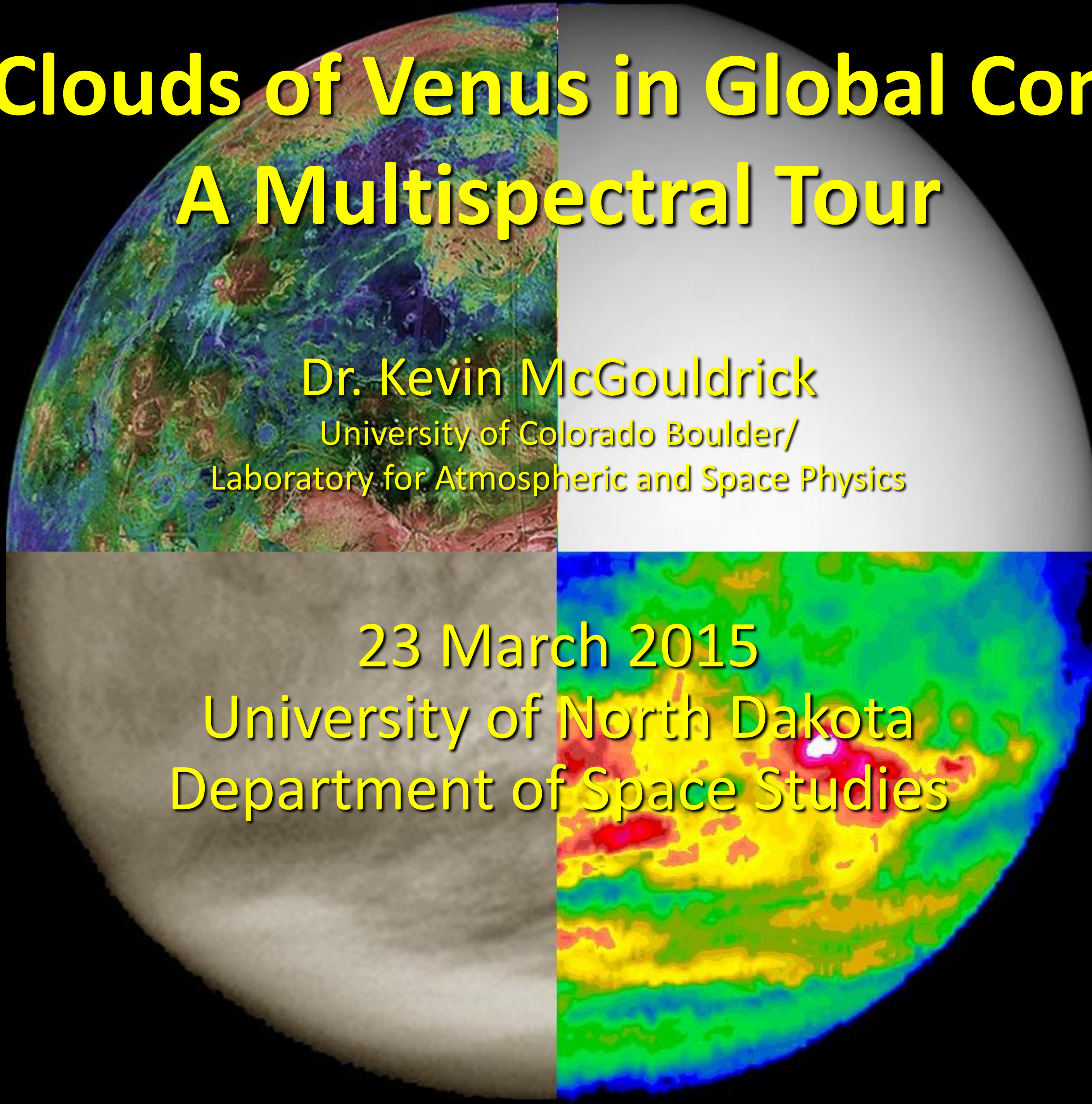
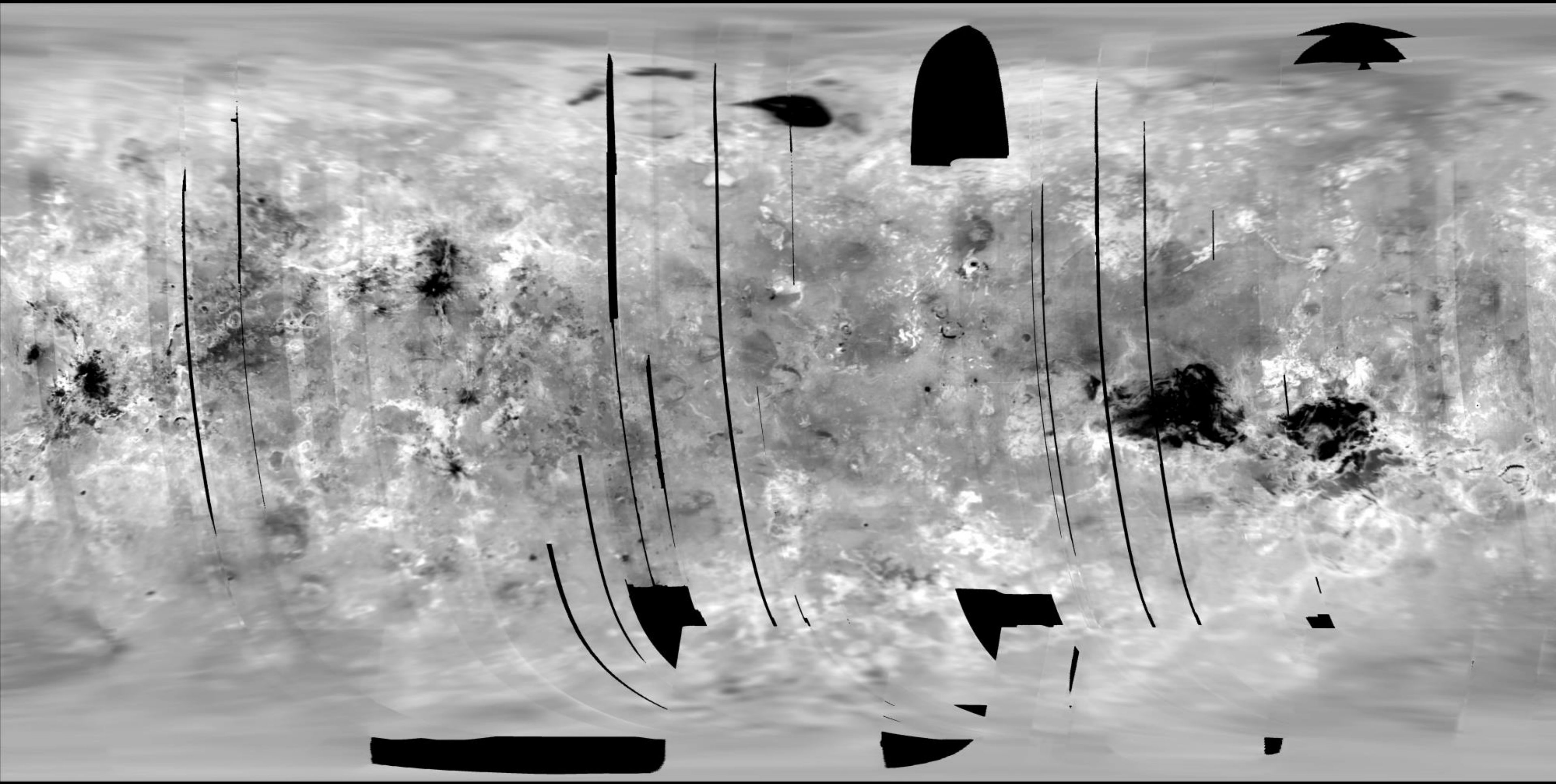
The Clouds of Venus in Global Context: A Multispectral Tour



Dr. Kevin McGouldrick
University of Colorado Boulder/
Laboratory for Atmospheric and Space Physics

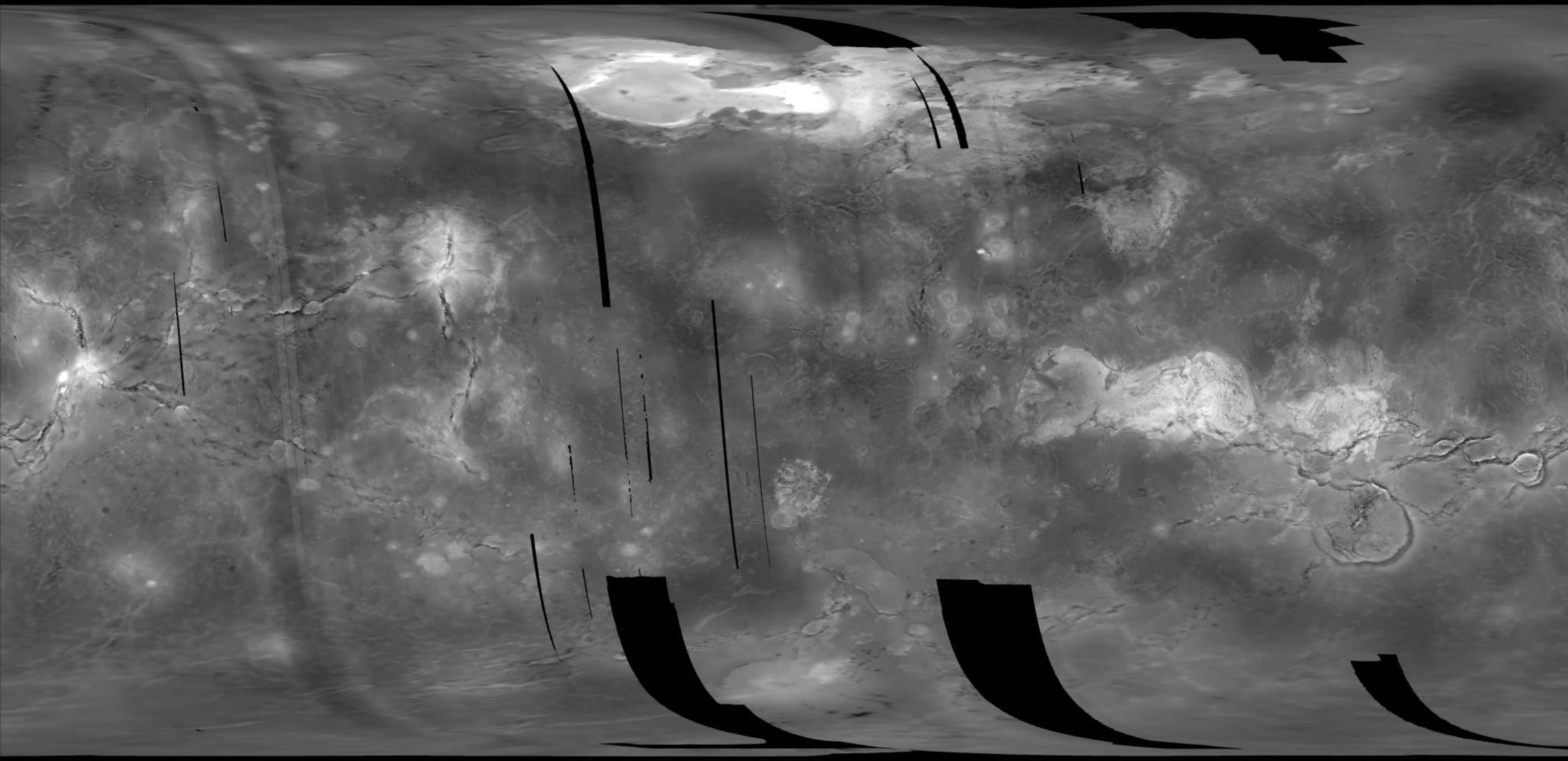
23 March 2015
University of North Dakota
Department of Space Studies

Venus Microwave emissivity



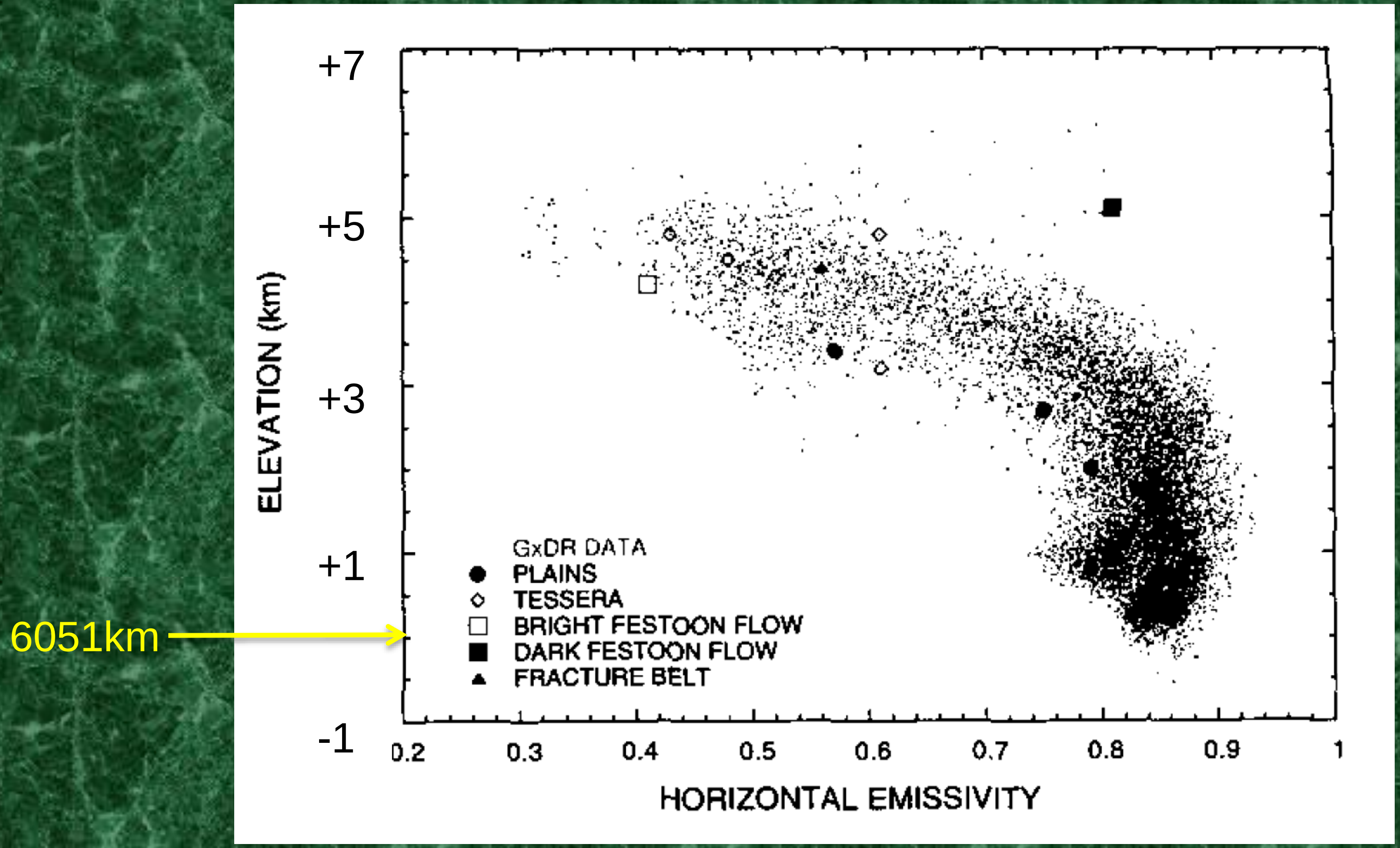
- Down to 100m spatial resolution
- Global mean ~0.87m (consistent with basalt)
- Range from ~0.5 to ~1.0

