Past, present and future of the Venus exploration

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1. History of the Venus exploration

Ancient views of Venus

- **Babilon:** ***Ishtar- the Mother of the God who invokes the power of dawn***
- **Maya:** *Kukulcan - the Sun's brother, patron planet of warfare*
- **Early Christians:** *Lucifer*
- **Greeks / Romans:** ***Aphrodite / Venus – the goddess of beauty and love***

Venus before the space era

- *1610 – Galileo Galilei observed phases of Venus. Early indication of that the planets rotate around the Sun not the Earth*

- *Venus transits were used to determine distances in the Solar System*

- *1761 - discovery of the atmosphere by Lomonosov*

Venus before the space era

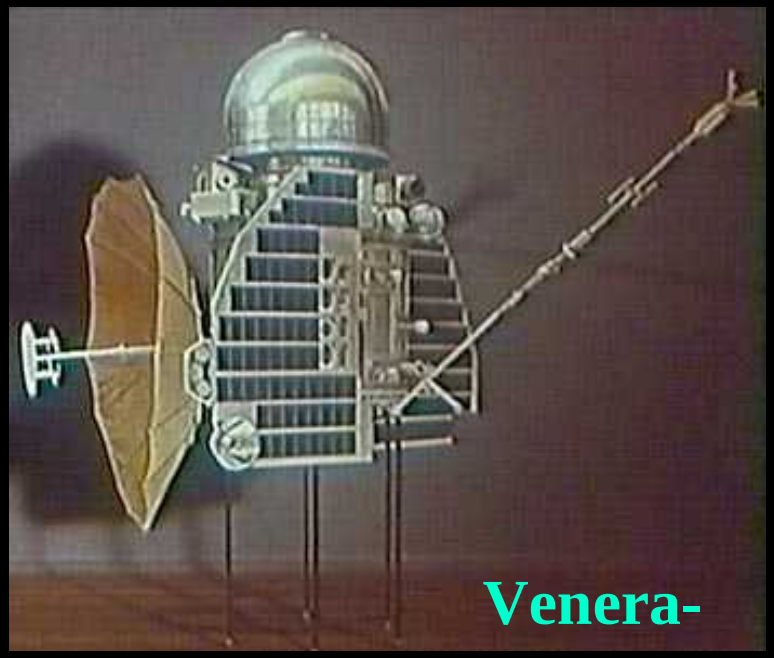
- *20-th century – the birth of spectroscopy*
- *1920s - cloud top temperature of ~ 240K*
- *1930s - CO_2 composition, low H_2O abundance*
- *1950s – radio investigations: planet rotation, hot surface*
- *Venus models: from Earth-like to hell-like*

Venus surface according to S. Arrhenius

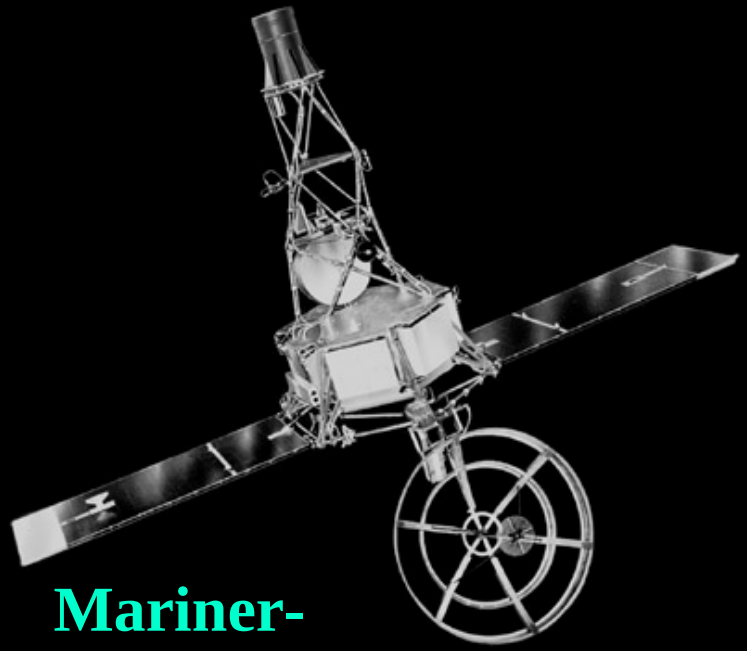
Who will be the first to reach Venus?

- *1960s – interplanetary spacecraft for Mars and Venus exploration was built by the Soviet Union. The first launch failed. The second one (12.02.1961) succeeded but communication was lost.*

- *1962 – Mariner -2 – first Venus fly-by and data returned*



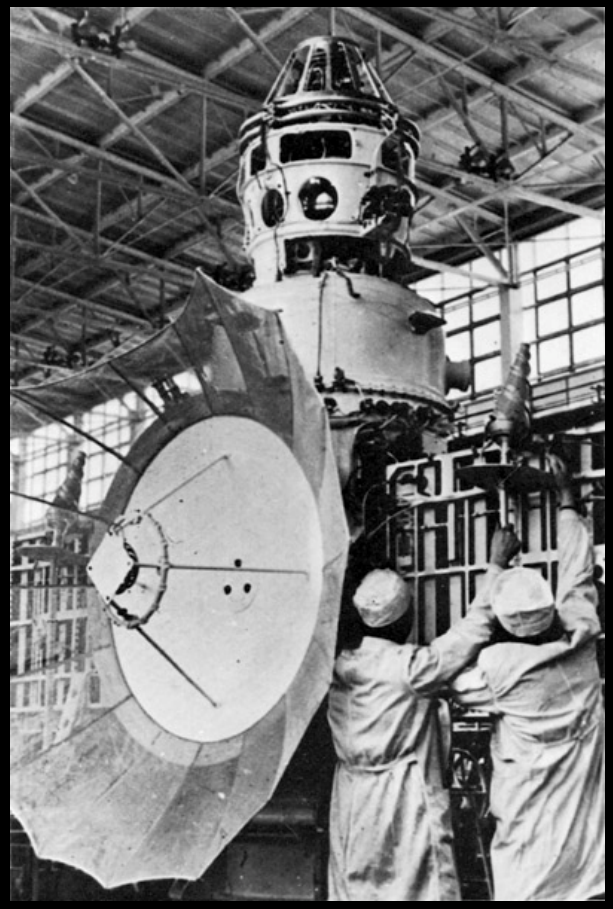
Venera-



Mariner-2

Goal - to reach the surface !

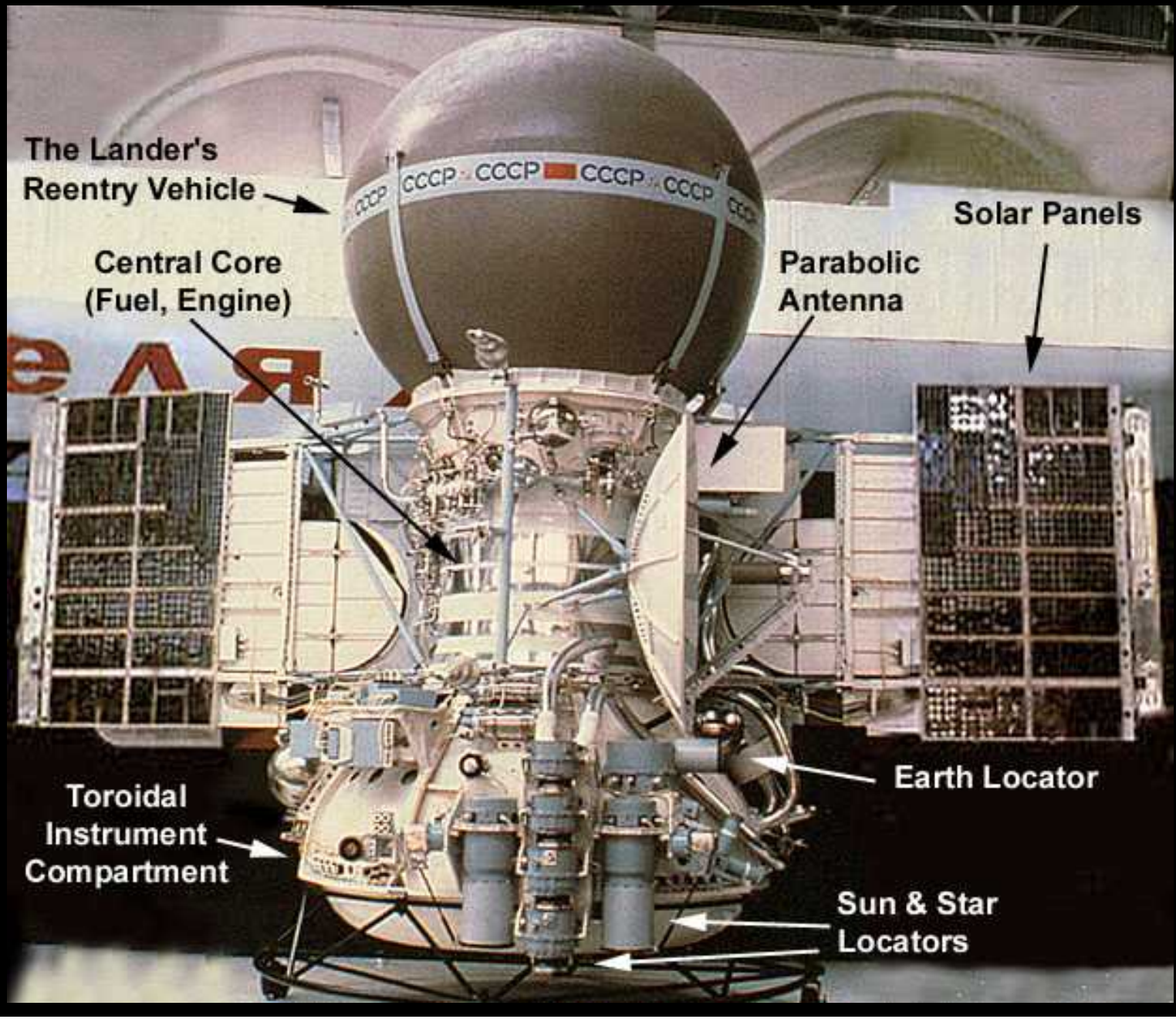
- *Venera - 4, 5, 6 reached ~20 km*
- *Venera-7 – soft landing !*



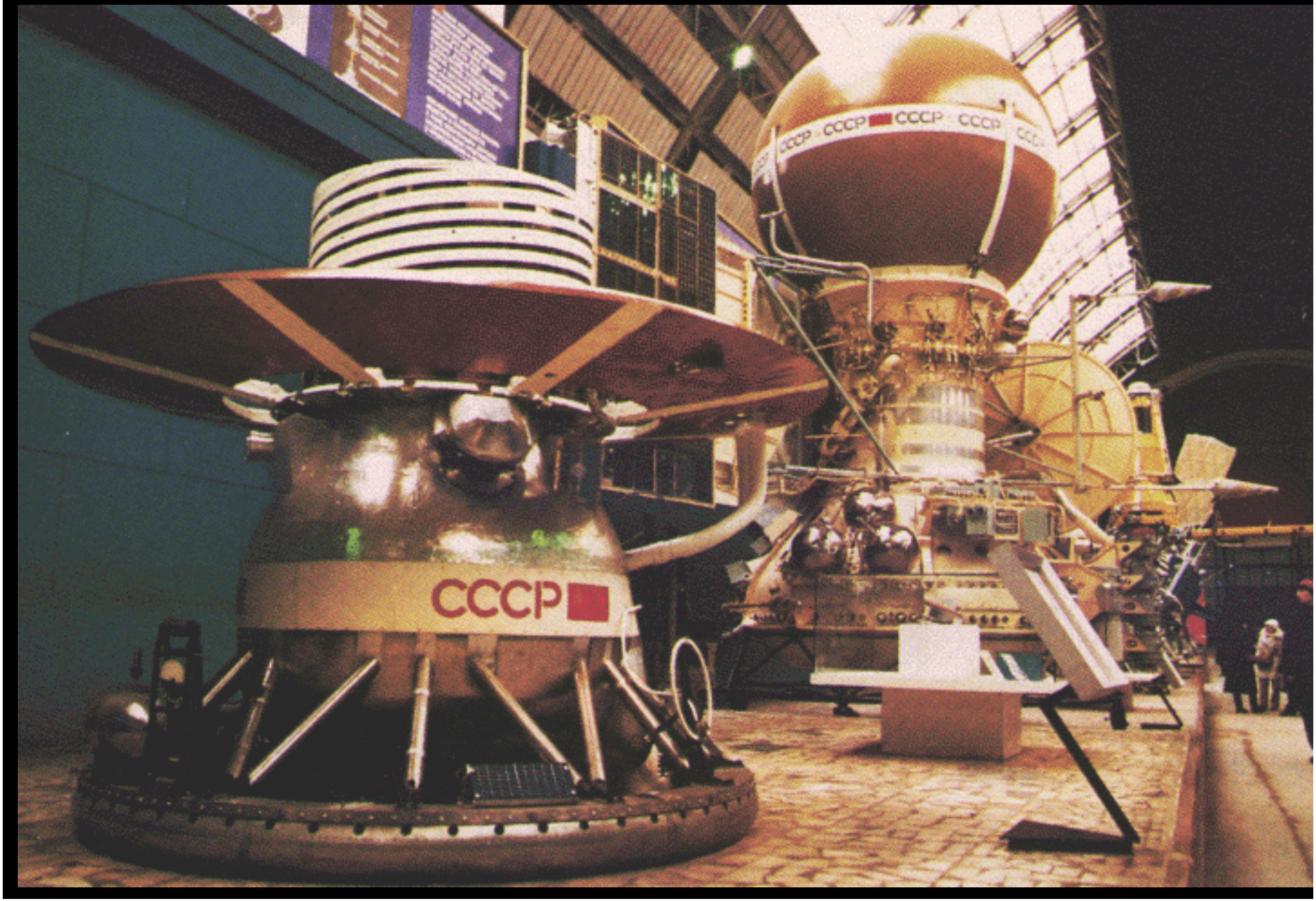
Venera-7

Venera-4

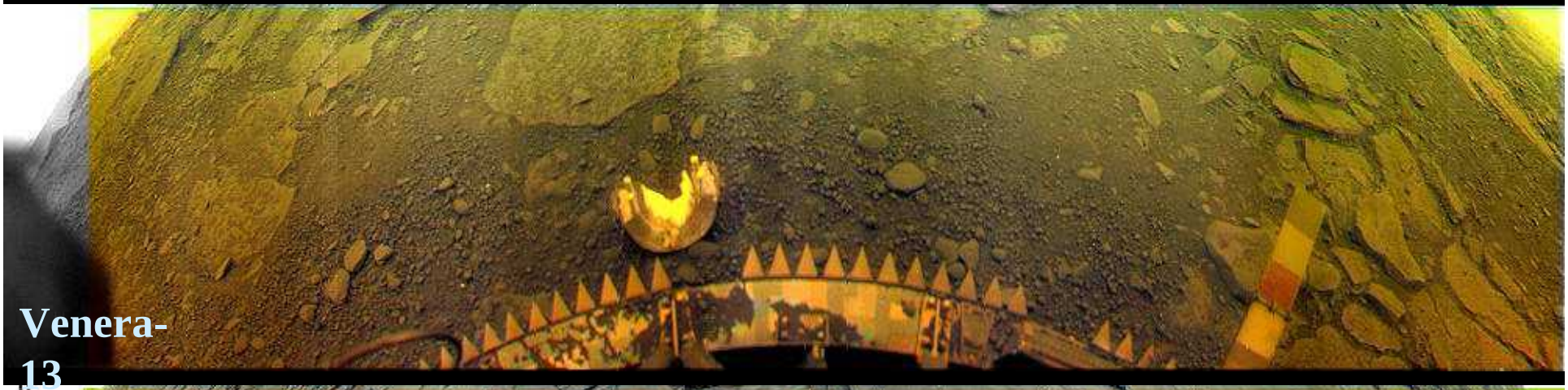
Second generation of the Venera spacecraft (1970-80)



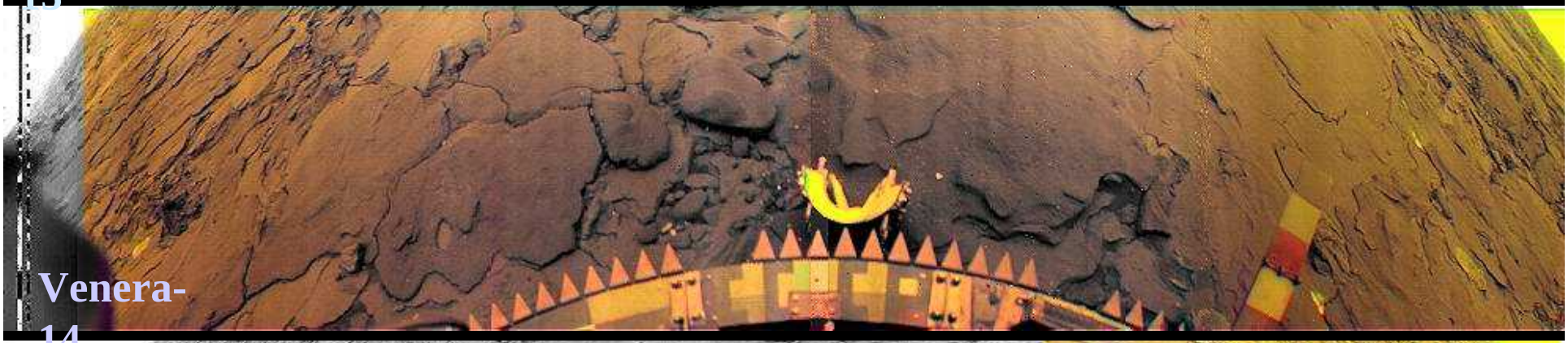
Second generation of the Venera spacecraft (1970-80)



First panoramas



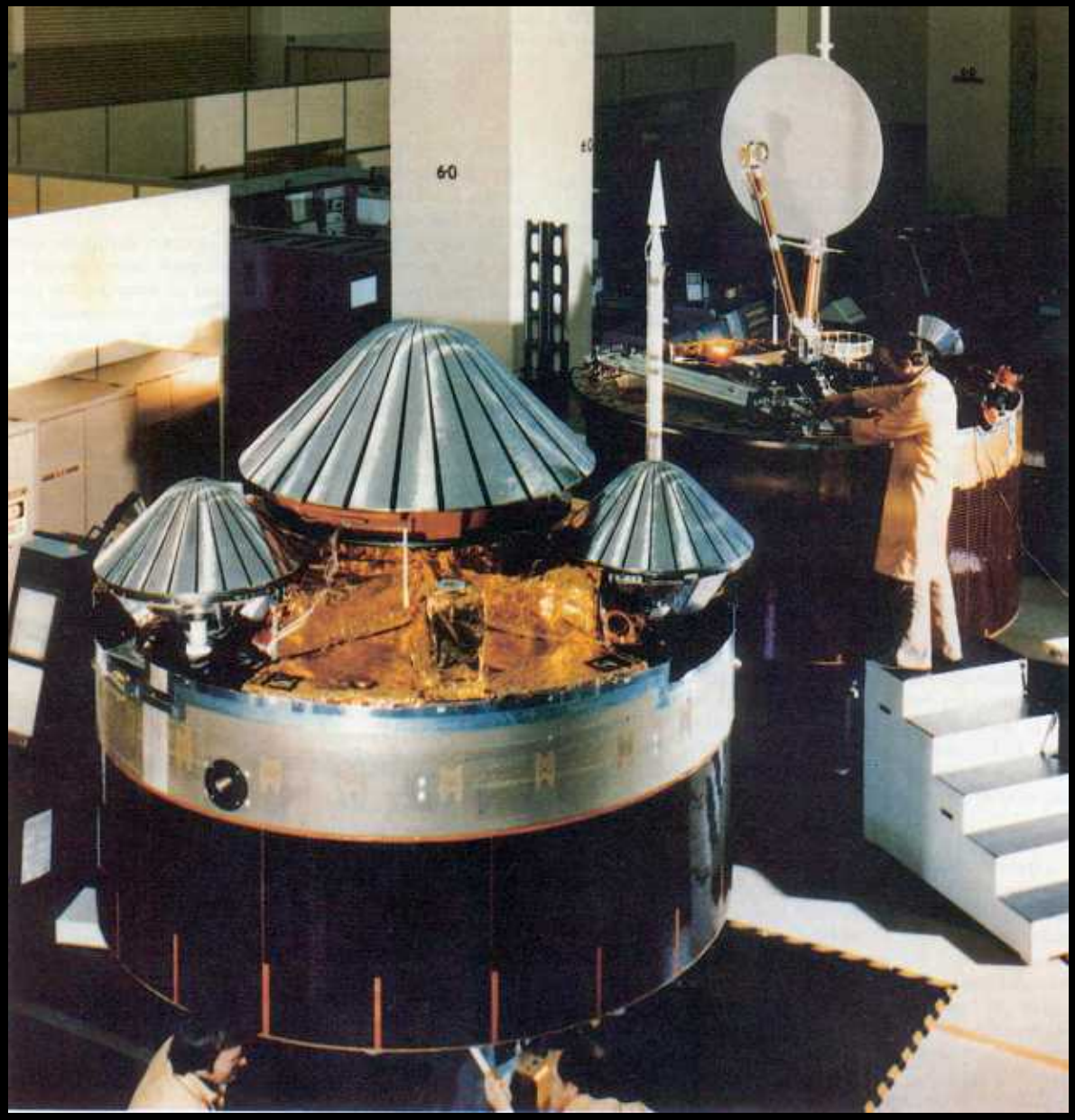
Venera-13



Venera-14

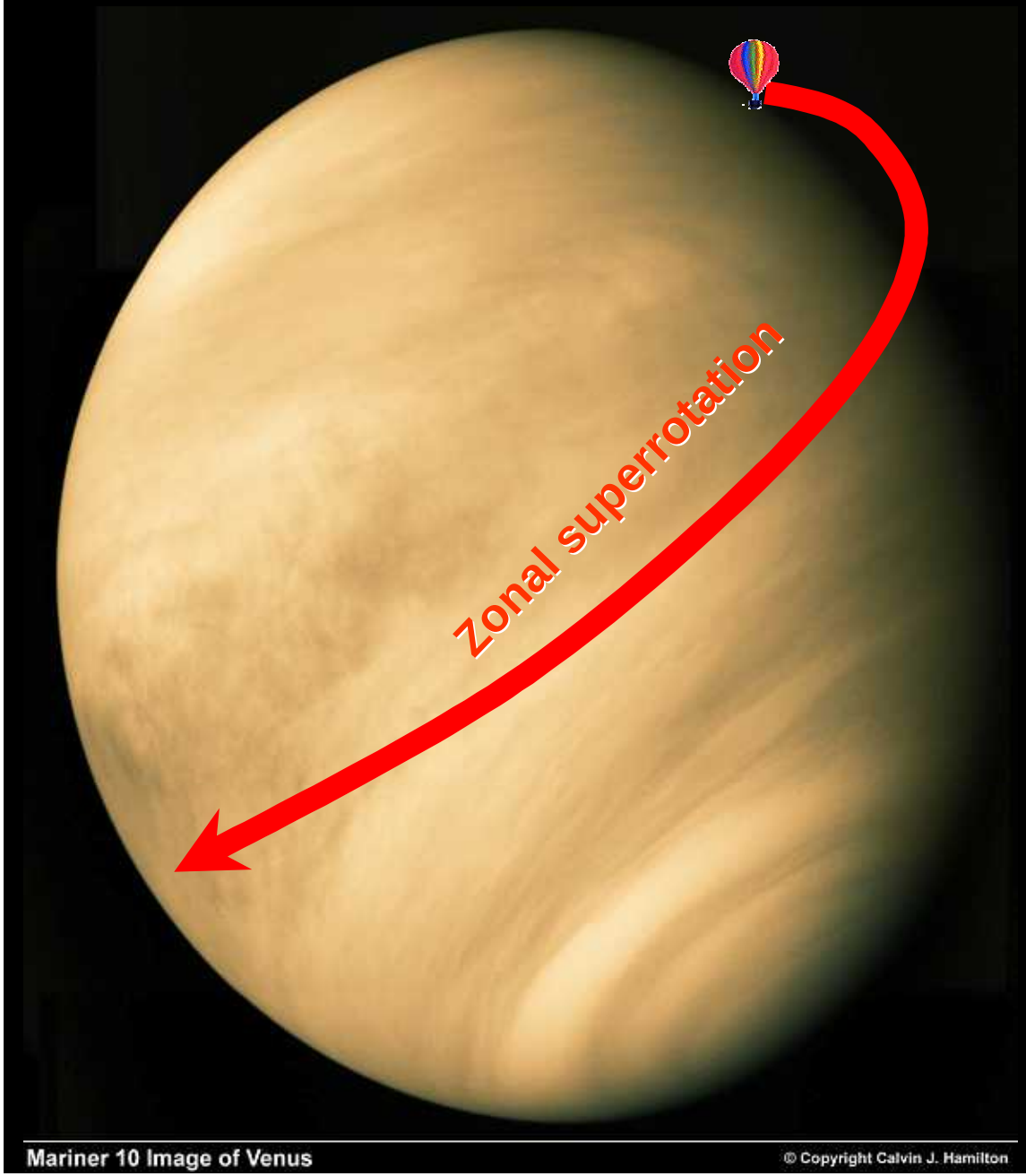
Venera-14

Pioneer Venus multiprobe mission (1978-92)

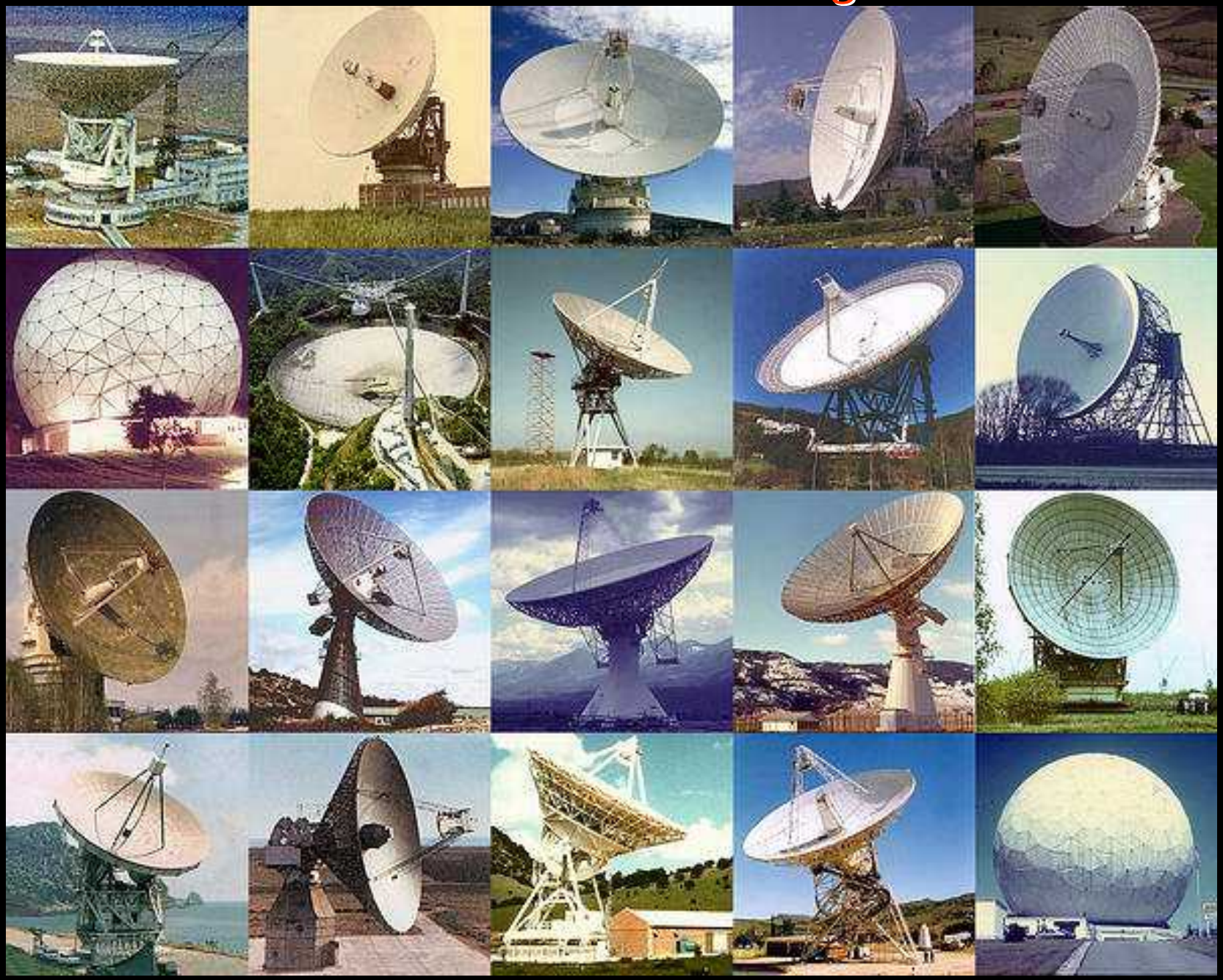


- *Atmospheric studies from orbit*
- *In-situ investigations*
- *Plasma monitoring*
- *Surface radar mapping*

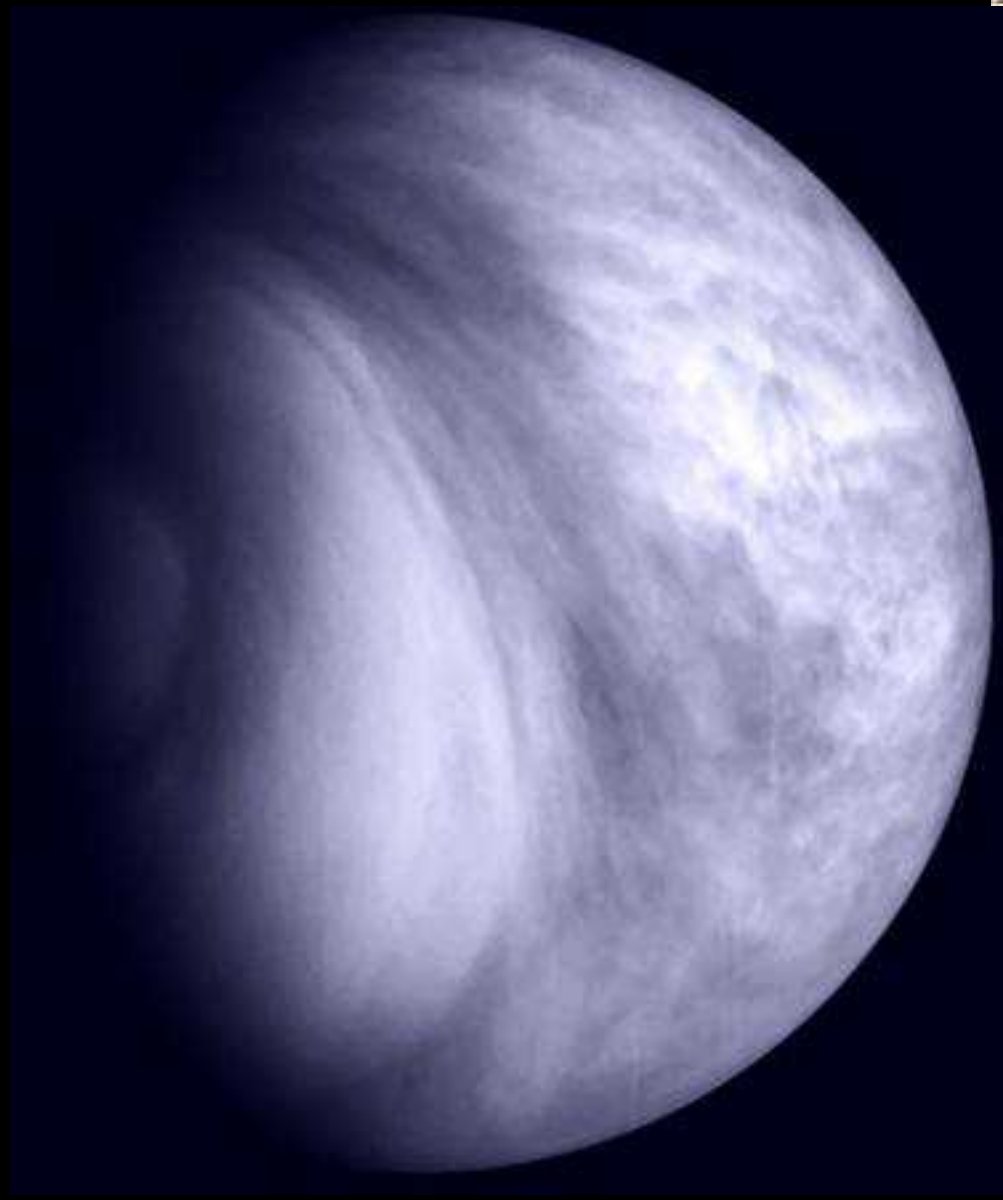
VEGA Balloons (1984)



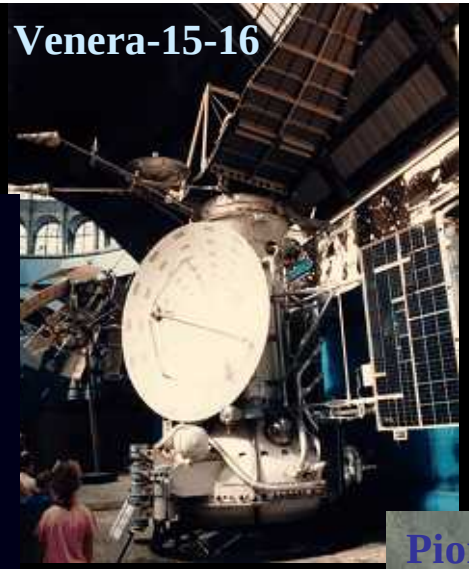
Global network of balloon tracking stations

