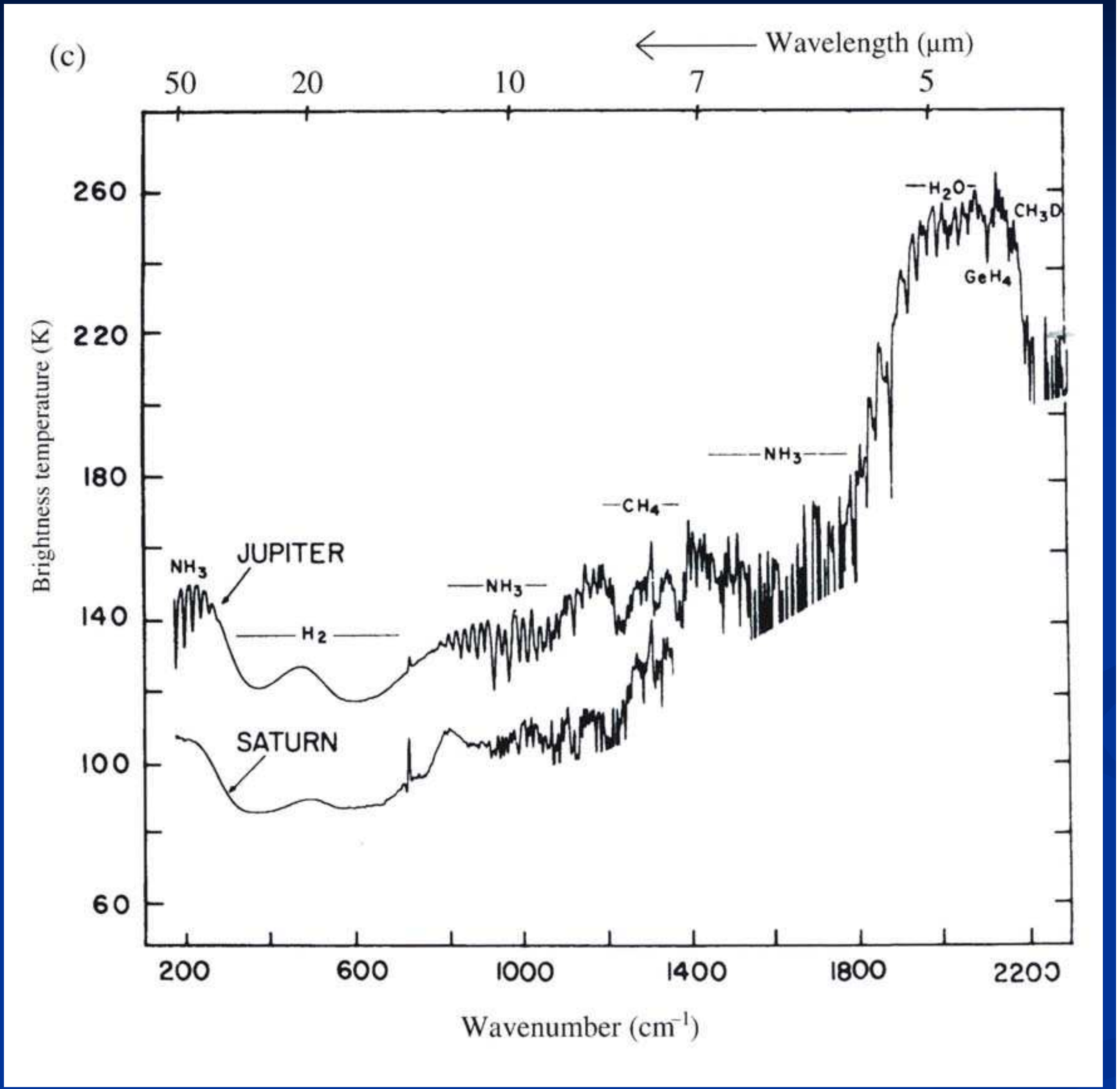
RF signal processing, amplification, analysis, etc. does not add noise

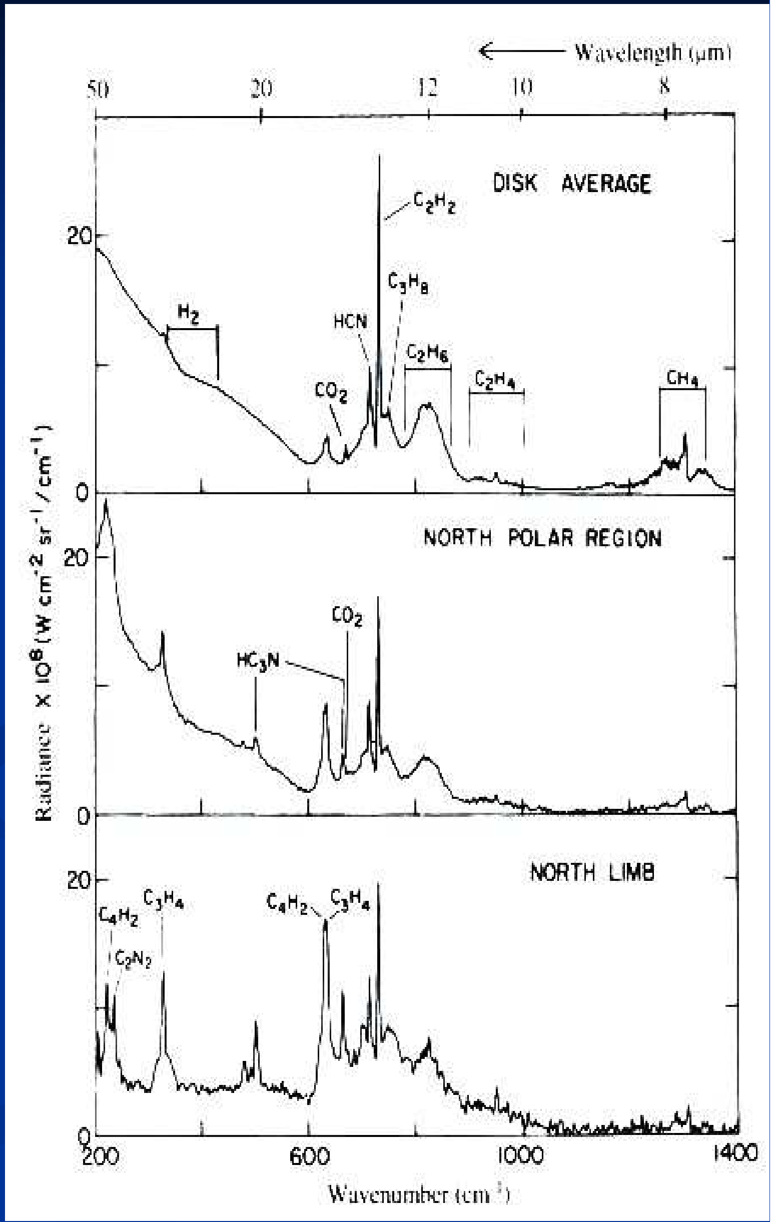
The main advantage is the capability to provide high-resolution spectroscopy!

Thermal emissions spectra of terrestrial planets



Thermal emission spectra of Giants and Titan





Spectrometry of the thermal radiation

- **Wavelength range mid – far-IR *(3 – 1000 µm)***
- ***Wavelength range microwaves (0.1mm- 10cm)***
- **Good sensitivity to**
  - ***1. atmospheric temperature and***
  - ***2. total number of molecules***
- **Both day and night side observations**
- **Multiple scattering is usually of minor importance**

How? Ingredients

Observations

Deriving information from the spectra

Forward model – Inversion Algorithm

To model the expected observed emission spectra

To retrieval physical parameters as the mixing ratio

Technique to retrieve profiles of temperature and volume mixing ratio

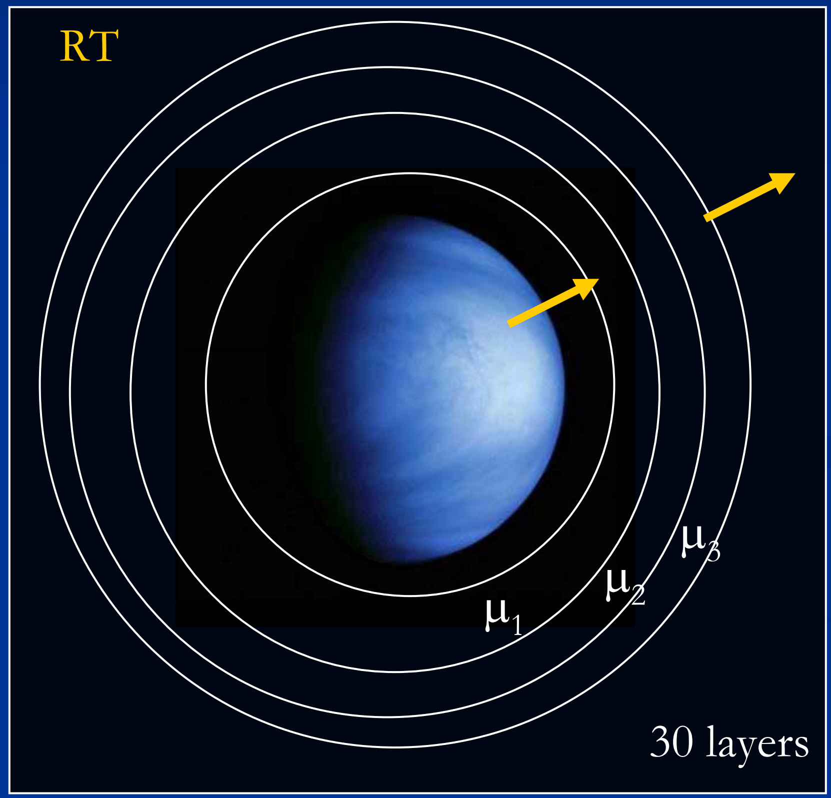
Input parameters → Abundance profiles → Radiative Transfer → Synthetic Spectra → Comparison with data

Optimal estimation algorithm

T profile →

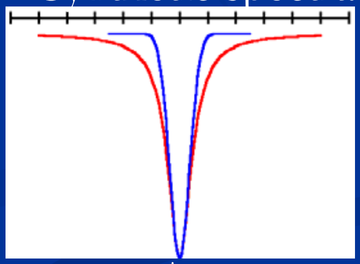
P profile →

Vmr profile →

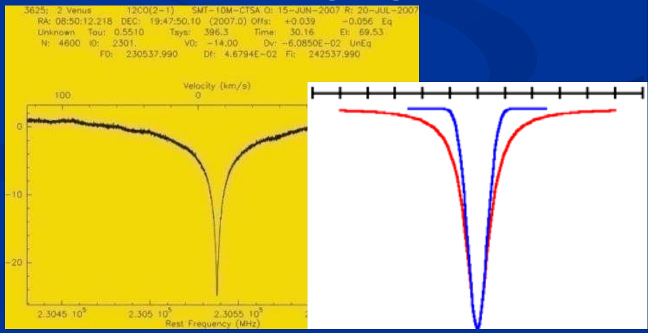


μ_i=absorption coefficient

Synthetic spectra

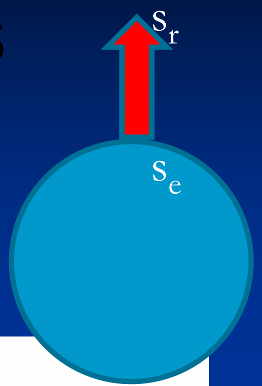


Fitting algorithm



New set of parameters

Physical and mathematical basis of the forward and retrieval models



RT : Asuming LTE,

Specific intensity of the radiation at S_r

$$I_\nu(s_r) = I_\nu(s_e)e^{-\tau_\nu(s_e,s_r)} + \int_{s_e}^{s_r} \alpha_\nu(s)B_\nu(\mathrm{T})e^{-\tau_\nu(s,s_r)}\,\mathrm{d}s.$$

Radiation entering the atmosphere

$$T_B(\nu, s_r) \equiv \frac{c^2}{2k_B\nu^2} I_\nu(s_r)$$

$$\tau_\nu(s_1, s_2) = \int_{s_1}^{s_2} \alpha_\nu(s')\,\mathrm{d}s'$$

opacity

Absorption coefficient

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/k_BT} - 1}$$

Source function

T_B= brightness temperature
h= Planck‘s constant
c= speed of light
k_B= Botzmann‘s constant

Retrieval model: Inverse problem and OEM

$$y = F(x,b) + \varepsilon_y.$$

$$\hat{x} = I(y,b,c)$$

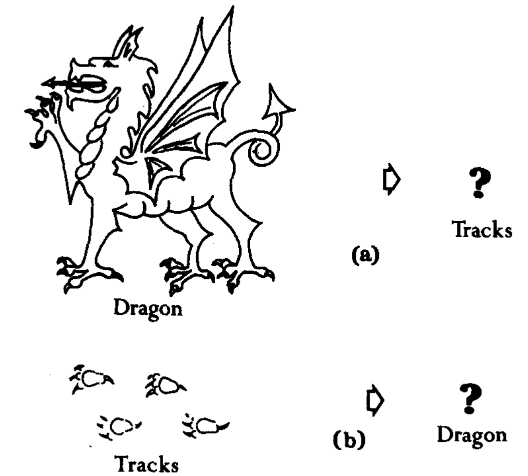


Figure 1.5 (*a*) The direct problem: Describe the tracks of a given dragon. (*b*) The inverse problem: Describe a dragon from its tracks.

y = measurements

F = Forward model

x = unknown parameters to be retrieved (T, abundances)

b = remaining model parameters

c = additional parameters (a priori)

Ey = error

$$\chi^2 = (y - F(x,b))^T S_y^{-1} \cdot (y - F(x,b)) + (x - x_a)^T \cdot S_a^{-1} \cdot (x - x_a)$$

x_a = a priori state vector
S_y = error covariance matrix for y
S_a = error covariance matrix por x_a

Weighting functions

$$K_x = \left.\frac{\partial F(x,b)}{\partial x}\right|_{x_a,b_a}, \quad K_b = \left.\frac{\partial F(x,b)}{\partial b}\right|_{x_a,b_a}$$

OEM solution

$$\hat{x}_{n+1} = x_a + (K_x^T \cdot S_y^{-1} \cdot K_x + S_a^{-1} + \gamma \cdot U)^{-1}$$
$$\times [K_x^T \cdot S_y^{-1} \cdot \{(y - F(\hat{x}_n,b)) + K_x \cdot (\hat{x}_n - x_a)\} + \gamma \cdot U(\hat{x}_n - x_a)]$$

Gamma = Levenberg-Marquardt parameter

U = unit matrix (S_a^{-1})

Principles of the temperature remote sensing

- **In strong bands thermal radiation forms at different altitudes depending on wavelength (*τ ~ 1 rule*)**
- **Gas should be well mixed, not variable, with known abundance**
- **Local thermodynamic equilibrium (LTE)**
- **Vertical resolution ~ half a scale height**

$$\int_{+\infty}^{-\infty} B_\nu[T(\xi)]\cdot K_\nu(\xi)d\xi = \mathrm{I}(\nu) \qquad B_\nu[T] = B_\nu[T_0] + \frac{\partial B}{\partial T}\Delta T(\xi)$$

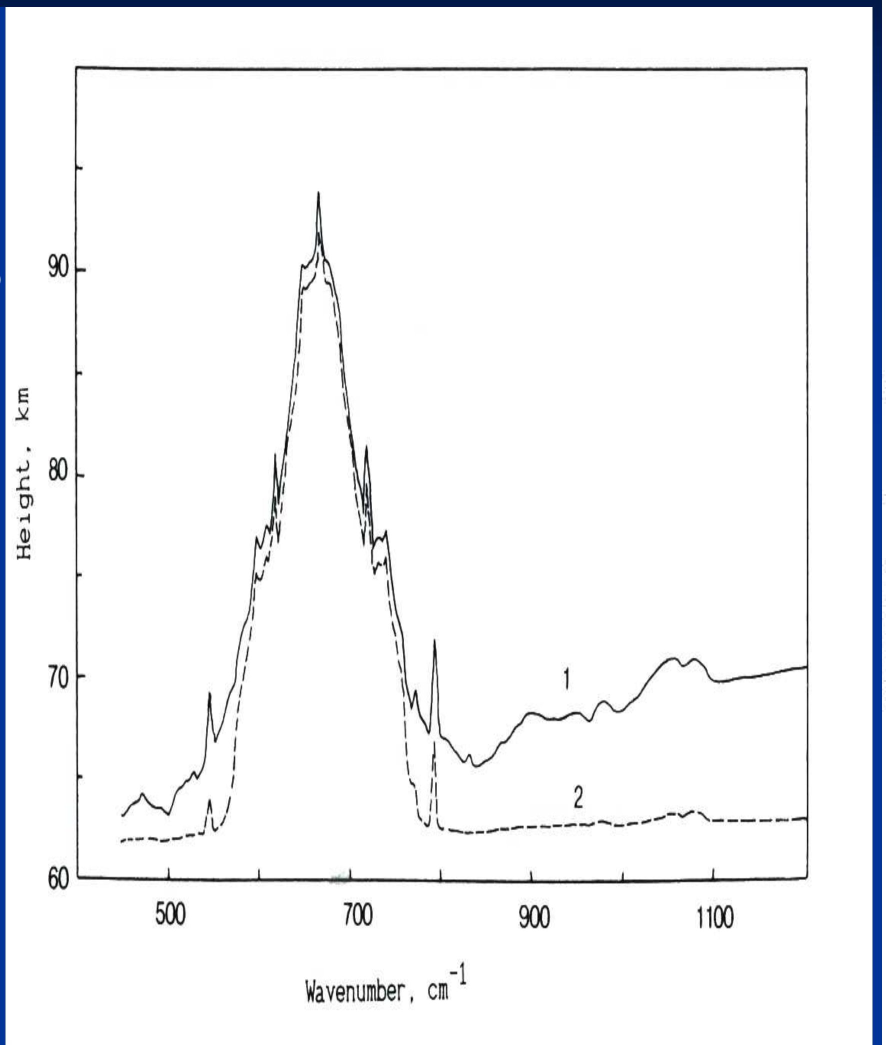
$$\int_{+\infty}^{-\infty} K_\nu(\xi)\cdot\frac{\partial B}{\partial T}[T_0]\cdot\Delta T(\xi)d\xi = \mathrm{I}_\nu - \mathrm{I}_\nu[T_0]$$

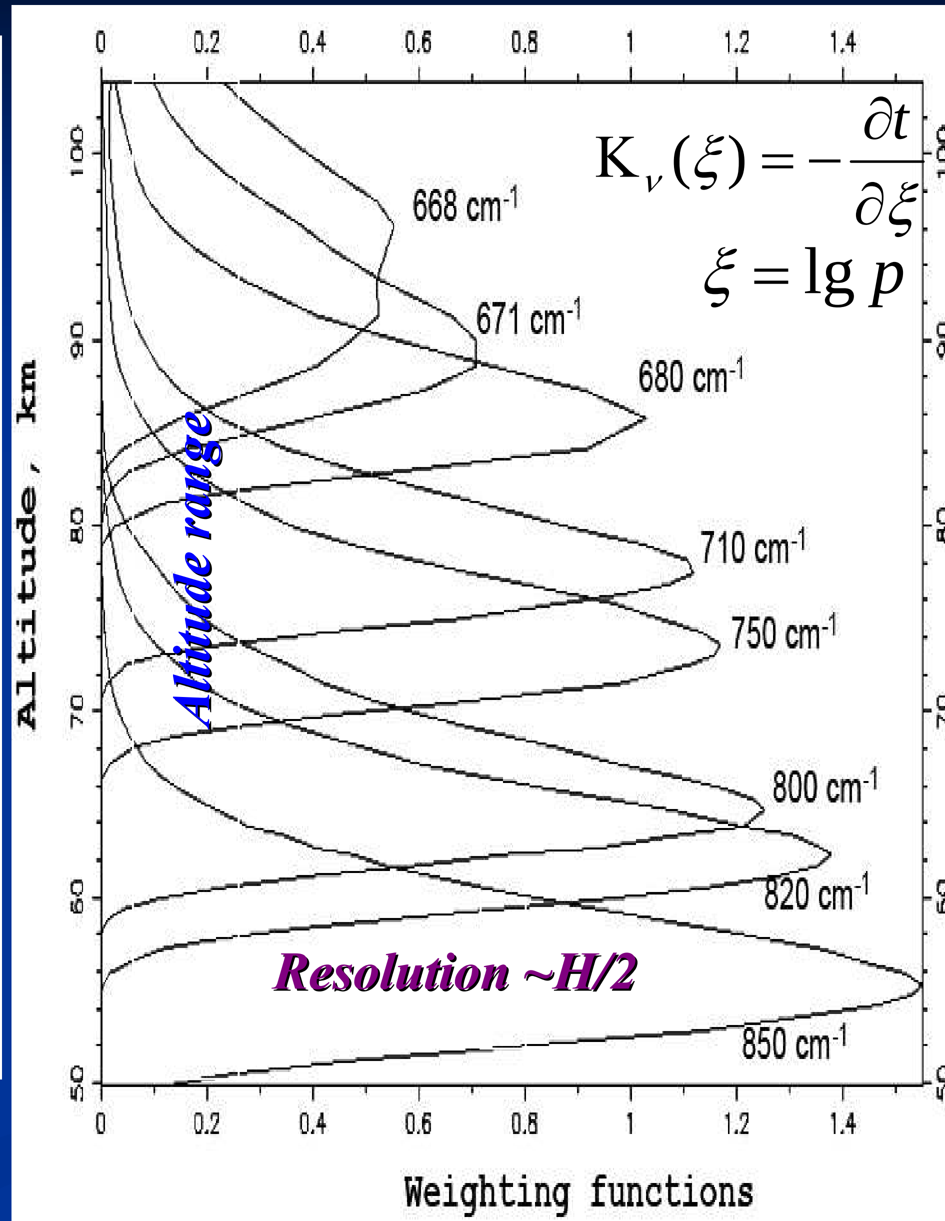
Temperature retrieval is an ill-posed problem.

Special stabilization (regularization) methods are required

Vertical sounding of the temperature structure

Altitude of the level τ = 1

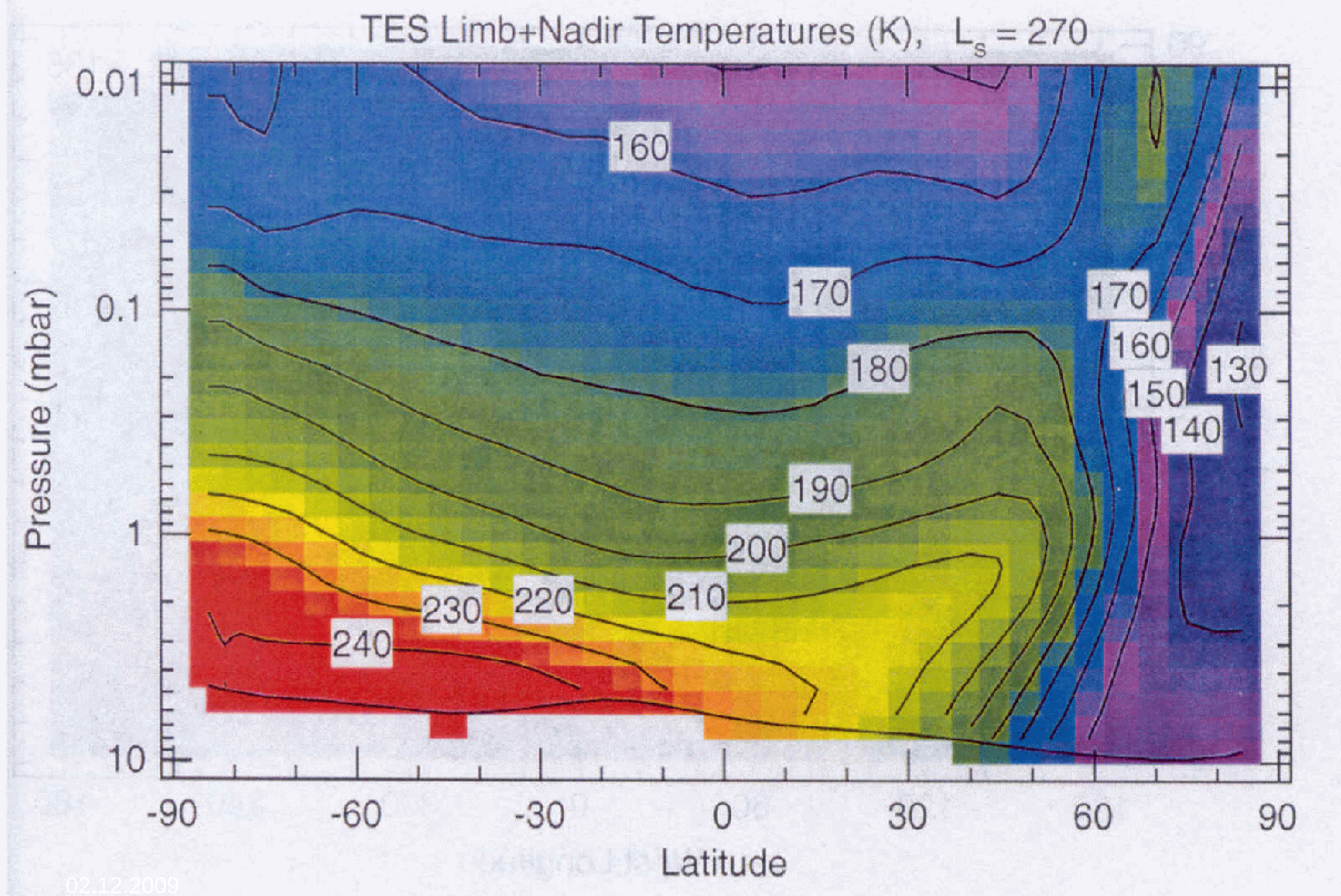


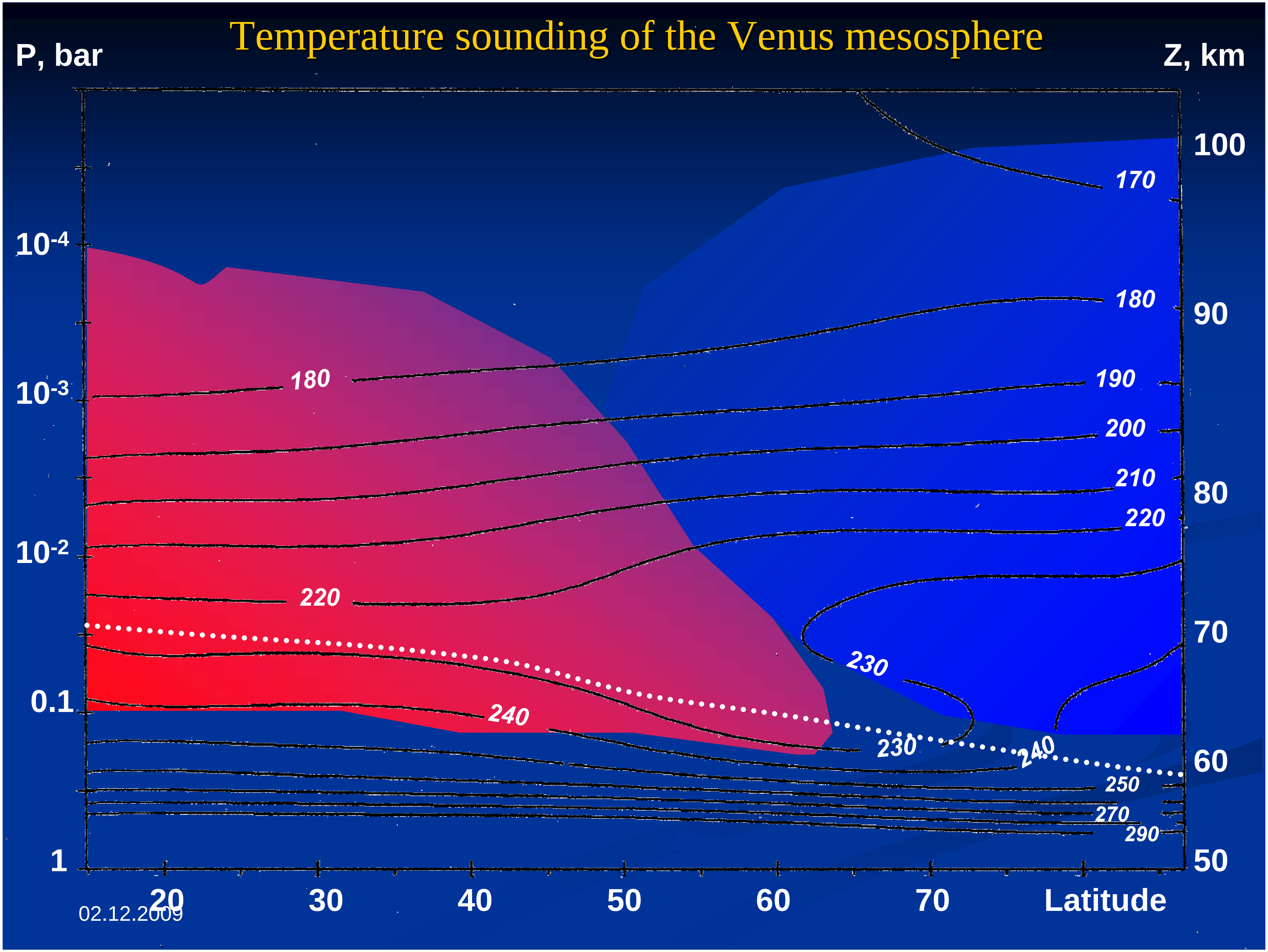


Wavenumber, cm^{-1}

τ ~ 1 rule

Mars atmospheric temperatures





Temperature sounding of the Venus mesosphere
P, bar
Z, km
10-4
10-3
10-2
0.1
1
100
90
80
70
60
50
20
30
40
50
60
70
Latitude
170
180
190
200
210
220
230
240
250
270
290
02.12.2009

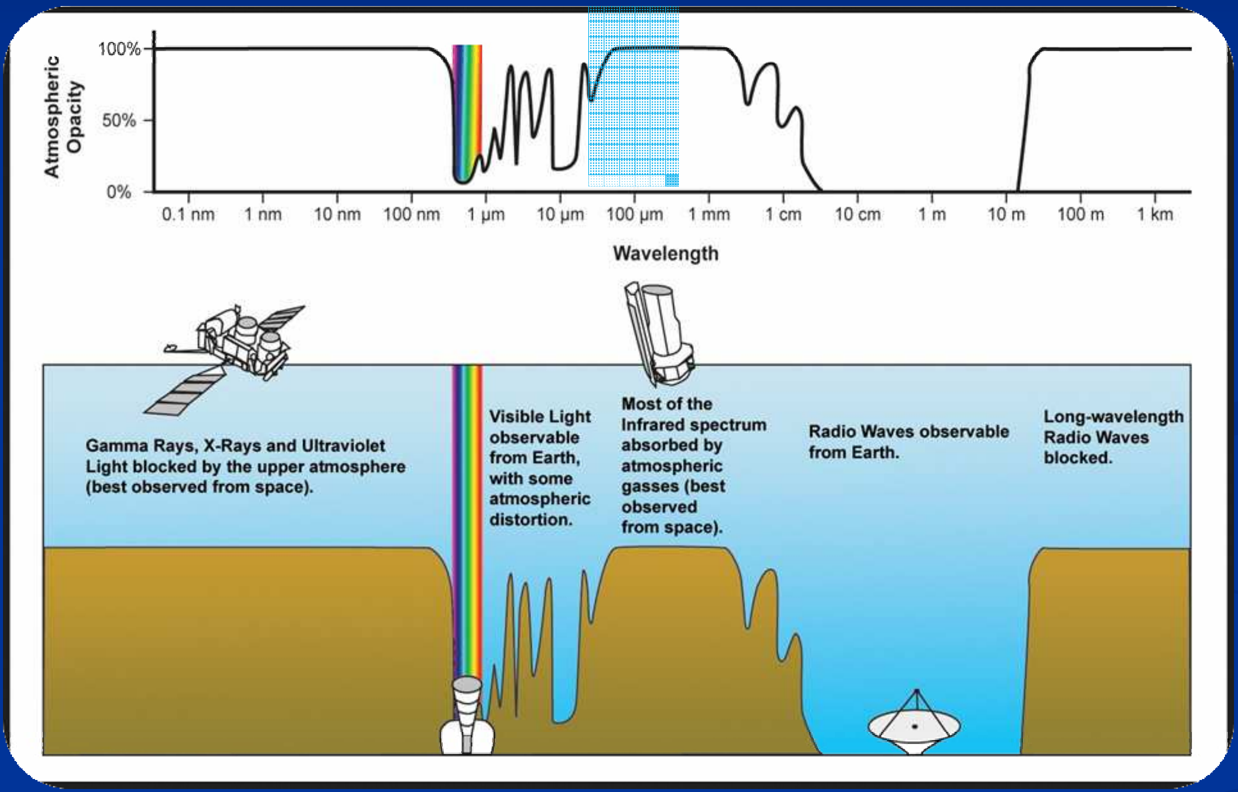
Ground-based observations of planetary atmospheres

The Earth´s Atmospheric Window

Space-based astronomy

Herschel

the Earth's atmosphere is partially transparent



Ground-based astronomy

numerous water vapour absorption bands: observing sites have to be dry, cool, and with stable weather conditions

These various atmospheric 'windows' determine which kinds of astronomy can be done from the ground, and which have to be done from space.

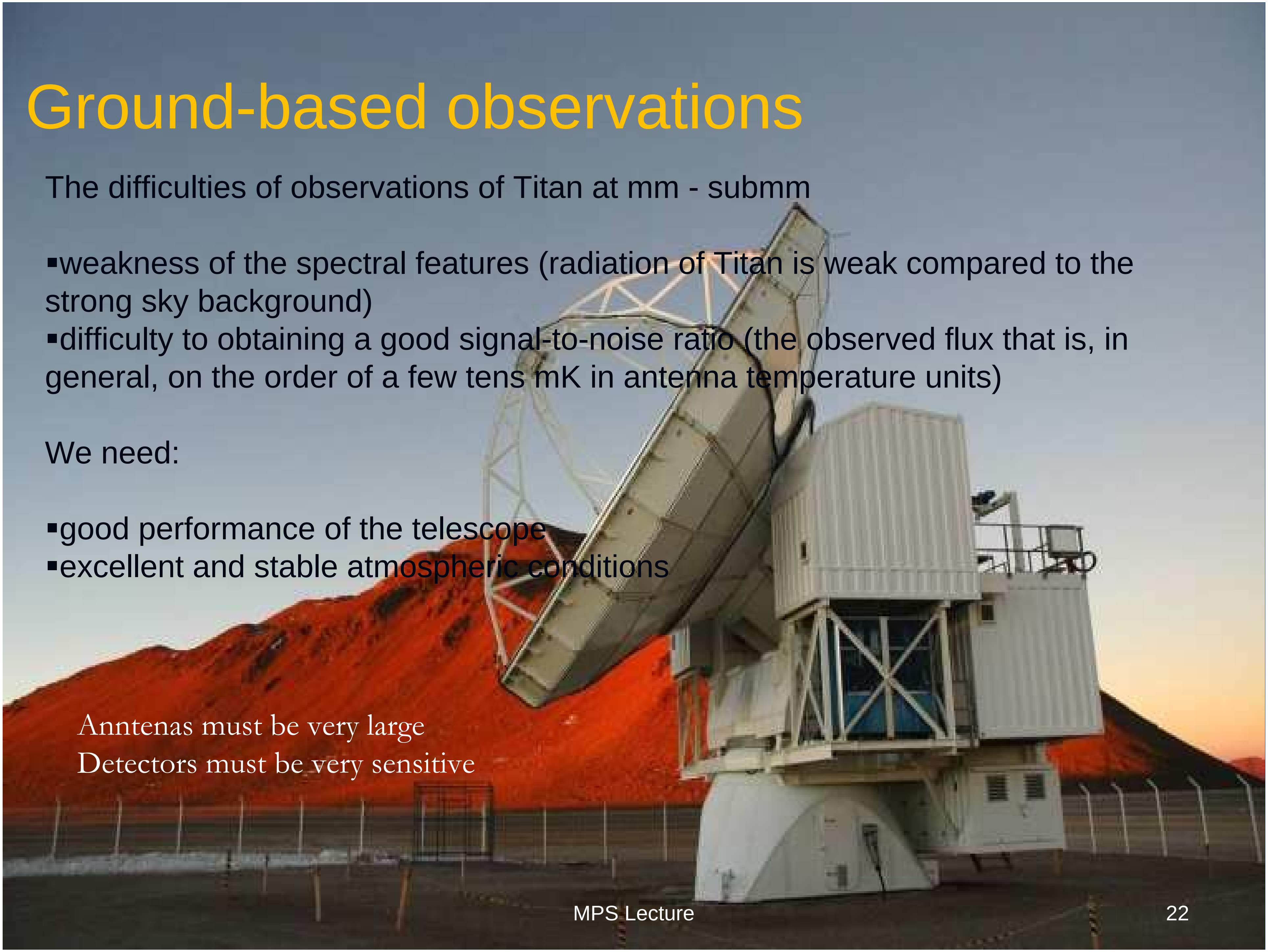
Ground-based observations

The difficulties of observations of Titan at mm - submm

▪weakness of the spectral features (radiation of Titan is weak compared to the strong sky background)
▪difficulty to obtaining a good signal-to-noise ratio (the observed flux that is, in general, on the order of a few tens mK in antenna temperature units)

We need:

▪good performance of the telescope
▪excellent and stable atmospheric conditions



Anntenas must be very large
Detectors must be very sensitive

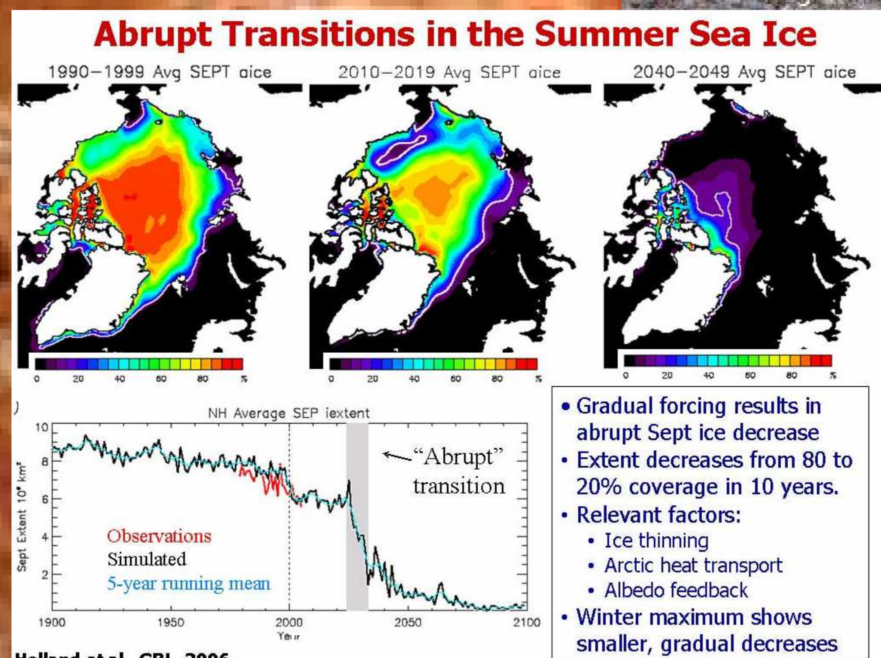
Example 1

Mesospheric Winds, Thermal Structure, and CO Distribution on Venus

Example 1

Why study Venusian atmospheric dynamics ?

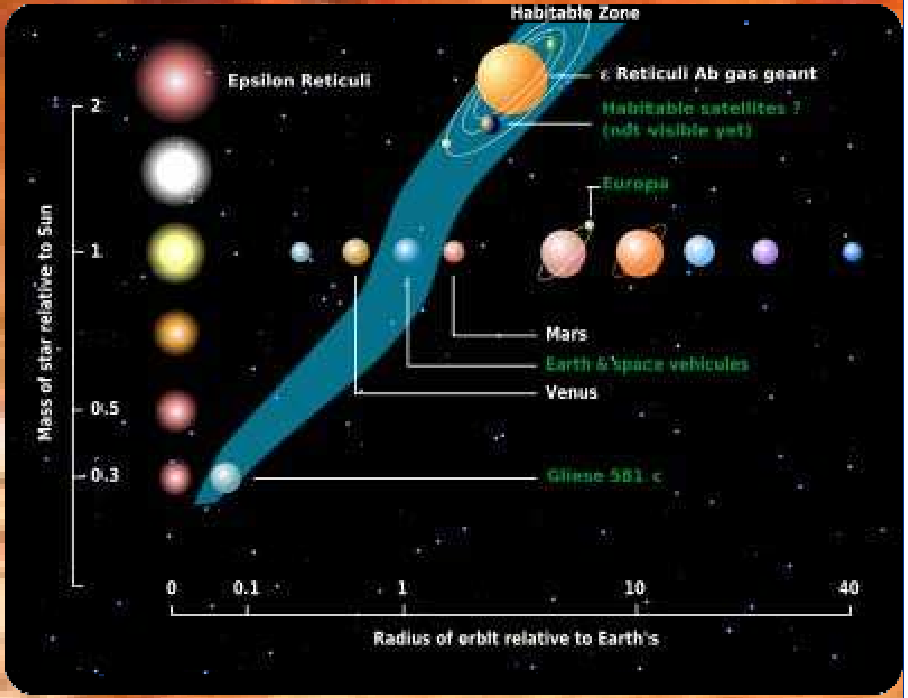
- To understand the possible consequences of future climate changes on Earth



Example 1

Why study Venusian atmospheric dynamics ?

- To assess extrasolar planet‘s habitability



Example 1

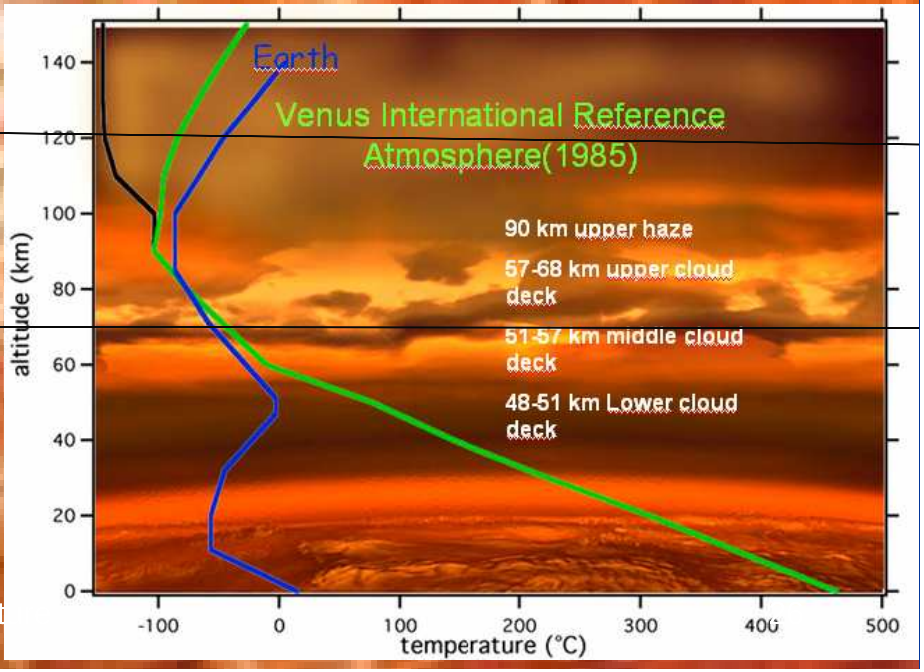
Why study Venusian atmospheric dynamics ?

- To learn about Venus itself

The atmosphere of Venus can be vertically split into three different dynamical regions :
(1) the ***troposphere***: below 70 km:
(2) the ***thermosphere***, above z = 120 km :
(3) the ***mesosphere***, between z=70 and 120 km.

❖ Combination of two different wind regimes
  sub-solar to anti-solar flow pattern
  time-variable retrograde super rotation

❖acts as a transition region



Example 1

On 5th June 2007: NASA **MESSENGER** spacecraft encompassed a flyby to Venus
ESA´s Venus Express orbites around Venus

Credits:JHU/APL

Both spacecrafts carried out multi-point observations of the Venusian atmosphere for several hours.

Example 1

A 1st coordinated observational campaign [23 May – 9 June (later) 2007]:

Space

Credits:JHU/APL

Spacecrafts & Satellites:
Venus Express
Messenger

Remote sensing from Earth - radio, submillimetre, infrared and visible -

IRTF Texes
JCMT-15m
VLT-UVES
Keck-HIRES
OHP/Sophie
Nobeyama
IRAM-30m
SMT

http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=41012

Example 1

A 2nd coordinated observational campaign [January – June 2009]:

Remote sensing from Earth - radio, submillimetre, infrared and visible -

Space

Credits:JHU/APL

Spacecrafts & Satellites:
Venus Express

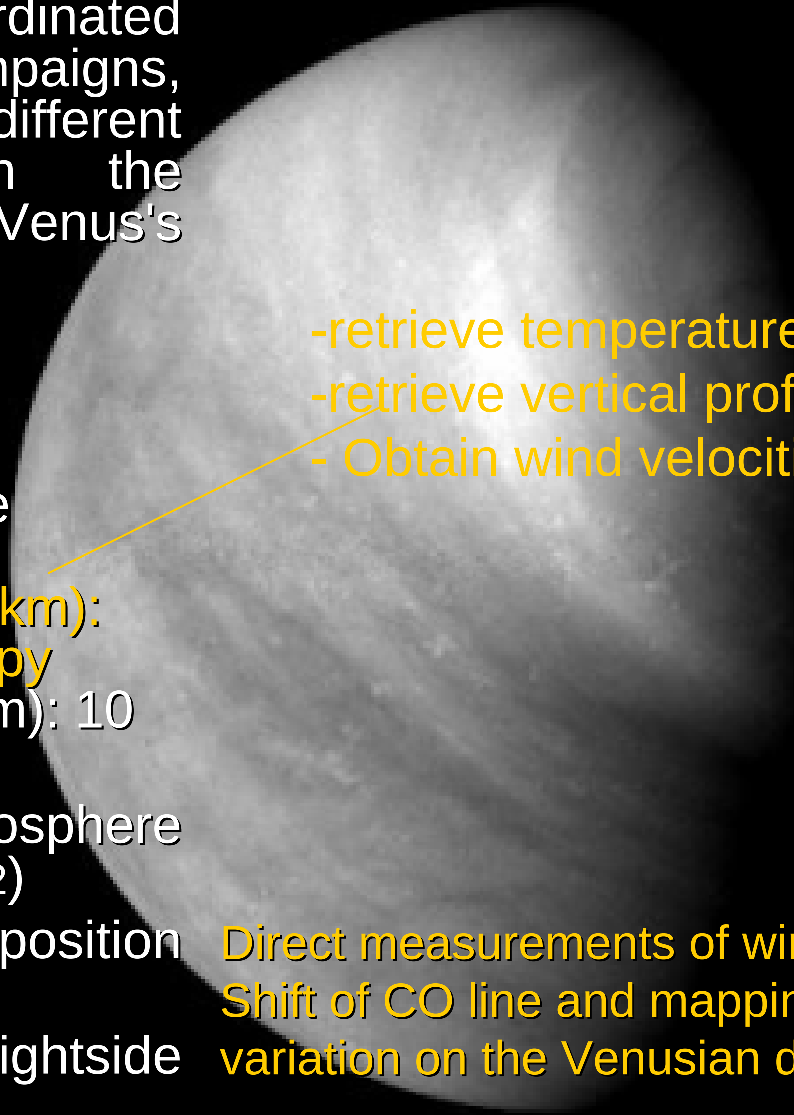
Keck-HIRES
APO/ARCES
CFHT/ESPaDOnS
Okayama/HIDES
AAT/IRIS 2
JCMT-HARP/ACSIS
SMA
SMT
CARMA
Kitt Peak/THIS

Example 1

Science Goals

During the coordinated ground-based campaigns, observations by the different teams focuses on the atmosphere above Venus's cloud layer and include:

- Wind measurements at different altitudes
  - cloud top level: visible spectroscopy
  - mesosphere (90-105 km): mm/submm spectroscopy
  - thermosphere (120 km): 10 µm observations
- Morphology of the mesosphere airglow emission (O, O_2)
- Mesospheric composition (H_2O, SO, SO_2, HCl)
- Deep atmosphere nightside composition



-retrieve temperature vertical profiles

-retrieve vertical profiles of CO

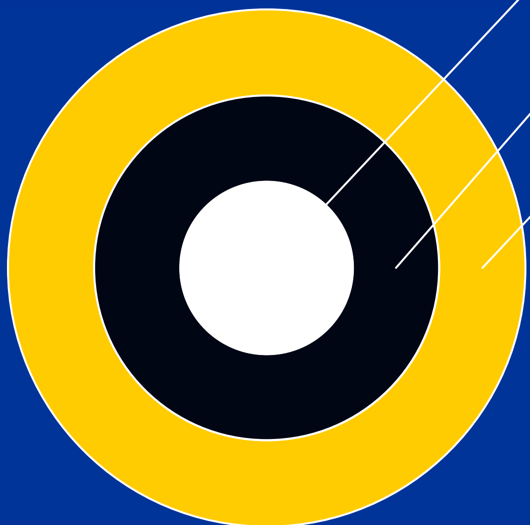
- Obtain wind velocities

Direct measurements of wind from Doppler Shift of CO line and mapping the wind velocity variation on the Venusian disk

Credits: ESA

Example 1

How? Ingredients



Observations

Deriving information from the spectra

Forward model – Inversion Algorithm

To model the expected observed emission spectra

To retrieval physical parameters as the mixing ratio

Example 1

II.- Spectral Line Observations of Venus

Between 7.6.07 and 16.6.07 (1st campaign)

10-m Submillimeter Telescope (HHSMT, Arizona)

Instrumentation used:

Receivers: 345 SIS, 2mmJT/1.33JT ALMA
[320-375] [210-279] GHz

Backends:

- Chirp Transform Spectrometer (40 kHz)
- Acousto-Optical-Spectrometers (AOS´s)
- Forbes Filterbanks (FFBS)

Results:

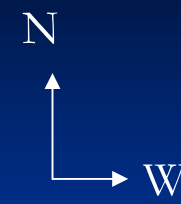
36 spectral line observations of Venus with the lines

CO J=3-2 - 15 min - SIS-345
^{13}CO J=2-1 - 30 min - 1.3mm ALMA
^{12}CO J=2-1 - 150 min - 1.3mm ALMA

at 15 different beam positions at the Venus disk

Example 1

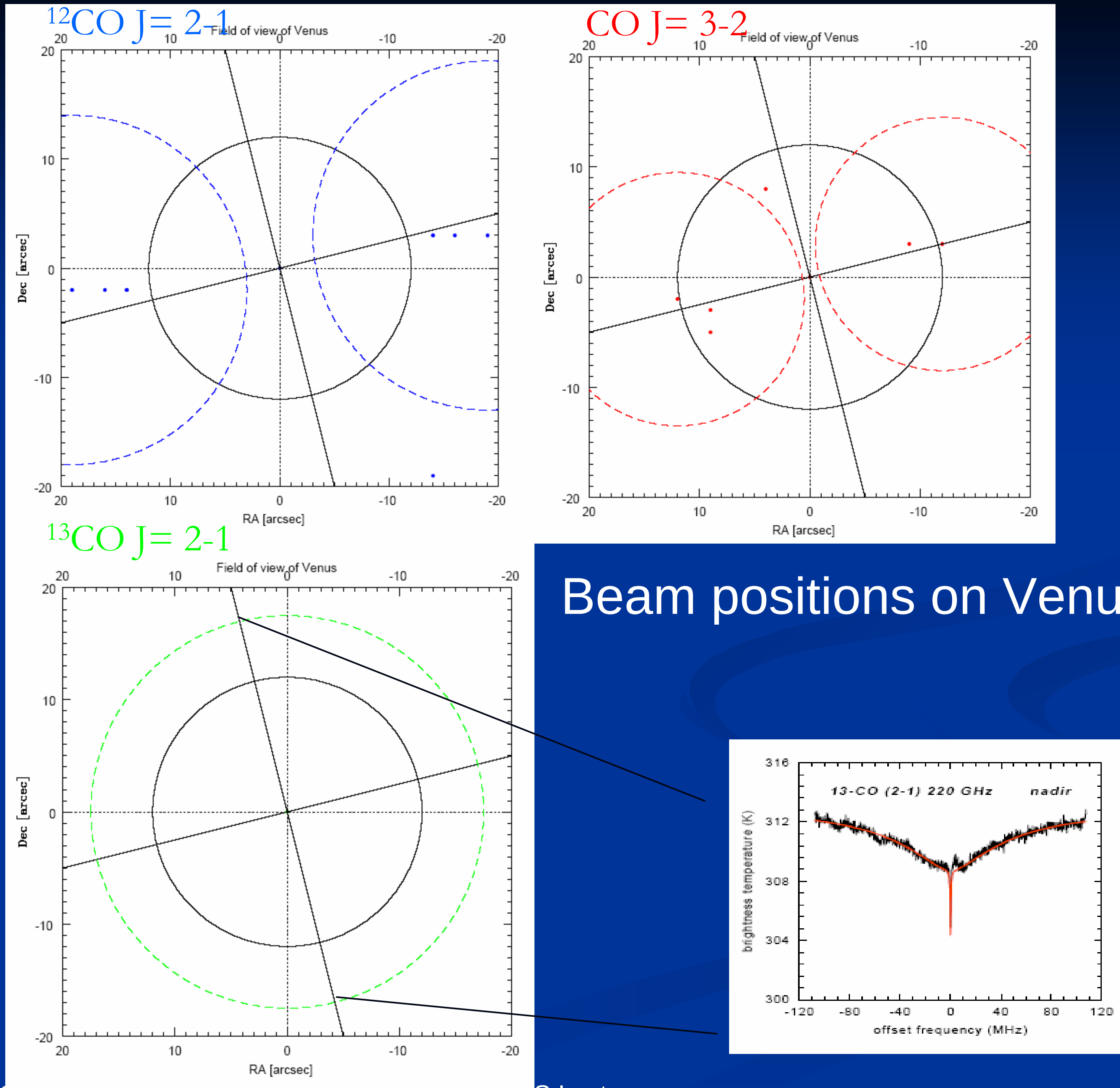
Fractional disk illumination



Apparent disk of Venus for 2007 Jun 8 and 16 at 20:00 UT

49.9 %   45.3 %

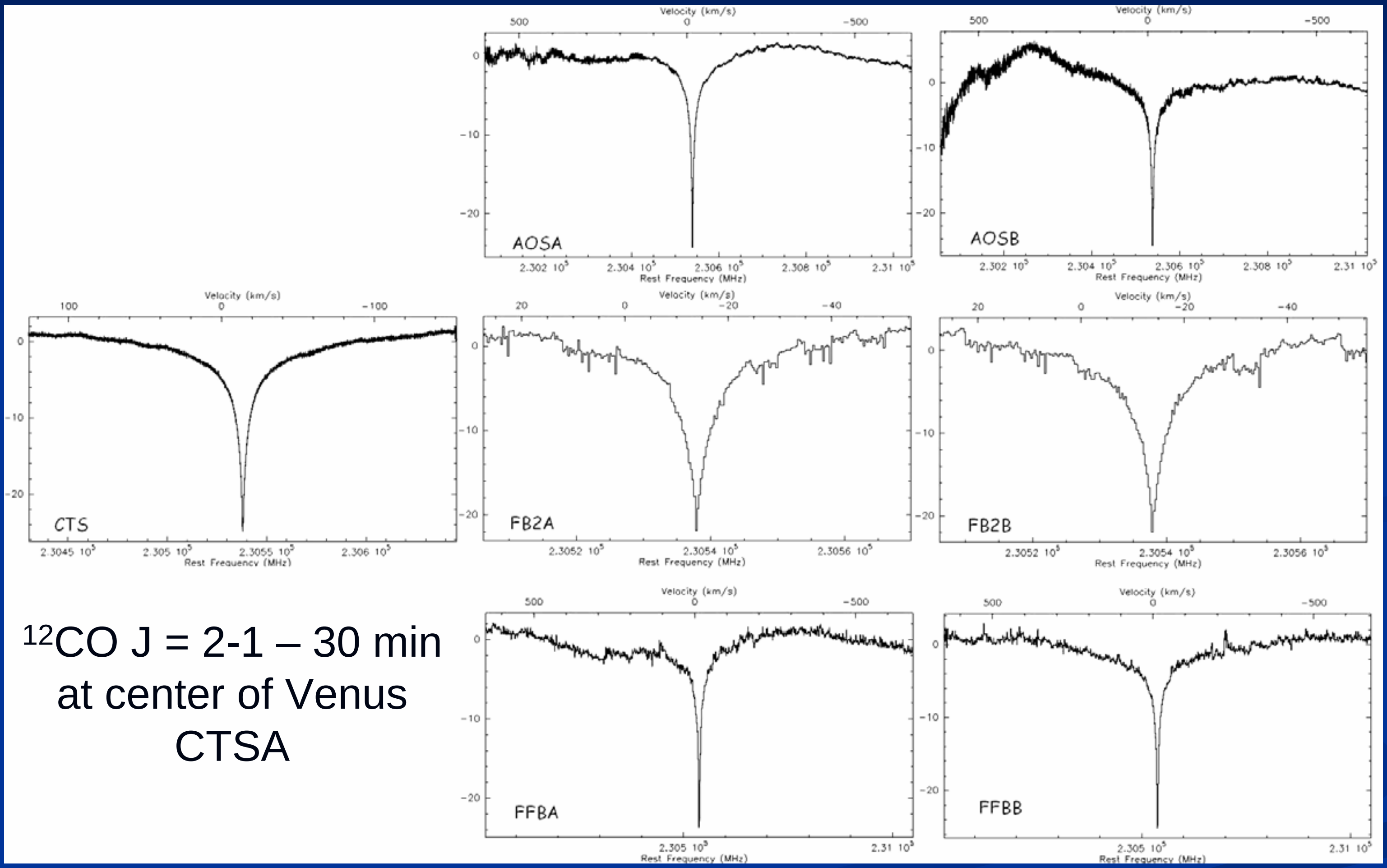
Example 1



Beam positions on Venus's disk

Example 1

Spectra Morphology for the ^{12}CO J = 2-1 line for different backends



Rengel, Hartogh, Jarchow, PSS 56, 1688, 2008

Very narrow, deep absoption lines
are obtained!