Venus topography from Magellan



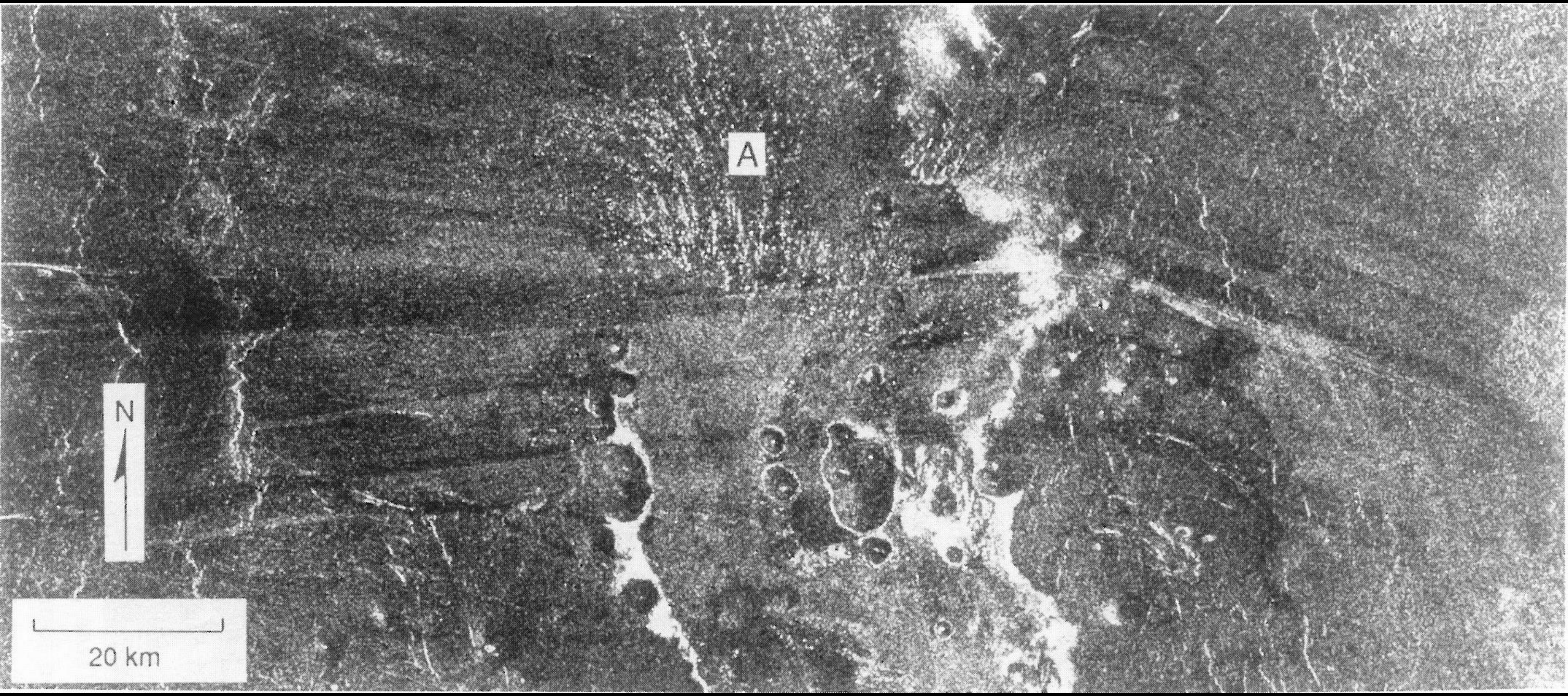
- 10km spatial resolution
- Unimodal distribution with ~8km range
- Correlation with emissivity?

Radar emissivity vs. Altitude



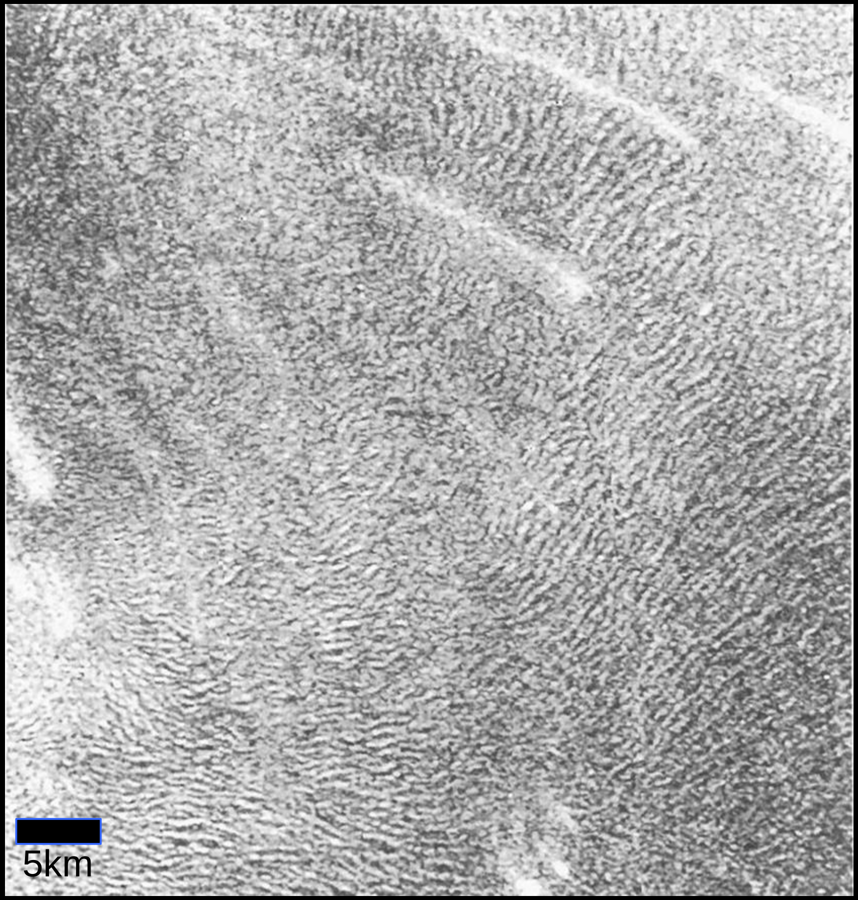
Arvidson, R. E. (1994) *Icarus* **112**, 171-186.

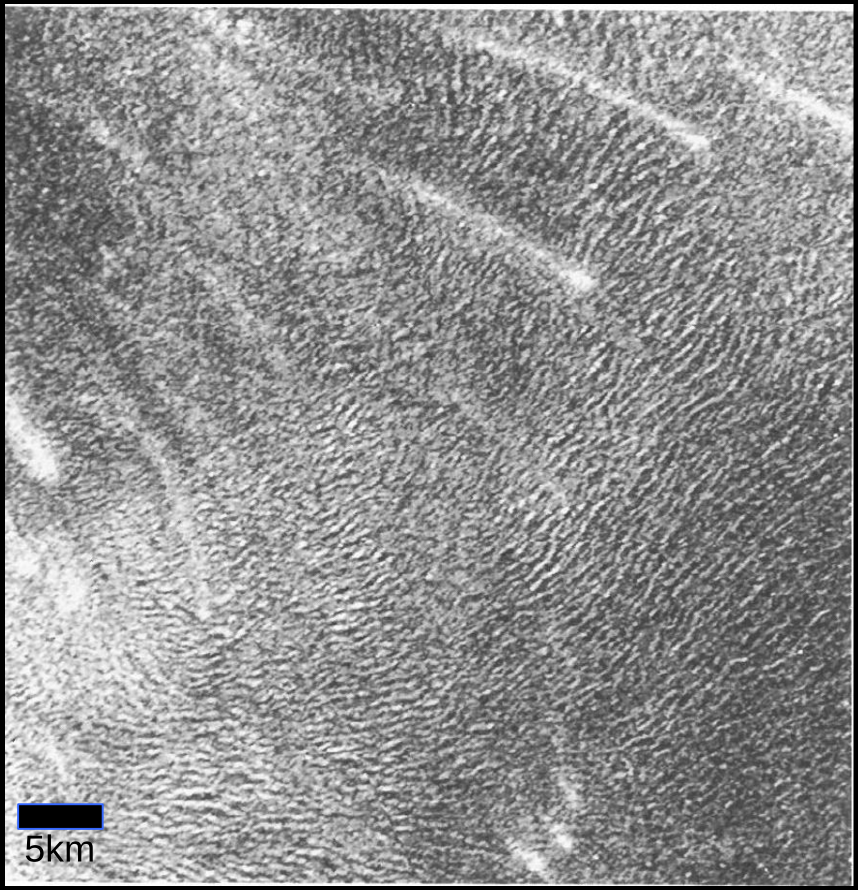
Aglaonice Dune field



- Many features are seen in the Magellan SAR data; since I am an atmosphericist, I'll concentrate on the aeolean features.
- Here is evidence of dines driven by East → West winds
- NB, even these, at km-scale, are too small to be noted in Magellan topography

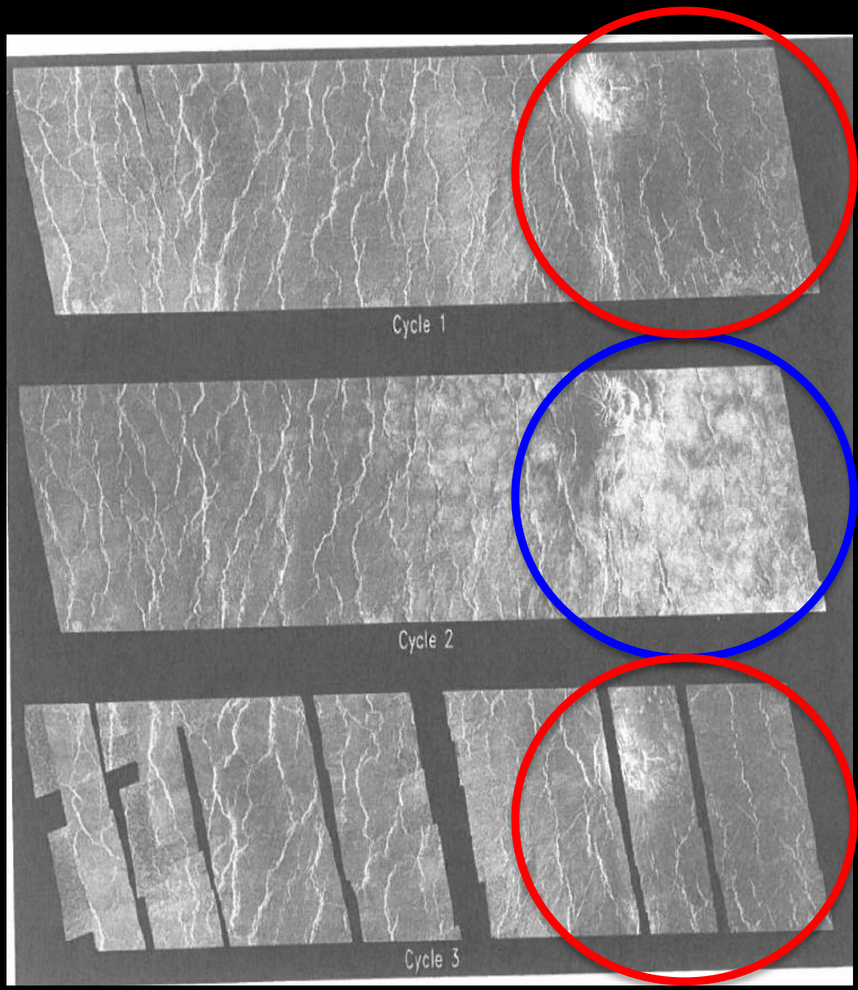
Fortuna Meshkenet Dunes





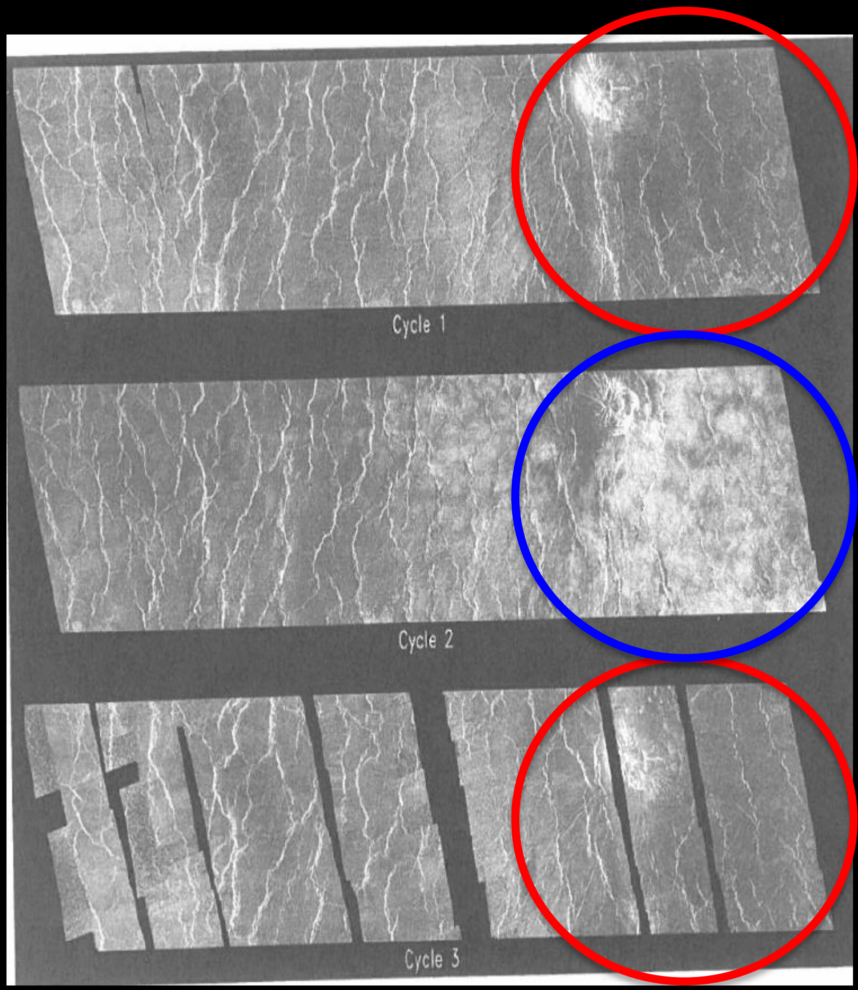
- Another example of possible spatially resolved dune fields.
- However, the curvature of the field hints that something different is going on here.
- Either prevailing winds not always E→W at the surface, or these are not wind-driven dunes.
- However, note the wind streaks…

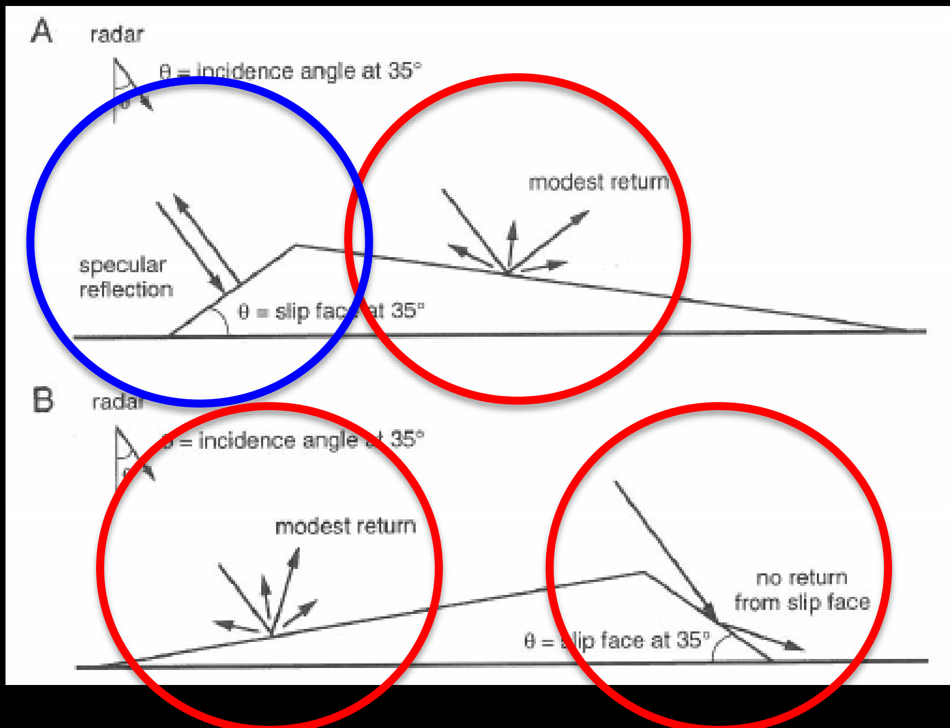
Microdunes near Stowe Crater



- Below limit of spatial resolution of Magellan SAR
- Top and bottom images show SAR data of the same region taken from the left at 25° incidence.
- Middle image shows same area imaged at 25° incidence from the right.
- Large changes in returned radiance suggest asymmetric dunes