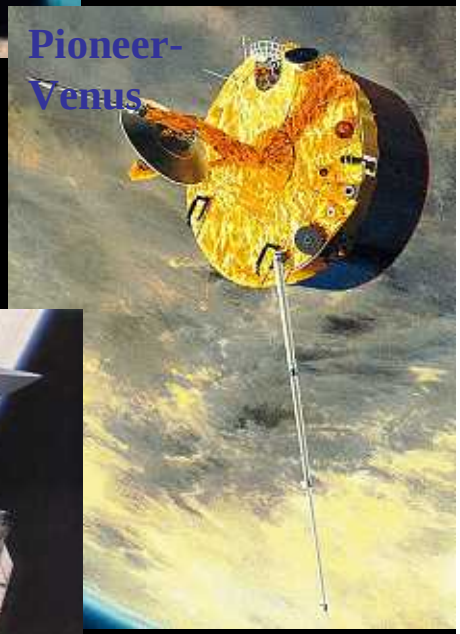


Venus unveiled…



Venera-15-16



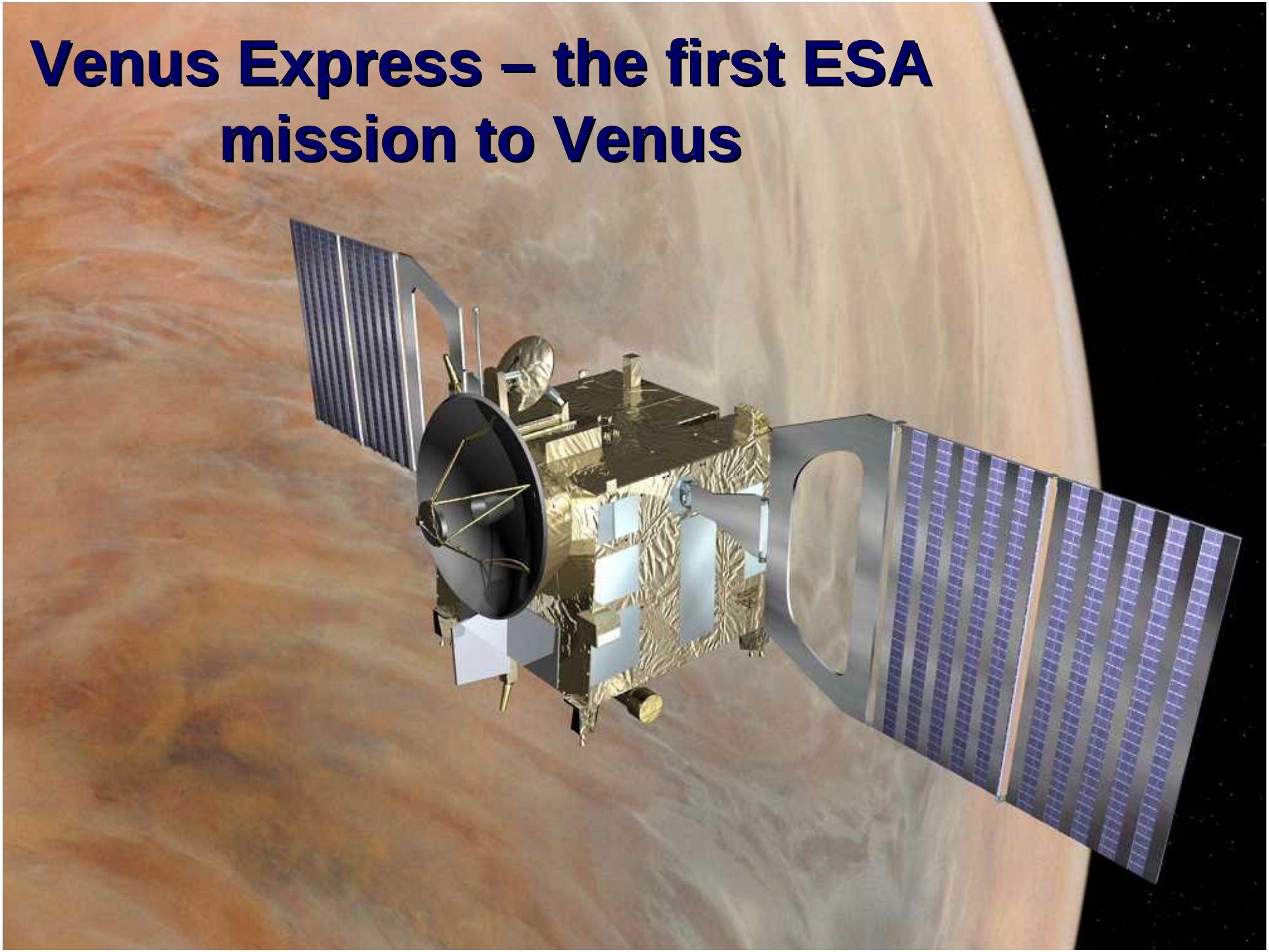


Pioneer-Venus

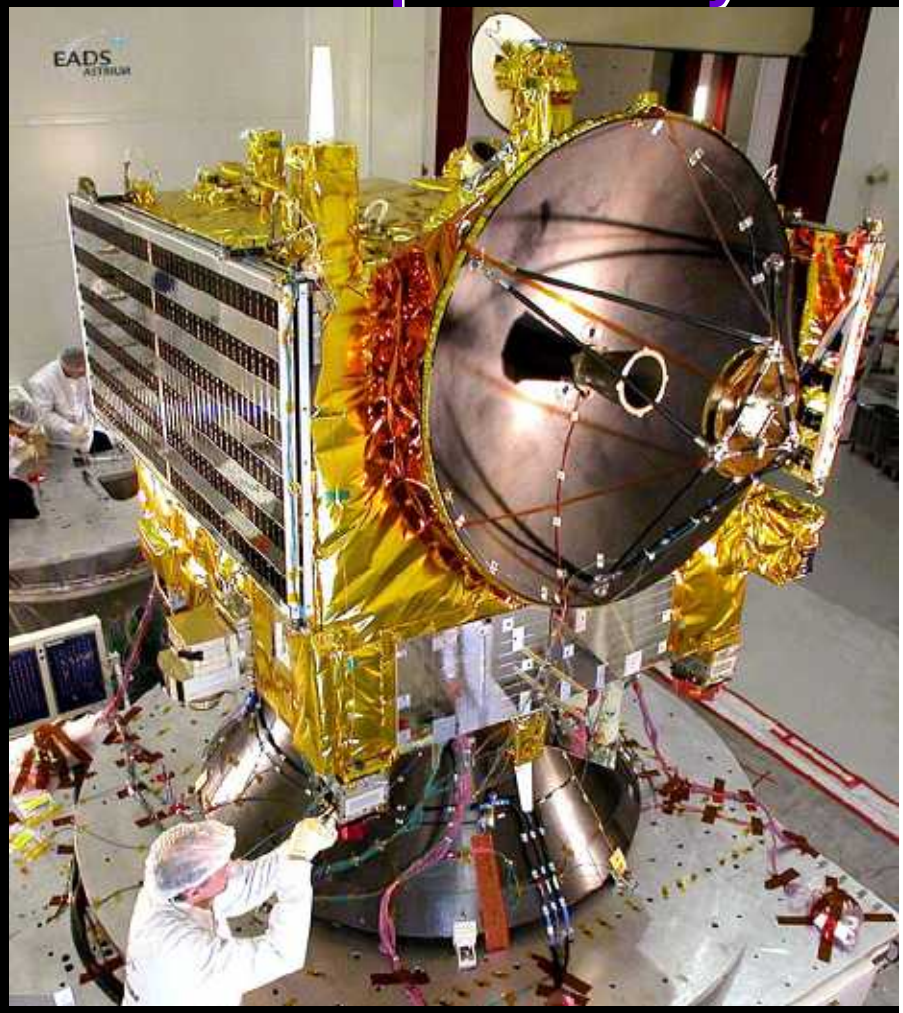
Magellan

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

Venus Express – the first ESA mission to Venus



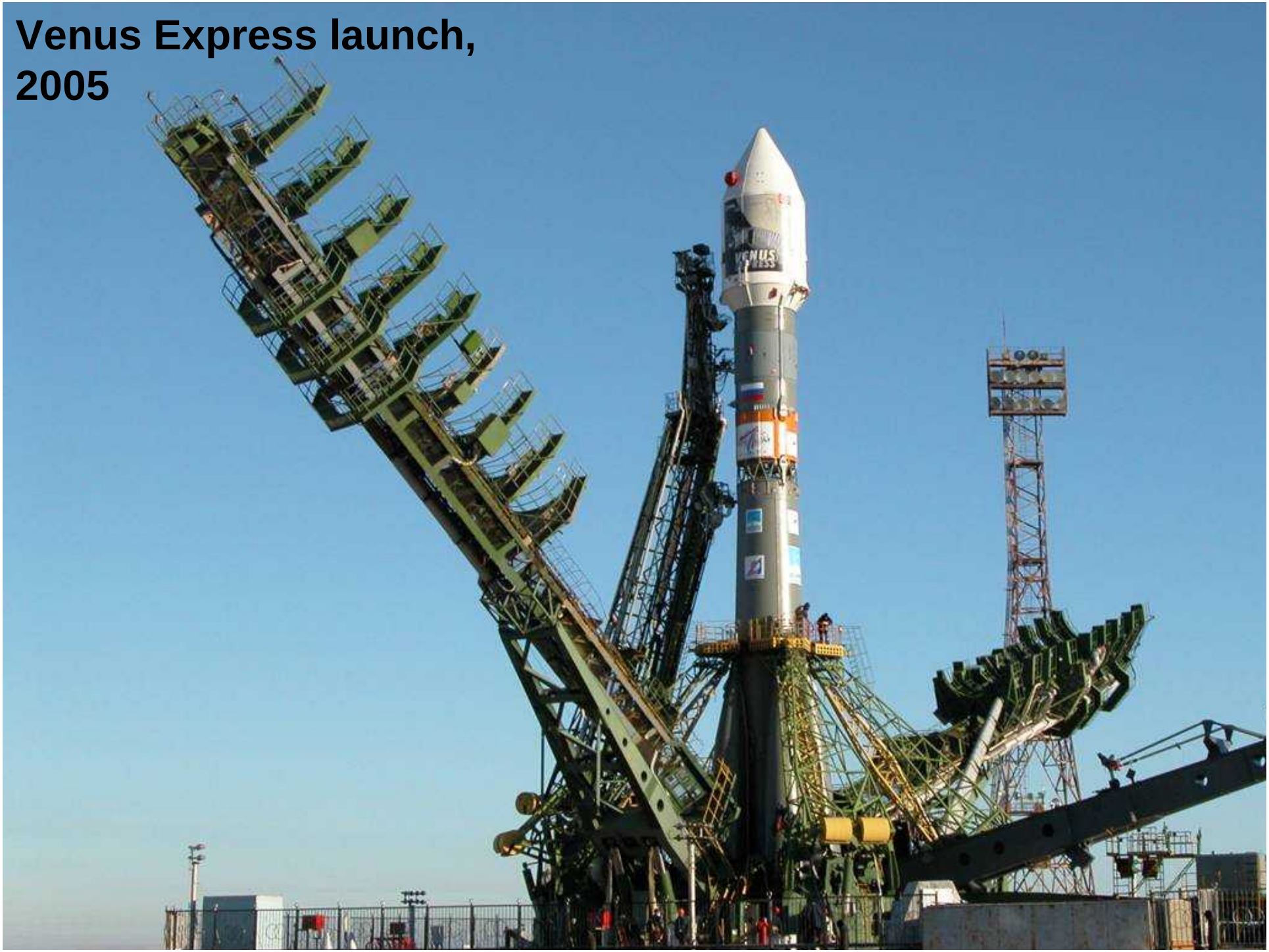
From Mars Express to Venus Express in 3 years



- *Solar panels: smaller and different composition*
- *Modified thermal design*

- *Accommodation of the new payloads*
- *Smaller dish of the main antenna*
- *Second antenna*

Venus Express launch, 2005



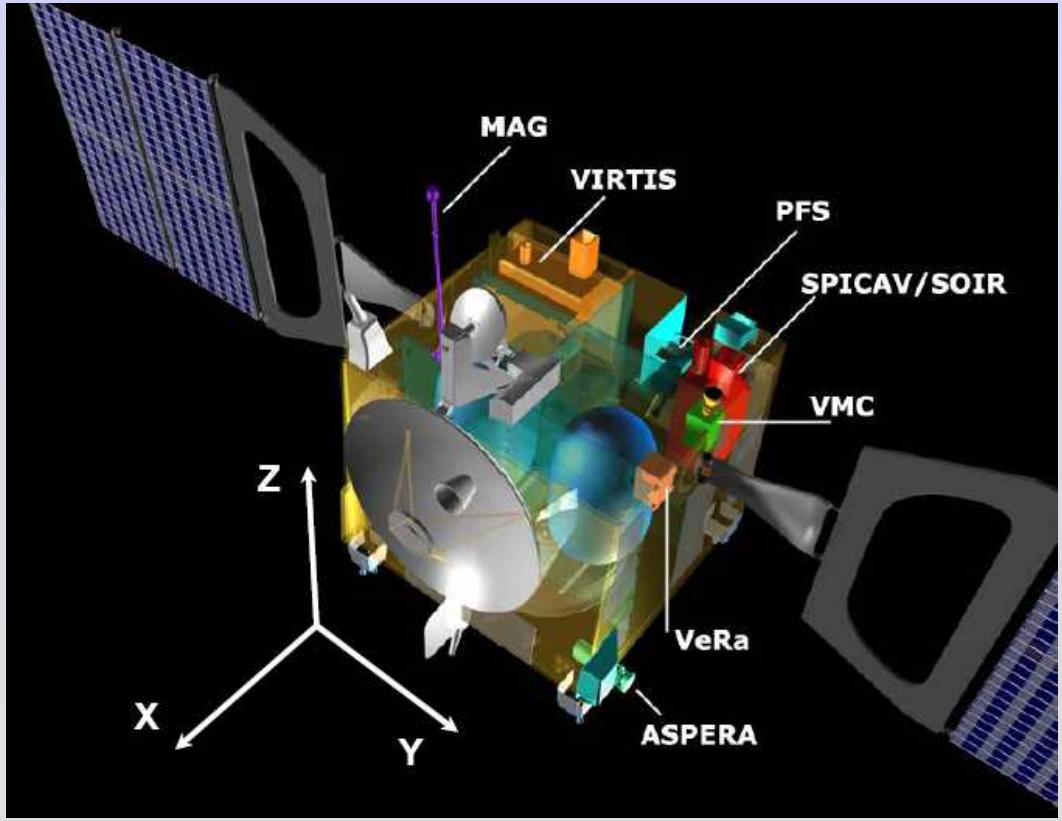
Souyz launch #1703
November 9, 2005,
3:33:33 UTC

Arrival at Venus:
April 11, 2006

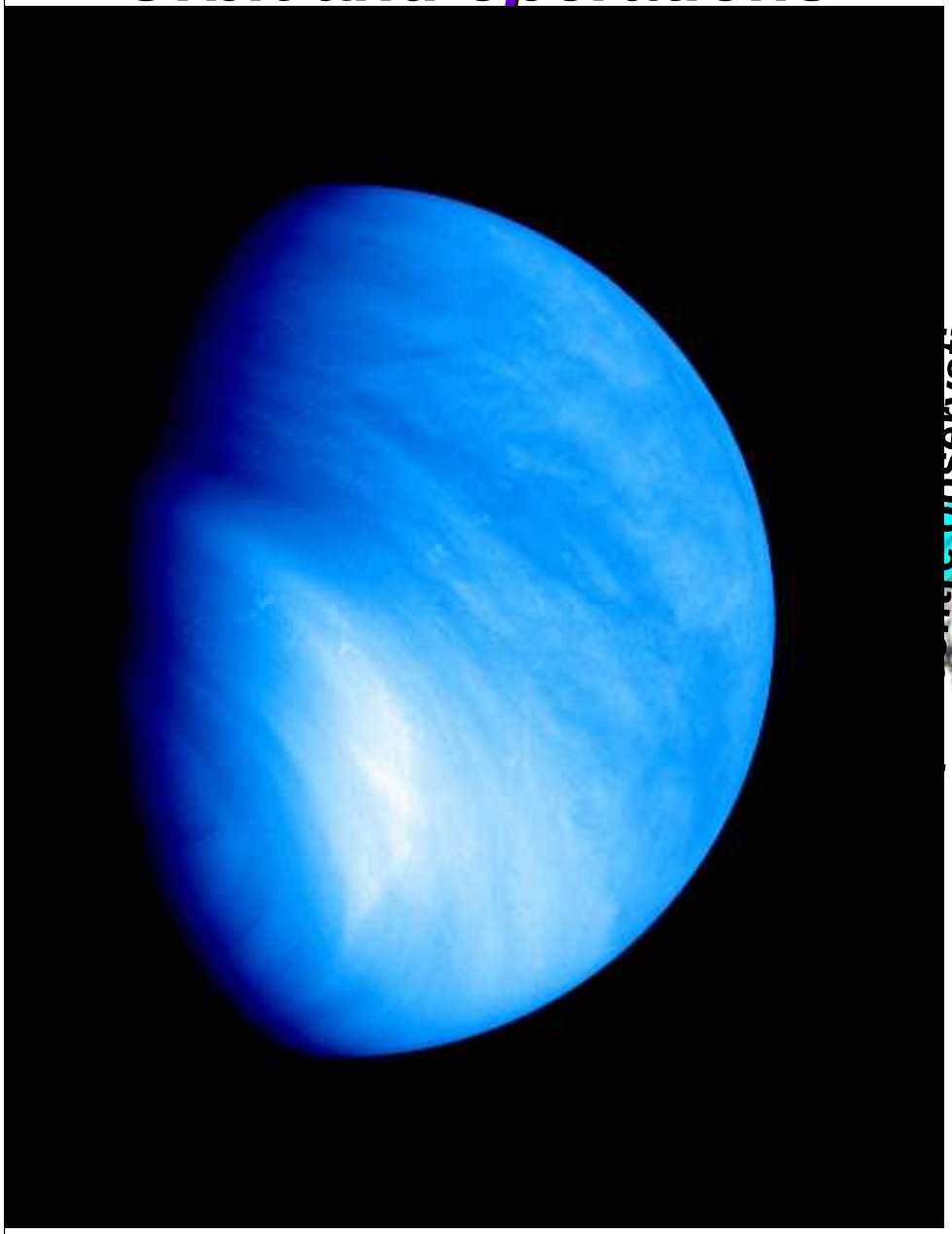
Venus Express payload

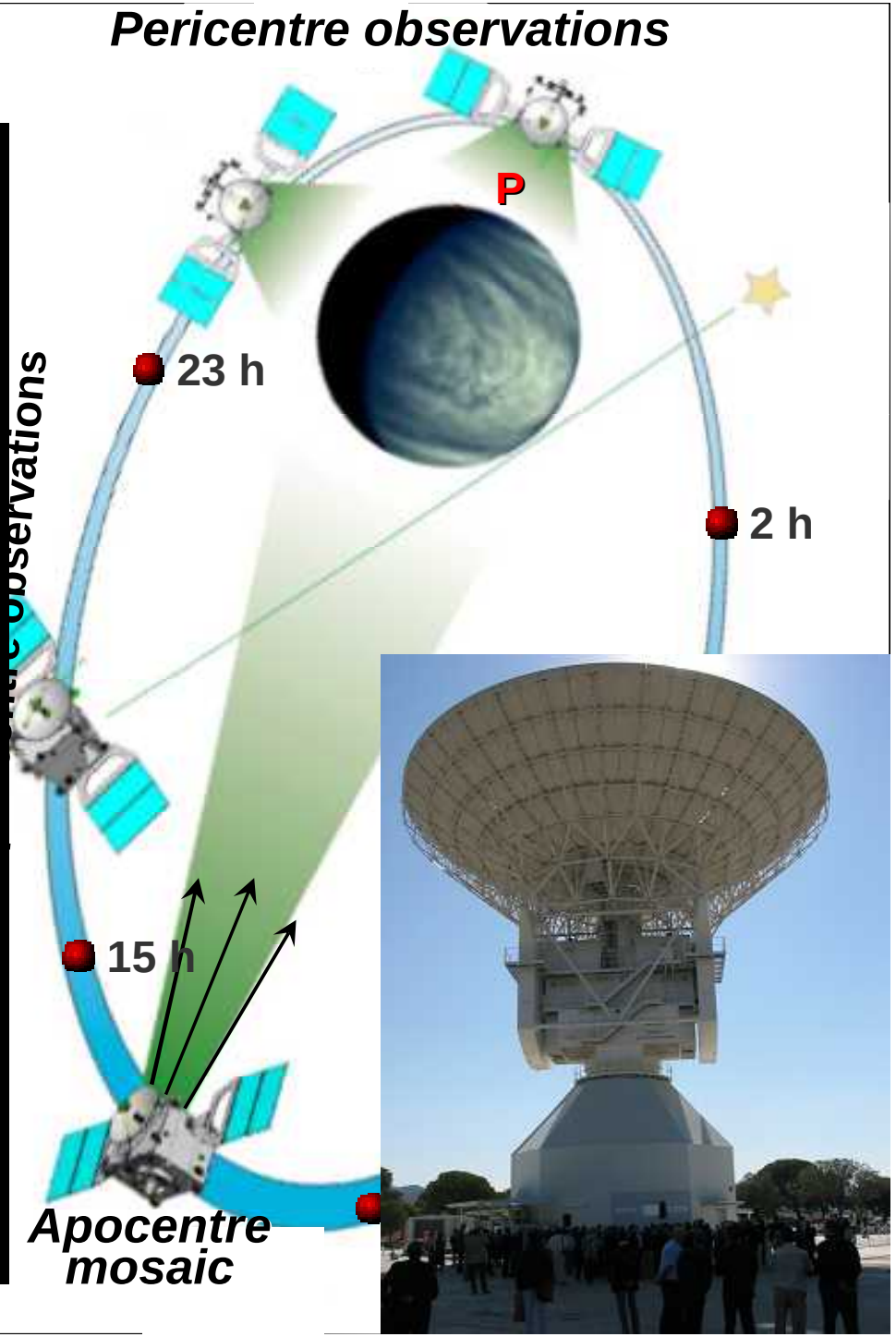
- **VIRTIS** (P. Drossart, G. Piccioni) - UV-vis-near IR imaging and high resolution spectrometer **(IPF/ DLR, MPS)**
- **SPICAV / SOIR** (J.-L. Bertaux, O. Korablev, P. Simon) -UV & IR spectrometer for solar/stellar occultations and nadir observations
- **PFS** (V. Formisano) - high resolution IR Fourier spectrometer **(IPF/ DLR)**
- **VMC** (W.J. Markiewicz) - Venus Monitoring Camera **(MPS, IPF/ DLR, IDA/ TU-BS)**

- **VeRa** (B. Häusler, M.Pätzold) - radio science experiment **(Uni Bundeswehr, Uni Koeln)**
- **ASPERA** (S. Barabash) - Analyzer of Space Plasmas and Energetic Atoms **(MPS)**
- **MAG** (T. Zhang) – Magnetometer **(TU-BS)**



Orbit and operations





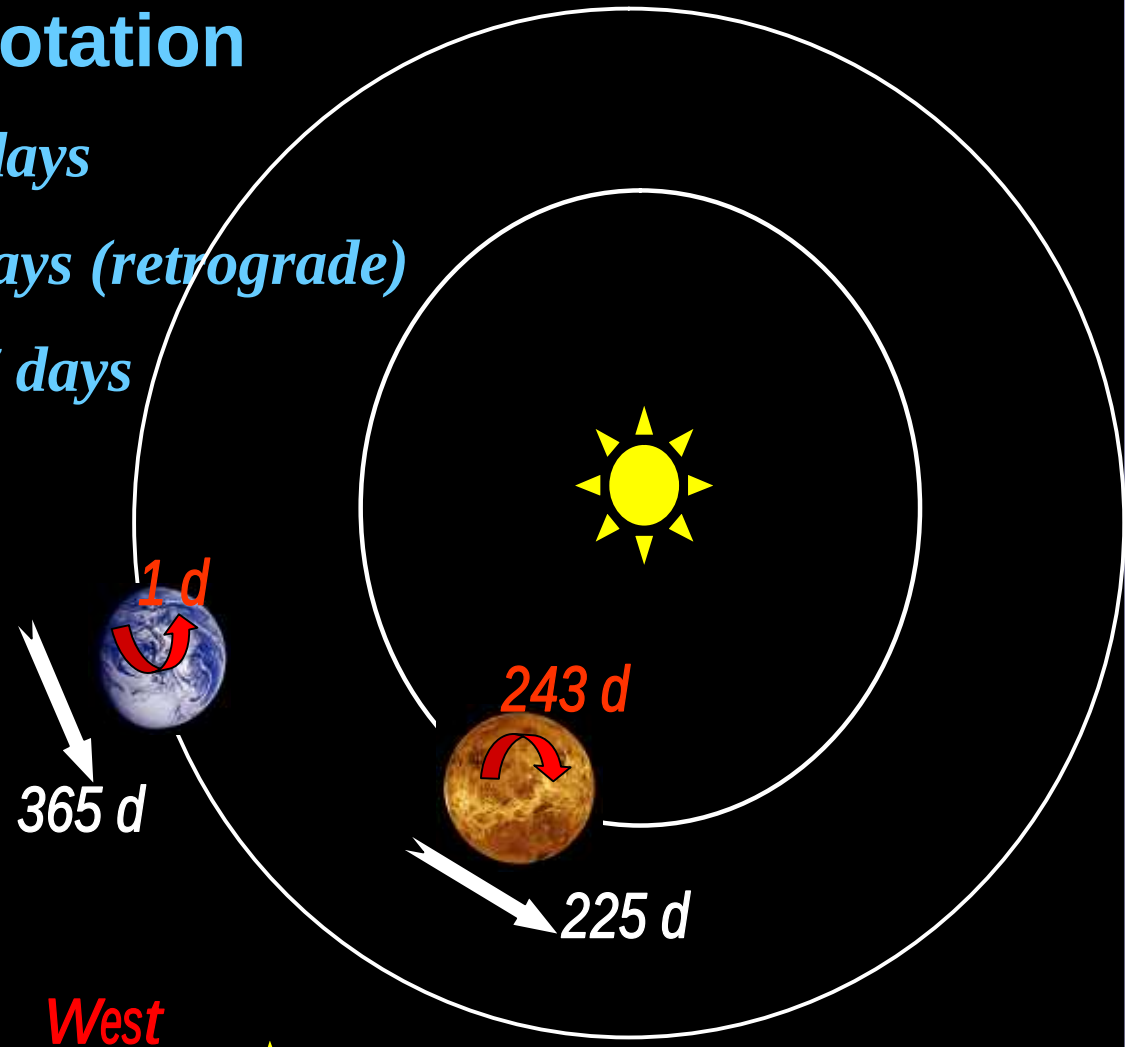
2. Venus in the Solar System

Venus as a Planet

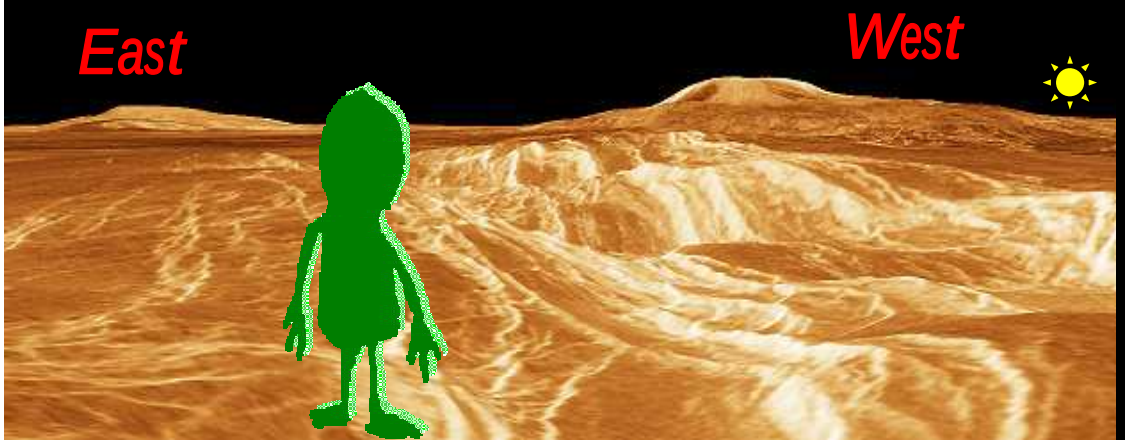
- *Radius = 6070 km (0.95 R_E)*
- *Mass = 0.815 M_E*
- *Equator-to-orbit inclination = 3 deg*
- *Distance to the Sun: 0.72 a.u.*
- *Solar flux = 2 Φ_{Earth}*

Venus strange rotation

- *Sidereal Year → 225 days*
- *Sidereal Day → 243 days (retrograde)*
- *Solar Day (sol) → 117 days*

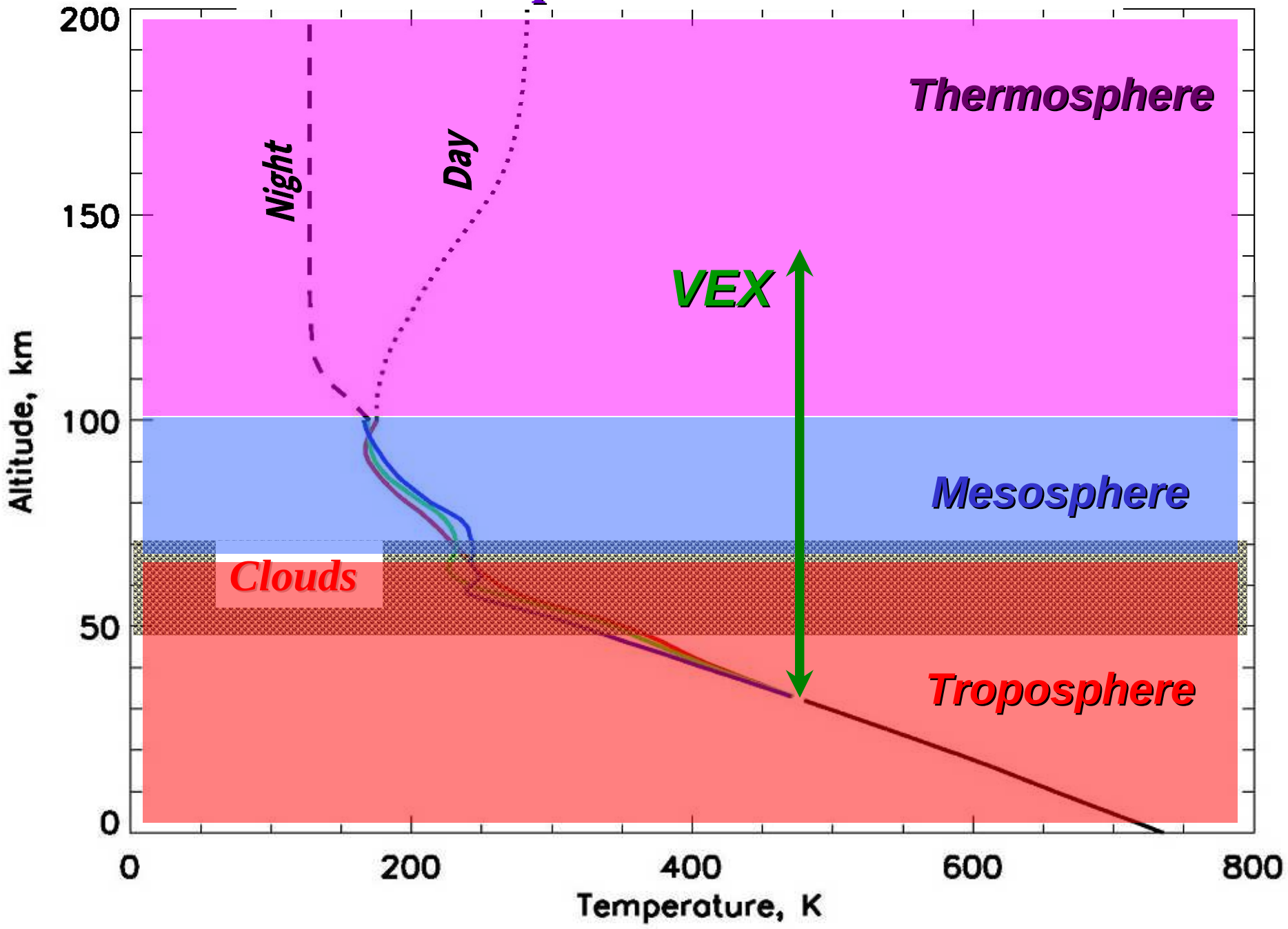


Sun in the Venus sky

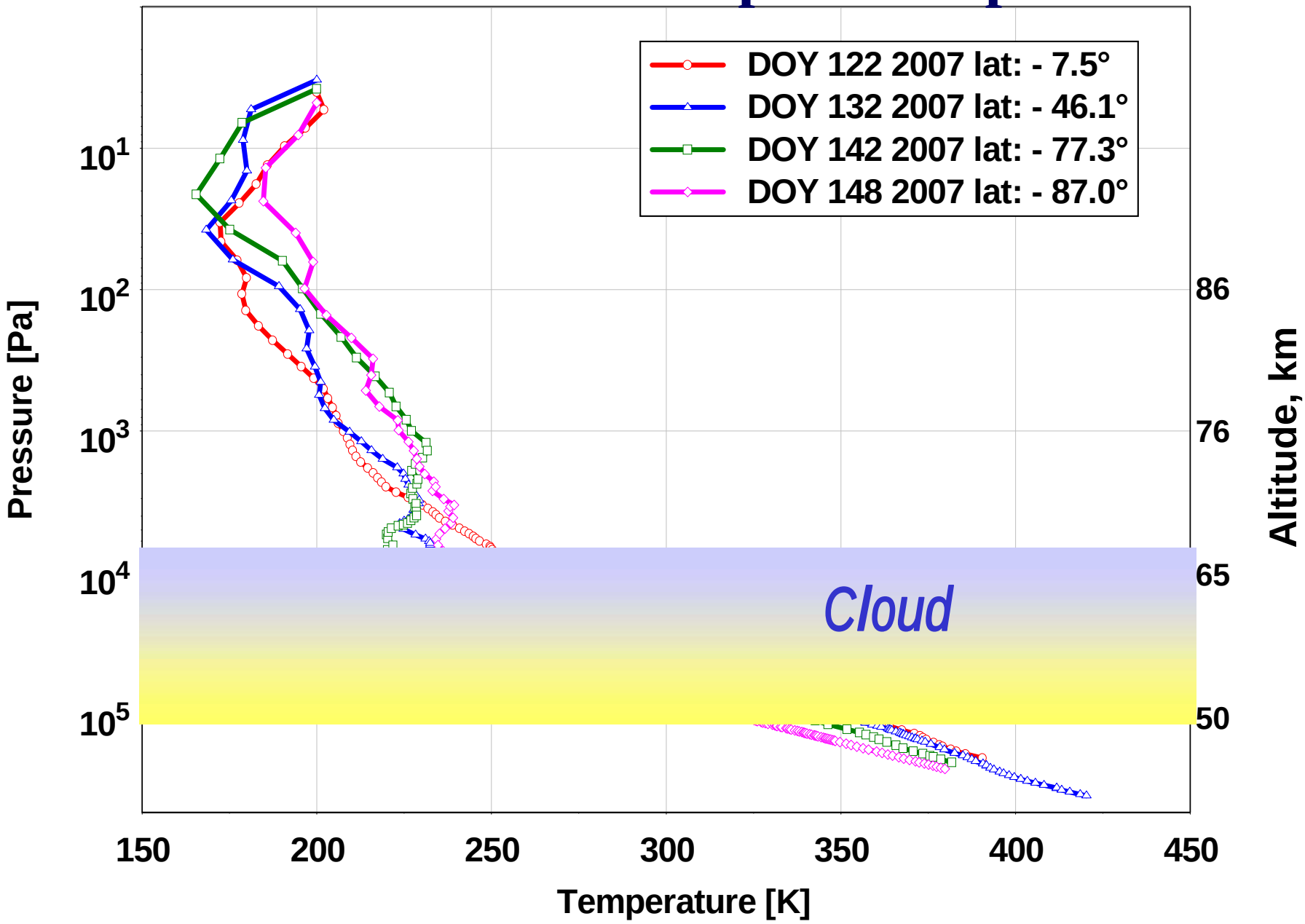


3. Structure of the Atmosphere

Temperature structure

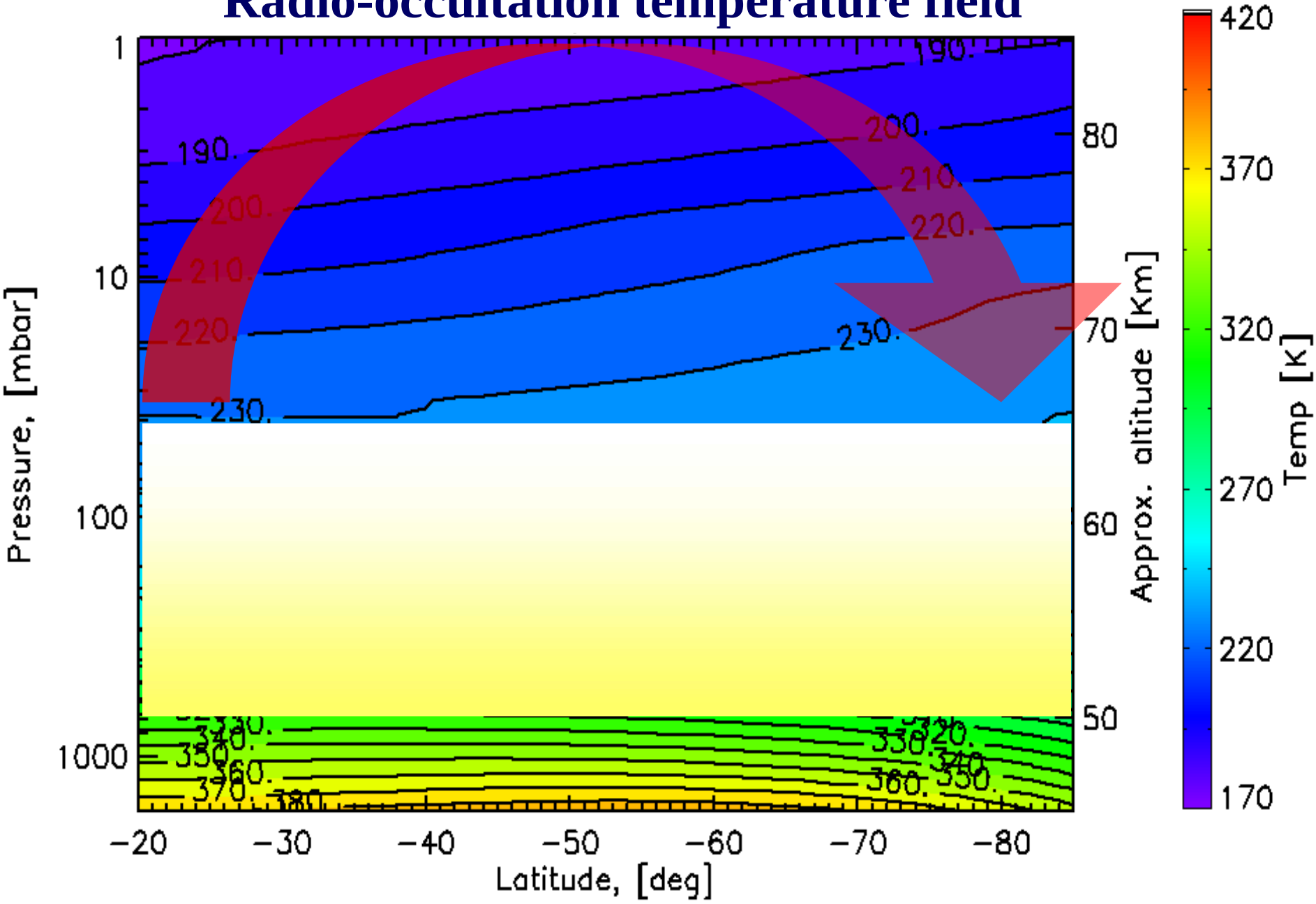


Radio-occultation temperature profiles



Tellmann et al, JGR, 2009.