Example 1

III. Technique to retrieve profiles of temperature and CO volume mixing ratio

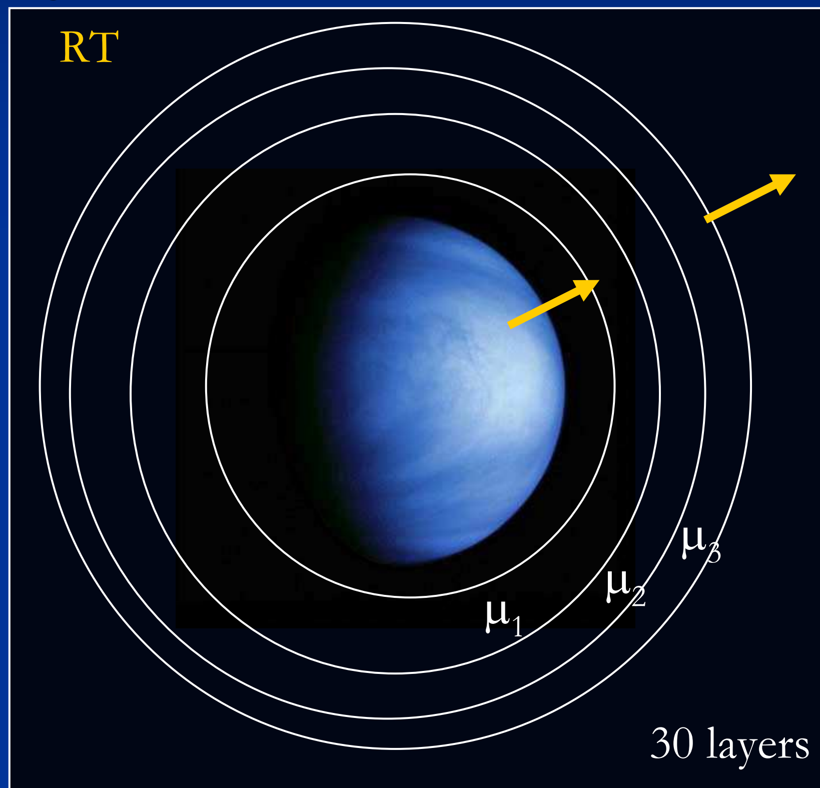
Input parameters → Abundance profiles → Radiative Transfer → Synthetic Spectra → Comparison with data

Optimal estimation algorithm

T profile →

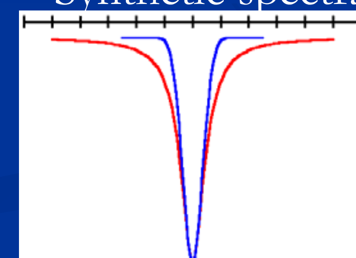
P profile →

Vmr profile →

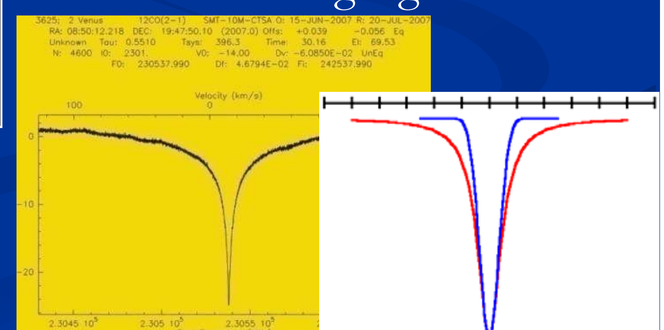


μ_i=absorption coefficient

Synthetic spectra



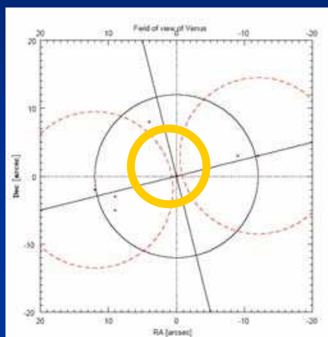
Fitting algorithm

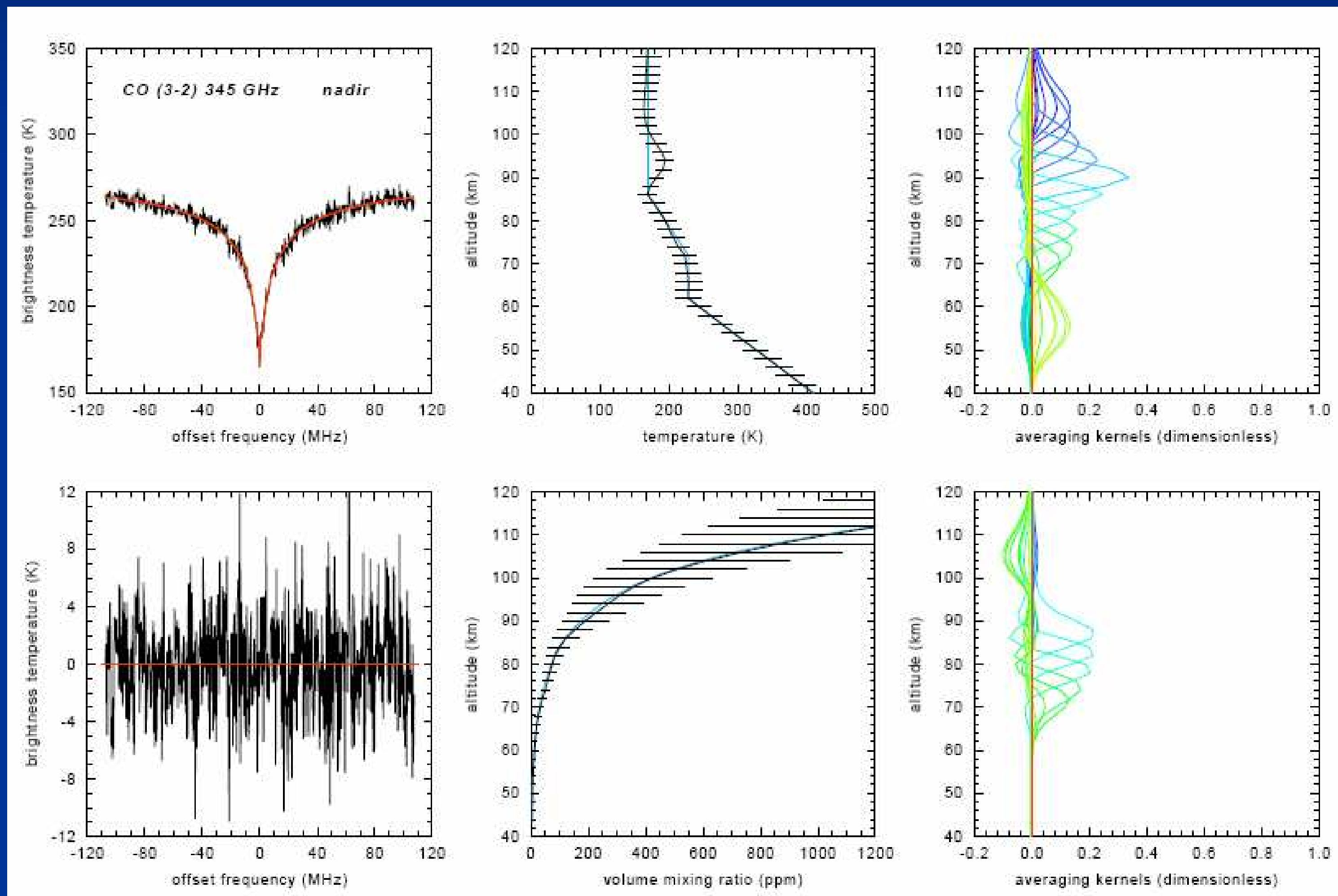


New set of parameters

Example 1

IV.- Results: Thermal structure and CO Distribution

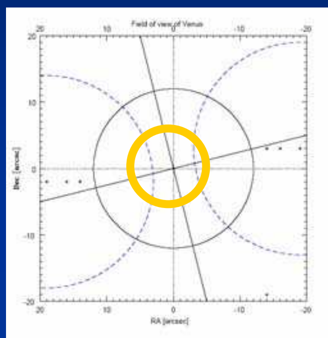


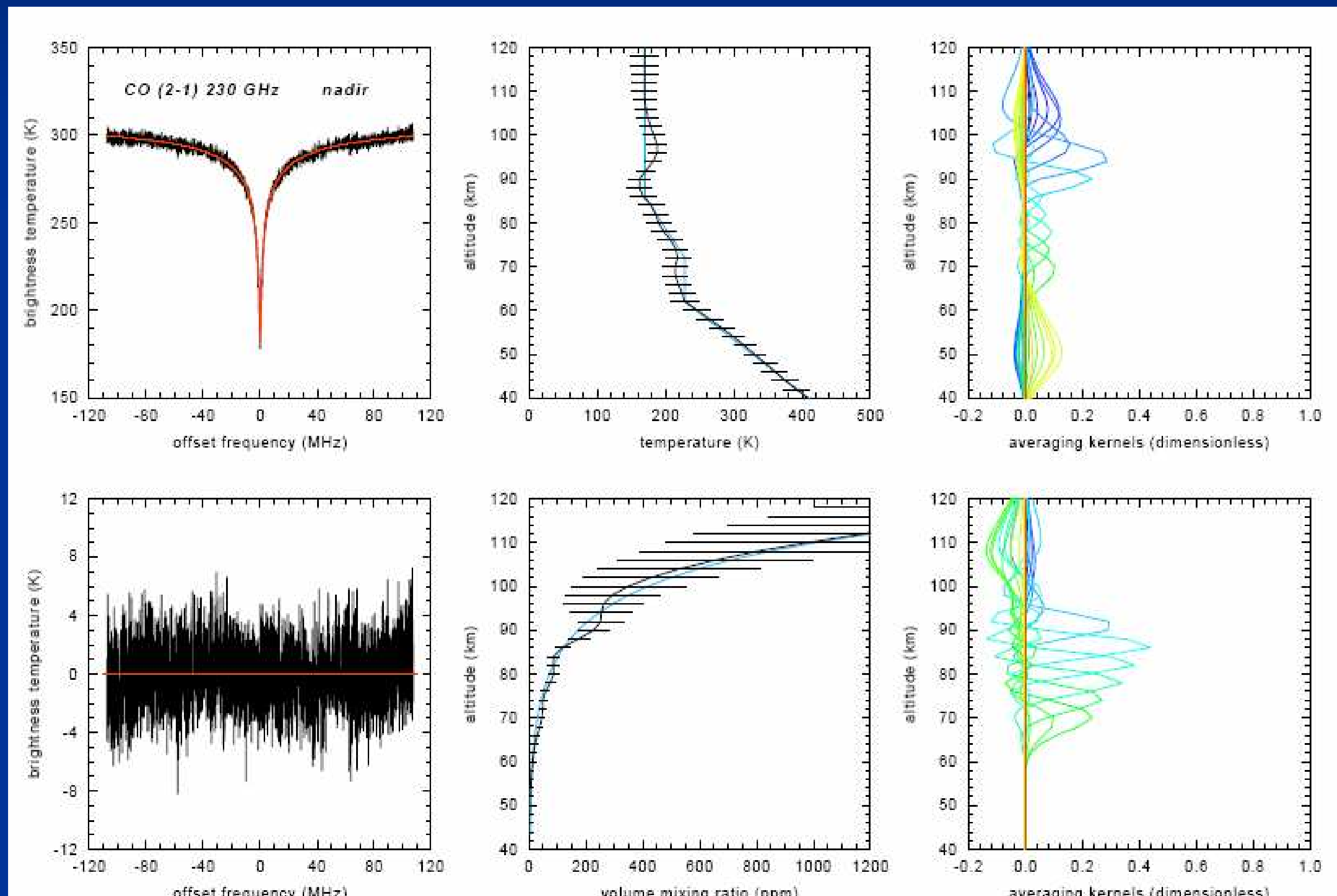


Rengel, Hartogh, Jarchow, PSS 56, 1688, 2008

Example 1

IV.- Results: Thermal structure and CO Distribution





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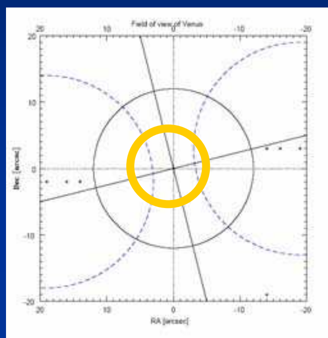
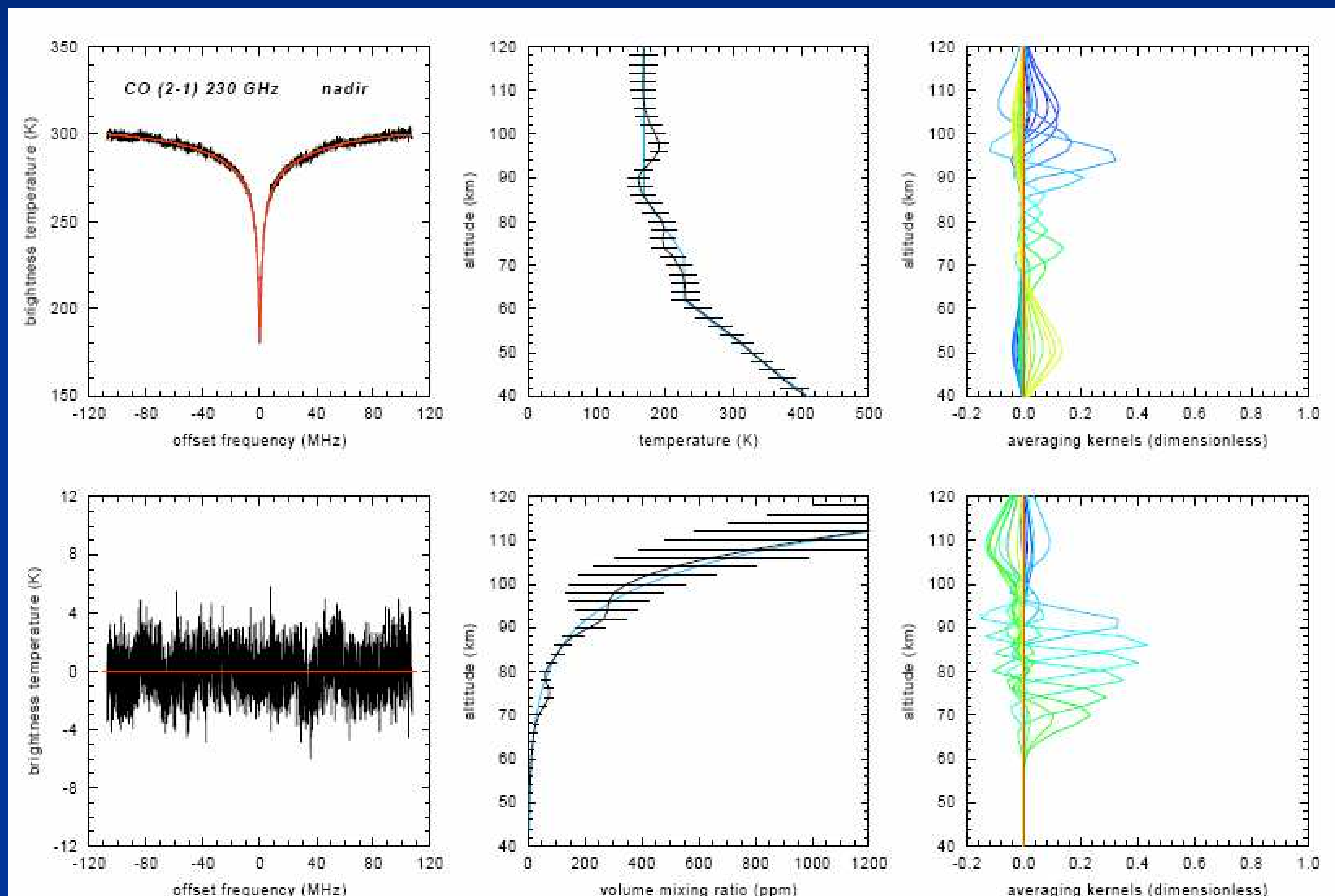
Example 1

IV.- Results: Thermal structure and CO Distribution

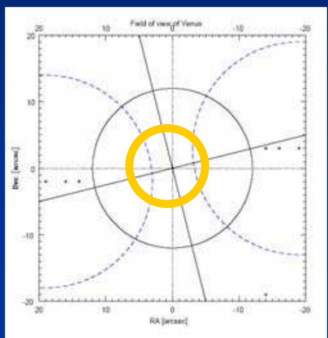


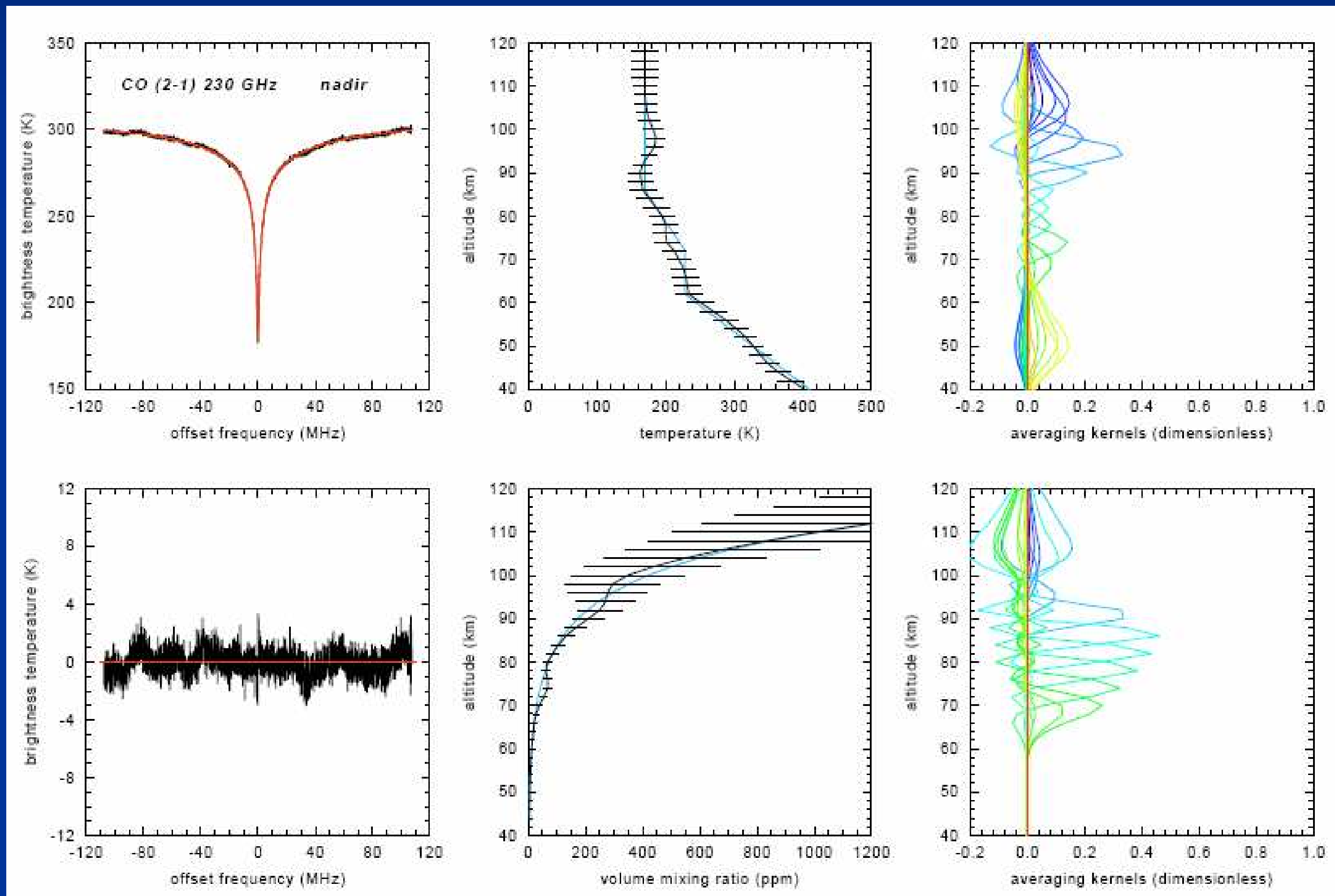


Rengel, Hartogh, Jarchow, PSS 56, 1688, 2008

Example 1

IV.- Results: Thermal structure and CO Distribution





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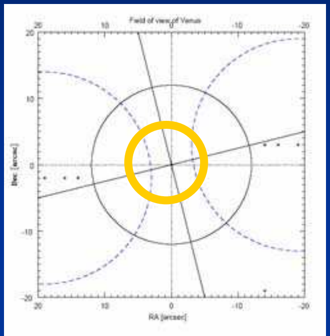
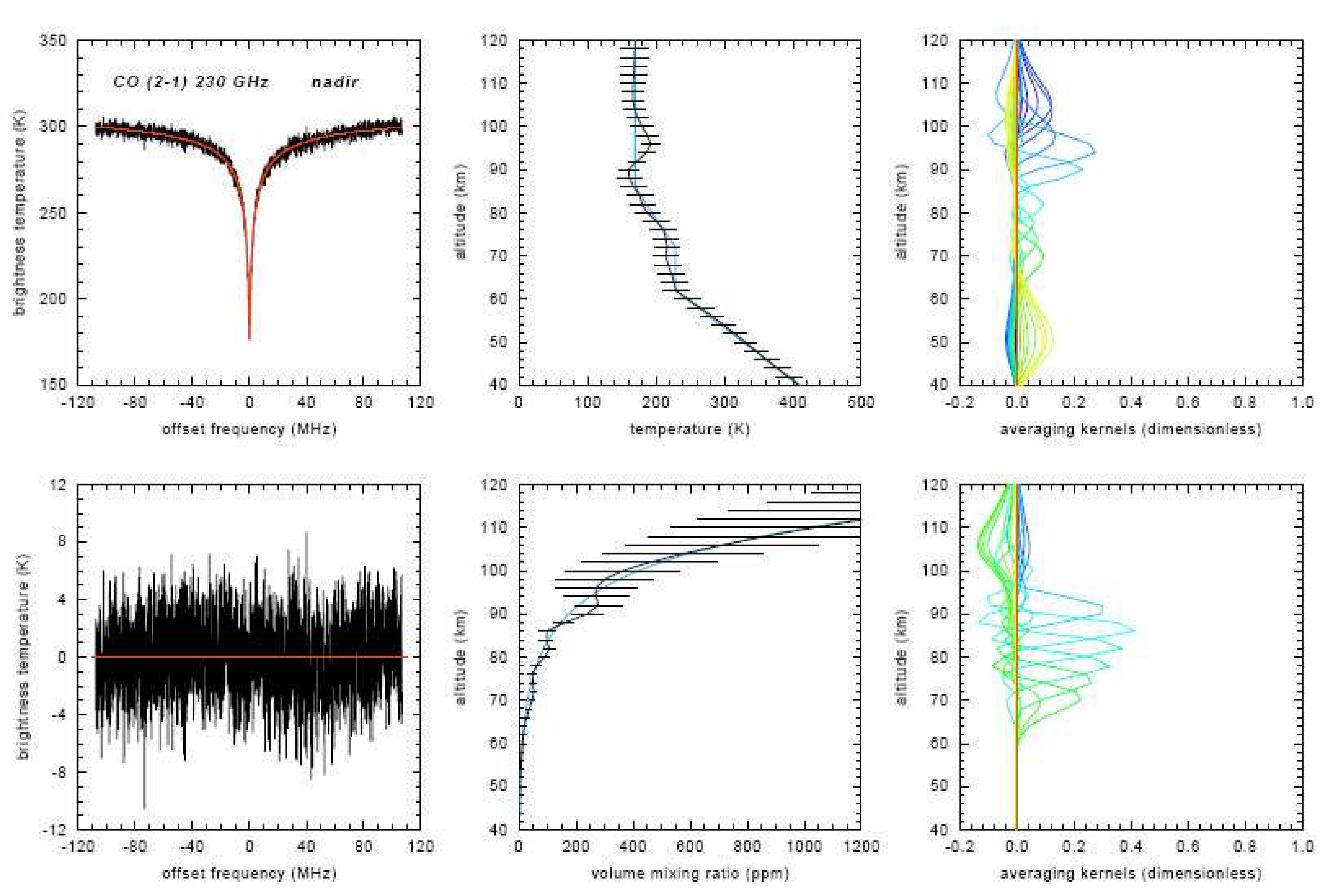
IV.- Results: Thermal structure and CO Distribution





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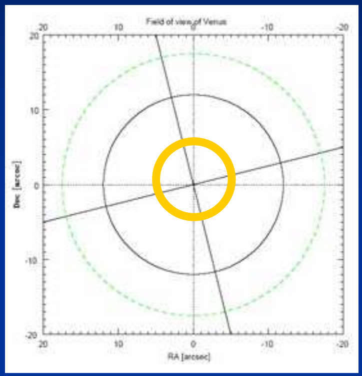
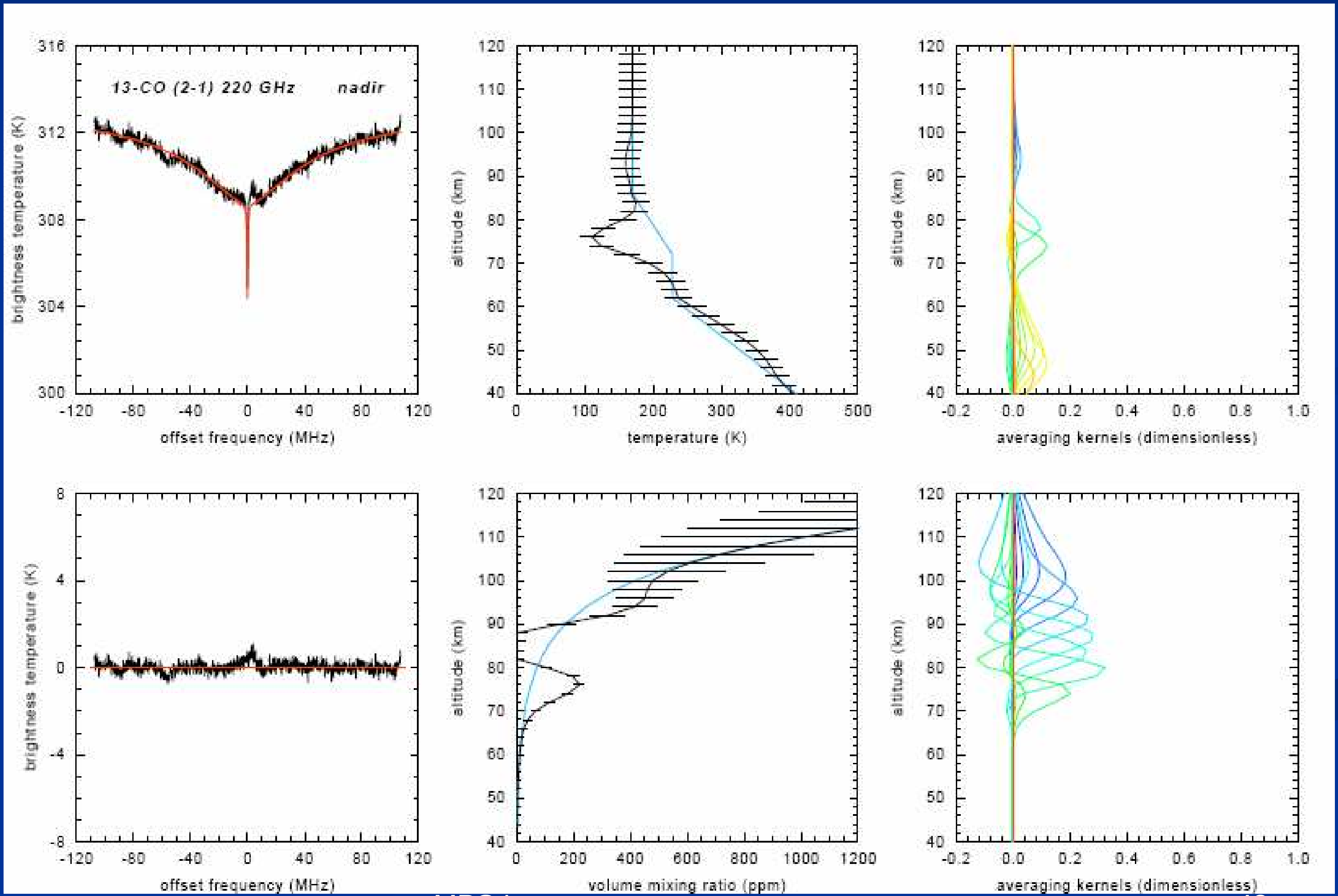
Example 1

IV.- Results: Thermal structure and CO Distribution





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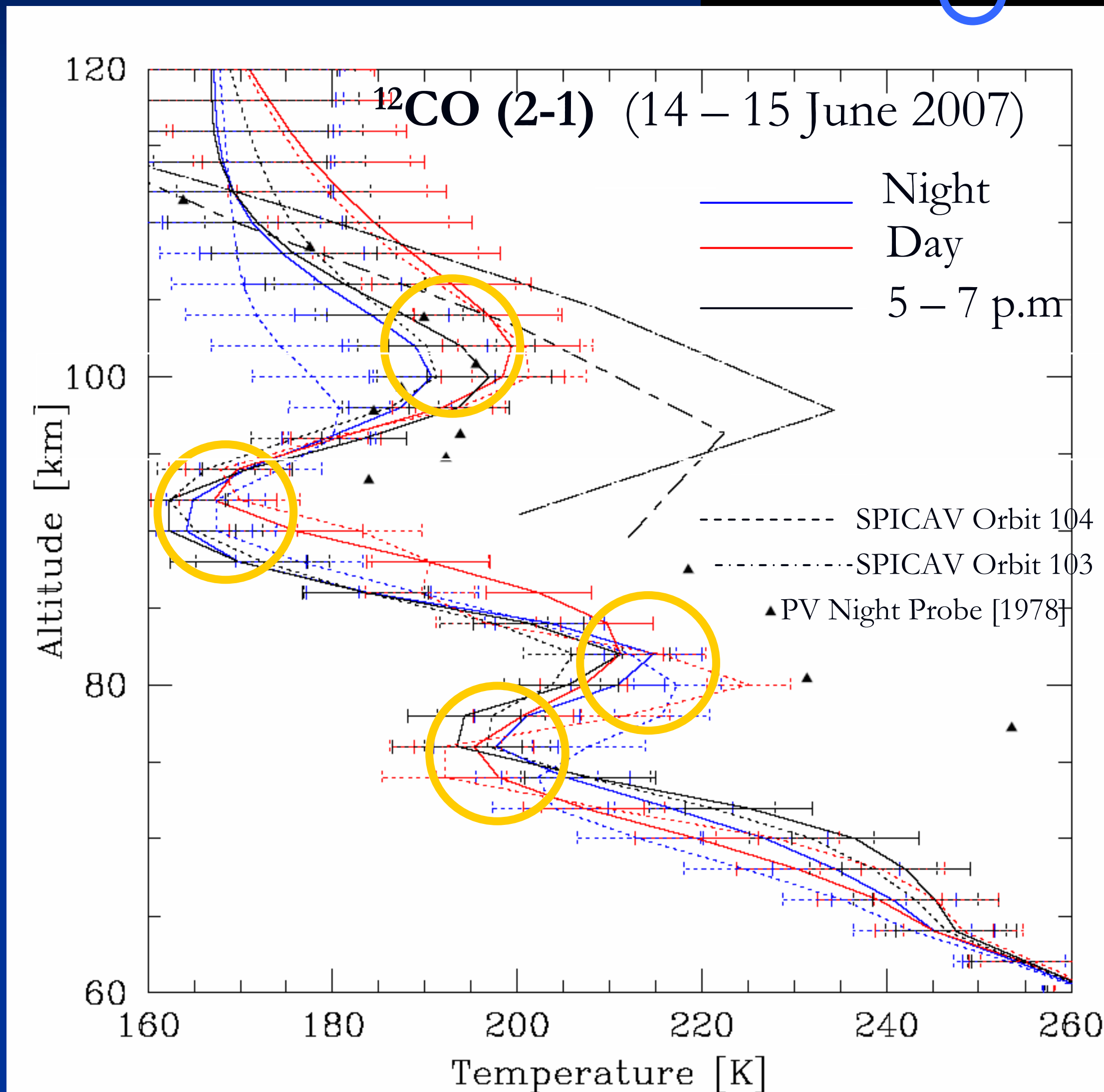
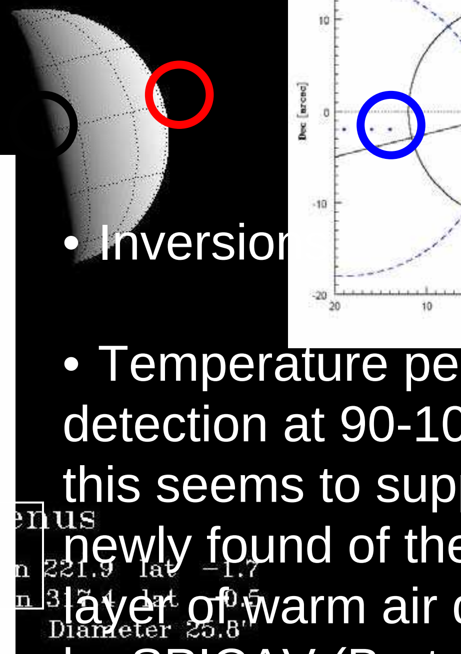
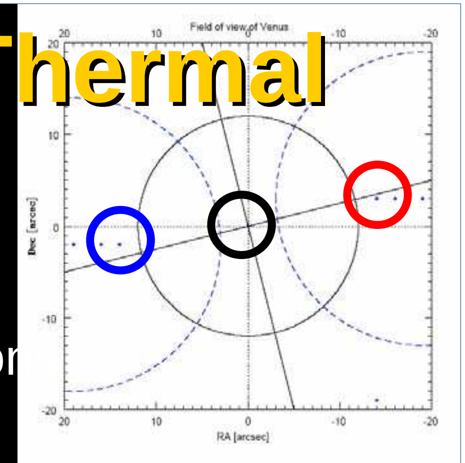
Example 1

IV.- Results: Changes in the Thermal Structure



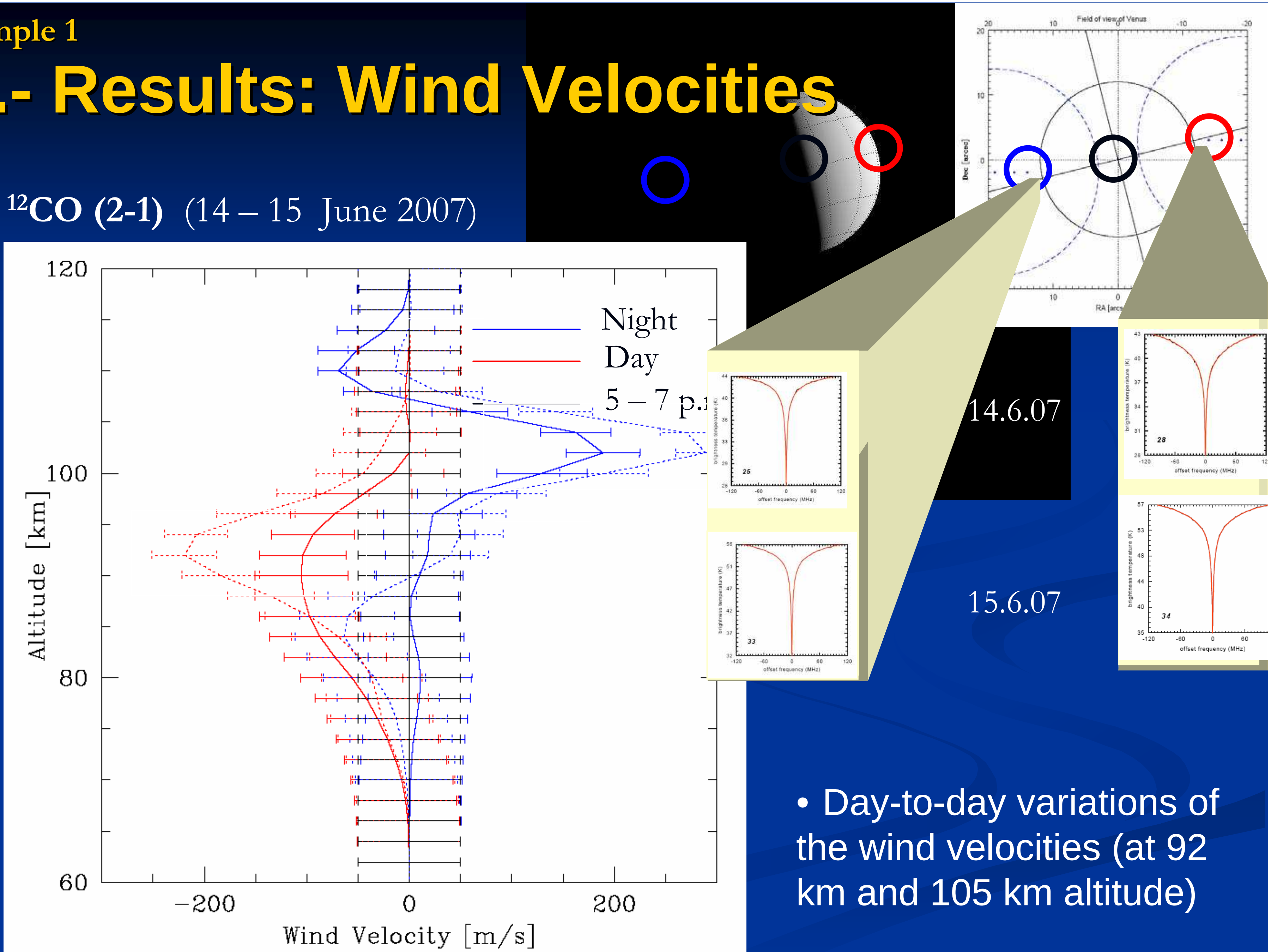




- Inversion
- Temperature peak detection at 90-100 km – this seems to support the newly found of the extensive layer of warm air detected by SPICAV (Bertaux et al. 2007).
- Day-to-night temperature variations ~25 K at 100 km (15 June)
- Temporal diurnal temperature variations ~10 K at 80 km and nocturnal at 100 km.

Example 1

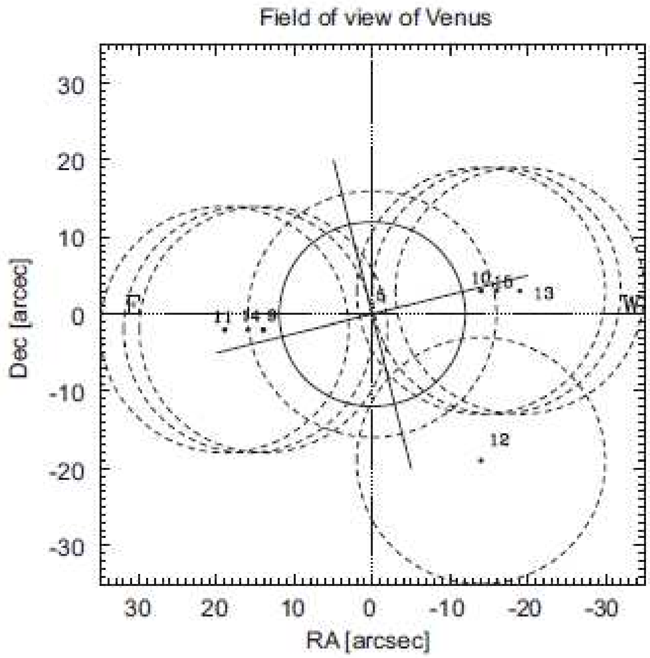
IV.- Results: Wind Velocities



- Day-to-day variations of the wind velocities (at 92 km and 105 km altitude)

Example 1

IV.- Results: Wind Velocities



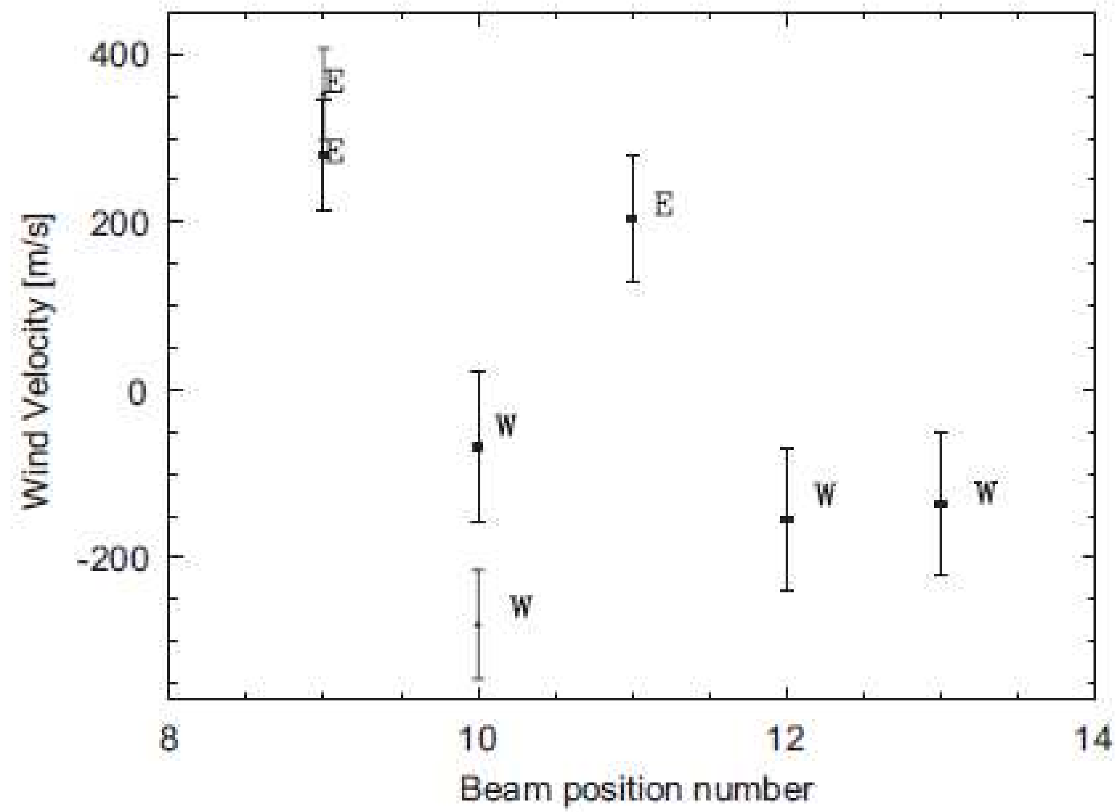


Fig. 15. Retrieved wind velocity measurements for different beam positions on the Venus' disc for two observing days. Squares: 14 June, triangles: 15 June. Retrieved velocity error bars are indicated. E: East, W: West.

Rengel, Hartogh, Jarchow, PSS 56, 2008, 1368

Example 1

Winds measurements

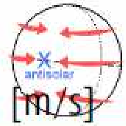
date	alt.	RZ [m/s] 	SSAS [m/s] 	reference	observatory
Dec 1985, Oct 1986, Mar 1987	109 ± 10	25 ± 15	**120 ± 20**	Goldstein etal. 1991	IRTF, 10 micron heterodyne. dayside only.
Apr. May 1988	99 ± 6	**132 ± 10**	< 40	Shah etal. 1991	OVRO, interferometer ^{12}CO (1-0)
Aug 1991	95 ± 6 105 ± 10	35 ± 15 95 ± 10	45 ± 15 90 ± 15	Lellouch etal. 1994	IRAM, single dish ^{12}CO (1-0) & (2-1)
Nov 1994	95 ± 6 105 ± 10	45 ± 30 75 ± 20	50 ± 35 110 ± 20	Rosenqvist etal. 1995	
Oct 2002	105	**dominant**	-	Clancy 2005	JCMT, single dish ^{12}CO (2-1)
Nov 2002	105	-	**dominant**		
May-Sep 2007	Strong variability			#1 VEx - GBO Campaign (PSS 2008)	IRAM, APEX, JCMT, SMT PdBI, NMA

Table credits: Sagawa

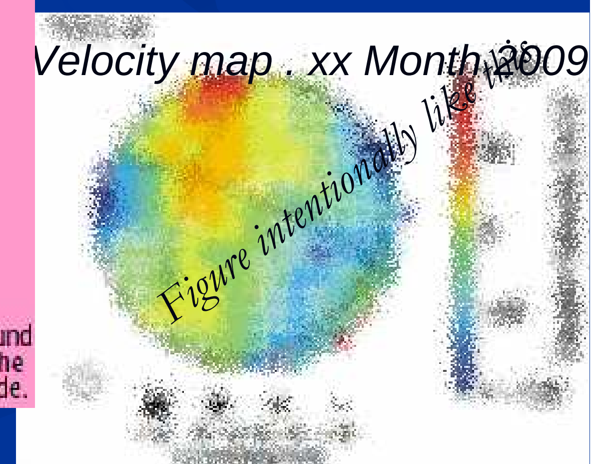
Example 1

Interferometric CO observations

→ **status:**
Data analysis

	SMA (Submillimeter Array)		CARMA (Combined Array for Research in Millimeter-wave Astronomy)
Observed Date	[redacted]		
Venus Diameter			
Day-Night Configuration	~50% of the disk is day-/nightside		antisolar
Antenna	8 × 6 m [#1]		6 × 10.4 m, 9 × 6.1 m
Baseline length	9.5-25 m		11-150 m
Receiver Band	[redacted]		
Observed Lines			
Wind Sensing Alt. [#2]	95-105 km	105-110 km	95-100 km
FOV (FWHM)	48"	32"	60" (10m-antenna) [#3]
Spatial Resolution	4.3" × 3.0"	5.5" × 1.7"	4.9" × 4.6"
Freq. Resolution	100 kHz		30 kHz
Final Goal	Simultaneous retrieval of T(z), CO, wind vertical profiles by using 3 CO lines.		Visualize the wind pattern around the antisolar point, and map the enhancement of CO at nightside.

→Succesfully measurements of the wind map at night hemisphere
→Strong spatial inhomogenity in the wind pattern



Sagawa, Hartogh, Gurwell, Rengel, Moullet, in preparation

Example 1

V.- Conclusion 1st Example

- We have carried out several HHSMT 12CO J = 2–1 and 13CO J = 2–1 line observations on different beam positions on Venus disc during June 2007 around the MESSENGER flyby of Venus and observations from Venus Express mission

- From the spectra we retrieved vertical profiles of temperature, CO distribution, and wind velocities for the June 2007 mesosphere of Venus

- Changes in the thermal structure of the Venus mesosphere are detected

  Day-to-night small temperature variations and short-term (day-to-day) on a time scale as short as one day variations of winds and temperature are evident in our data.

  This is consistent with the picture of dramatic variability of the Venus mesosphere with changes in temperature occurring on short scales (Clancy et al., 2005; Sandor and Clancy, 2005).

- Retrieved winds show variations of around 100m/s between the winds on 14 June and those on 15 June.

- HHSMT line observations of 12CO J = 2–1 and 13CO J = 2–1 and retrieved thermal profiles of the mesosphere of Venus (the temperature peak detection at 90–100 km) seems to **support the finding of the extensive layer of warm air detected by SPICAV onboard Venus Express**.

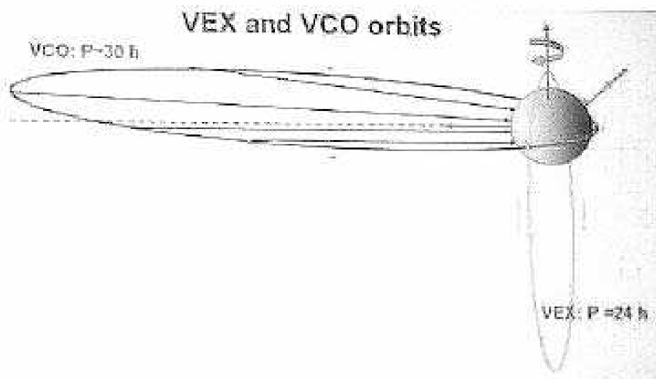
Example 1

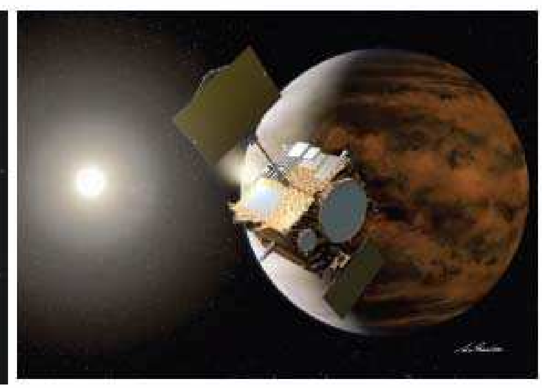
VI. - Outlook for the future

Dec. 2010 - Jan. 2011 3rd coordinated campaign

A proposed coordinated campaign in support of VEx-VCO at

VCO orbit insertion in Dec. 2010





JAXA's Venus Climate Orbiter

2nd Example

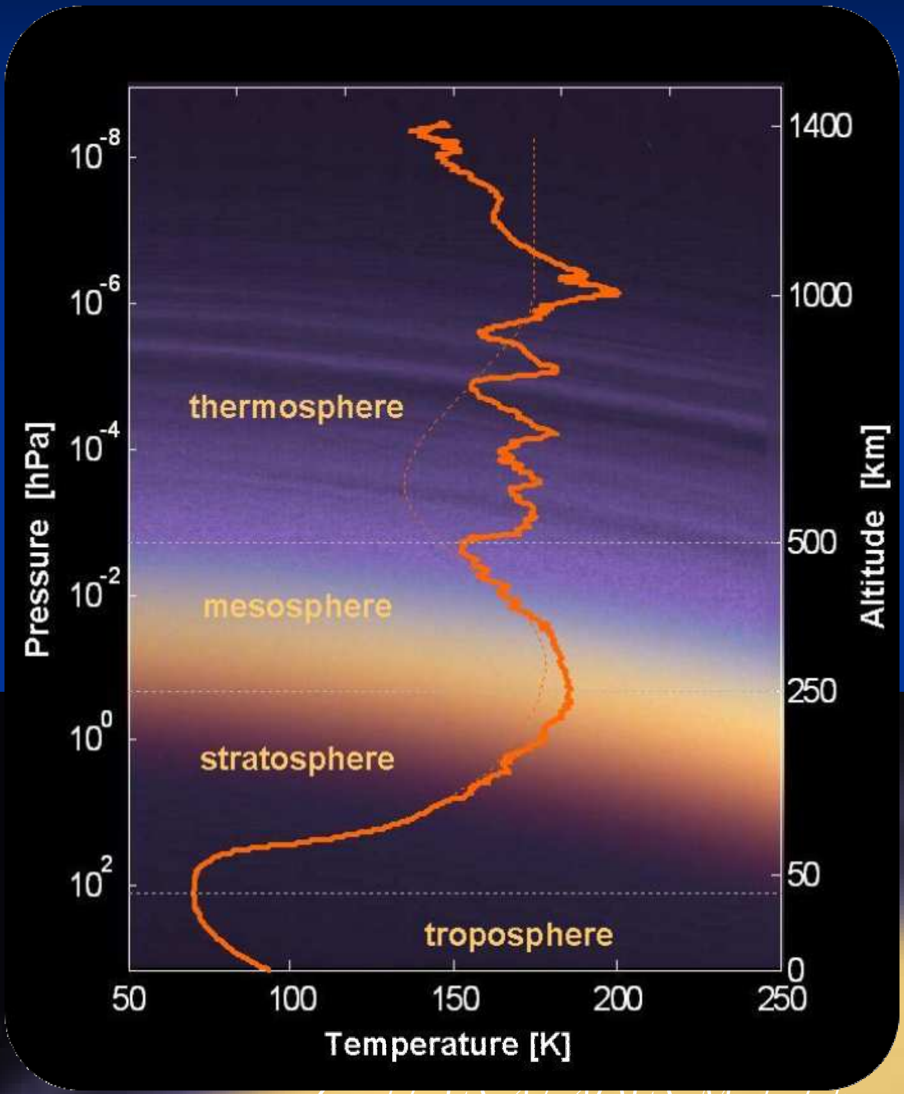
Atmospheric Gases of Titan:

APEX observations

Based of the ESO project E-081.F-9812A-2008

Example 2

Temperature profile



Credits:ESA/AOES Medialab

1655 Christiaan Huygens discovered *Mimas*
1847 John Herschel suggested the name of Titan (sisters and brothers of *Cronos*, the Greek Saturn.)

The atmosphere of Titan can be vertically split into four different dynamical regions :

(1) the ***troposphere***: below 45 km
(2) the ***stratosphere***, between z=45 and 250 km
(3) the ***mesosphere***, between z=250 and 500 km
(4) the ***thermosphere***, above z = 500 km

Example 2

Why Titan?

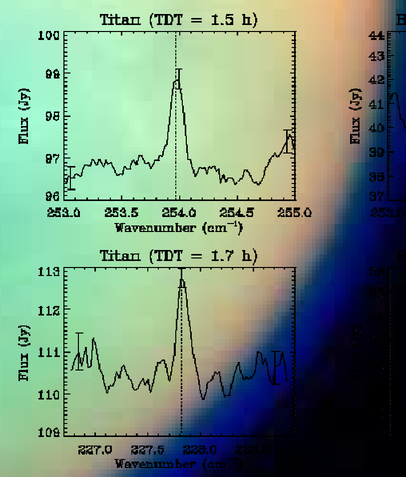
- The origin of Titan‘s atmosphere is poorly understood and its chemistry is complicated:

* CH_4 is the second most abundant specie detected

*HCN is the most abundant nitrile on Titan

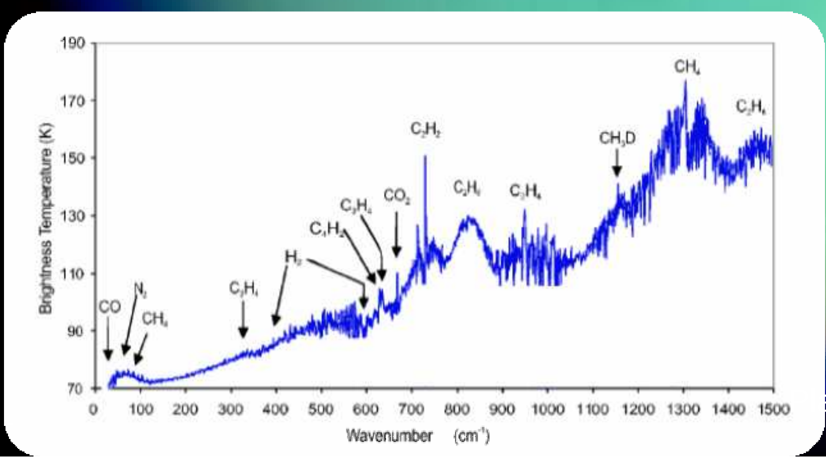
*CO origin is not well understood

Water, CO, nitriles, and hydrocarbons have been detected by spacecrafts and from Earth.



Titan observations with SWS/Grating of two water lines at 43.9 and 39.4 μm respectively, along with the off-source spectra.

Coustenis et al. A&A. 336, L85-L89 (1998)



Coustenis et al .