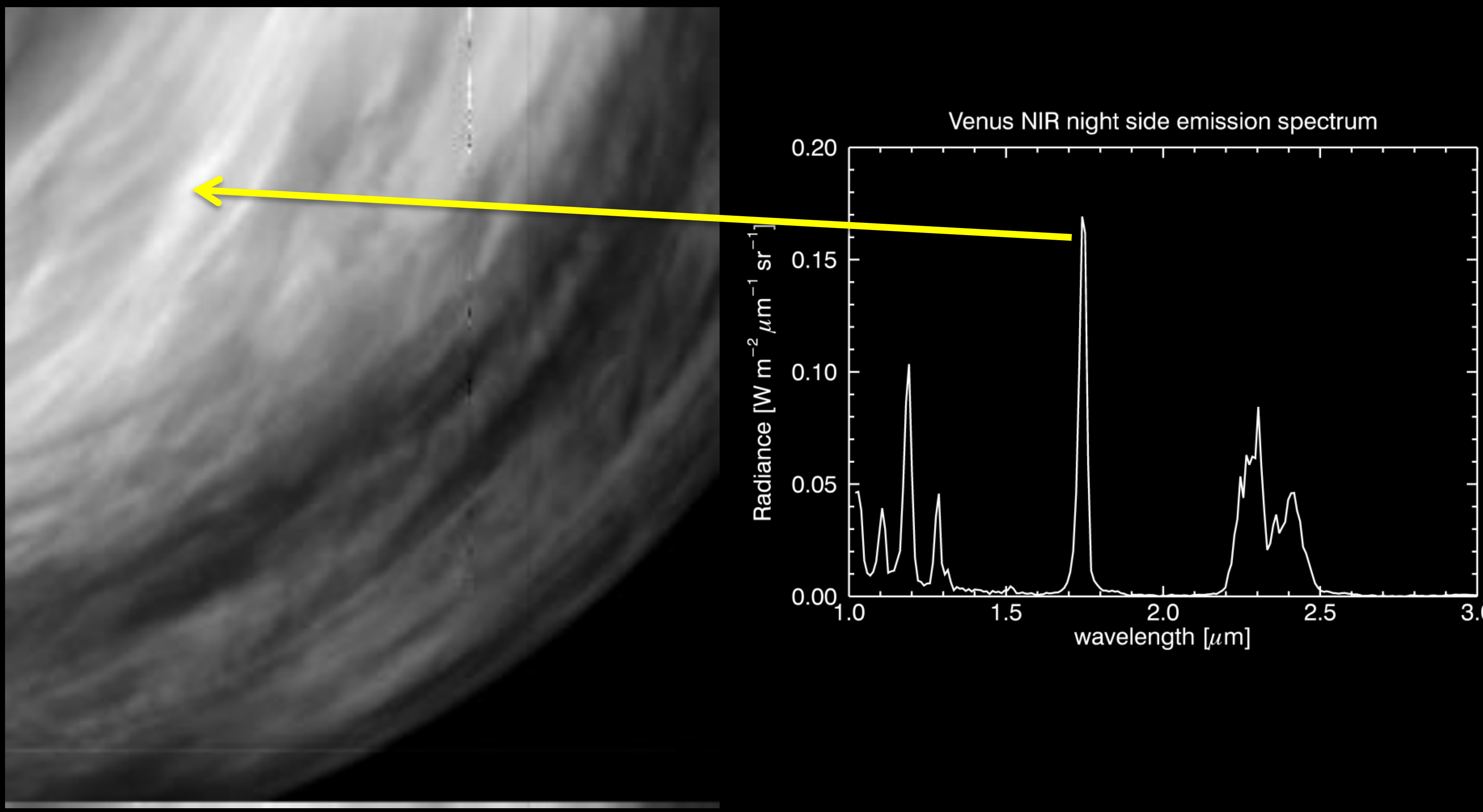
Microdunes near Stowe Crater



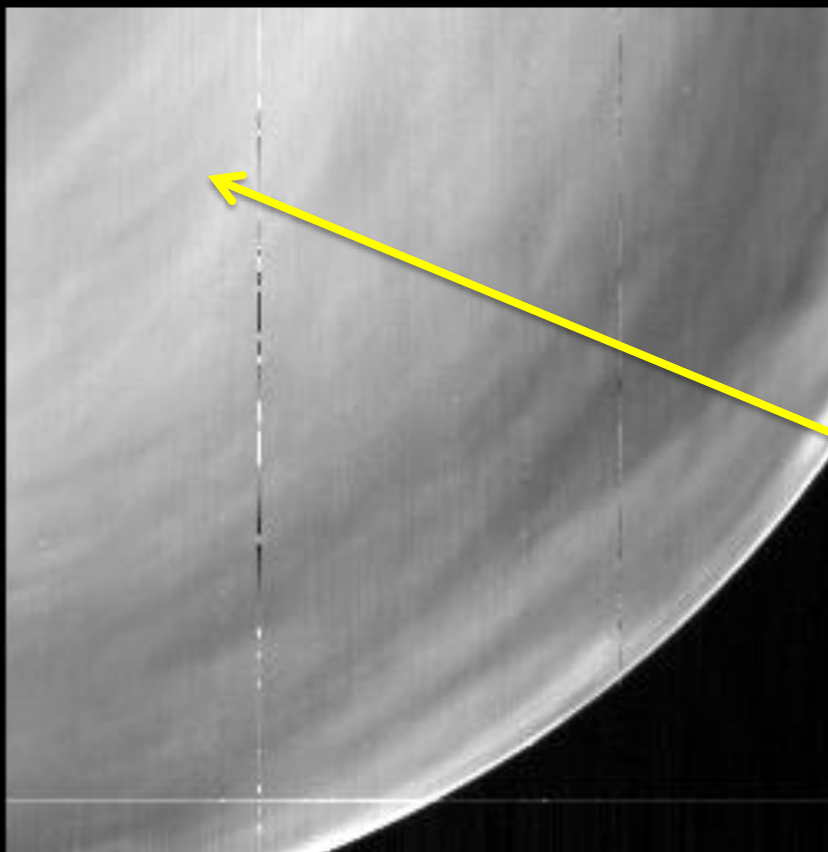


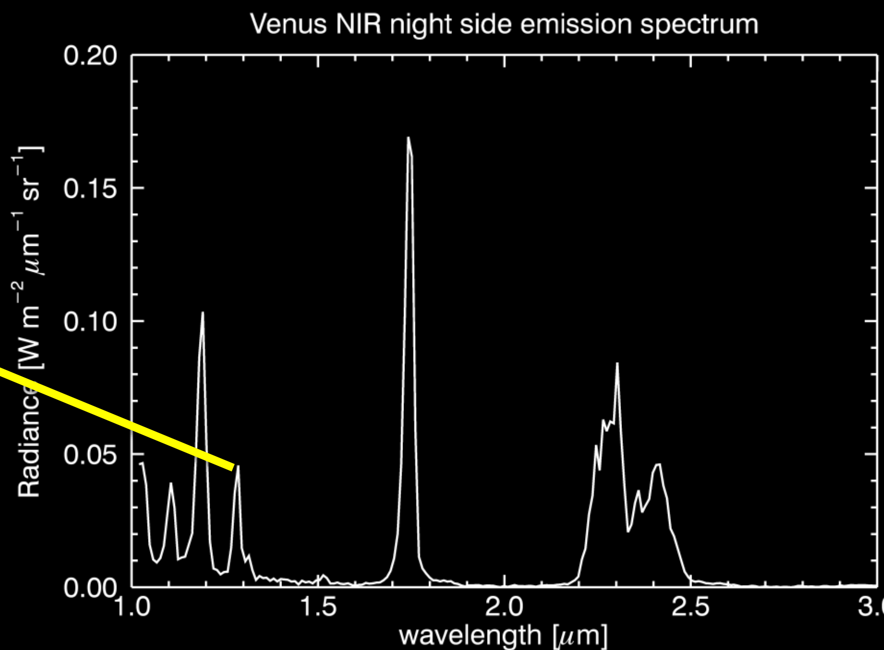
- Large changes in returned radiance suggest asymmetric dunes