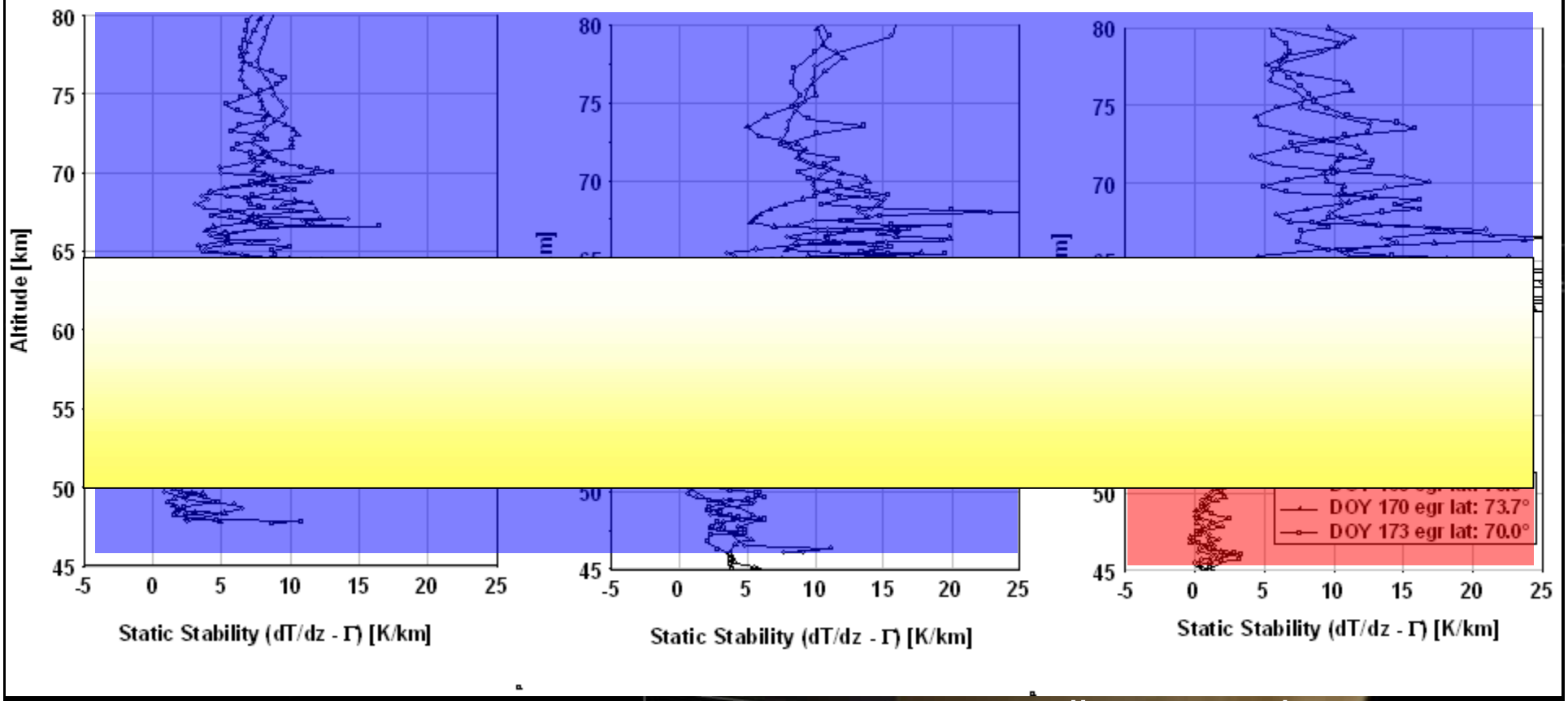
Radio-occultation temperature field



Tellmann et al, JGR, 2009

Static stability (VeRa)

low latitudes | middle latitudes | high latitudes



Tellmann et al, JGR, 2009

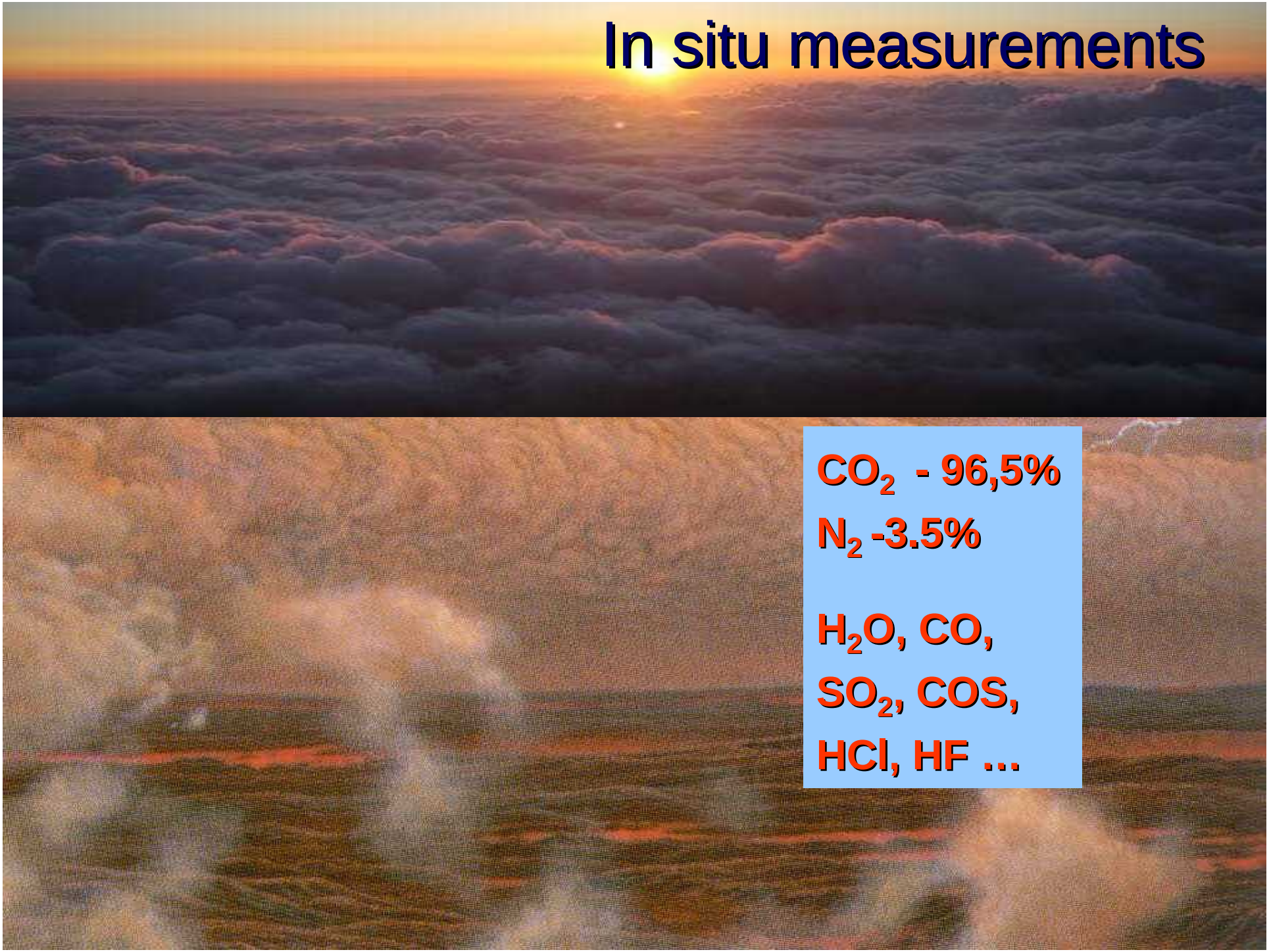
Universität der Bundeswehr München

Argelander-Institut für Astronomie

Planetary Research

4. Atmospheric composition

In situ measurements



CO_2 - 96,5%

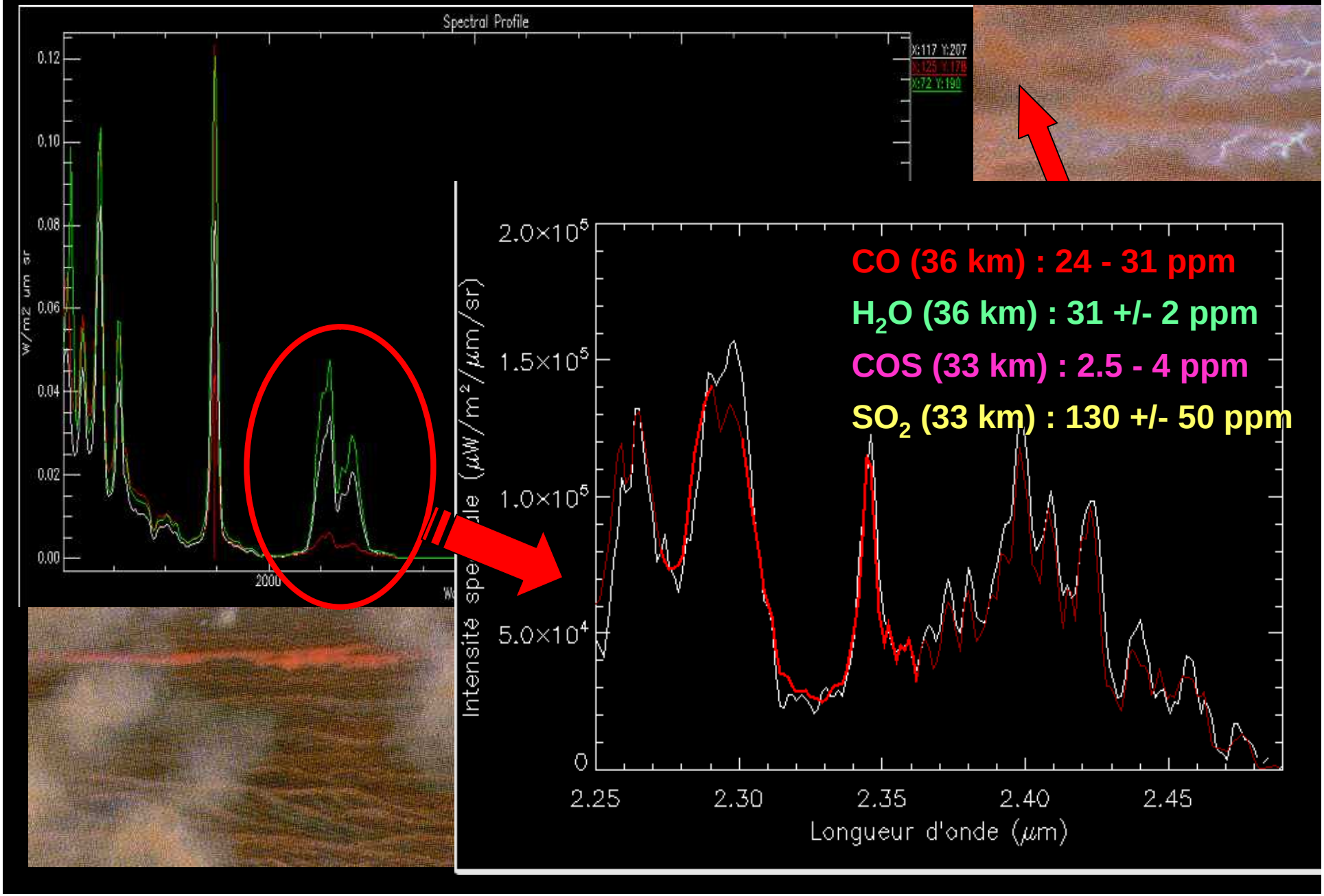
N_2 -3.5%

H_2O, CO,

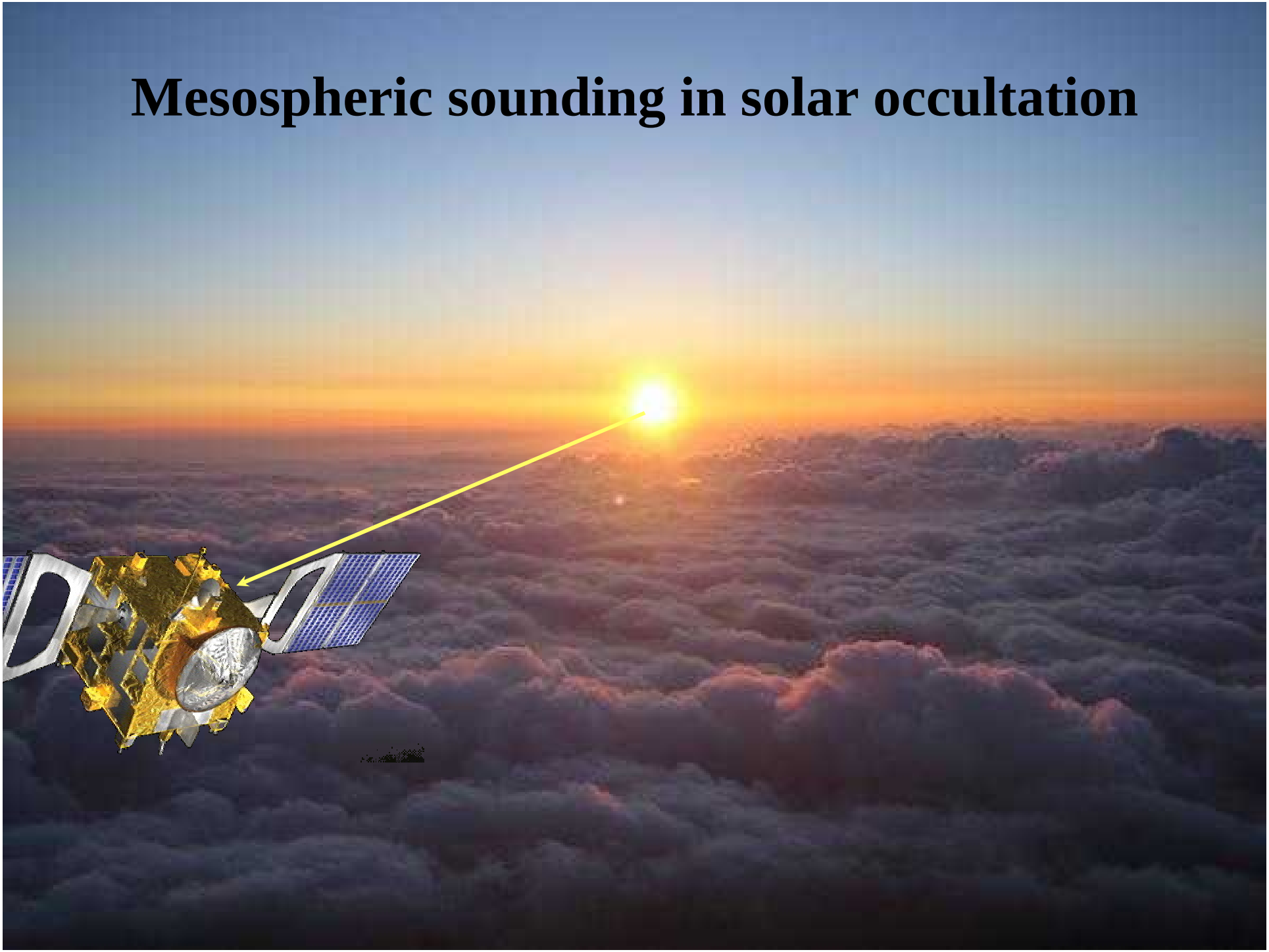
SO_2, COS,

HCl, HF …

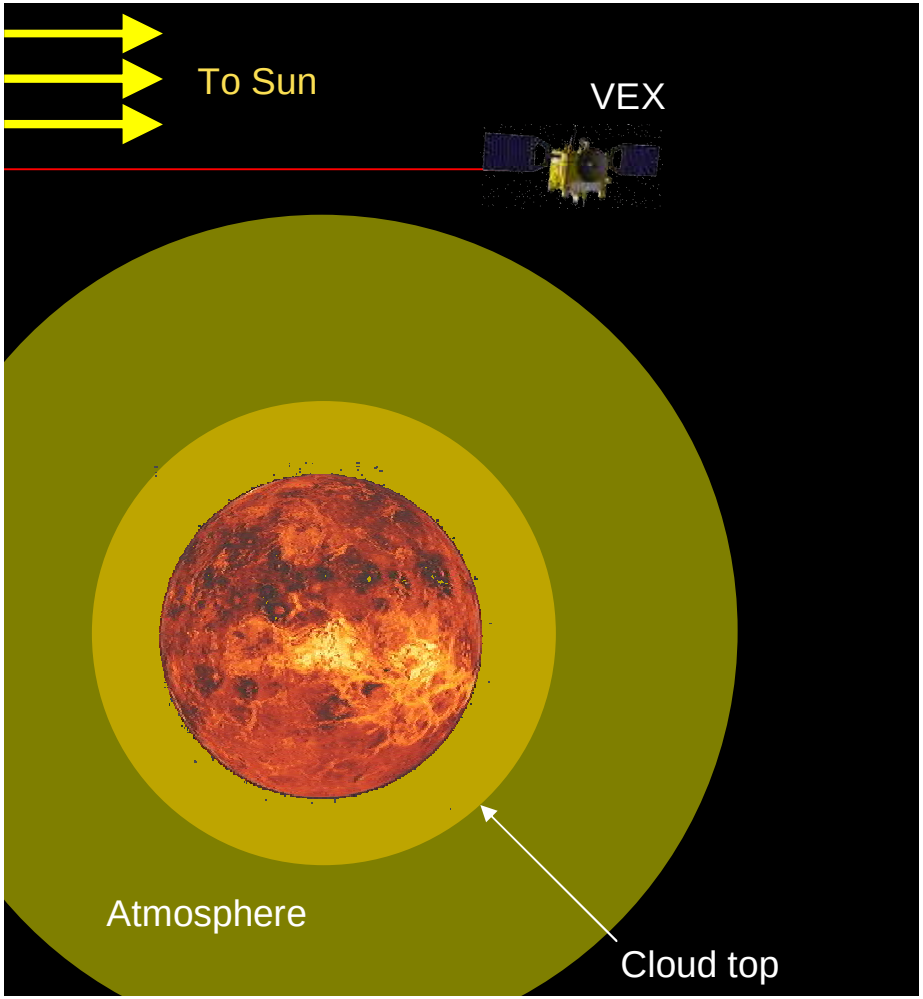
Composition of the lower atmosphere by VIRTIS



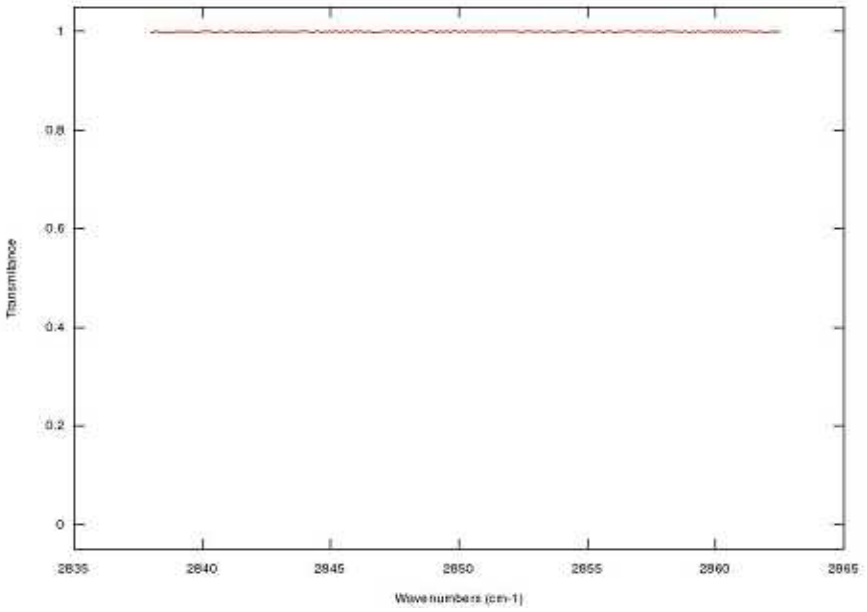
Mesospheric sounding in solar occultation



SPICAV/SOIR solar occultation



Orbit 232 – Order 129

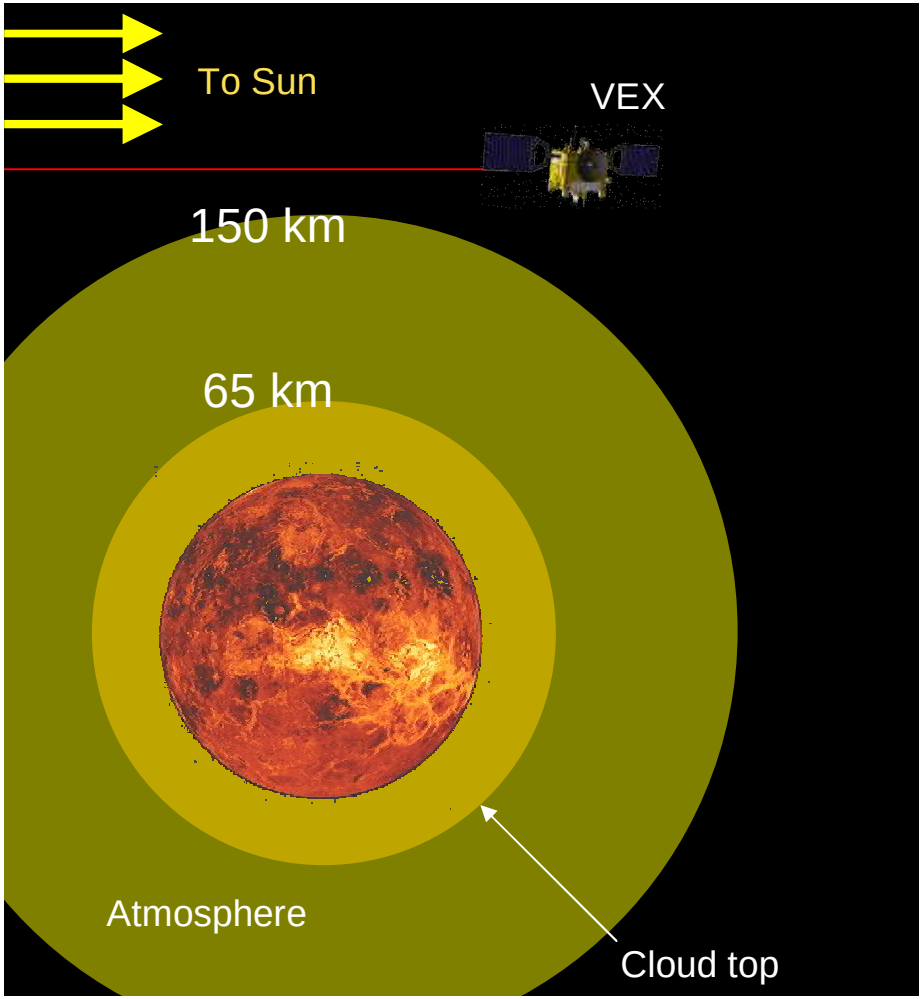


aeronomie.be

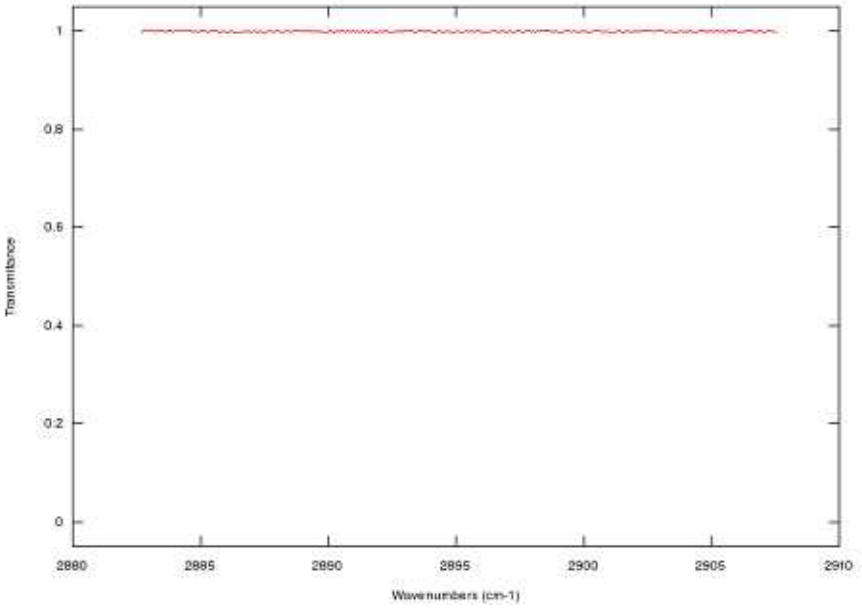
SPICAV/SOIR solar occultation

Detected molecules:

CO_2, H_2O, HDO, CO, HCl, SO_2



Orbit 232 – Order 129



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Examples of SOIR spectra

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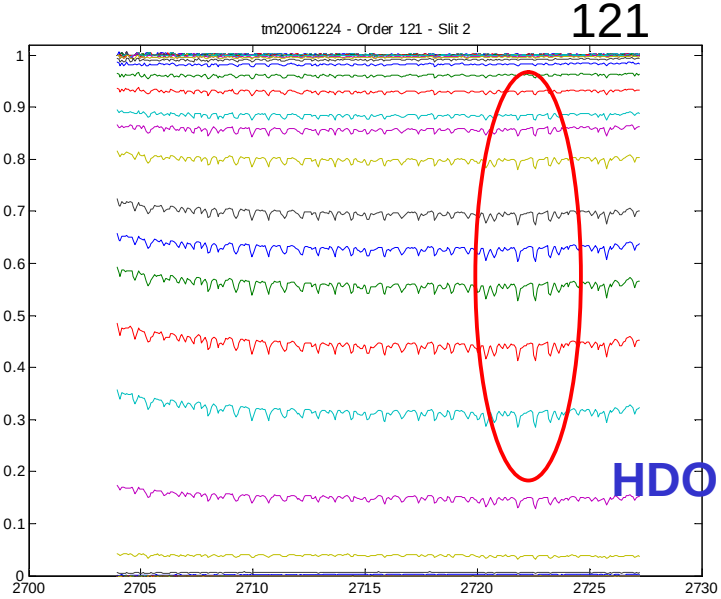

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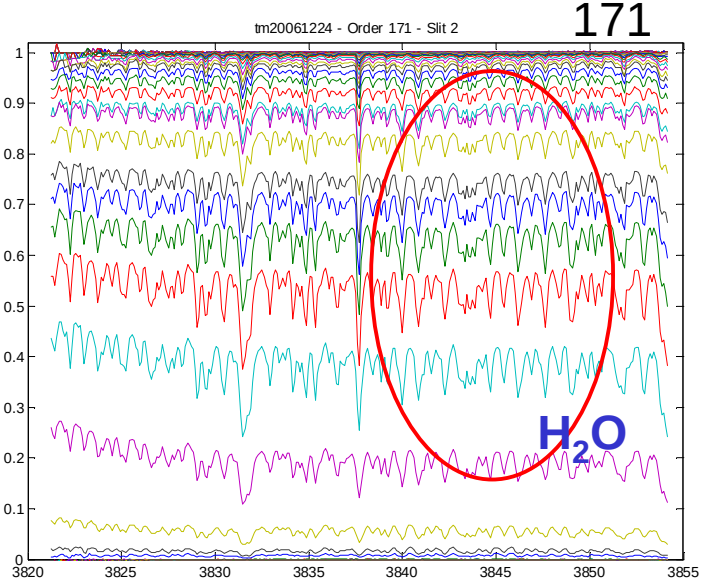

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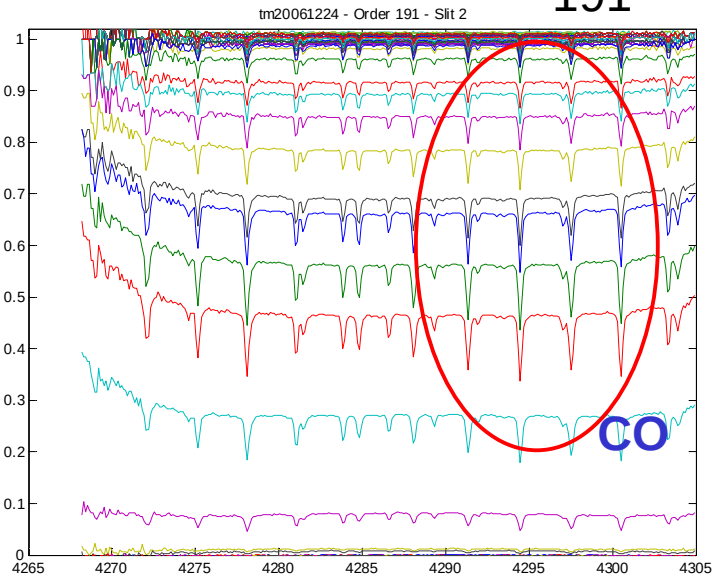

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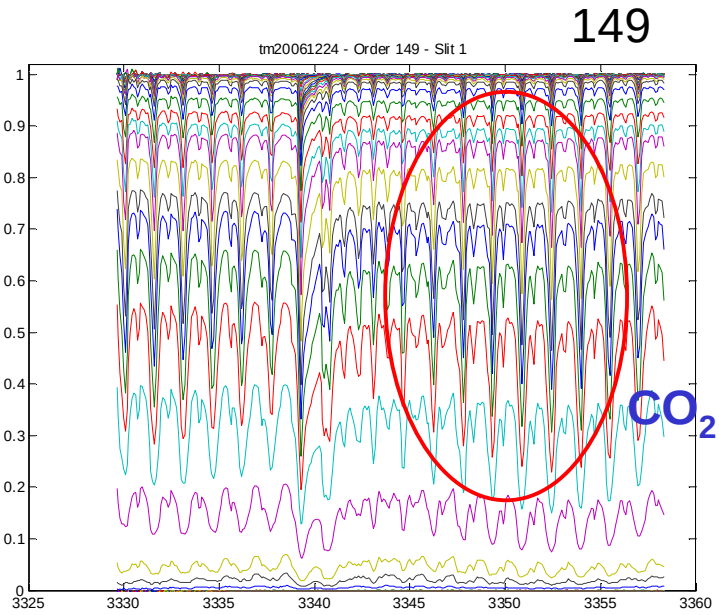
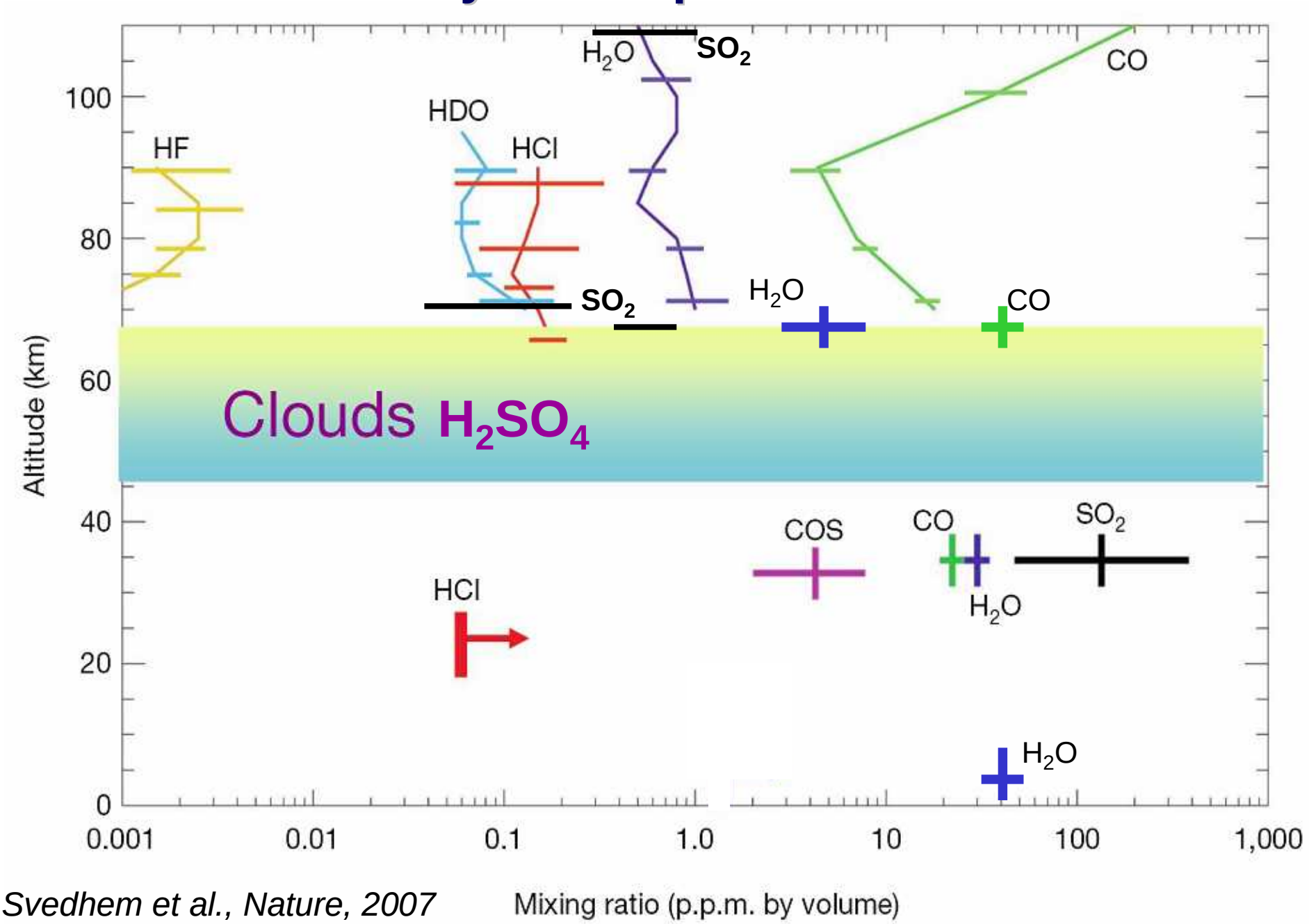
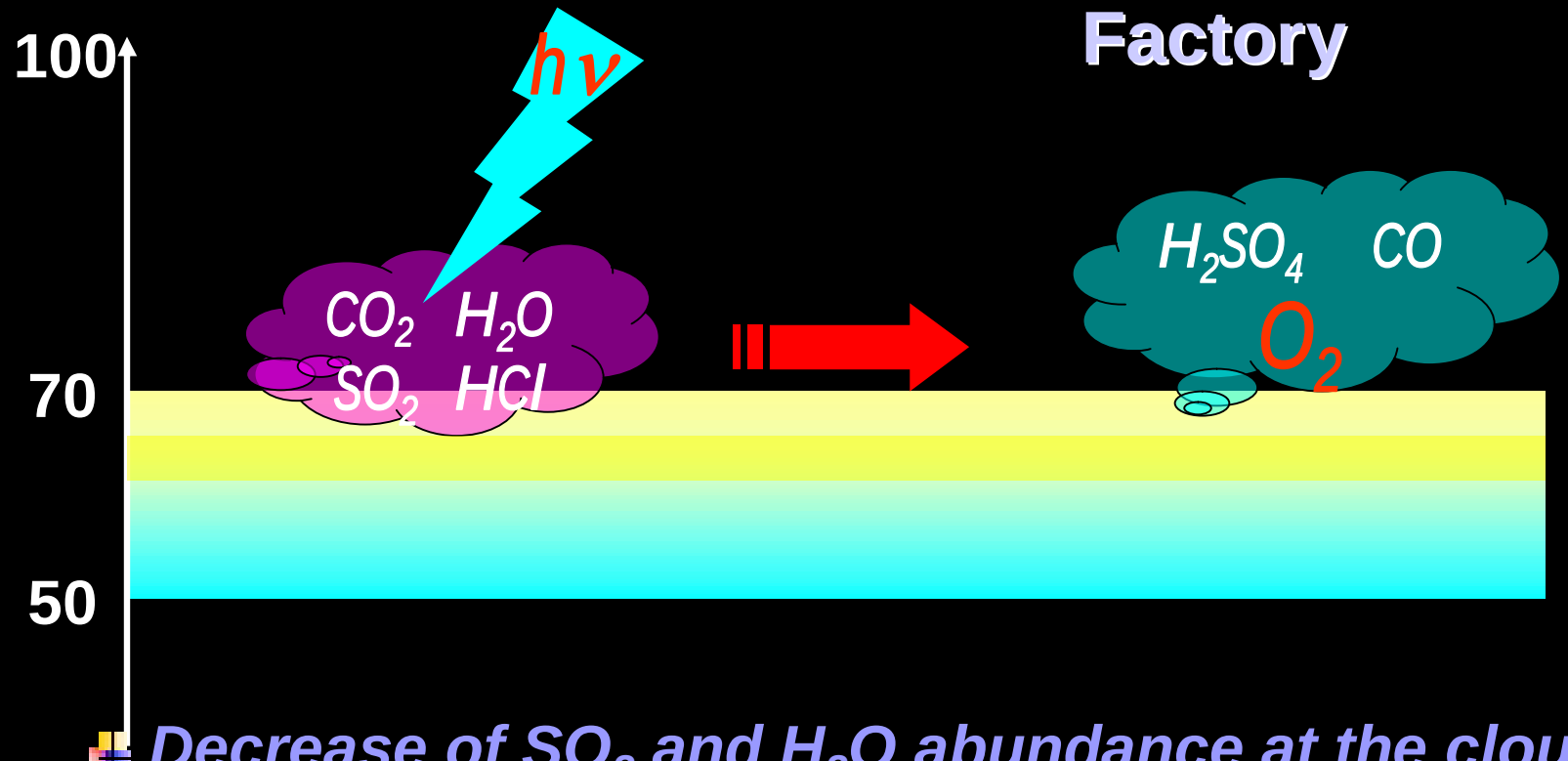