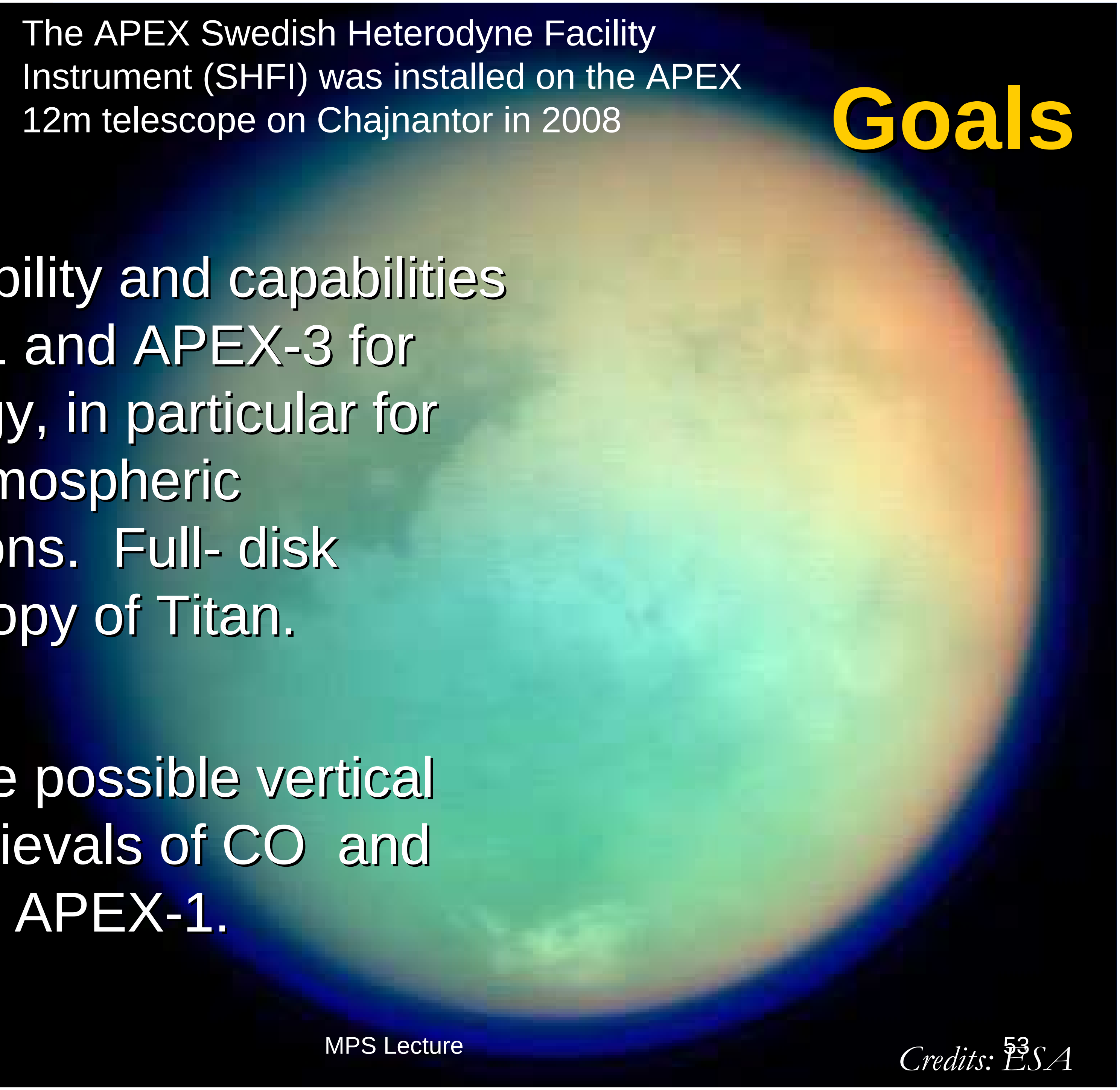
Example 2

The APEX Swedish Heterodyne Facility Instrument (SHFI) was installed on the APEX 12m telescope on Chajnantor in 2008

Goals

- Test feasibility and capabilities of APEX-1 and APEX-3 for planetology, in particular for Titan´s atmospheric observations. Full- disk spectroscopy of Titan.

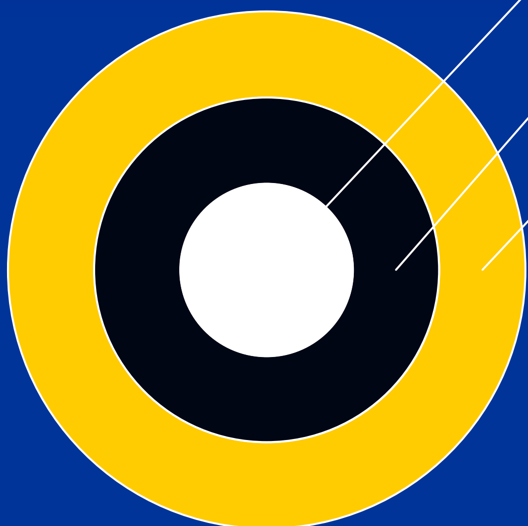
- Investigate possible vertical profile retrievals of CO and HCN with APEX-1.



Credits: ESA

Example 2

How? Ingredients



Observations

Deriving information from the spectra

Forward model – Inversion Algorithm

To model the expected observed emission spectra

To retrieval physical parameters as the mixing ratio

Example 2

Spectral Line Observations of Titan

Proposed lines: **Time allocated: 11.5 hrs**

(8.2 hrs observed - 2.5 hrs in very bad weather)

12-m APEX Telescope (Chile)

APEX-1:

Specie	*Frequency*	*Integration Time*
HCN (3-2) ✓	265.886 GHz	60 min (PWV 2 mm, rms 0.04 K, FFTS 16384)
$HC^{15}N$ (3-2) ✓	258.156 GHz	39 min (PWV 2 mm, rms 0.04 K, FFTS 16384)
CO (2-1) ✓	230.538 GHz	36 min (PWV 2 mm, rms 0.033 K, FFTS 16384)
[redacted]	[redacted]	56 min (PWV 2 mm, rms 0.025 K, FFTS 16384)
		1.4 h (PWV 2 mm, rms 0.025 K, FFTS 16384)

APEX-3

$HC^{15}N$ (5-4) X	430.235 GHz	2 h (PWV 0.5 mm, rms 0.08 K, FFTS 16384)
CO (4-3) X	461.040 GHz	1.9 h (PWV 0.5 mm, rms 0.09 K, FFTS 16384)
[redacted] X	4[redacted]z	1.6 h (PWV 0.5 mm, rms 0.055 K, FFTS 16384)

Between 21.3.08 and 27.6.08

Instrumentation used:

SHFI **Receivers**: APEX-1 [211-270] GHz

Backends:

FFTS1 (up to 122 kHz, Bandwidth 1 GHz)

Mode: Position switching

Results:

-Improvement of the control software. After this project it was possible to properly point and track data on a moving target.

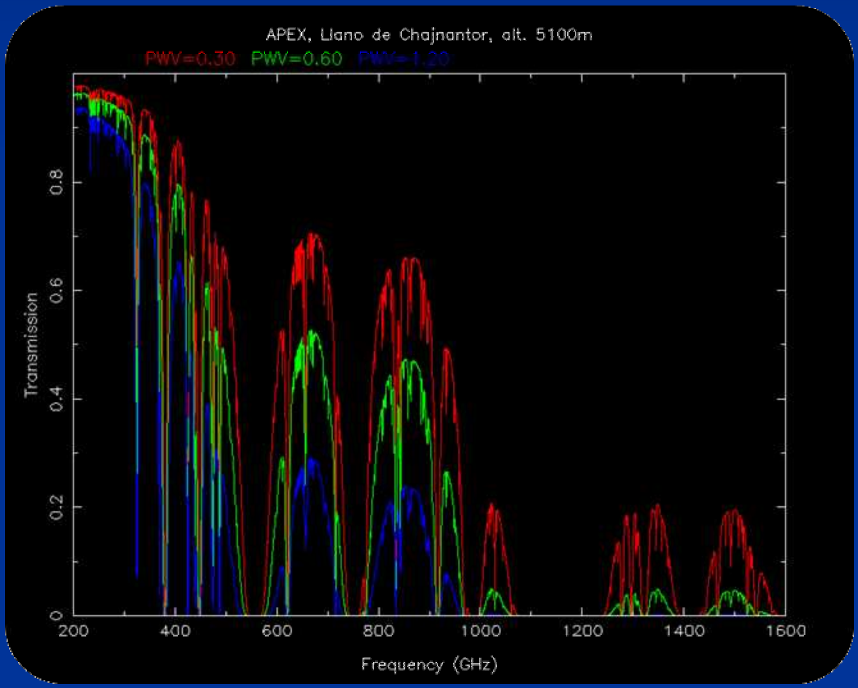
- spectral line observations of Titan with the lines

CO J=2-1 - 13 min

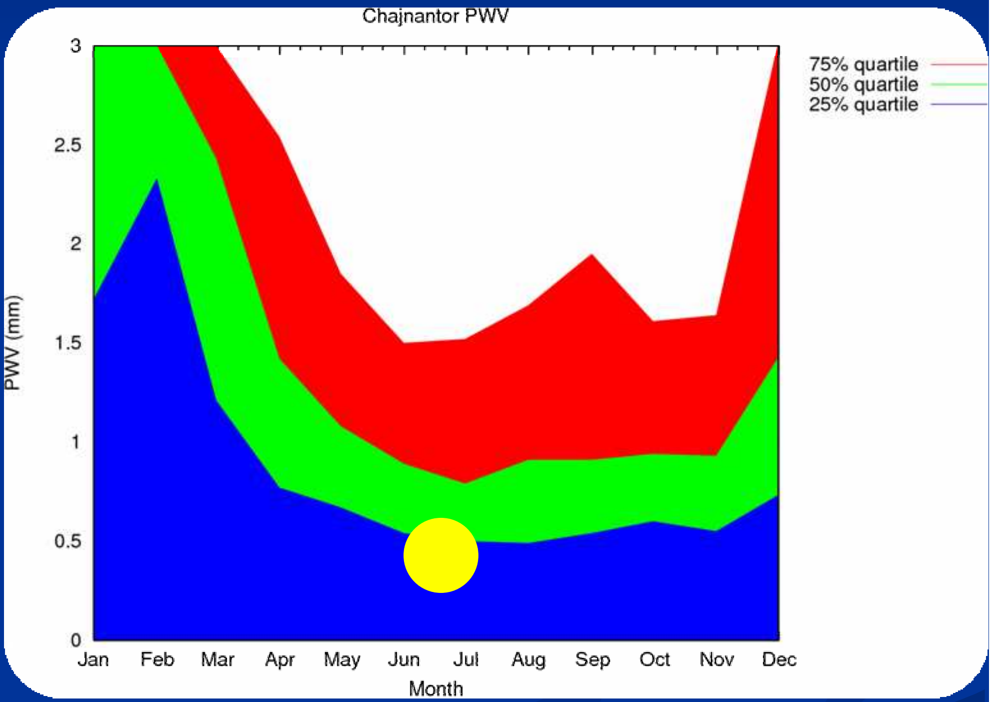
HCN J=3-2 - 19 min

The atmosphere above Llano de Chajnantor during these observations

Atmospheric window at Chajnantor



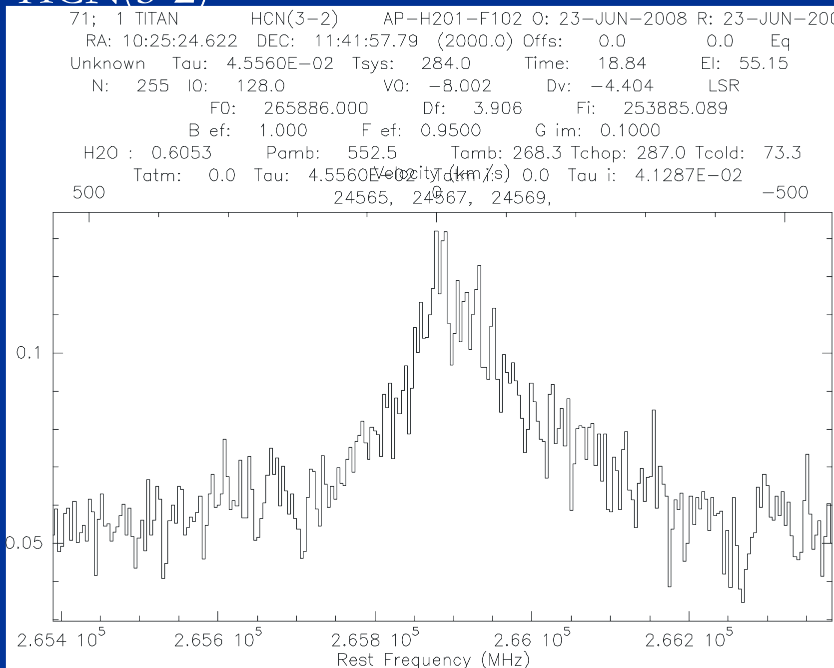
Annual variation of PWV at Chajnantor



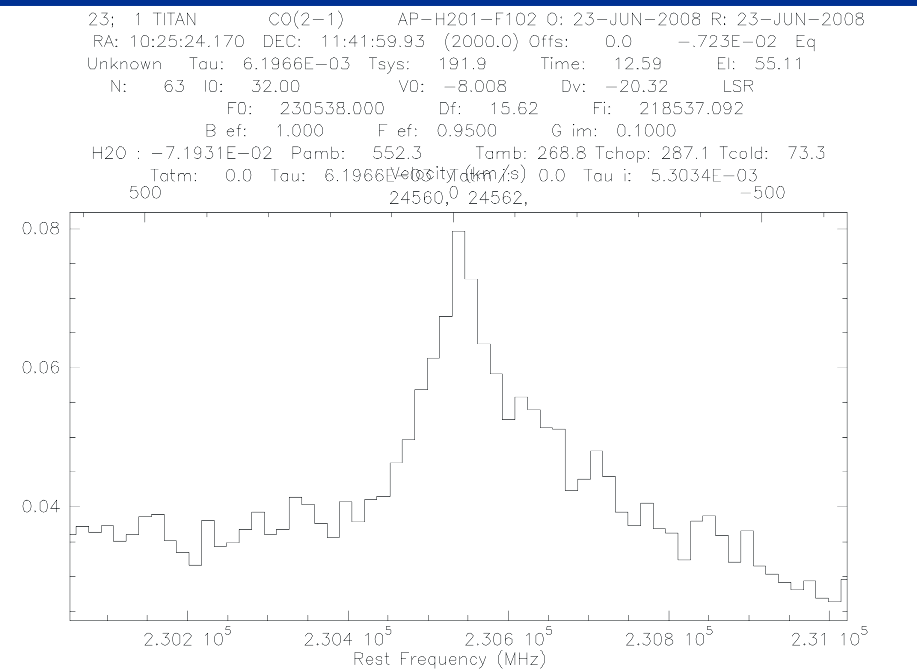
APEX-1

Results: Titan´s spectra

HCN(3-2)



CO(2-1)



Smooth 5

Smooth 7

First observations of a planet/satellite with APEX-1

But not optimal for retrievals of vertical distributions… However

S/N = 5

Example 2

III.- Modeling procedure

3rd step:

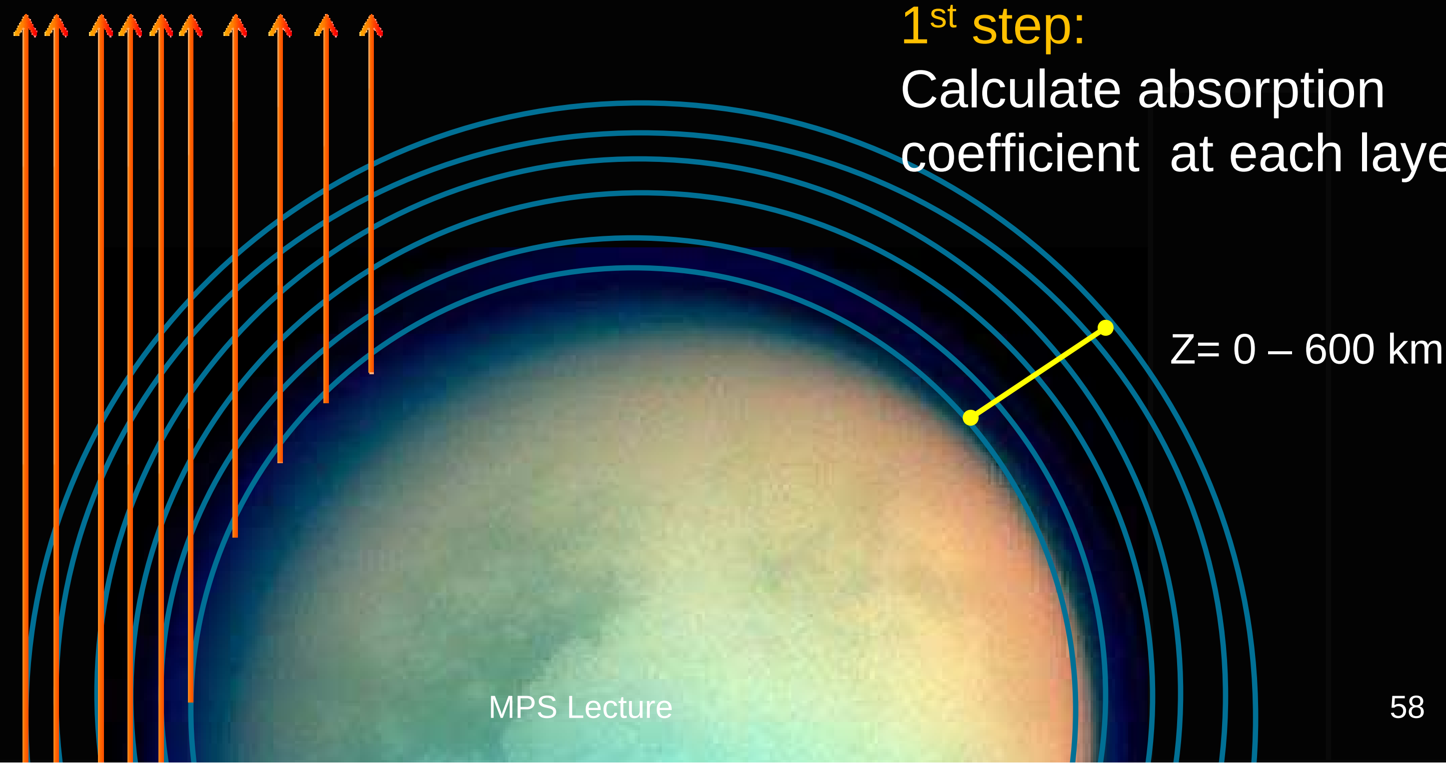
Integrate and convolve with the antenna pattern

2nd step:

Calculate RT along each ray path

1st step:

Calculate absorption coefficient at each layer



Example 2

Adopted Titan's thermal and pressure profiles for the opacity calculations

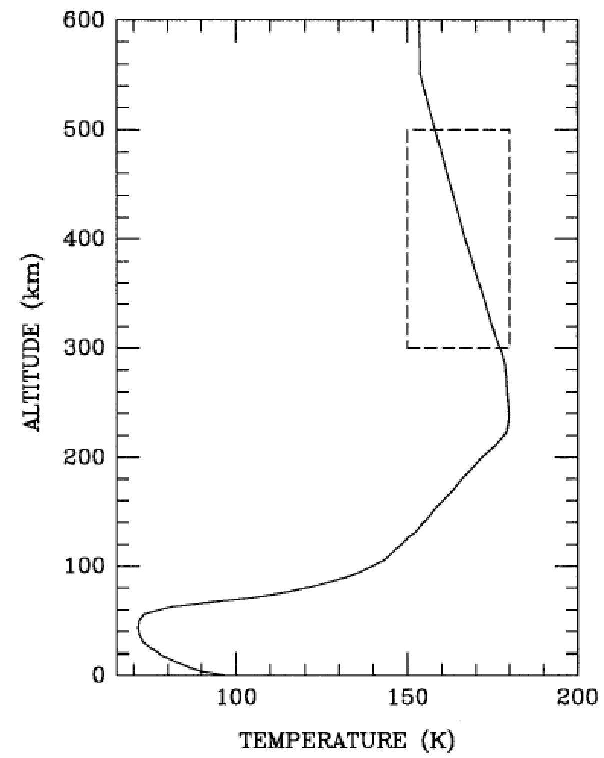
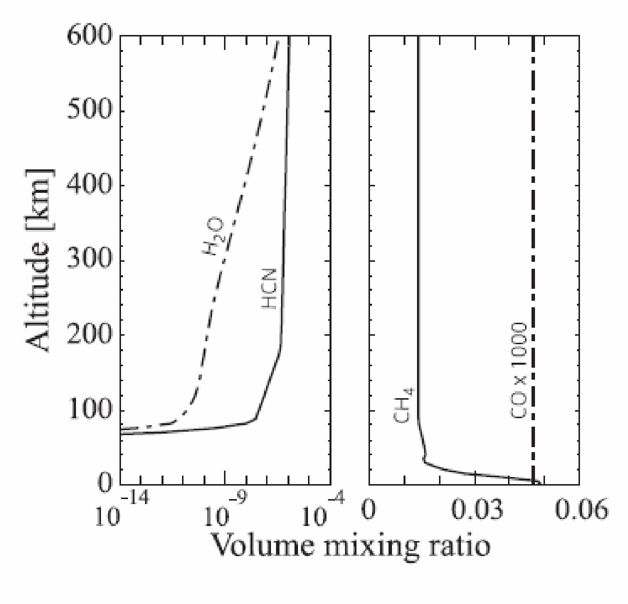


FIG. 2. Titan's temperature profile adopted from Coustenis and Bézard (1995). The upper part (above 300 km) is from Yelle (1991). This profile is used as a "nominal" model to simulate the observed spectra.

Hidayat et al. 1998

Profile based on *Coustenis and B´ezard 1995 & Yelle et al. 1991.*

Atmospheric composition based on



Marten et al. 2002 *Kok et al. 2007*

Also used by:
Gurwell 1995, 2000 CO
Marten et al. 2002 HCN

The resulting spectra allow the retrieval of stratospheric CO and HCN profiles

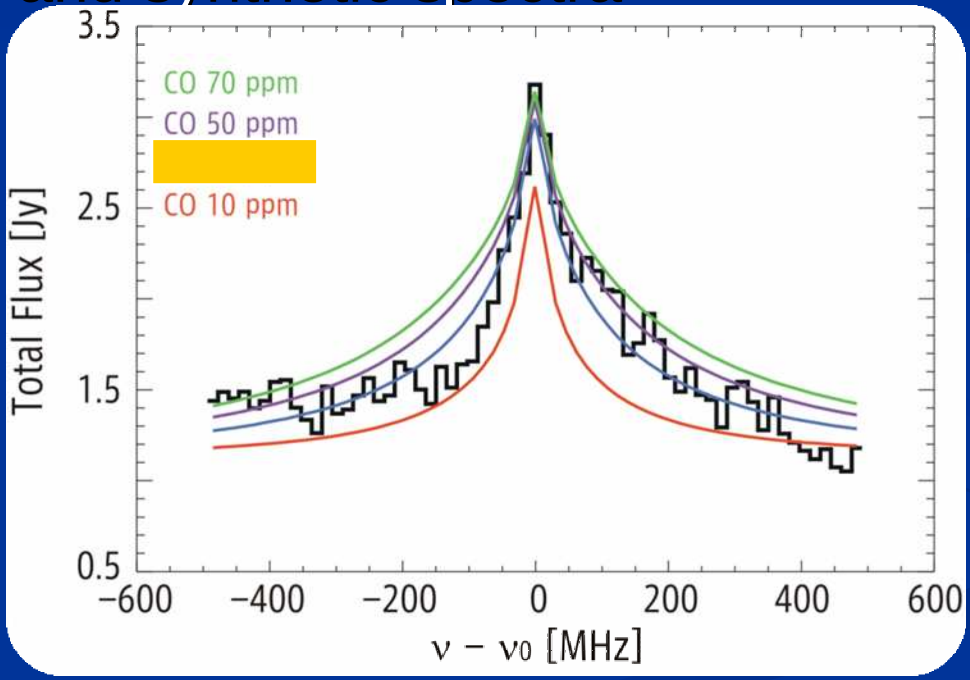
Example 2

IV.- Results

We investigate the possibility to retrieve the mixing ratio profiles of CO and HCN

- Mixing ratio of CO (2-1)

assuming that CO is constant with altitude, we just compare observational and synthetic spectra



With 15 MHz spectral resolution: spectrally resolve the absorption line

Example 2

Table 2. CO mixing ratios

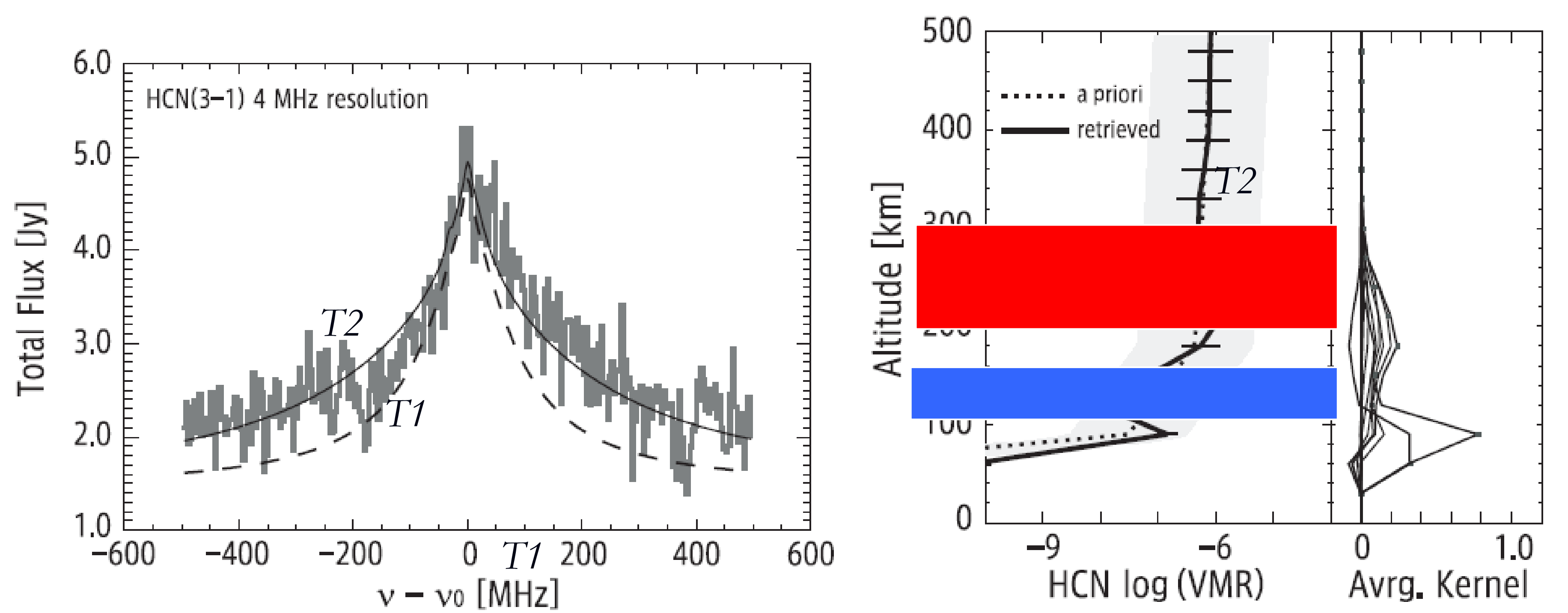
Altitude [km]	Mixing ratio (ppm)	Wavelength	Facility	Reference
Stratosphere	30–180	115.27 GHz	Modeling	30
Stratosphere	60±40	2.6 mm	Owens Valley/2 elements interferometers	1
Troposphere	48^{+100}_{-32}	1.57 μm	Kitt Peak/Fourier transform interferometer	31
Stratosphere	2^{+2}_{-1}	2.6 mm	IRAM-30m/3-mm SIS receiver	32
Stratosphere	50±10	2.6 mm	Owens Valley/6 10.4 m diam. antennas	33
Troposphere	10^{+10}_{-5}	4.8 mm	UK IR Telescope/CGS4 spectrograph	34
Stratosphere	52±6	1.3 mm	Owens Valley/antennas	35
Stratosphere	51±4	345 GHz	SMA/5 and 6 antennas	17
153–350	60	4.50-4.85 μm	VLT/ISAAC	36
Tropo-Stratosphere	45±15	4.64 μm	Cassini/CIRS	37
Stratosphere	47±8	30–60 cm^{-1}	Cassini/CIRS	38

Rengel, Sagawa, Hartogh, submitted to AdGeo

Example 2

■ Mixing ratio profile of HCN

-Try to retrieve the HCN vertical profile with the nominal T1 profile → no fits
- Try to retrieve the HCN vertical profile with T2



Rengel, Sagawa, Hartogh, submitted to AdGeo

Simulated observations and fitted spectra, HCN distributions for the simulated observations

Example 2

Poor S/N here
Comparing these results must be considered cautiously…

Table 3. HCN mixing ratios

Altitude [km]	Mixing ratio	Wavelength	Facility	Reference
Stratosphere	3.0×10^{-7}	88.6 GHz	IRAM-30m/SIS receiver	2
Stratosphere	1.6×10^{-7}	$713\,cm^{-1}$	Voyager/IRIS	40
Stratosphere	$(0.75–52)\times 10^{-7}$	88.6	IRAM 30-m/SIS receiver	41
Stratosphere	$4.7\times 10^{-8}–1.5 \times 10^{-6}$	$713\ cm^{-1}$	Voyager/IRIS	18
Stratosphere	$(0.5–4) \times 10^{-7}$	88.6 GHz	IRAM 30-m/SIS receiver	42
Stratosphere	3.0×10^{-7}	$713\,cm^{-1}$	ISO/SWS	43
83	3×10^{-5}	177.26 GHz	SMA/5 and 6 antennas	17
300	0.4×10^{-5}	177.26 GHz	SMA/5 and 6 antennas	17
400	$\sim 2 \times 10^{-5}$		Model prediction	44
400	10^{-6}		Model prediction	45
400	10^{-6}	88.6 GHz	IRAM-30m/SIS receiver	39
400	10^{-5}		Model prediction	46
500	10^{-6}	$712.25\,cm^{-1}$	Cassini/CIRS	47
$\sim$600	7×10^{-3}	3 μm	Keck II/NIRSPEC	46
700	10^{-5}		Model prediction	45
700	10^{-4}		Model prediction	46

Rengel, Sagawa, Hartogh, submitted to AdGeo

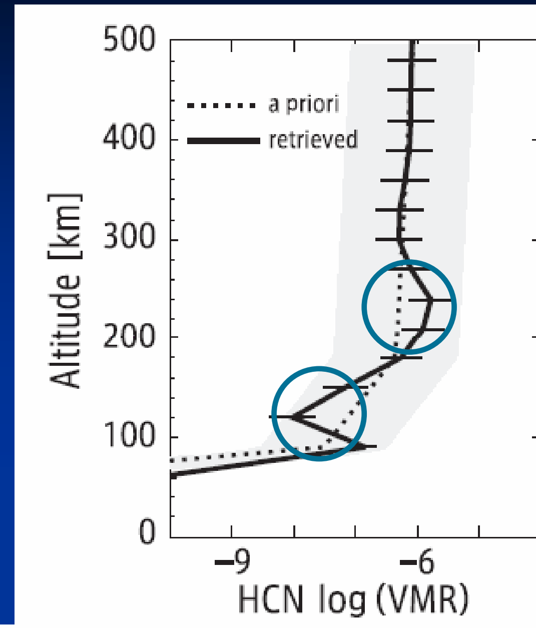
▪ HCN

Although still in progress, the retrieved HCN mixing ratio suggests higher HCN abundances than Marten's result, in particularly at altitude of 200-300 km km.

Vertical profiles set up by photochemistry and condensation can be modified by atmospheric dynamics.

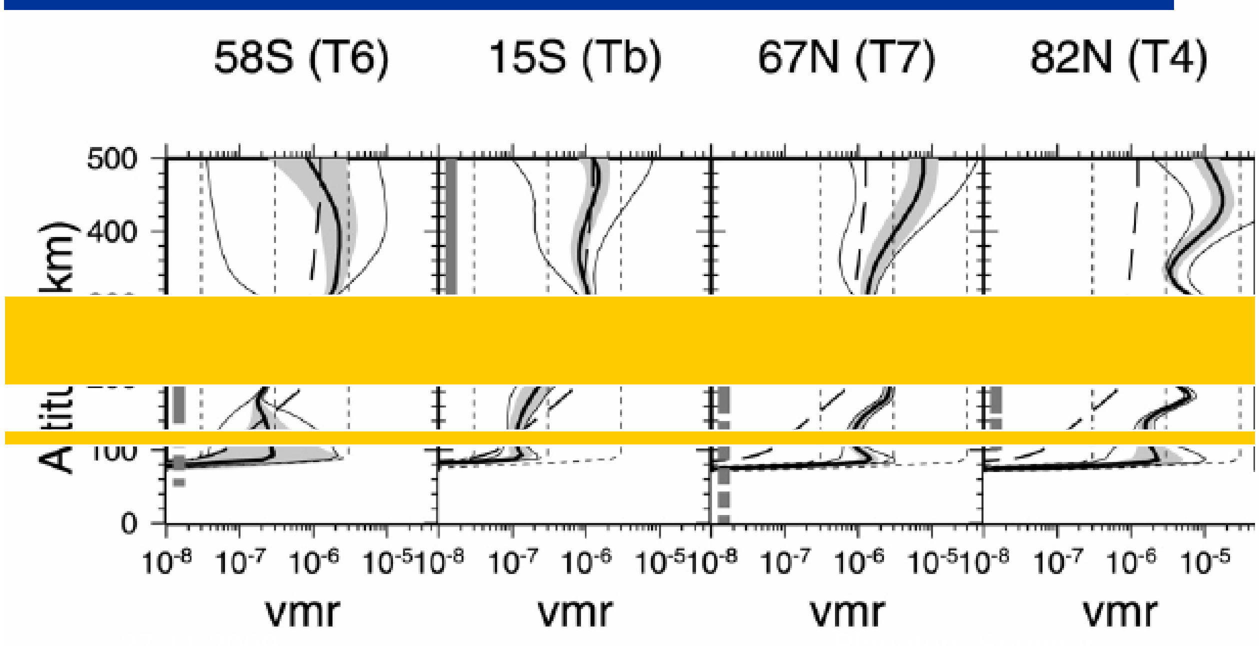
HCN profiles retrieved from CIRS data:

- HCN is enriched in the north compared to the south

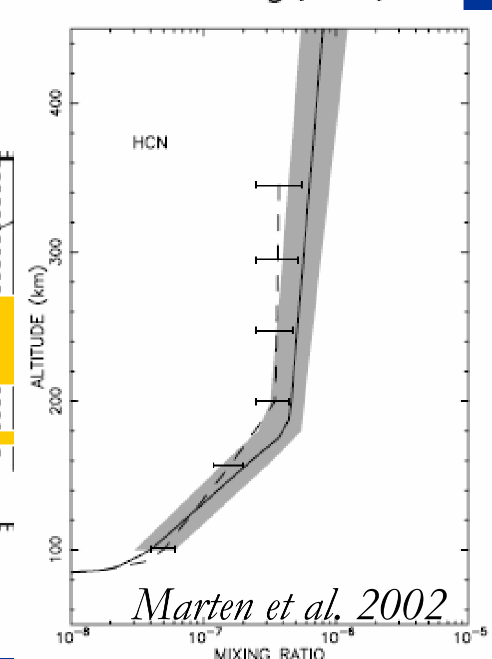


3.2 times

5 times



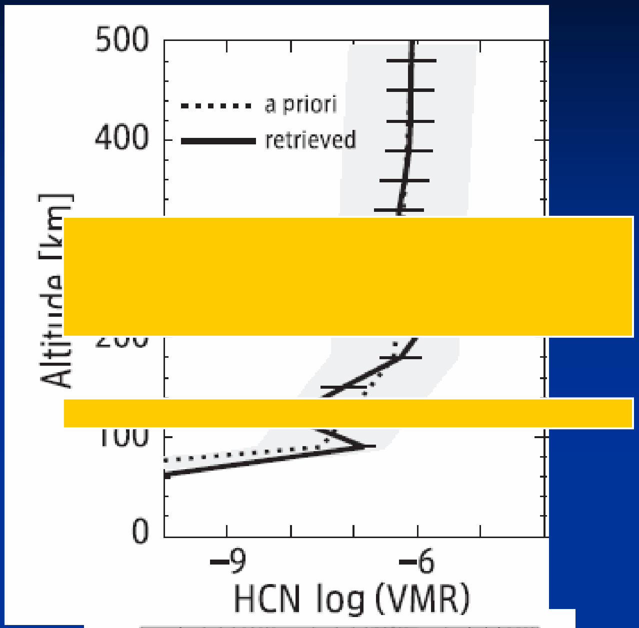
Teanby et al. 2006



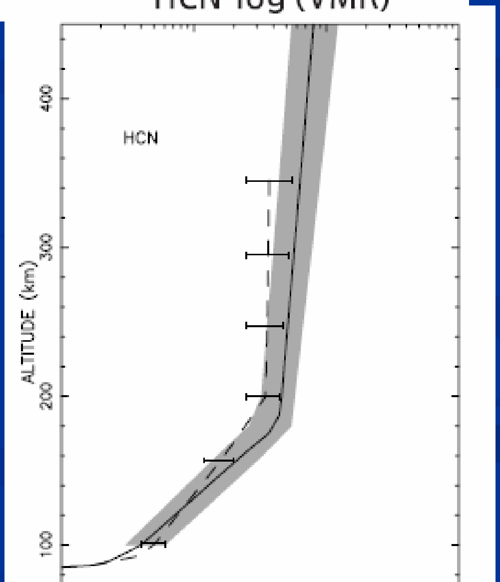
Marten et al. 2002

■ HCN Although still in progress, the retrieved HCN mixing ratio suggests higher HCN abundances than Marten's result, in particularly at altitude of 200-300 km.

Maybe this layer is an enriched HCN layer



Enriched air from the north pole becomes entrained in a Hadley type circulation cell and is advected to lower latitudes



Marten et al. 2002

Example 2

V.- Conclusion 2d Example

- We report the first observations obtained with the APEX-1 instrument on a planetary/satellite atmosphere taken during SV : CO(2-1) and HCN(3-2) on Titan.
- These observations improved the control software of the APEX telescope, now it is possible to track planets
- We investigate the CO and HCN composition of Titan's stratosphere. Our CO mixing ratio aproximation is consistent with some other authors. HCN profiles require further investigation.
- Nitriles and CO appears very favorable in the submillimeter range explored with the APEX telescope

VI.- Work to do

- 1.3 THz Observations at the APEX Telescope

This receiver covers a frequency band that won't be observed with the HIFI instrument of Herschel, and therefore both instruments could benefit from each other. The HIFI band 5 currently reaches 1271 GHz, therefore at least the **CO(11-10)** and **CS(26-25)** are observable with both receivers, which is very important for cross calibration purposes.

Increase pointing measurements

- only initial relative offsets were found between the different bands within SHFI.

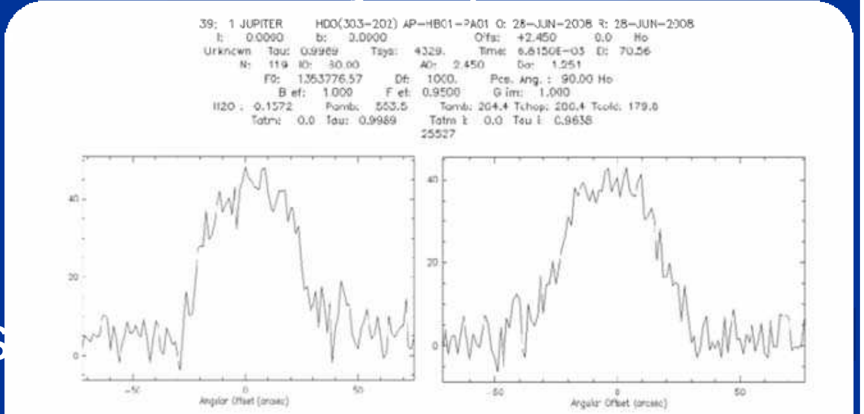


Fig. 15. Jupiter pointing in elevation (left) and azimuth (right).

Risacher et al. 2009

Example 3

3rd Example

Atmospheric Gases of Titan Predictions from Herschel

Credits:ESA/AOES Medialab

Example 3

II.- Herschel-based observations/simulations

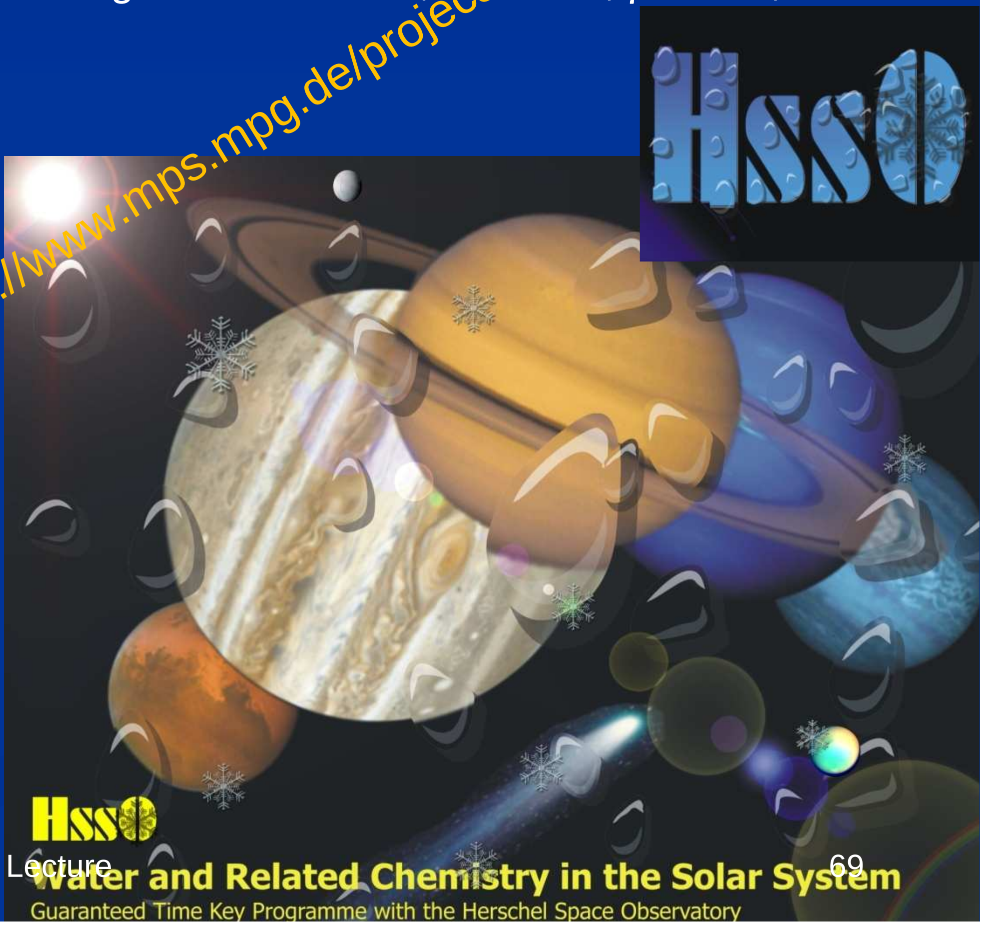
Herschel Space Observatory will observe the „cool universe"

Credits:ESA/AOES Medialab

Key Programme with guaranteed time:

"Water and Related Chemistry in the Solar System"
P.I.: Paul Hartogh (MPS Lindau)
Hartogh et al. *PSS 57, Issue 13, p. 1596, 2009.*

p://www.mps.mpg.de/projects/Herschel/HssO/index.html



The HssO Program will result in a comprehensive set of sensitive and well-calibrated spectra of water, its isotopologues, and chemically related species in Solar System objects: Mars, **Outer Planets, Titan and Enceladus**, comets .

Example 3

HssO Participants

- Marek Banaszkiewicz[1],
- Frank Bensch[2]
- Edwin A. Bergin[3]
- Francoise Billebaud[4]
- Nicolas Biver[5]
- Geoffrey A. Blake[6]
- Maria I. Blecka[1]
- Joris Blommaert[20]
- Dominique Bockelée-Morvan[5]
- Thibault Cavalié, (Associate)
- José Cernicharo[7] (mission scientist)
- Régis Courtin[5]
- Jacques Crovisier[5]
- Gary Davis[8]
- Leen Decin[20]
- Pierre Encrenaz[9] (mission scientist)
- Thérese Encrenaz[5]
- Trevor Fulton
- Thijs de Graauw[10] (ex HIFI-PI)
- Armando Gonzalez (Affiliate)
- Paul Hartogh[11] (PI, coordinator)
- Damien Hutsemékers[12]
- Christopher Jarchow[11] (CoI)
- Emmanuël Jehin[12]
- Mark Kidger[22]
- Michael Küppers
- Arno de Lange
- Luisa-Maria Lara[13]

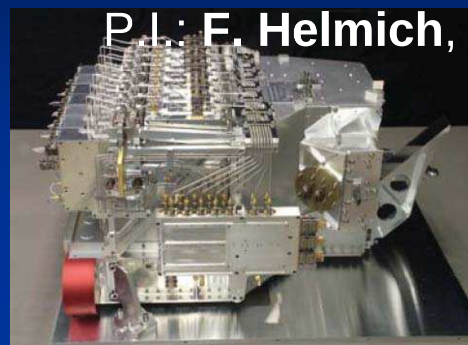
- Sarah Leeks
- Emmanuel Lellouch[5]
- Dariusz C. Lis[6]
- Rosario Lorente22
- Jean Manfroid21
- Alexander S. Medvedev[11] (CoI)
- Raphael Moreno5
- David Naylor14
- Glenn Orton15
- Ganna Portyankina
- Miriam Rengel[11] (CoI, HIFI Calibration Scientist)
- Hideo Sagawa (Associate)
- Miguel Sánches-Portal22
- Rudolf Schieder16
- Sunil Sidher17
- Daphne Stam18
- Bruce Swinyard17
- Slawomira Szutowicz1
- Gillian Thornhill22
- Nicolas Thomas19
- Miguel de Val Borro (Associate)
- Bart Vandenbussche20
- Eva Verdugo22
- Christoffel Waelkens20
- Helen Walker17

Example 3

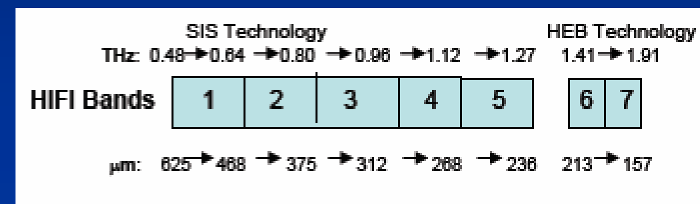
Planned Spectral Line Observations of Titan

Instruments onboard Herschel:

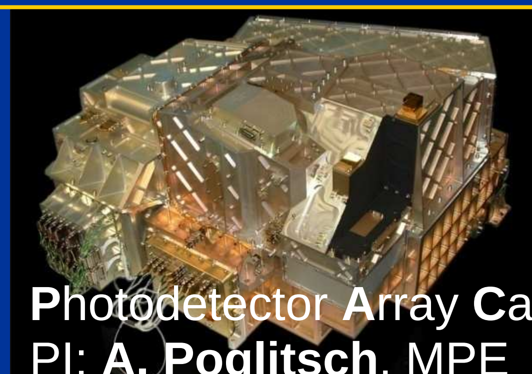
Heterodyne **I**nstrument for the **F**ar-**I**nfrared (**HIFI**).
P.I.: **F. Helmich**, SRON



Resolutions: 140, 280, 560 kHz, 1.1 MHz



480 – 1150 GHz 1410-1910 GHz



Photodetector **A**rray **C**amera and **S**pectrometer (**PACS**).
PI: **A. Poglitsch**, MPE
55 – 210 µm

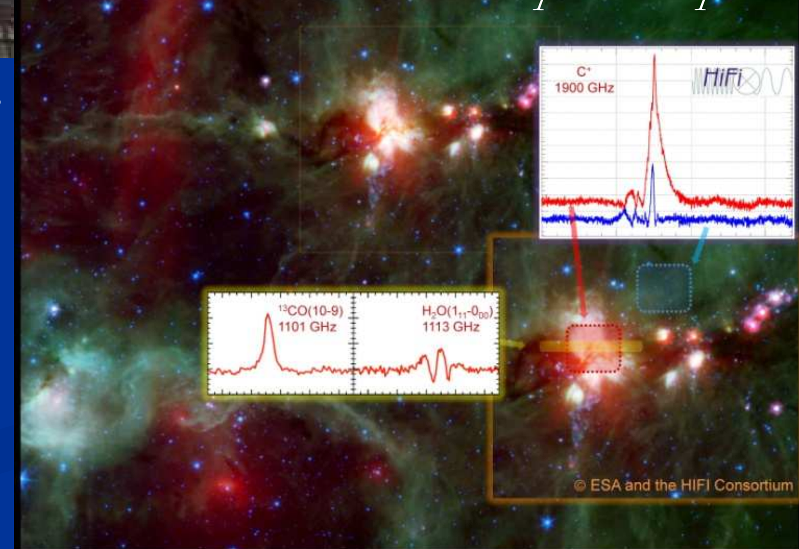
Spectral and **P**hotometric **I**maging **Re**ceiver (**SPIRE**).
PI: **M. Griffin**, Cardiff University
Photometer: 250, 350, 500 µm
Spectrometer: 194- 672 µm.

Example 3

Herschel and Planck launch: Fantastic launch, good performance, great ground segment.

Credits: ESA,

All three instruments started up without problems



HIFI: Perfect switch on, great performance. But the LCU event

Example 3

Table 8: Detailed list of outer planet observations

Target	Instr.	Line Freq. (GHz)	Resol. /Mode	Time (hour)	S/N [1]	Repetition	Total (hour)	Goal
Jupiter	HIFI	[redacted]						
	HIFI							
	HIFI							
	HIFI							
	PACS							
	PACS							
	PACS							
Saturn	HIFI							
	HIFI							
	HIFI							
	HIFI							
	PACS							
	PACS							
	PACS							
Titan	HIFI							
	SPIRE							
	PACS	Full range	Nyquist	3.450	100-300	No	3.450	Exploration+H_2O
	PACS	Full range	SED	0.912	50-150	3 times	2.736	Monitoring
	PACS	7 lines	Line scans	3.788	100	No	3.788	Vert. profile
	PACS	4512	Line scan	0.147	50	3 times	0.440	H_2O variab.
	PACS	[redacted]						
Enceladus	PACS							
Uranus	HIFI							
	SPIRE							
	PACS							
	PACS							
	PACS							
	PACS							
	PACS							
	PACS							
Neptune	HIFI							
	SPIRE							
	PACS							
	PACS							
	PACS							
	PACS							
	PACS							
	PACS							

[1] Per resolution element for HIFI; per line for PACS line scan; on the continuum for SPIRE and PACS full range spectra

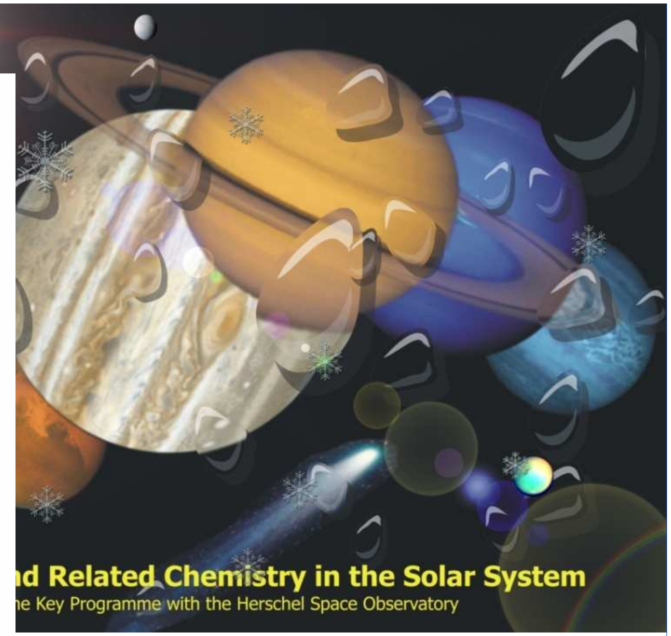


Table 9: Observation times (sec) for H_2O line spectral scans with PACS

Line (GHz)	Uranus	Neptune	Titan
4600	2250	2250	4100
4512	250	250	500
4469	450	450	800
3977	350	350	650
3654	1100	1100	2000
2774	290	290	550
2392	2040	2040	3800
Total	2h	2h	3.5 h

Investigate possible vertical profile retrievals of H_2O, HCN, and CO with HIFI and PACS for the expected signal-to-noise ratios.

Example 3

III.- Modeling procedure

3rd step:

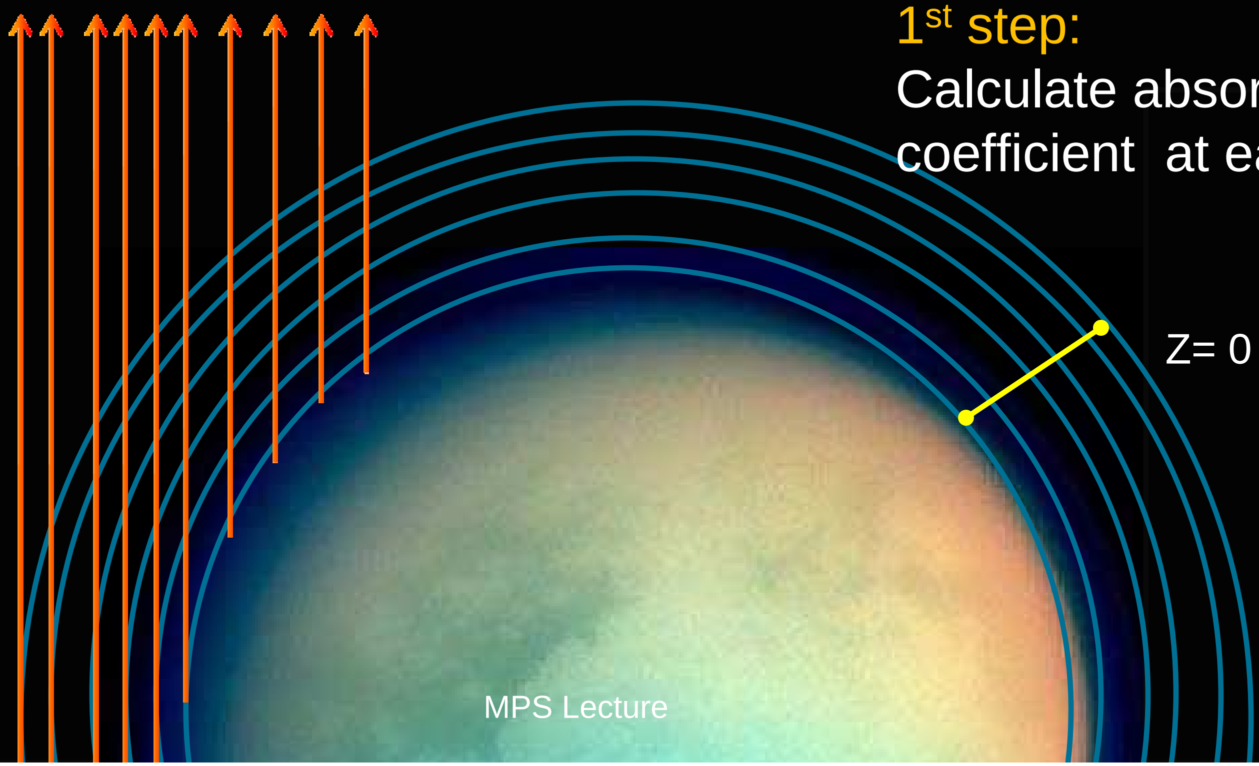
Integrate and convolve with the antenna pattern

2nd step:

Calculate RT along each ray path

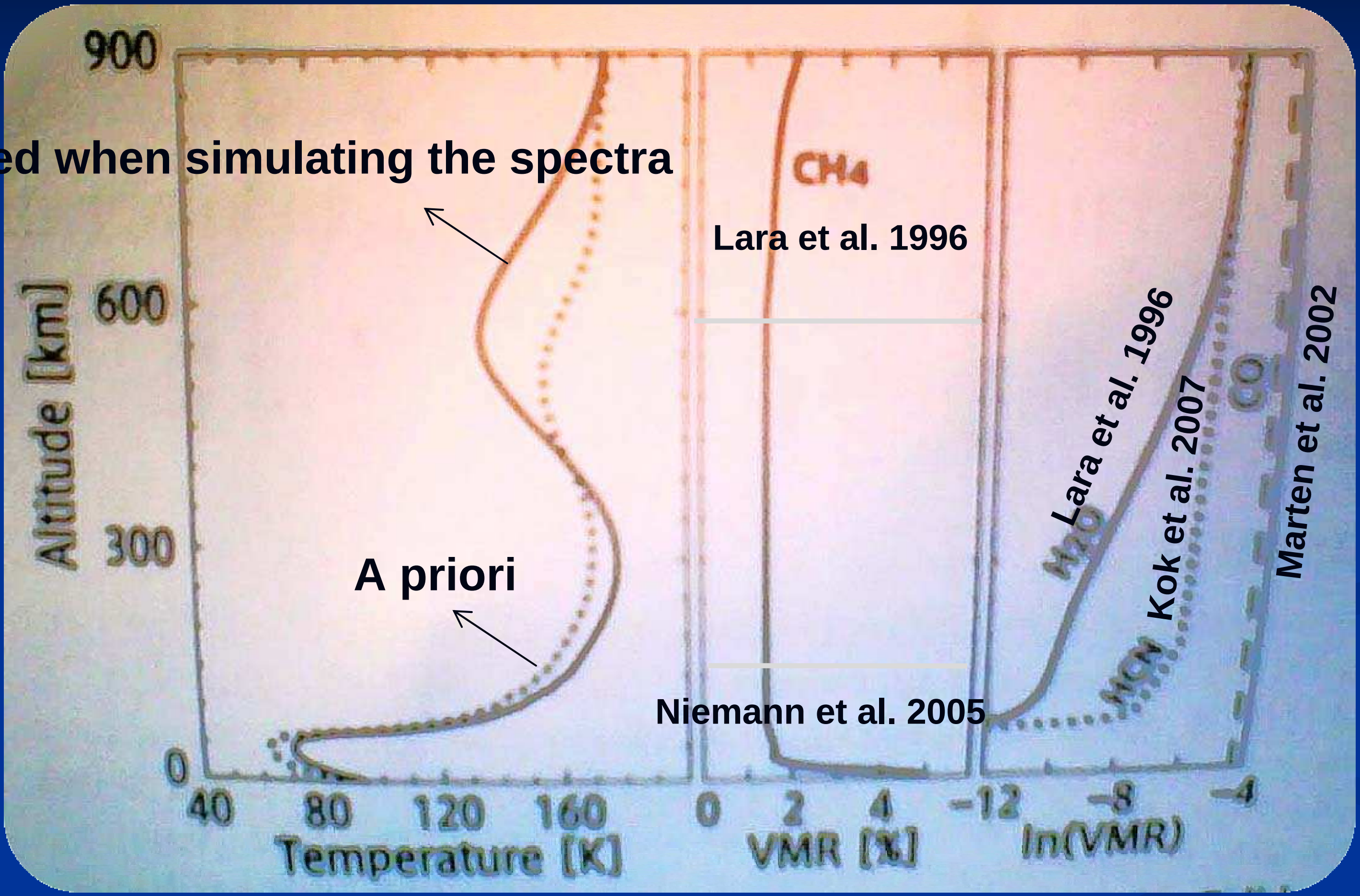
1st step:

Calculate absorption coefficient at each layer



Example 3

Adopted Titan's thermal and pressure profiles for the opacity calculations



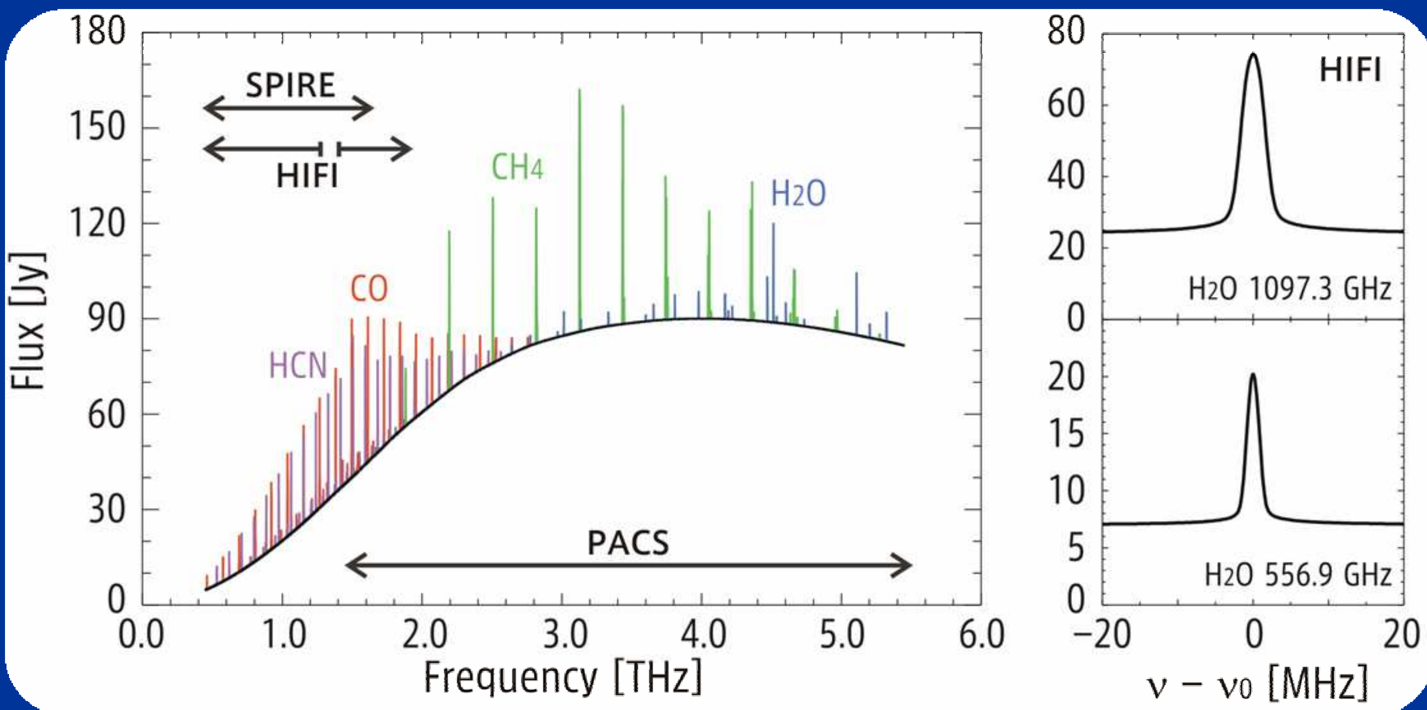
Example 3

IV.- Results

- Synthetic spectra of the Herschel Spectroscopic observations of Titan

- We show model calculations of the synthetic spectrum of Titan's atmosphere (CH4, H2O, HCN and CO) with the SPIRE (0.04 cm-1), PACS (1-4 GHz) and HIFI (1 MHz) spectral resolutions.