NIR emission spectrum of Venus

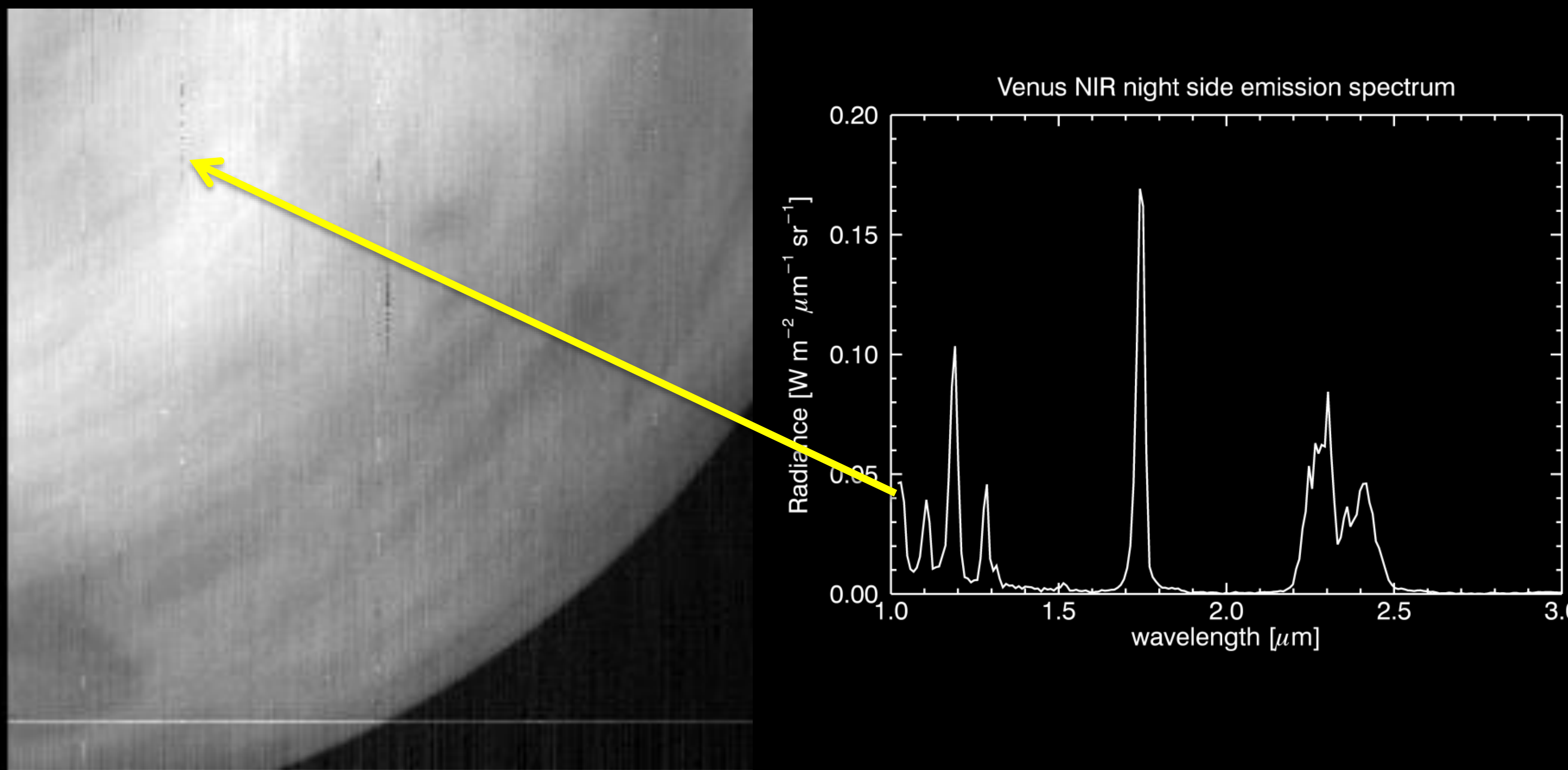


1.28 micron window

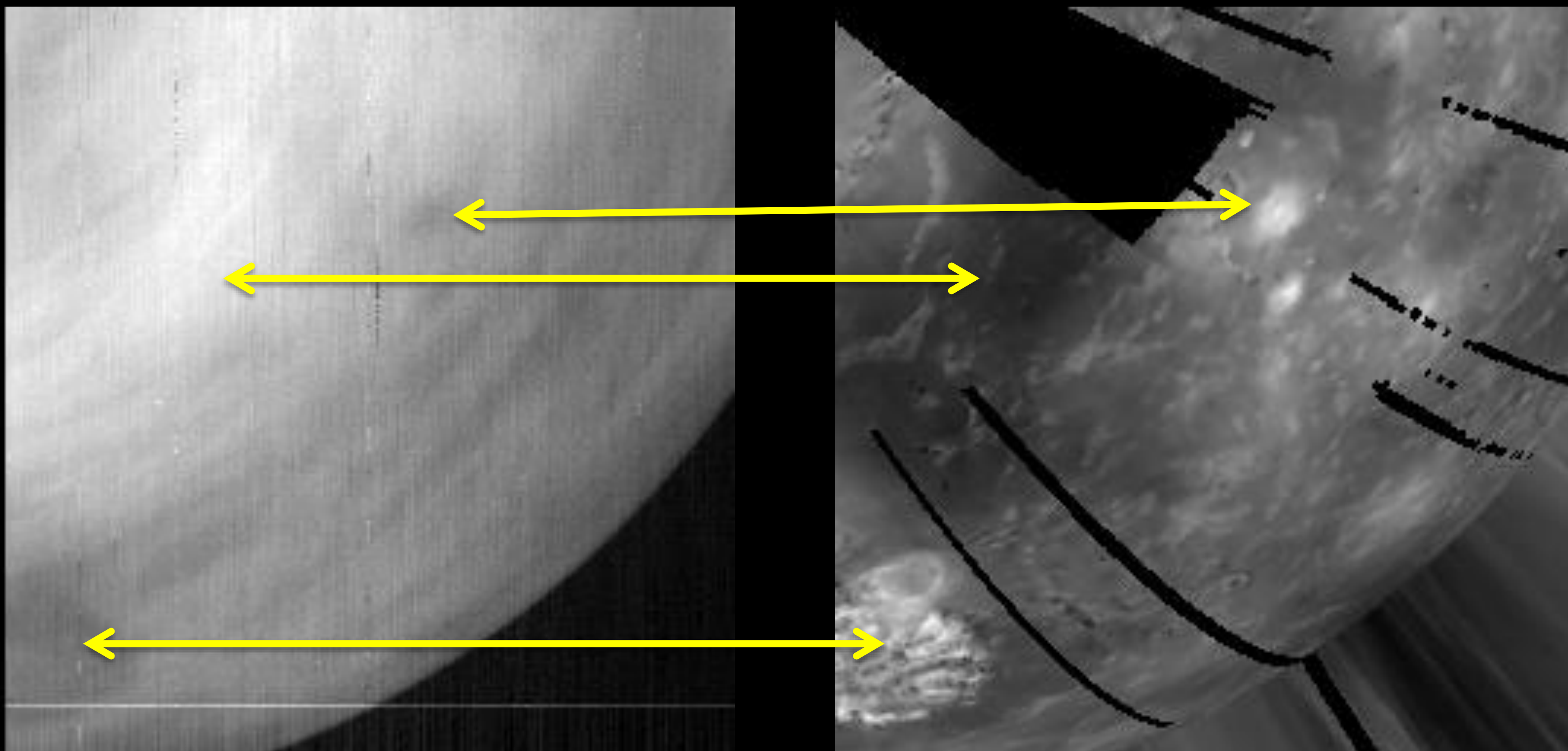




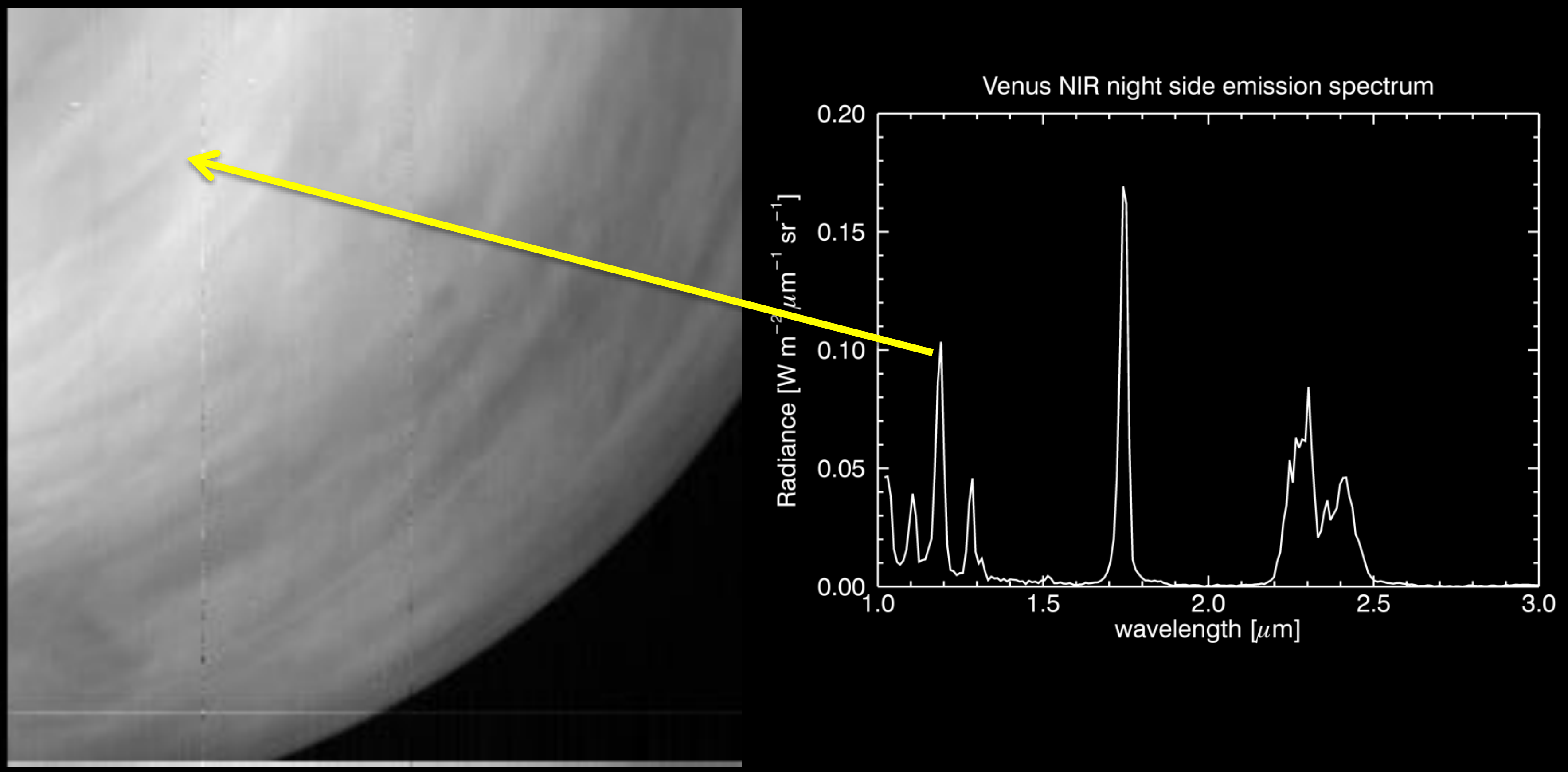
1.02 micron spectral window



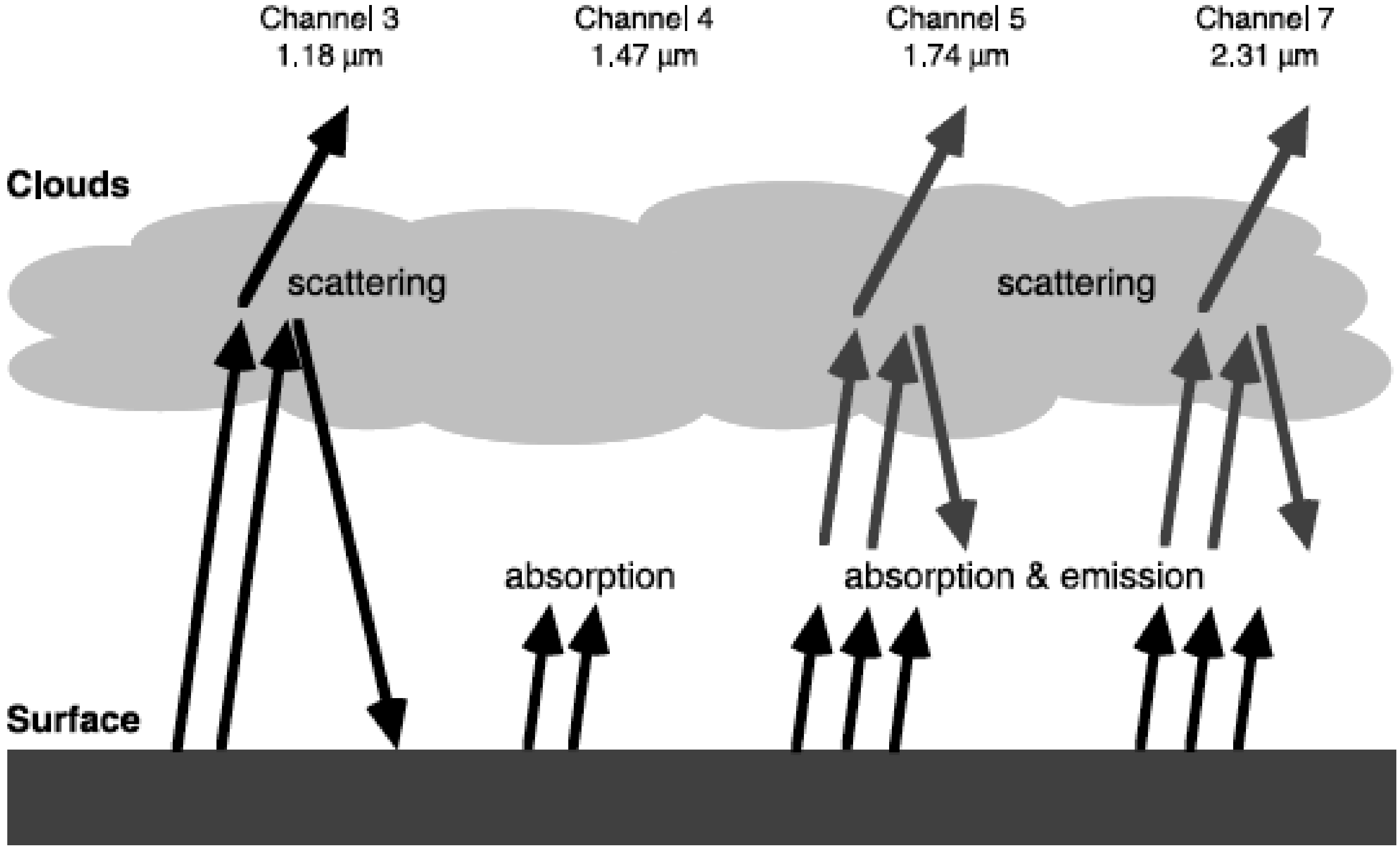
1.02 micron image compared with Magellan surface elevation



1.18 micron spectral window

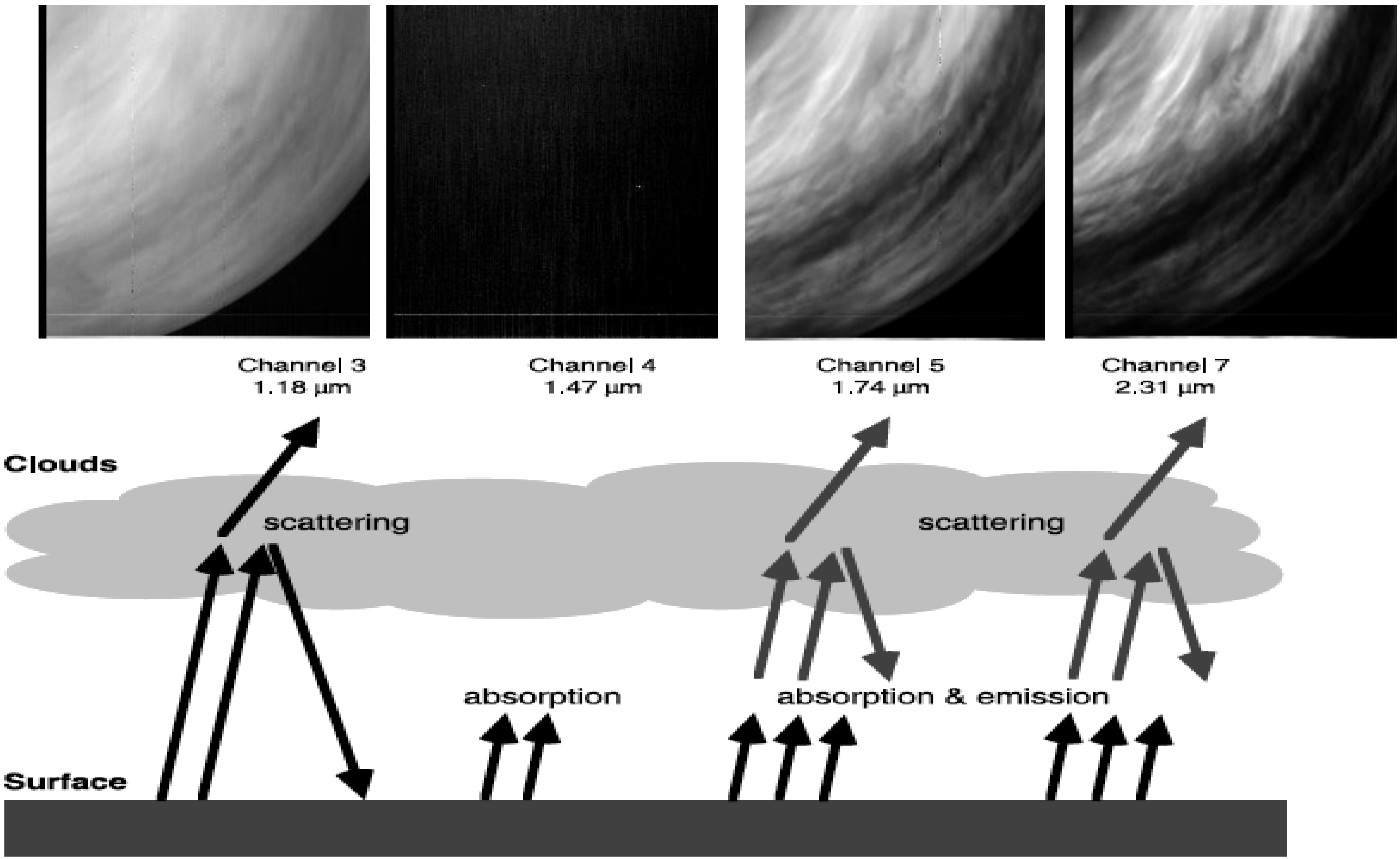


Schematic of Cloud “removal” from Galileo NIMS data



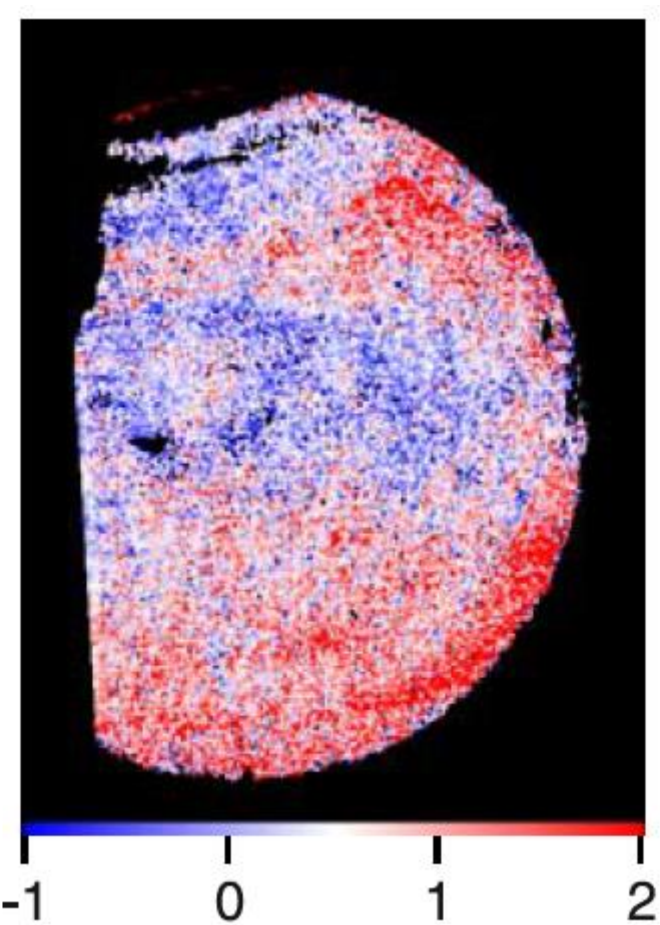
Hashimoto et al 2008 JGR 113:E00B24

Schematic of Cloud "removal"