Summary of composition results

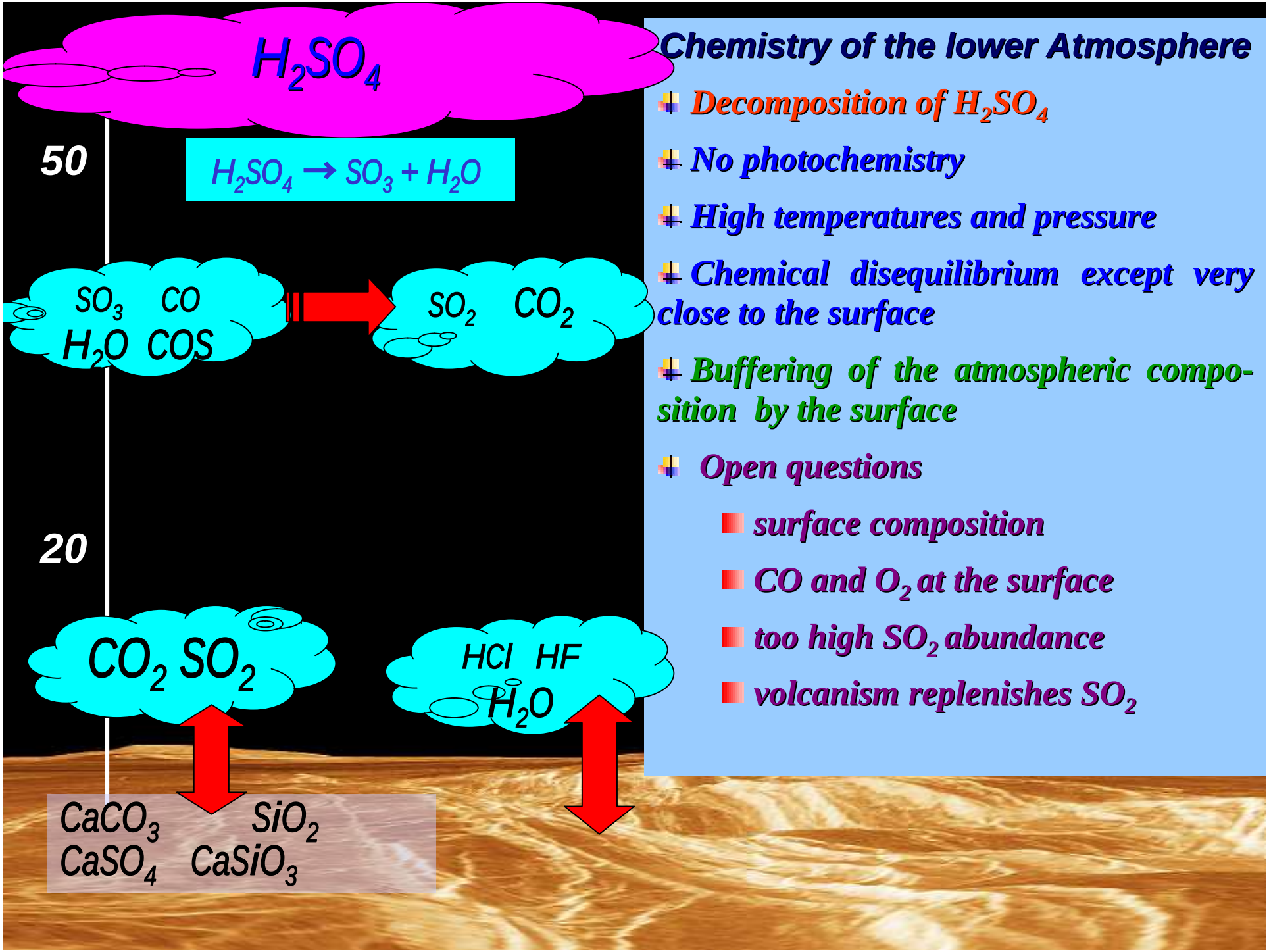


Svedhem et al., Nature, 2007

Mesospheric Photochemical Factory



- *Decrease of SO_2 and H_2O abundance at the cloud tops*
- *Formation of 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

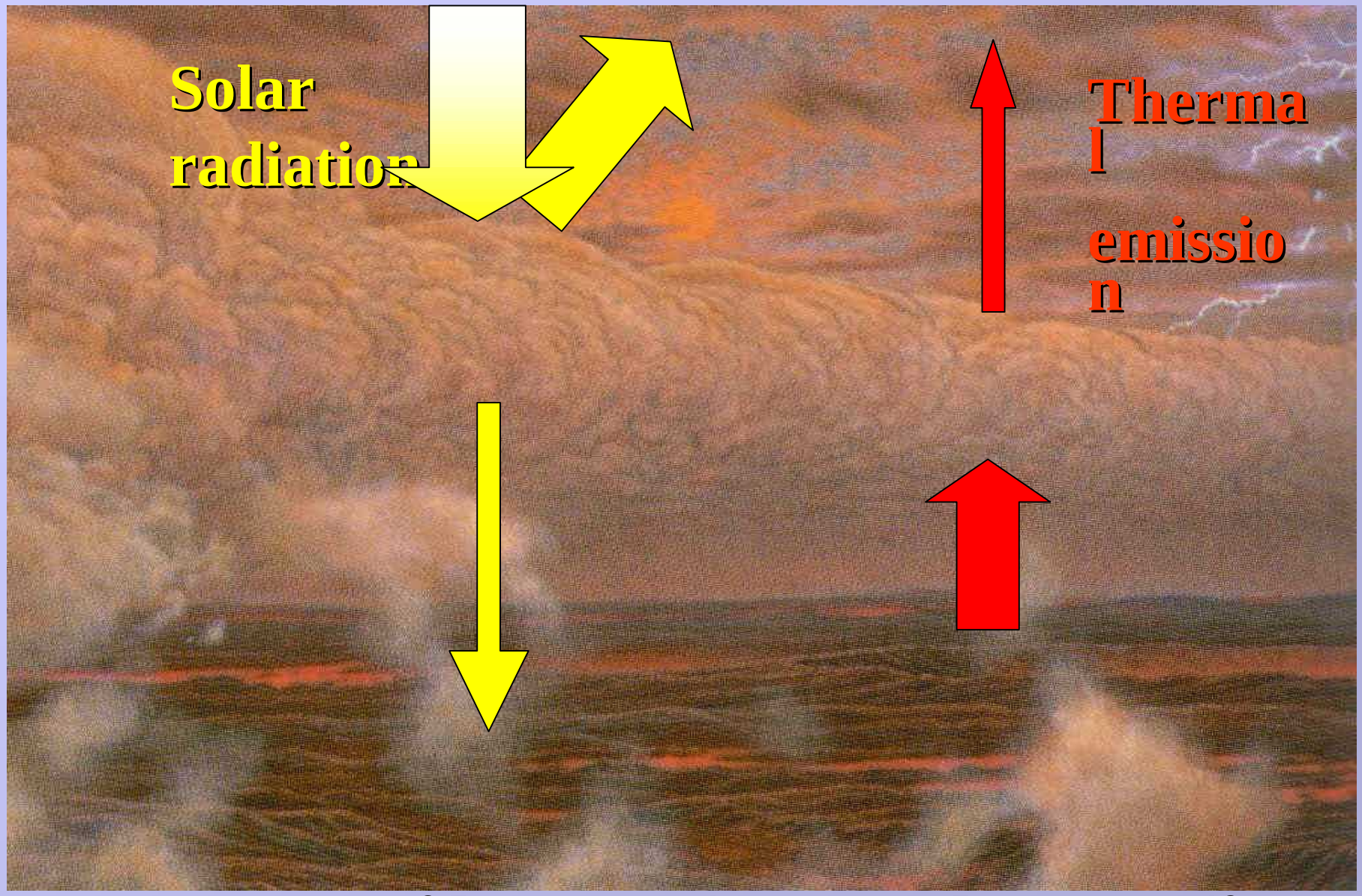
- *Decomposition of H_2SO_4*
- *No photochemistry*
- *High temperatures and pressure*
- *Chemical disequilibrium except very close to the surface*
- *Buffering of the atmospheric composition by the surface*
- *Open questions*
  - *surface composition*
  - *CO and O_2 at the surface*
  - *too high SO_2 abundance*
  - *volcanism replenishes SO_2*

So different twins

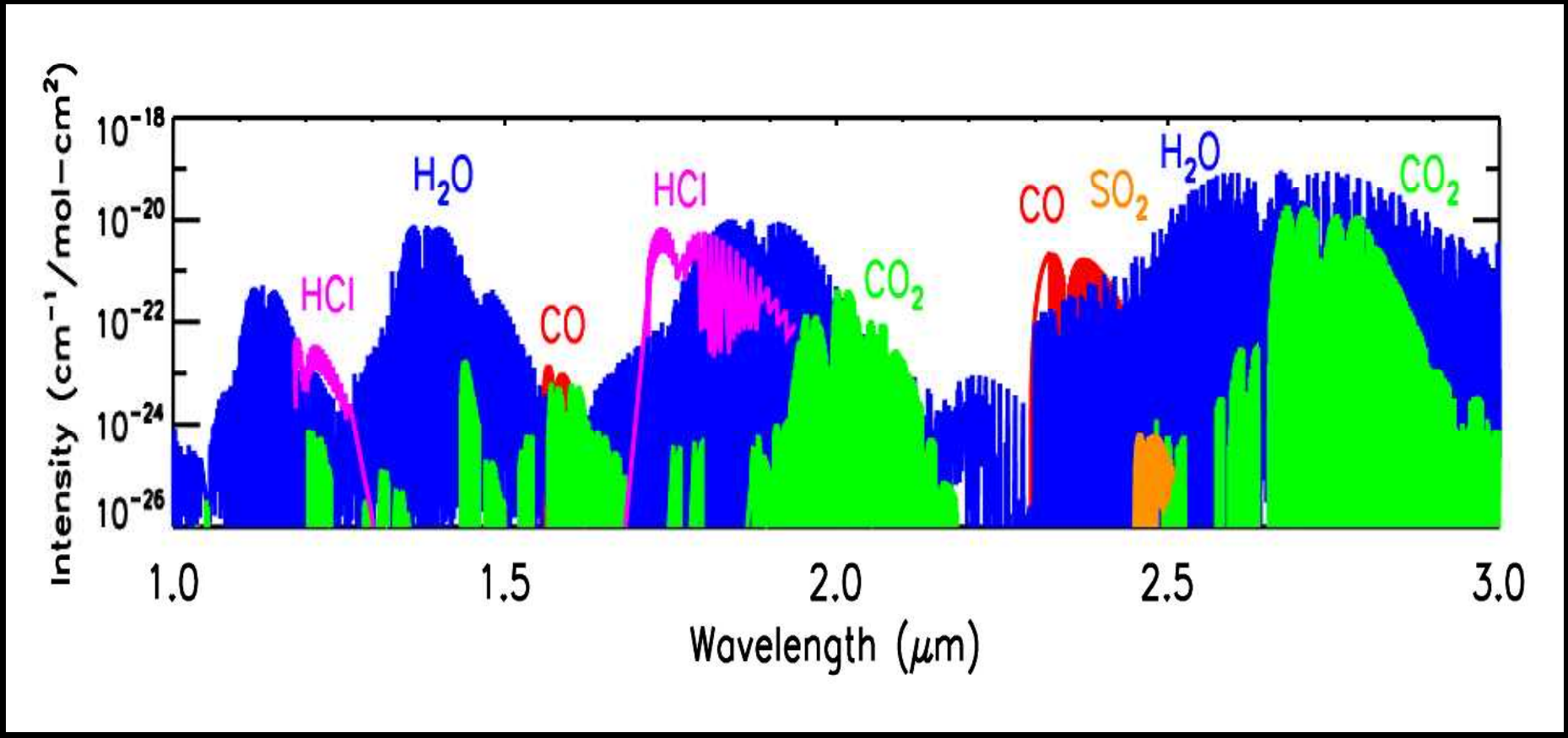
	Earth	Venus
Surface P, bar	1	**90**
Surface T, ° C	+15	**+ 460 (!)**
Composition , %		
N_2	**0.78**	0.035
O_2	**0.21**	~ 0
Atmospheric H_2O	< 0.03	0.00005
Total H_2O, cm	**~$3 \cdot 10^5$**	~3
CO_2	0.0003	**0.965**
SO_2	~0	0.0001
Clouds	**H_2O**	**H_2SO_4 +?**

5. Greenhouse effect

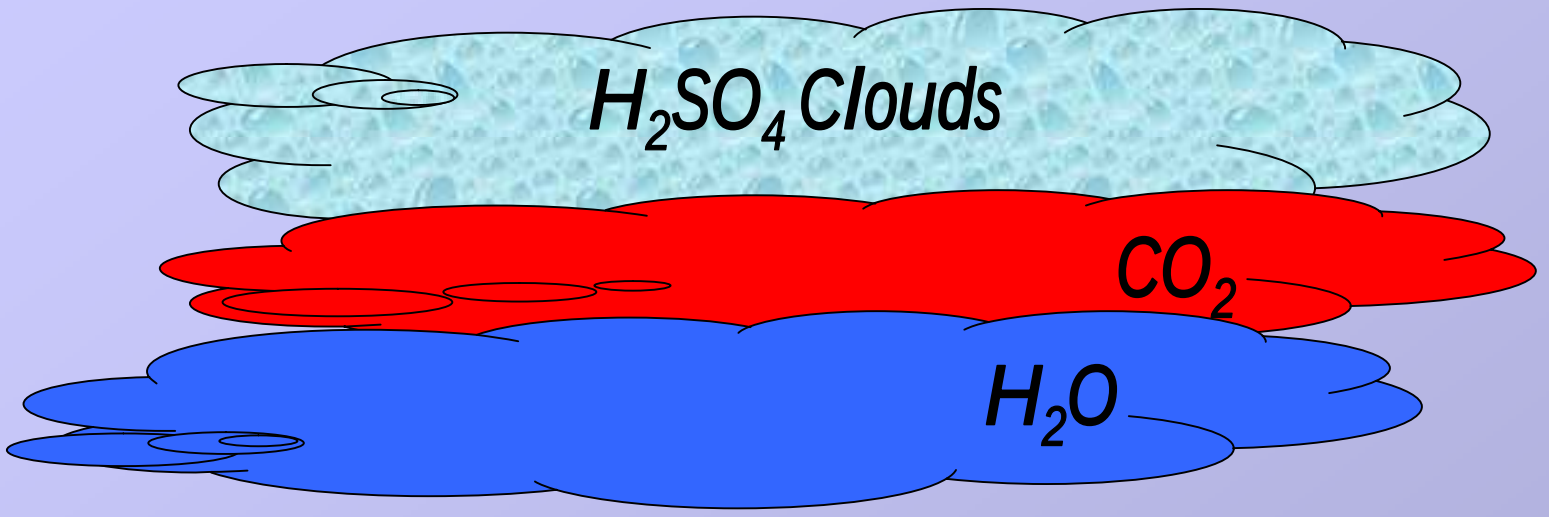
Basics of the greenhouse effect



Absorption bands of the atmospheric gases



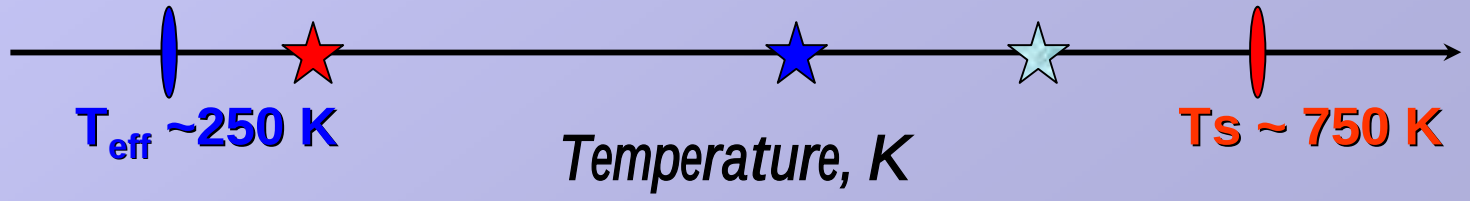
Contribution of the atmospheric components to the greenhouse effect on Venus



CO_2 – 460K

H_2O – 220K

Clouds – 100K

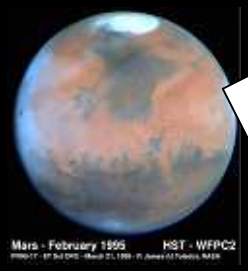


Greenhouse effect on terrestrial planets

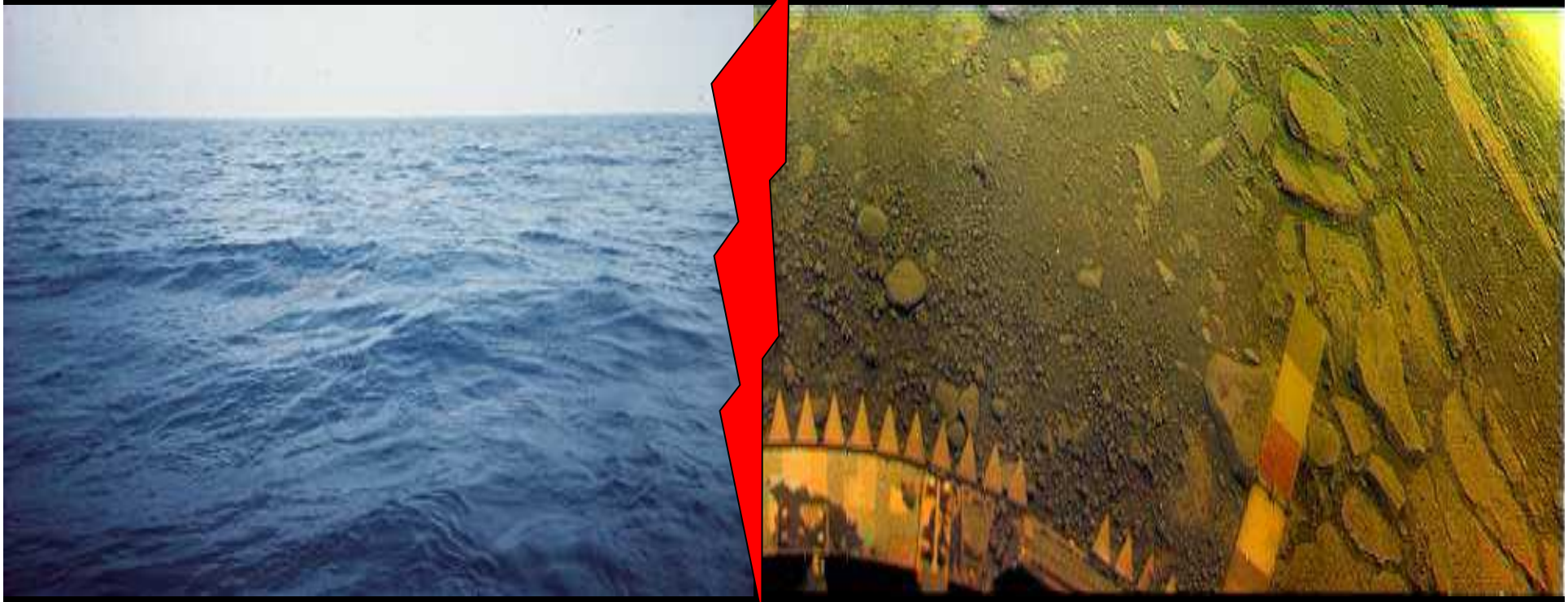
Venus – 500K

Earth – 40K

Mars – 5K

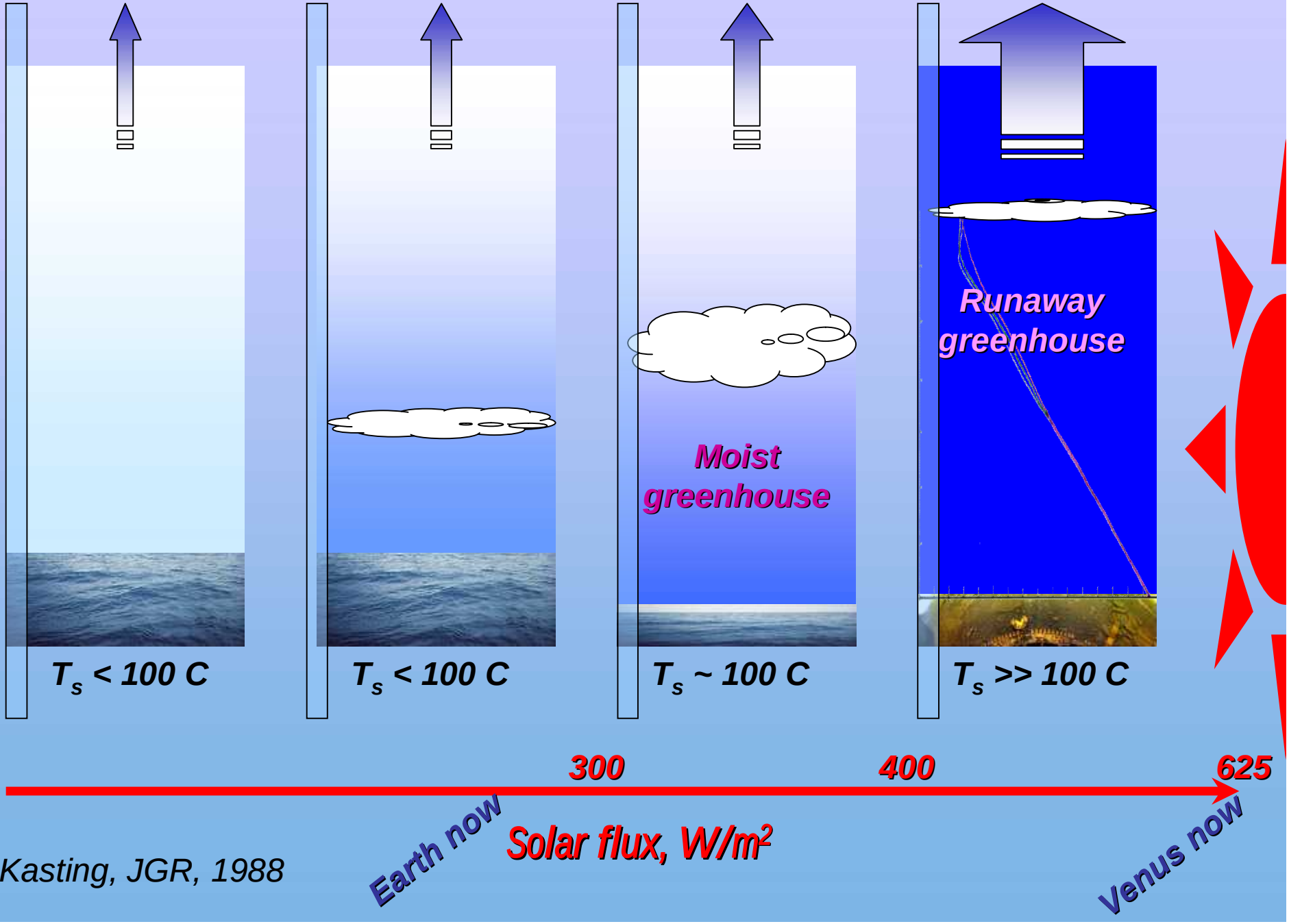


Greenhouse effect and water loss (1)



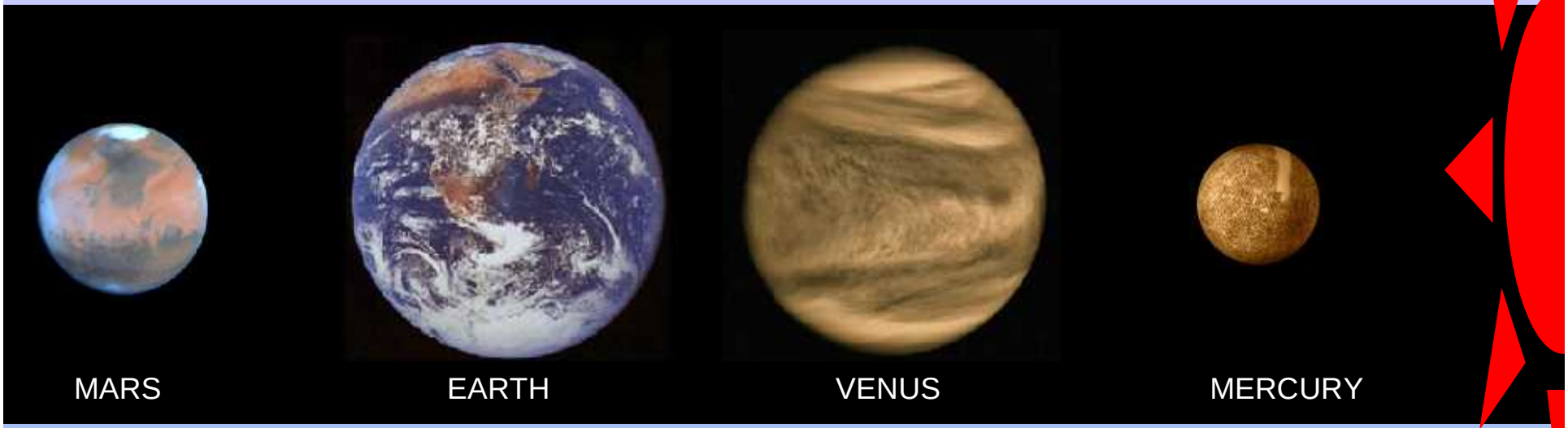
- Similar volatile inventories at origin
- Present water amount: $H_2O_{VENUS} \sim 10^{-5}\ H_2O_{EARTH}$
- Deuterium enrichment: $(D/H)_{VENUS} \sim 150\ (D/H)_{EARTH}$

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



Kasting, JGR, 1988

Greenhouse effect and habitability zone



1.52 1 0.72 0.39

Distance, AU

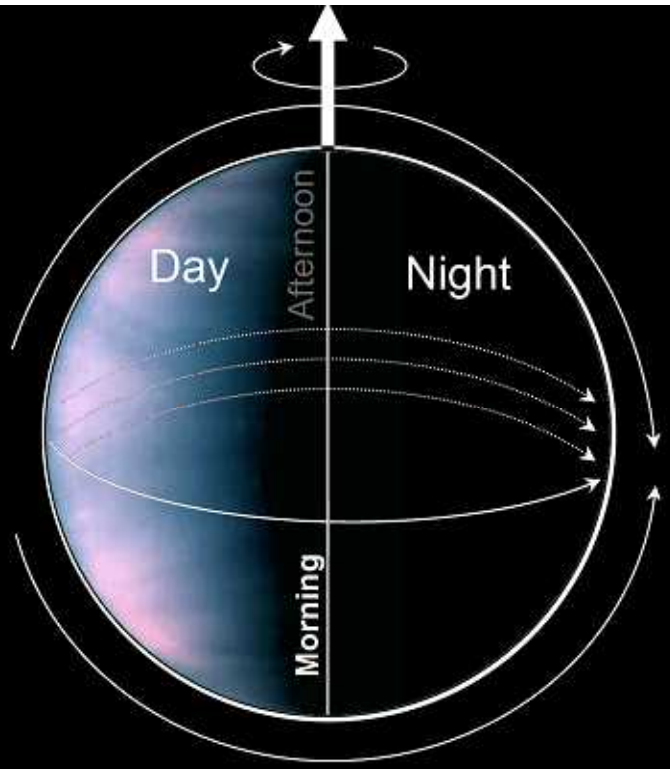
Global fridge

Paradise

Runaway greenhouse

6. Non-LTE emissions

Origin of airglow on Venus



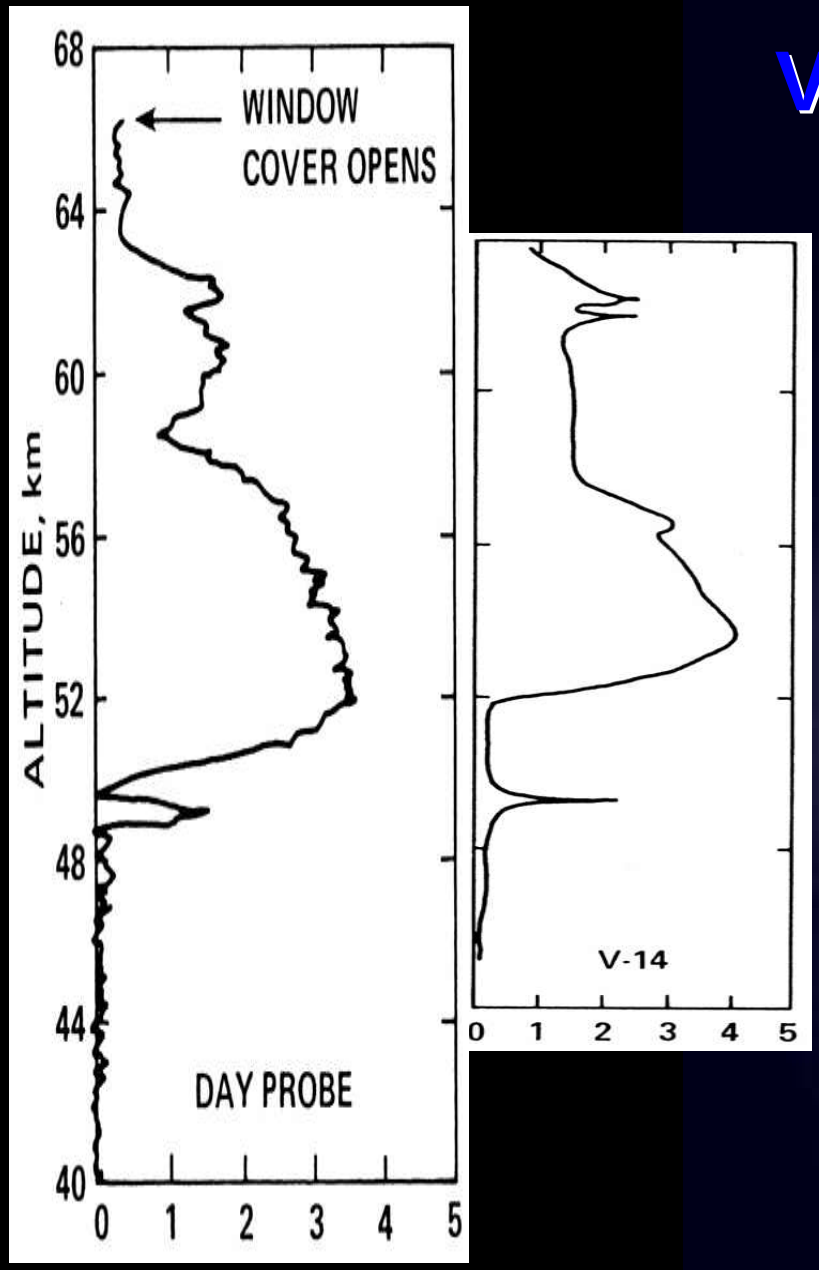
Recombination	**$O + N \rightarrow NO^*$**
3-body recombination	**$O + N + CO_2 \rightarrow NO + CO_2$**
Emission	**$NO^* \rightarrow NO + h\nu$**
Loss	**$N + NO \rightarrow N_2 + O$**