•

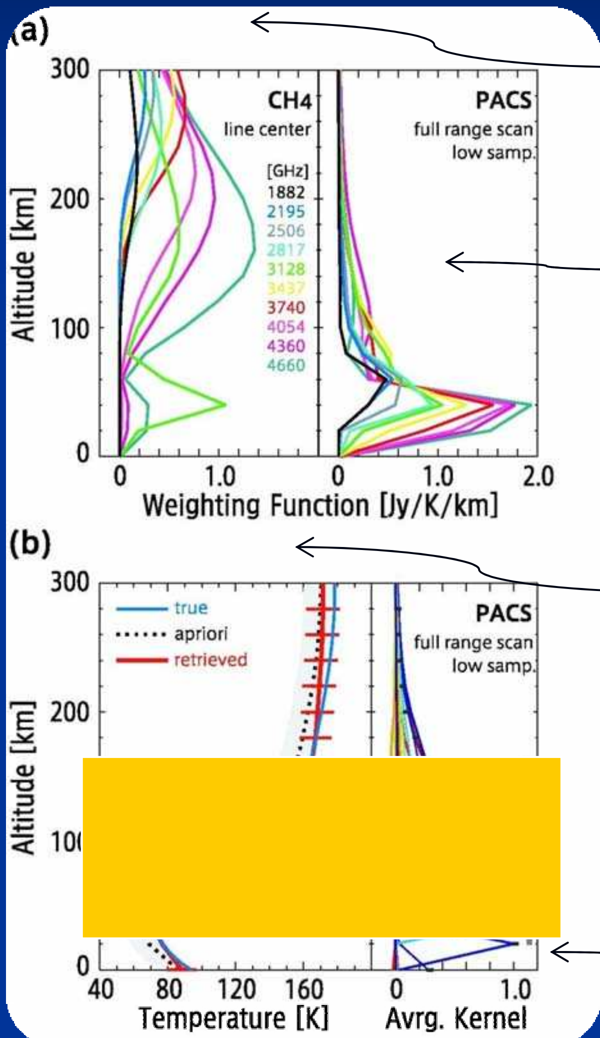


Expected Wat spectra observations with HIFI

Example 3

Results - PACS

We determine a temperature profile from the emission spectra of CH_4
We retrieve the mixing ratio profiles of the species



- Temperature profile

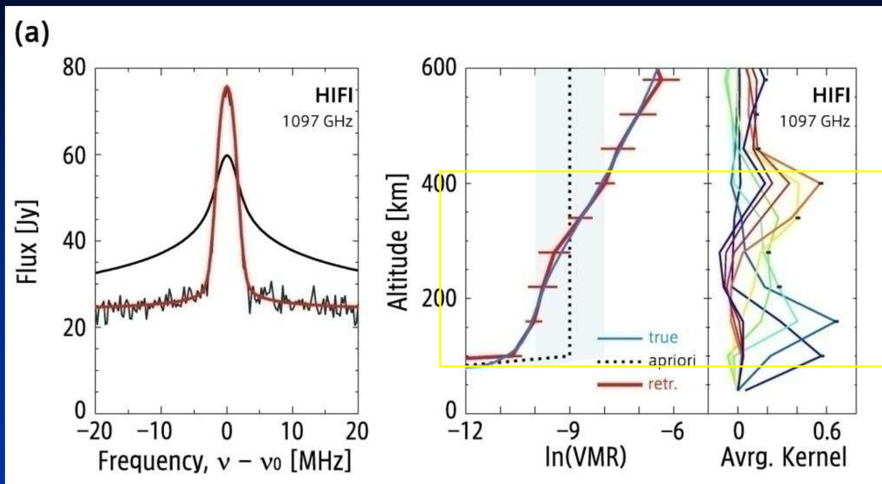
Temperature weighting functions for CH_4

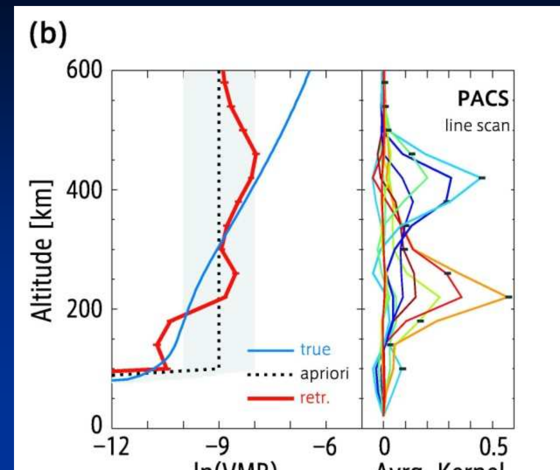
Results after considering PACS spectral resolution and range Scan mode.

Temperature retrieval from the PACS CH_4 range scan mode (S/N 100).
Blue : used to calculate the synthetic spectra
Red: retrieved profile

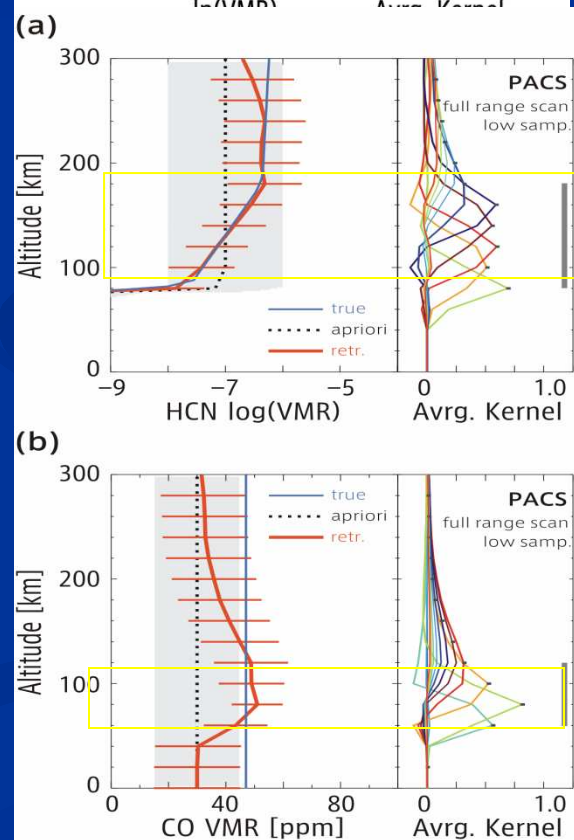
Averaging kernels of the retrieved temperature

Example 3: Retrieval simulations of water mixing rations





Line scan mode Combination of 10 lines



S/N=10

We investigate how PACS low sampling full range scan is sensitive to the HCN and CO distributions

H_2O, HCN, and CO mixing ratios

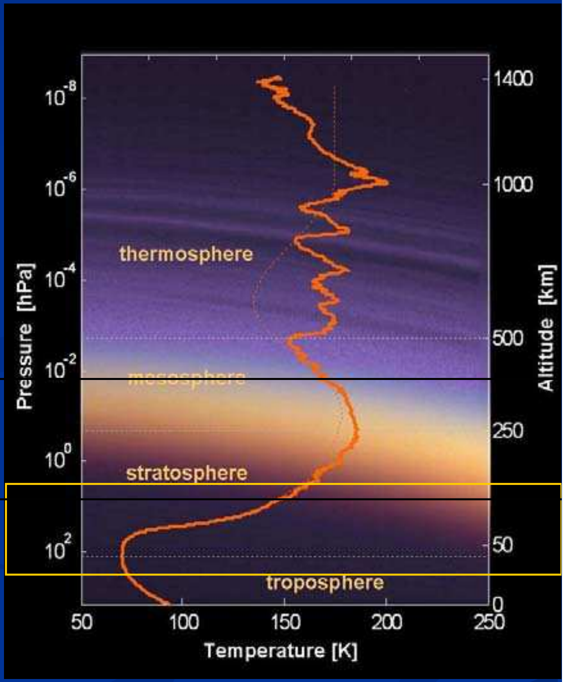
PACS mixing ratio retrievals require the use of multiple-line observations with different line opacities for each specie.

IV.- Conclusion 3rd Example

We have calculated the expected full range spectra of Titan´s with HIFI, PACS and SPIRE.
More than 10 CH4 rotational lines are expected to be detected by PACS, but it is not able to resolve the shape lines. → A combination of lines lets to retrieve the Titan´s atmospheric temperature at 20-140 km.

High spectral resolution spectra of water is expected to be observed with HIFI, which enable us to retrieve the water mixing ratio at the altitude range of 100-400 km.

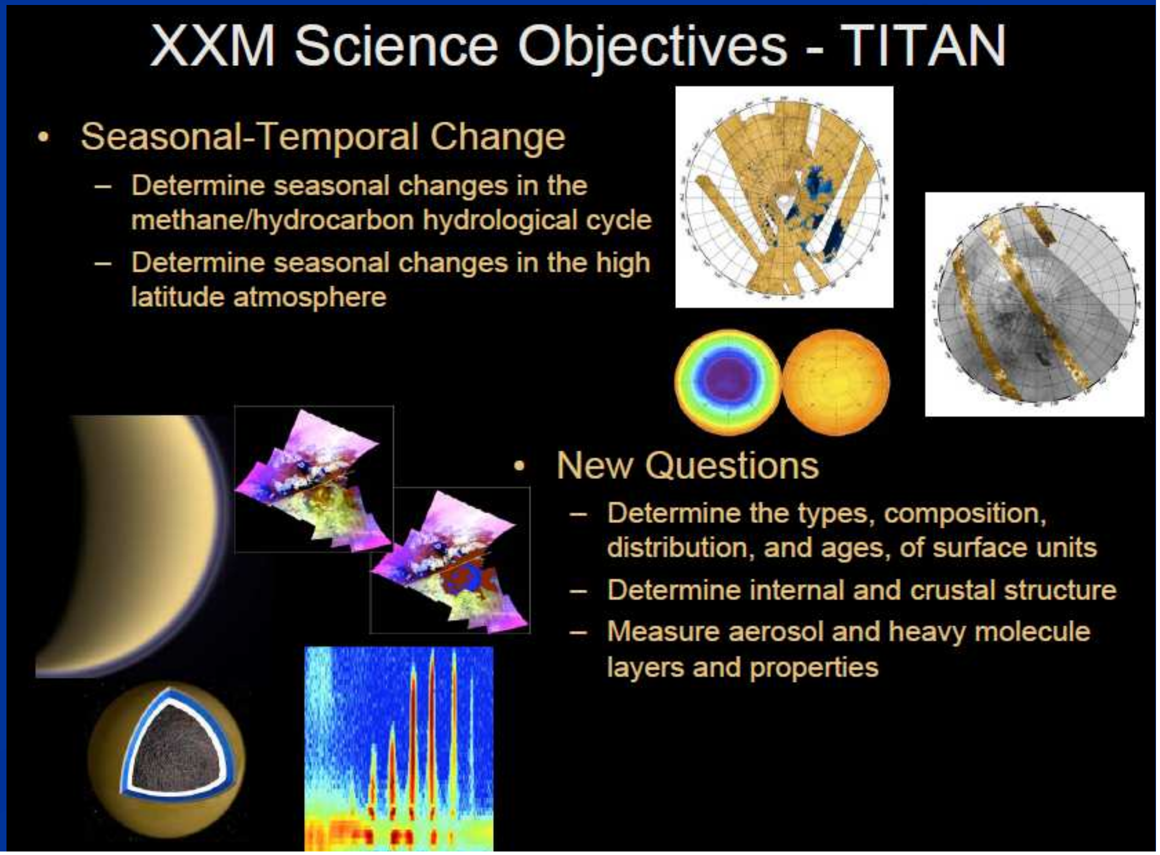
It is also expected that the line scan observations of multiple water lines with PACS will contribute to constraints the water abundances.



These results in preparation for Herschel show out technique to be a promising tool for the analysis of Titans´atmospheric data.

26 Titan flybys

Proposed Cassini-Huygens Solstice Mission (additional 7-year phase**)**



Future of planetary observations in the mm/submm

- **Atacama Large Millimeter Array Project (ALMA)**

0.3 mm – 9.6 mm

50 12m dishes

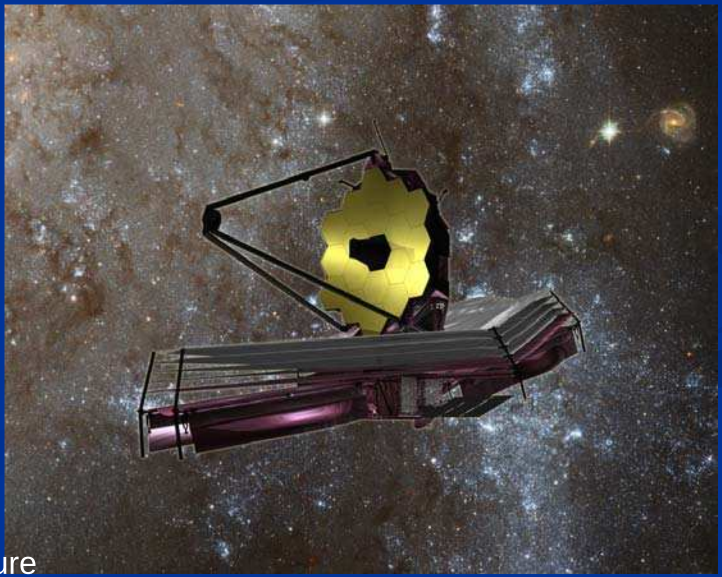
Ready in 2012

James Webb Space Telescope (JWST)

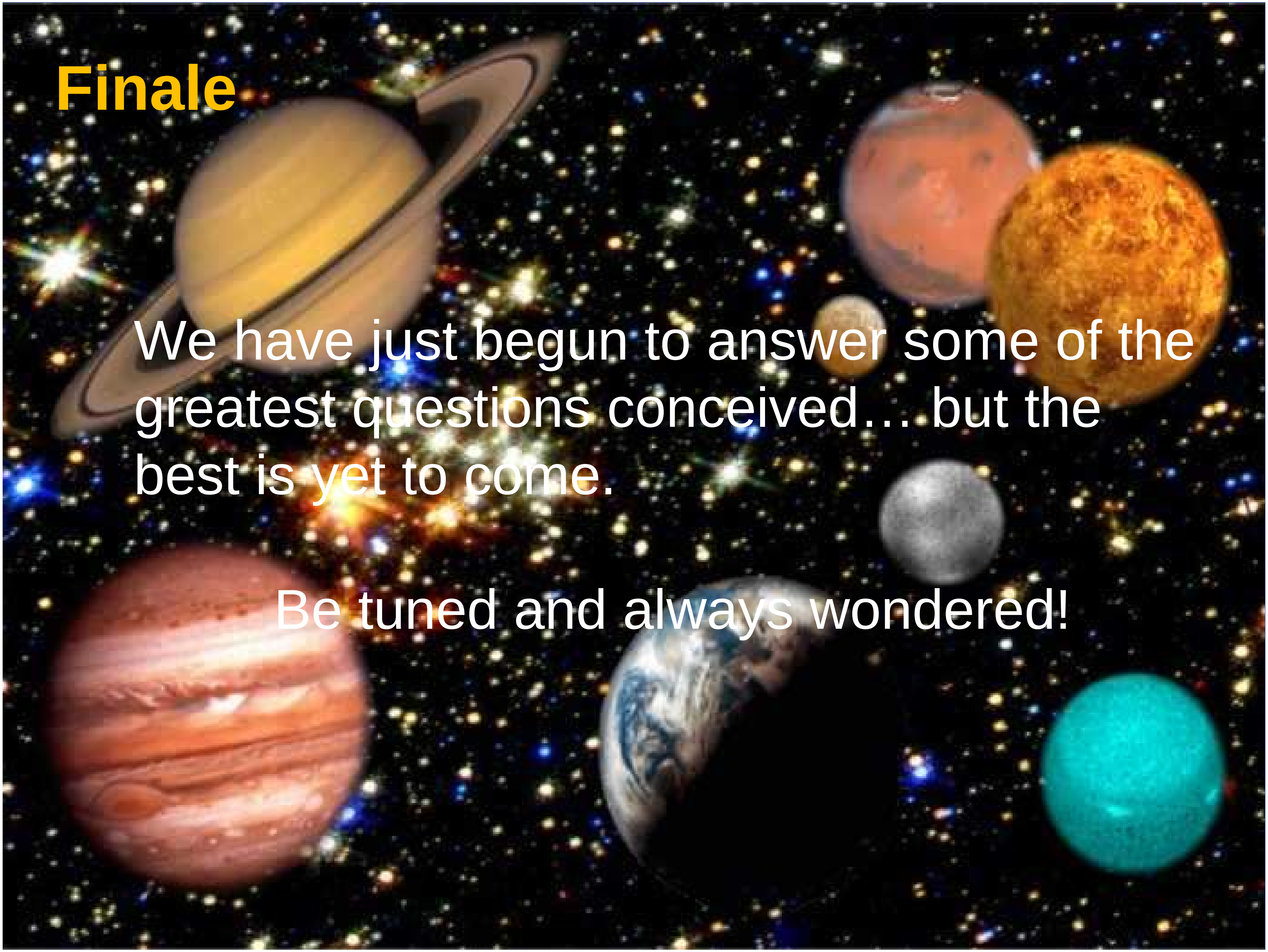
0.6 µm – 28 µm

Telescope 6.5m

Launch: 2013



Finale

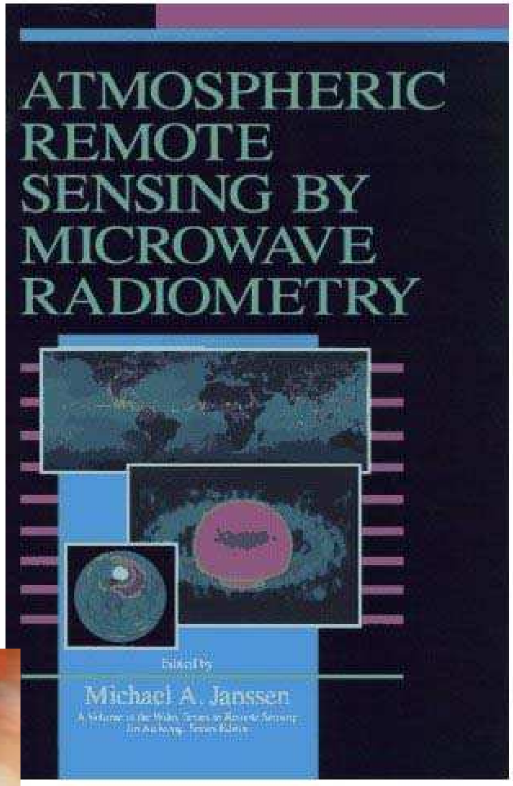


We have just begun to answer some of the greatest questions conceived… but the best is yet to come.

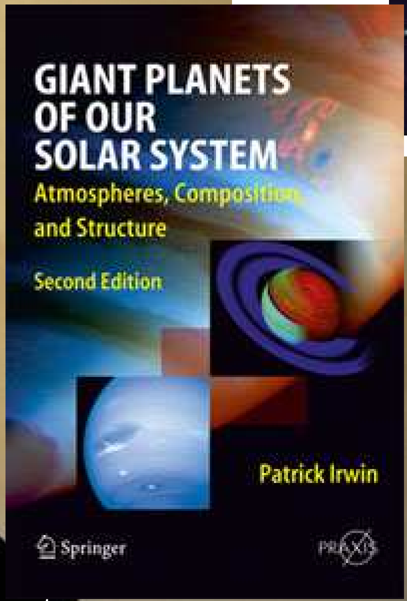
Be tuned and always wondered!

Where to consult?

Atmospheric Remote Sensing by Microwave Radiometry
Michael A. Janssen (Editor)



Giant Planets of Our Solar System: Atmospheres, Composition, and Structure
Patrick G.J. Irwin (Author)



Where to consult?

- Venus

M. Rengel, P. Hartogh, C. Jarchow. **"HHSMT Observations of the Venusian Mesospheric Temperature, Winds, and CO abundance around the MESSENGER Flyby"**, 2008, Planetary and Space Science, 56, 1688-1695. doi:10.1016/j.pss.2008.07.014

M. Rengel, P. Hartogh, C. Jarchow. **Mesospheric vertical thermal structure and winds on Venus from HHSMT CO spectral-line Observations "**, 2008, Planetary and Space Science, Volume 56, Issue 10, , Ground-based and Venus Express Coordinated Campaign, Ground-based and Venus Express Coordinated Campaign, August 2008, Pages 1368-1384. DOI information: 10.1016/j.pss.2008.07.004

- Titan - APEX

Rengel, Sagawa, Hartogh, Adv Geo, submitted AdvGeo

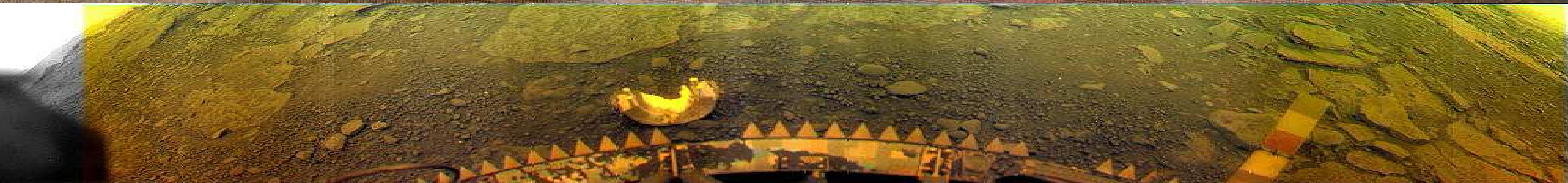
- Herschel plans/project

Hartogh P., Lellouch E., Crovisier J., and the HssO Team, "Water and related chemistry in the Solar System. A Guaranteed Time Key Program for Herschel", PSS 57, Issue 13, 2009, pags 1596-1606. doi:10.1016/j.pss.2009.07.009

- Titan : preparations for Herschel

Rengel M., Sagawa H., Hartogh P. "Retrieved Simulations of Atmospheric Gases from Herschel observations of Titan". Advance in Geosciences, in press

Radiative Energy Balance in the Planetary Atmospheres

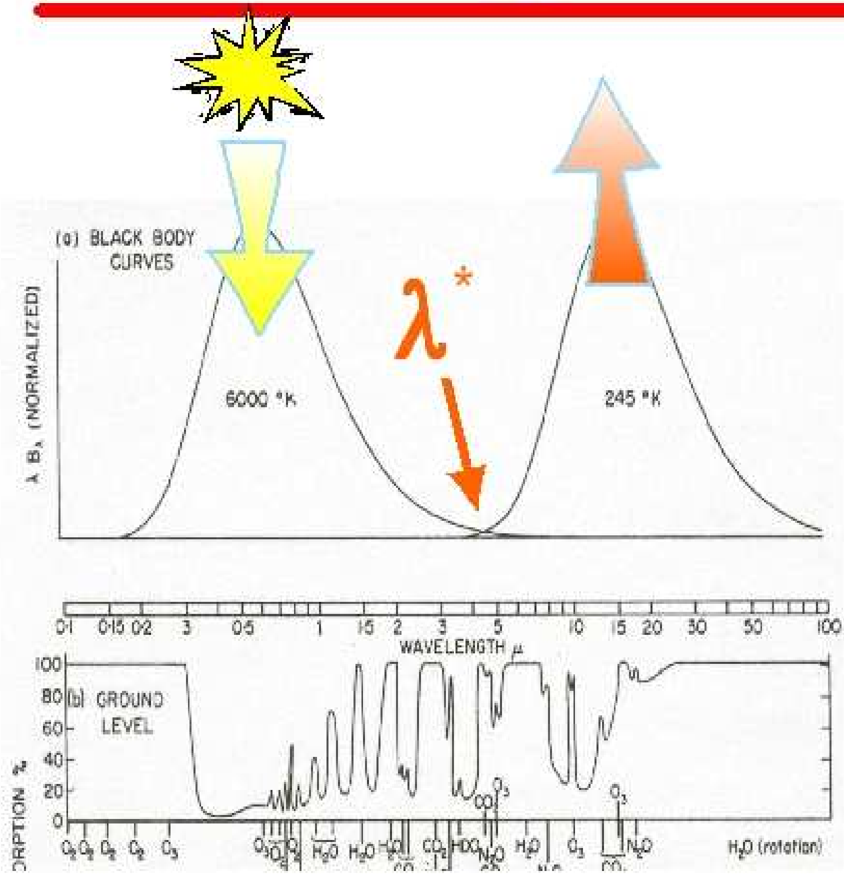


Outline of the talk

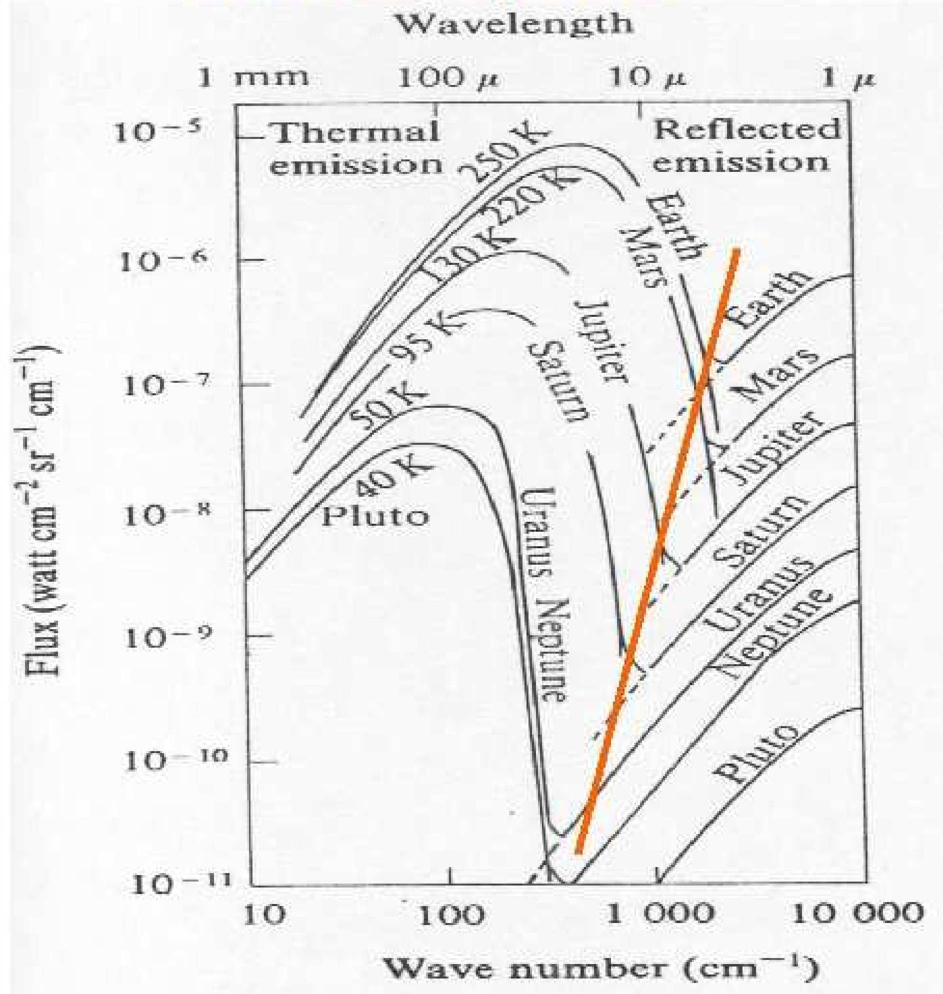
- *radiative energy budget*
- *forcing of the general circulation*
- *greenhouse effect*
- *balance of entropy*

Radiative energy budget

Energy balance of planets



Planetary spectra



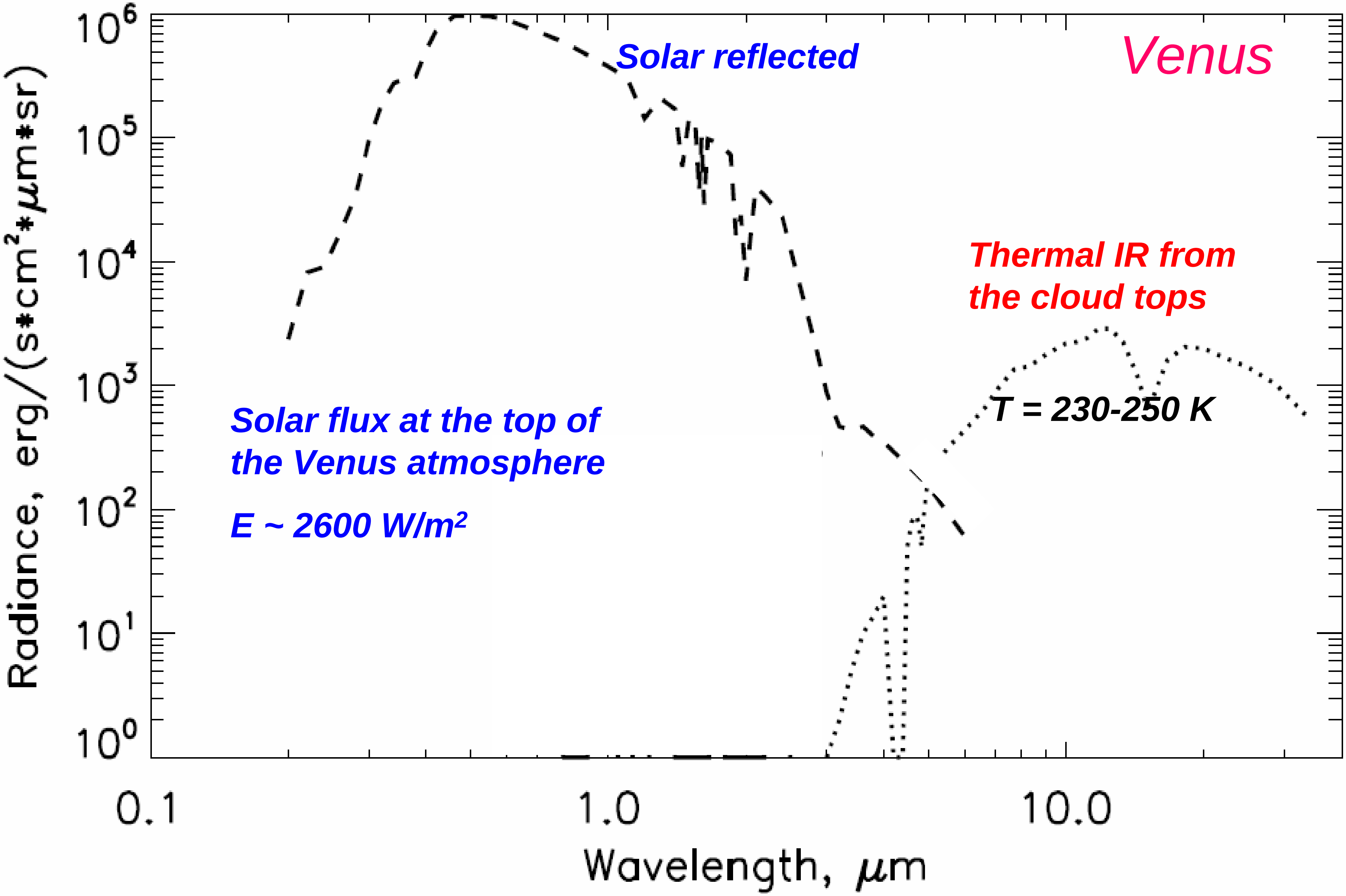
Effective temperature

$$E(1-A) = 4\sigma T^4_{eff}$$

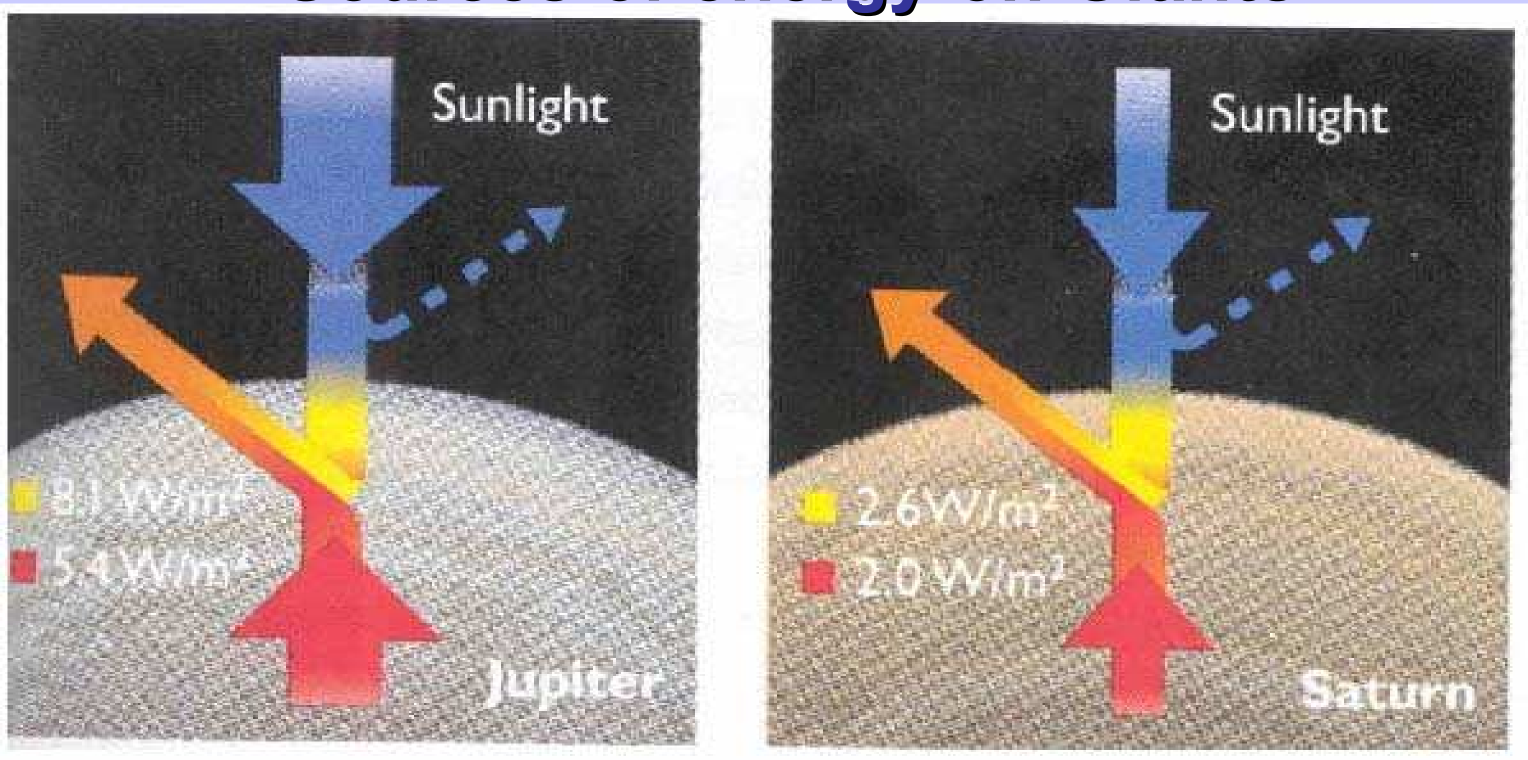
Solar constant

$E_\oplus = 1370\ W/m^2$

Composite spectrum of the outgoing radiation

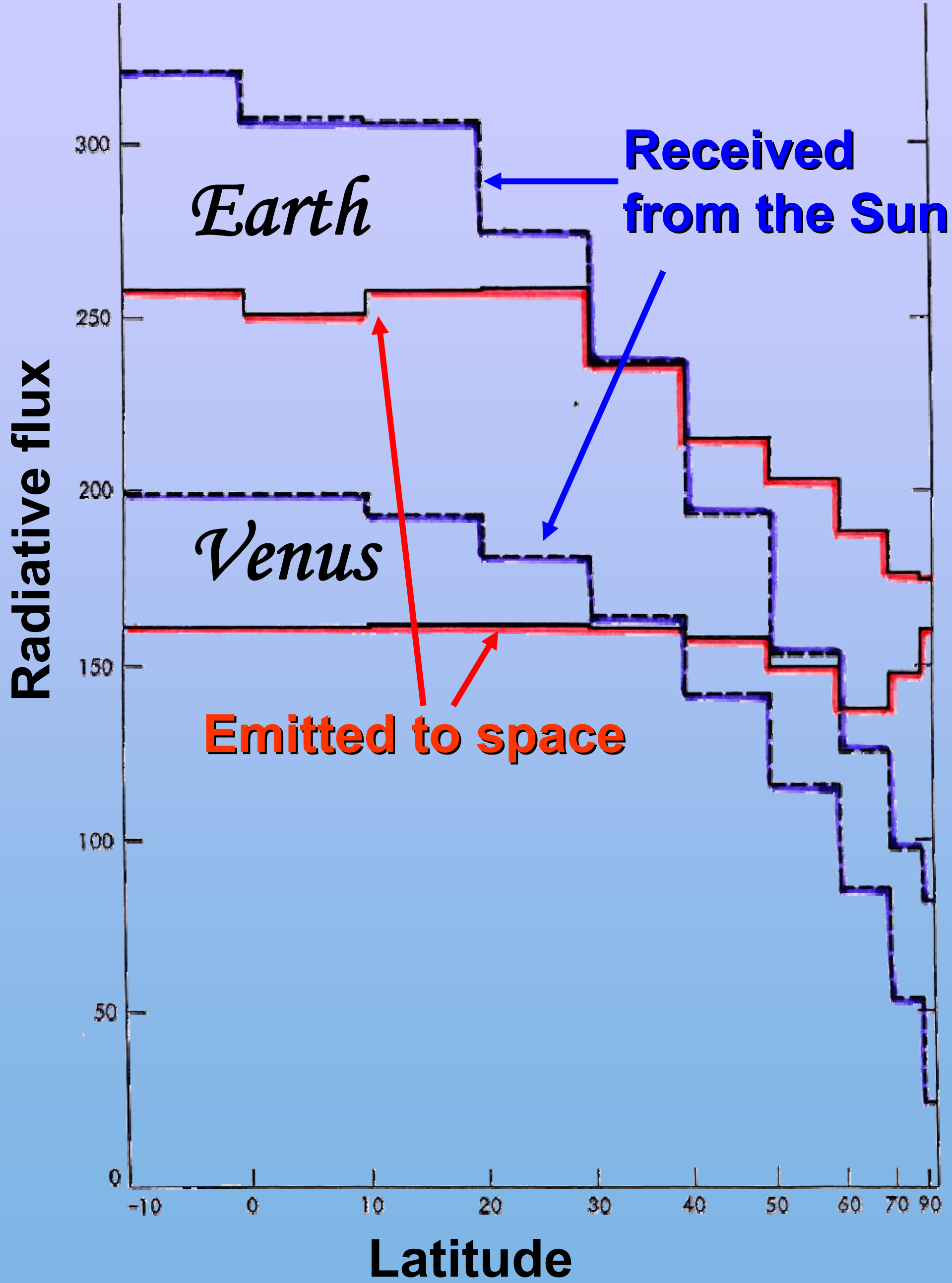


Sources of energy on Giants



	Earth	Jupiter	Saturn	Uranus	Neptune
D, au	1	5.2	9.56	19.22	30.11
Solar flux, W/m^2	1370	50.66	15	3.7	1.51
Energy balance, F_{IR} / F_{abs}	1	1.67	1.78	1.06	2.61

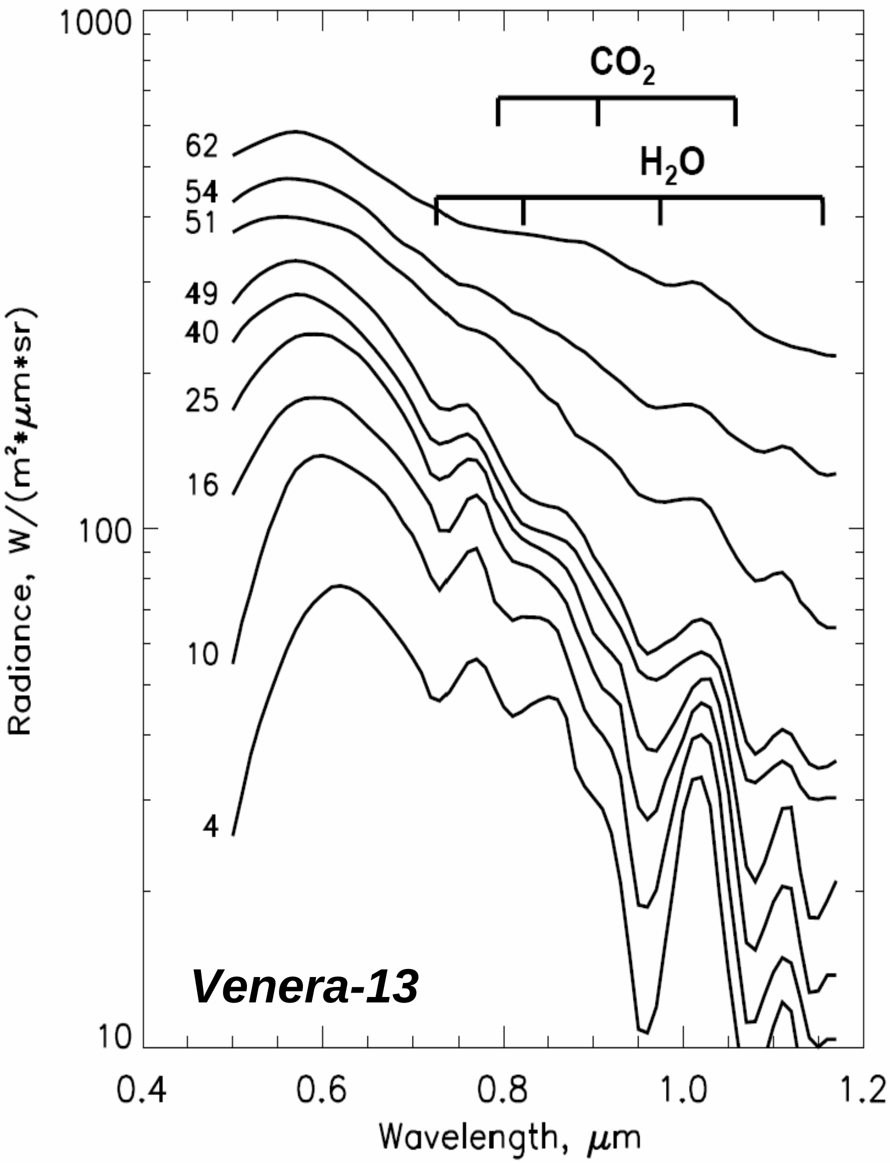
Latitudinal distribution of energy sources and sinks

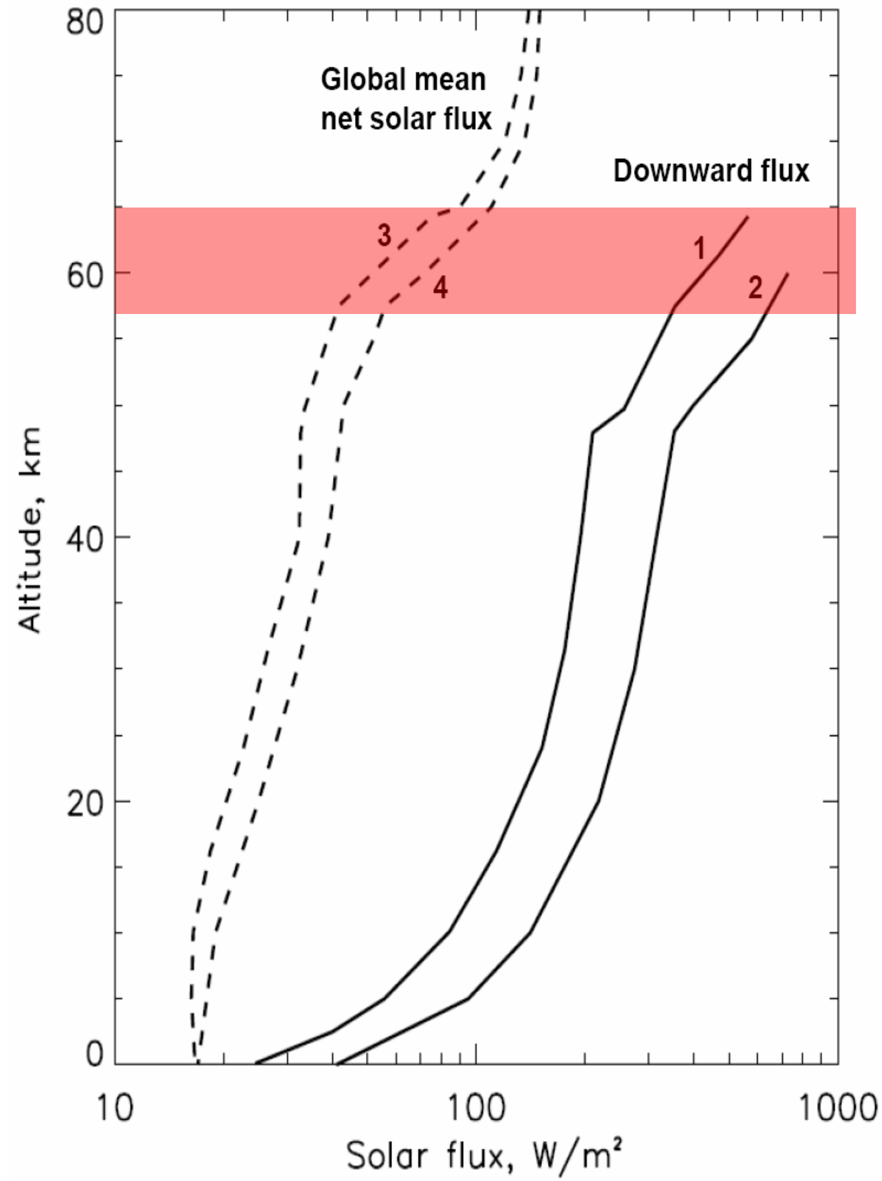


- *Venus gets less energy than the Earth !*
- *Net heating at equator, net cooling on poles*
- *Latitudinal distribution of radiative balance implies energy transport by circulation*

Taylor et al., 1983

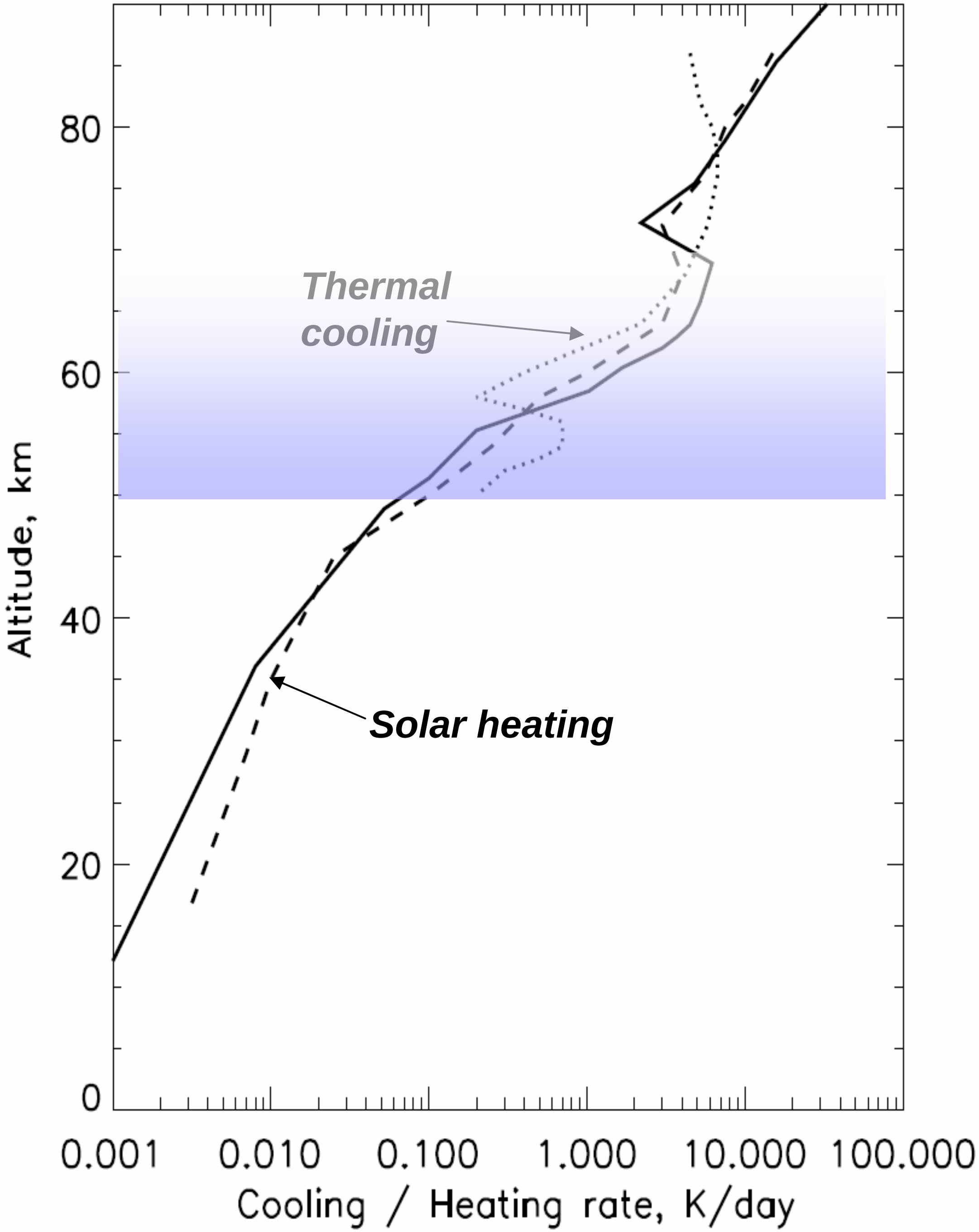
Vertical distribution of deposited solar energy





Ekonomov et al., 1983

Global mean heating and cooling rates



- *half of solar energy deposited on Venus is absorbed by the unknown UV absorber in the cloud layer*

Tomasko et al., 1985

Crisp & Titov, 1997

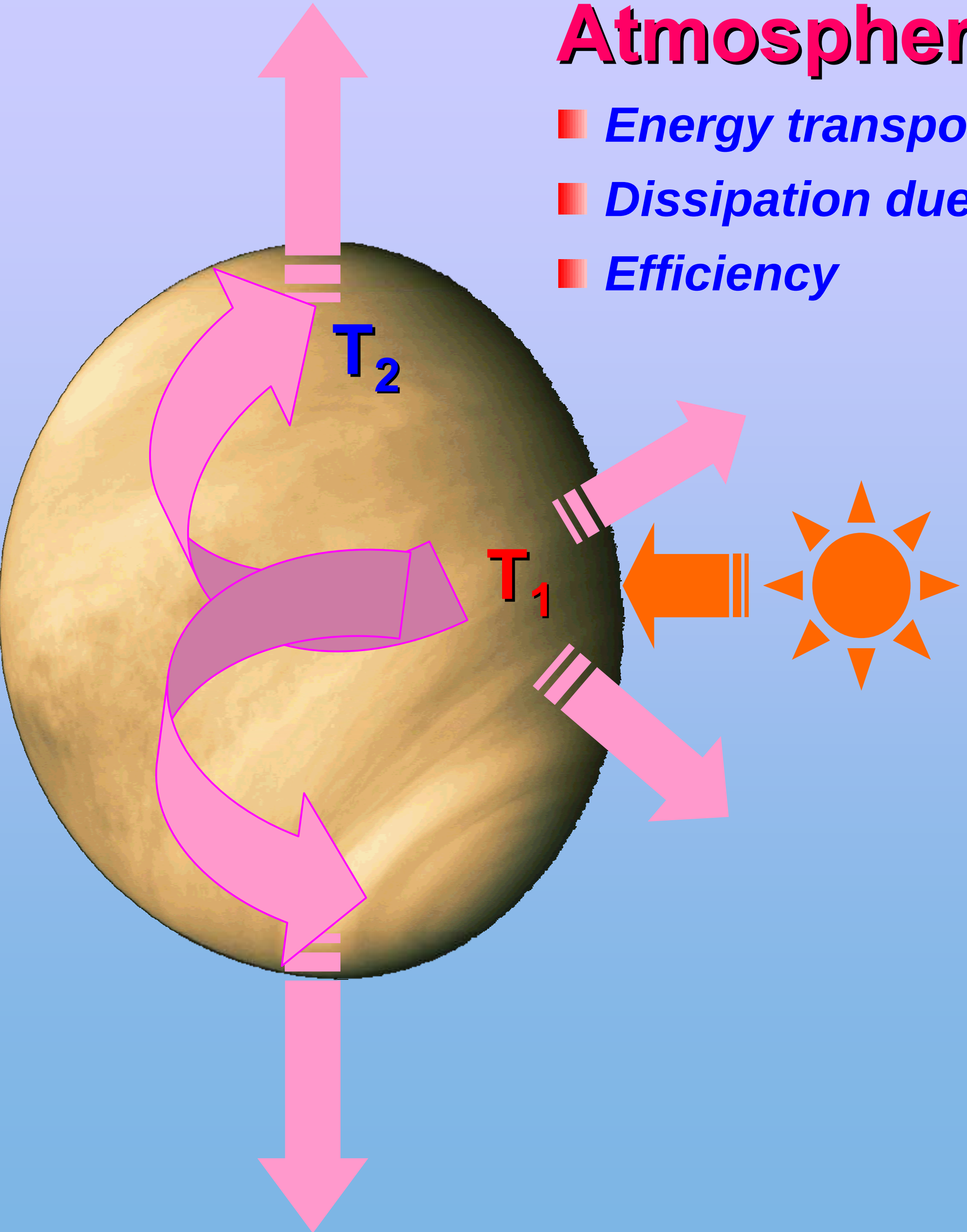
Mean deposition of solar energy on terrestrial planets [W/m^2]