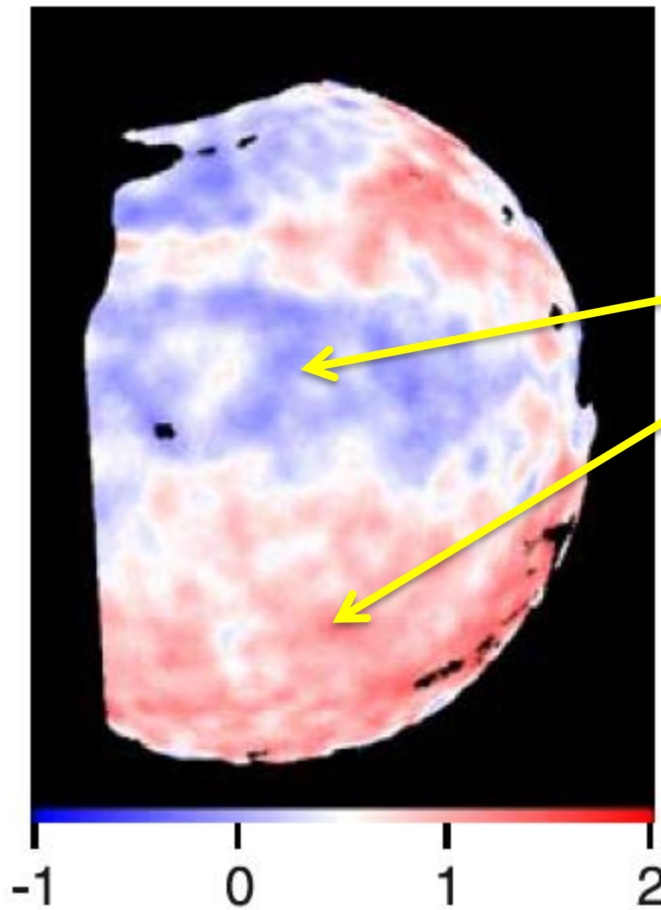


Hashimoto et al 2008 JGR 113:E00B24

Retrieval of 1.18 micron surface emissivity variations from Galileo NIMS



Binned to 250km resolution

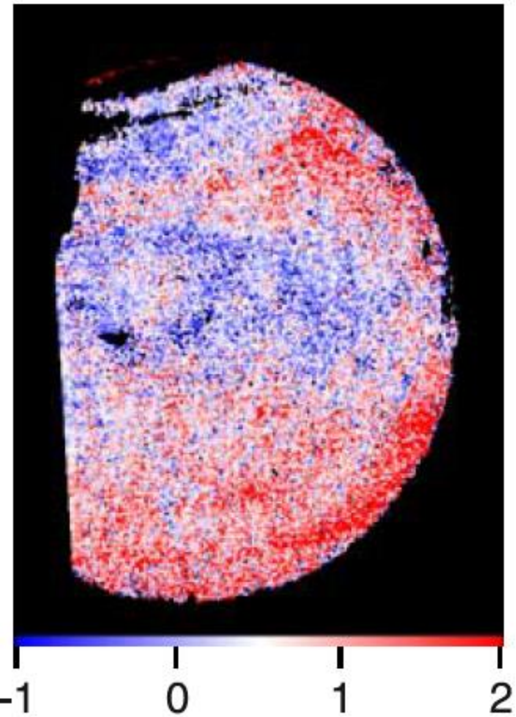


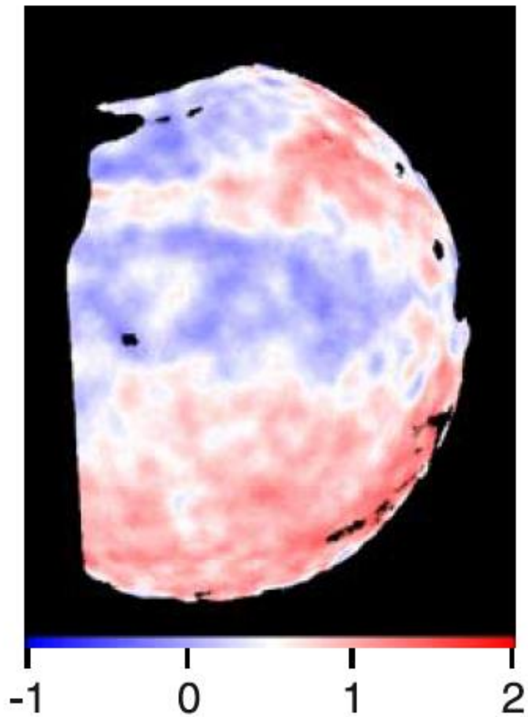
Note larger average surface emissivity in SH vs. NH.

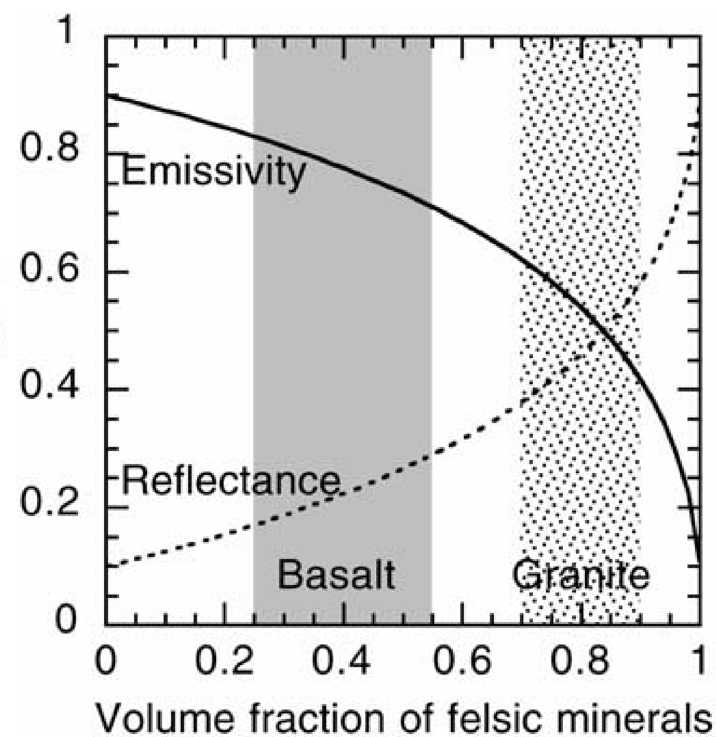
Large errors/noise because using band ratios; could improve with spectroscopy.

Hashimoto et al 2008 JGR 113:E00B24

Retrieval of 1.18 micron surface emissivity variations from Galileo NIMS



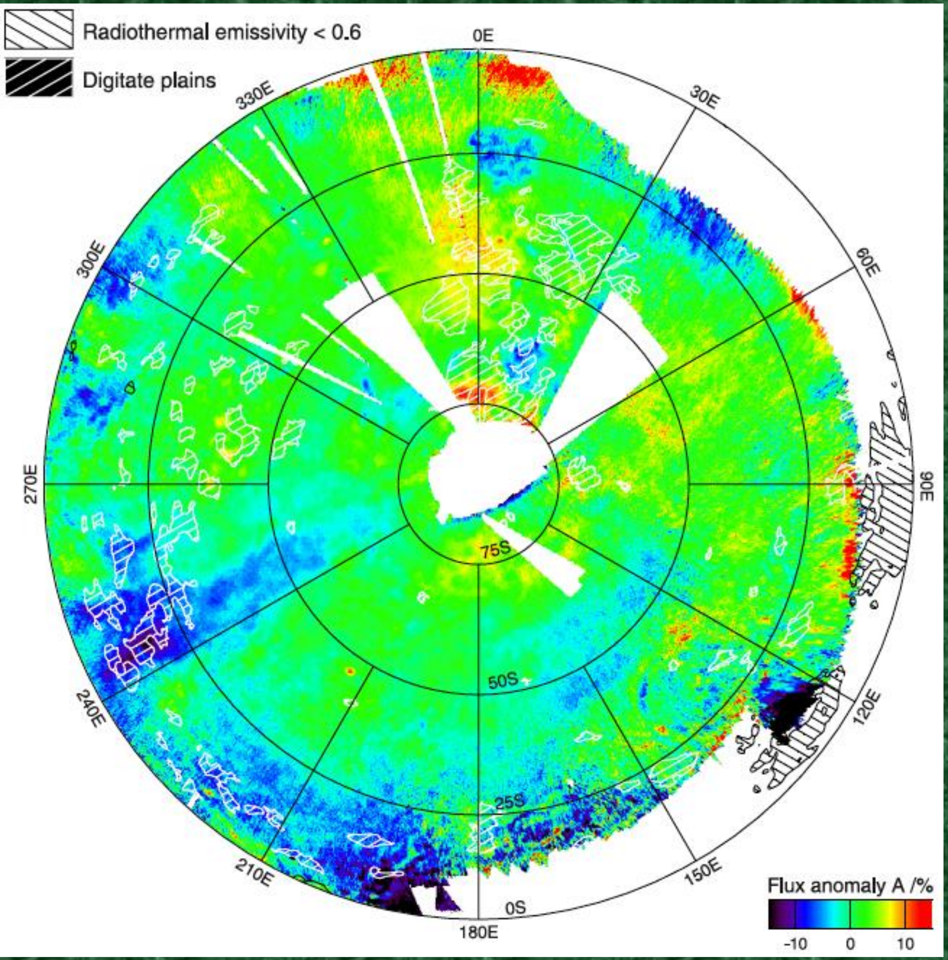




VEx/VIRTIS was capable of observing/measuring this much change in the surface emissivity with much better spectral and spatial resolution than Galileo NIMS.

Hashimoto et al 2008 JGR 113:E00B24
Hashimoto and Sugita 2003 JGR (2003JE002082)

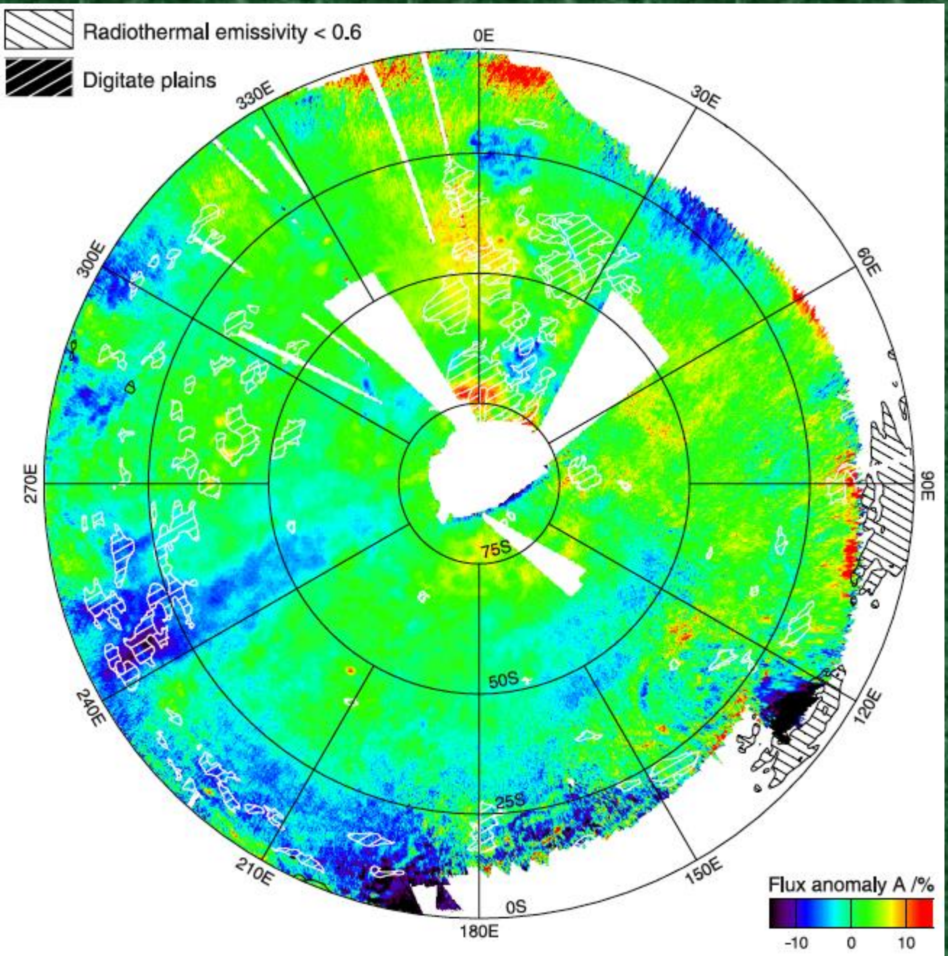
VIRTIS 1.02 micron thermal emission

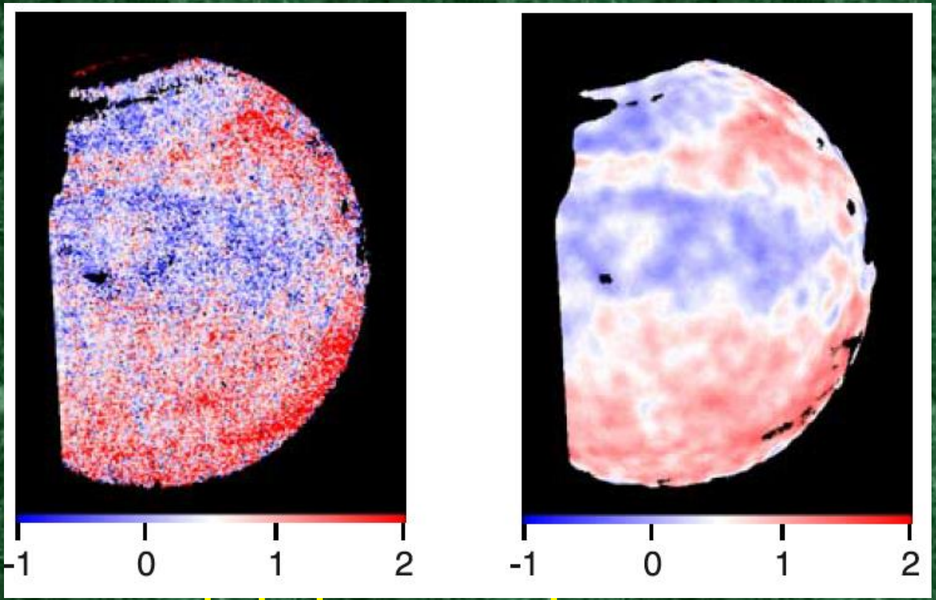


- 1.02 micron Flux anomaly from VIRTIS compared to surface features identified from Magellan.
- Negative anomalies match tessera terrain
- Unfortunately much of the low emissivity regions are NH…

Mueller et al 2008 JGR 113:E00B17

VIRTIS 1.02 micron thermal emission





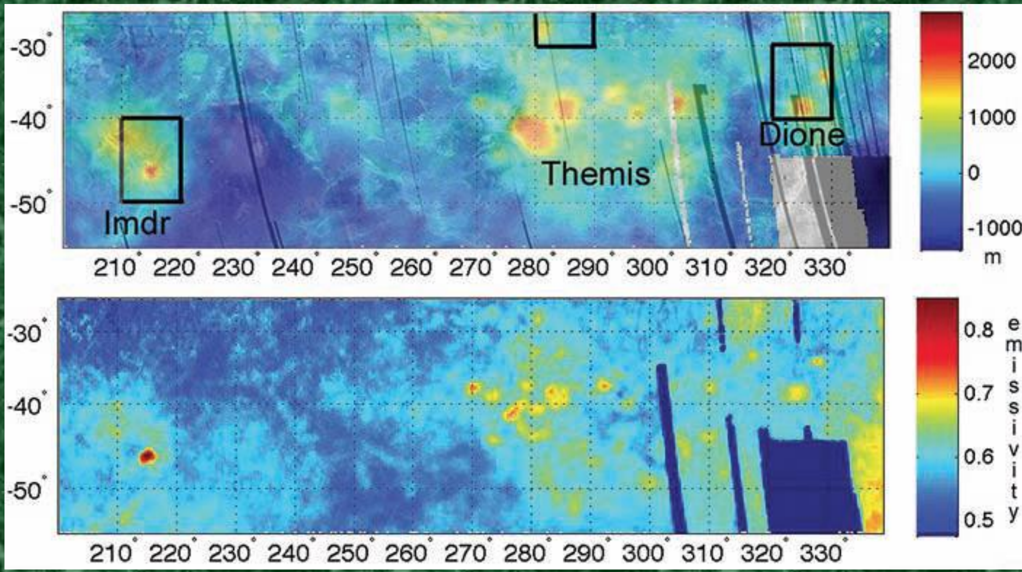
match tessera terrain

- Unfortunately much of the low emissivity regions are NH…

Mueller et al 2008 JGR 113:E00B17

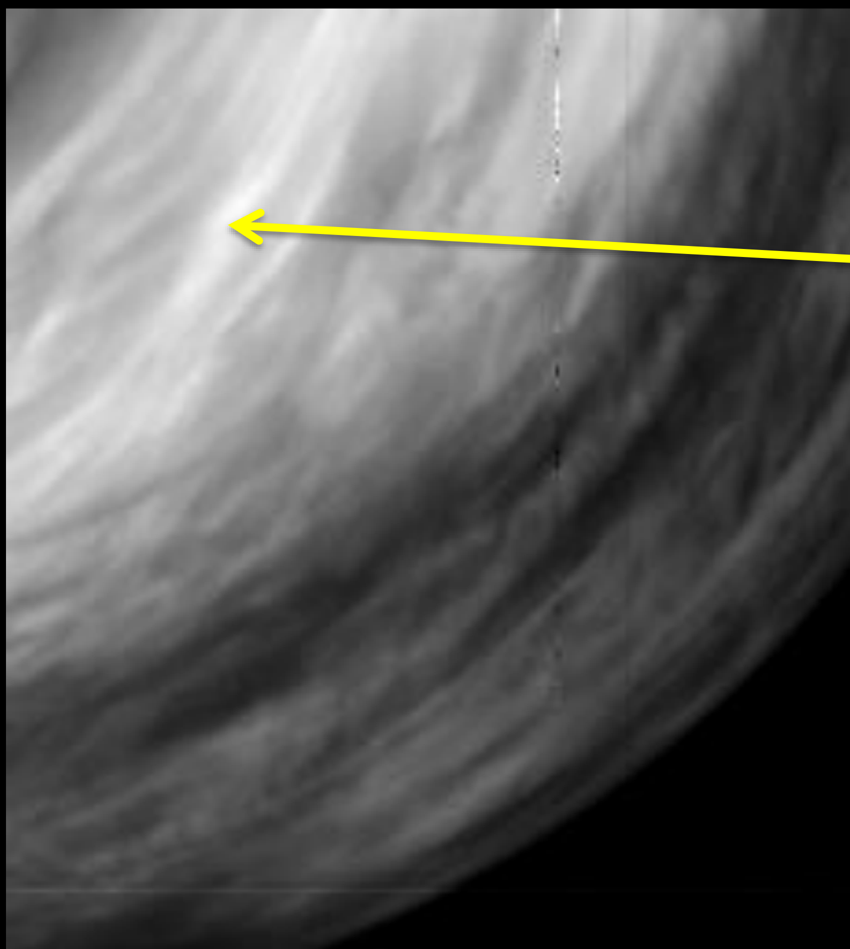
Evidence for geologically recent resurfacing on Venus