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

R. Hueso, private communication

7. Clouds and hazes

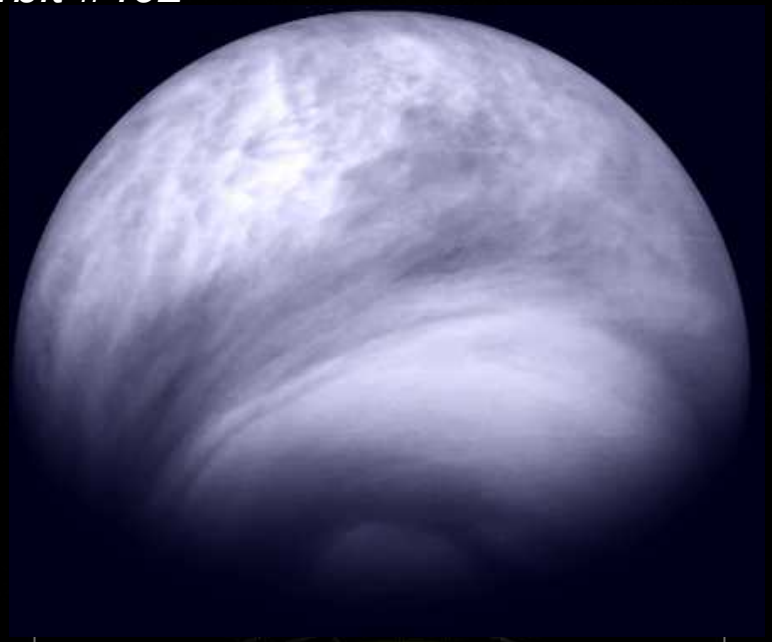
Venus Cloud Properties

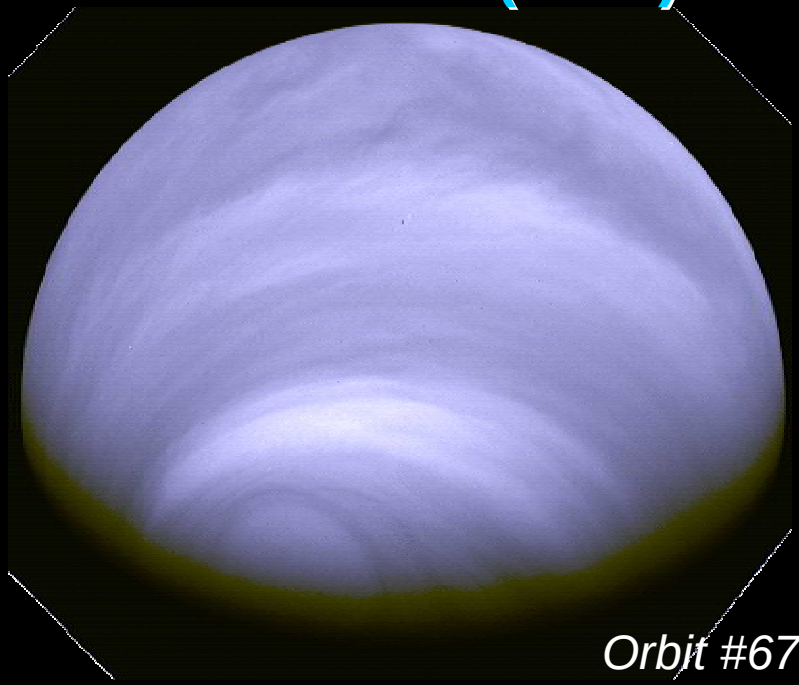


- *Altitude range 75 – 45 km*
- *Total opacity 20-40*
- *Visibility > 300 m*
- *Particles:*
  - *R = 1-10 μm*
  - *N = 100-1000 cm^{-3}*
- *Composition:*
  - *H_2SO_4 + ? (S_n, $AlCl_3$, H_3PO_4, …)*

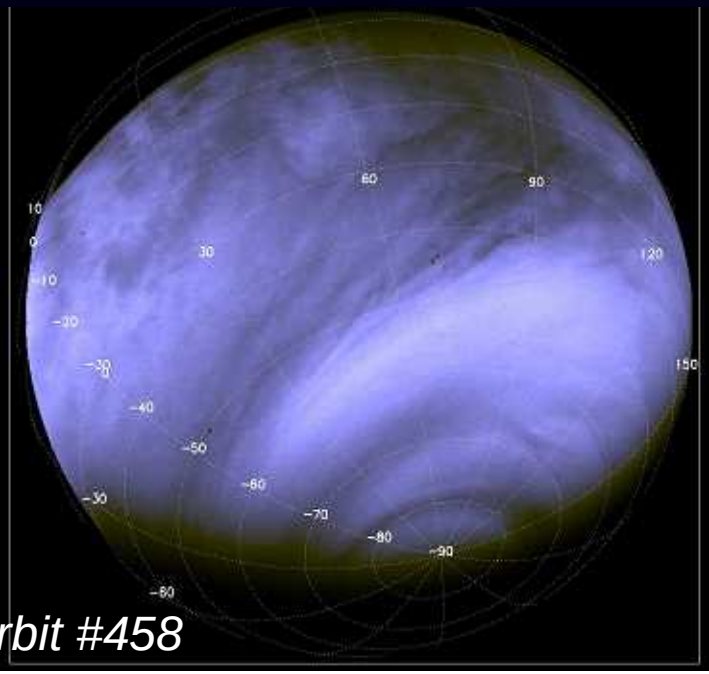
Cloud morphology: Global UV view (VMC)

Orbit #462

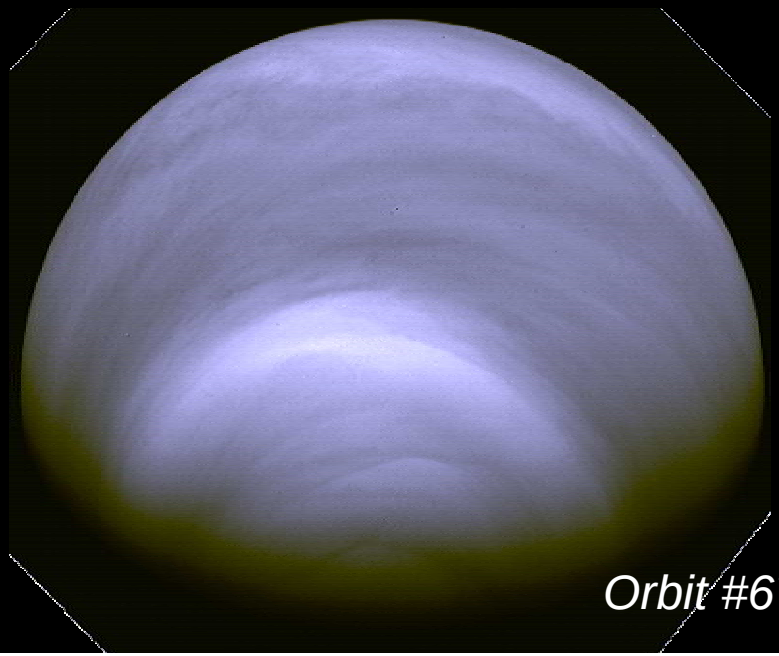




Orbit #673

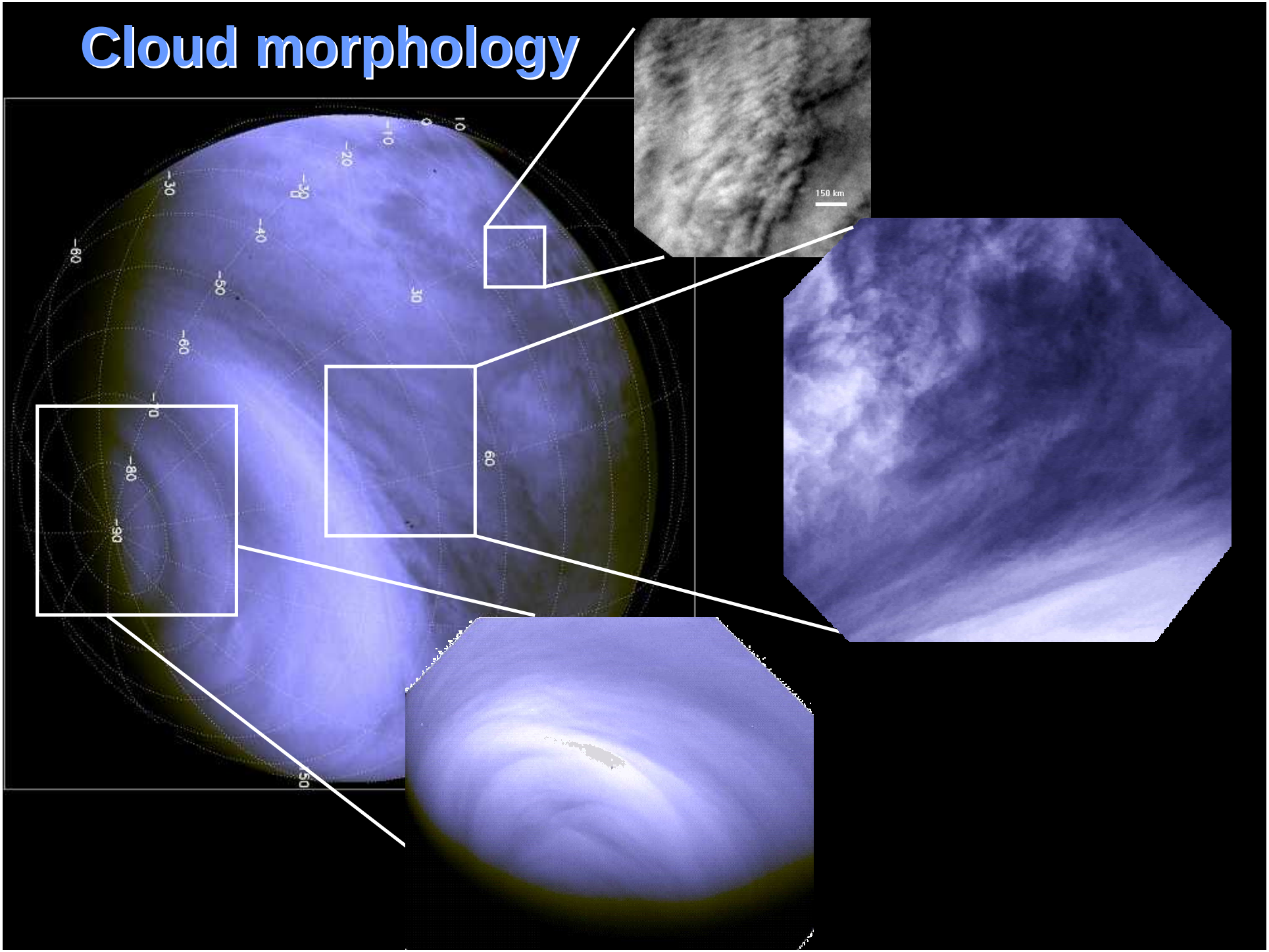


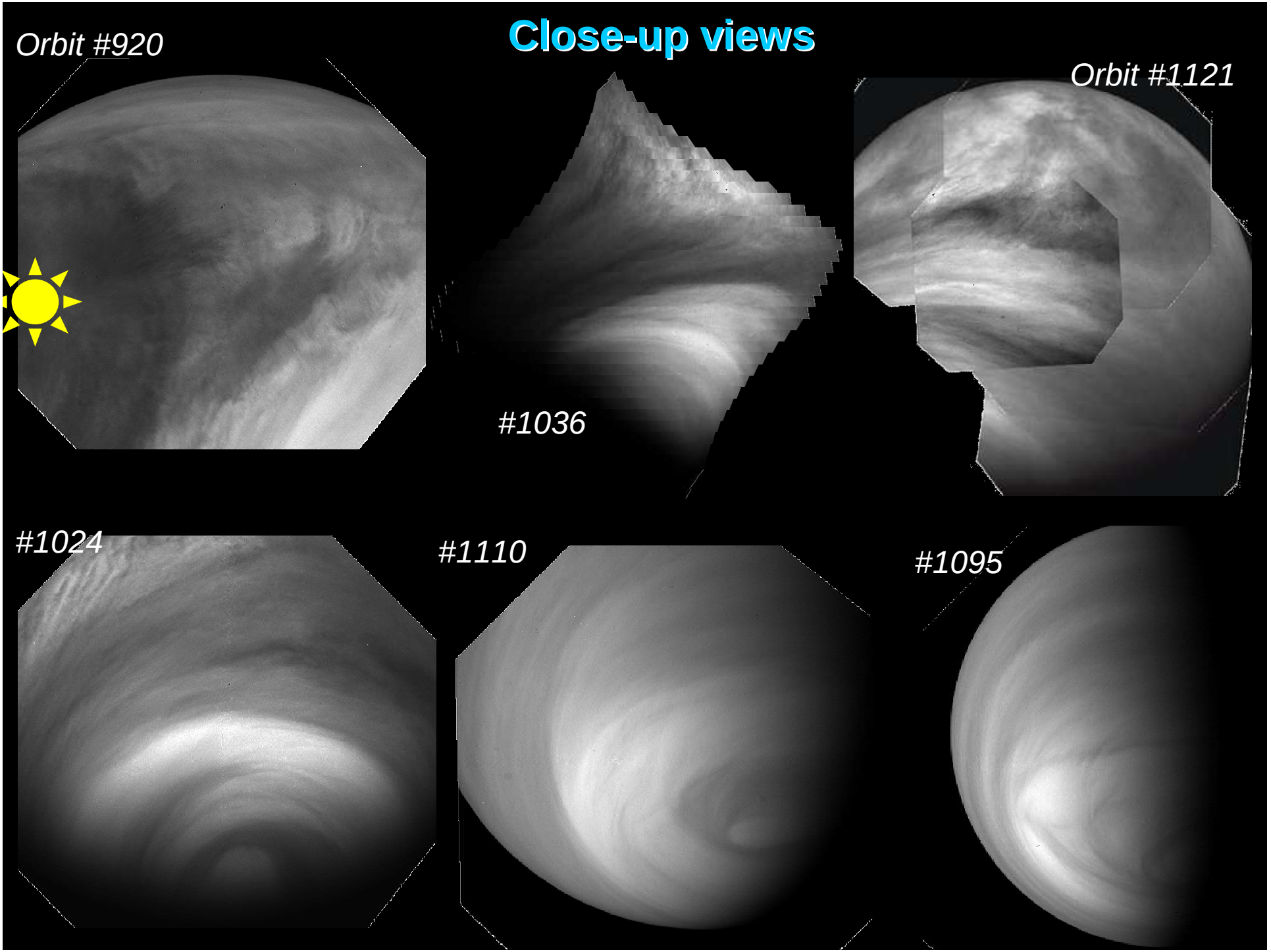
Orbit #458

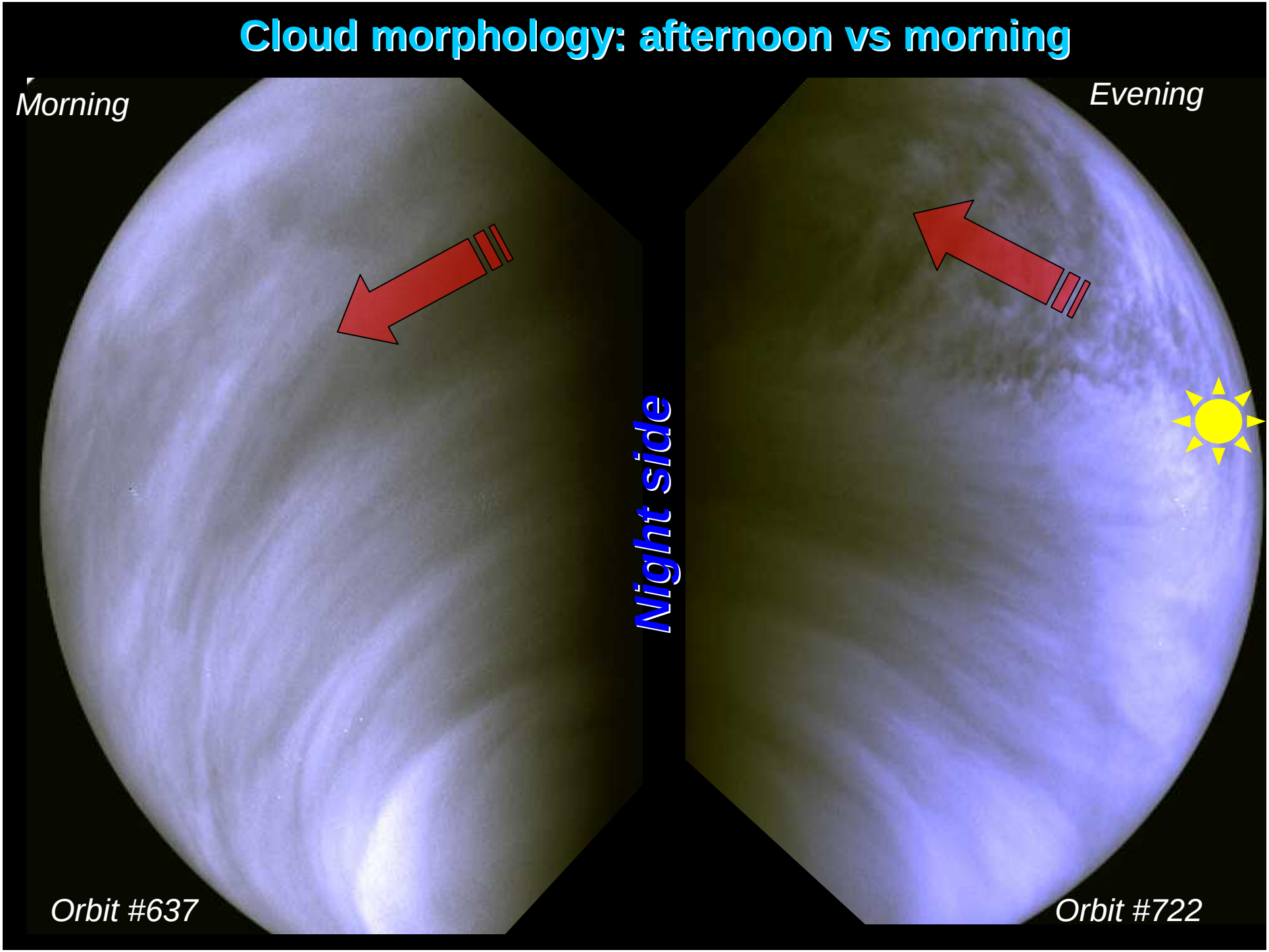


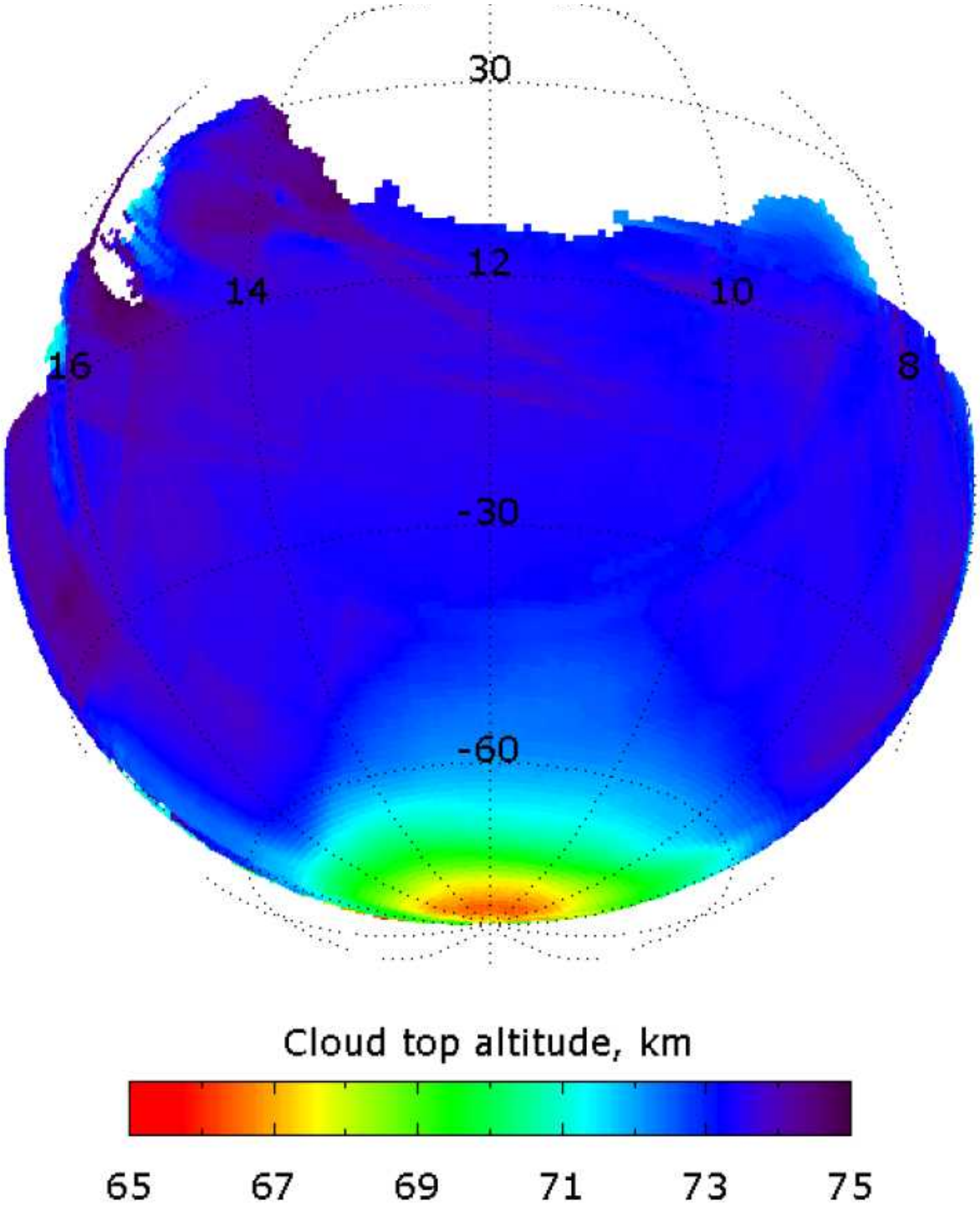
Orbit #679

Cloud morphology

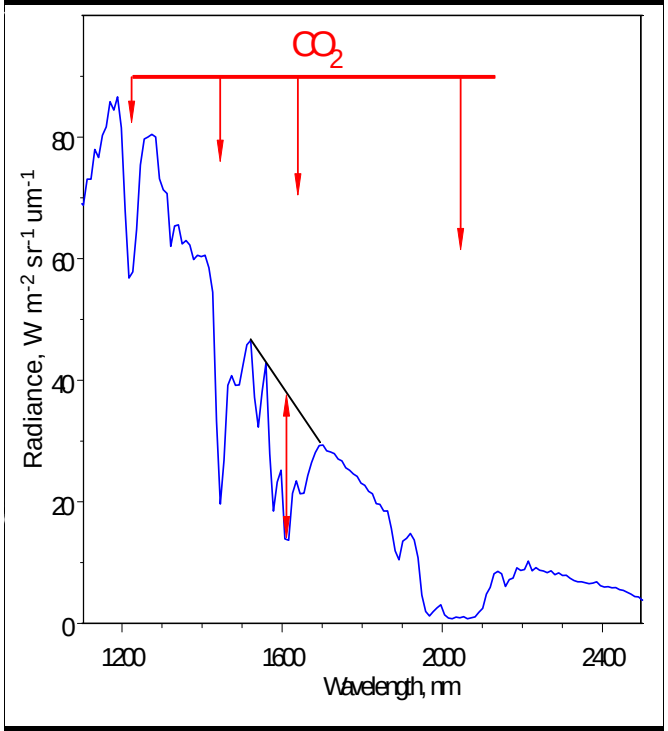



Close-up views
Orbit #920
#1036
Orbit #1121
#1024
#1110
#1095


Cloud morphology: afternoon vs morning
Morning
Evening
Night side
Orbit #637
Orbit #722

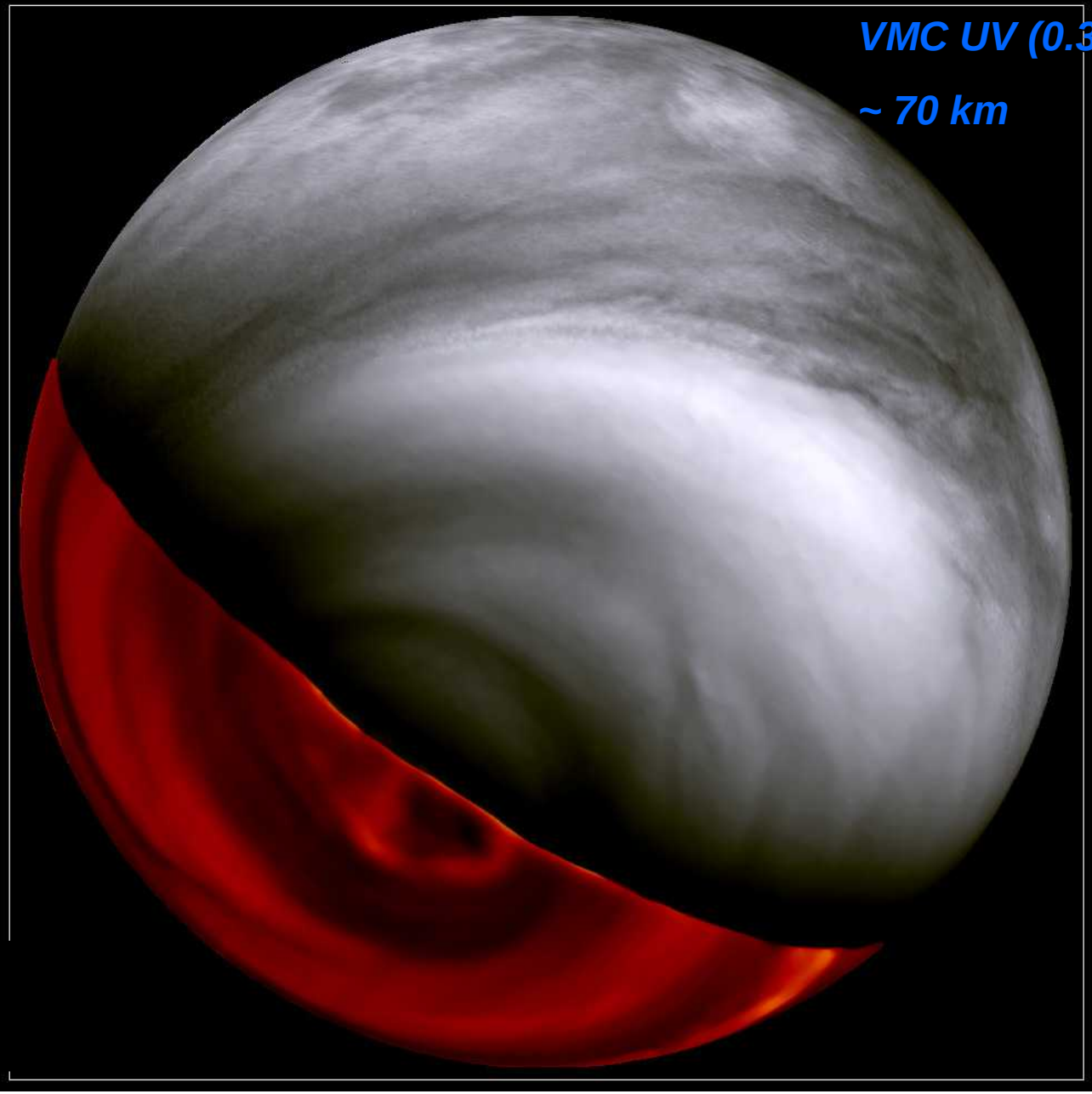


d top altitude

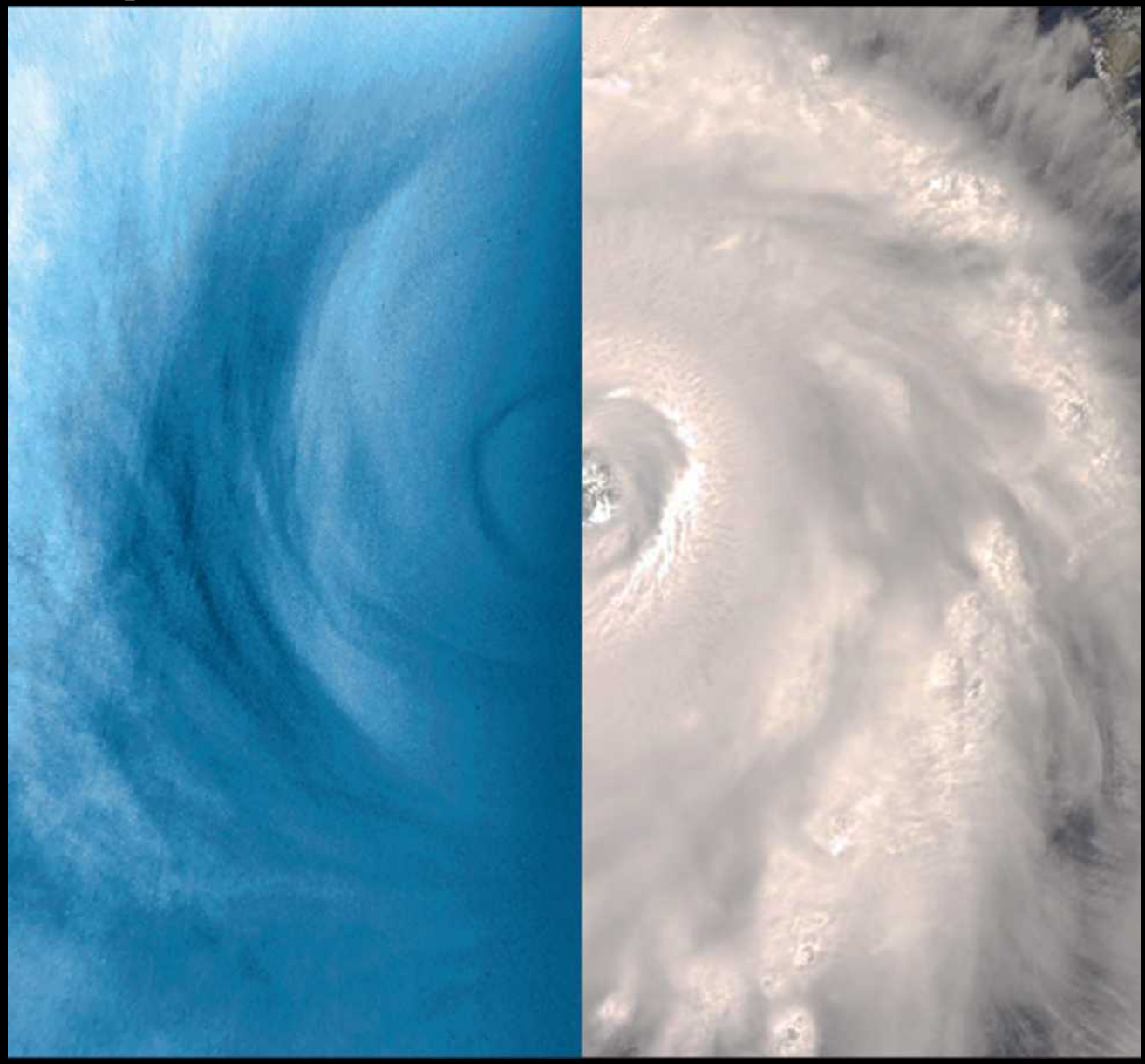


v et al., JGR, 2009

Venus planetary vortex



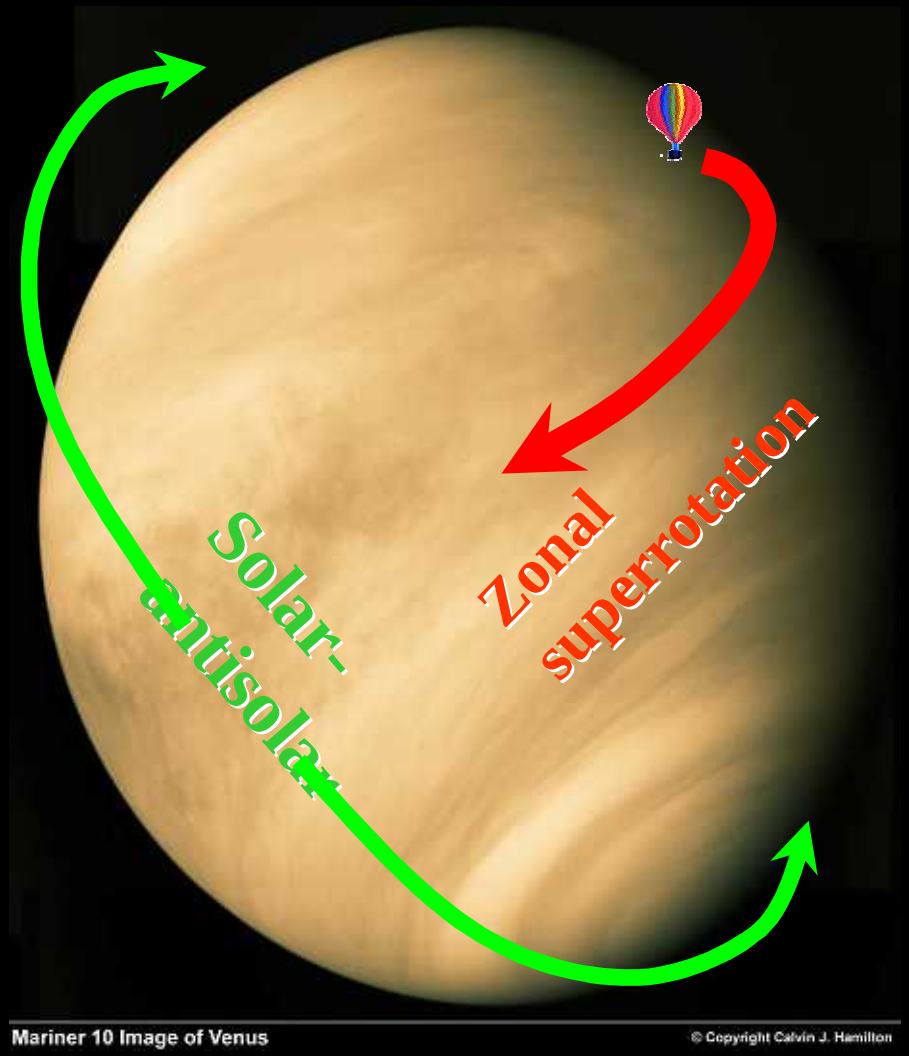
Venus polar vortex and hurricane Frances