	Venus	Earth	Mars
Atmosphere	130	70	~0
Surface	20	170	125

Atmospheres as heat engines

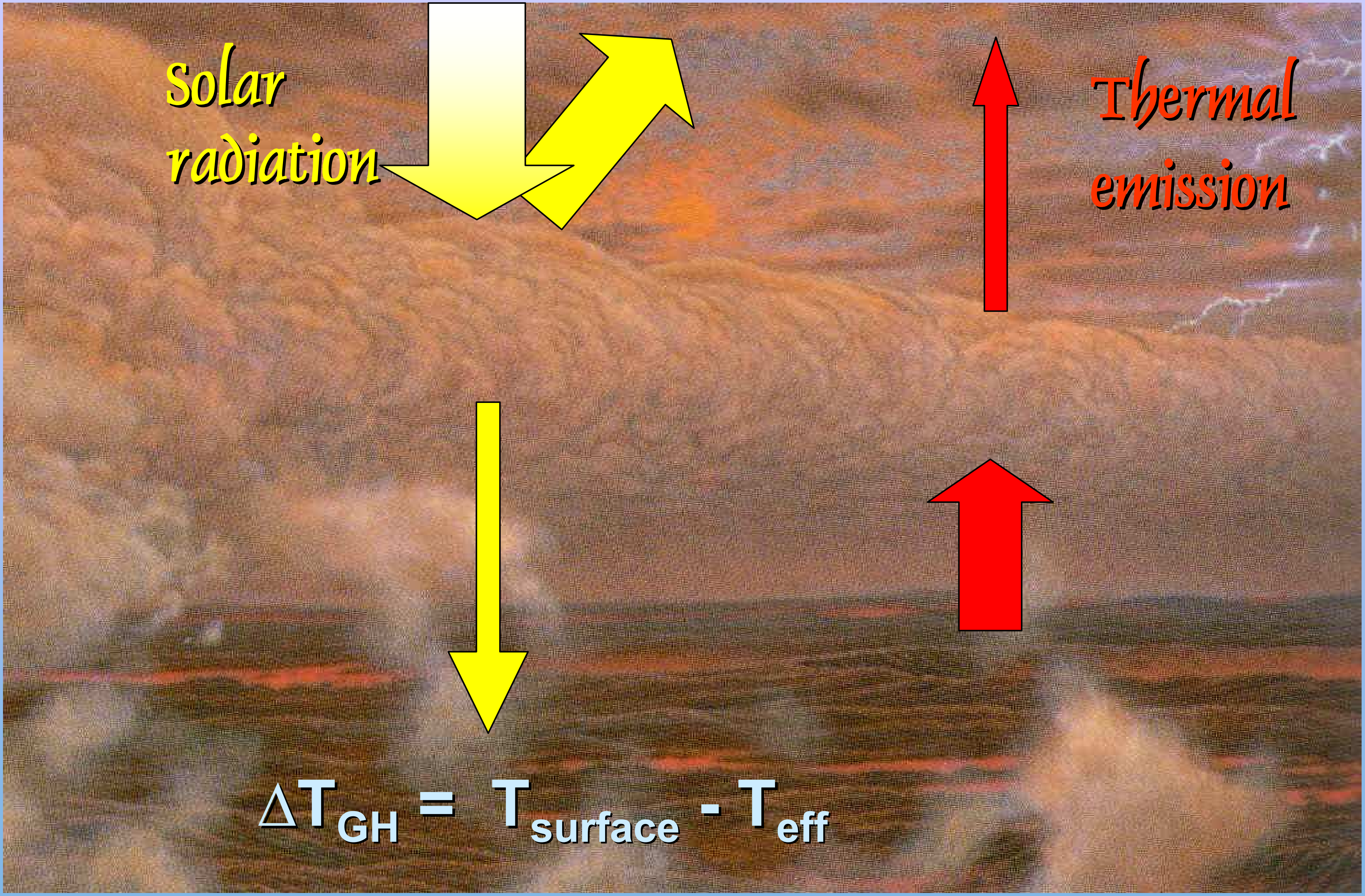
- *Energy transport by atmospheric motions*
- *Dissipation due to friction*
- *Efficiency*

$$\varepsilon \le 1 - \frac{T_2}{T_1}$$



Greenhouse effect

Basics of the greenhouse effect

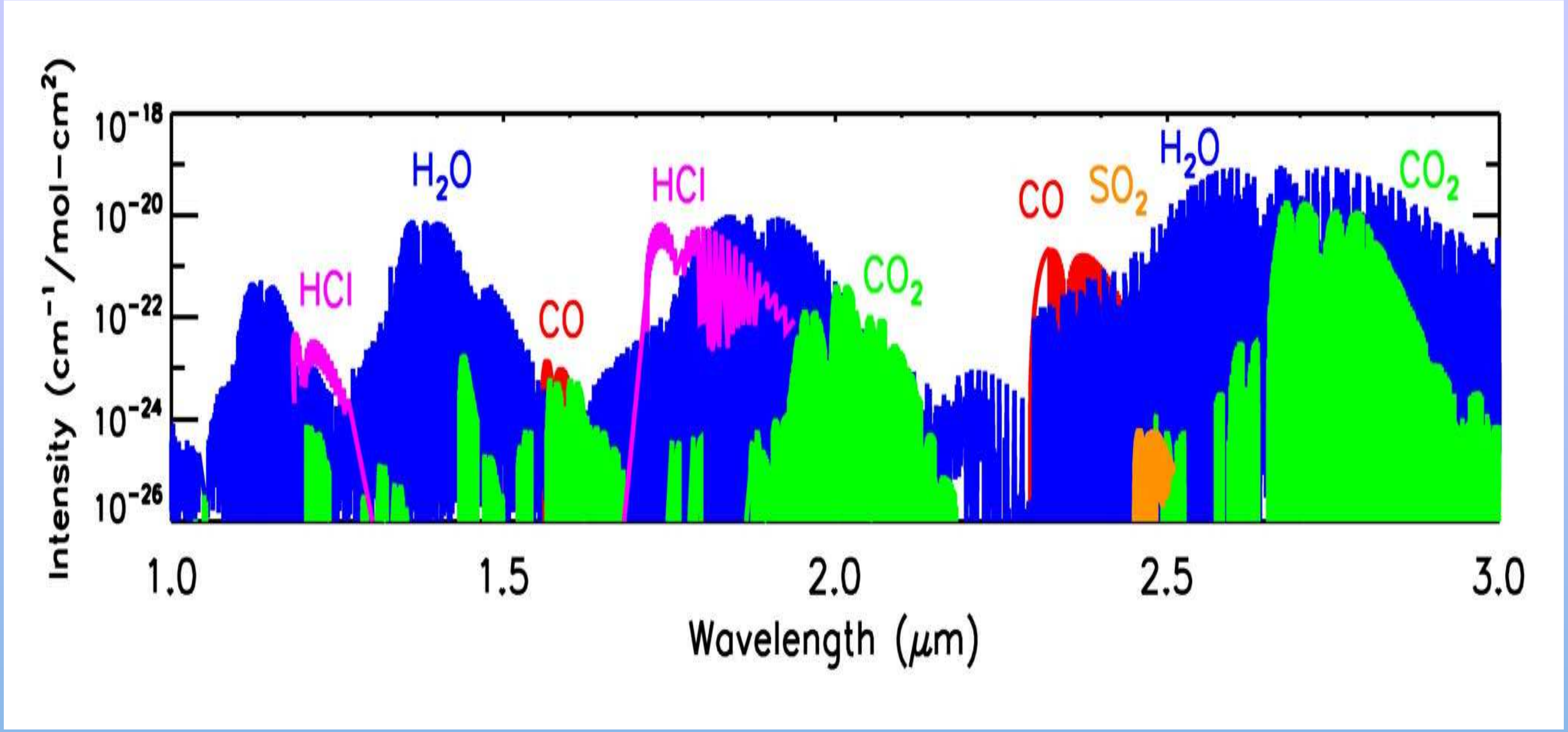


$$\Delta T_{GH} = T_{surface} - T_{eff}$$

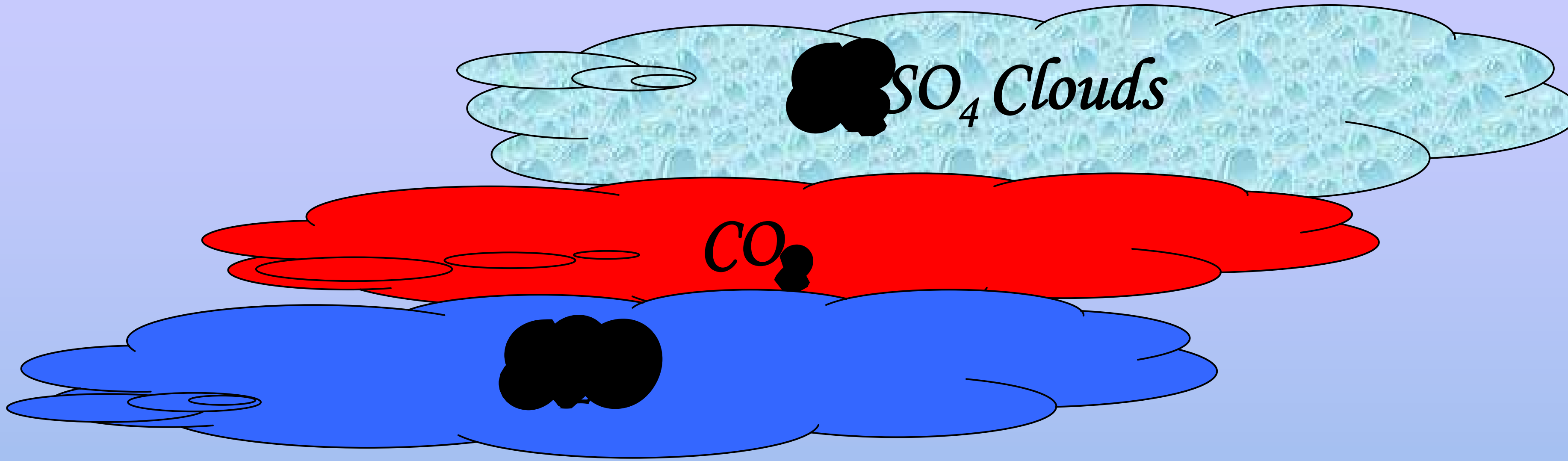
0.5 μm 1 μm 5 μm 10 μm

Wavelength, microns

Absorption bands of the atmospheric gases



Venus – the queen of greenhouse



CO_2 – 420K

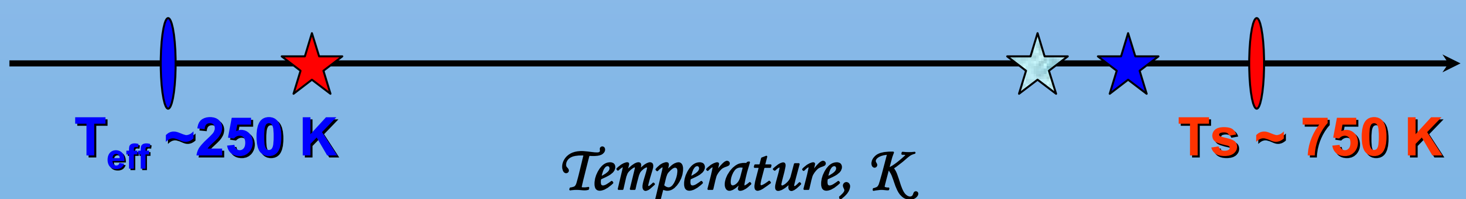
H_2O – 70K

Clouds – 140K

COS – 12K

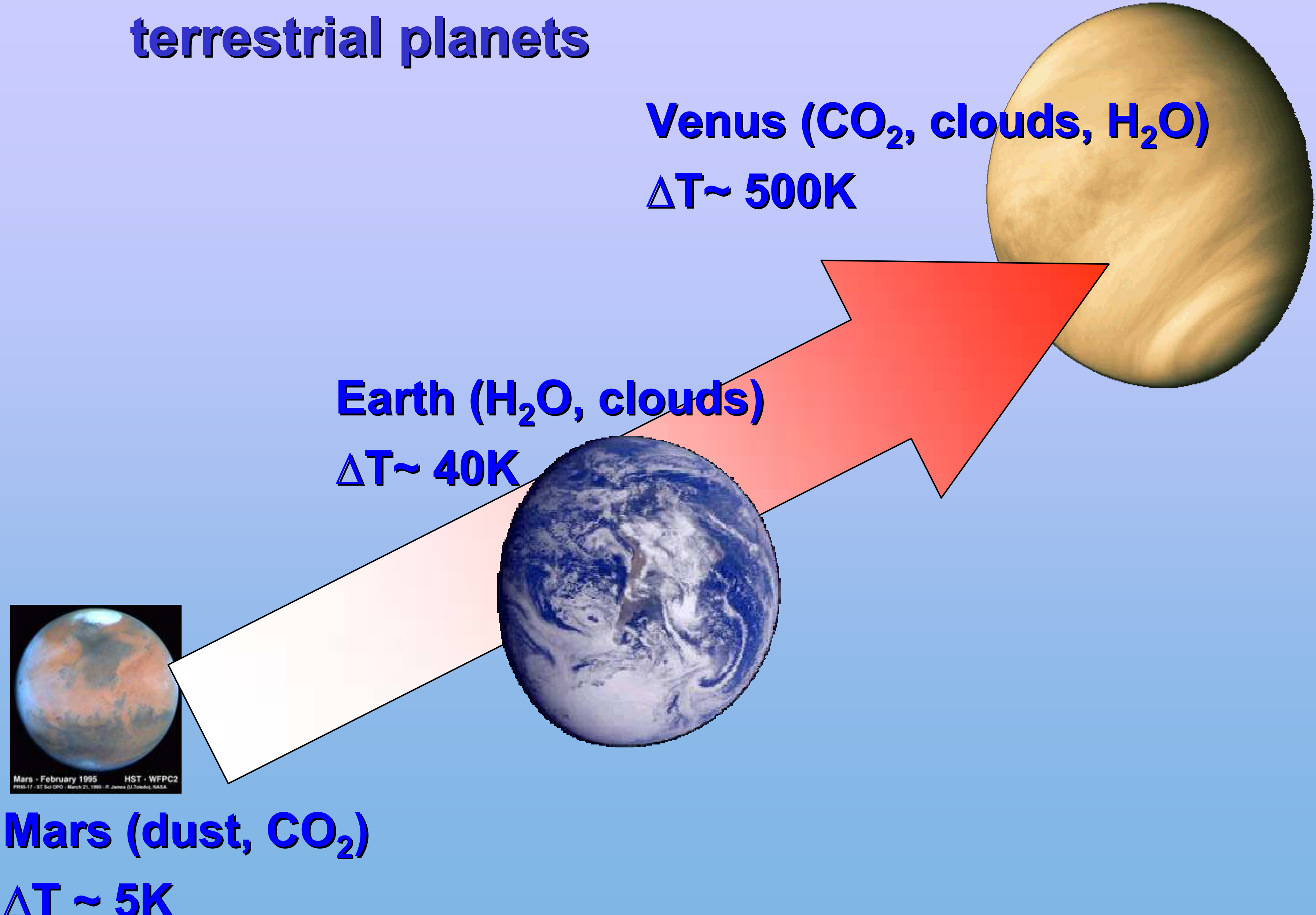
CO – 3K

SO_2 – 3K



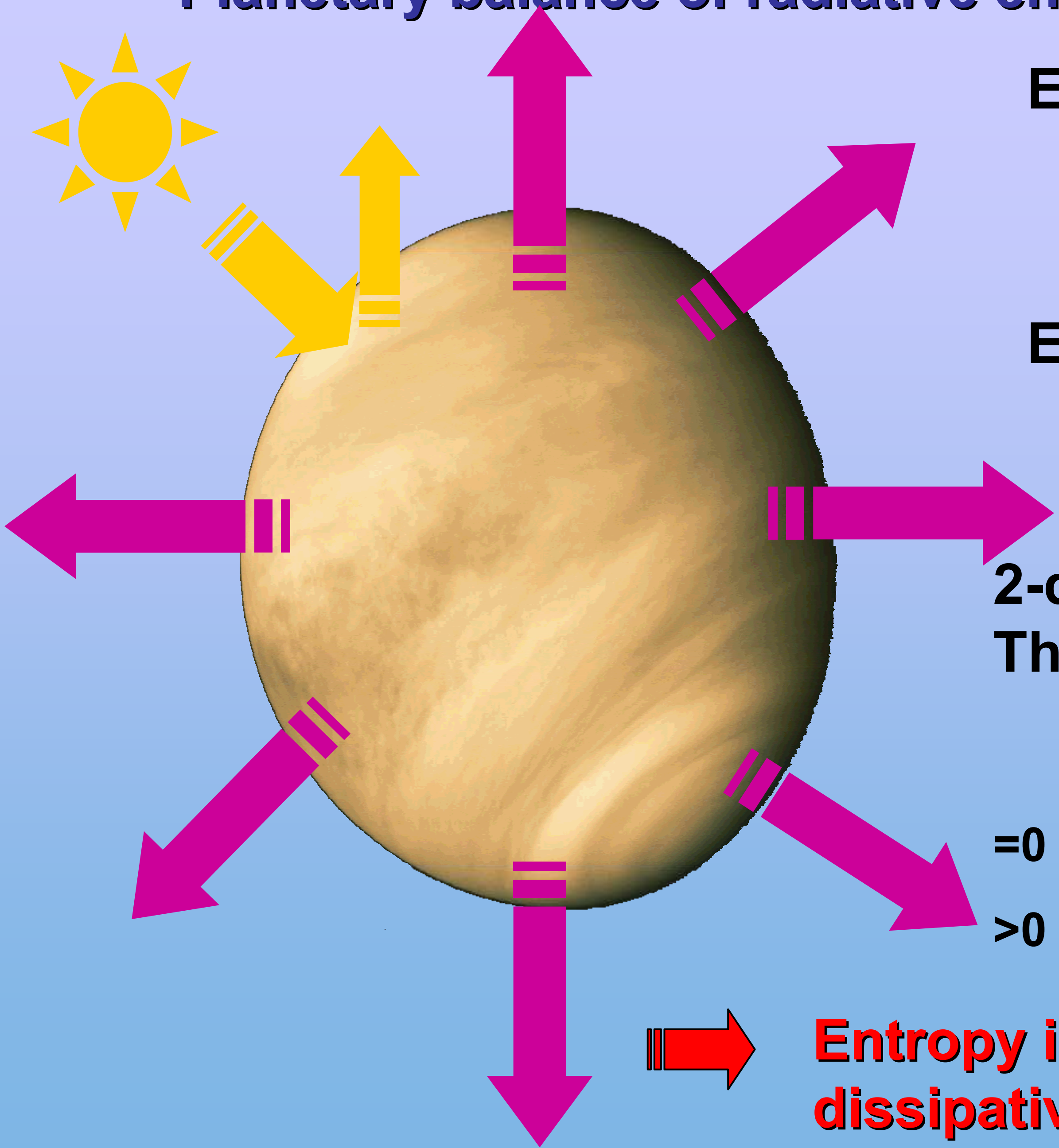
Bullock, 2007

Greenhouse effect on the terrestrial 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:

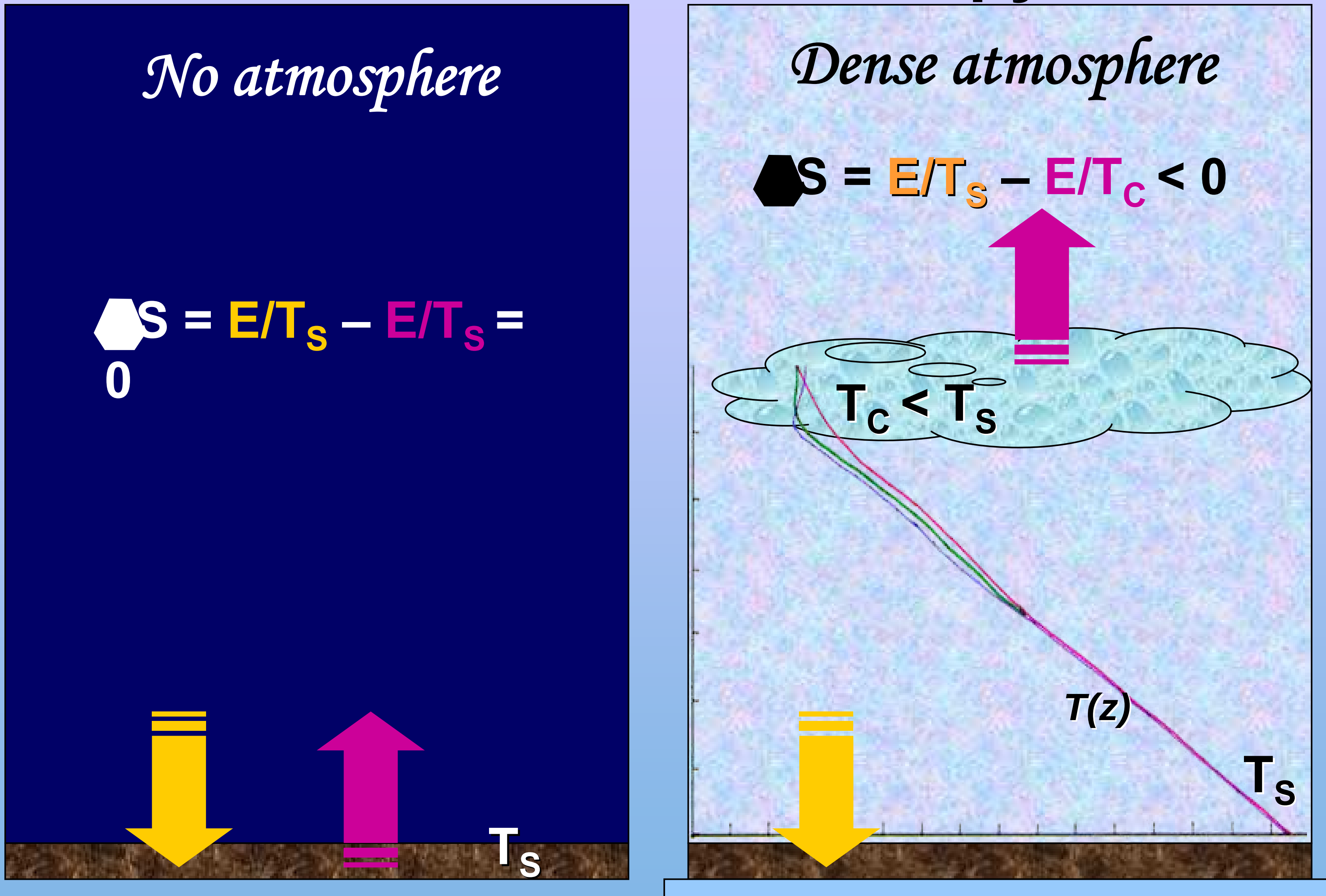
$$\Delta S \geq 0$$

=0 - reversible processes

>0 – irreversible processes

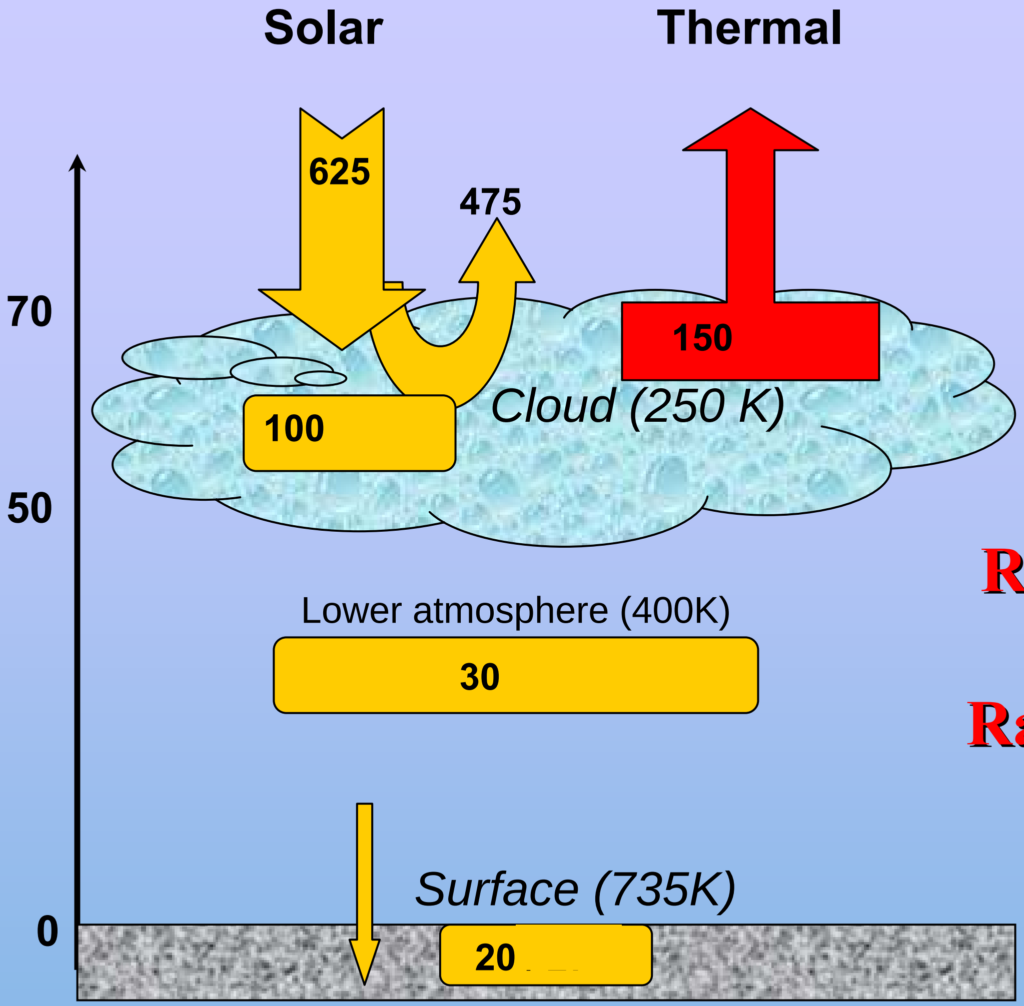
Entropy is a measure of dissipative processes

Flux of radiative entropy



Planets receive negative entropy from the Sun

Radiative Energy / Entropy balance on Venus



Radiative energy balance

$\Delta E \approx 0$

Radiative entropy balance

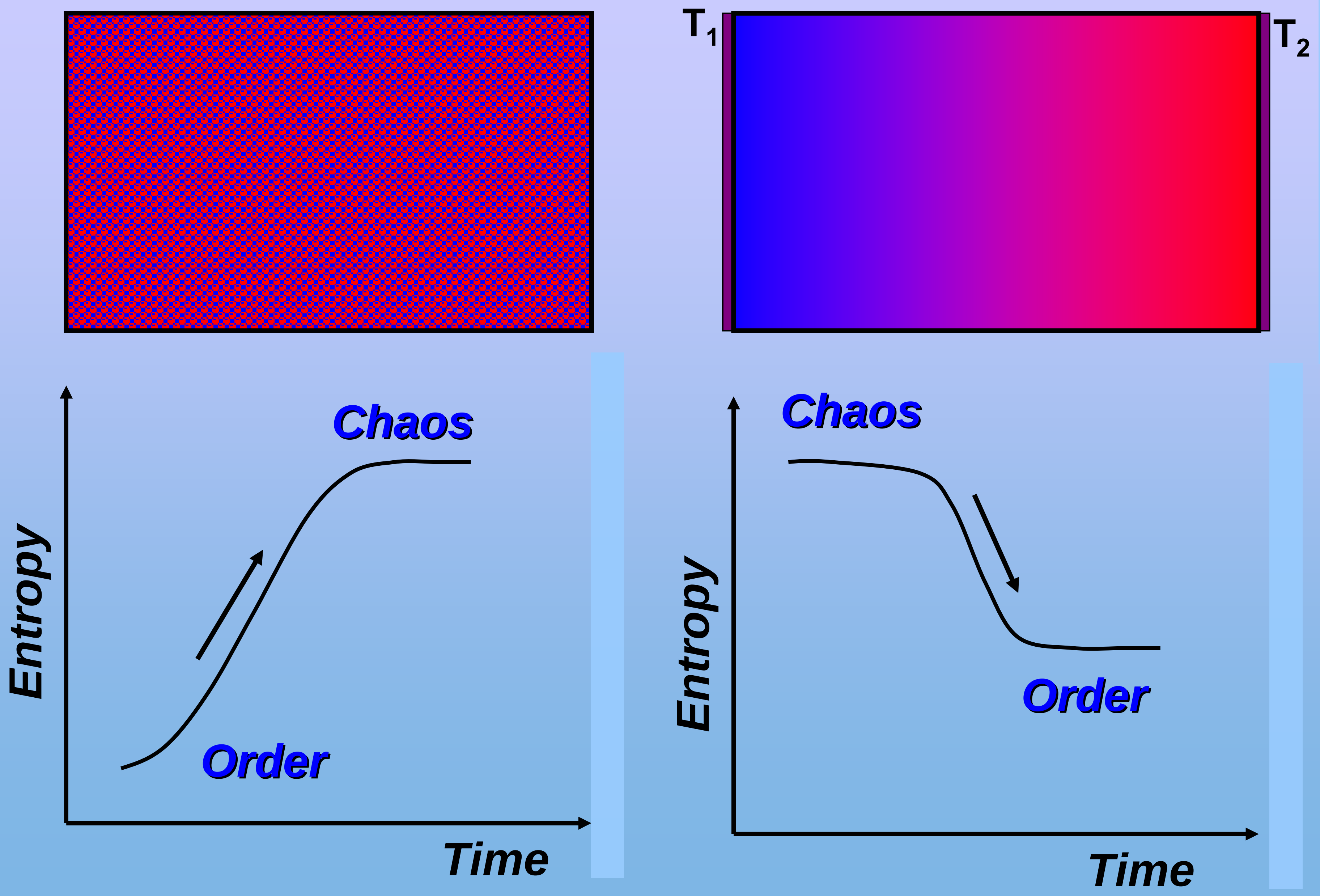
$\Delta S \approx -100$ mW/m^2/K

Entropy balance on Earth and Venus

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

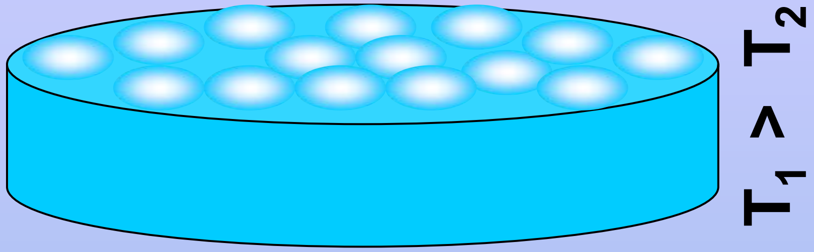
Dissipative processes in the Venus atmosphere - ????

Equilibrium and non-equilibrium thermodynamics

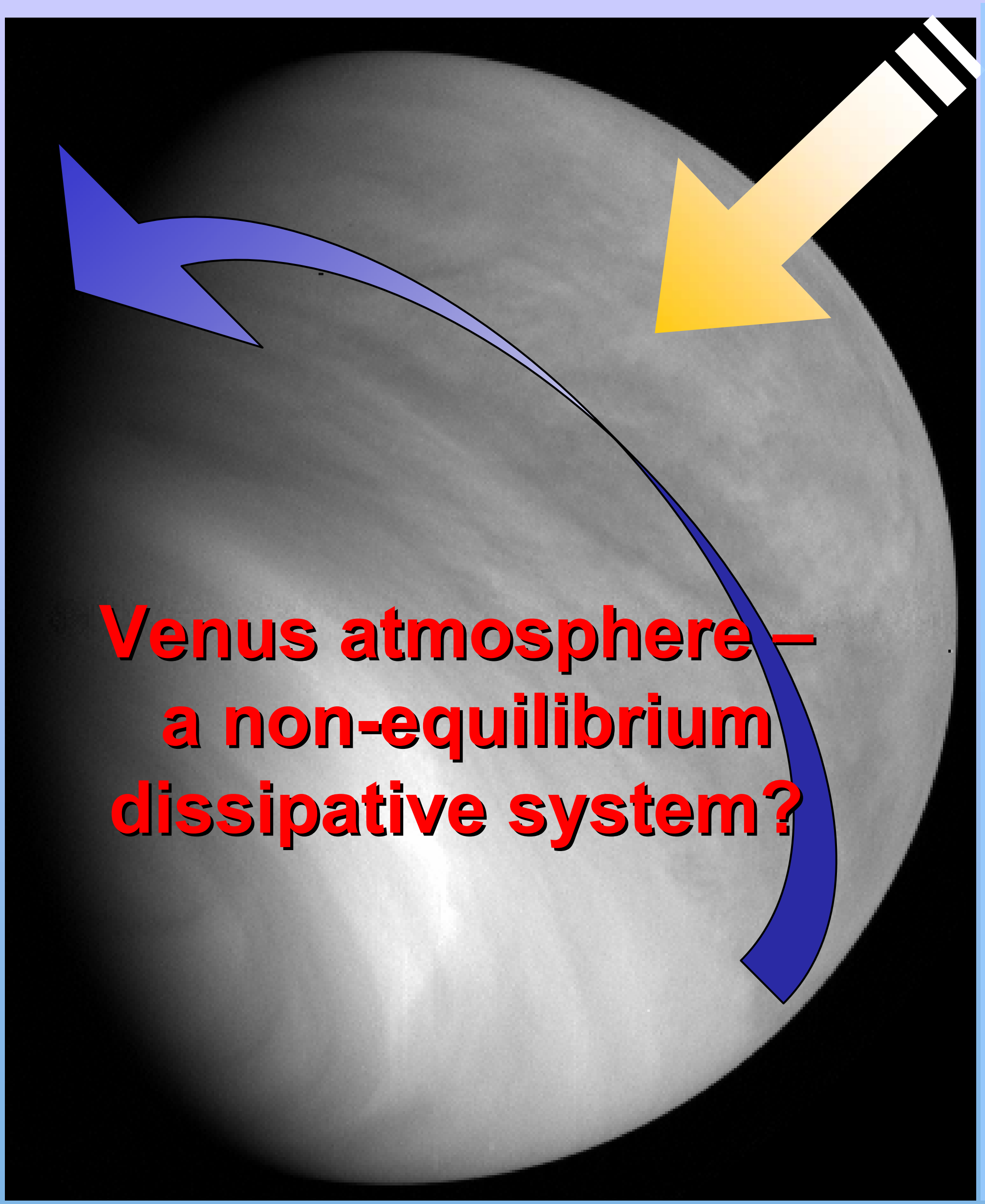


Non-equilibrium dissipative systems

Benard convection

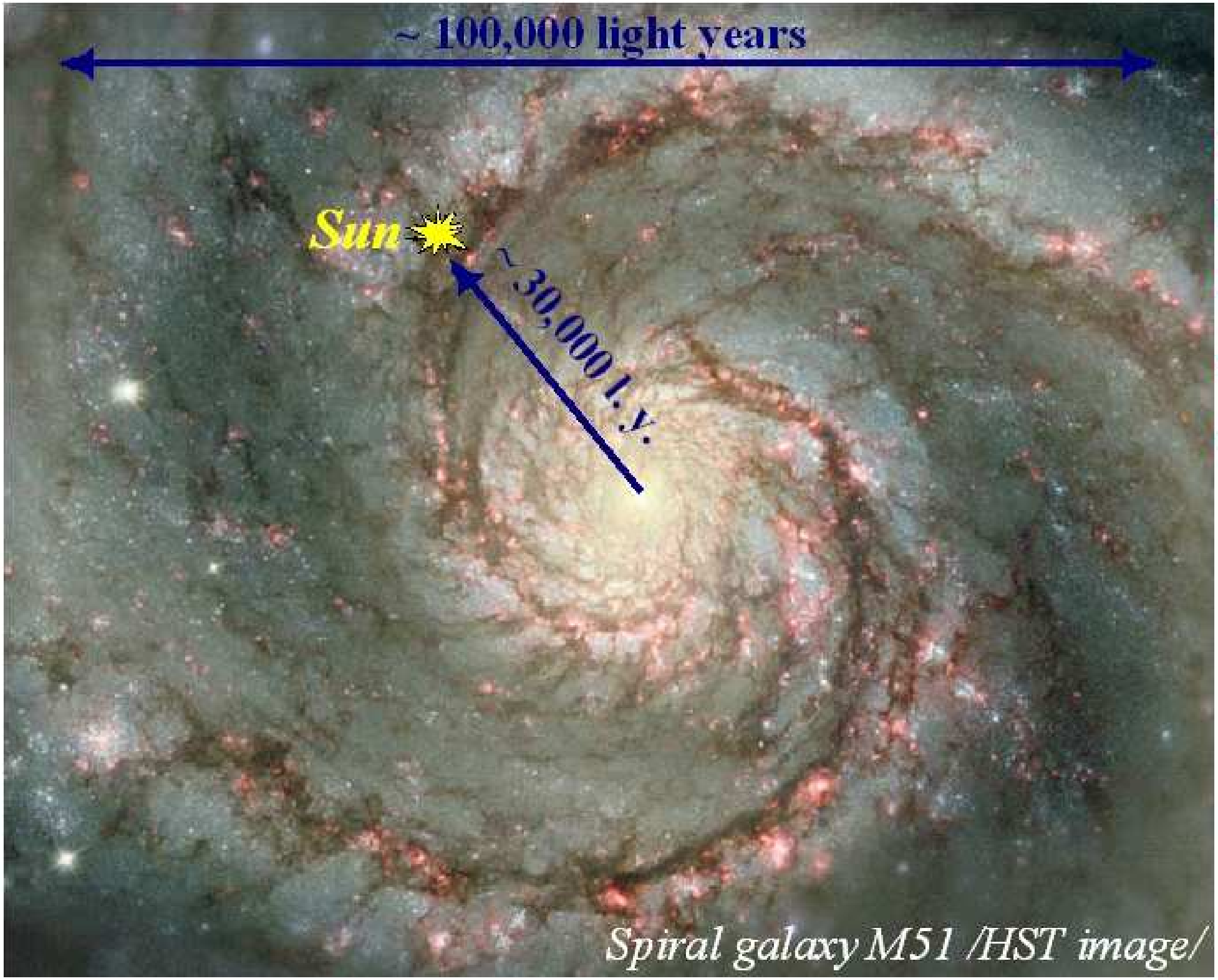


- critical temperature gradient
- high level of order
- high entropy production



Origin and evolution of planetary atmospheres

Sun in the Galaxy

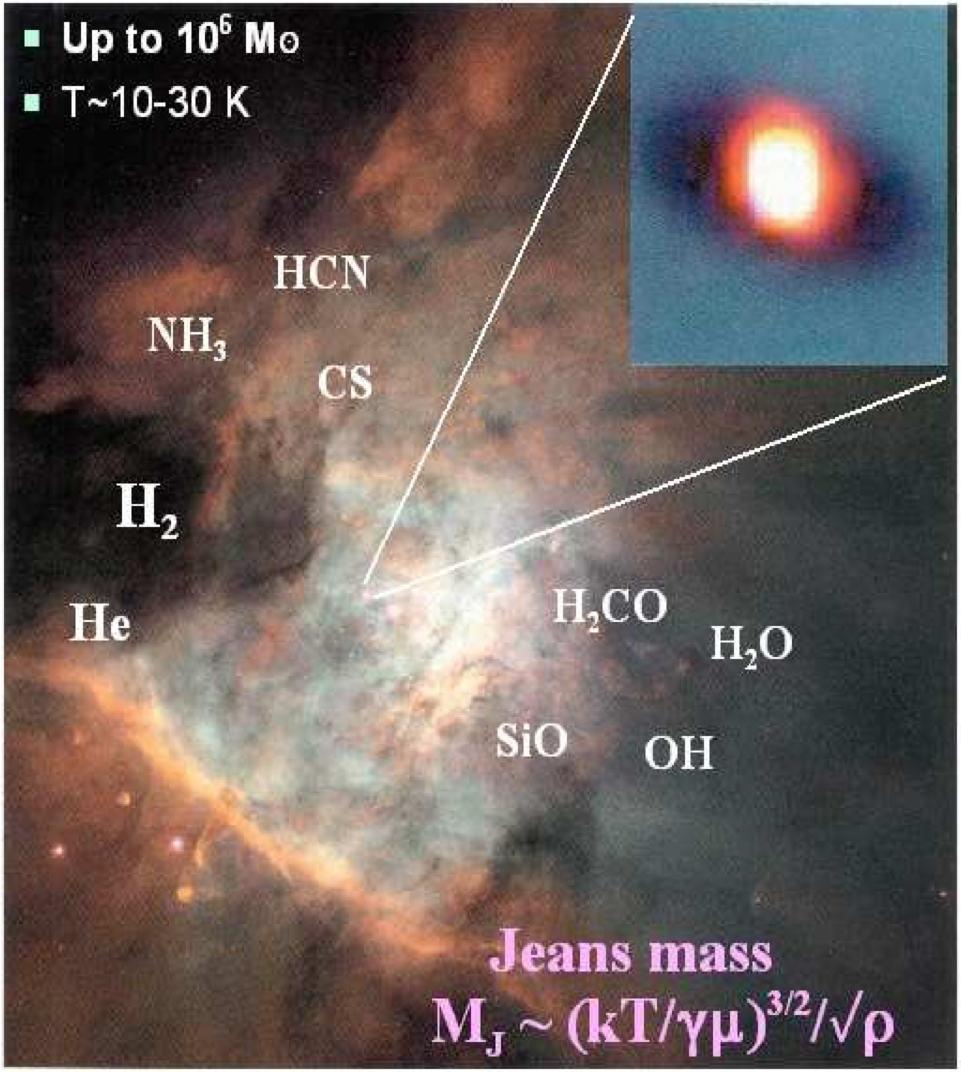


Spiral galaxy M51 /HST image/

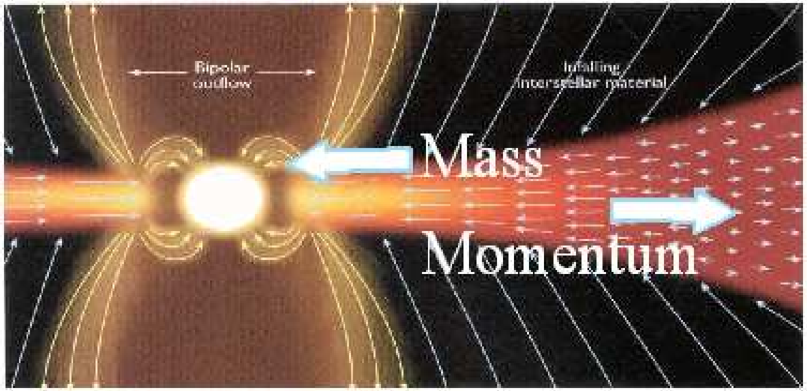
- $N \sim 10^{11}$ stars
- $R_{Sun} \sim$ 30,000 l.y.
- $\rho \sim$ 1star/300 (l.y.)^3
- $V_{Sun} \sim$ 250 km/s
- $T_{Sun} \sim$ 250 Myears

Origin of the solar system

Orion nebula



Protoplanetary disc

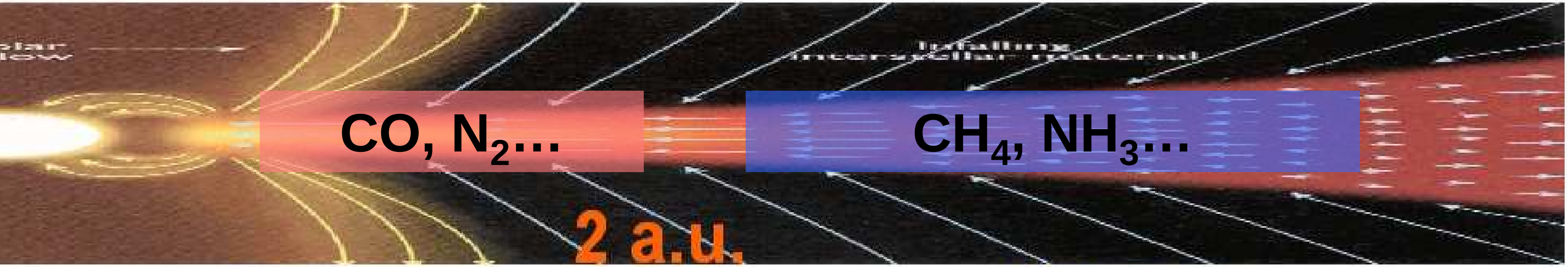


- Gravitational collapse of a molecular cloud (N~10^4, T~ 30K)
- Infall stage (10^5 - 10^6 years)
- Formation of protoplanetary disc
- Momentum re-distribution
  - Magnetic field
  - Gravitational torques
  - Turbulent viscosity
- Fragmentation
- Clearing stage (T-Tauri) 10^6 - 10^7 years after protostar formation
- Observations of *proplyds* - disc like structures (~100 a.u.) Around the young stars

Here comes the Sun...

- $R_\odot \sim 7 \cdot 10^5$ km = 109 $R_\oplus$
- $M_\odot \sim 2 \cdot 10^{33}$ g
- $\rho_\odot \sim 1.4$ g/cm^3
- Composition
  - H_2 = 76.4%
  - He = 21.8%
  - Heavy elements < 2%
- Spectral class G2
- $T_{ef} \sim 5800$ K
- Age ~ $5 \cdot 10^9$ years

Formation of planets



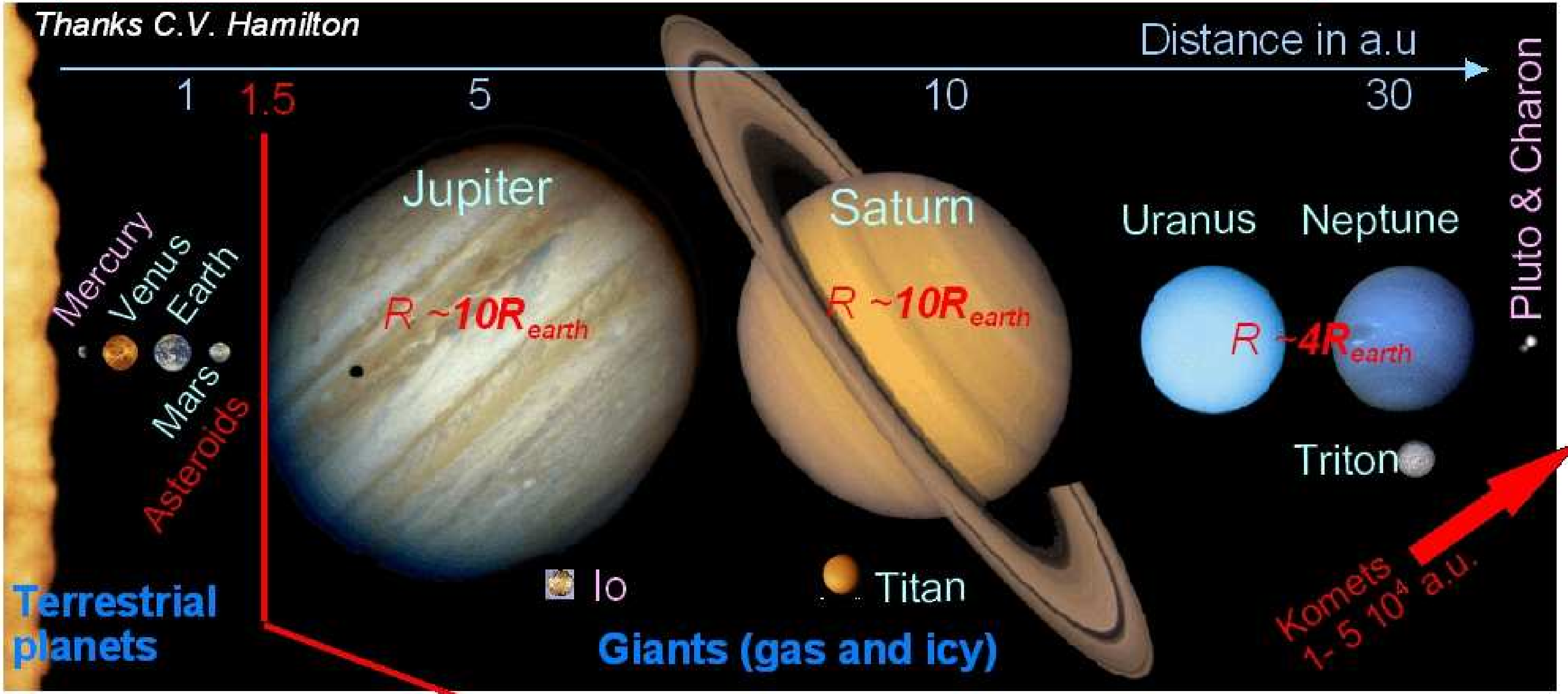
Inner zone

- T~ 500-1000 K
- Silicate and iron compounds
- Chondrules ⇒Fast cooling processes
- Growth to 1 km size planetesimals
  - Gravitational instabity in quiet disc
  - Or two-body colisions in turbulent disc
- From planetesimals to protoplanets
  - Collisions between planetesimals
  - Runaway growth of embrios ($v << v_{esc}$)
  - Time scale ~10^7 - 10^8 years
- Formation of planets
  - Differentiation of interiors
  - Formation of proto-atmospheres (blanketing effect)

Outer zone

- T~ 100K
- H_2 , He and ices H_2O, CO_2, NH_3....
- Significant amount of heavy elements as compared to solar
- Fast accretion of gas (t~10 My)
- Effective accretion of heavy elements
- **Scenario 1: Gravitational collapse**
  - Disagreement with the data on compositio and structure
- **Scenario 2: Accretion + gas accumulatio**
  - Formation of solid core (**0.1M$_{earth}$**, 1My)
  - Gas runaway accretion (**10M$_{earth}$**, 10My)
  - Contraction (~0.01-0.1 My)

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

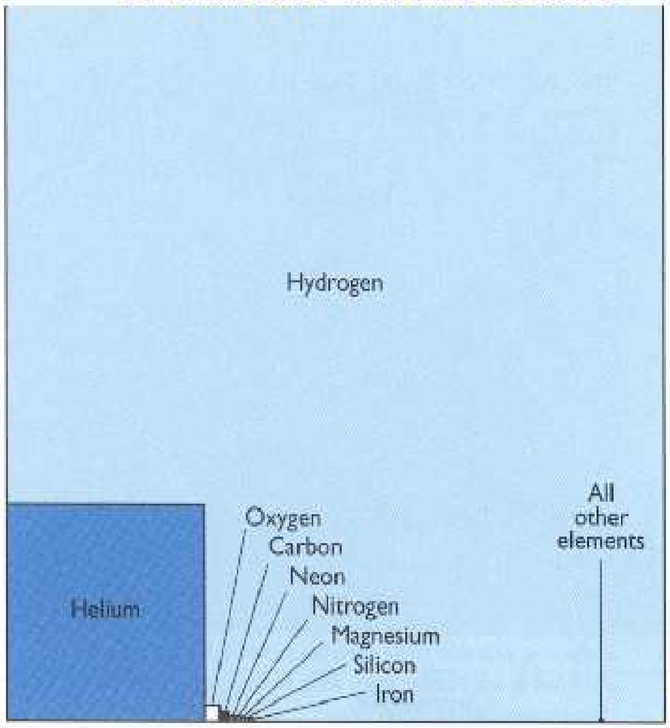
Atmospheres: CO_2, N_2, O_2, H_2O, SO_2

- $M > 20M_{earth}$
- $\rho \sim 1.5$ 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

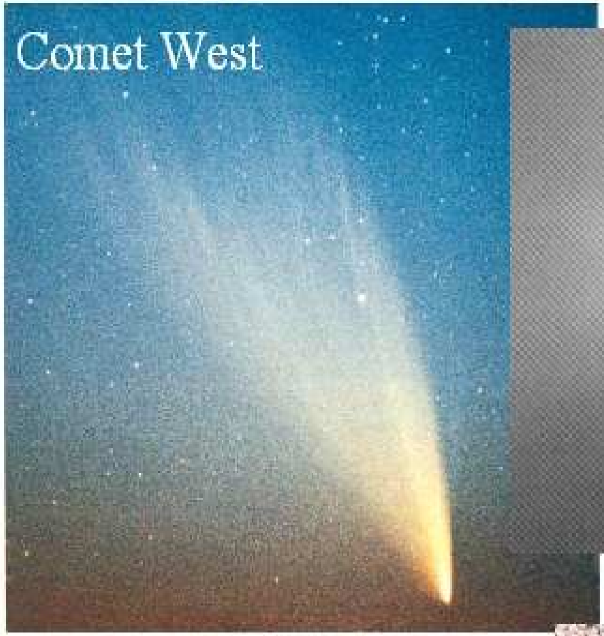
Atmospheres: H_2, He, CH_4, H_2O, NH_3, H_2S