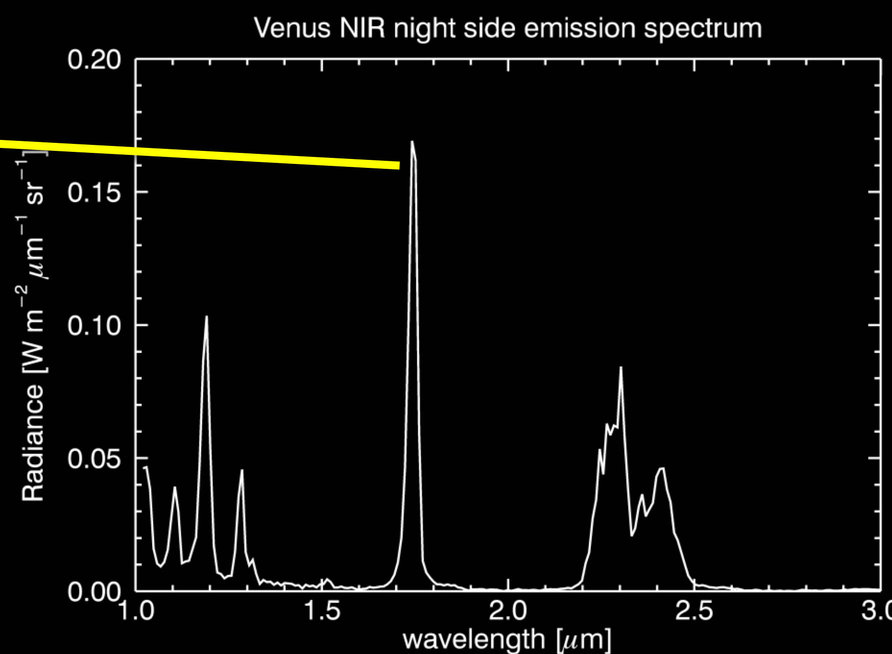
- Regions that are morphologically likely to exhibit recent volcanism also are seen to exhibit emissivity anomalies.
- These anomalies are interpreted as regions that have experienced less surface weathering, indicating a surface with a local age of 2.5Myr, perhaps even lower than 250Kyr.



Smrekar et al. Science 328:605. 2010.

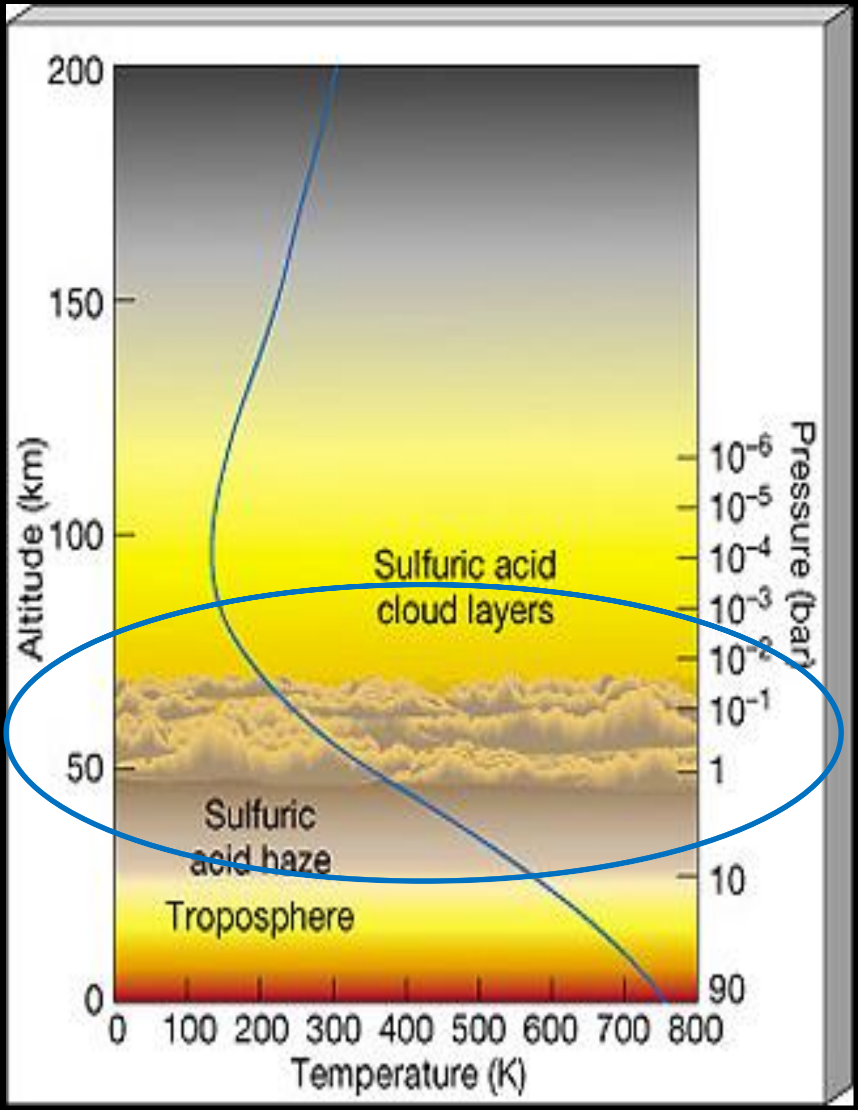
1.74 micron window again



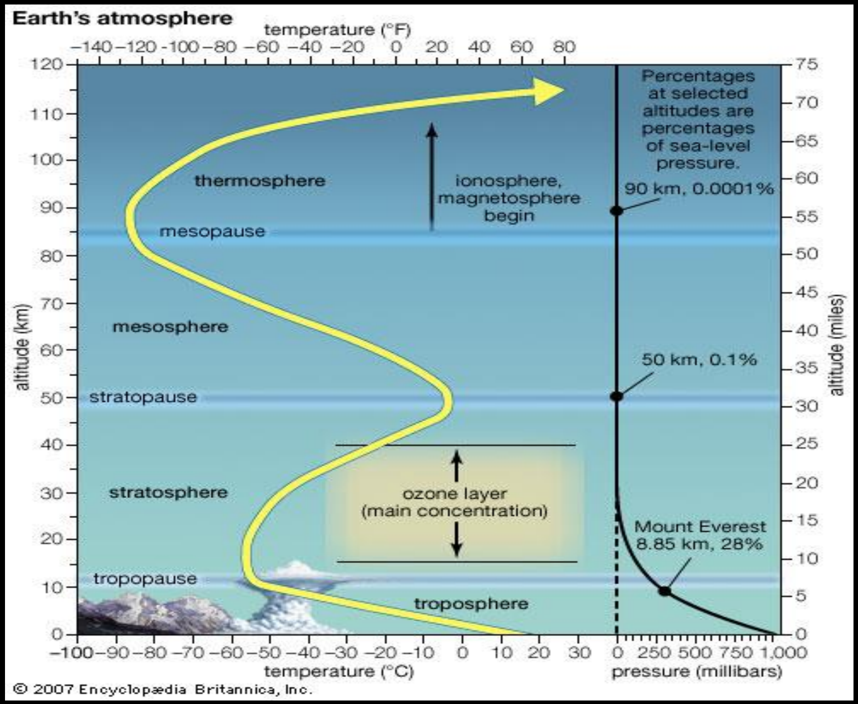


Venus

Earth

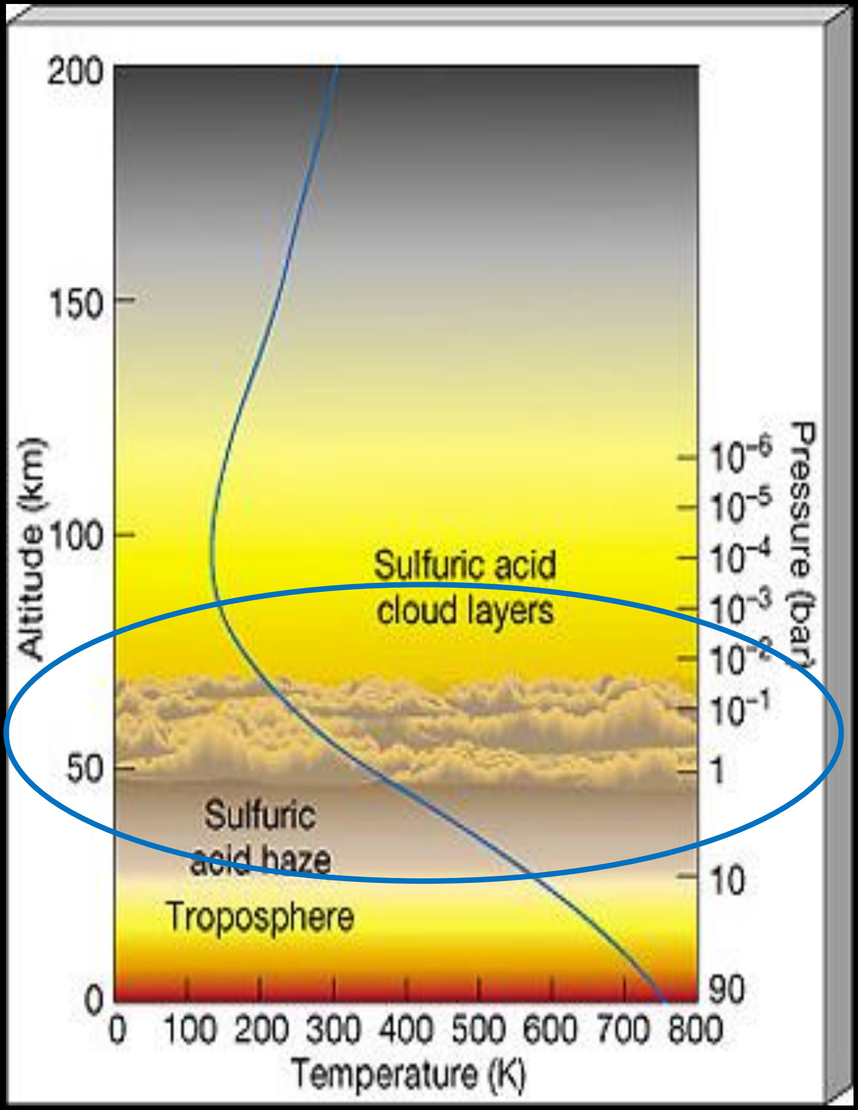


Altitude (km)
Temperature (K)
Pressure (bar)
Sulfuric acid
cloud layers
Sulfuric
acid haze
Troposphere



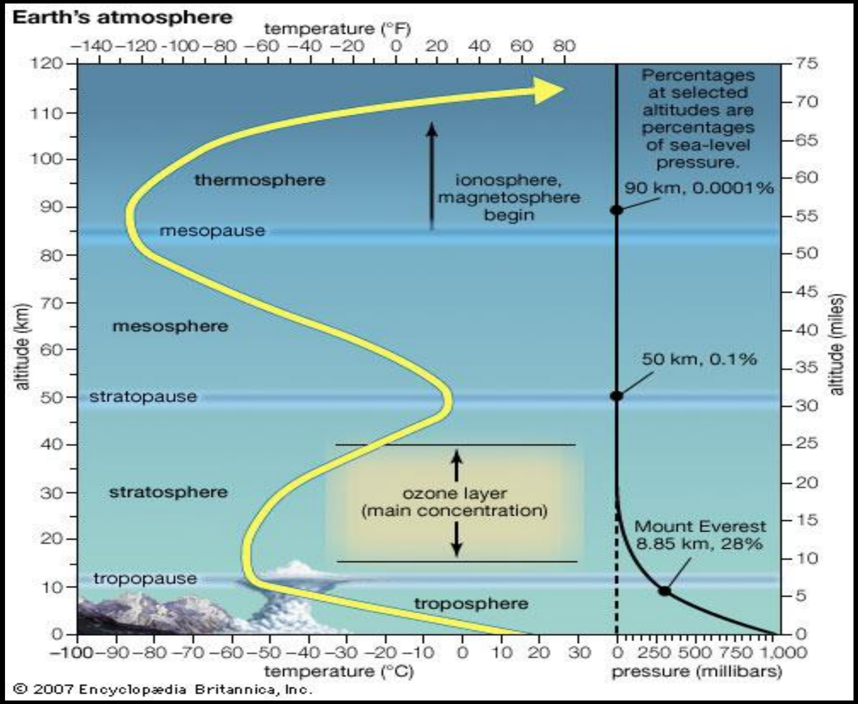
Earth's atmosphere
temperature (°F)
thermosphere
ionosphere, magnetosphere begin
mesopause
mesosphere
stratopause
stratosphere
ozone layer (main concentration)
tropopause
troposphere
Percentages at selected altitudes are percentages of sea-level pressure.
90 km, 0.0001%
50 km, 0.1%
Mount Everest 8.85 km, 28%
altitude (km)
altitude (miles)
temperature (°C)
pressure (millibars)
© 2007 Encyclopædia Britannica, Inc.