S. Limaye et al., GRL, 2009

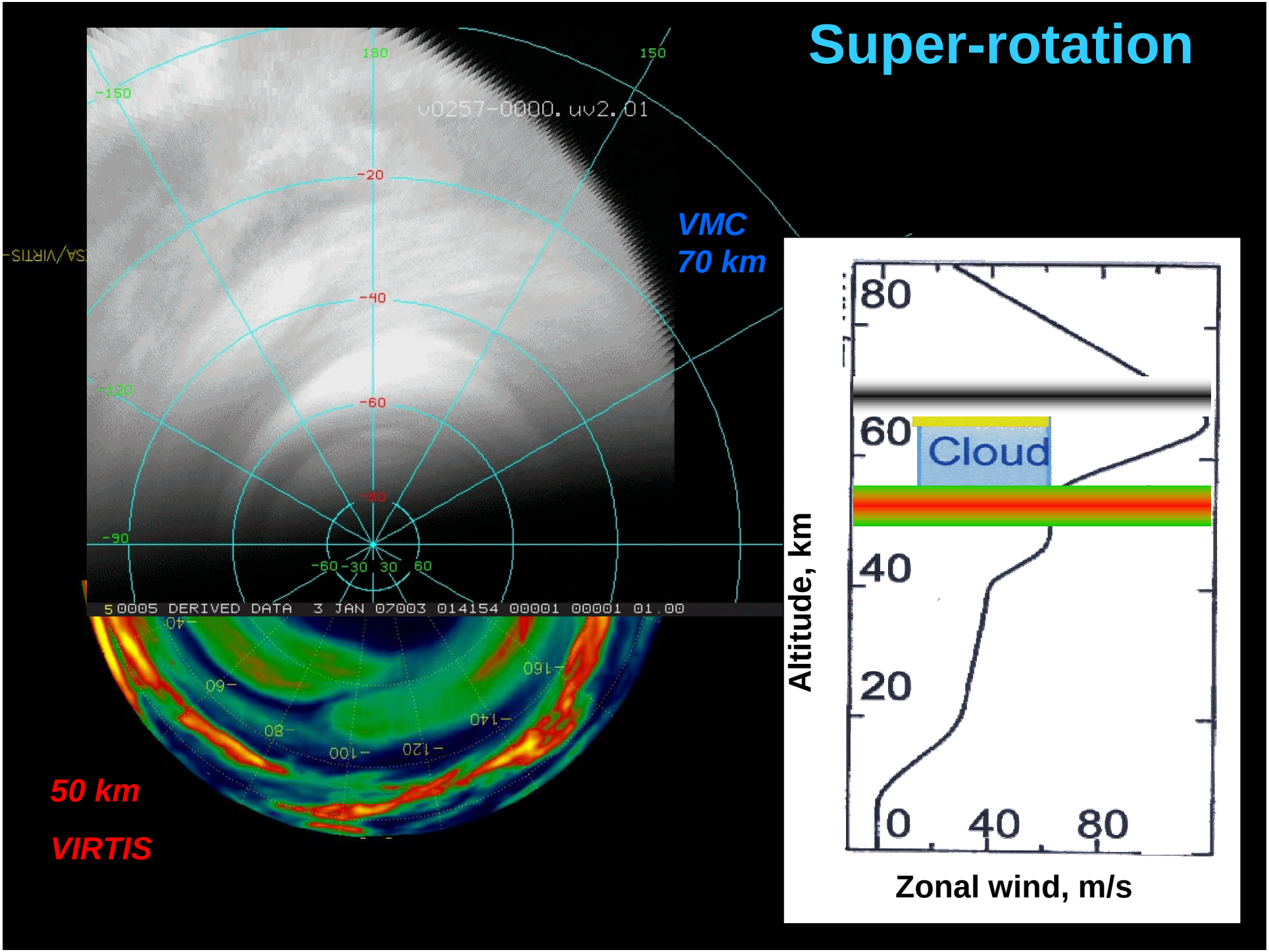
8. Atmospheric dynamics

Global Circulation Regimes

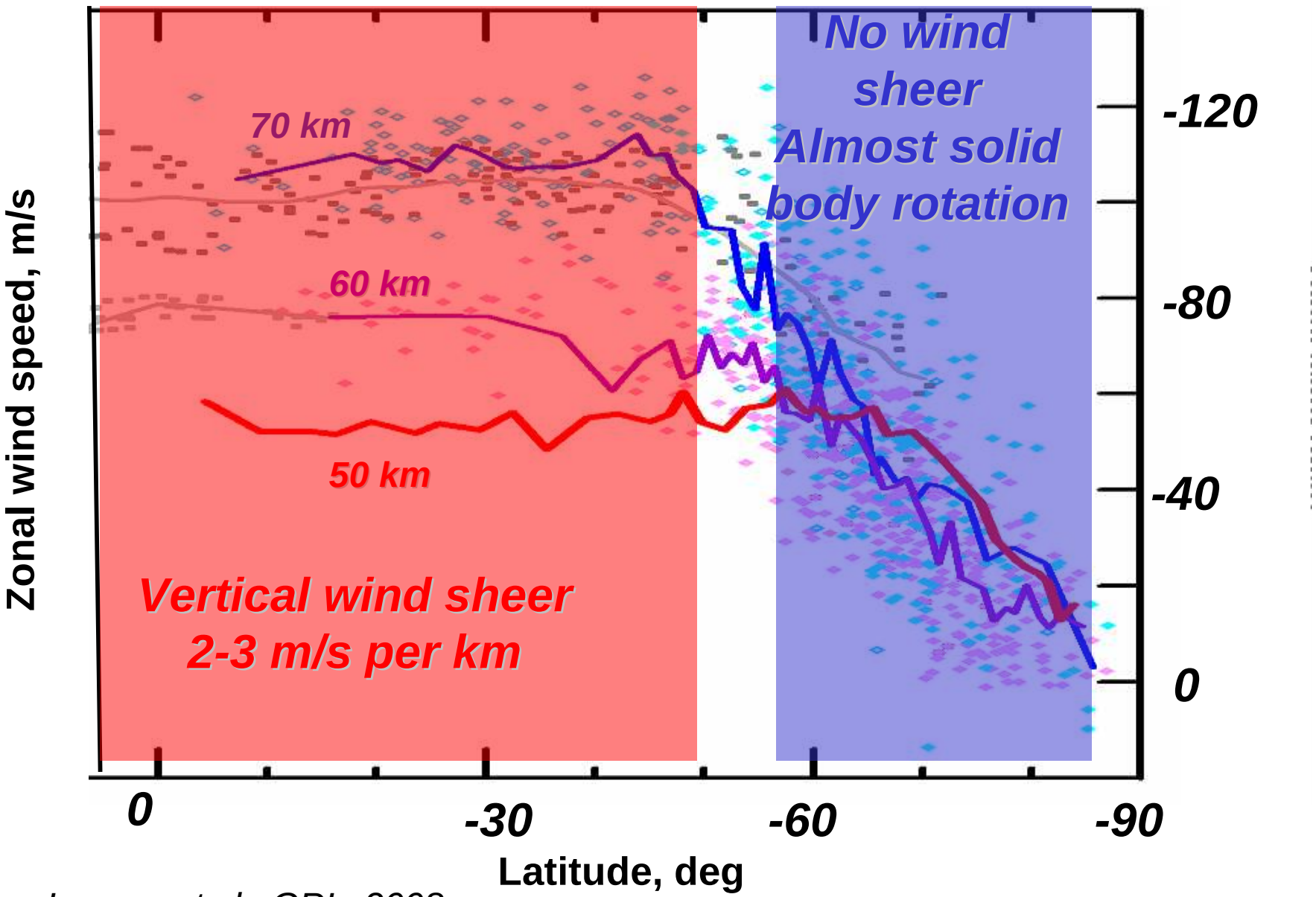


- *Troposphere and mesosphere*
  - *Zonal superrotation (>100 m/s)*
  - *Poleward winds v ~ 10 m/s*
- *Thermosphere (> 120 km)*
  - *Zonal superrotation (~100 m/s)*
  - *Solar-antisolar circulation (~200 m/s)*

Super-rotation



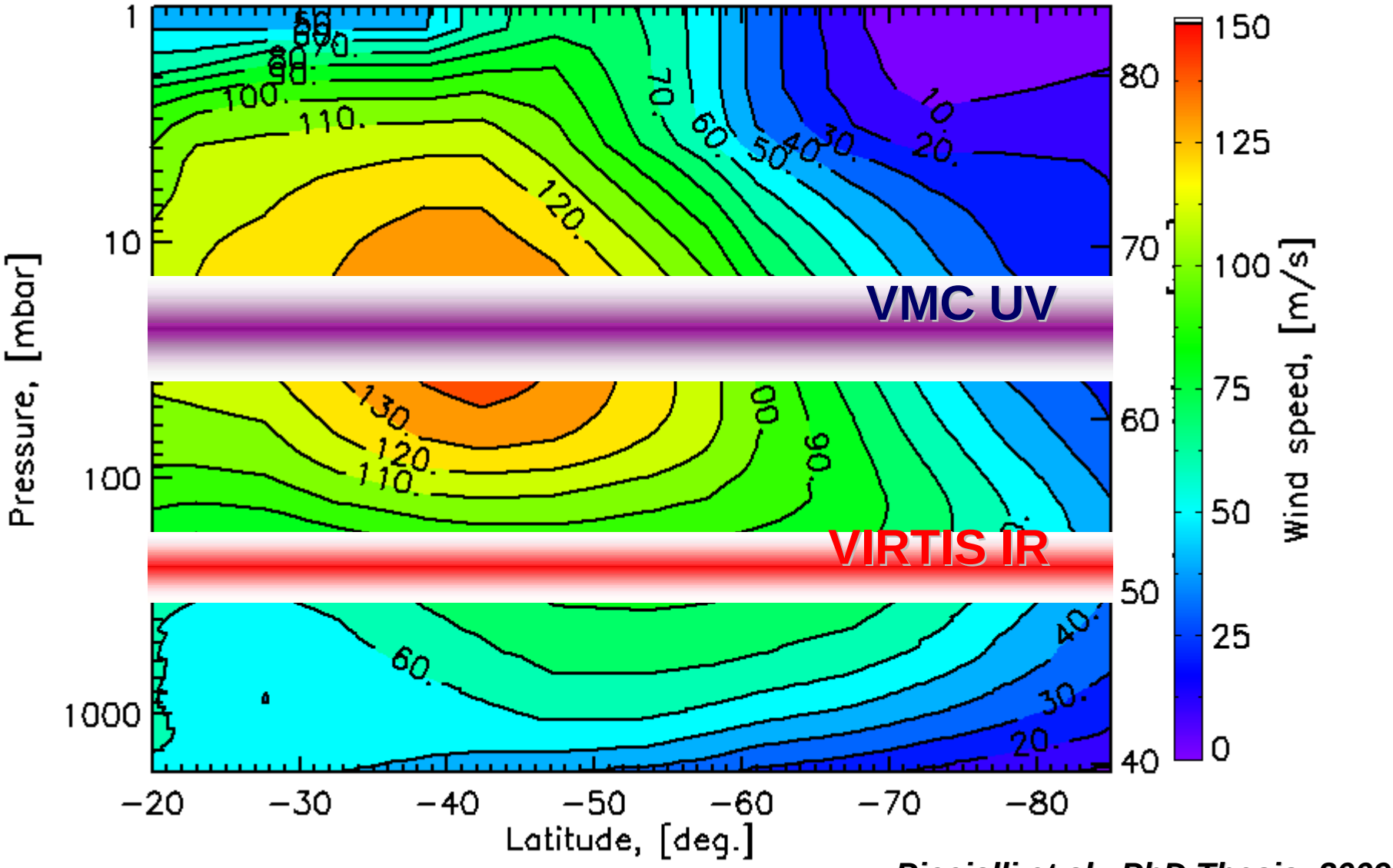
Zonal wind field



Sanches-Lavega et al., GRL, 2008

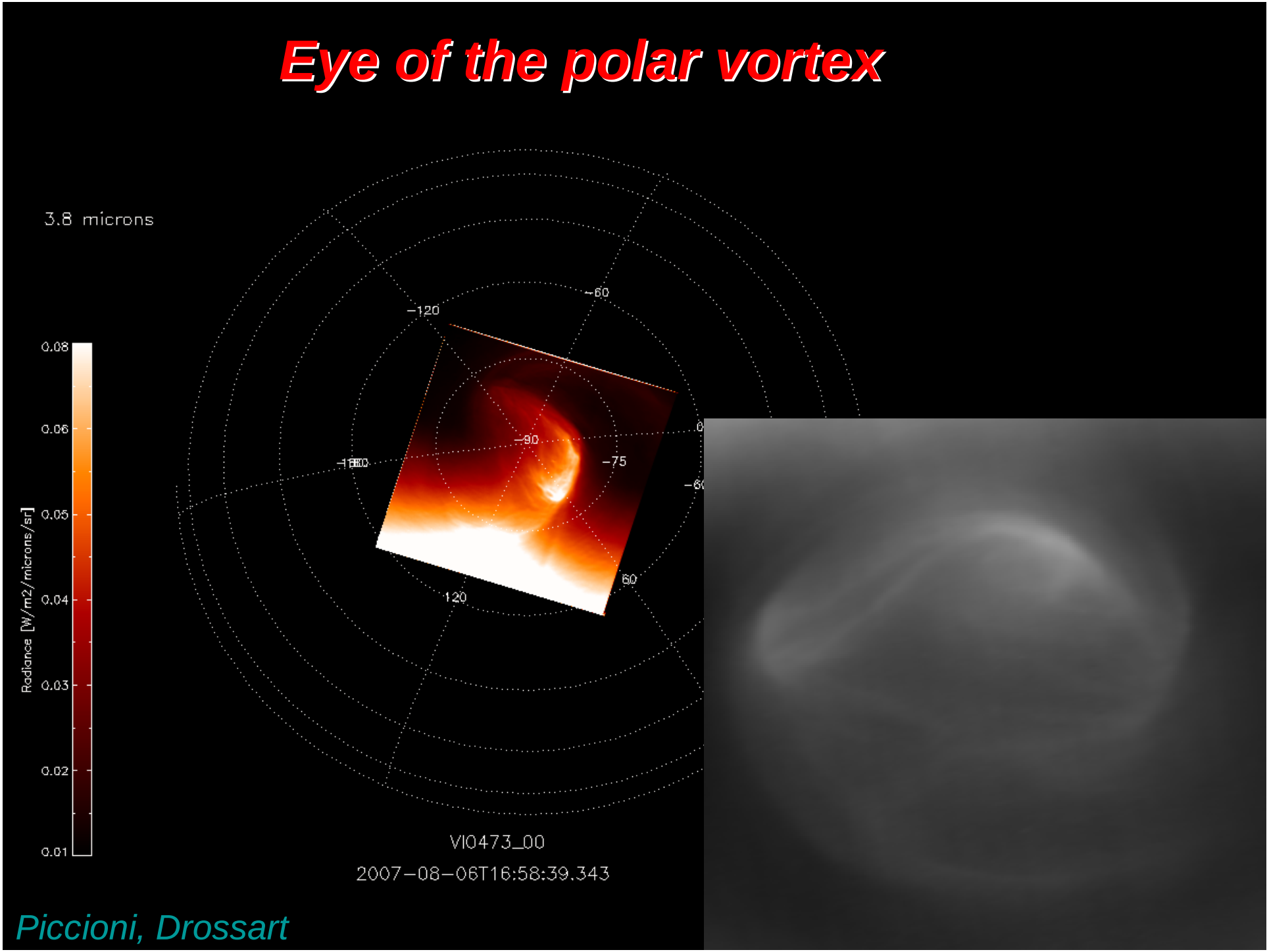
Thermal (cyclostrophic) wind from Radio-occultation

$$2u\frac{\partial u}{\partial \xi} = -\frac{R}{\tan\phi}\frac{\partial T}{\partial \phi}$$



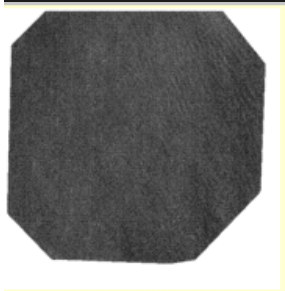
Piccialli et al., PhD Thesis, 2009

Eye of the polar vortex



Piccioni, Drossart

Waves in polar region (65-70 N)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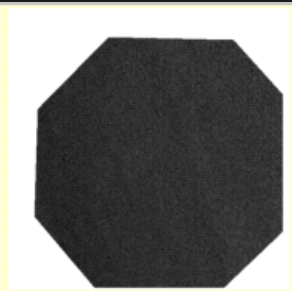
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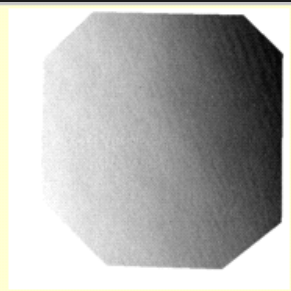
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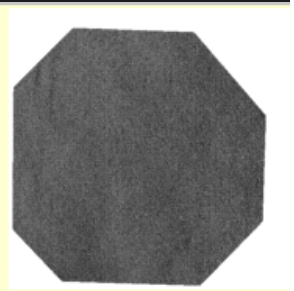
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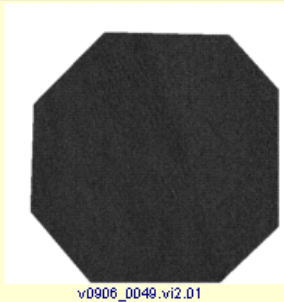
v0906_0048.n22.01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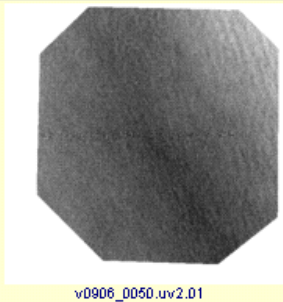
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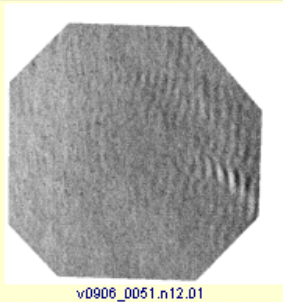
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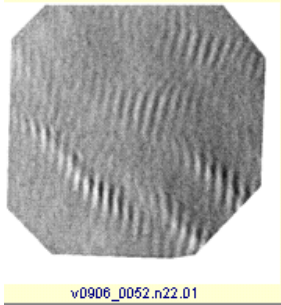
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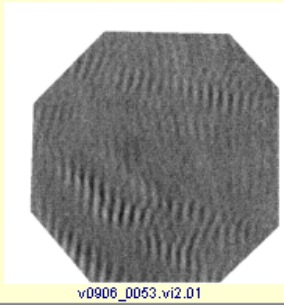
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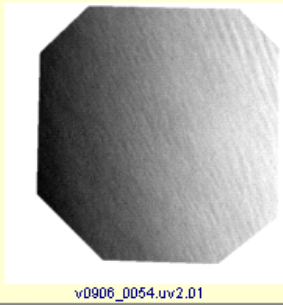
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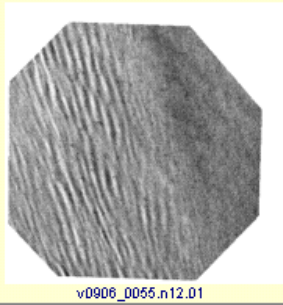
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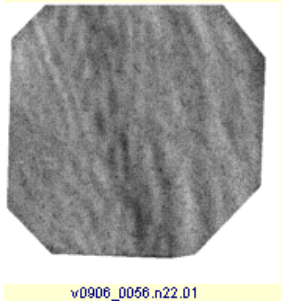
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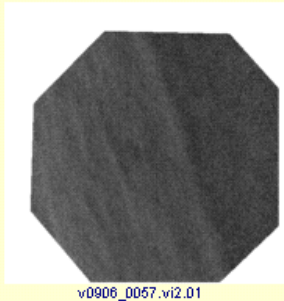
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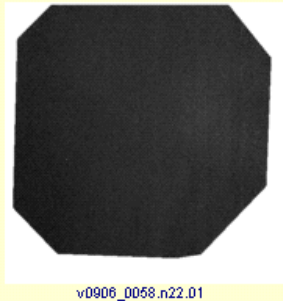
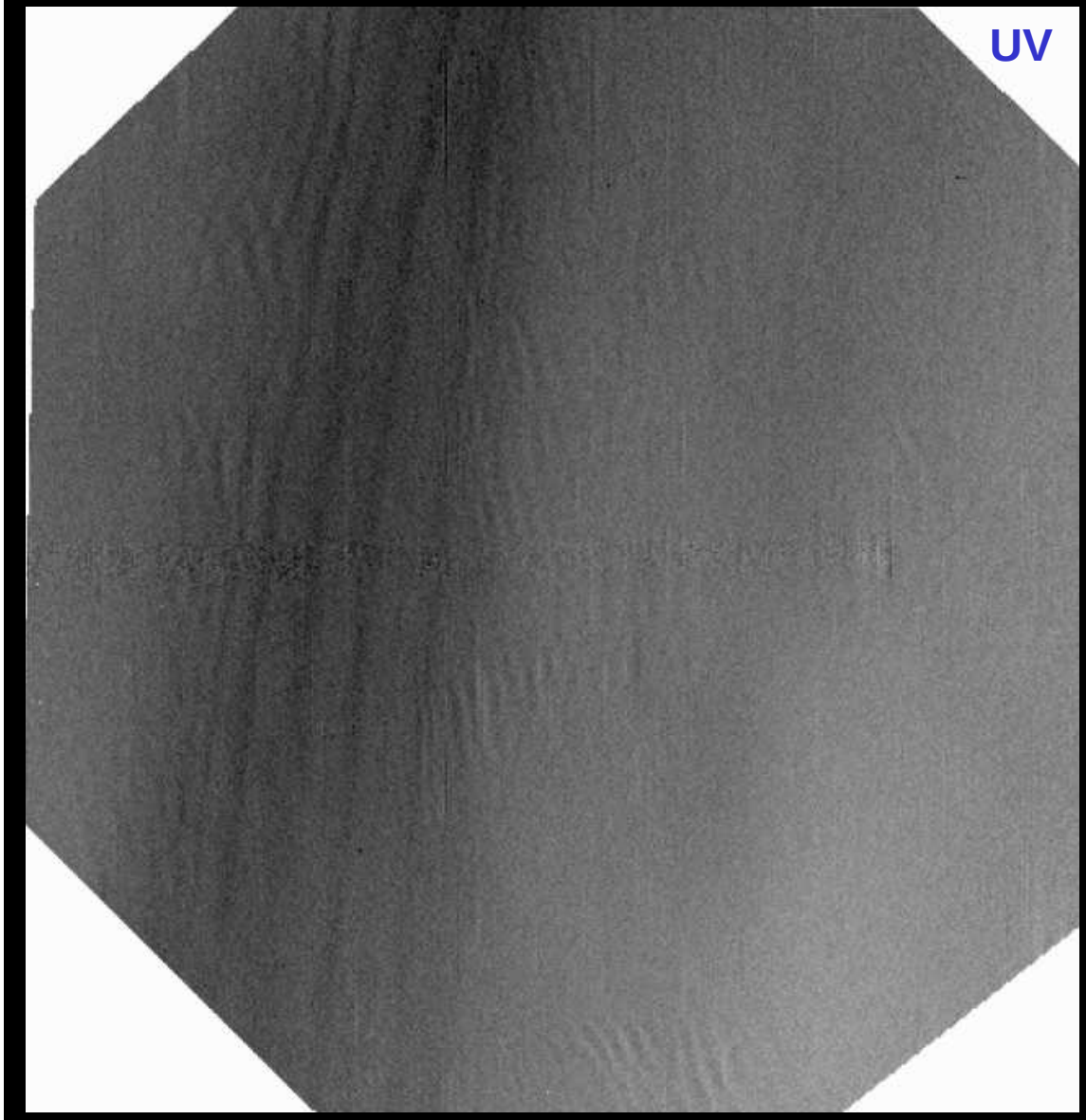
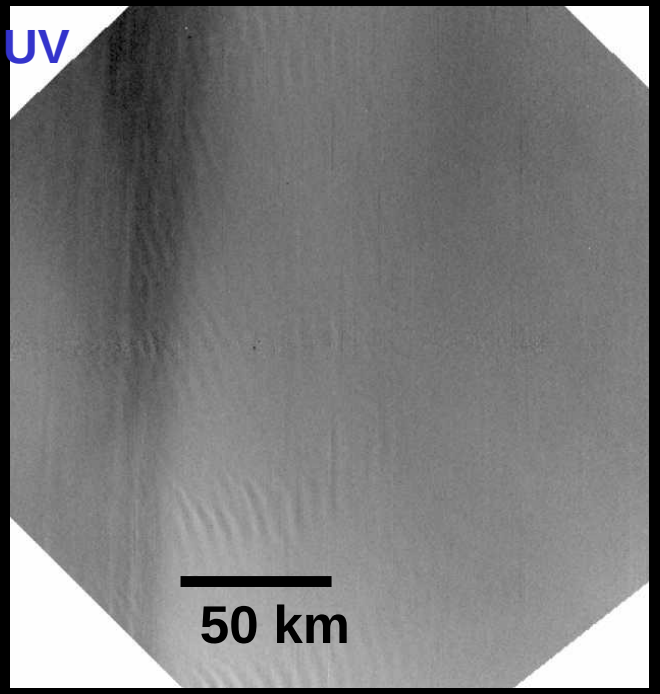
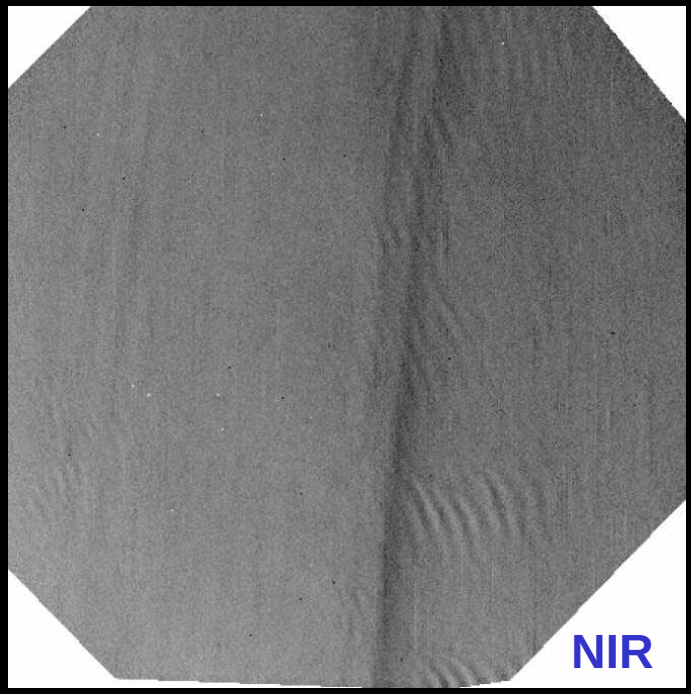
v0906_0058.n12.01


v0906_0058.n22.01

Waves in polar region (65-70 N) (VMC)

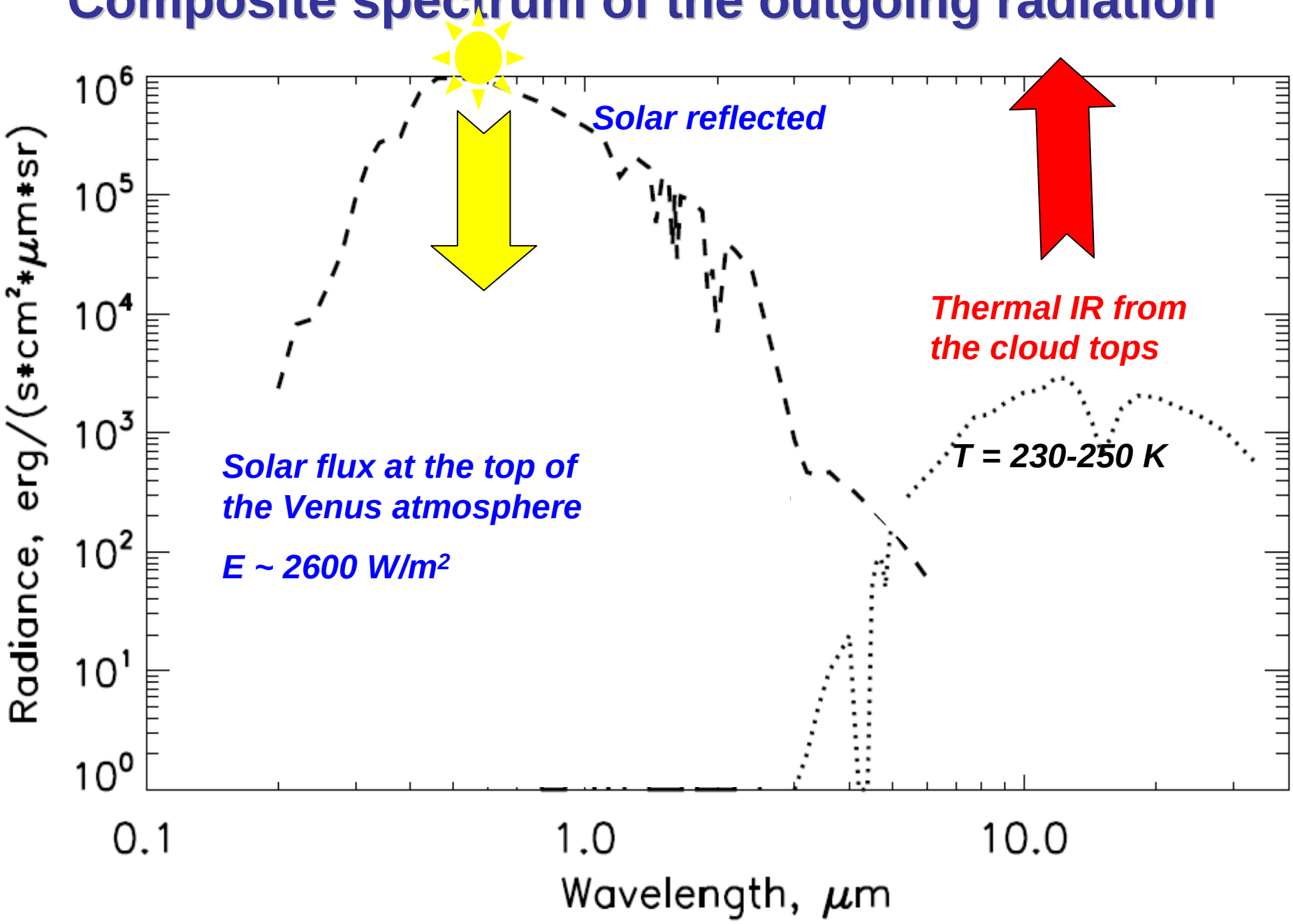




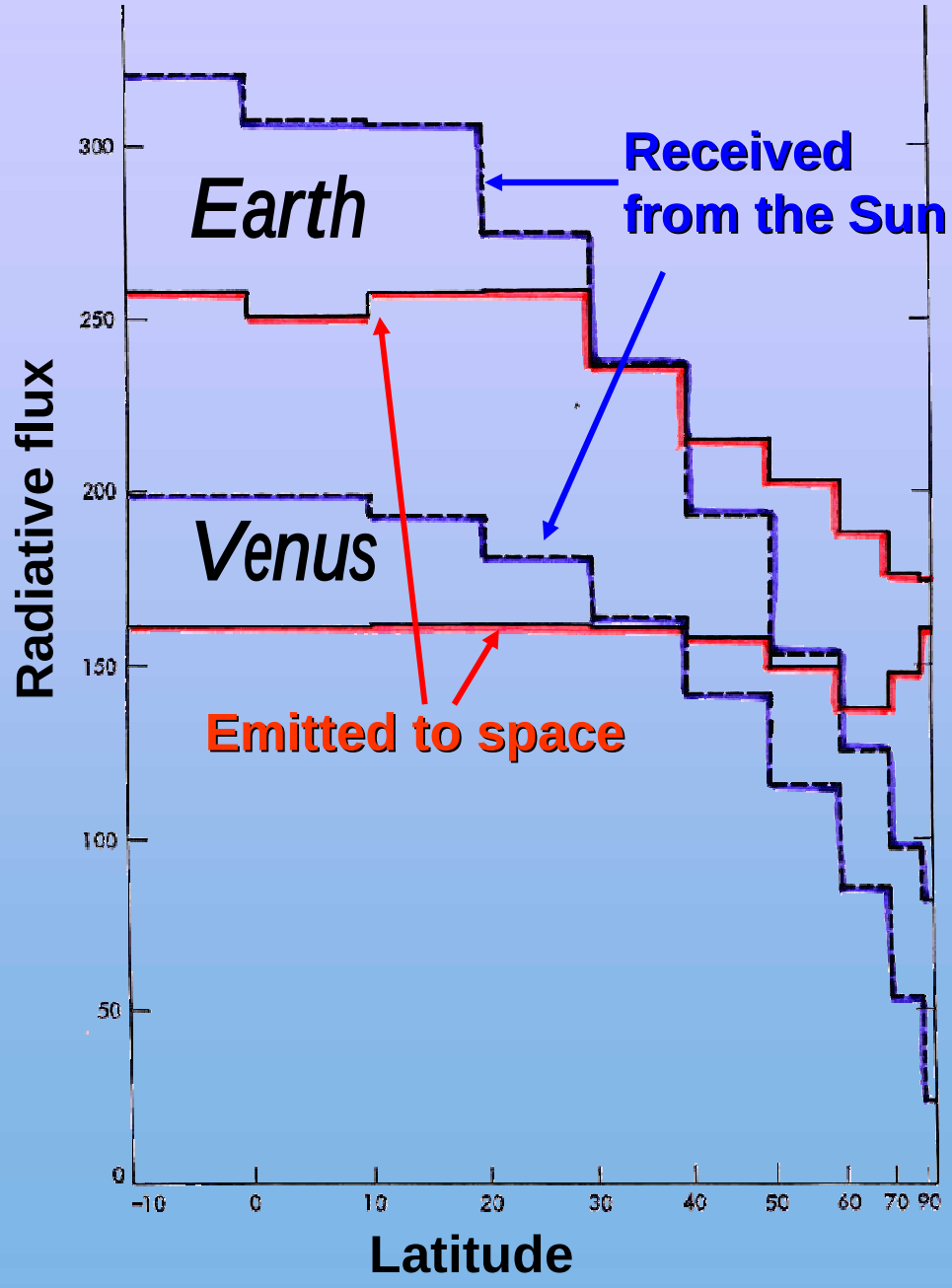


9. Radiative energy balance

Composite spectrum of the outgoing radiation



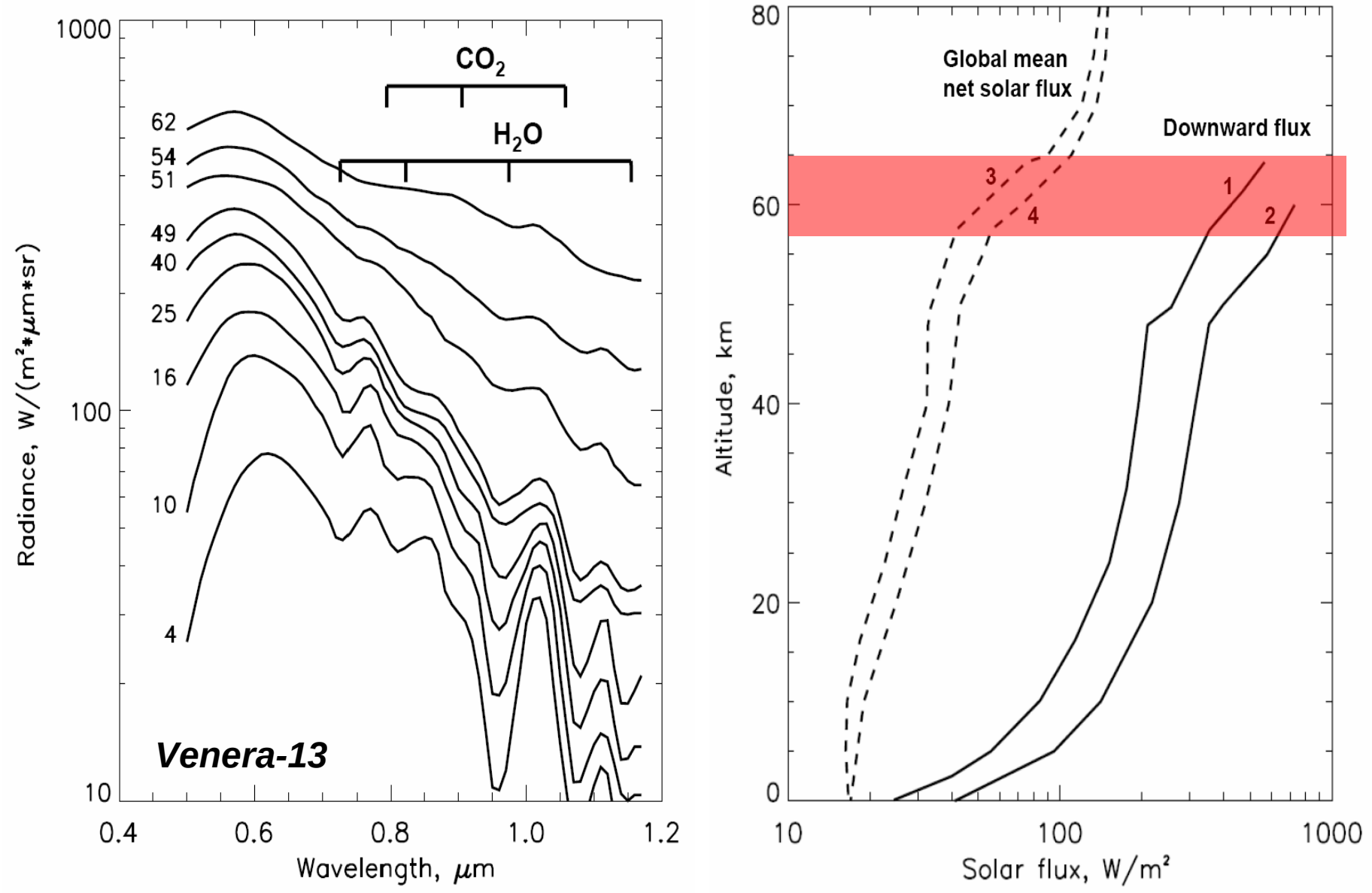
Latitudinal distribution of energy sources and sinks