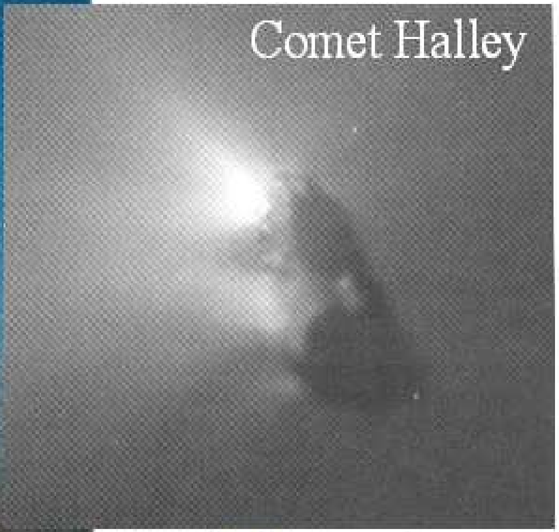
Composition of the nebula

Element abundance

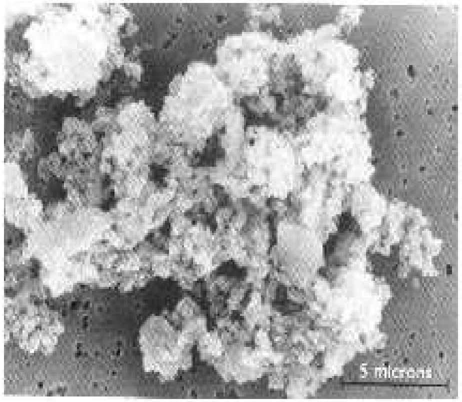


Samples of primitive material





Cometary particles

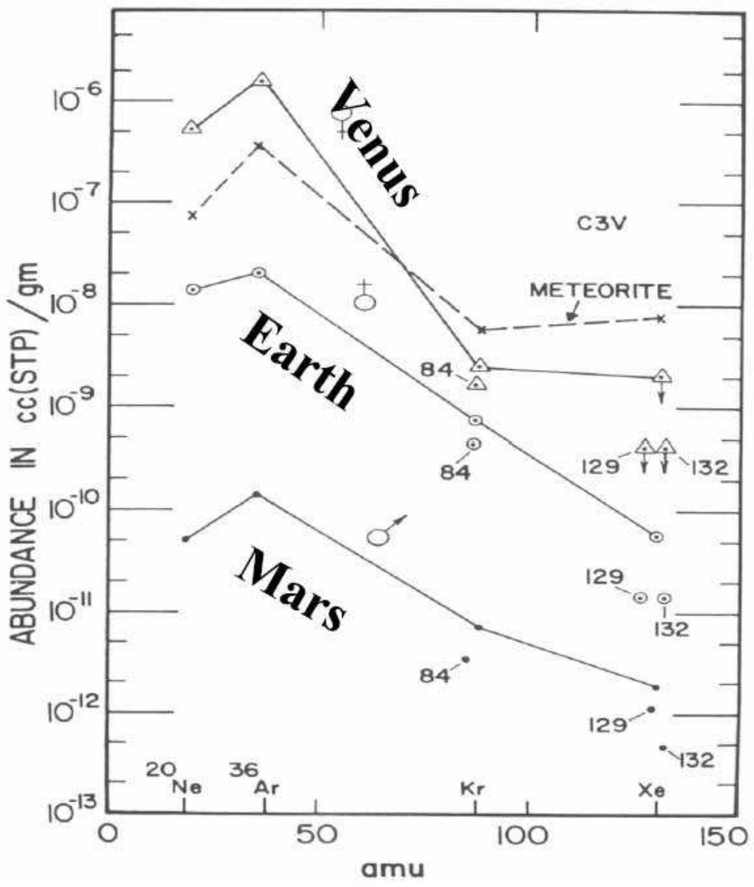


Meteorites

Age ~4.5 By

Records of atmospheric evolution

Noble gases on terrestrial planets

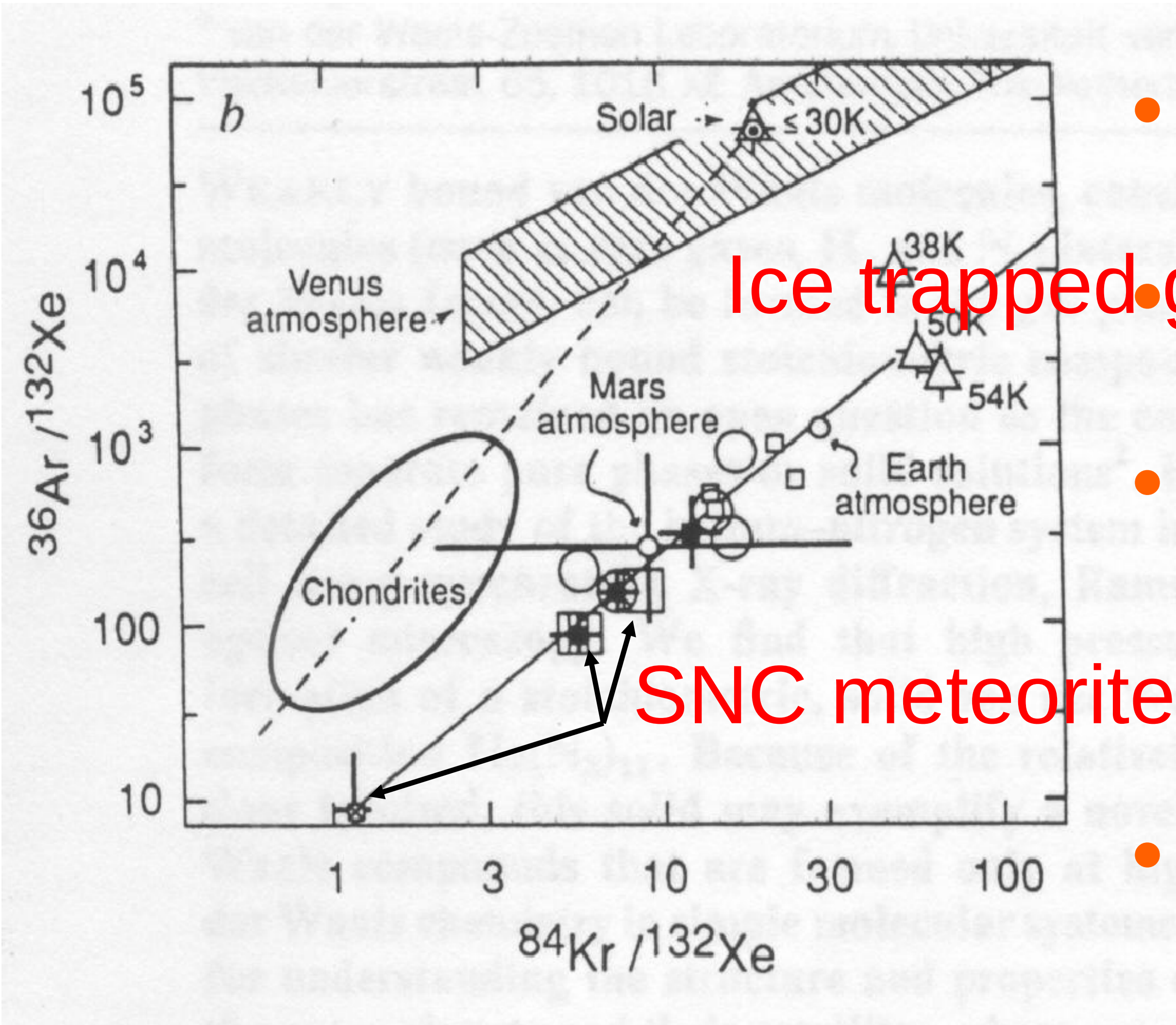


- Terrestrial atmospheres were degassed from planetesimals, not accreted from nebula
- Gases (except Ne) were trapped in the planetesimals at ~30K
- Venus atmosphere is more primordial
- Mars and Earth has possibly survived severe impact erosion
- Possibly two reservoirs - planetesimals and comets -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

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 eruptions
- Cometary supply

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 ar Mars can explain depletion of Ne*
  - *On Venus - isotope escape differentiation*
- Venus is closer to solar composition

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)**
  - $M_e/M \sim d^2$

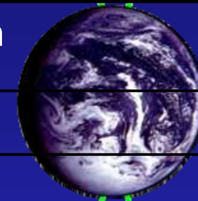
Main factors and processes in evolution of terrestrial planetary atmospheres

- ***Earth***
  - *removal of CO_2 by silicate weathering (Urey reaction)*

$CO_2 + H_2O + CaSiO_3$ → carbonates ($CaCO_3$)

  - *CO_2 recycling by plate tectonics*
  - *self-regulation of CO2 abundance by weathering and outgassing*
  - *photosynthesis of O_2*
  - *antropogenic production of CO_2*
- ***Venus***
  - *runaway greenhouse → water escaped to space*
  - *no liquid water, no plate tectonics → CO_2 stays in the atmosphere*
  - *global resurfacing ~700 MiY ago → sulfur-bearing gases*
- ***Mars***
  - *possible impact erosion*
  - *small size of the planet*
  - *obliquity changes*
  - *warmer and wetter climate before ~3.8 BiY → CO_2 loss*

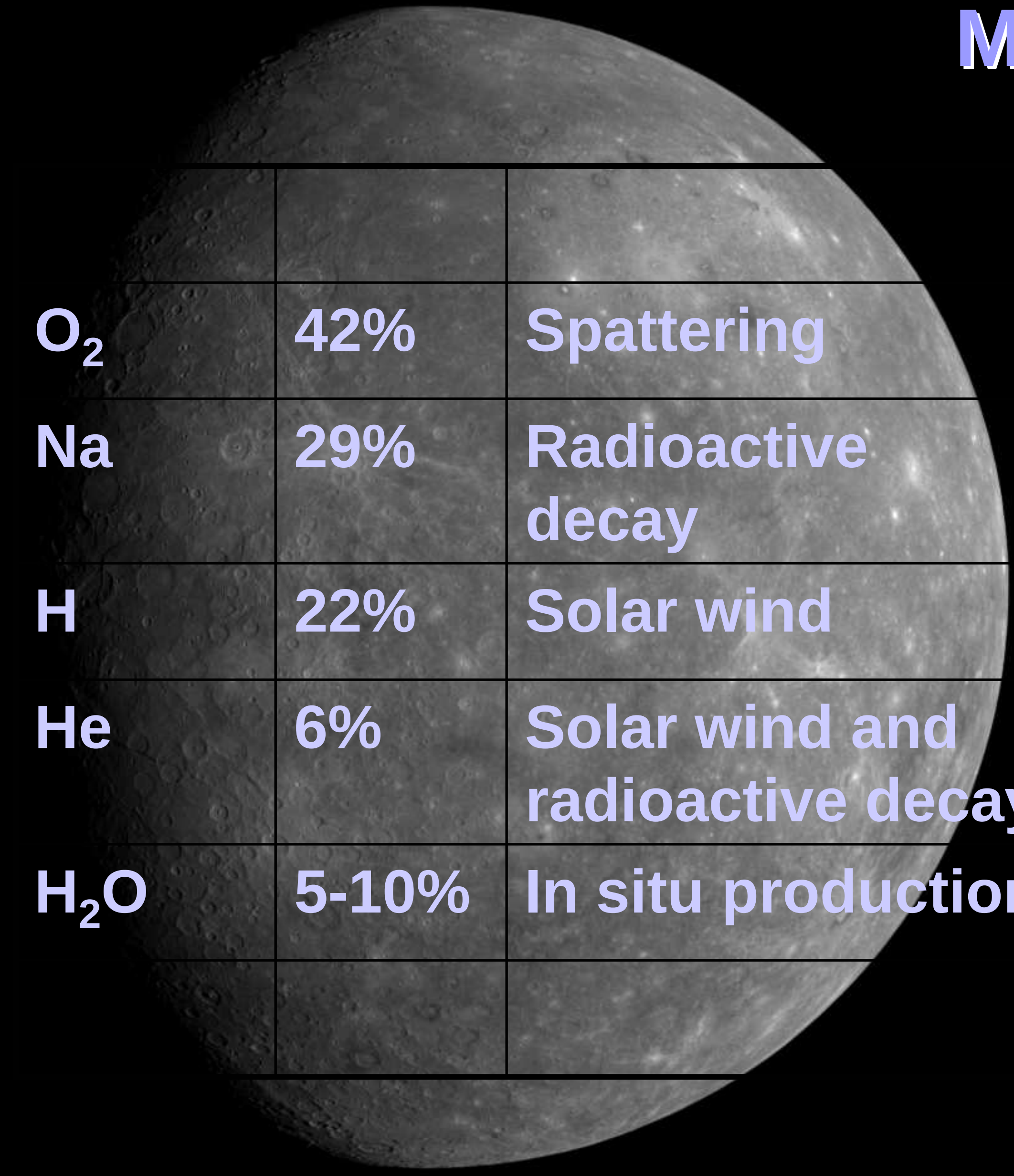
Why Earth, Mars, Venus so different?

Property	Venus 	Earth 	Mars 
Mass [10^{12}Gt]	4.9	6.0	0.64
Radius [km]	6049	6371	3390
SolarDistance [AU]	0.72	1.0	1.52
SolarConstant [W/m^2]	2613	1367	589
Atmosphere Mass[10^6Gt]	500	5.1	0.31
N_2 [%]	<2	78	<3
O_2 [%]	$<10^{-4}$	21	<0.25
CO_2 [%]	98	0.035	>96
H_2O[%]	<0.3	<4	<0.001
D/H ratio [10^{-4}]	240	1.5	9
EscapeVelocity** [km/s]	10.3	10.8	4.8
EscapeEnergy [eV]	H:0.54 O:8.64	H:0.61 O:9.69	H:0.12 O:1.91
ExobaseTemp* [K]	275	1000	300
ExobaseAltitude* [km]	200	500	250
IonosphereAltitude*** [km]	120	300	150
ThermalEscape [t/a]	0.0013	2800	7800

*Upper limit of collisional domain **at exobase ***electron peak density

Planetary Atmospheres:
a Grand Tour

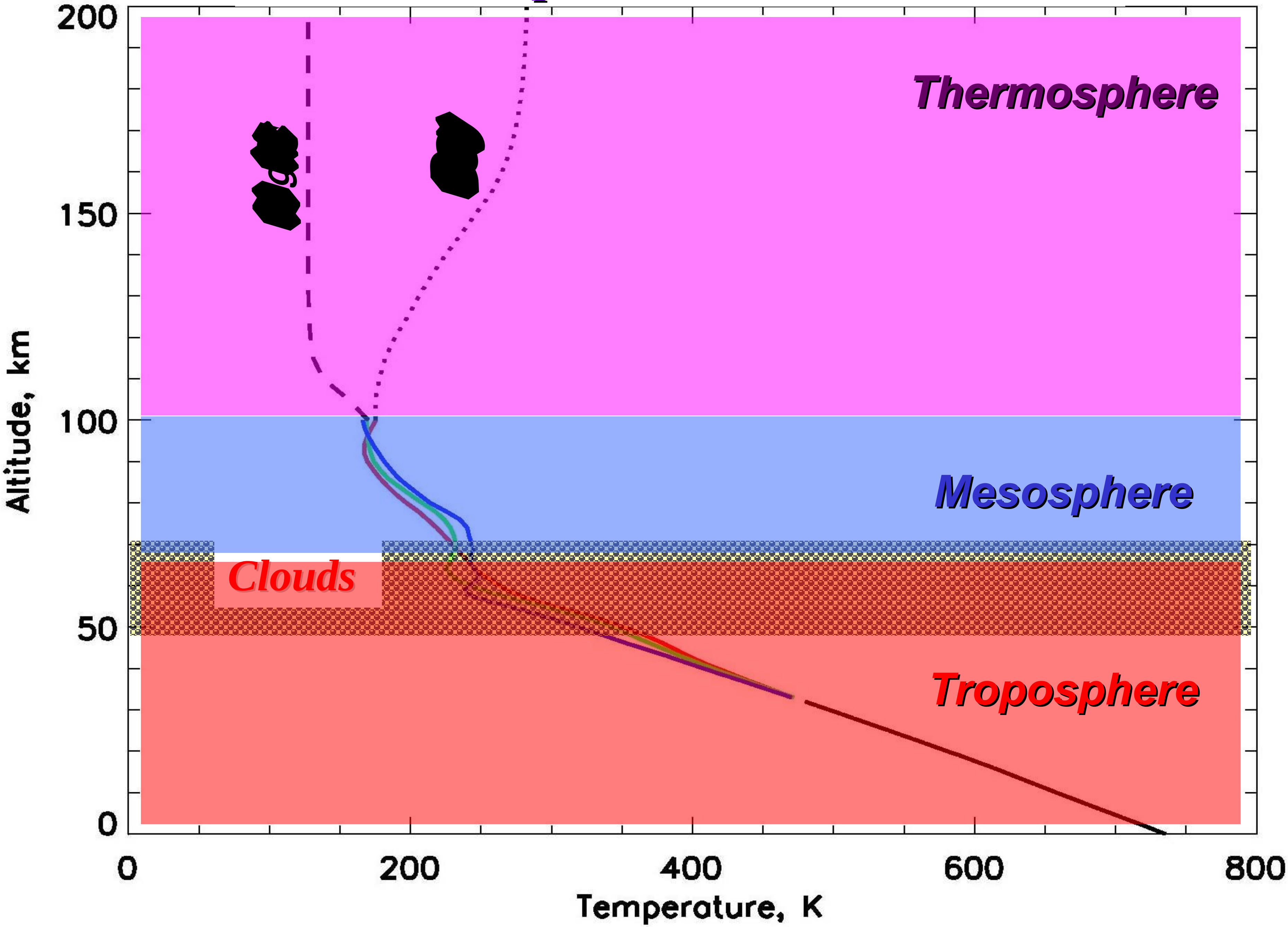
Mercury



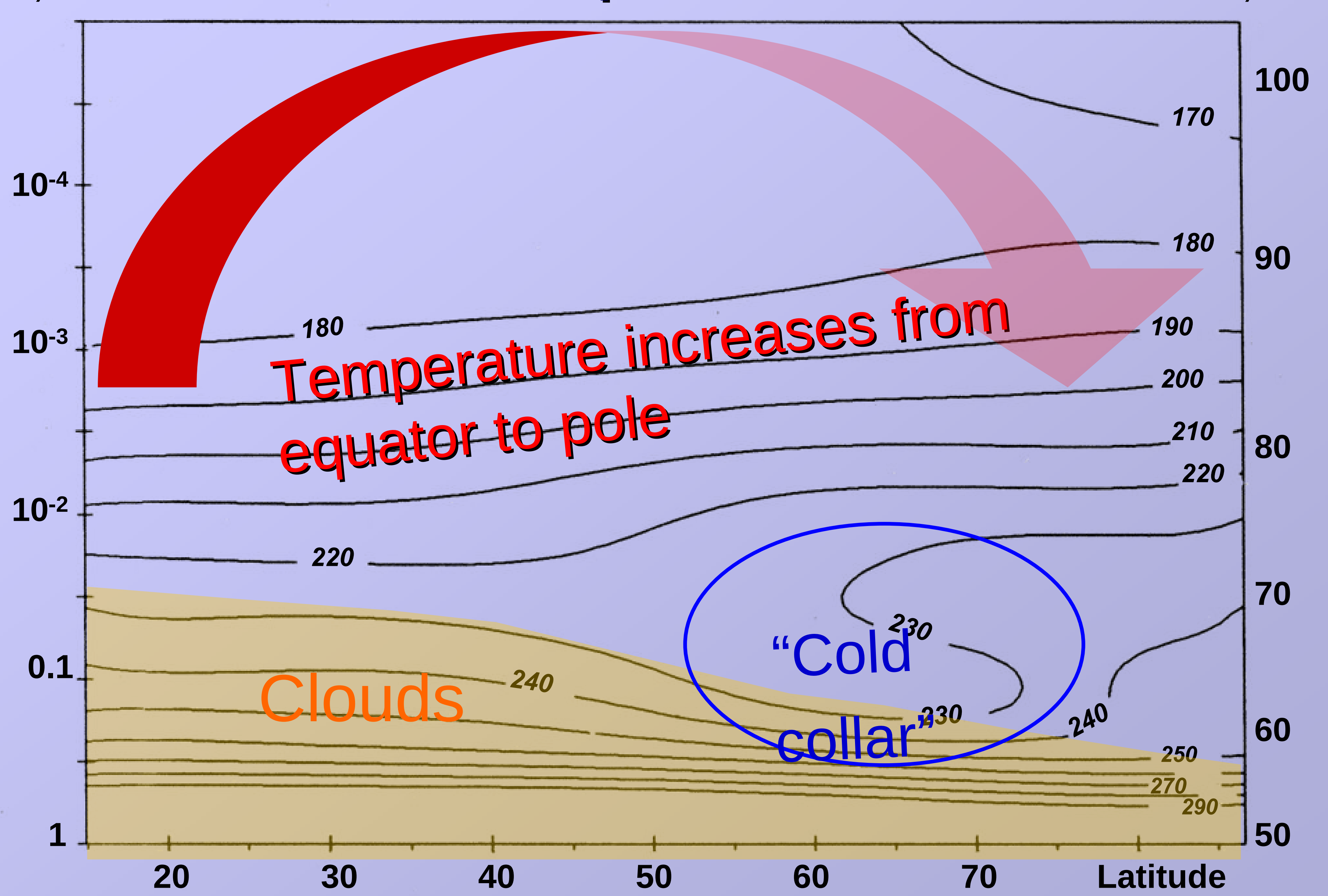
O_2	42%	Spattering
Na	29%	Radioactive decay
H	22%	Solar wind
He	6%	Solar wind and radioactive decay
H_2O	5-10%	In situ production

Venus

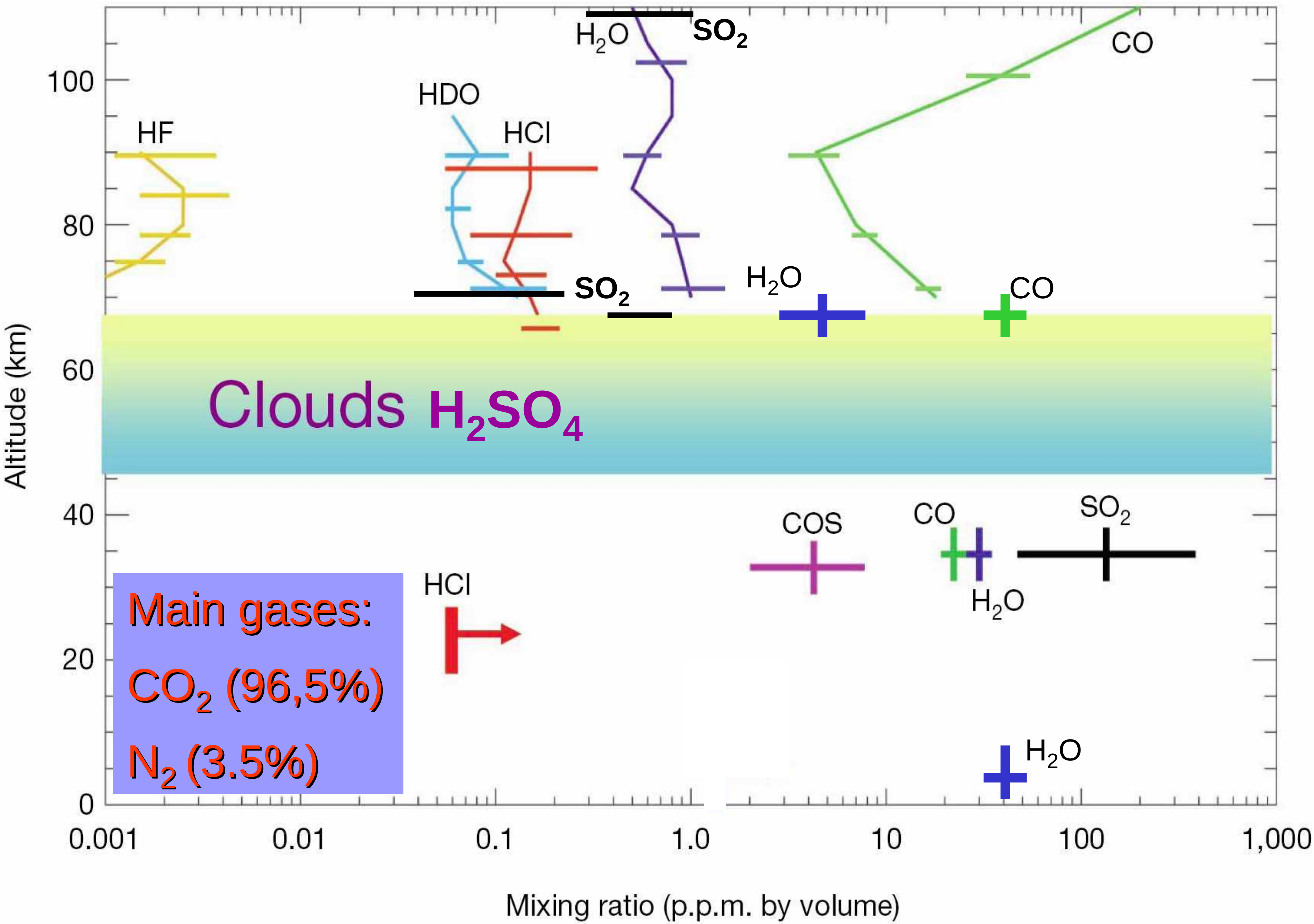
Temperature structure



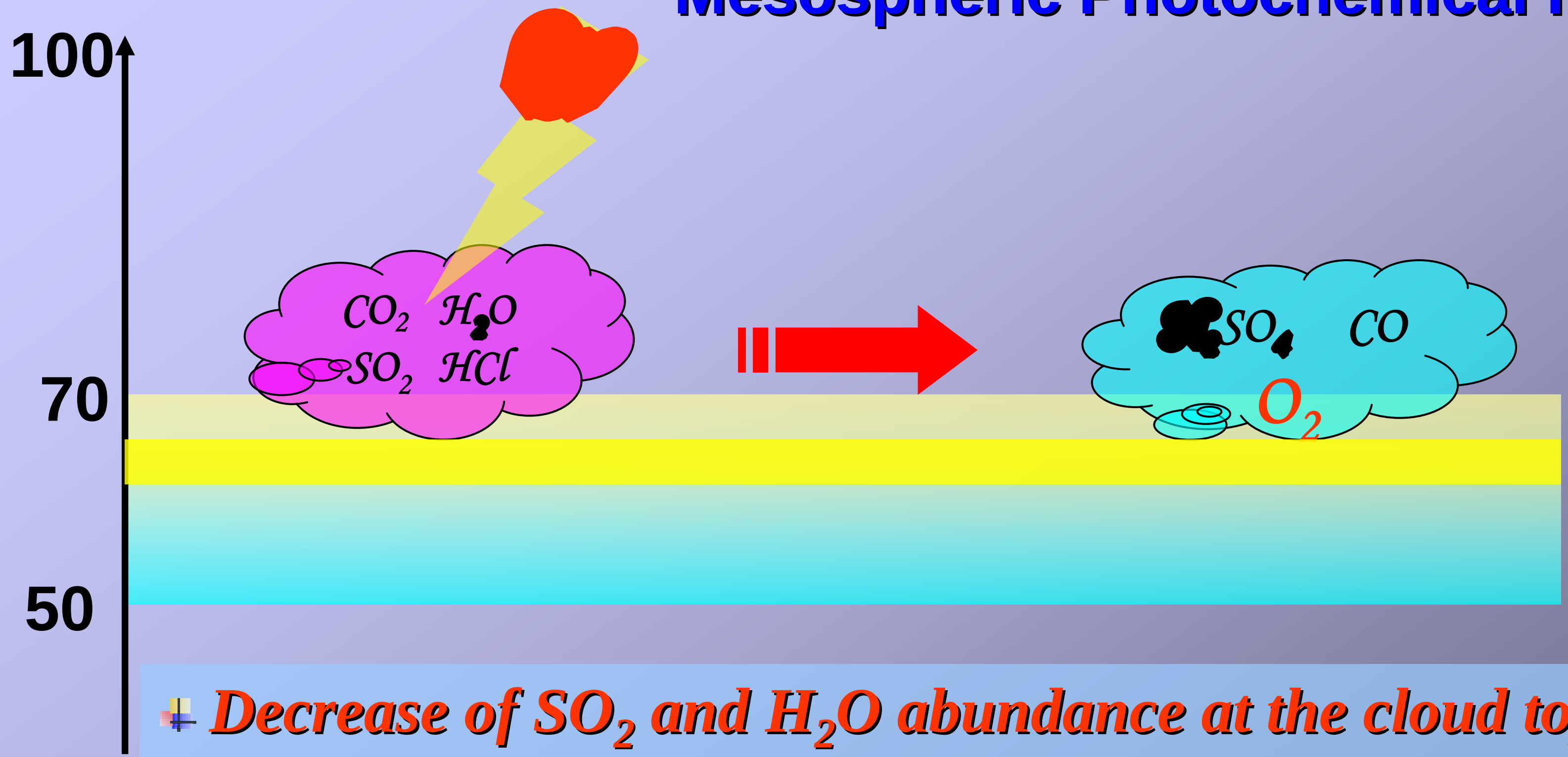
Mesospheric fields



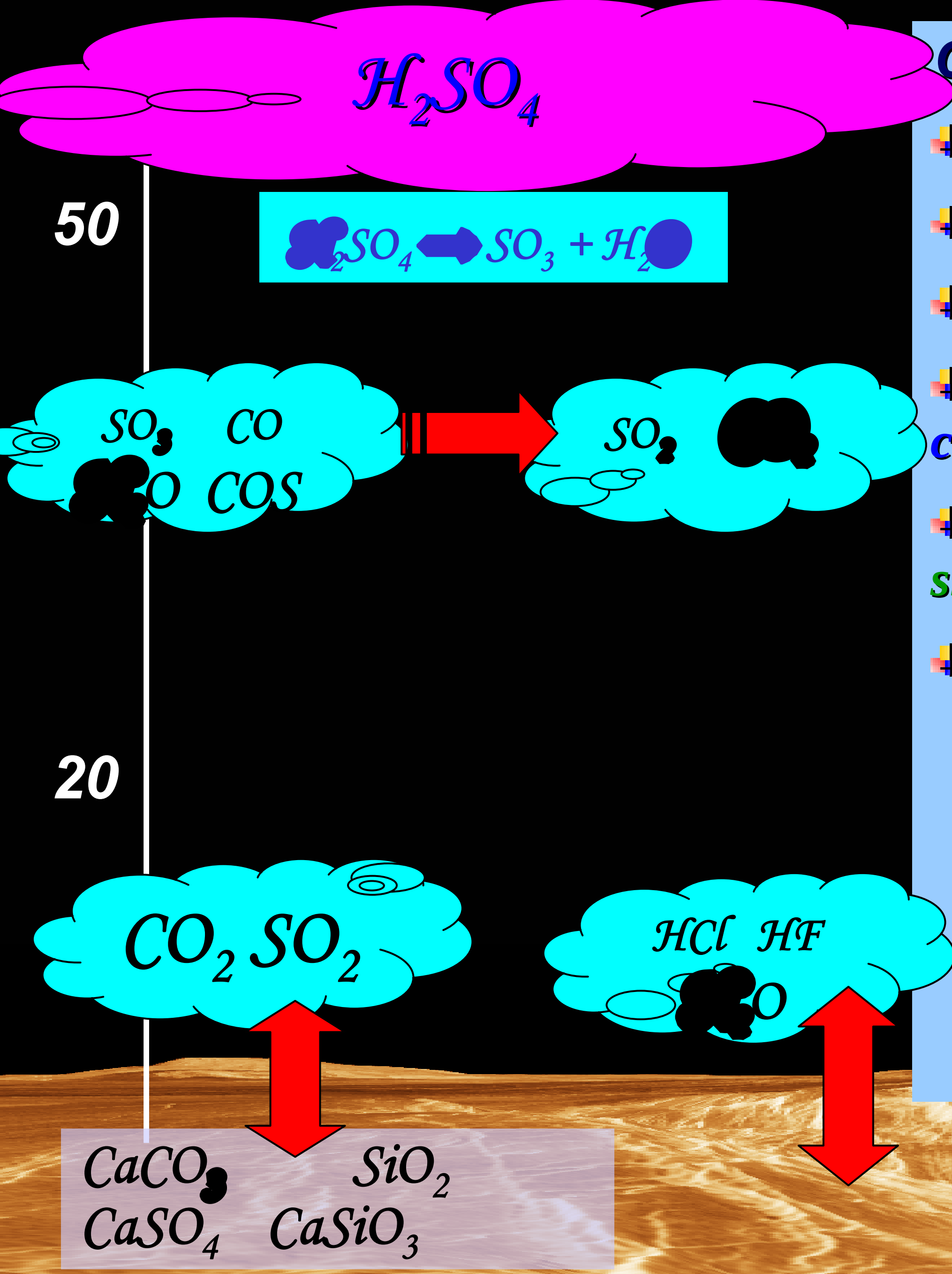
Composition of the Venus atmosphere



Mesospheric Photochemical Factory



- *Decrease of SO_2 and H_2O abundance 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*



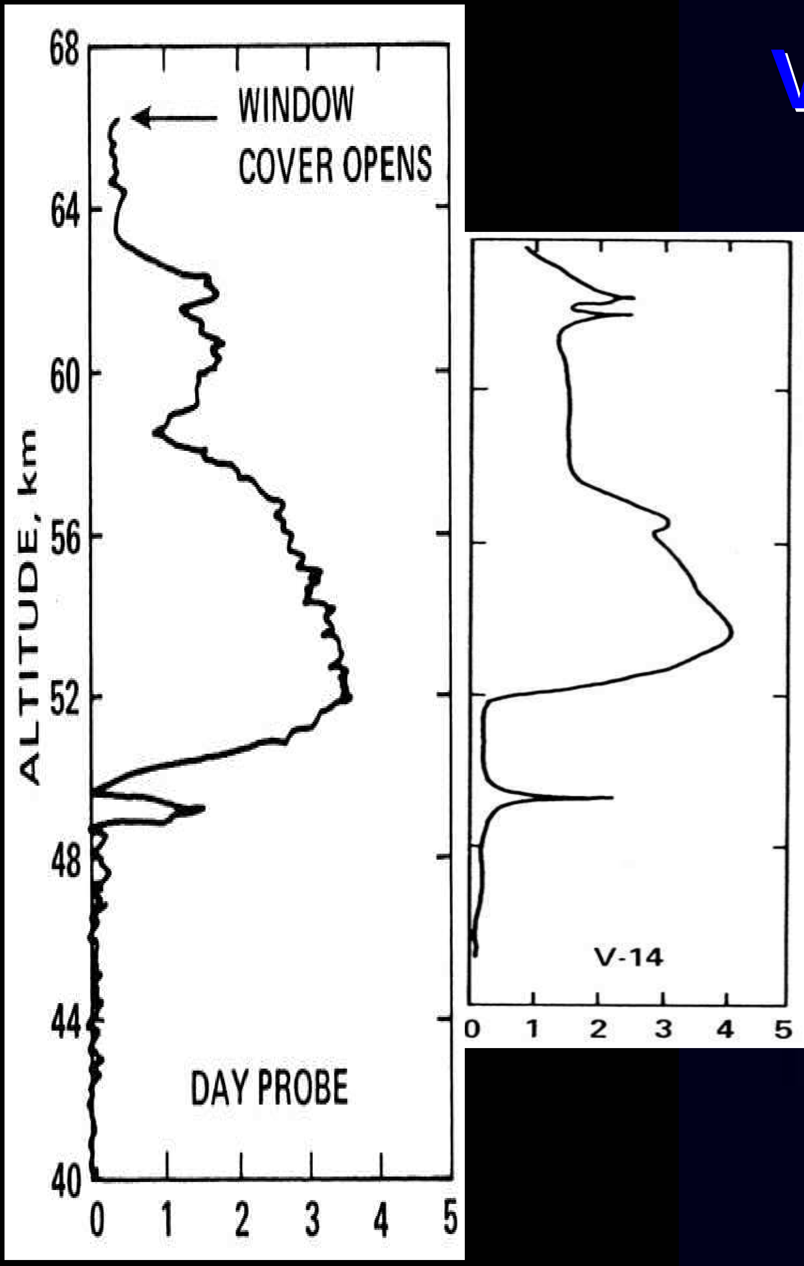
Chemistry of the lower Atmosphere

- Decomposition of H_2SO_4
- No photochemistry
- High temperatures and pressure
- 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

Climate and composition

	Earth	Venus
Surface P, bar	1	**90**
Surface T, °C	+15	**+ 460 (!)**
Composition , %		
N_2	**0.78**	0.035
O_2	**0.21**	~ 0
Atmospheric H_2O	< 0.03	0.00005
Total H_2O, cm	~3	**$\sim 3 \cdot 10^5$**
CO_2	0.0003	**0.965**
SO_2	~0	0.0001
Clouds	**H_2O**	**H_2SO_4 +?**

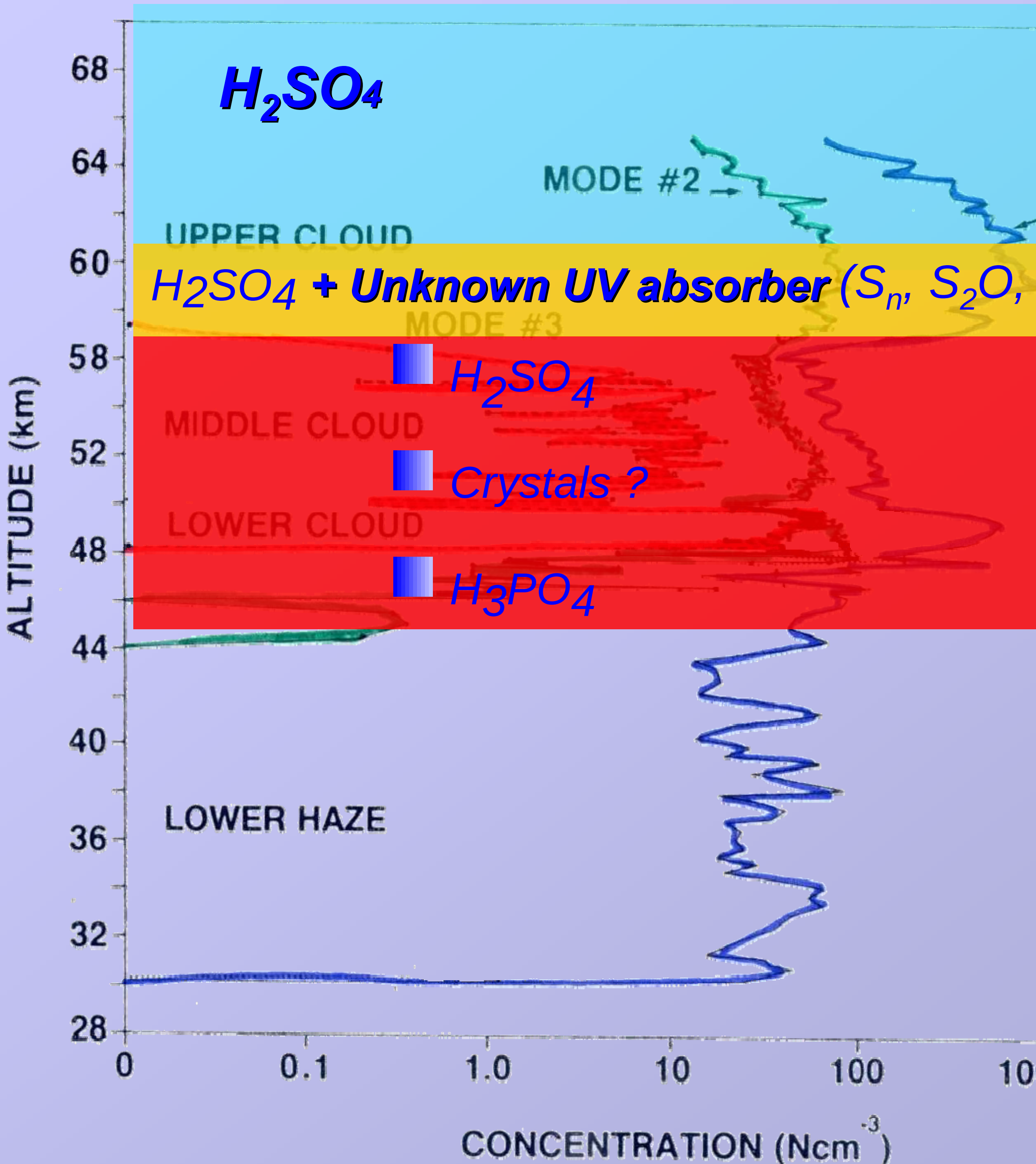
Venus Cloud Properties

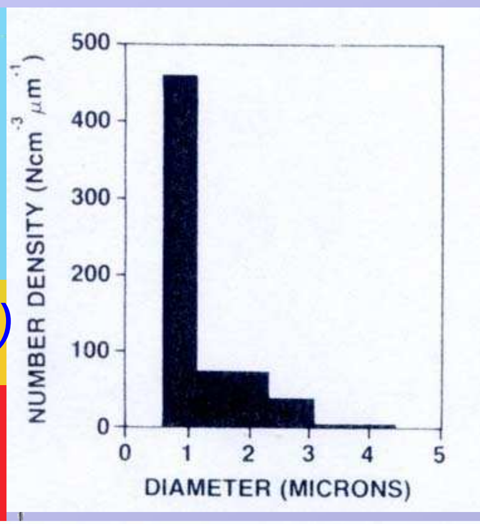


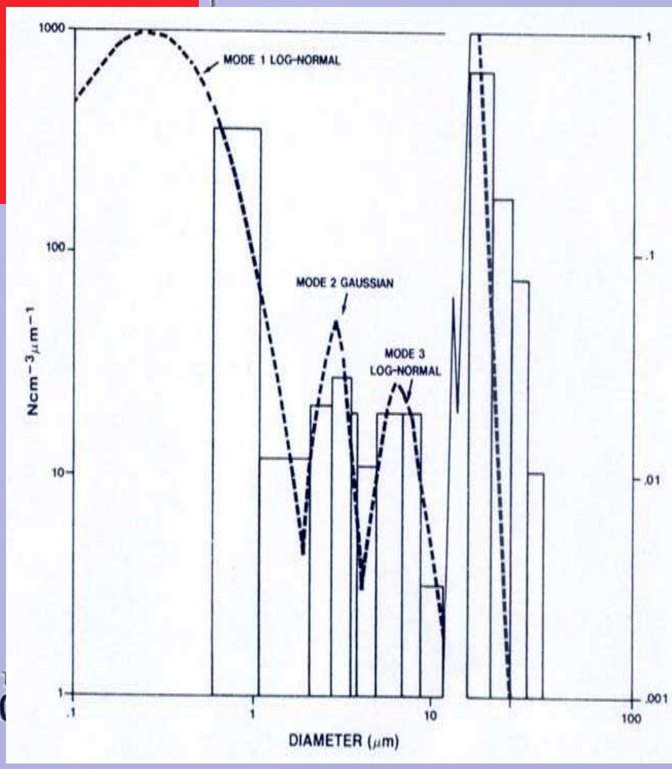
Aerosol extinction, km^{-1}

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

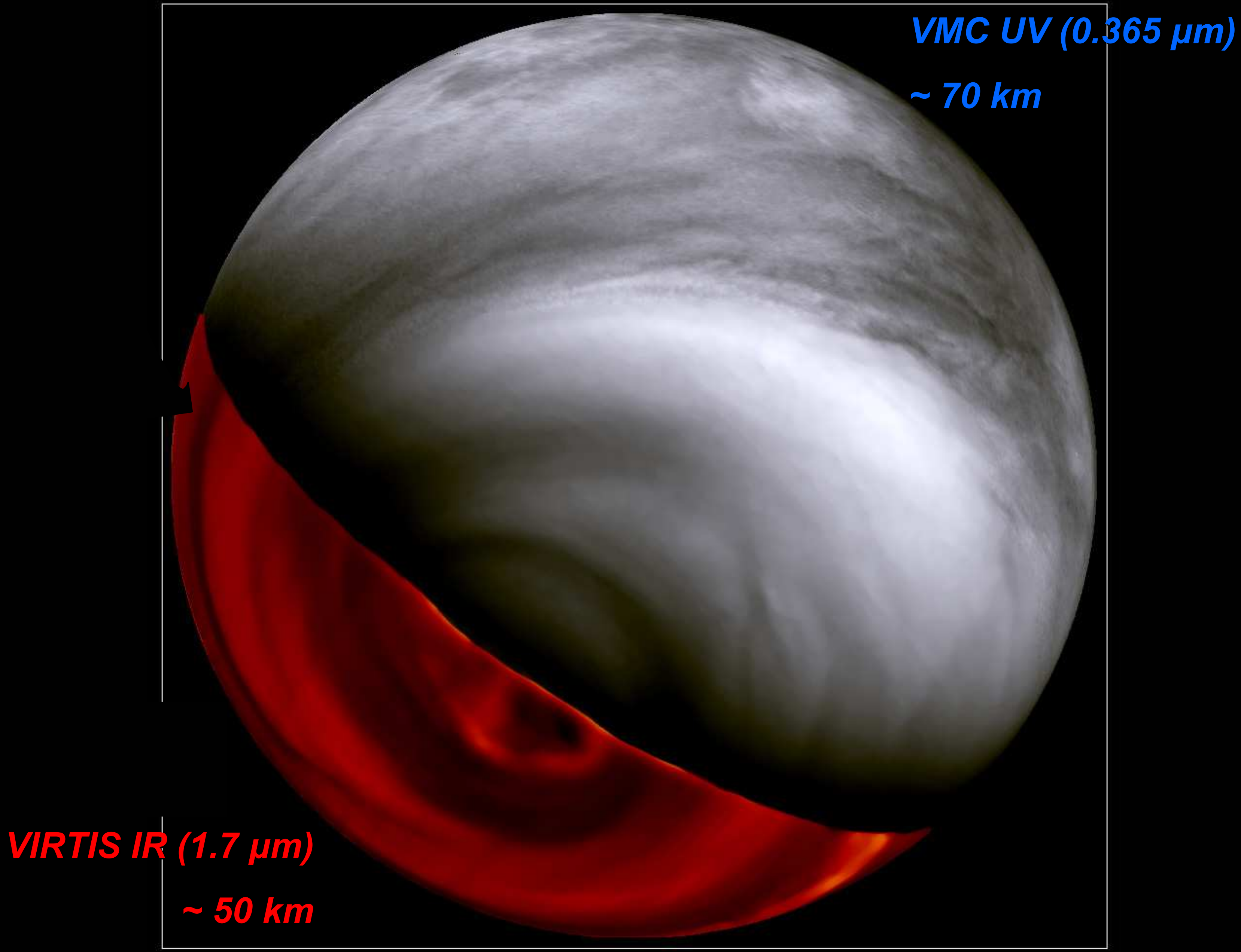
Aerosol population and composition



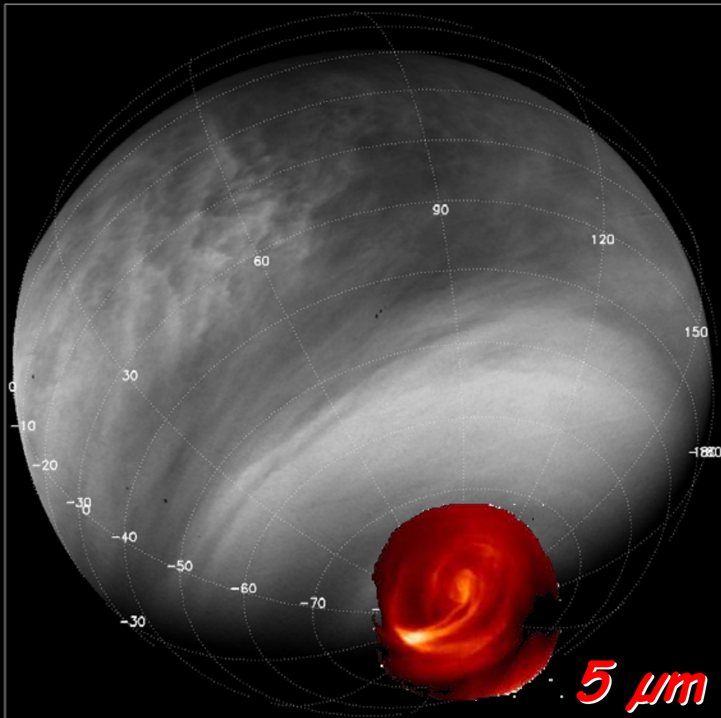


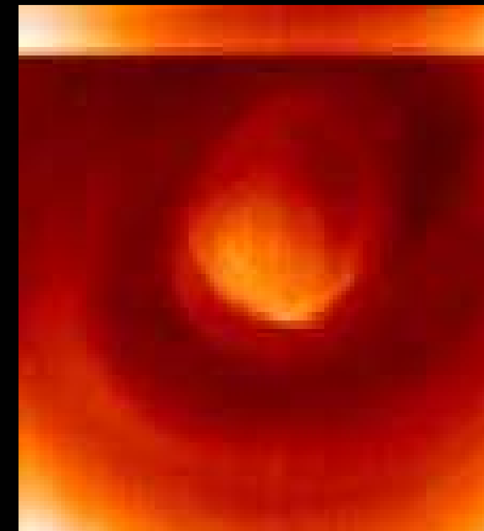


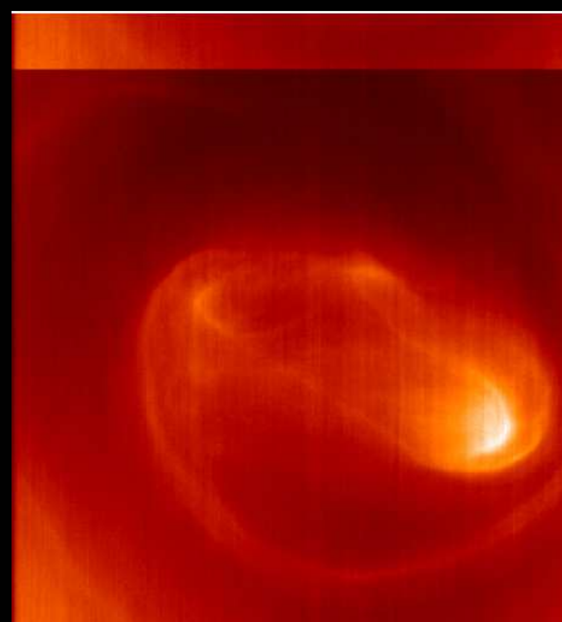
Venus planetary vortex

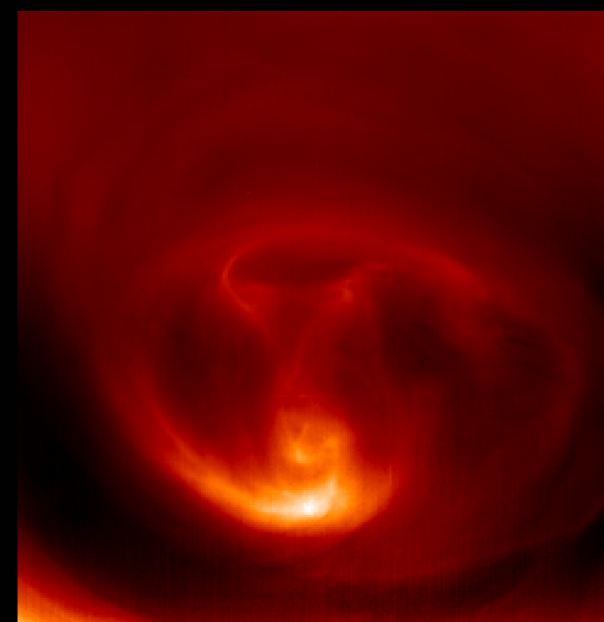


Polar “eye”

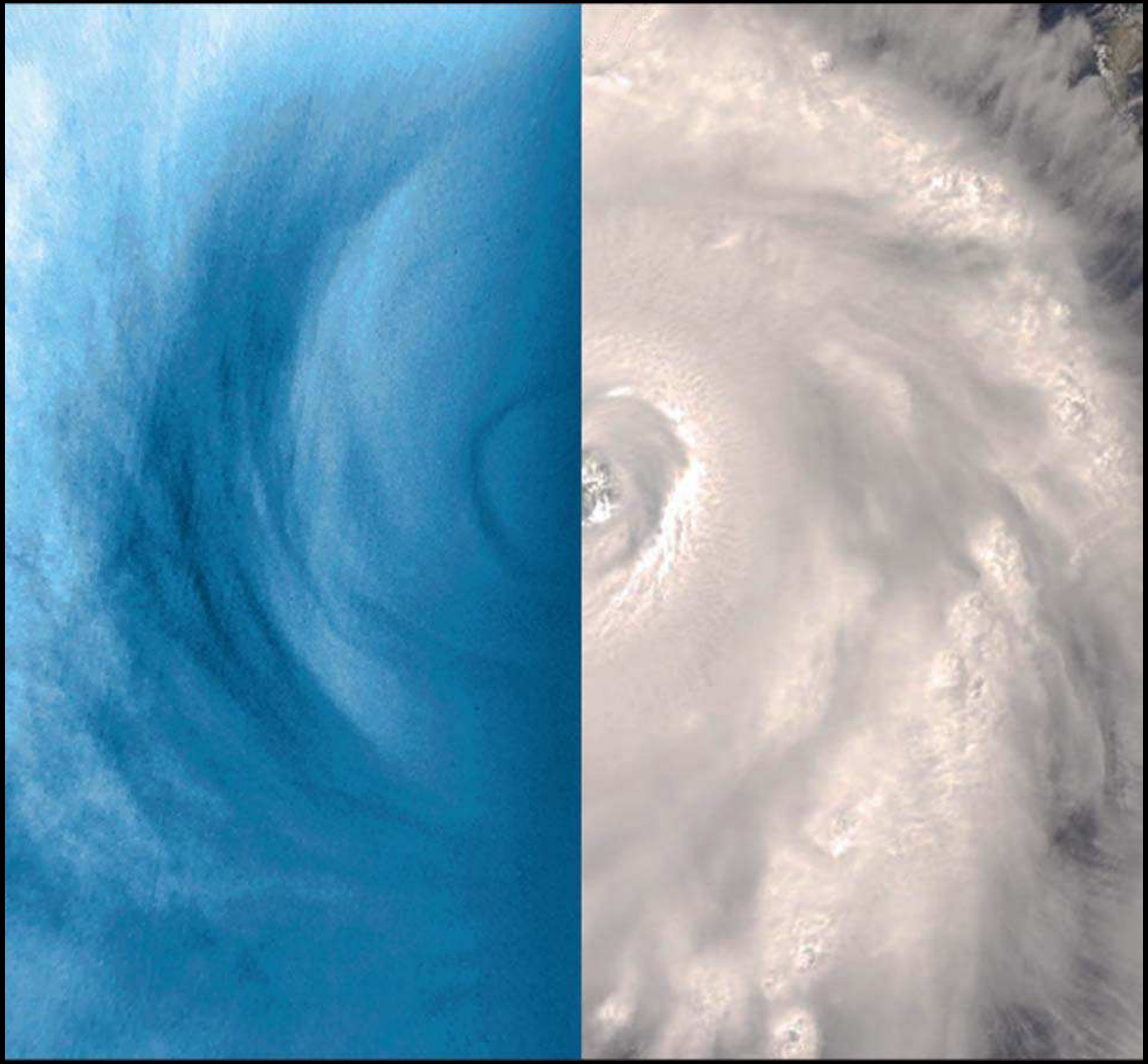






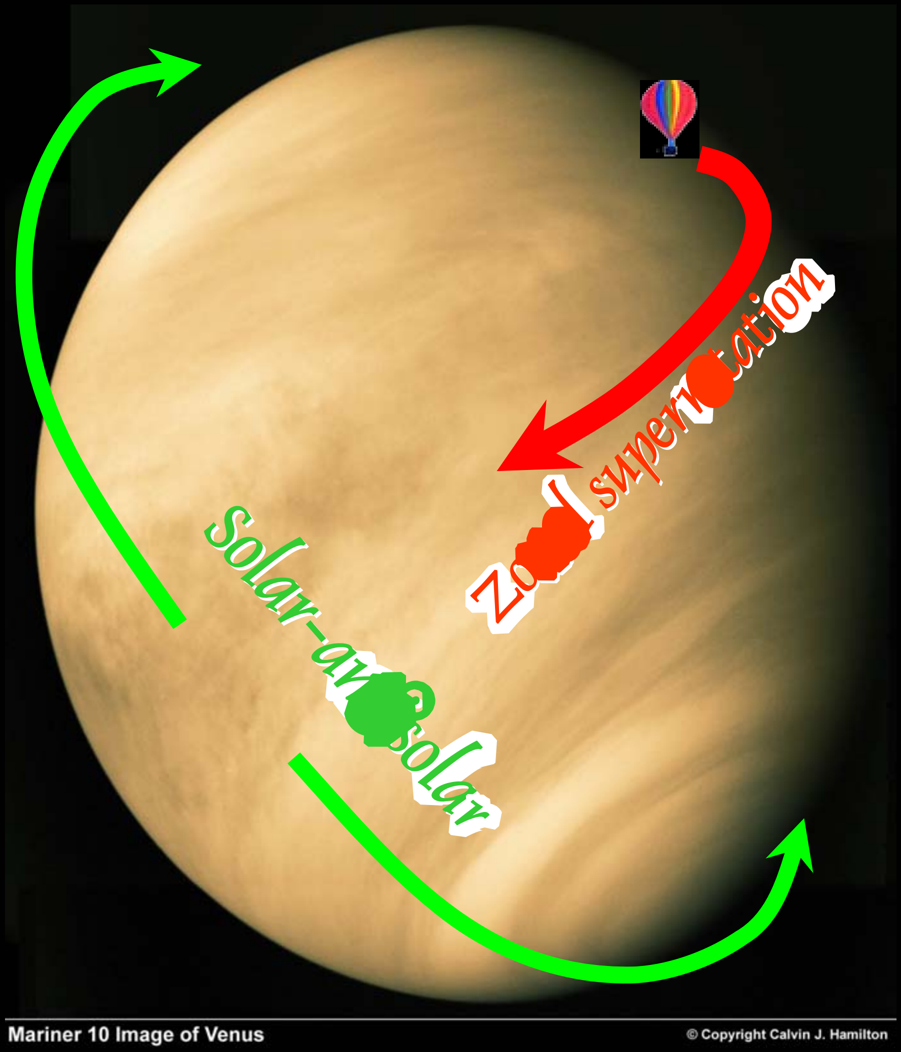


Venus polar vortex and hurricane Frances



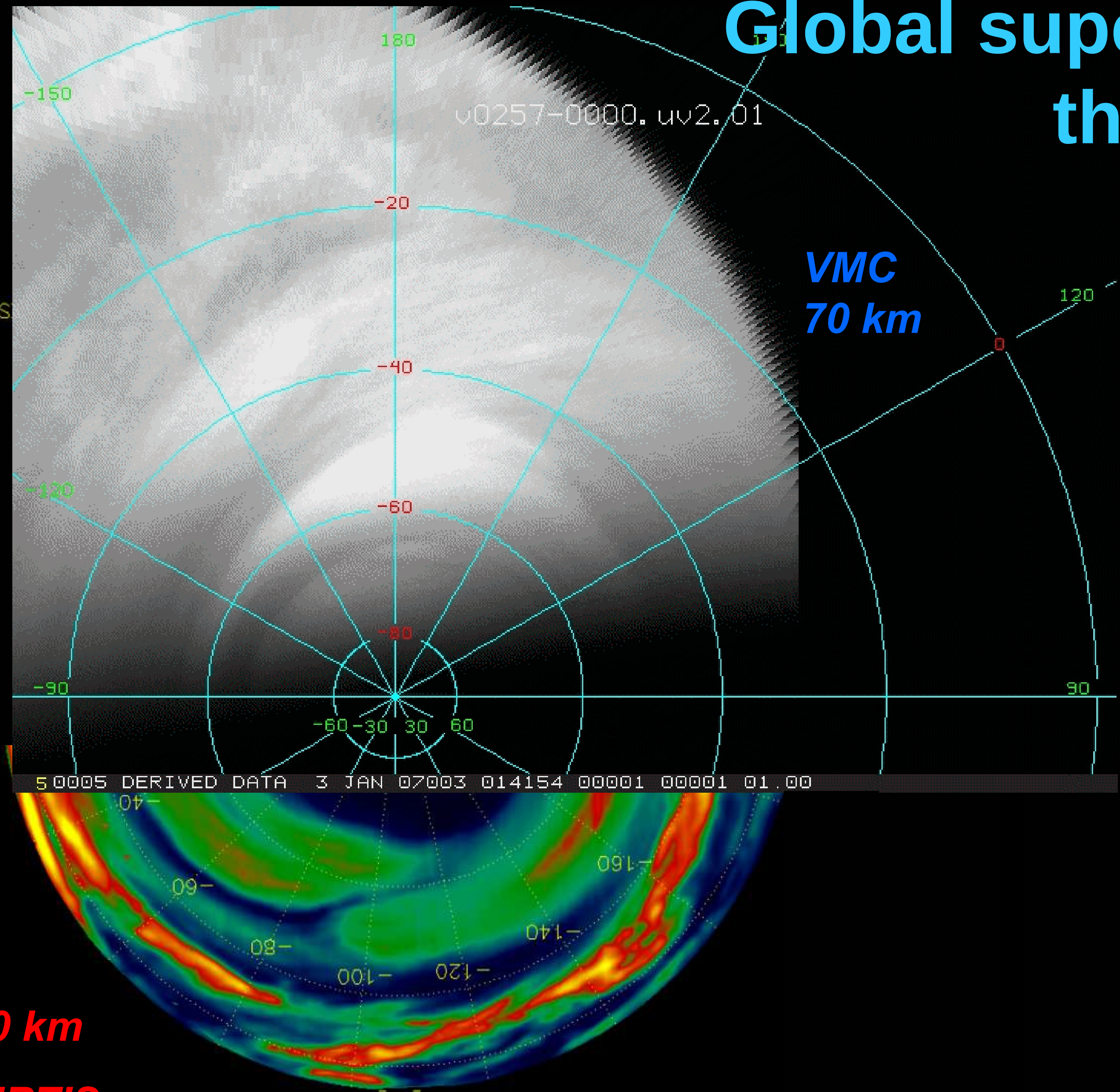
S. Limaye et al.