Venus



200
150
100
50
0
Altitude (km)
Sulfuric acid
cloud layers
Sulfuric
acid haze
Troposphere
0 100 200 300 400 500 600 700 800
Temperature (K)
Pressure (bar)
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
1
10
90

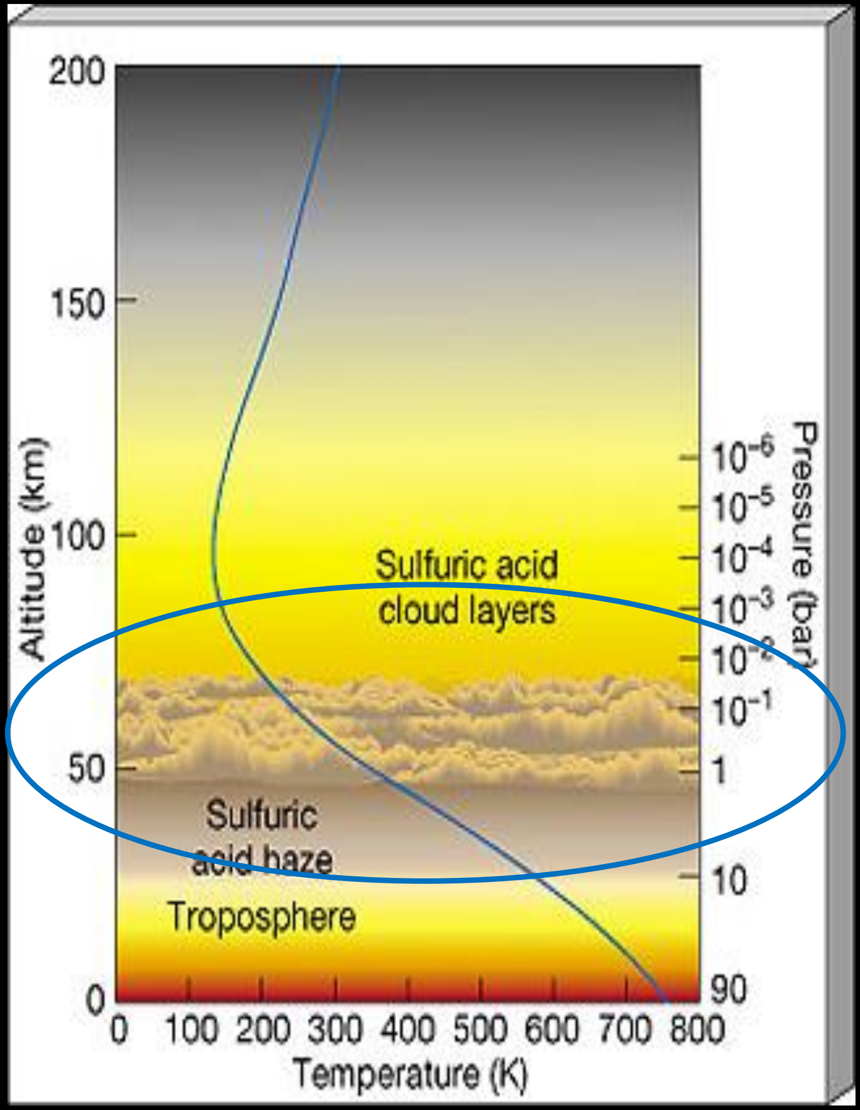
Earth



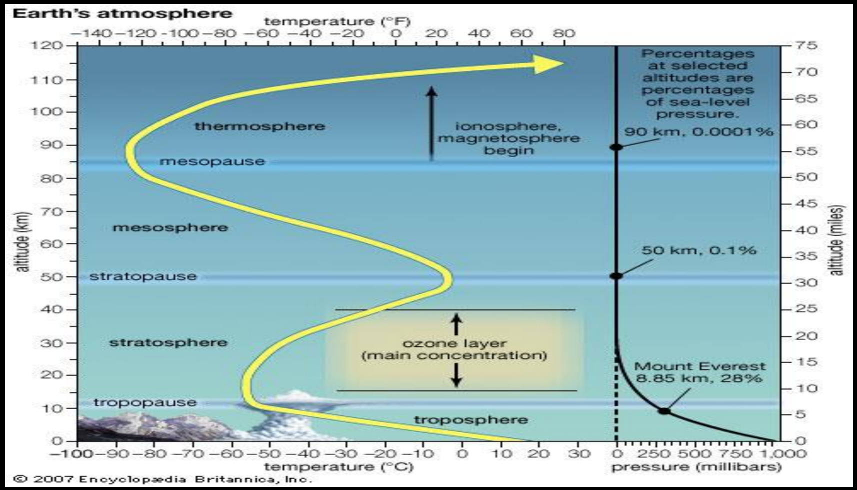
Earth's atmosphere
temperature (°F)
−140 −120 -100 −80 −60 −40 −20 0 20 40 60 80
thermosphere
ionosphere, magnetosphere begin
Percentages at selected altitudes are percentages of sea-level pressure.
90 km, 0.0001%
mesopause
mesosphere
50 km, 0.1%
stratopause
stratosphere
ozone layer (main concentration)
Mount Everest 8.85 km, 28%
tropopause
troposphere
altitude (km)
altitude (miles)
−100 −90 −80 −70 −60 −50 −40 −30 −20 −10 0 10 20 30
temperature (°C)
0 250 500 750 1,000
pressure (millibars)
© 2007 Encyclopædia Britannica, Inc.

Venus

Earth

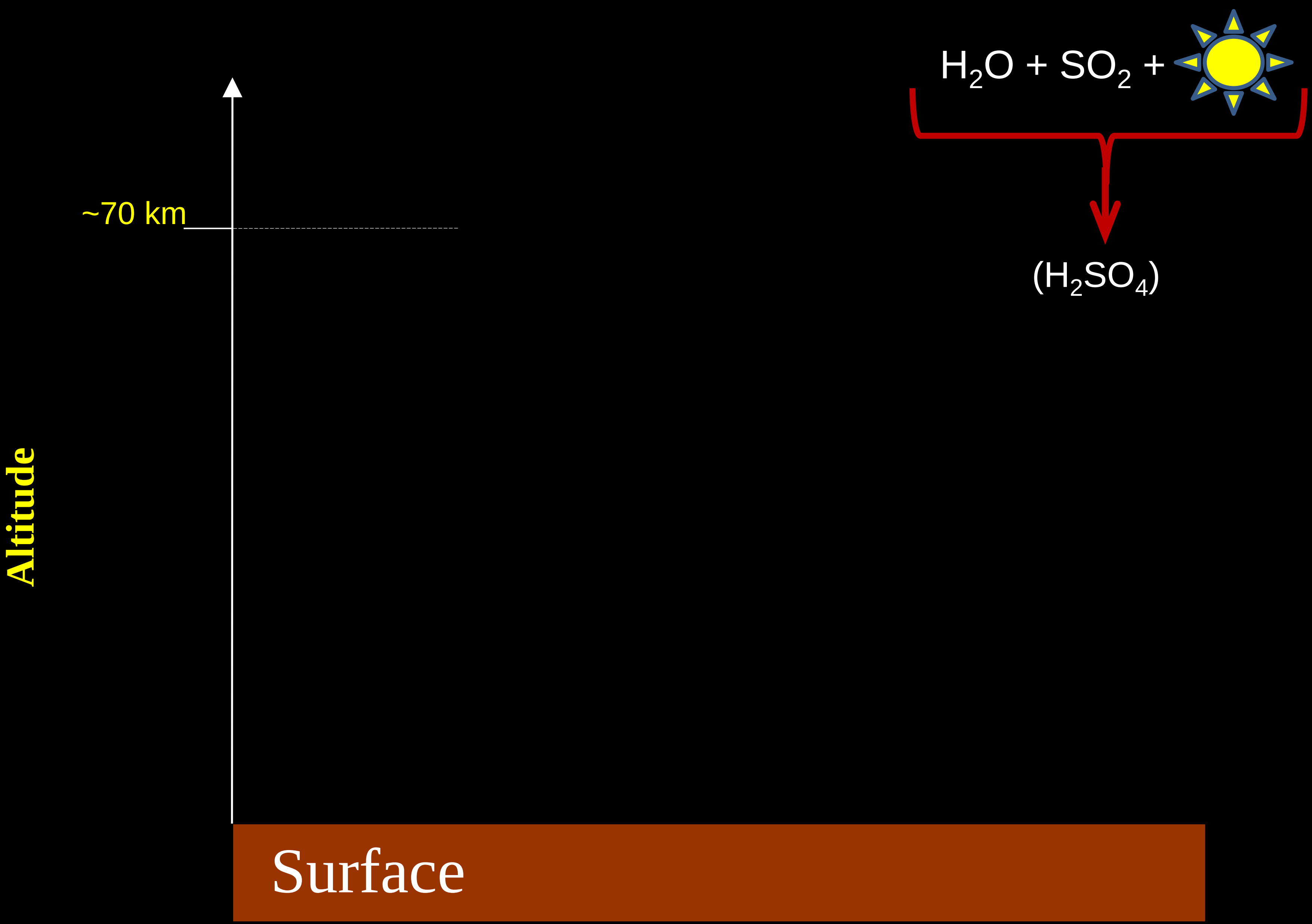


Altitude (km)
200
150
100
50
0
Sulfuric acid cloud layers
Sulfuric acid haze
Troposphere
Pressure (bar)
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
90
0 100 200 300 400 500 600 700 800
Temperature (K)

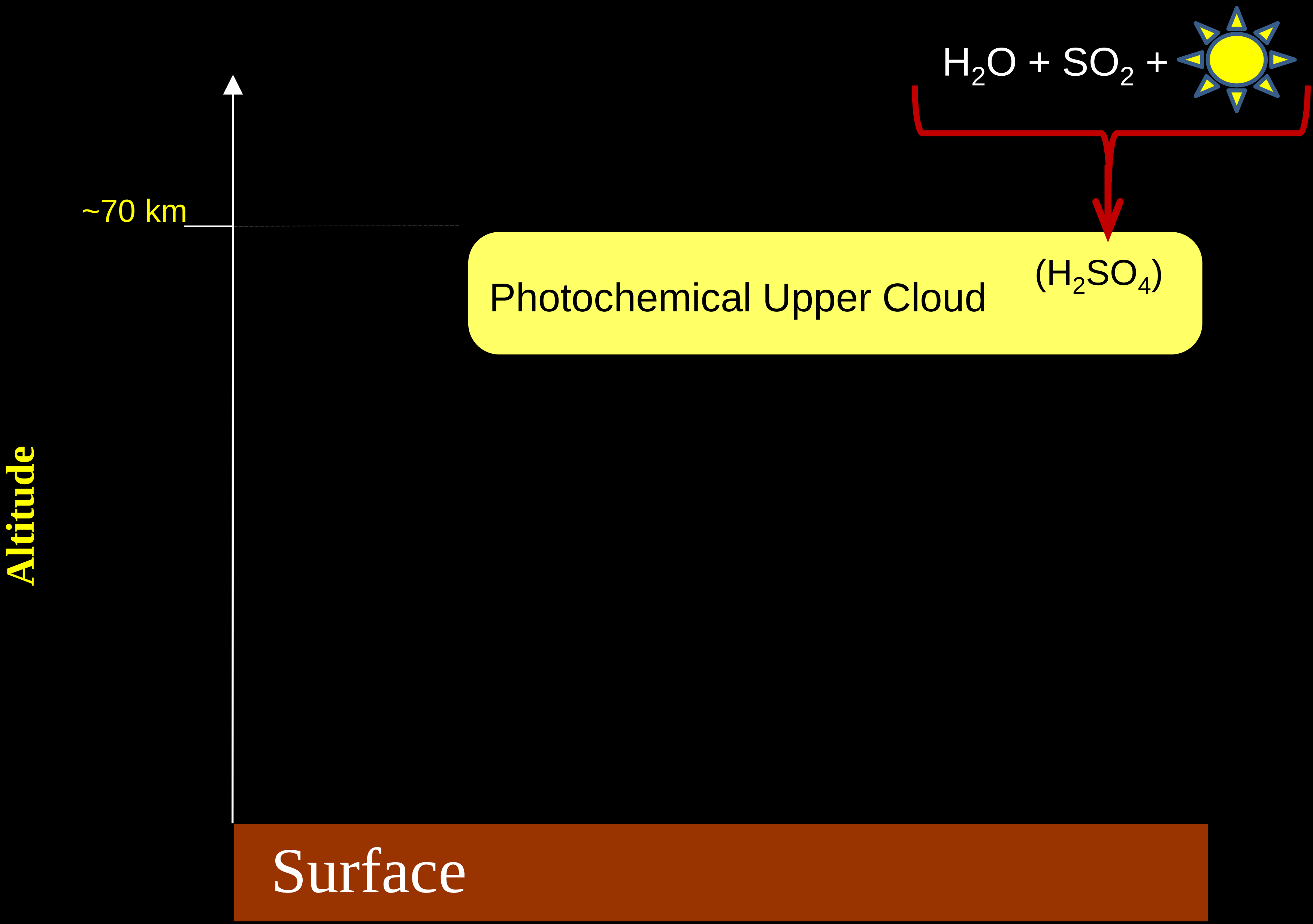


Earth's atmosphere
temperature (°F)
−140 −120 -100 −80 −60 −40 −20 0 20 40 60 80
altitude (km)
120 110 100 90 80 70 60 50 40 30 20 10 0
thermosphere
mesopause
mesosphere
stratopause
stratosphere
tropopause
troposphere
ionosphere, magnetosphere begin
ozone layer (main concentration)
Percentages at selected altitudes are percentages of sea-level pressure.
90 km, 0.0001%
50 km, 0.1%
Mount Everest 8.85 km, 28%
altitude (miles)
75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0
−100 −90 −80 −70 −60 −50 −40 −30 −20 −10 0 10 20 30
temperature (°C)
0 250 500 750 1,000
pressure (millibars)
© 2007 Encyclopædia Britannica, Inc.