- *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*

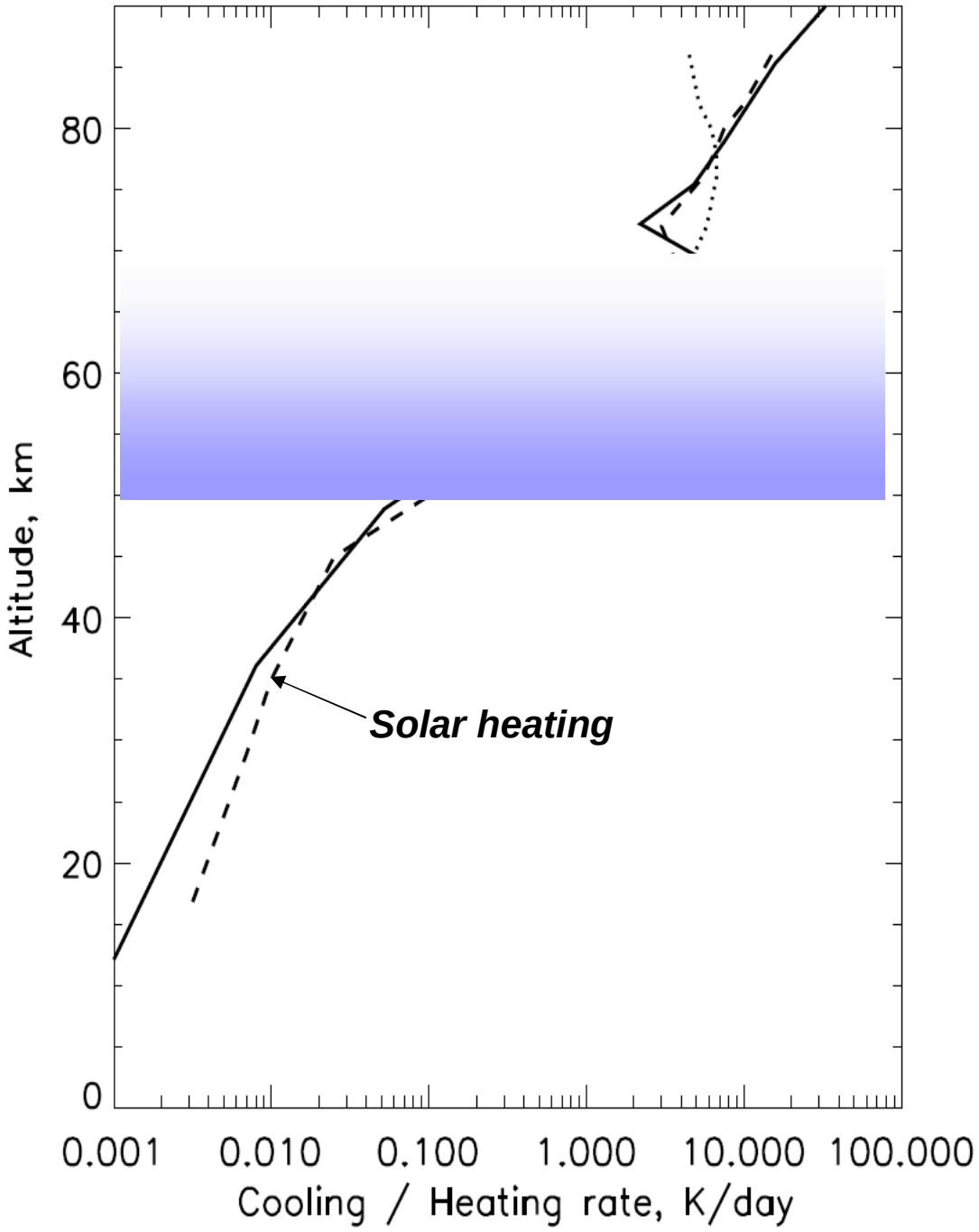
Taylor et al., Adv. Space Res, 1982

Vertical distribution of deposited solar energy



Ekonomov et al., Venus-1 book,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., Adv. Space Res, 1985

Crisp & Titov, Venus-2 book, 1997

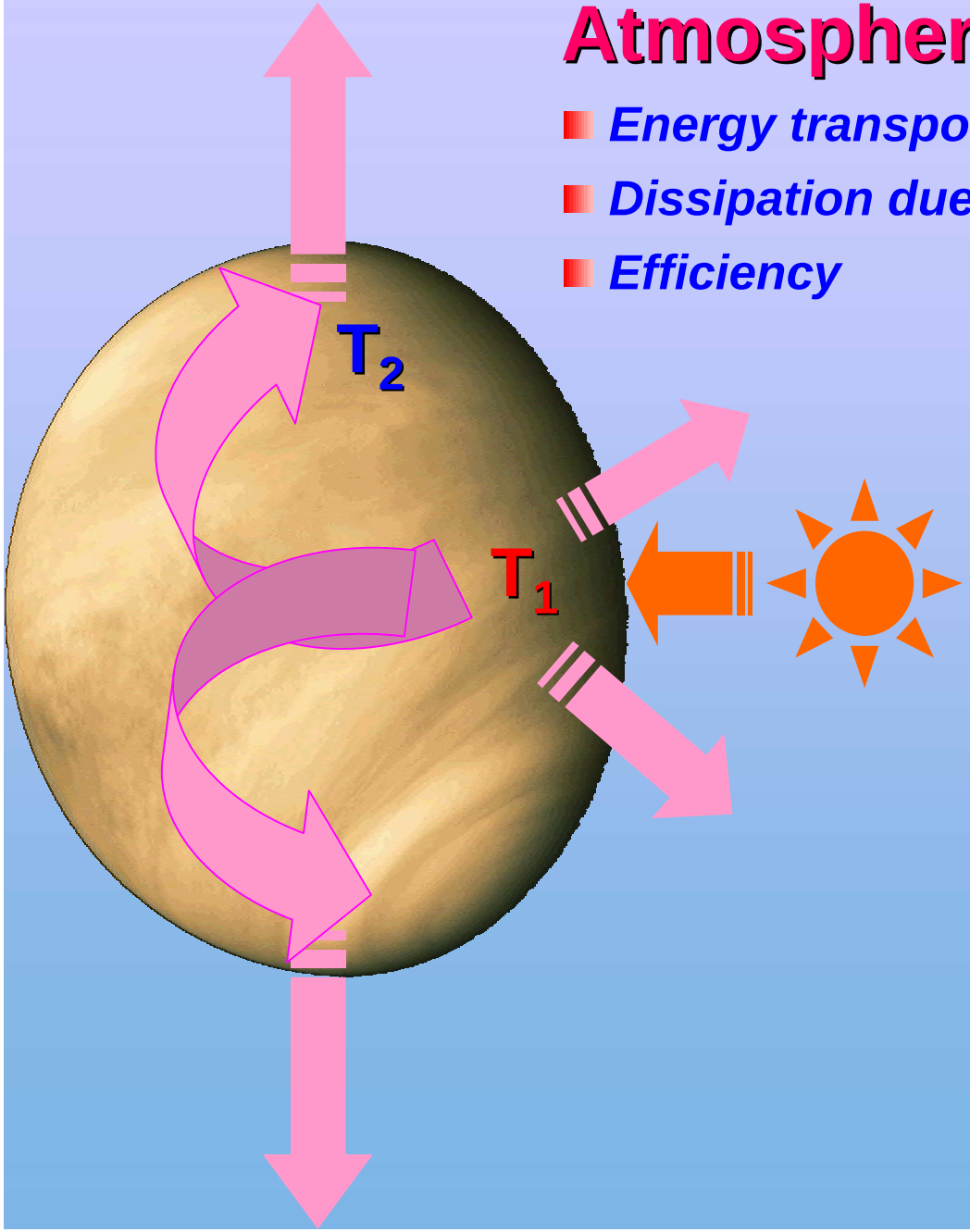
Mean deposition of solar energy on terrestrial planets [W/m^2]

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

Atmospheres as heat engines

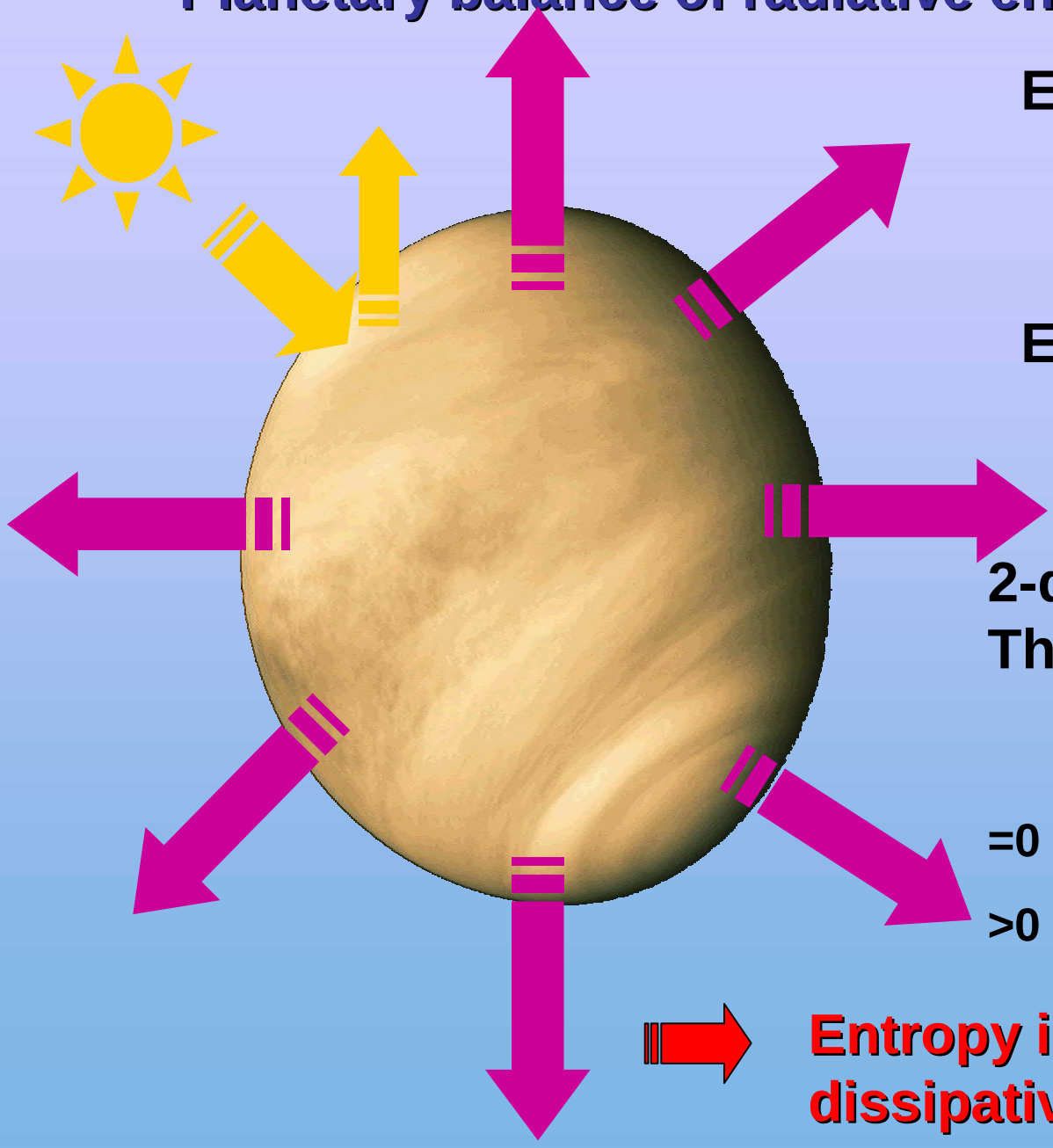
- *Energy transport by atmospheric motions*
- *Dissipation due to friction*
- *Efficiency*

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



10. 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:

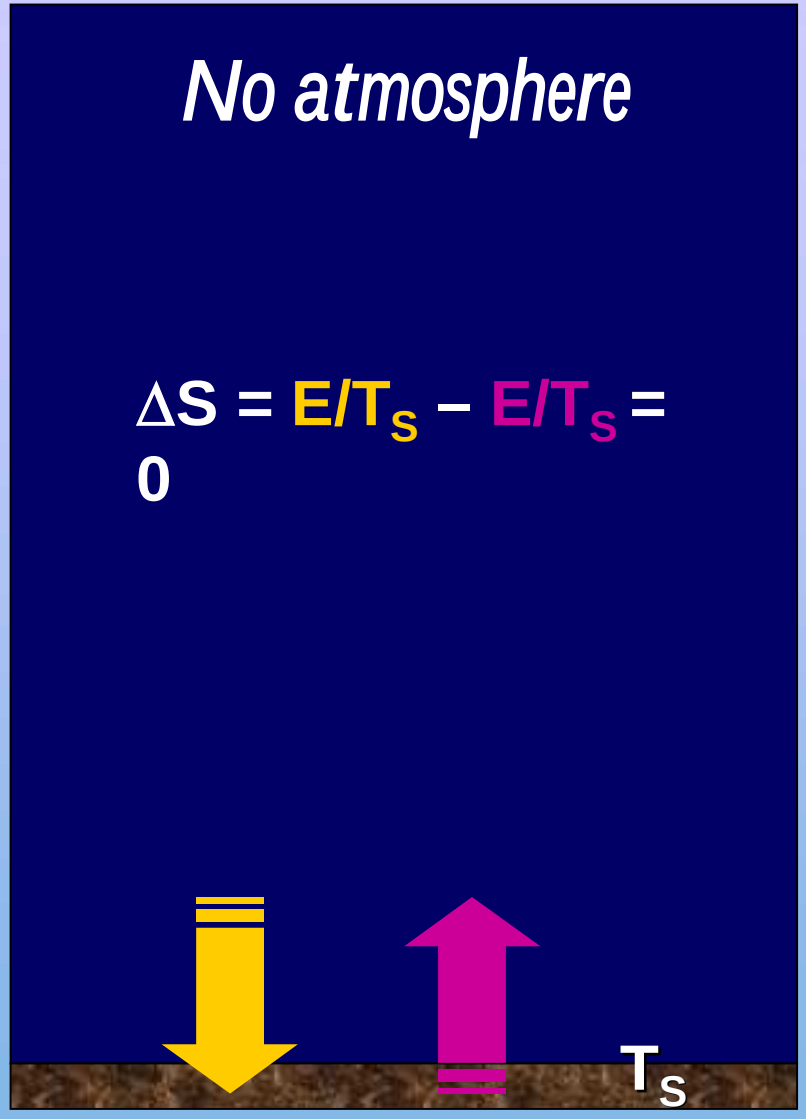
$$\Delta S \geq 0$$

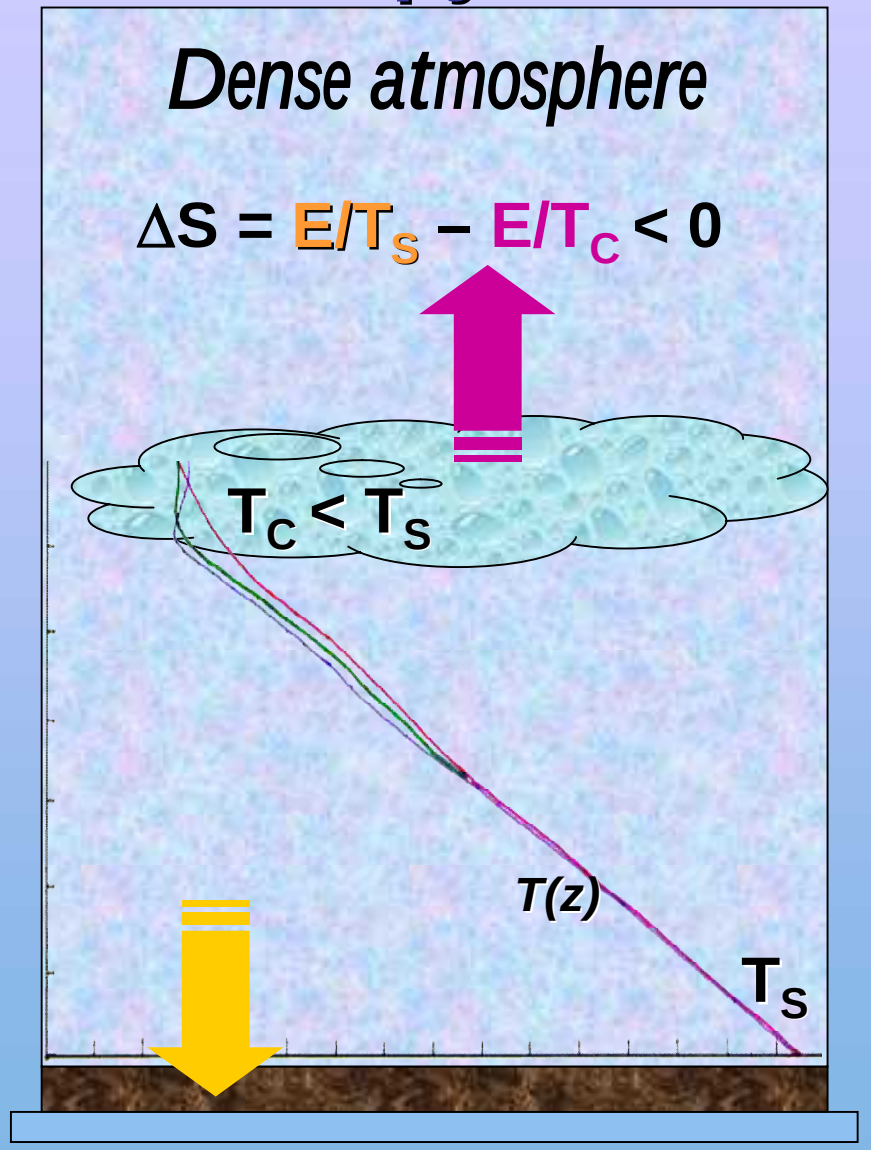
=0 - reversible processes

>0 – irreversible processes

Entropy is a measure of dissipative processes

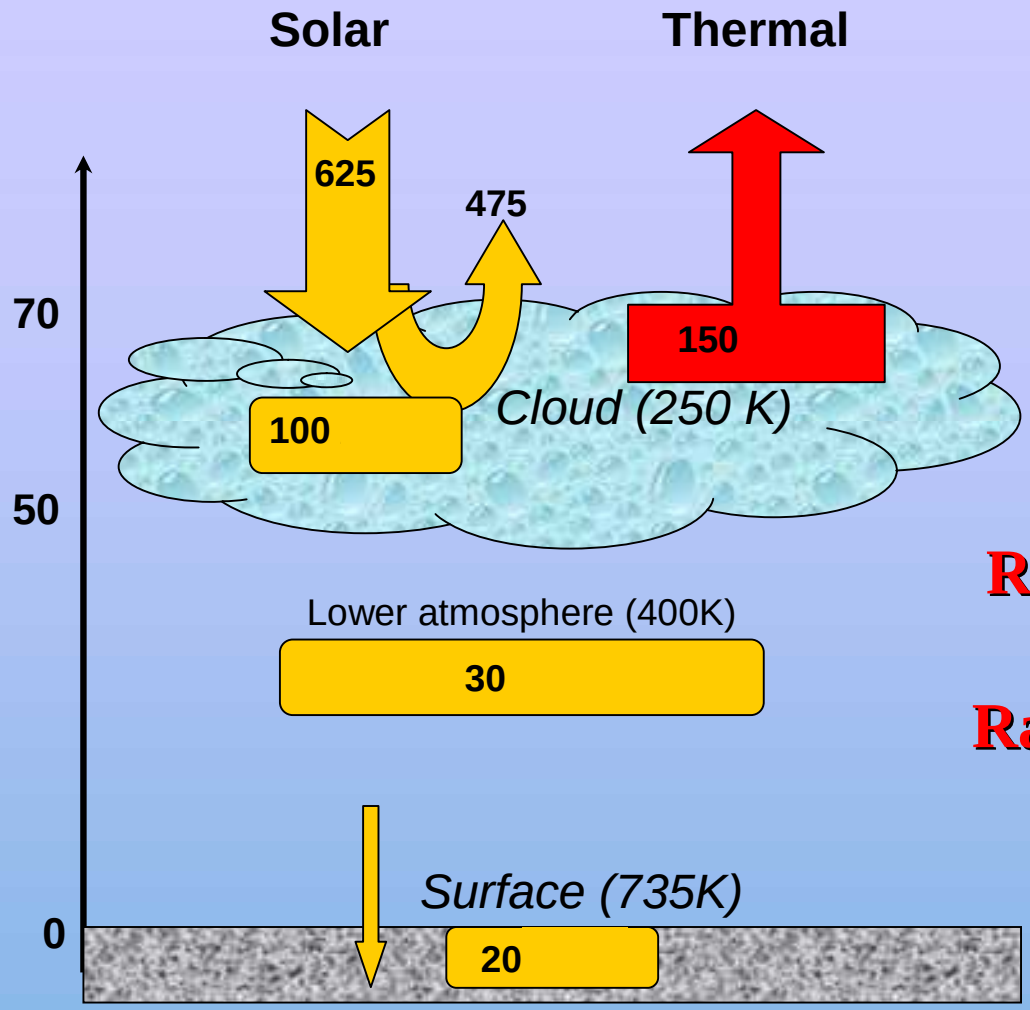
Flux of radiative entropy





Planets receive negative entropy from the Sun

Radiative Energy / Entropy balance on Venus



Radiative energy balance

$\Delta E \approx 0$

Radiative entropy balance

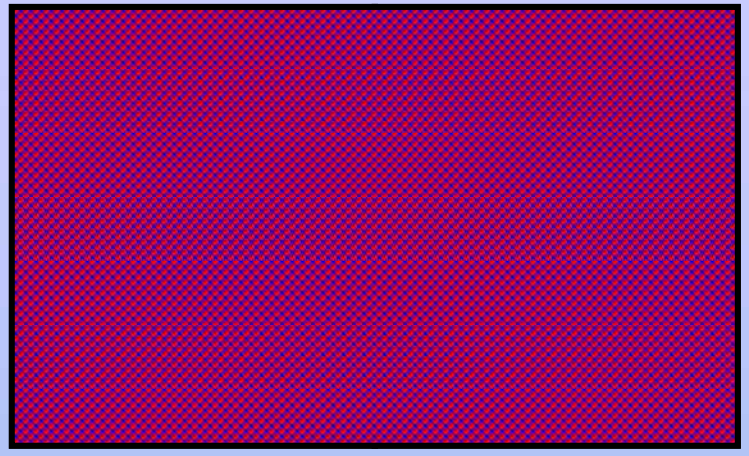
$\Delta S \approx -100\ mW/m^2/K$

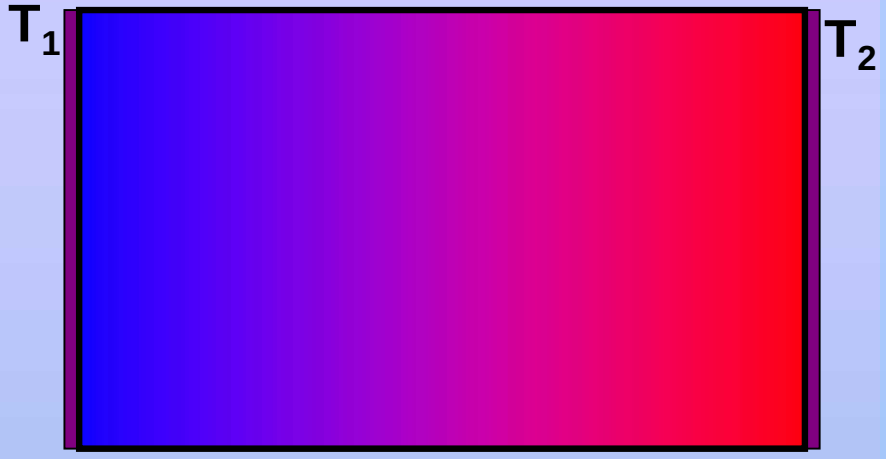
Entropy balance on Earth and Venus

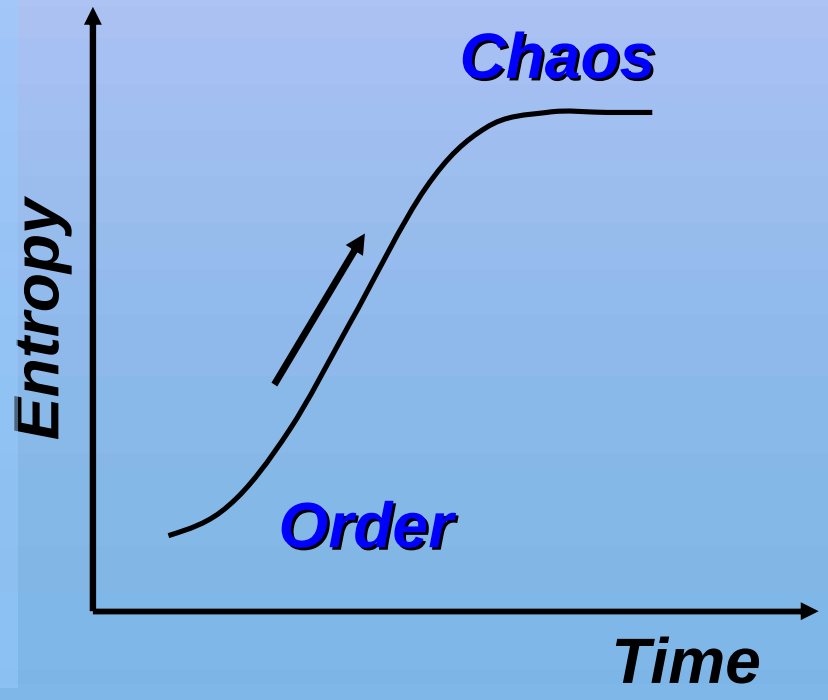
	Earth (Goody, 2000)	Venus
Net radiative sink	-70	-100
Moist convection	+55	0
Mechanical dissipation	+12	~1
Net balance	-3	-100

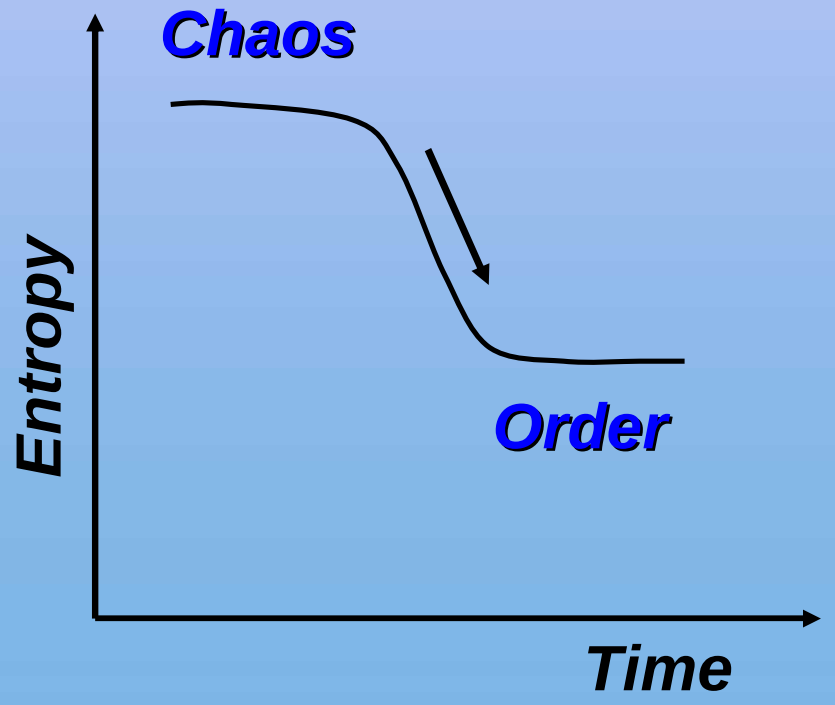
Dissipative processes in the Venus atmosphere - ????

Equilibrium and non-equilibrium thermodynamics



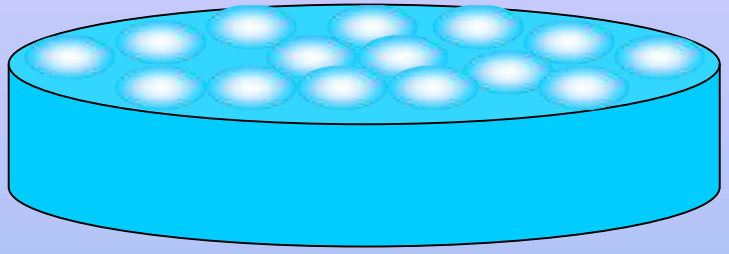






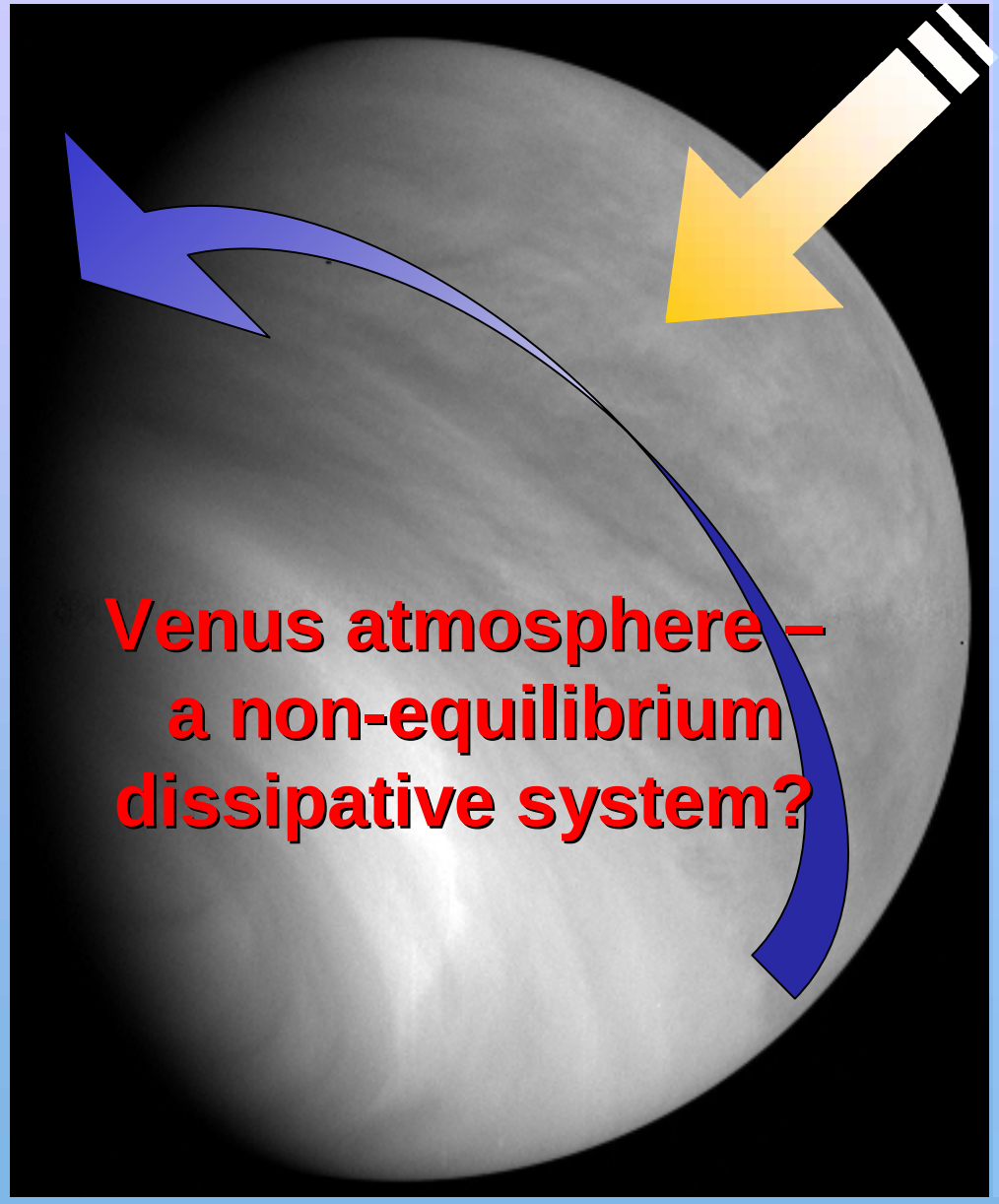
Non-equilibrium dissipative systems

Benard convection



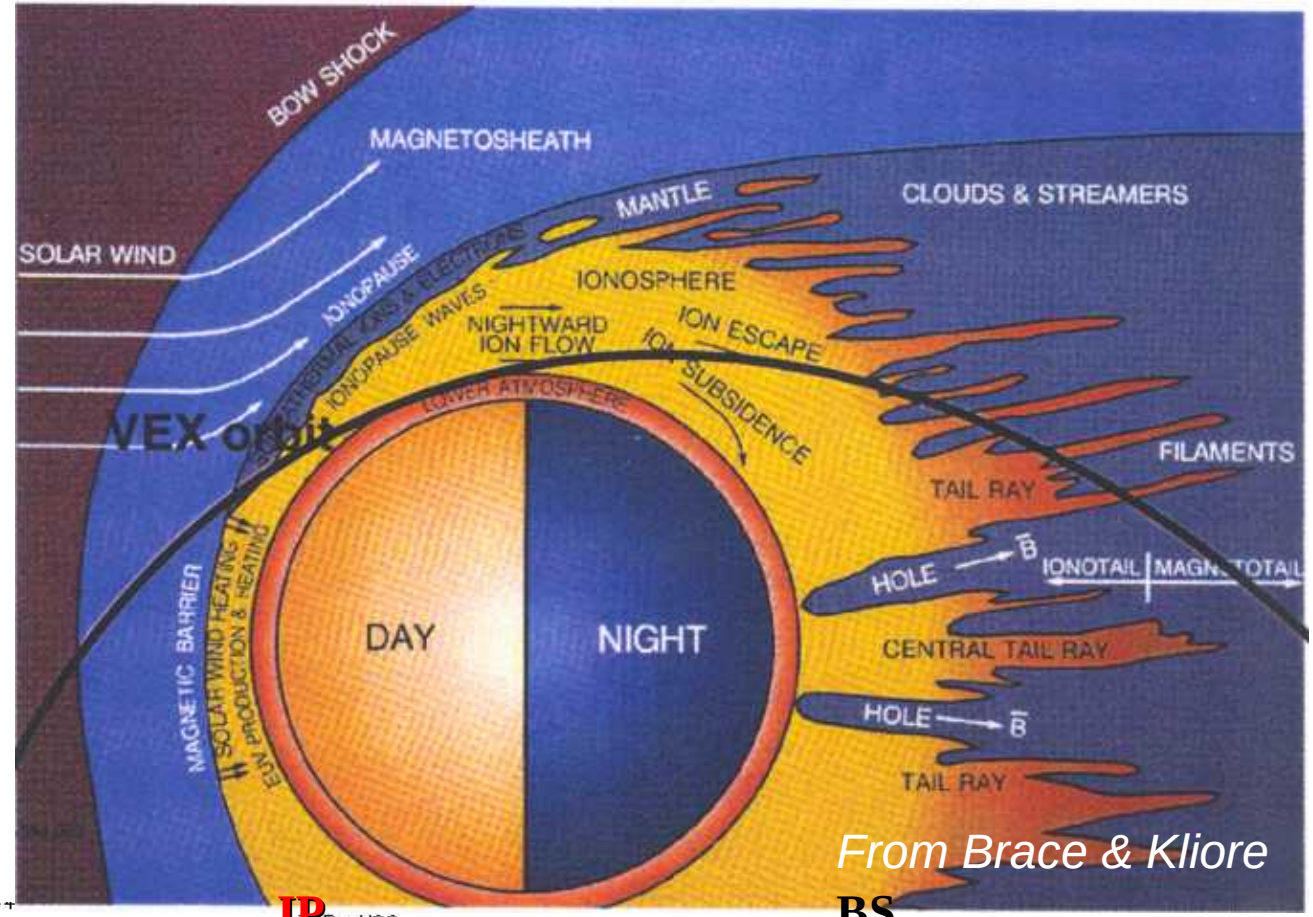
$T_1 > T_2$

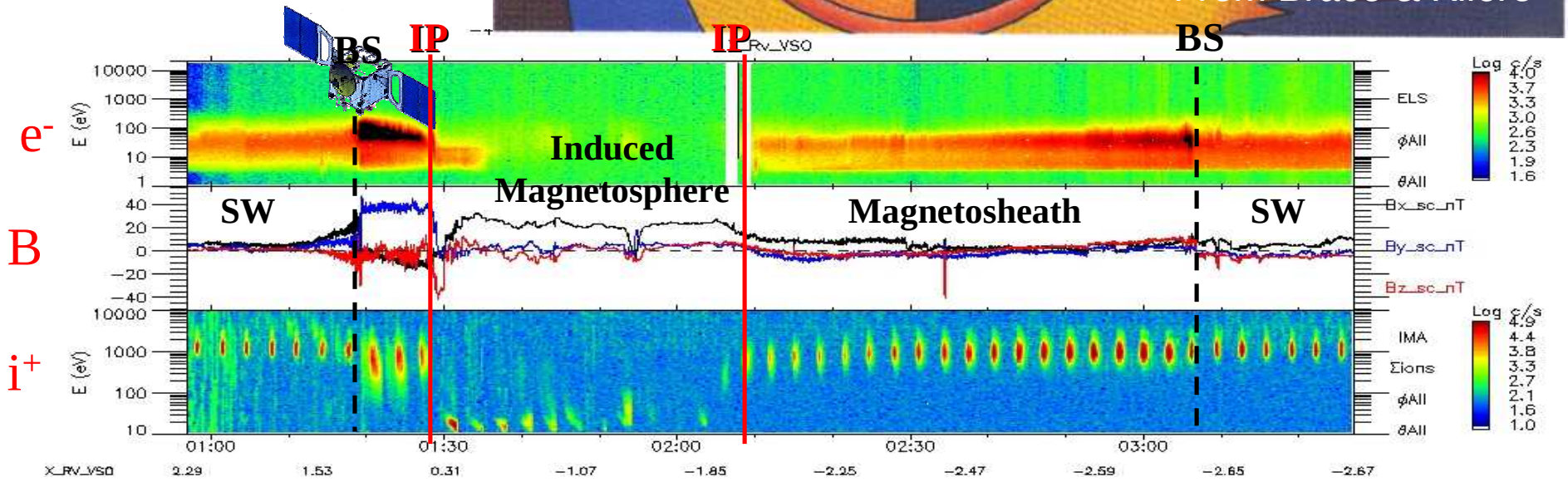
- critical temperature gradient
- high level of order
- high entropy production