Global Circulation Regimes



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

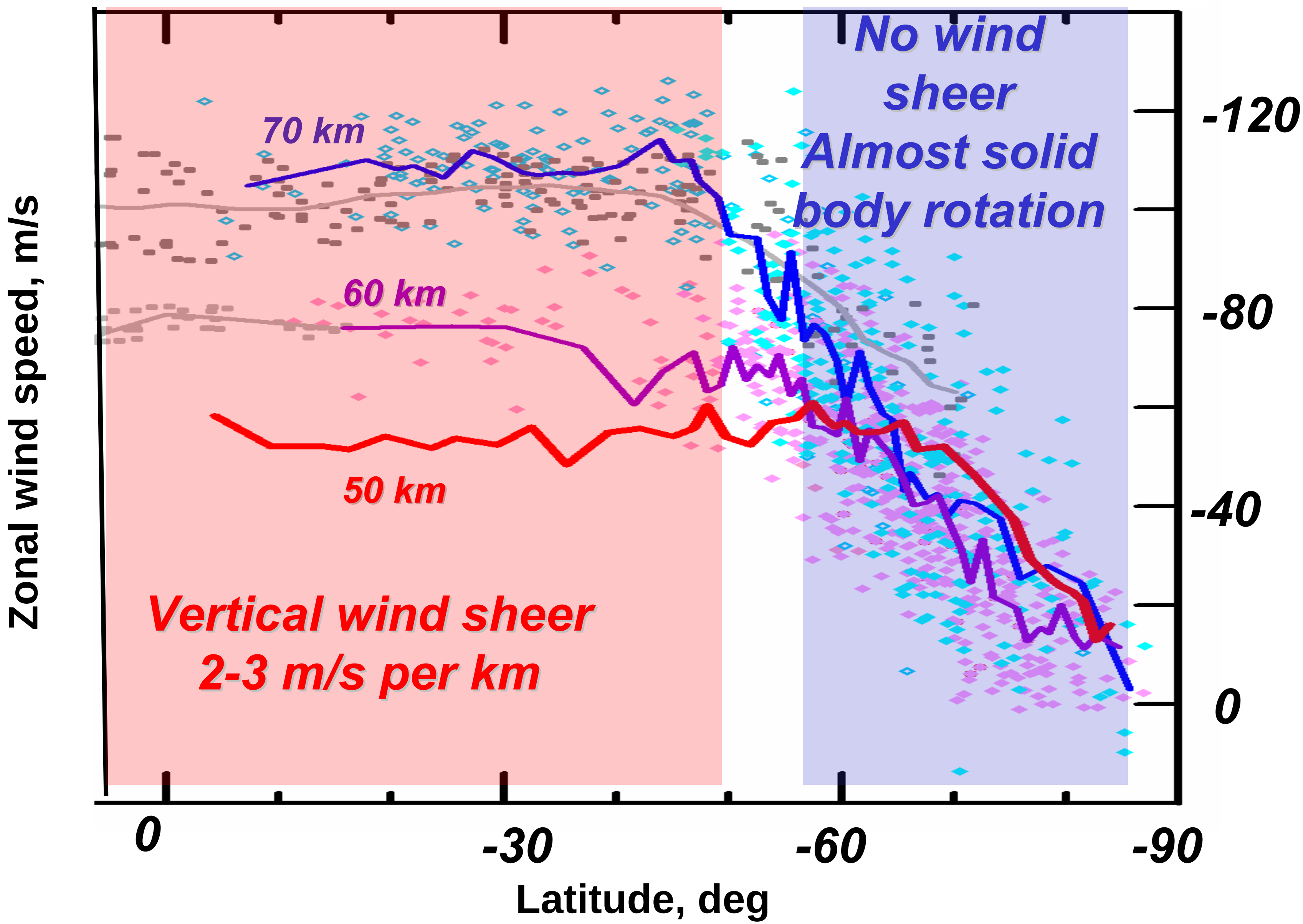
Global super-rotation at the cloud level



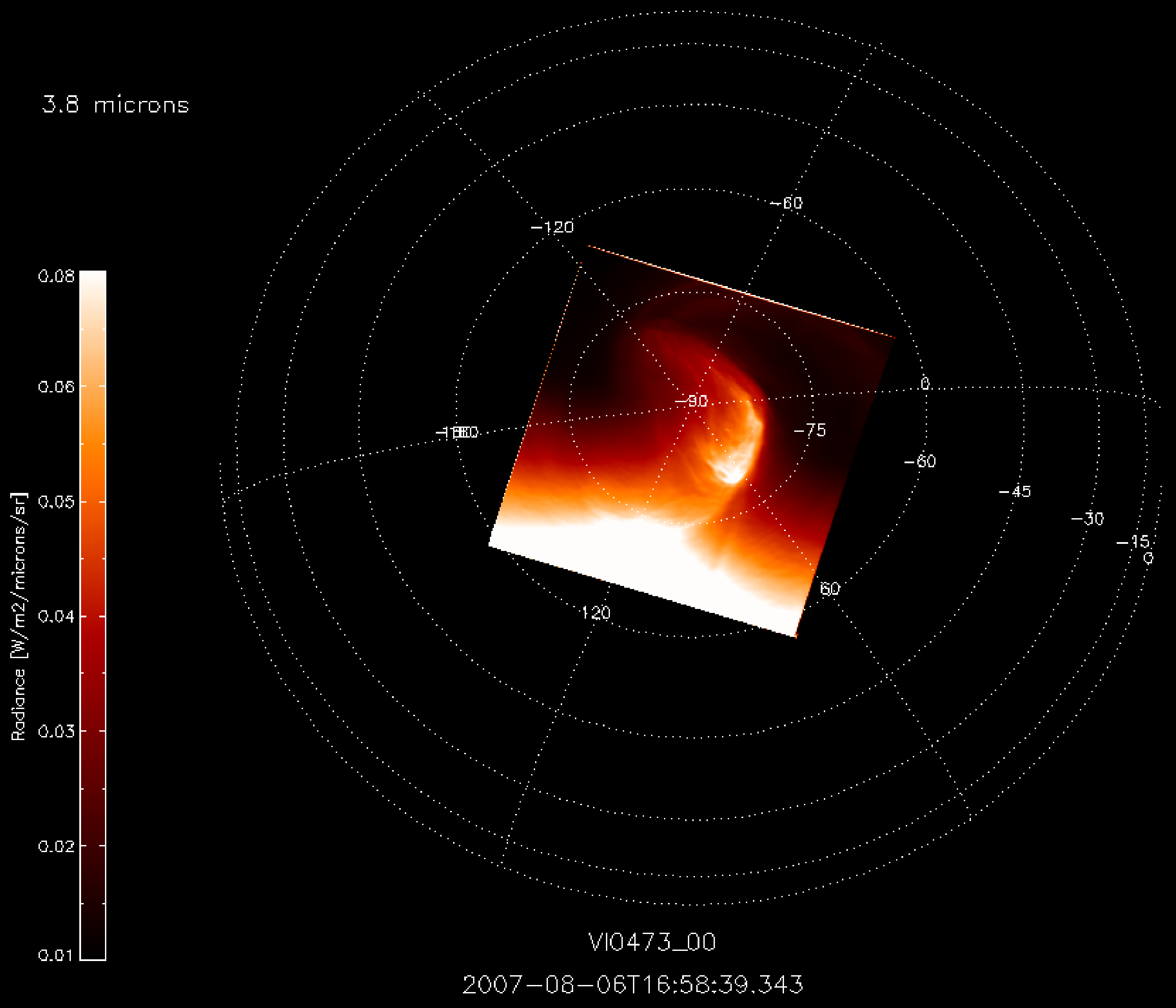
50 km

VIRTIS

Zonal wind field

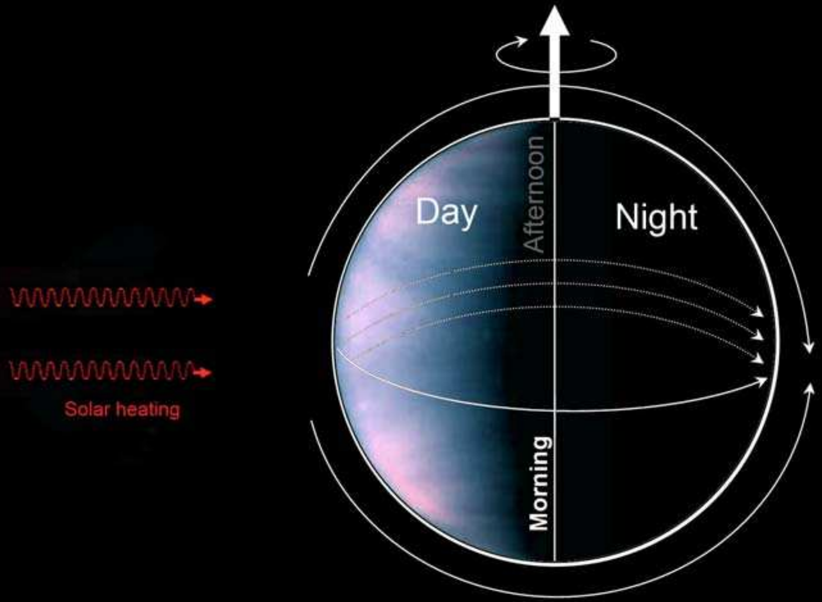


Eye of the polar vortex



Piccioni, Drossart

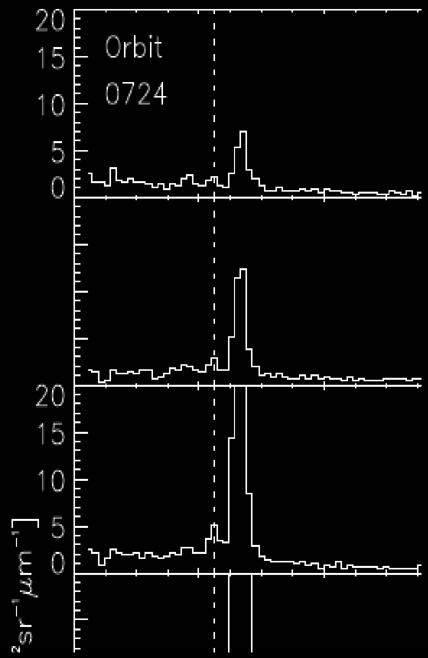
Venus night airglow

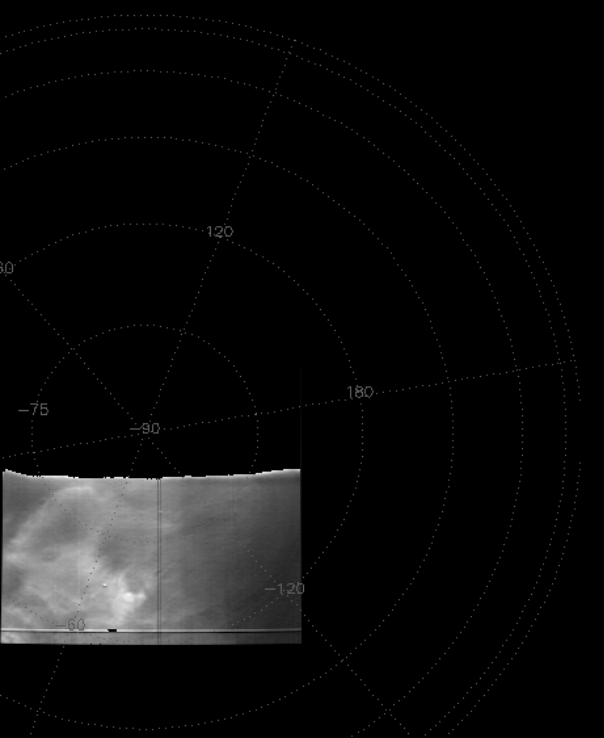


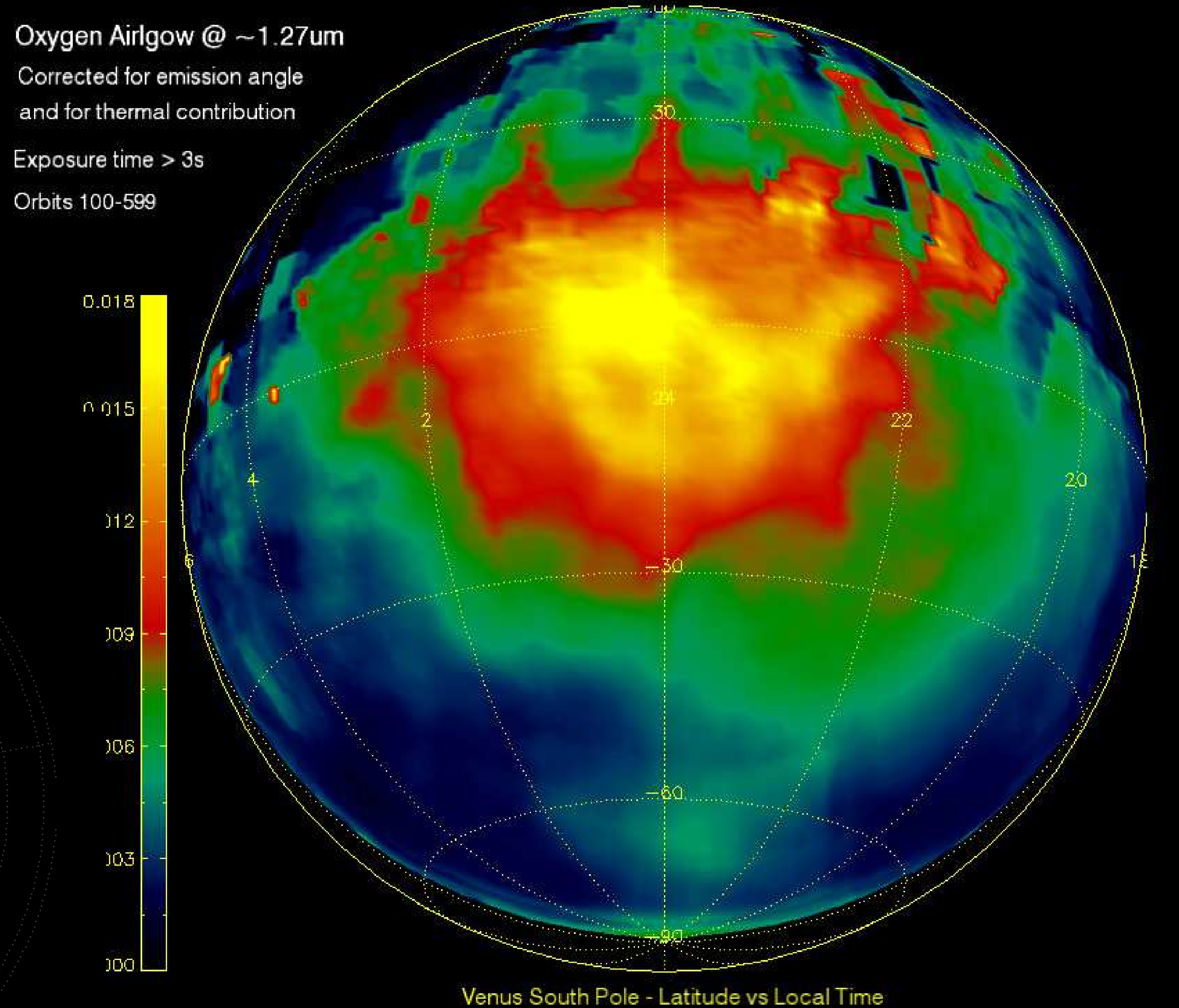
Recombination	$O + N \dashrightarrow NO^*$
3-body recombination	$O + N + CO_2 \dashrightarrow NO + CO_2$
Emission	$NO^* \dashrightarrow NO + h\nu$
Loss	$N + NO \dashrightarrow N_2 + O$

Recombination	$O + O + CO_2 \dashrightarrow O_2^* + CO_2 + 5.17\ eV$
De-excitation	$O_2^* \dashrightarrow O_2 + h\nu$
Quenching	$O_2^* + M \dashrightarrow O_2 + M$

O_2 airglow at 1.27 μm (VIRTIS)

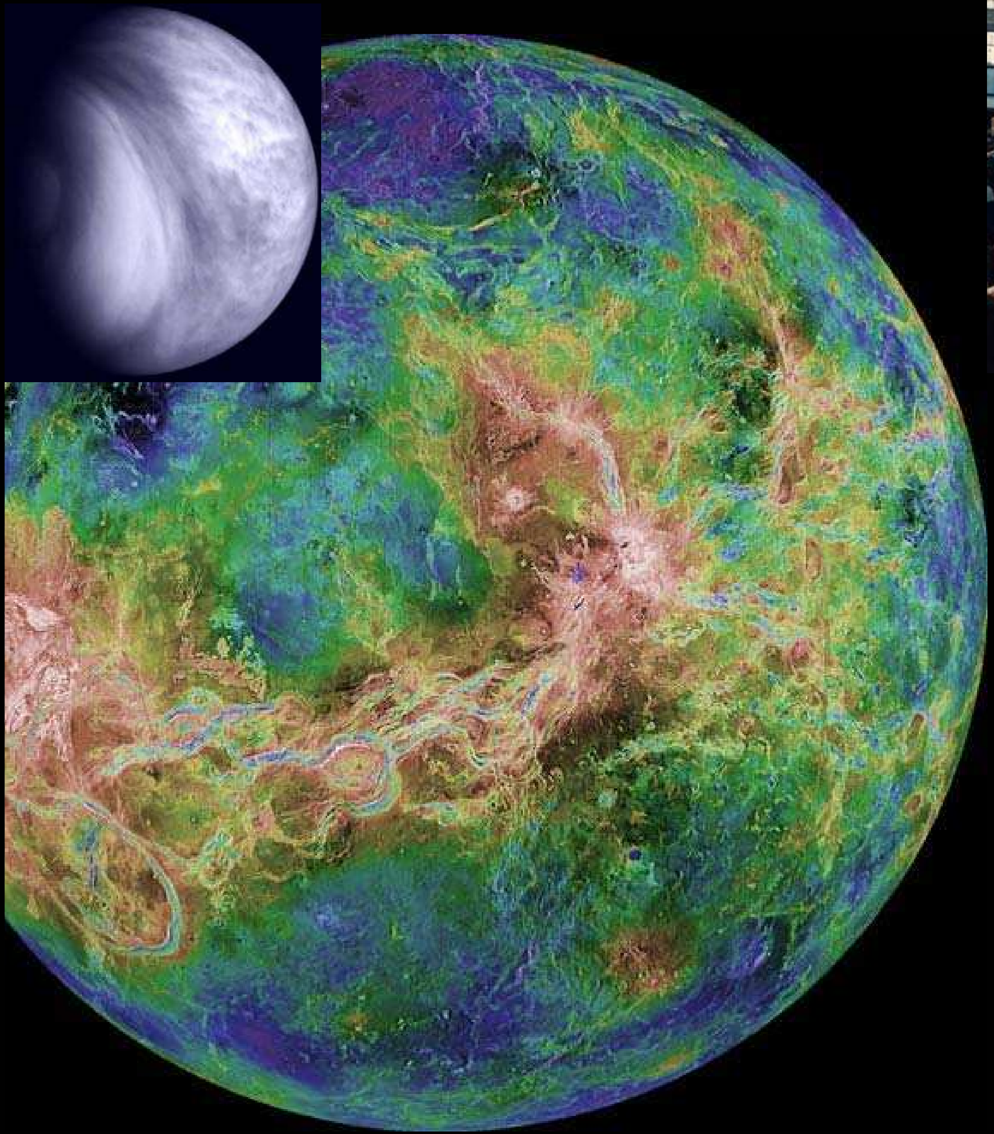


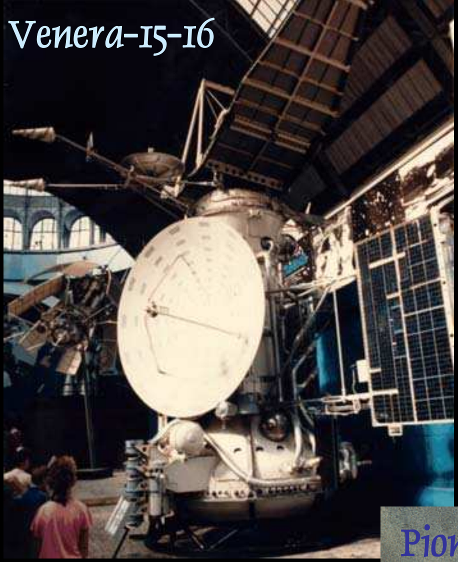


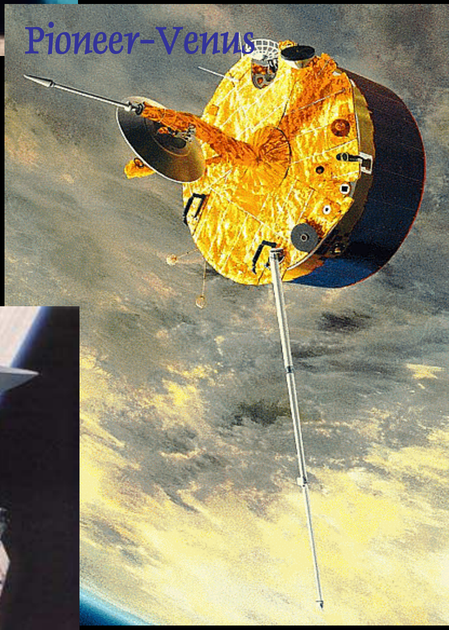


Gerard, Drossart, Piccioni

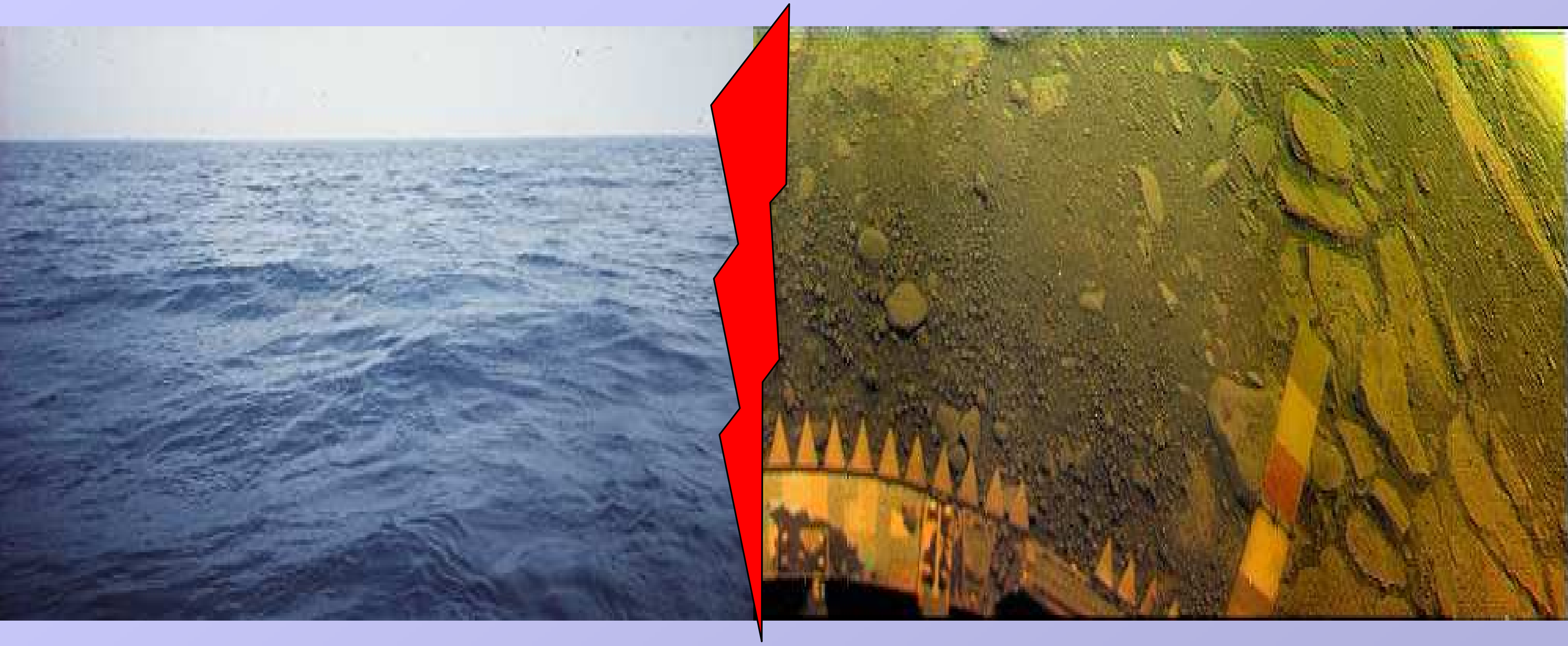
Venus unveiled…





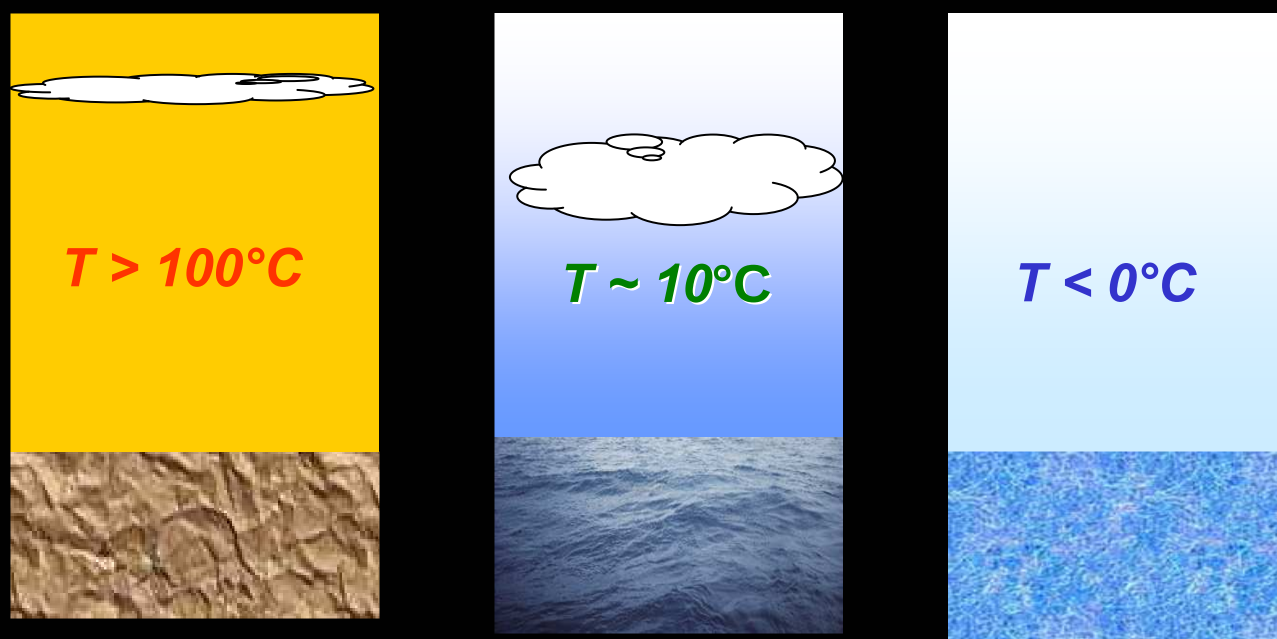


Greenhouse effect and water loss (1)

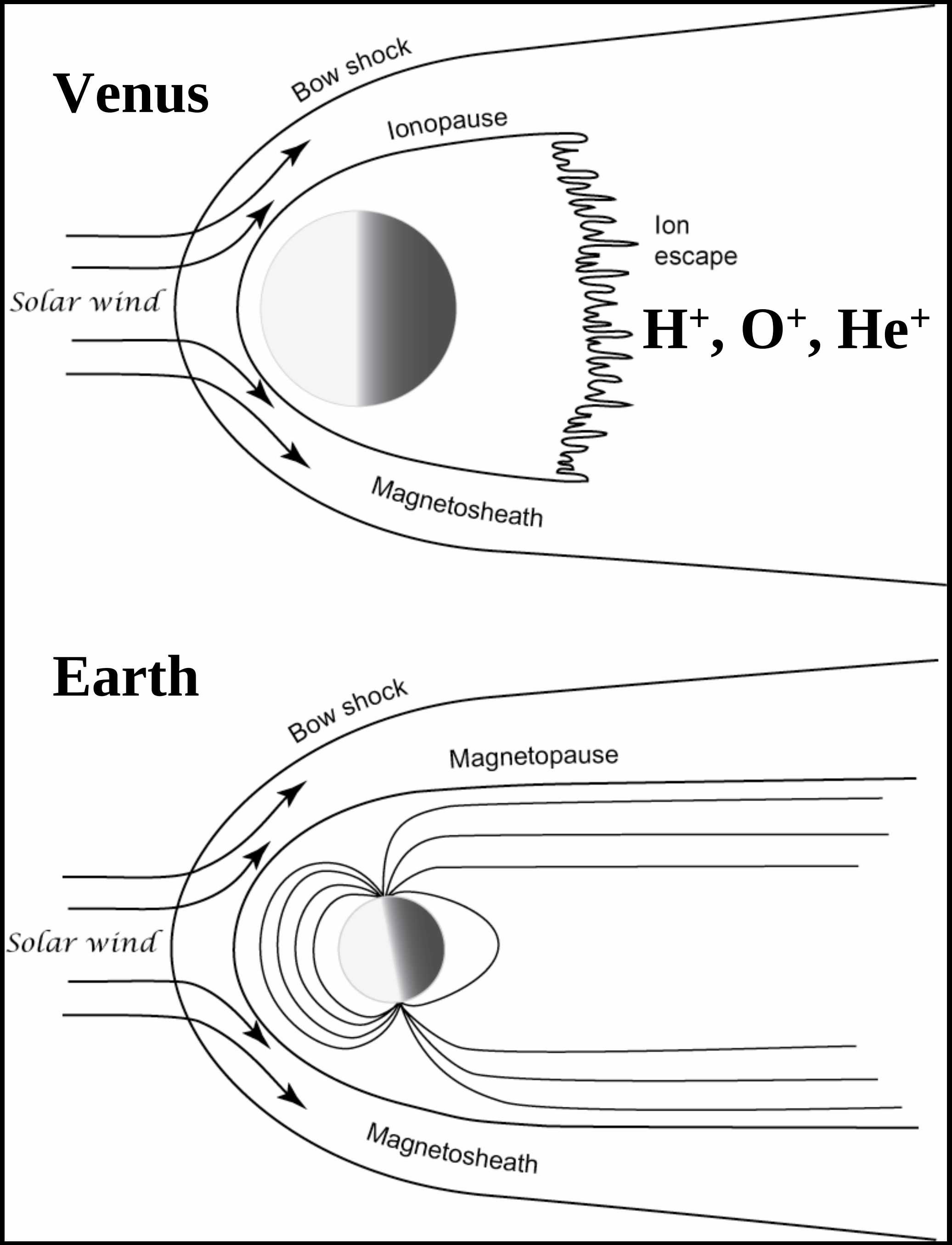


- Similar volatile inventories at origin
- Present water amount: $H_2O_{VENUS} \sim 10^{-5}\ H_2O_{EARTH}$
- Deuterium enrichment: $(D/H)_{VENUS} \sim 150\ (D/H)_{EARTH}$

“Earth” at different distances from the Sun

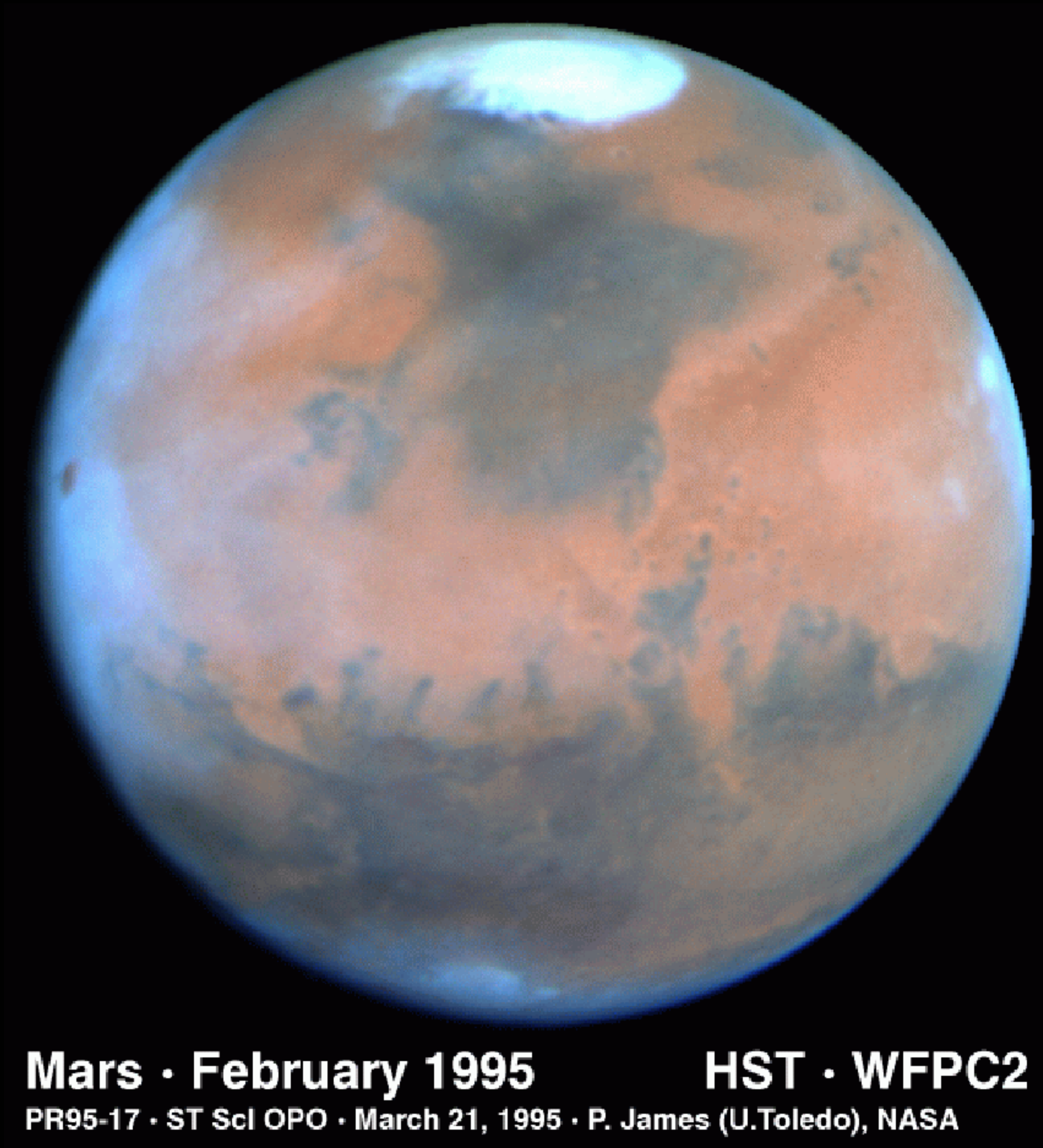


Plasma environment and escape processes



Mars

Basic facts about Mars

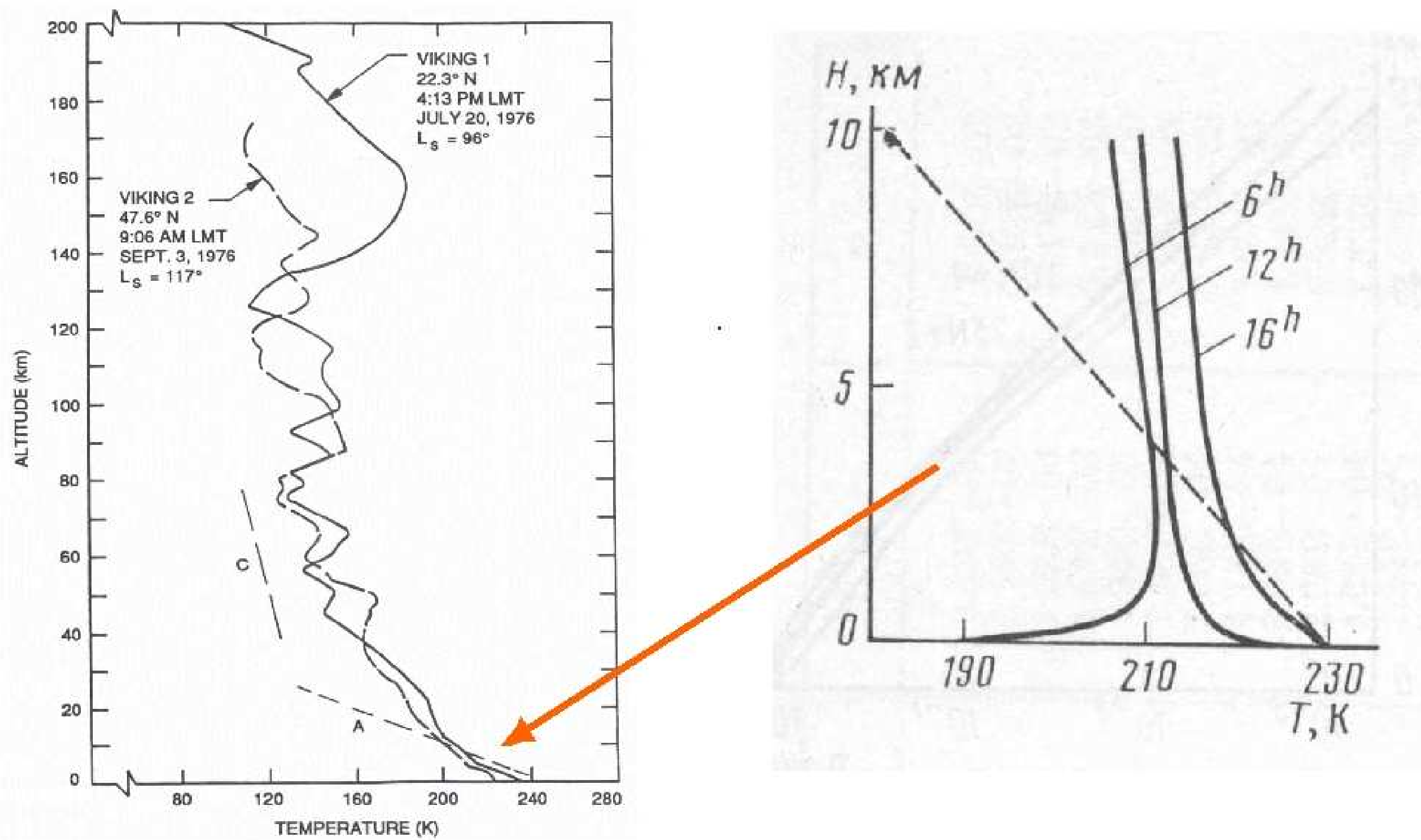


- Orbital radius - 1.52 a.u.
- Eccentricity ~0.09
- Obliquity 25 deg
- Sidereal day 24h 37 min
- Orbital period 687 days
- R ~ 3400 km
- Surface P ~ 6 mbar
- Surface T=120-280K
- Atmospheric composition
  - 95.3% CO_2
  - 2.7% N_2
  - 0.13% O_2
  - 100-1000 ppm H_2O

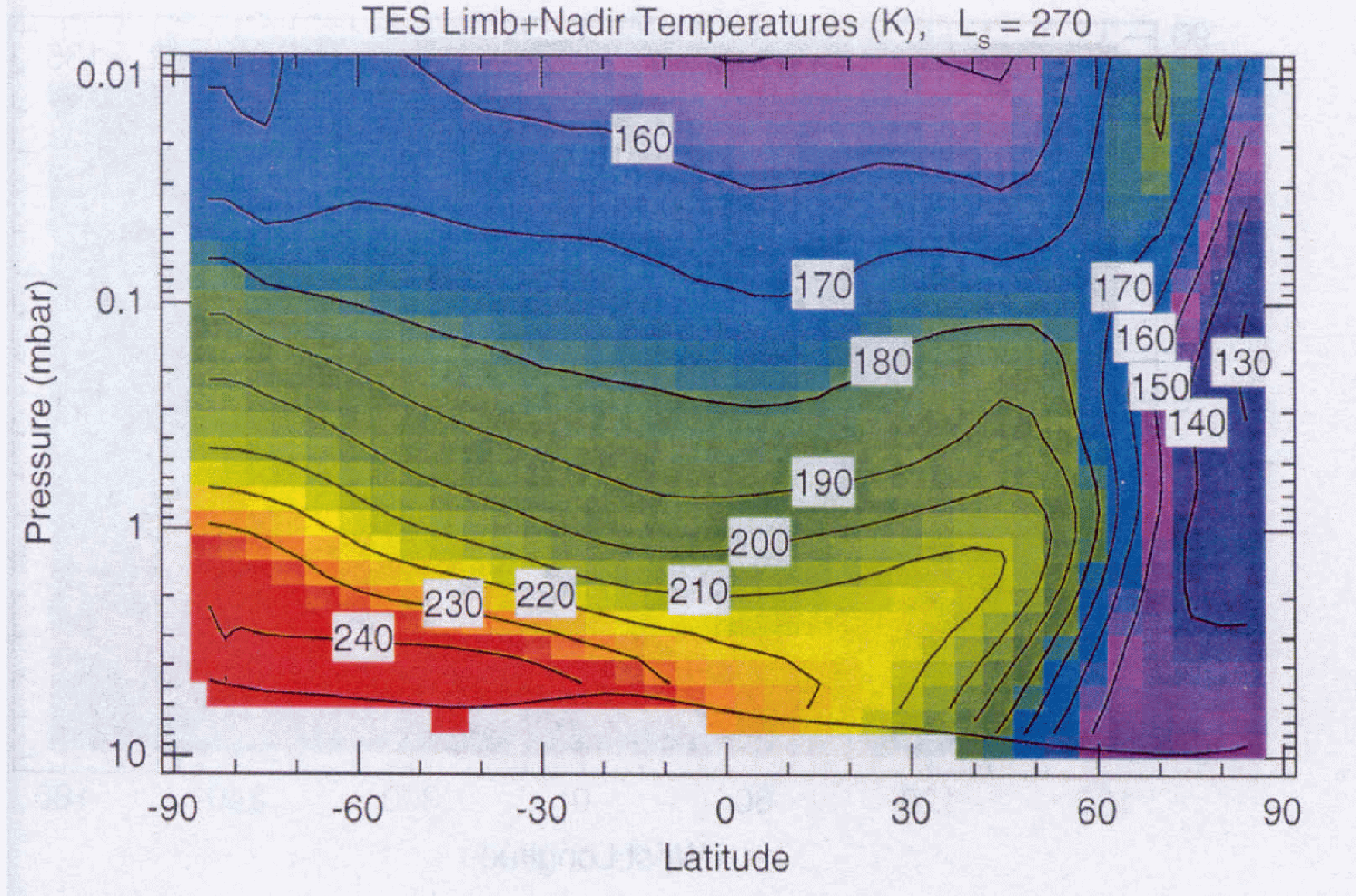
Atmospheric temperatures (1)

Viking landers

Boundary layer



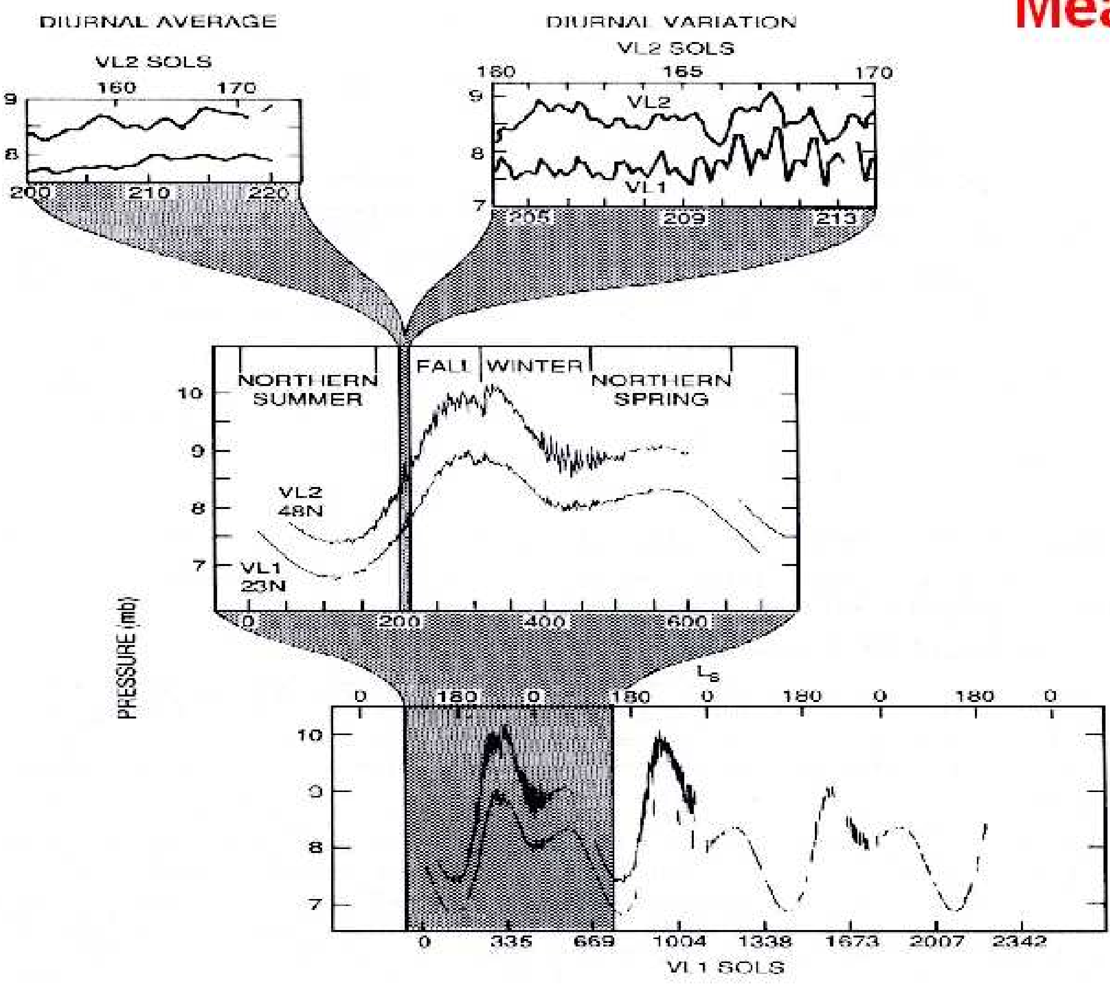
Mars atmospheric temperatures



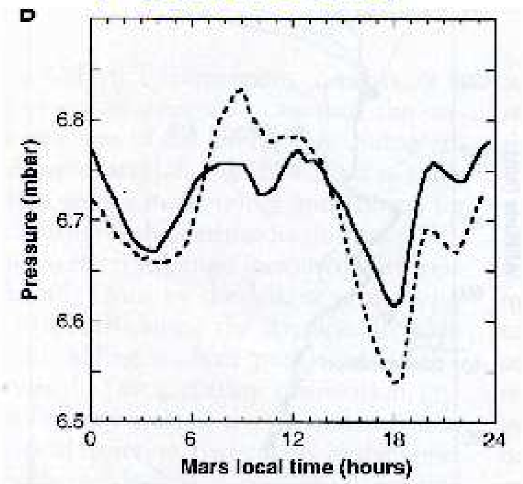
Surface pressure variations

Viking landers

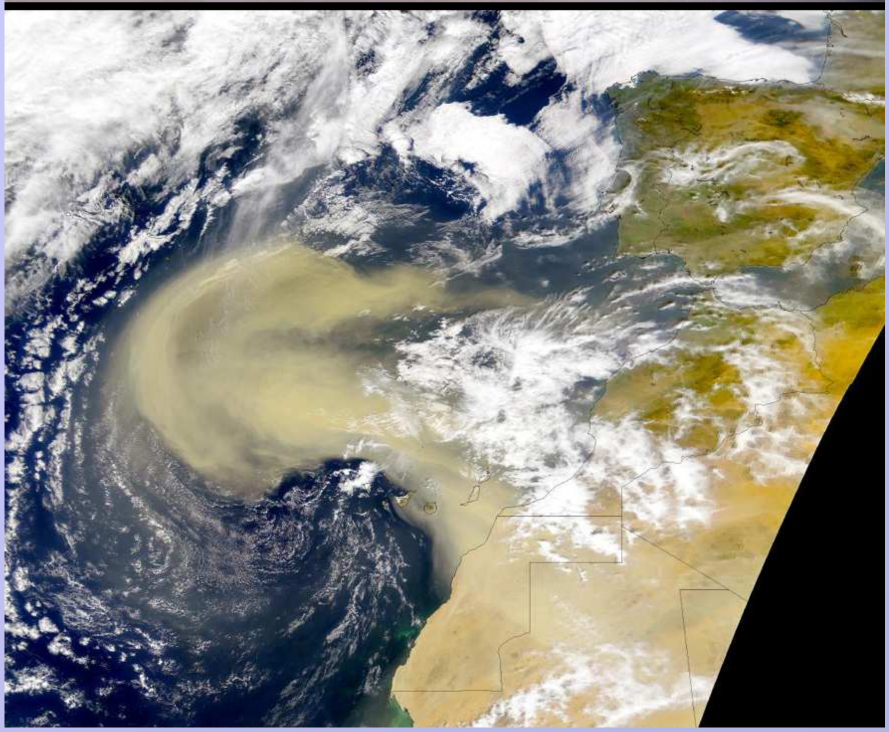
Mean pressure ~6.1 mbar

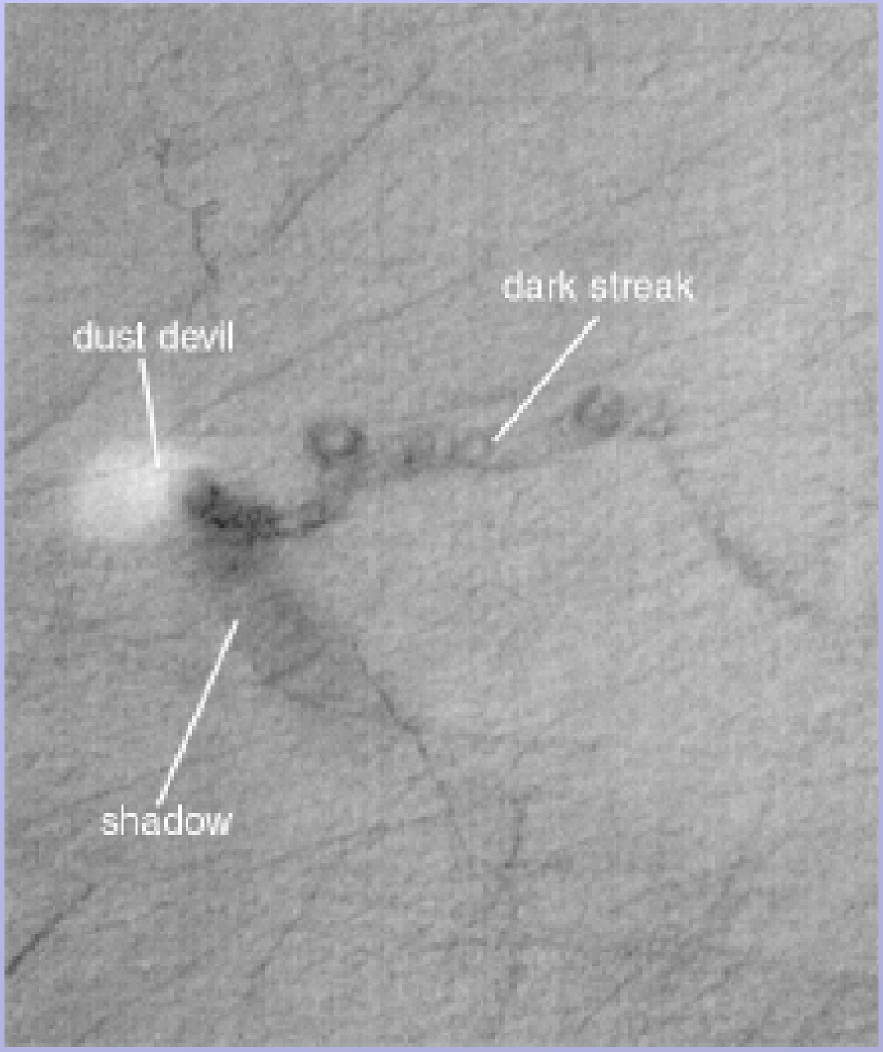


Pathfinder

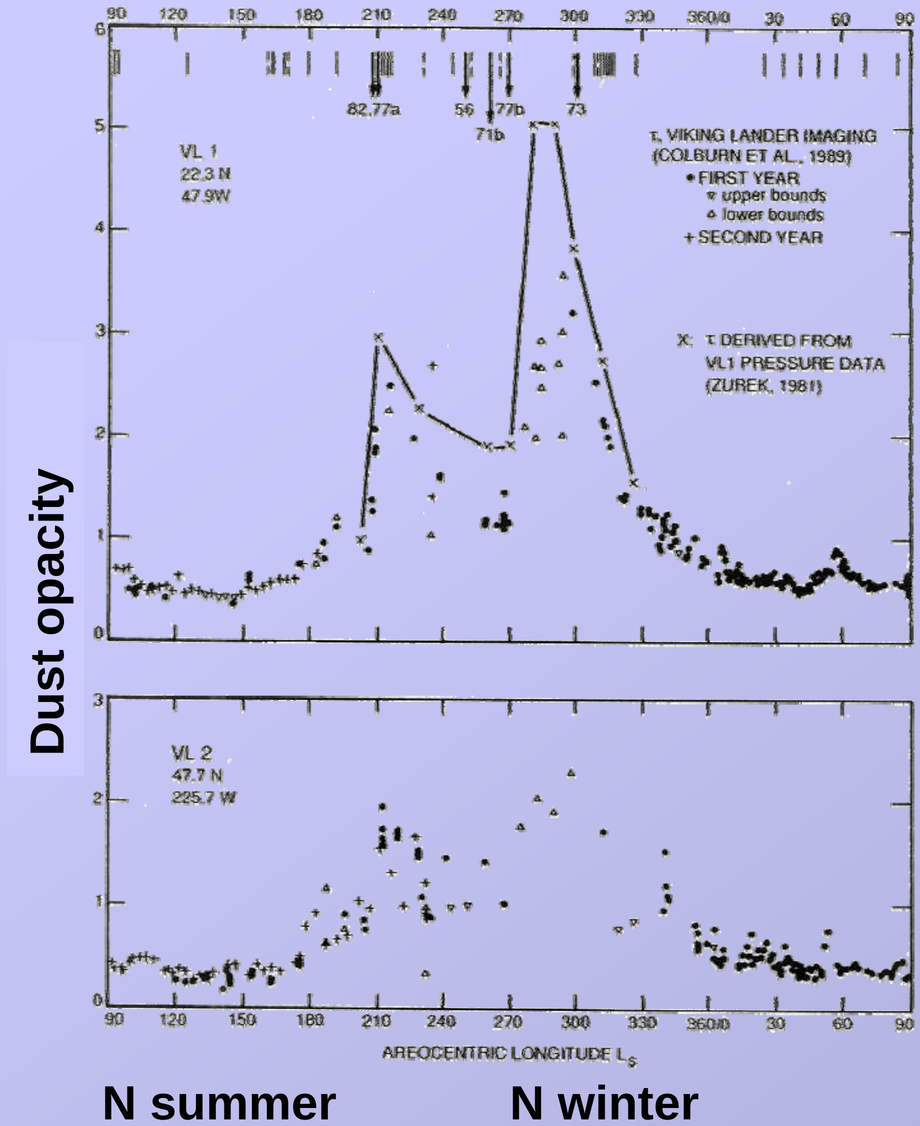


Dust storms and dust devils

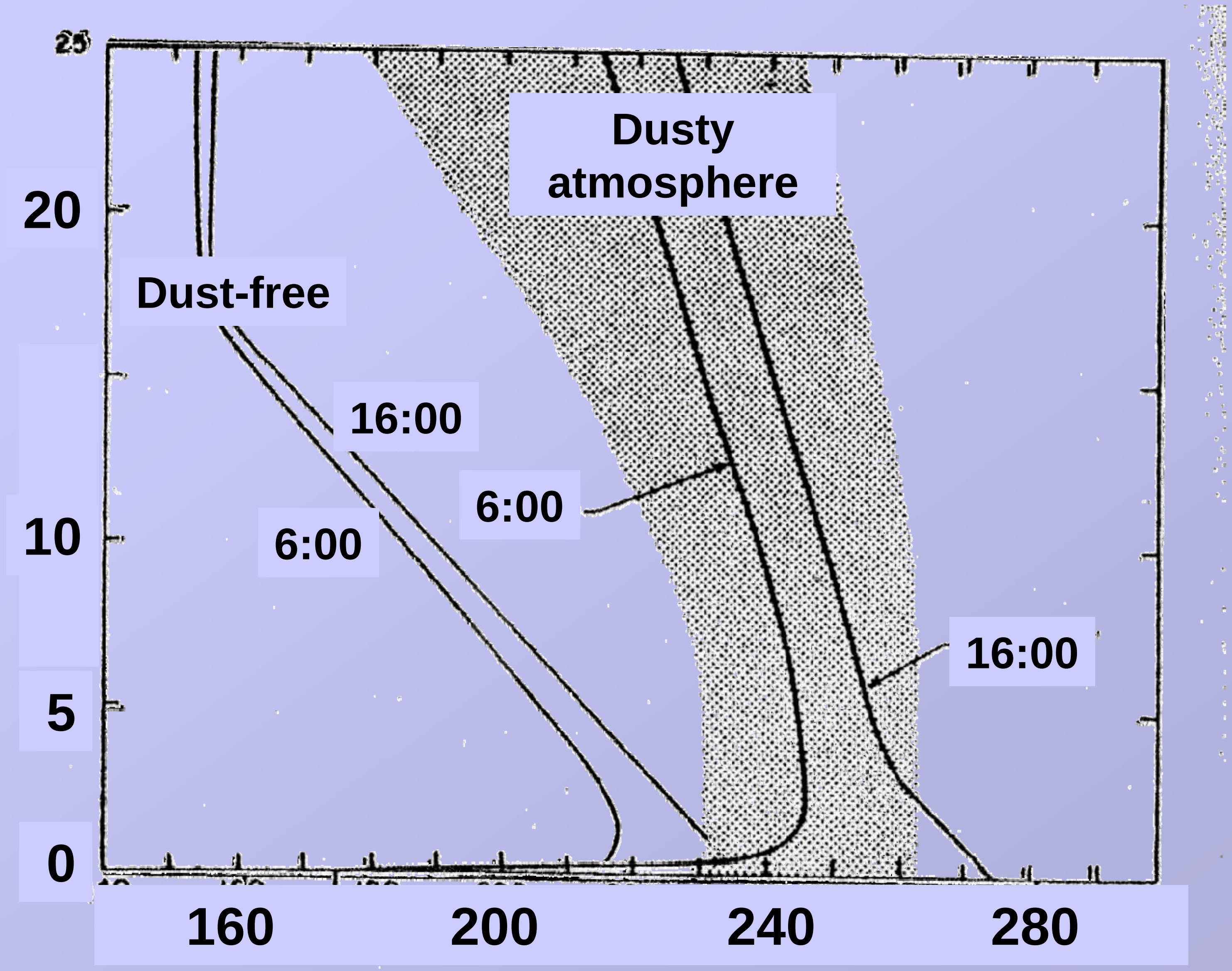




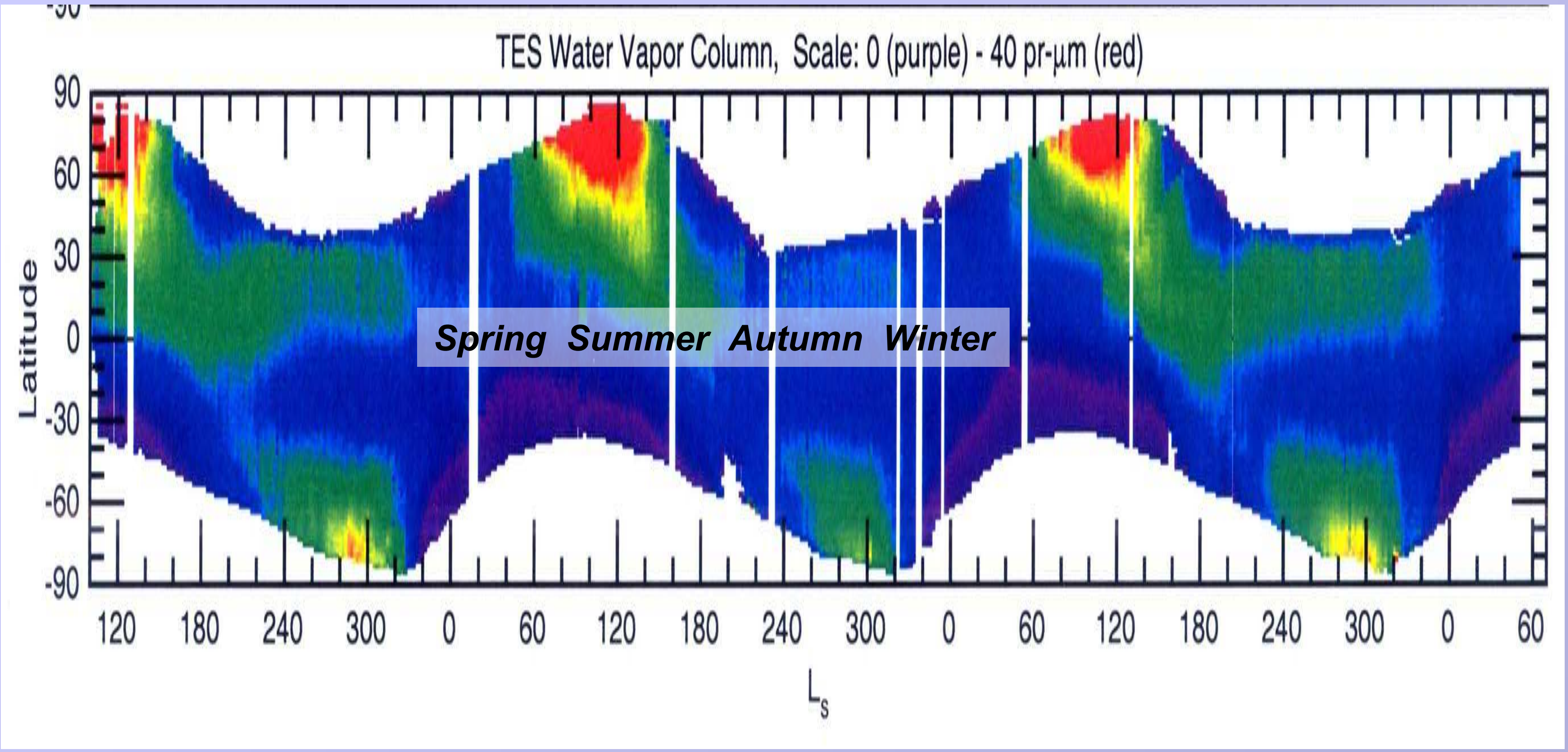
Global dust storms



Dust and atmospheric temperature



Seasonal water cycle on Mars



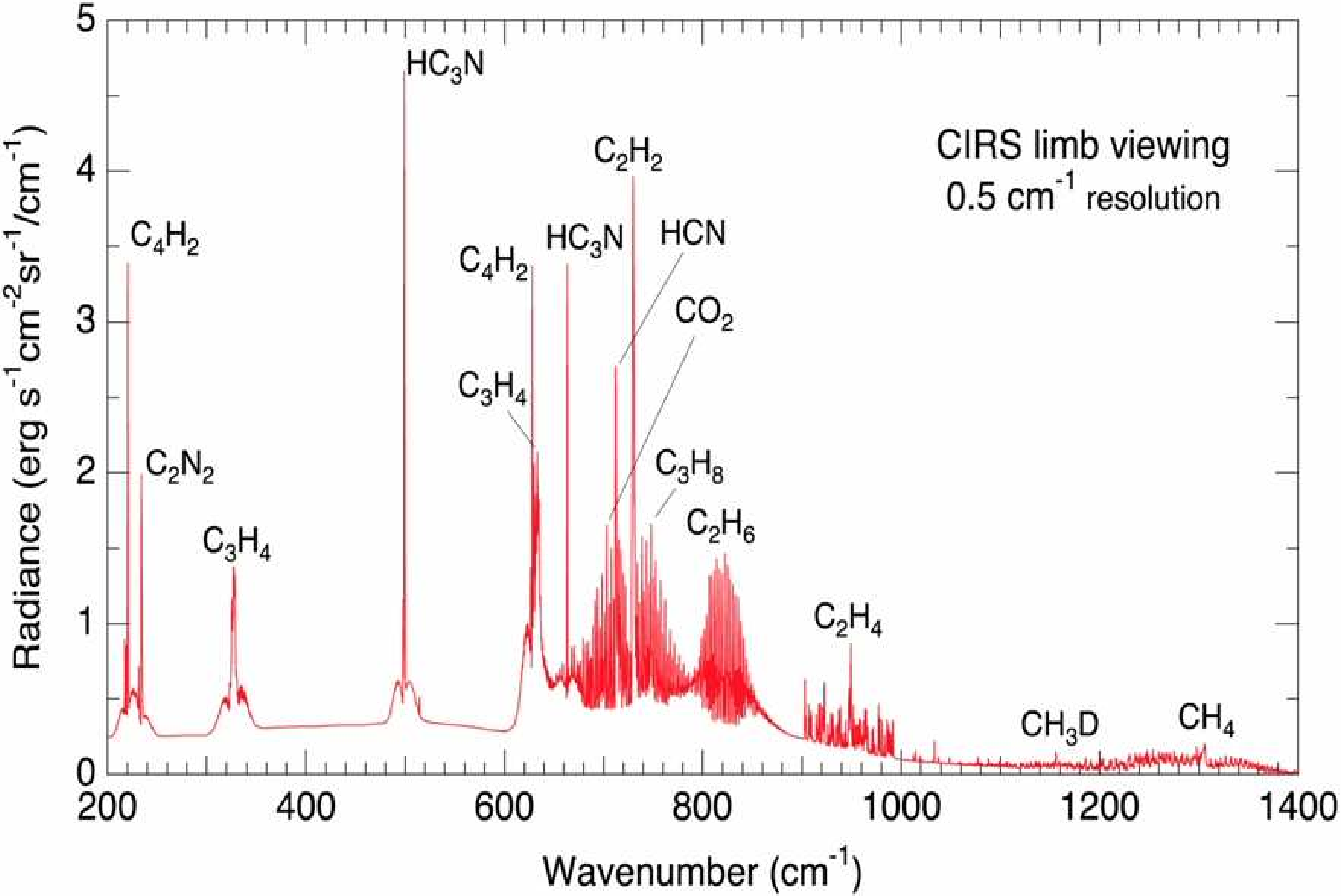
- Seasonal variability 100 – 1000 ppm
- Advective transport
- Non-atmospheric reservoirs (polar caps, regolith)

Titan

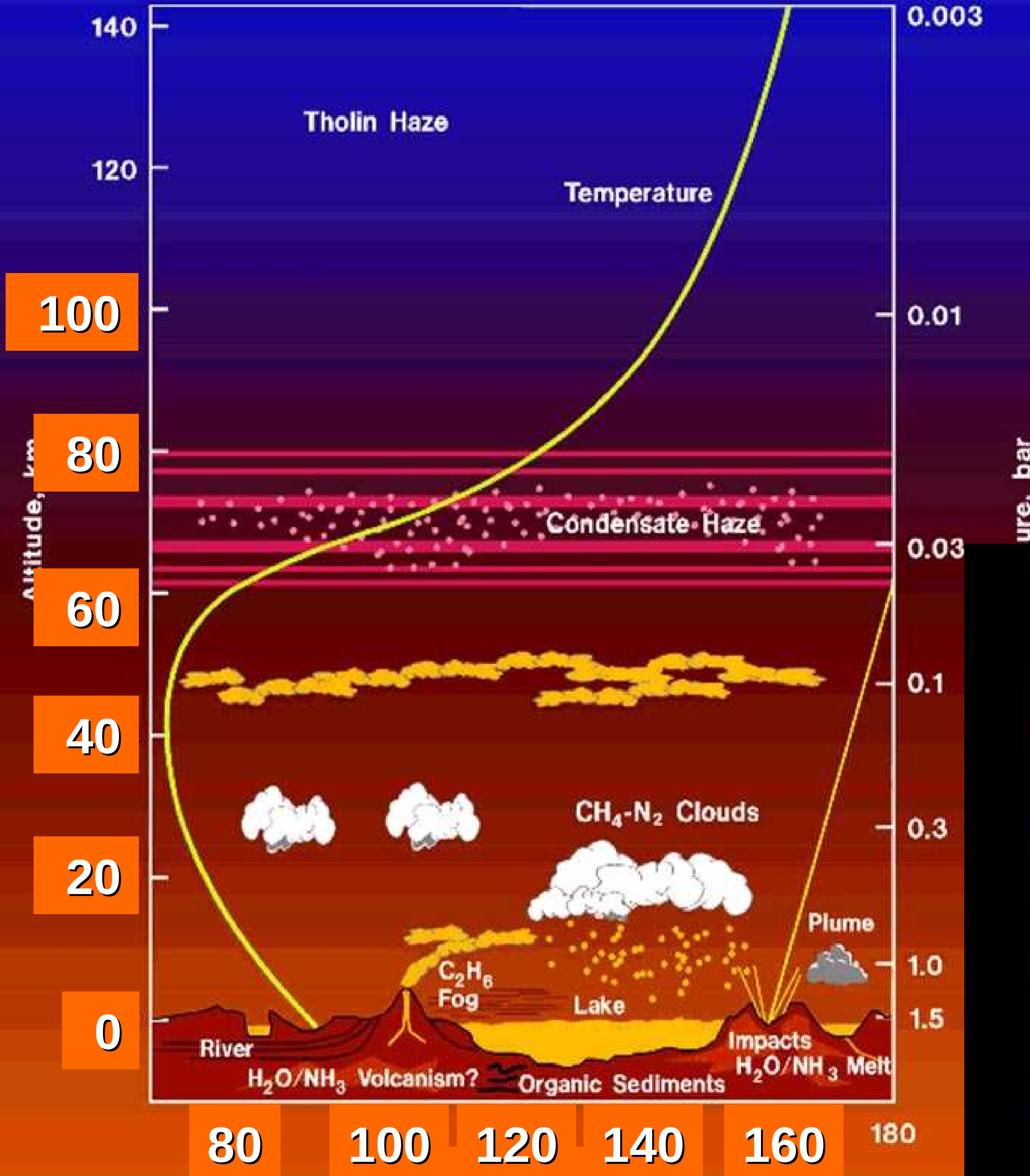
Titan

N_2	90-97%
CH_4	4%
C_2H_2	2 ppm
C_2H_6	10 ppm
CO_2	10 ppb
CO	10 ppm
H_2O	0.4 ppb

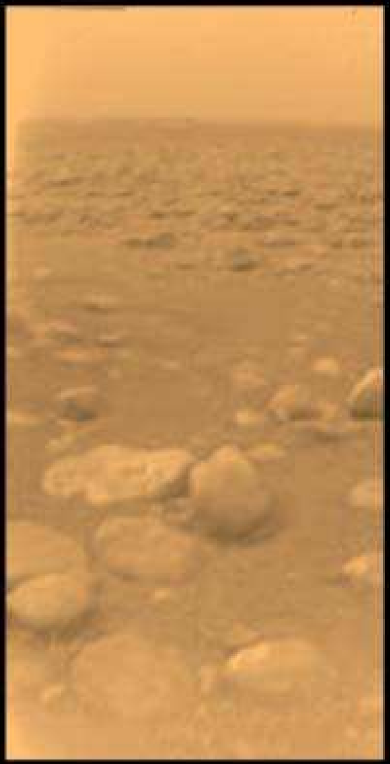
Thermal IR spectrum



Titan

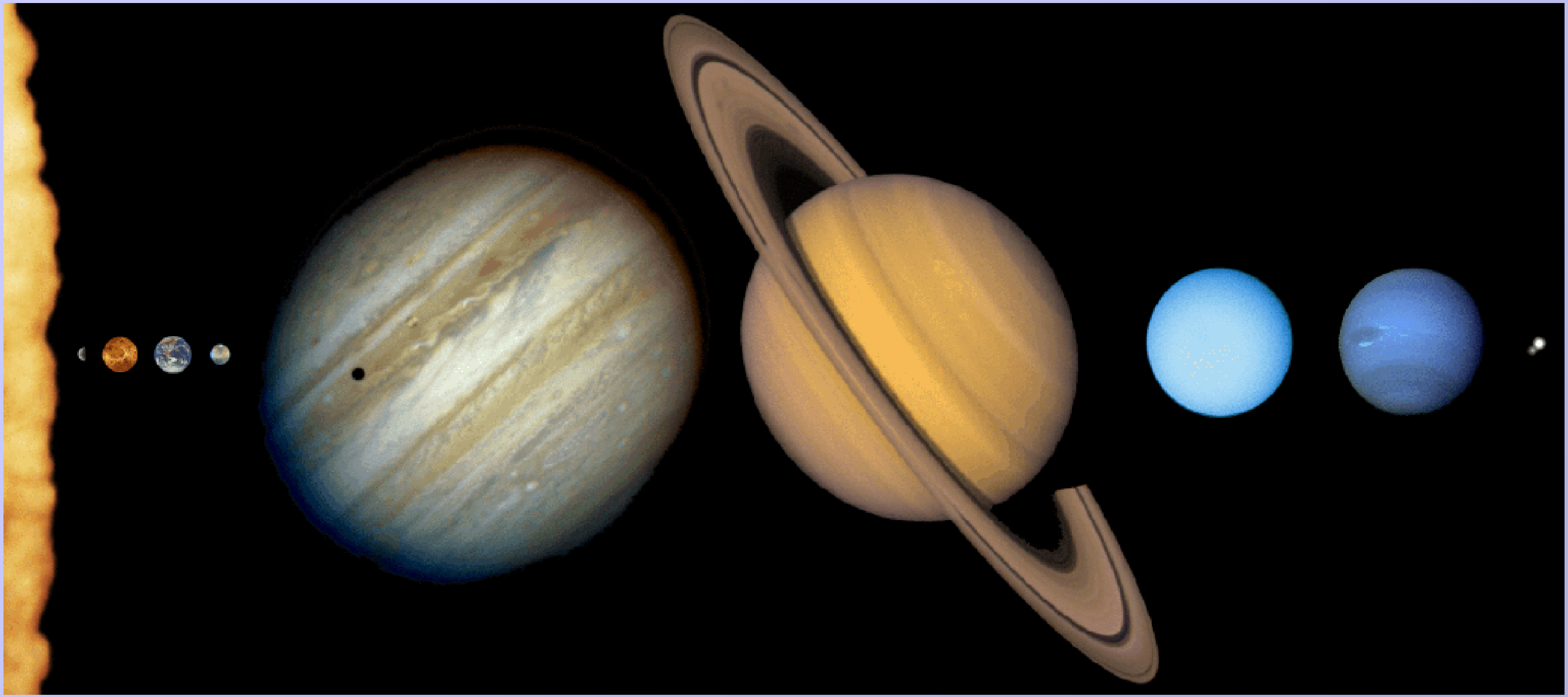


140
120
100
80
60
40
20
0
0.003
0.01
0.03
0.1
0.3
1.0
1.5
Tholin Haze
Temperature
Condensate Haze
CH_4-N_2 Clouds
Plume
C_2H_6 Fog
Lake
River
H_2O/NH_3 Volcanism?
Organic Sediments
Impacts
H_2O/NH_3 Melt
80
100
120
140
160
180



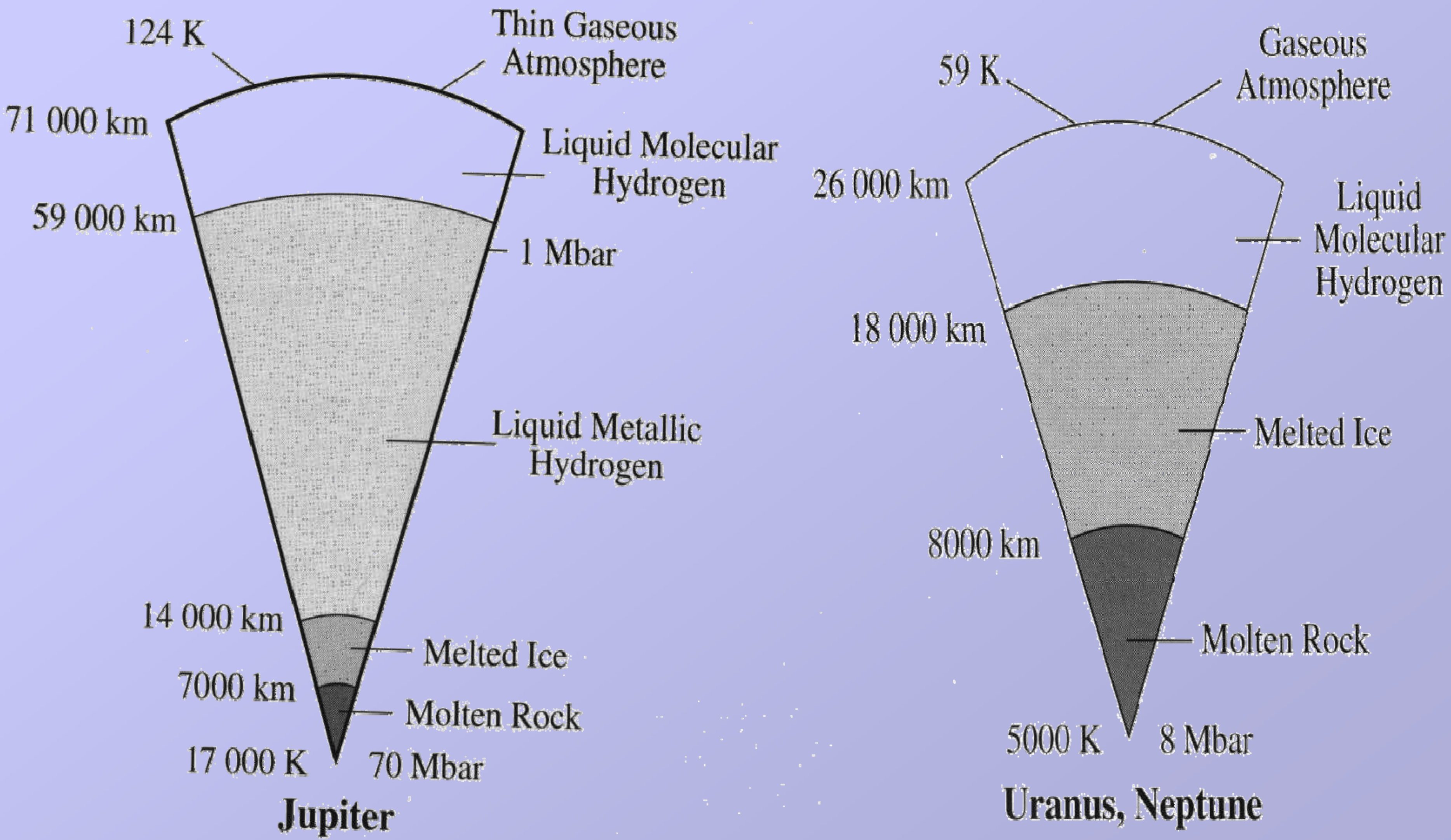
Giant planets

Basic Features

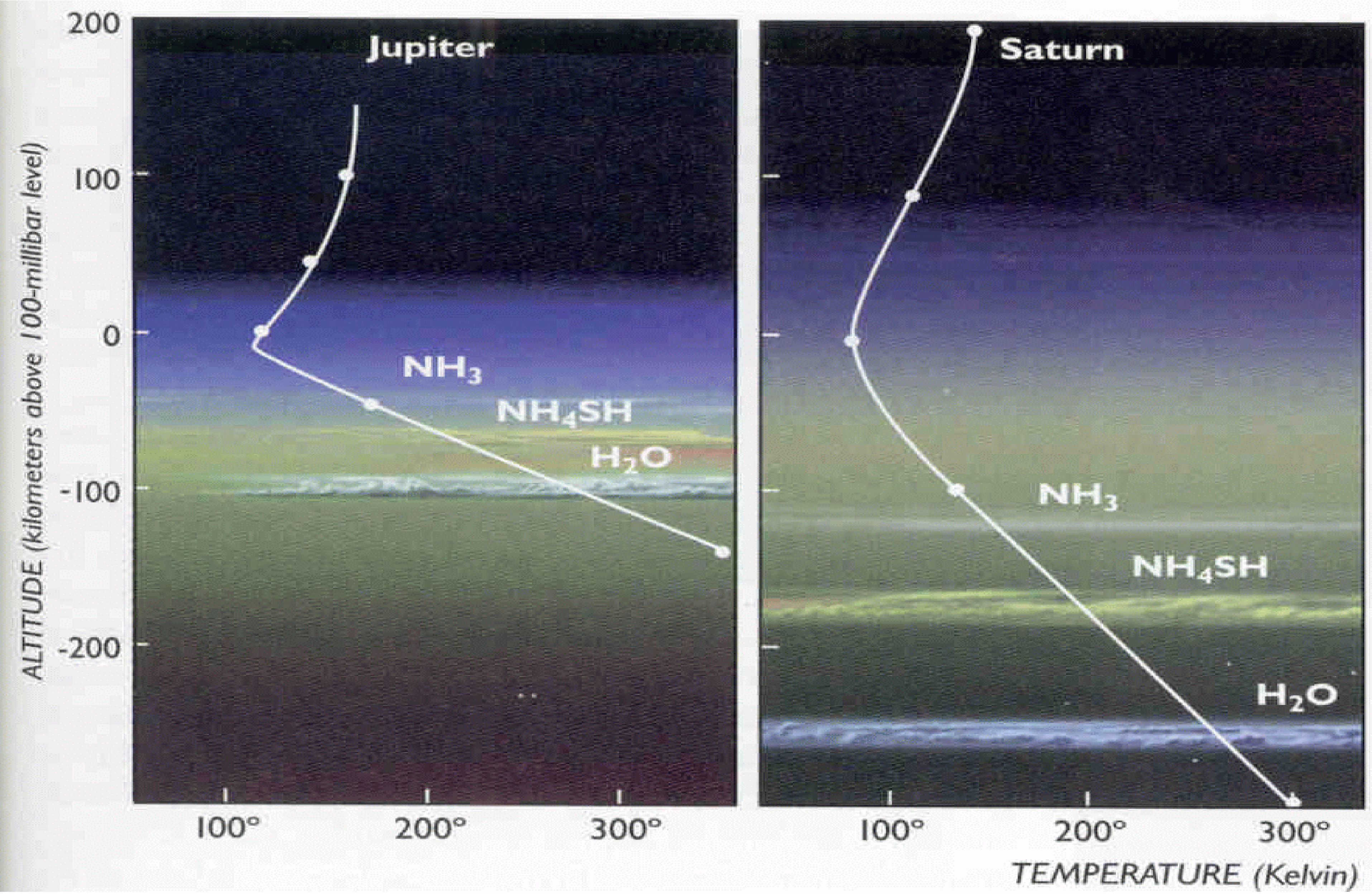


- Distance to the Sun > 5 a.u.
- $R = 10\text{-}4\ R_{Earth}$
- Composition: H_2, He, ices H_2O, NH_3, CO_2, H_2S, Ne, Ar, Kr, Xe
- Mean density ~1.3-1.6 g/cm^3
- Rotation periods ~10 -17 hours, non spherical shape
- Effective temperature 170 – 60 K

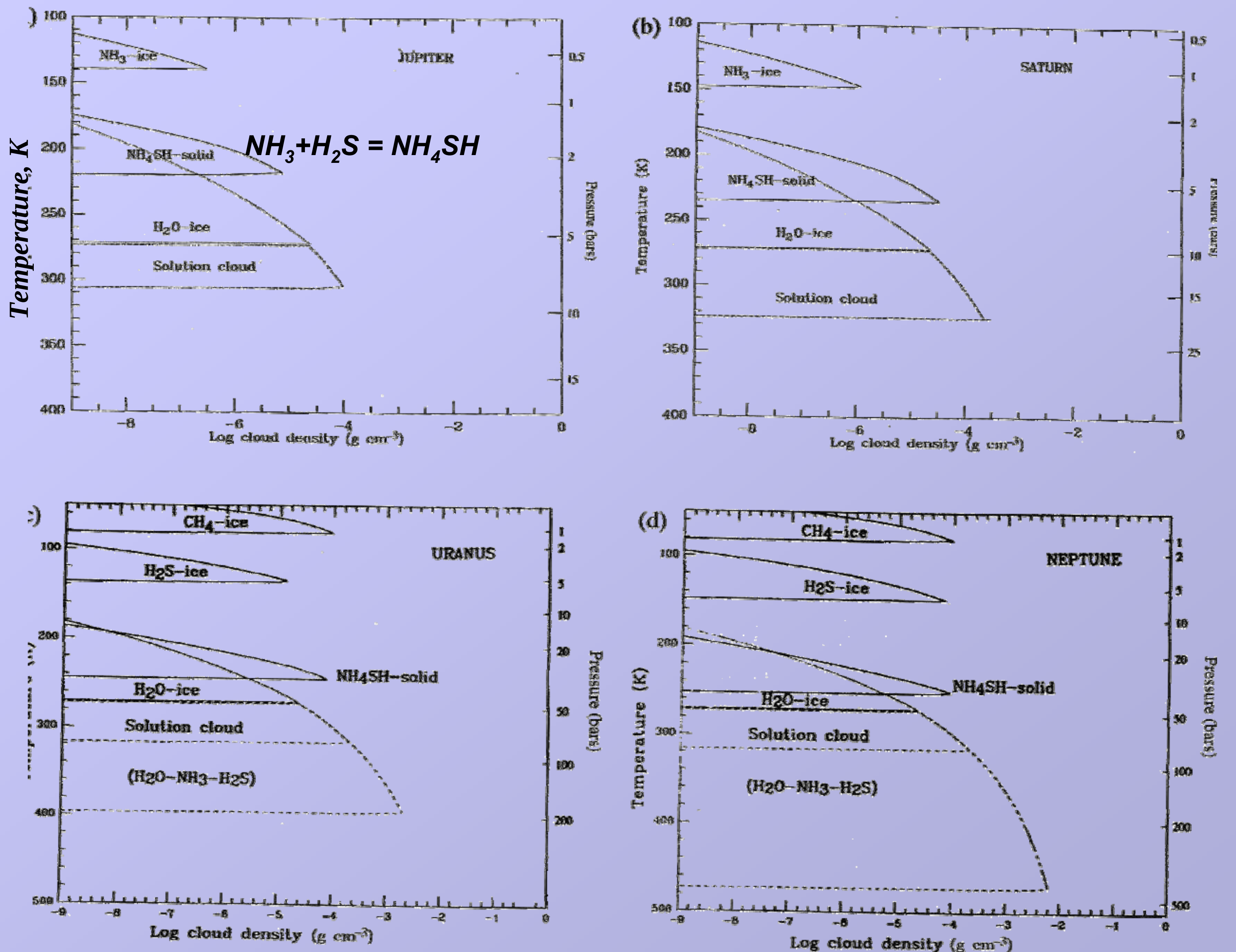
Inner structure of the Giants



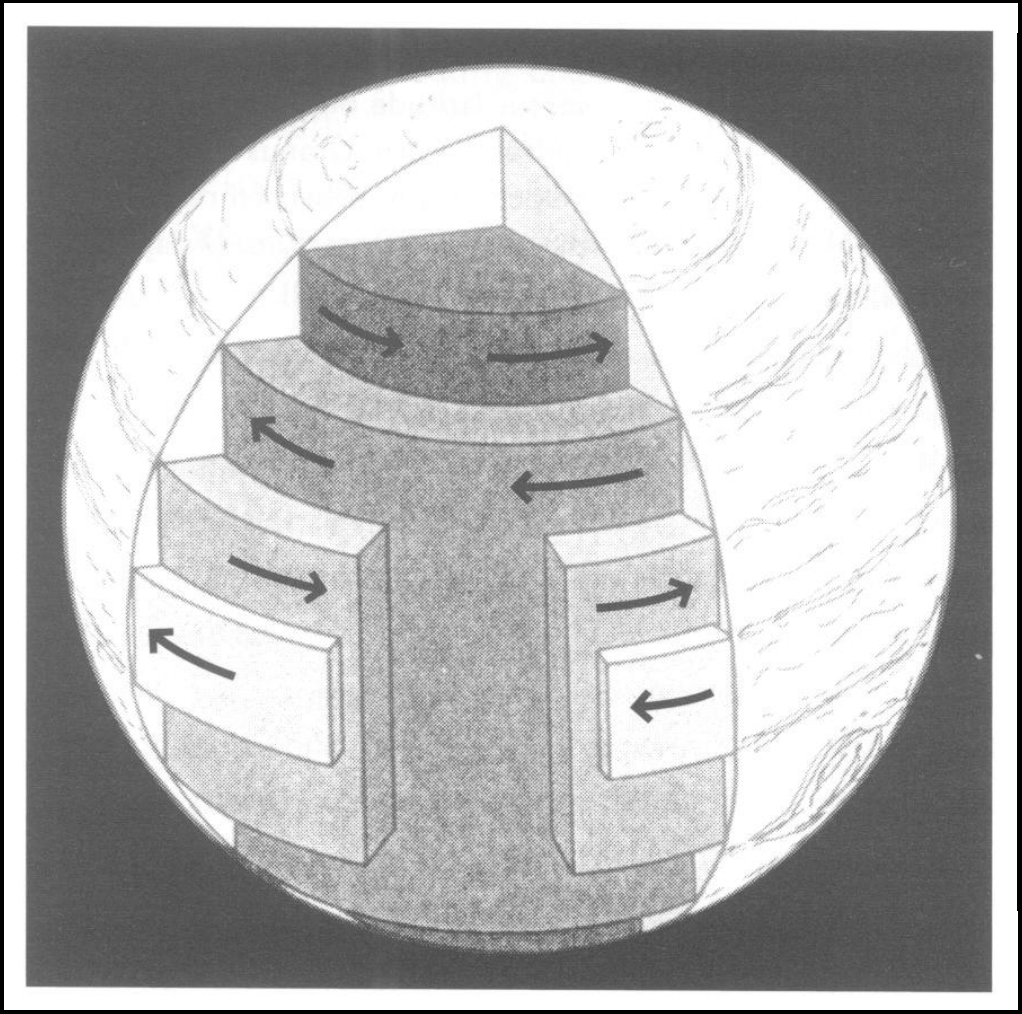
Atmospheric structure

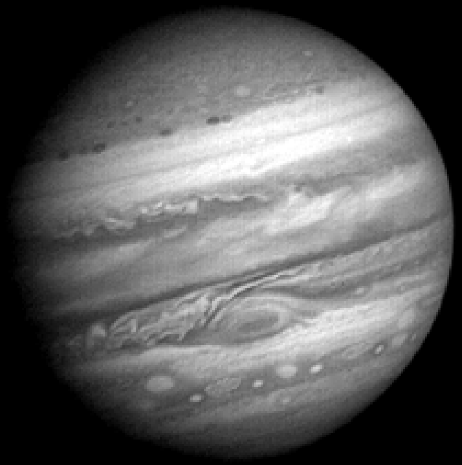


Clouds on the Giants

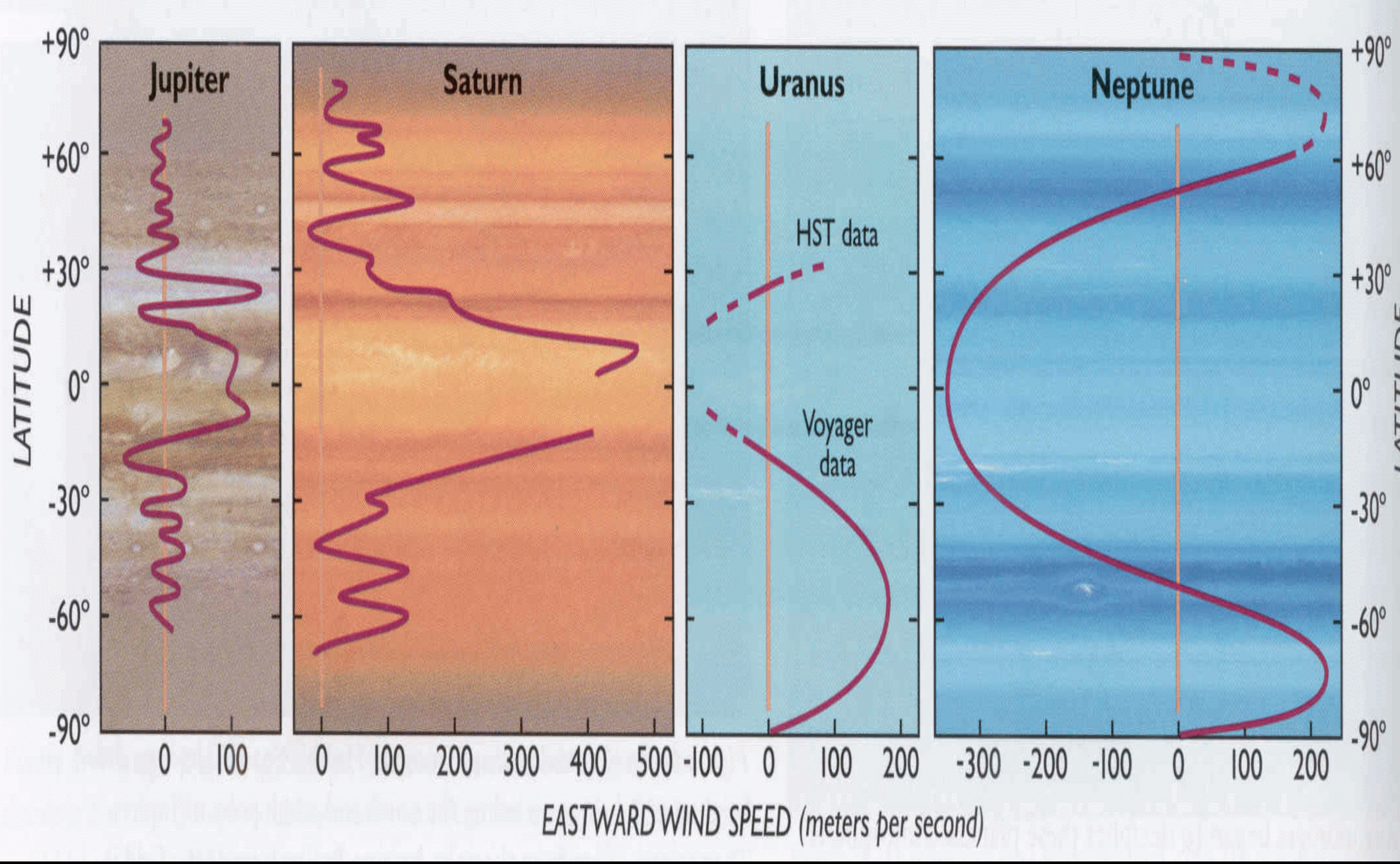


Jupiter band structure

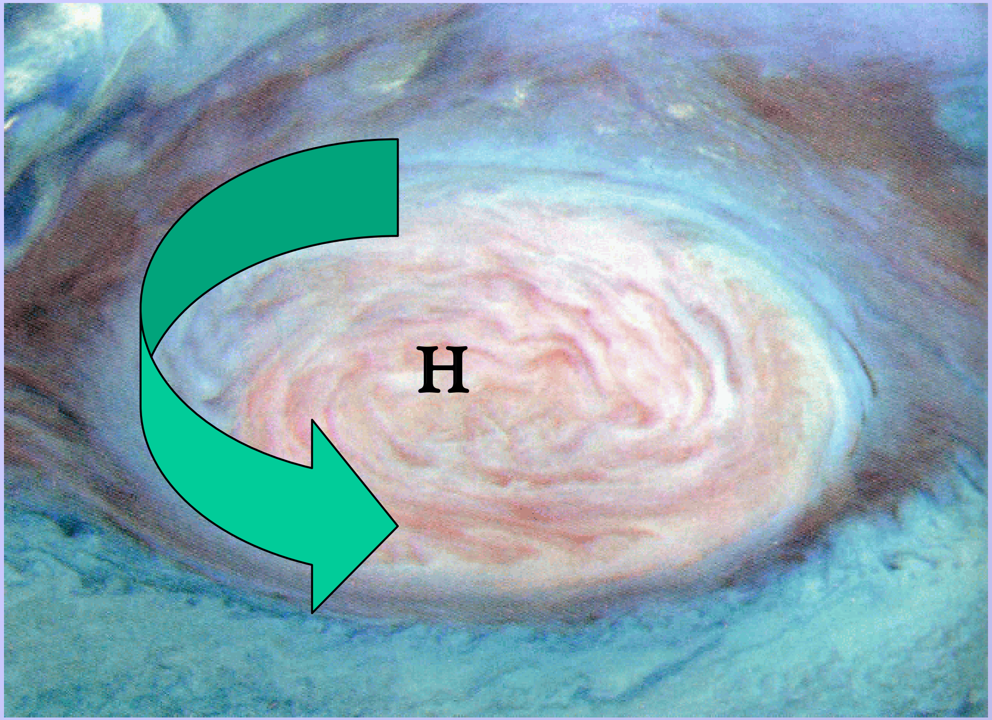


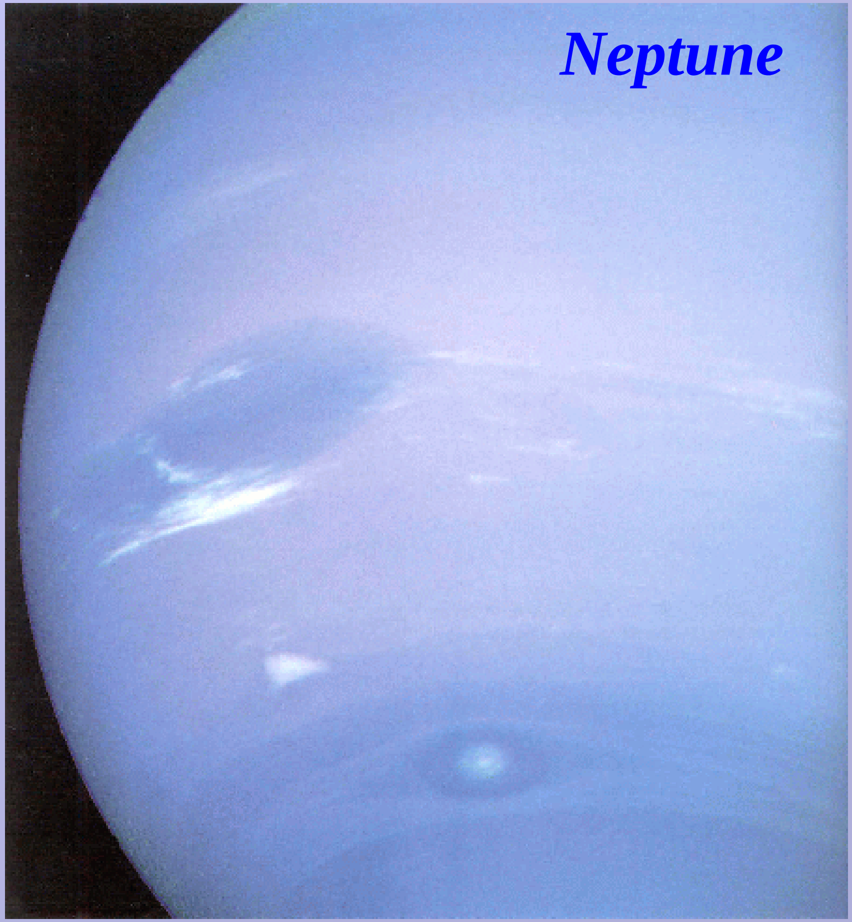


Winds at cloud top level



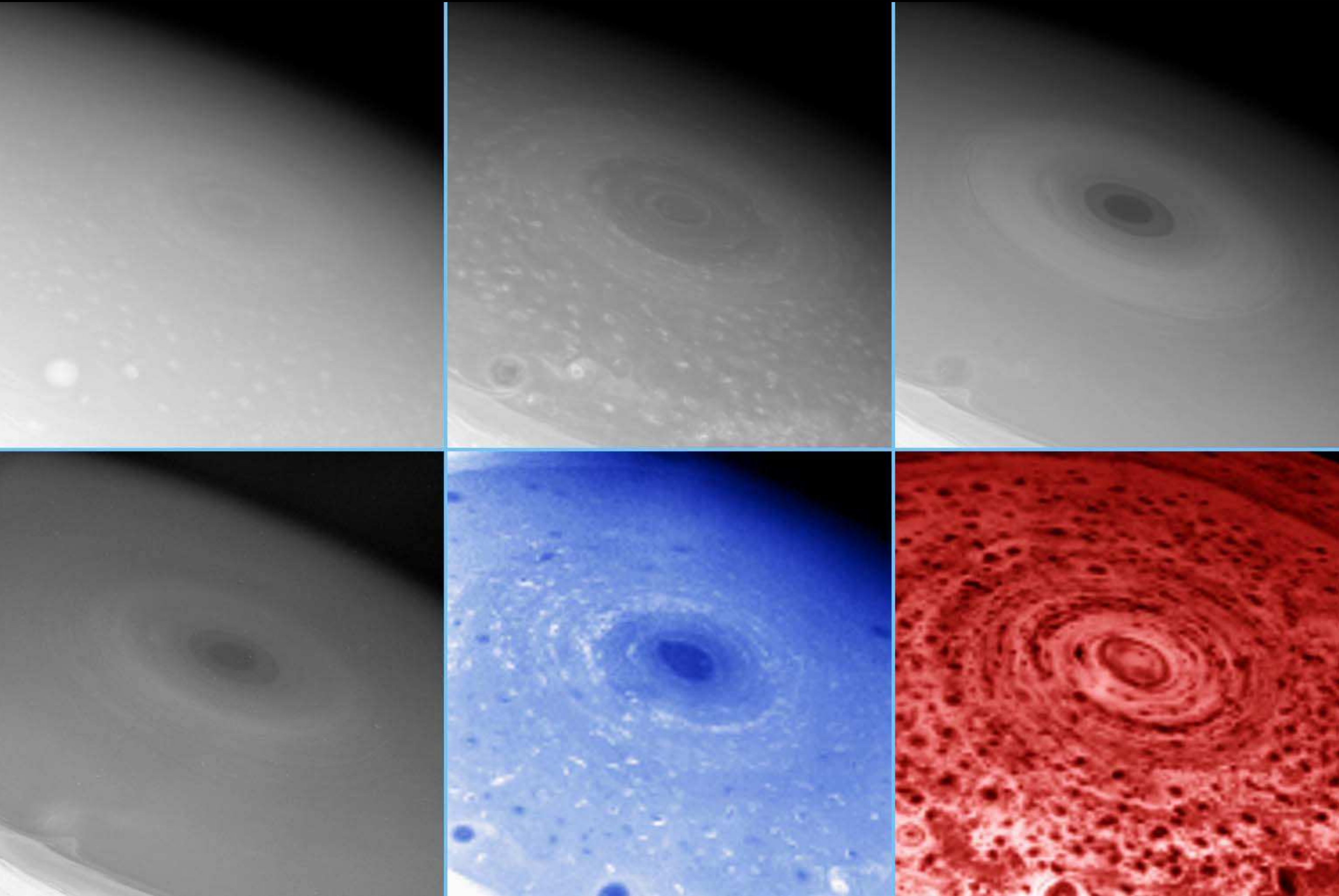
Great Red Spot



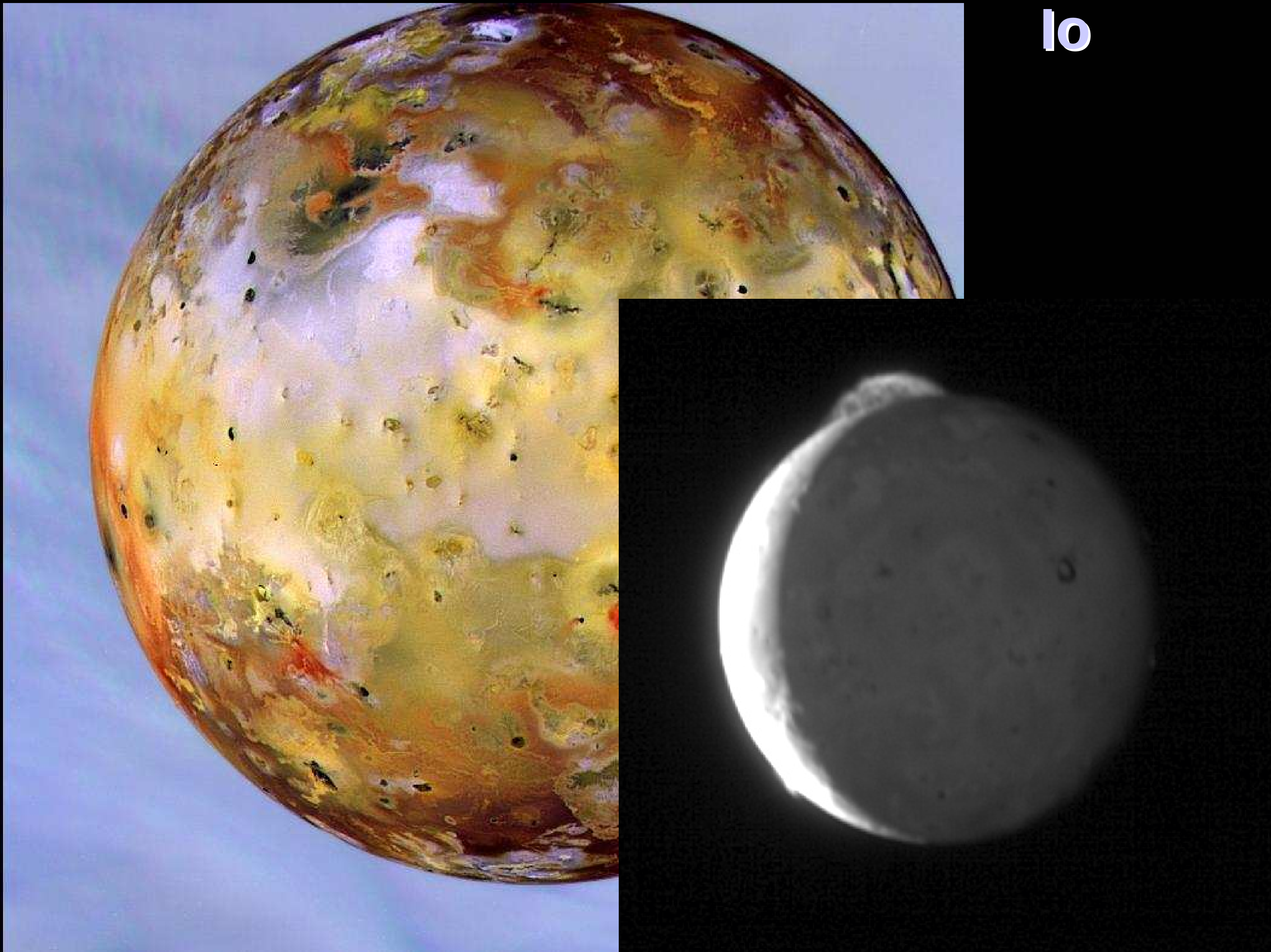


- **GRS is variable**
- **GRS looks cold in the IR**
- **anti-clockwise rotation**
- **GRS – long-living anticyclon**

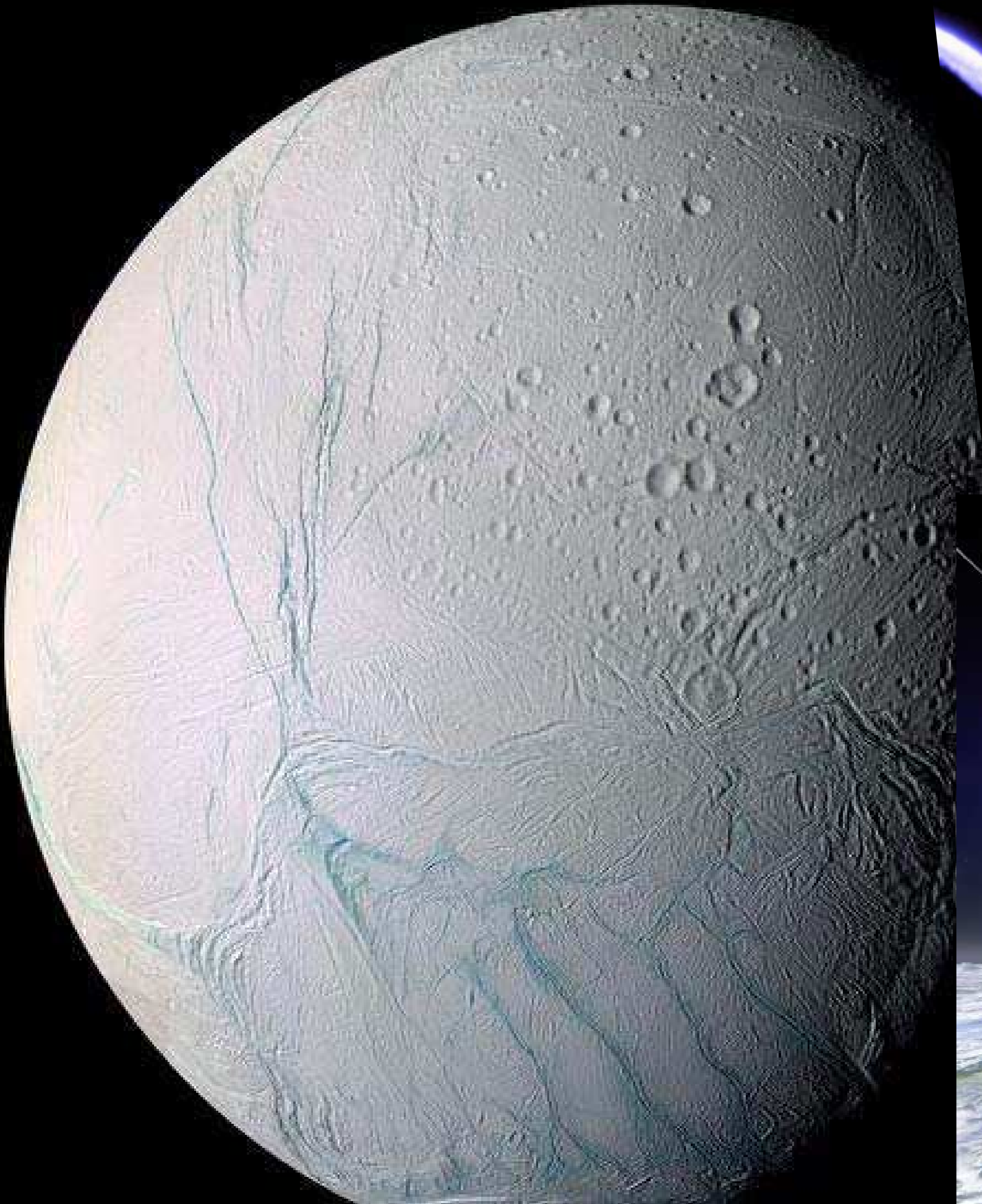
Saturn polar vortex

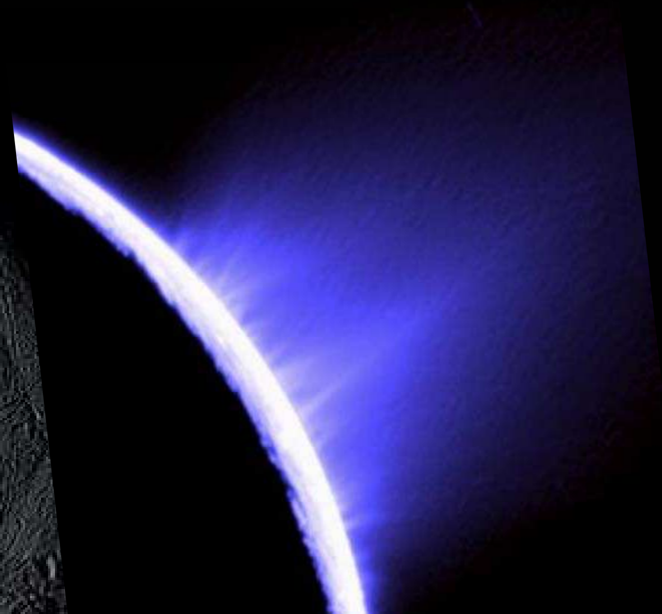


Io



Enceladus





Home, home again…