11. Plasma investigations

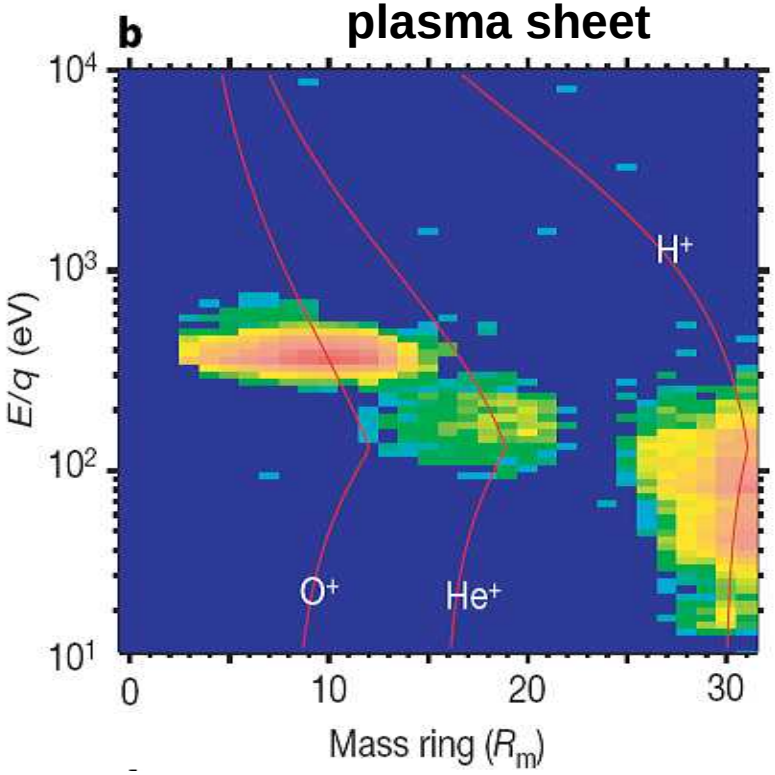
Plasma environment (ASPERA & MAG)



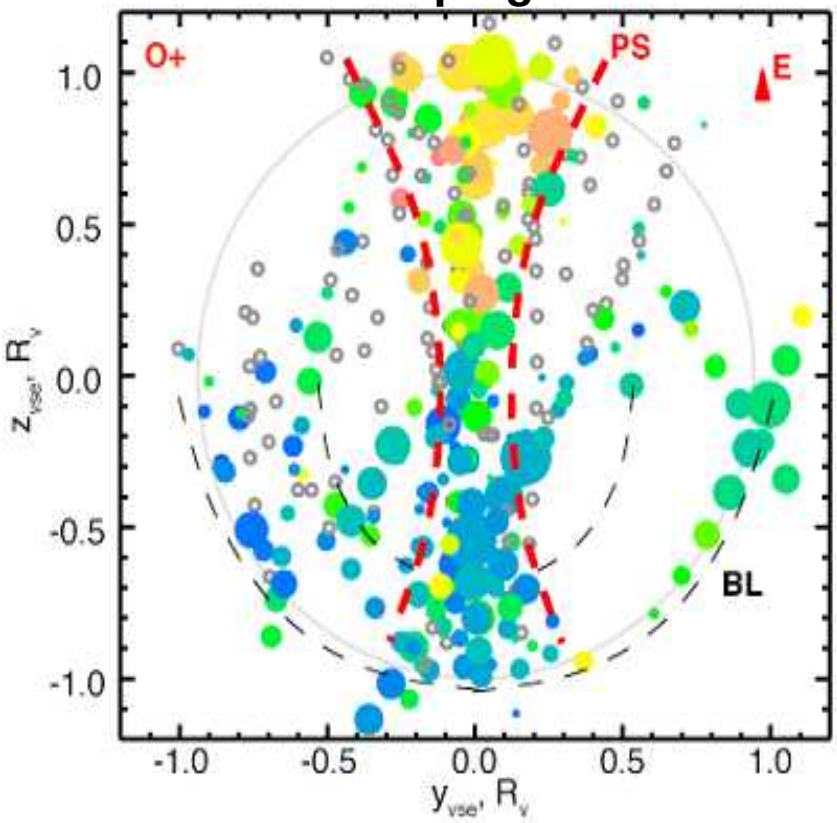


Ion escape (ASPERA)

Energy- mass matrix in the plasma sheet



Spatial distribution of escaping O^+



- **Escaping ions: H^+, He^+, O^+**
- **Energy ratio O^+ : He^+ : H^+ ~ 4:2:1 → ion pick-up**
- **Flux ratio H^+:O^+ ~ 2:1→ H_2O**

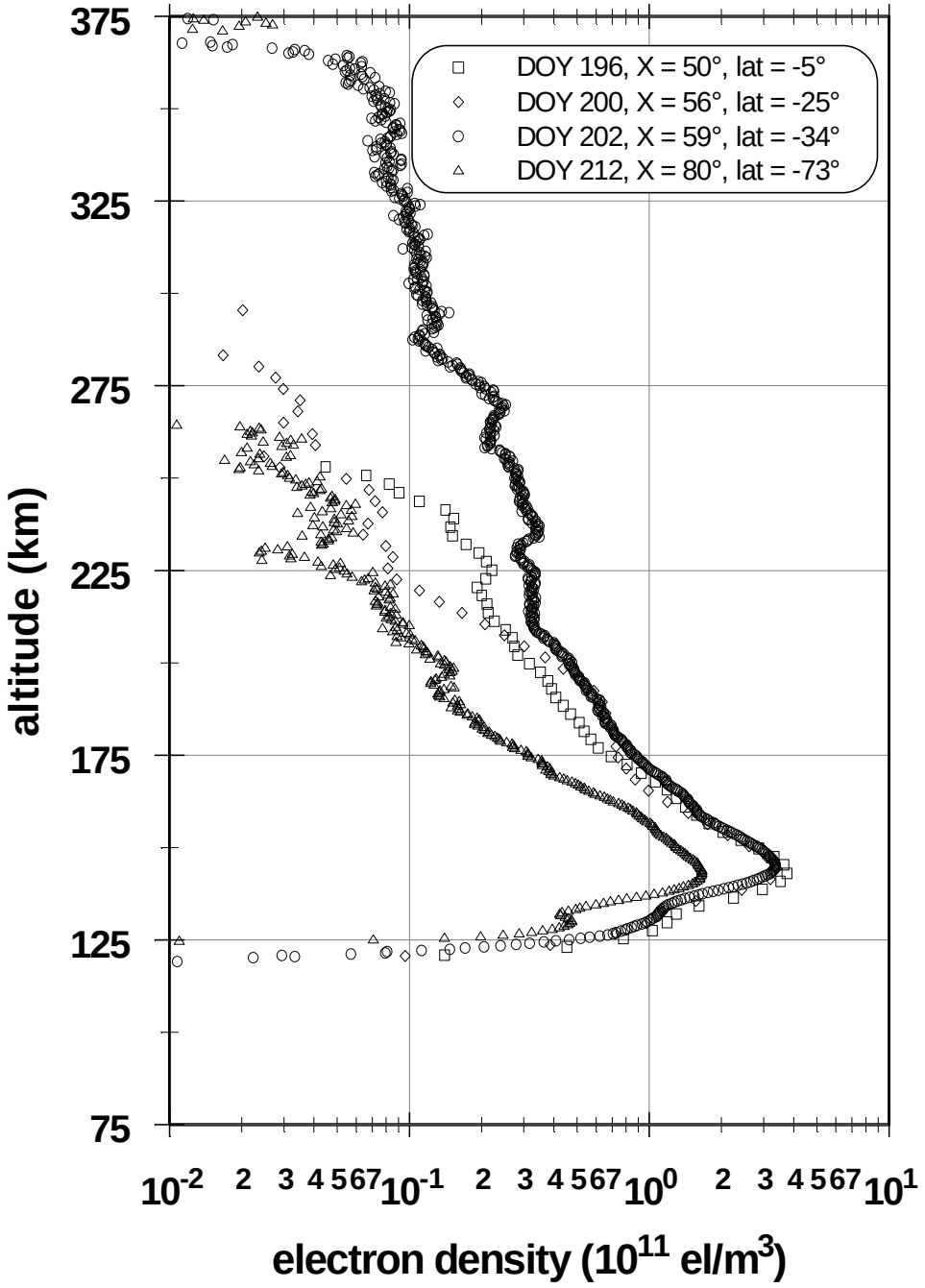
- **Escape occurs though the plasma sheet and induced magnetosphere boundary**

Barabash et al., Nature, 2007

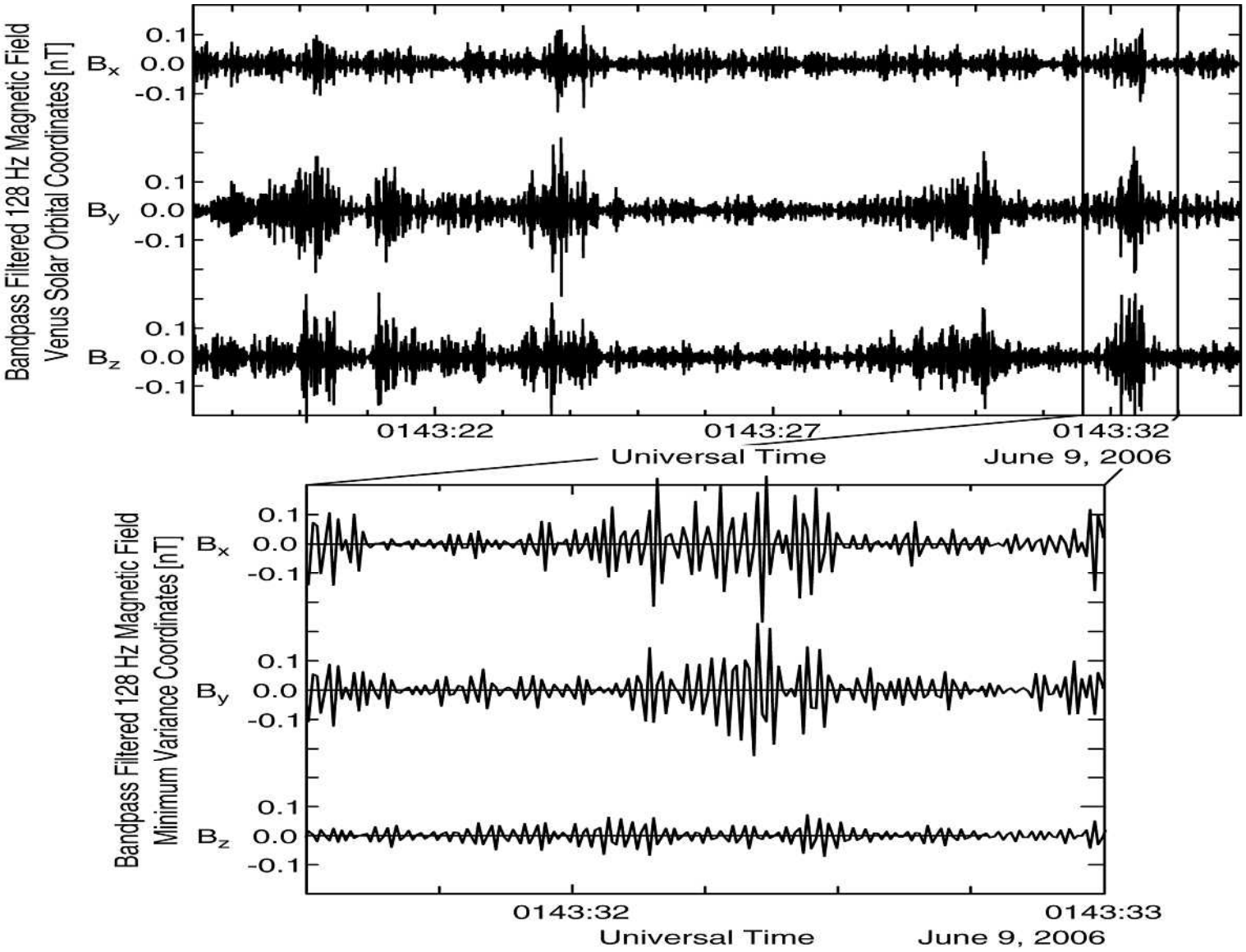
Structure of the ionosphere (VeRa)

	DOY	Lat[°]	SZA[°]
□	196	-5	50
◇	200	-25	56
○	202	-34	59
△	212	-73	80

Pätzold et al., Nature, 2007



Detection of lightning (MAG)

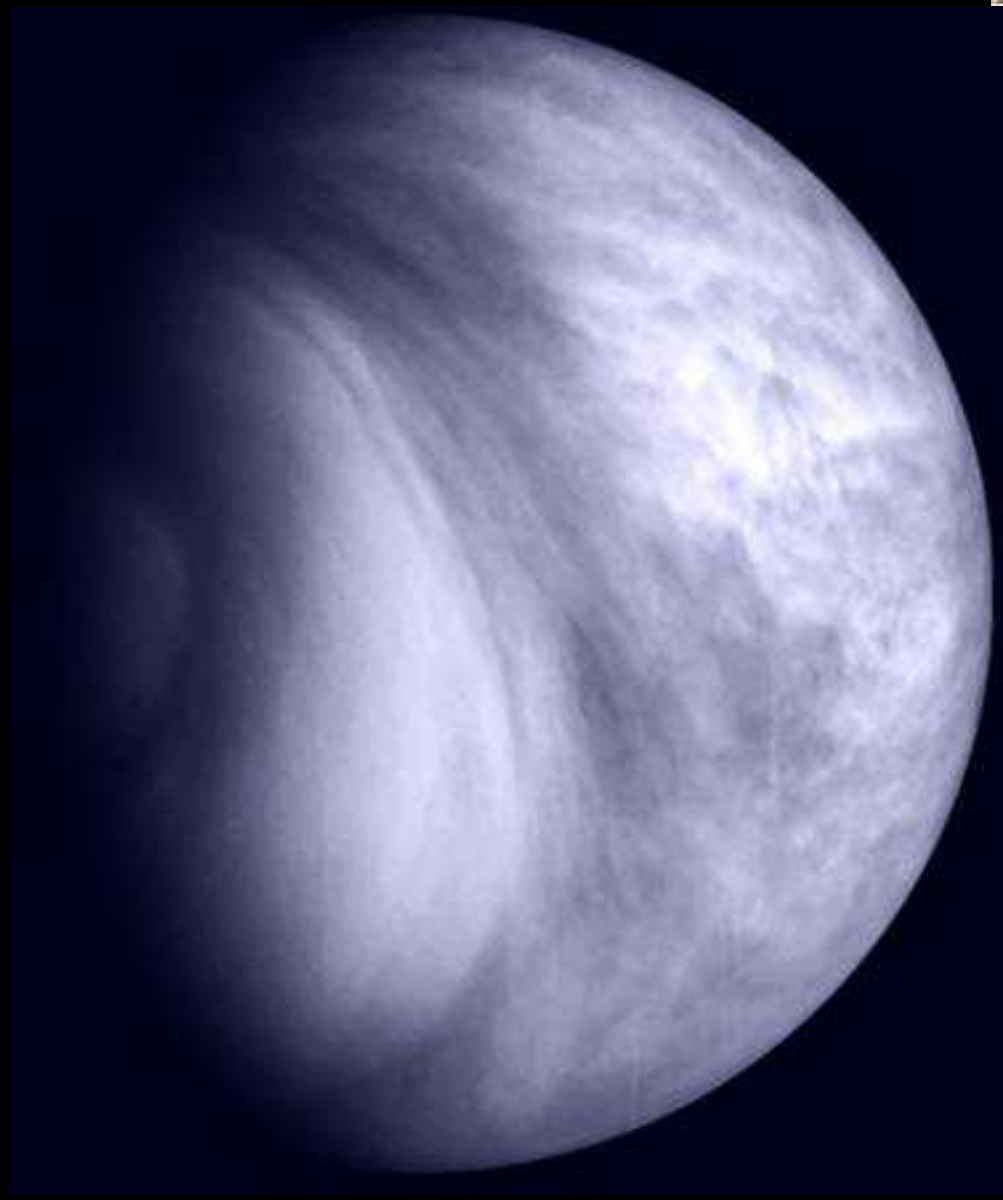


Russell et al., Nature, 2007

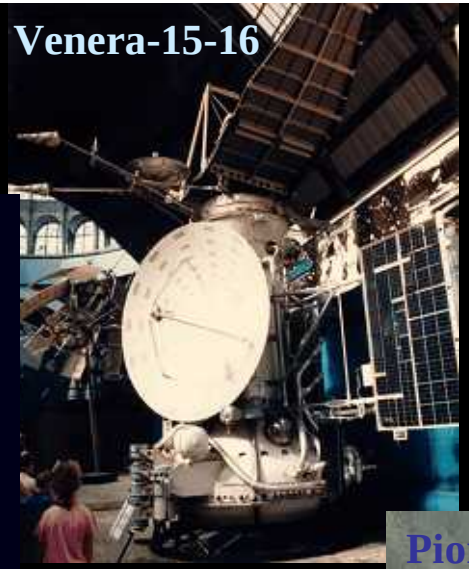
309 km altitude, 0516 LT, 85^{o} latitude

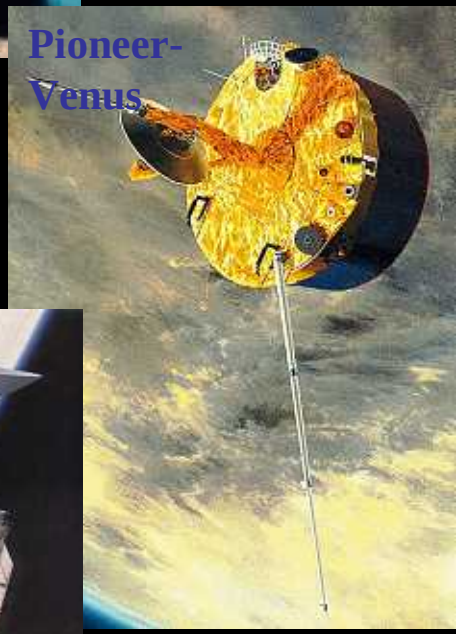
12. Surface

Venus unveiled…



Venera-15-16



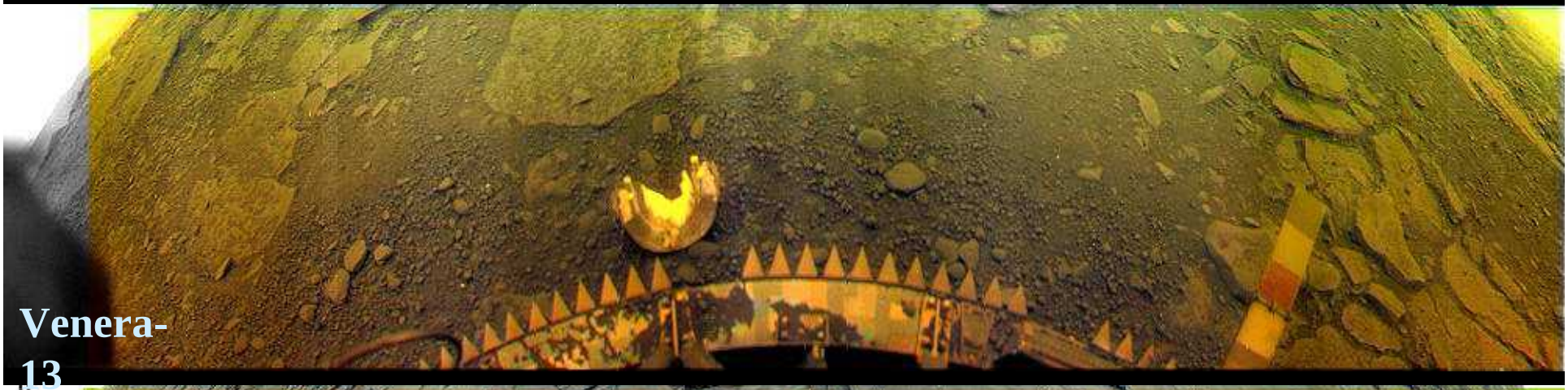


Pioneer-Venus

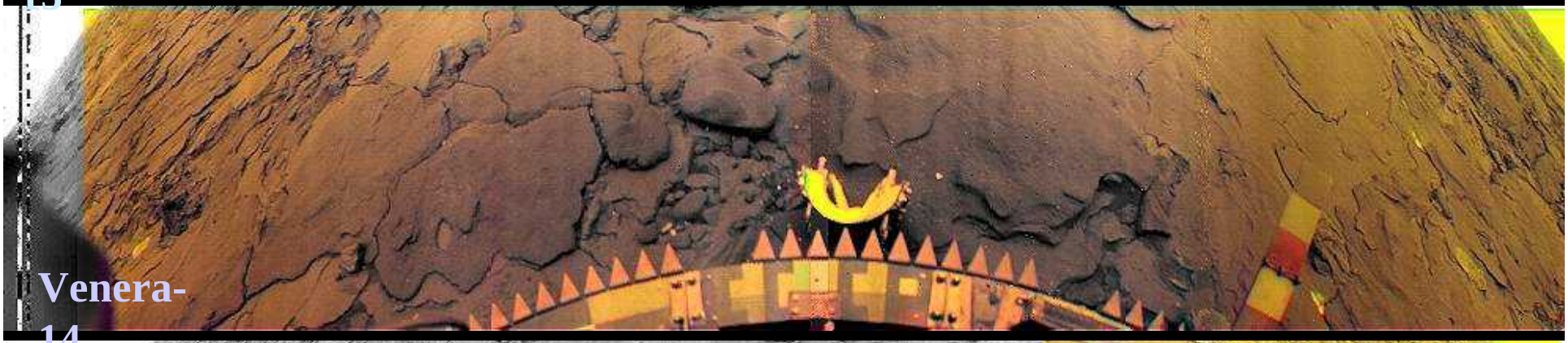
Magellan

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

Surface panoramas by Veneras

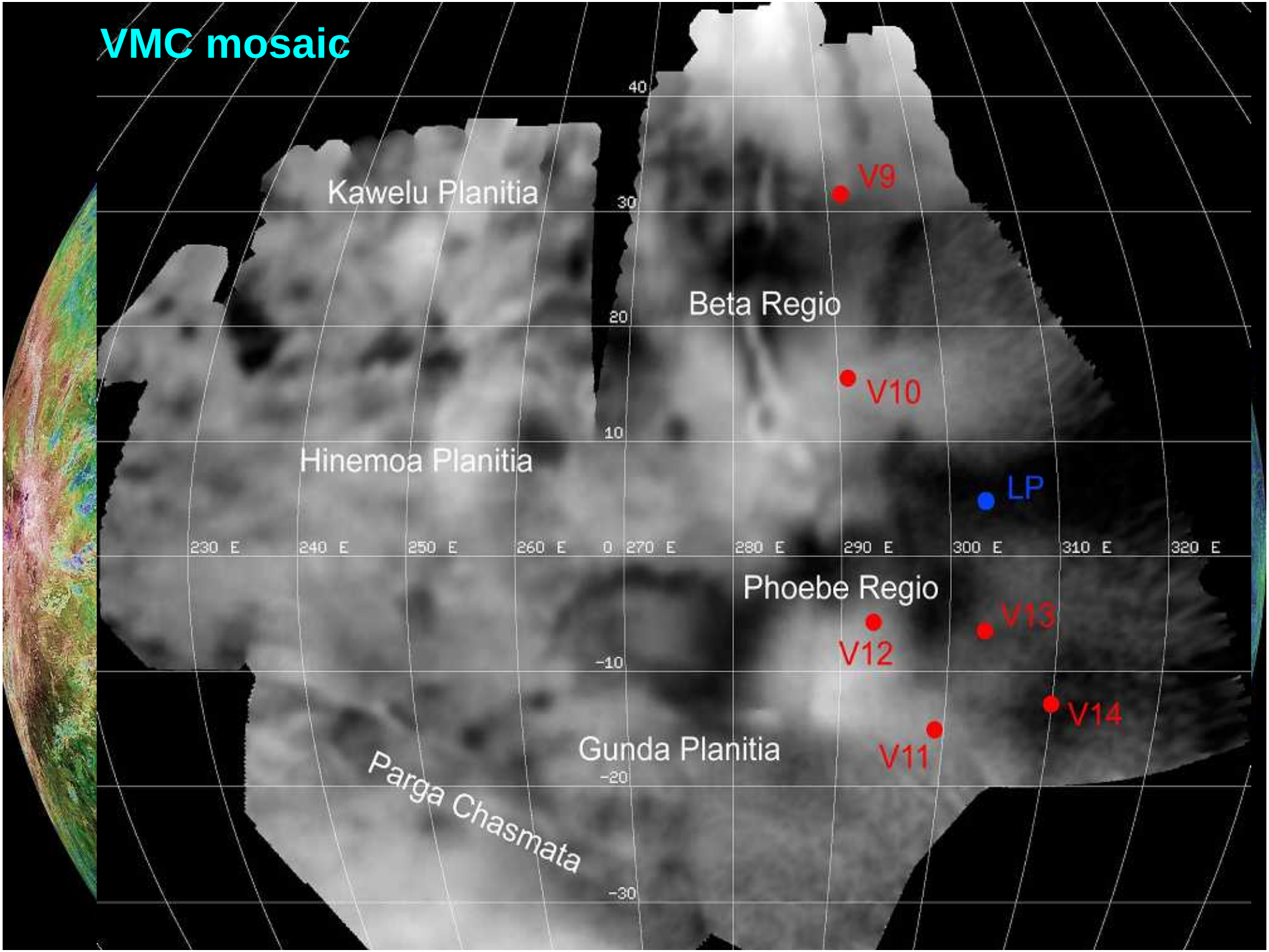


Venera-13

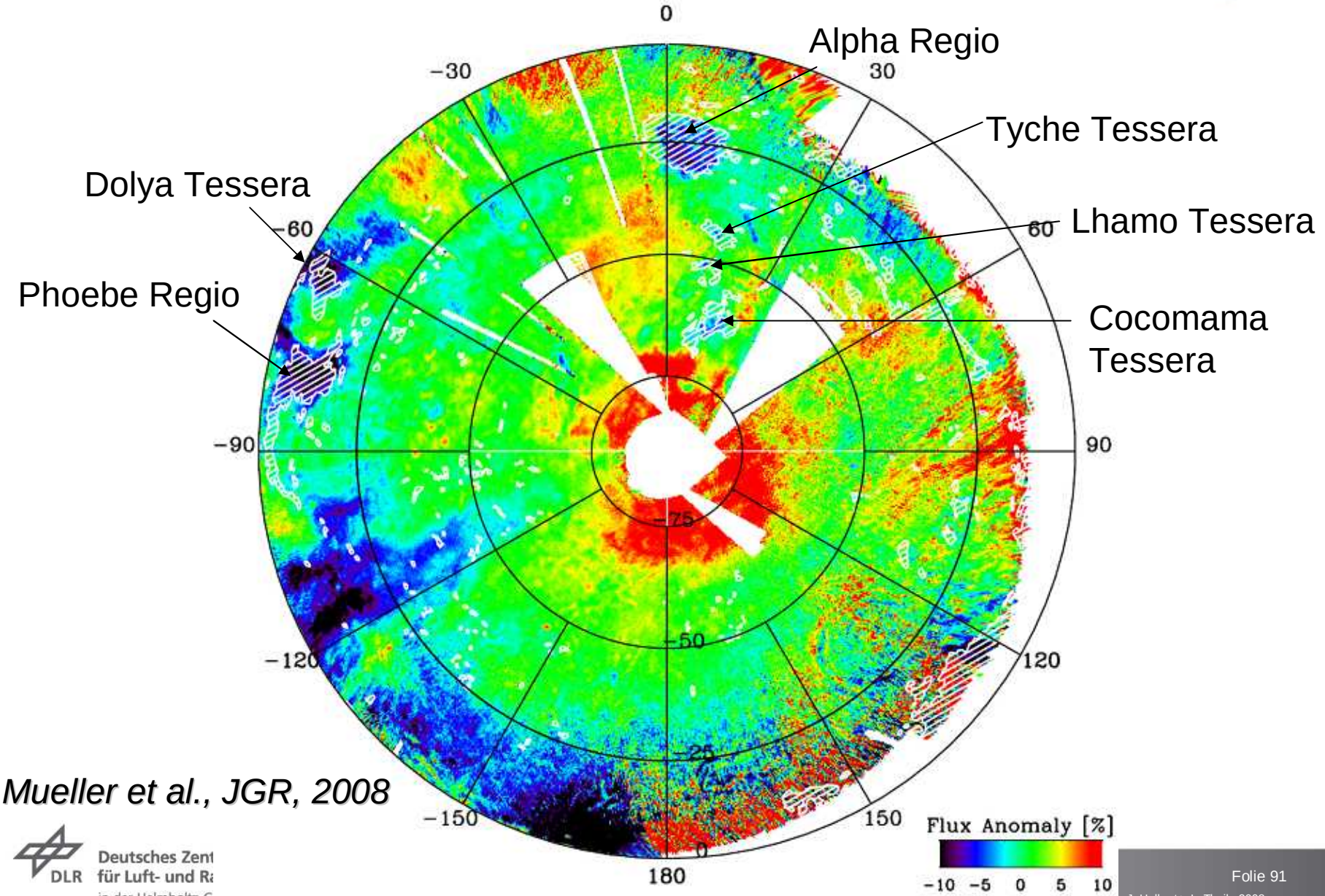


Venera-14

Venera-14


VMC mosaic
Kawelu Planitia
Beta Regio
Hinemoa Planitia
Phoebe Regio
Gunda Planitia
Parga Chasmata
V9
V10
LP
V12
V13
V14
V11
40
30
20
10
-10
-20
-30
230 E
240 E
250 E
260 E
0
270 E
280 E
290 E
300 E
310 E
320 E

Surface flux anomalies (VIRTIS)



N. Mueller et al., JGR, 2008

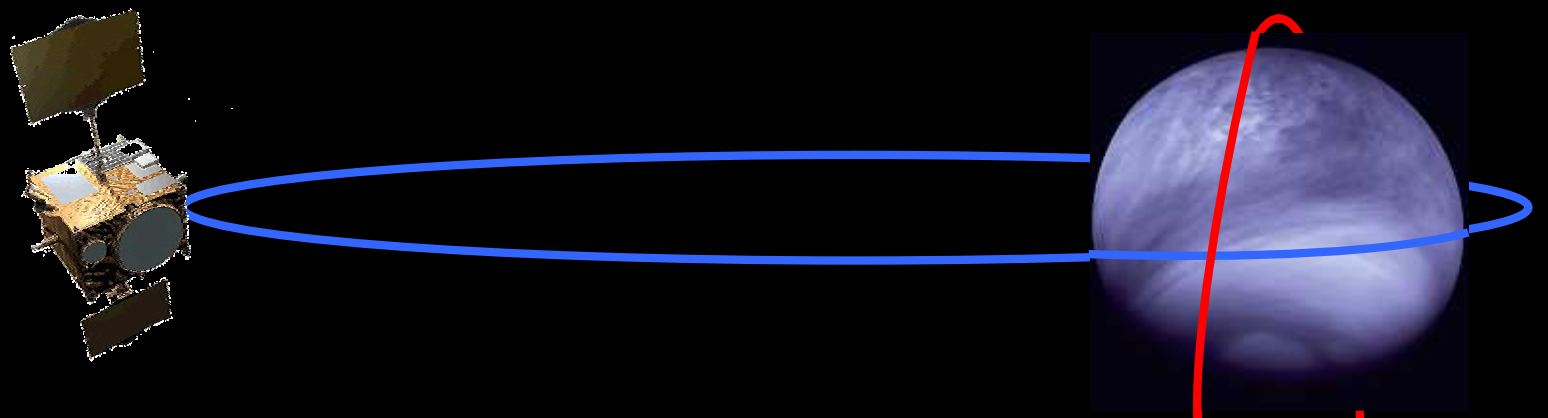
Future studies

- *Mission is extended till the end of 2012*
- *Venus Express: atmospheric drag experiment and aerobraking*
- *Joint observations with the Japanese orbiter mission Akatsuki (2011-12)*
- *Future in-situ missions (landers, balloons)*

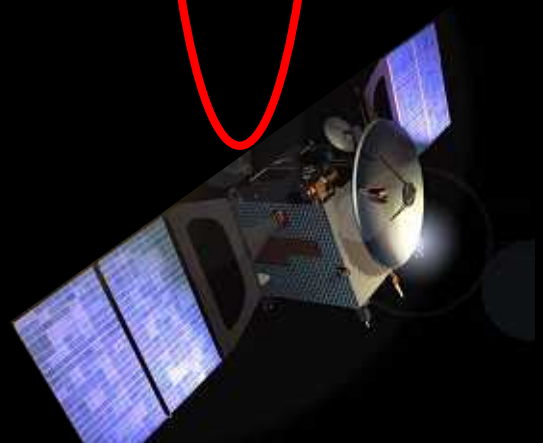
Conclusions

- *About 2 Tbits of data are collected in > 3 years*
- *Venus Express delivers global and detailed survey of the atmospheric and plasma properties and processes*
- *We are on the way to understanding how the processes led to so different planet*
- *Revival of the interest to Venus in science community and Space Agencies*
- *Main problem – the lack of science resources*

Coordinated VEX-Planet-C observations



- **Simultaneous observations of cloud morphology**
- **Complementary dynamics studies**
- **Joint airglow observations**
- **Complementary radio-science investigations**



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