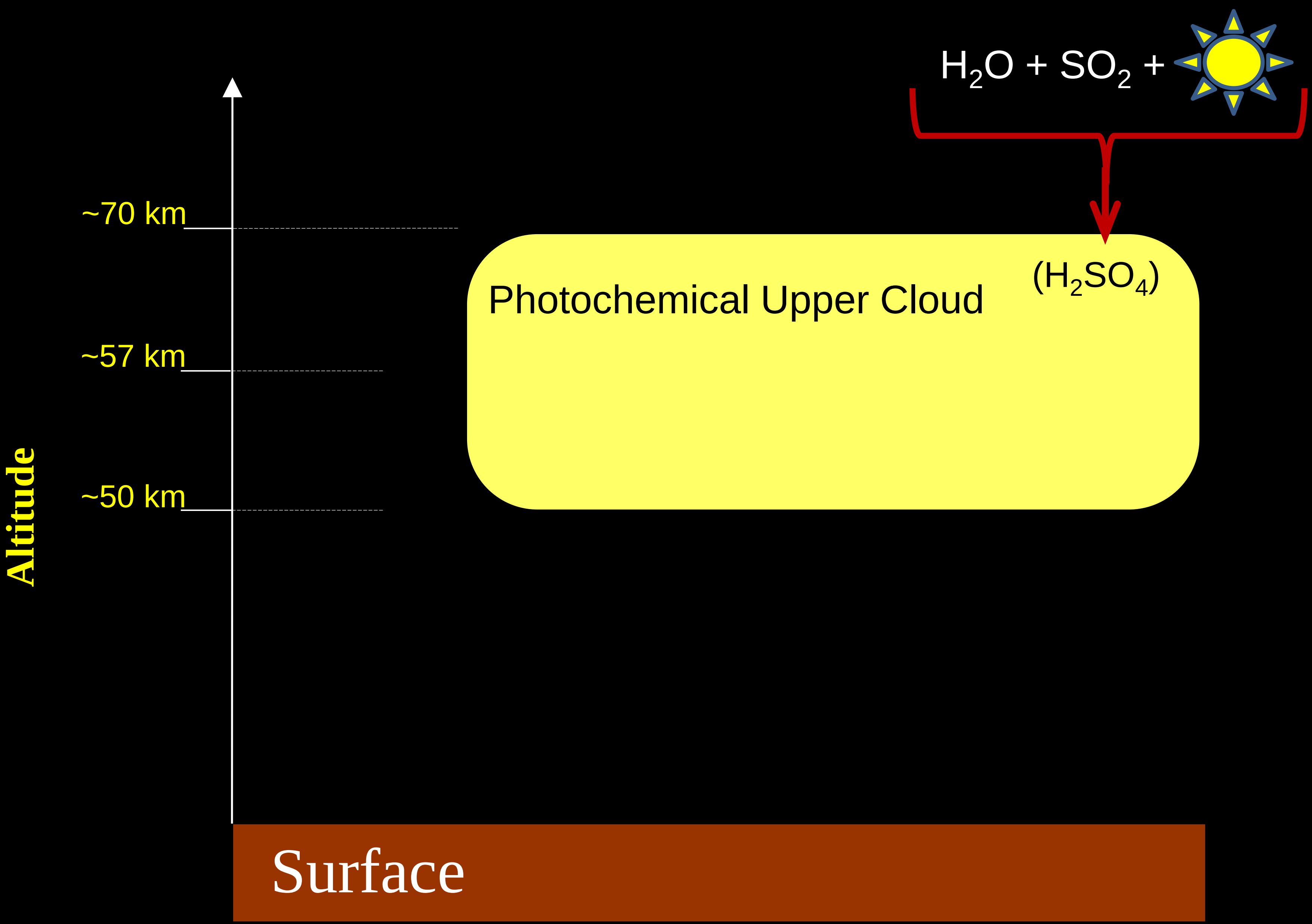
The Venusian Cloud Decks



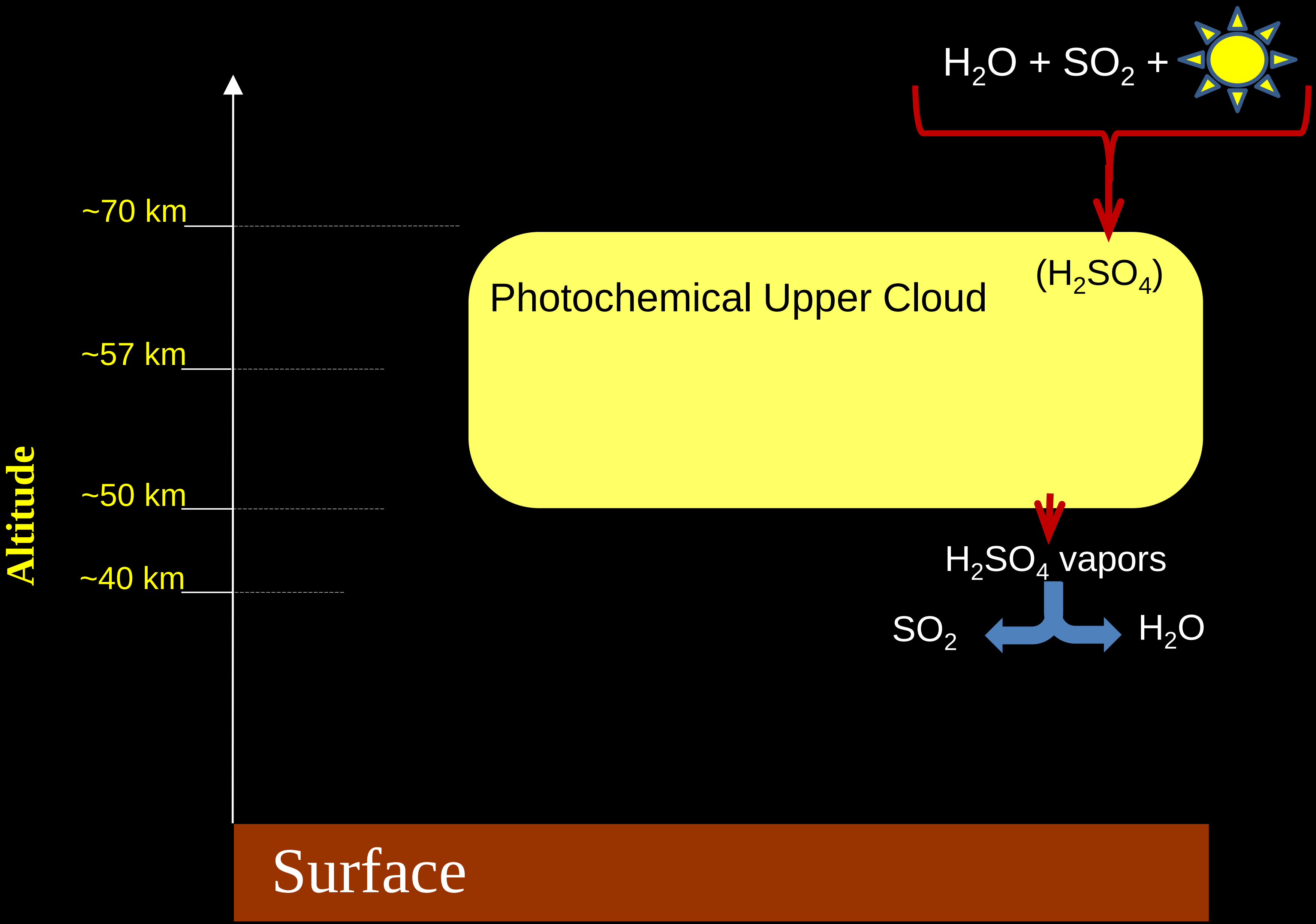
The Venusian Cloud Decks



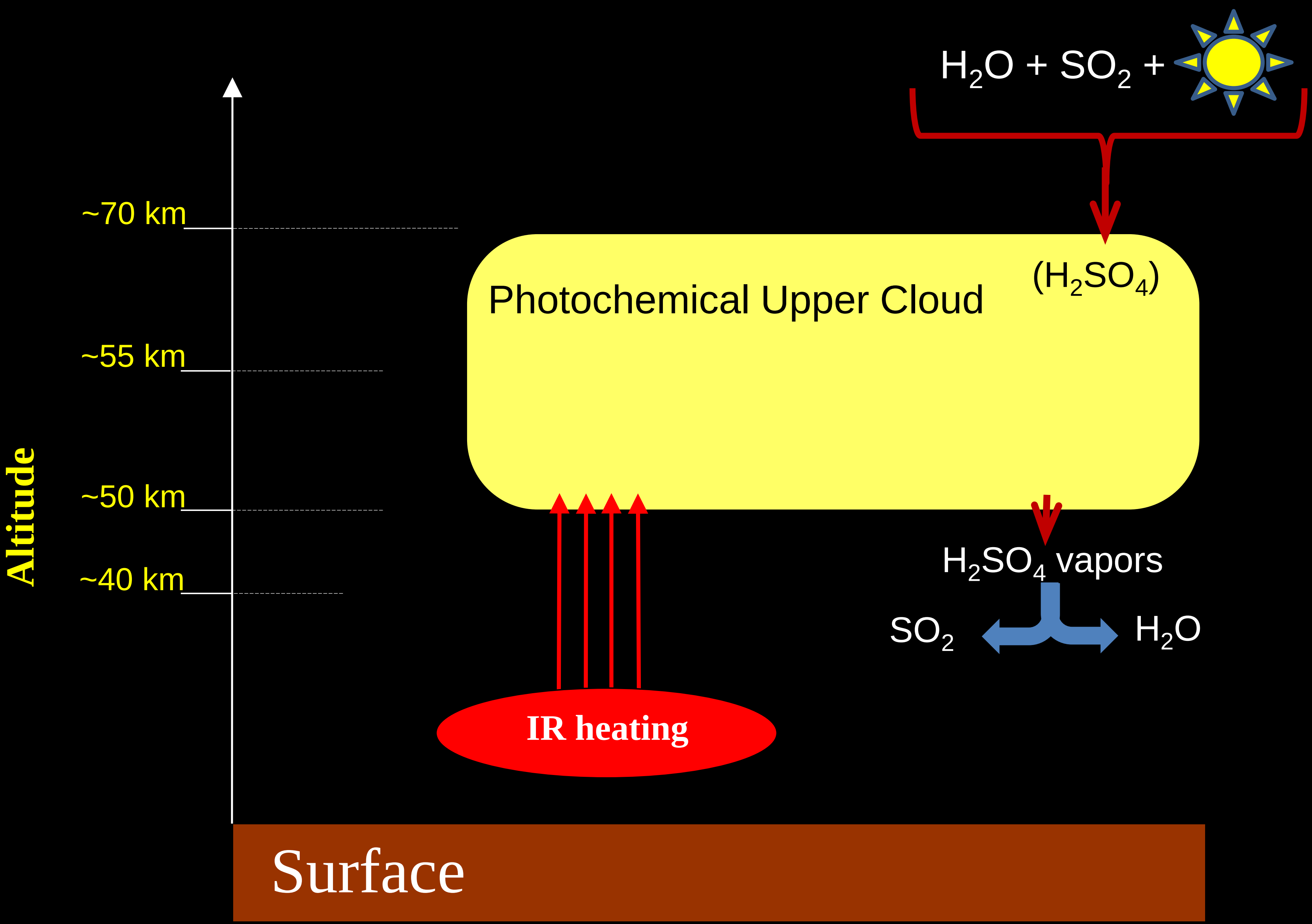
The Venusian Cloud Decks



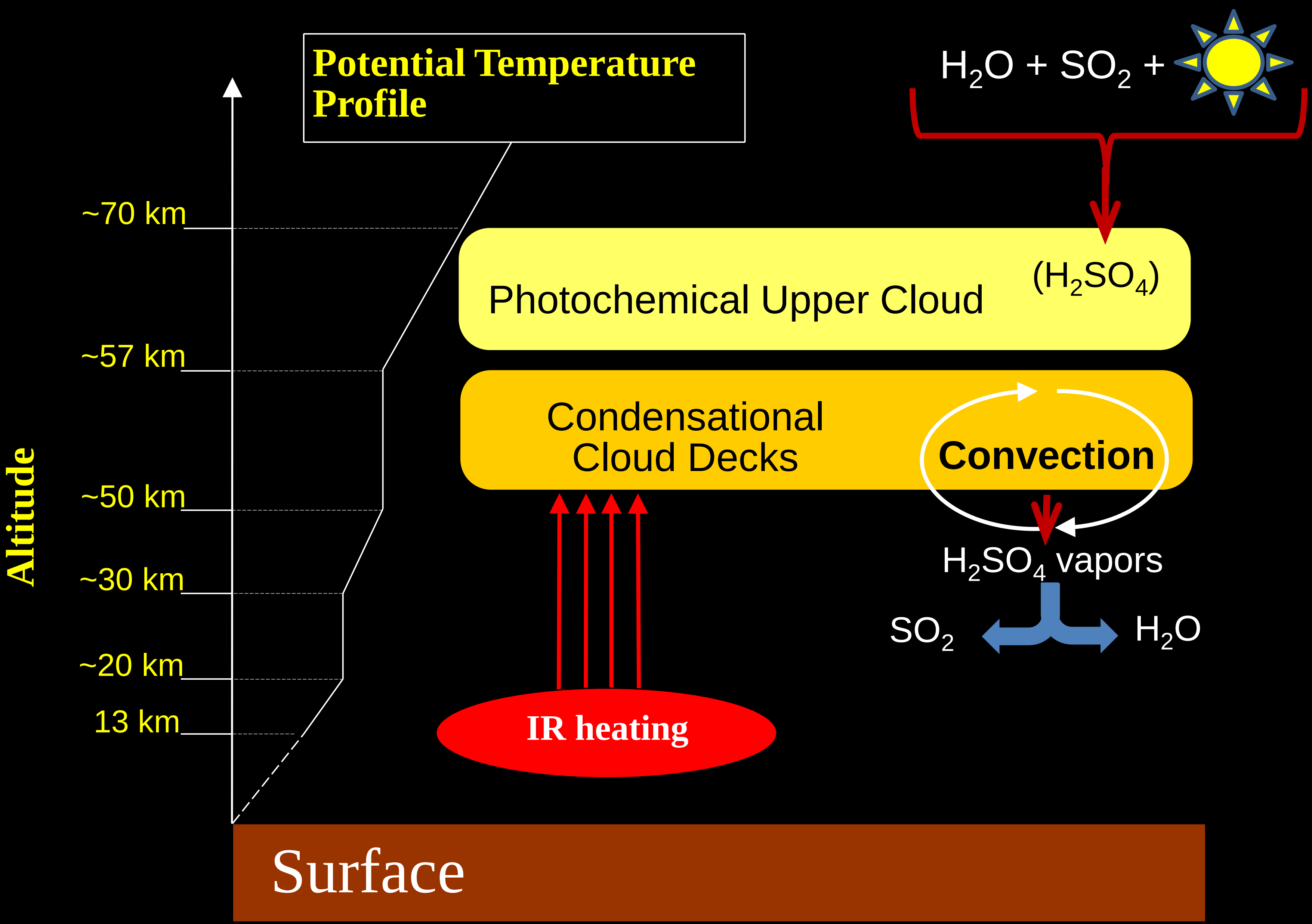
The Venusian Cloud Decks



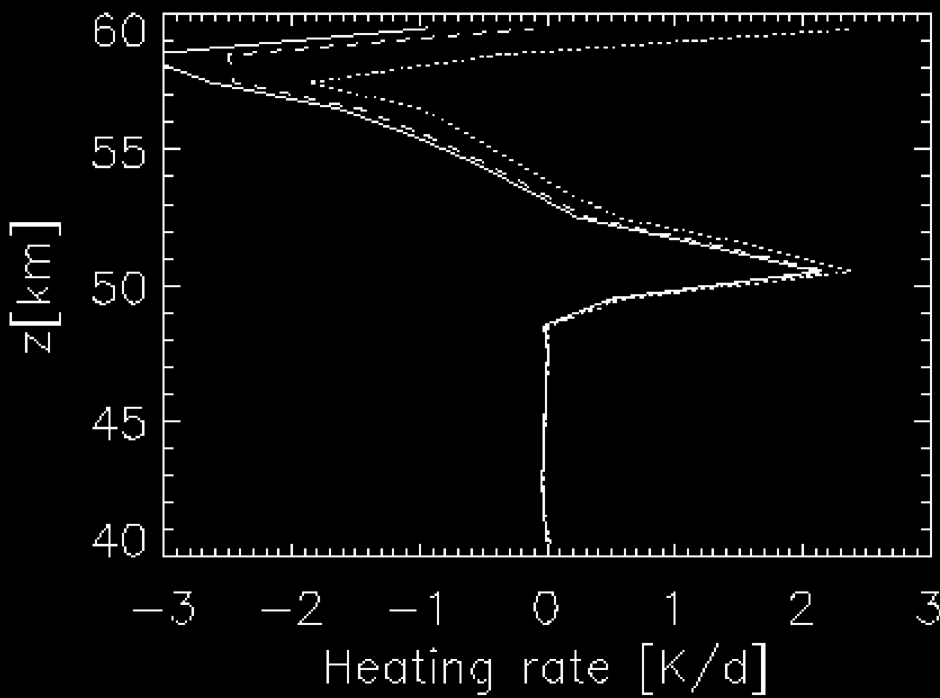
The Venusian Cloud Decks

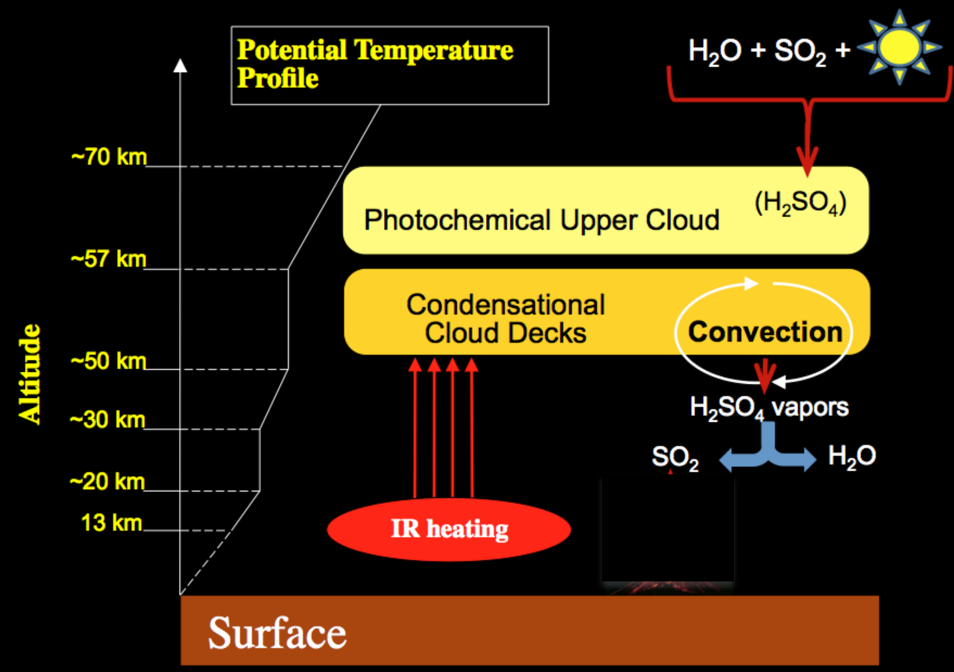


The Venusian Cloud Decks



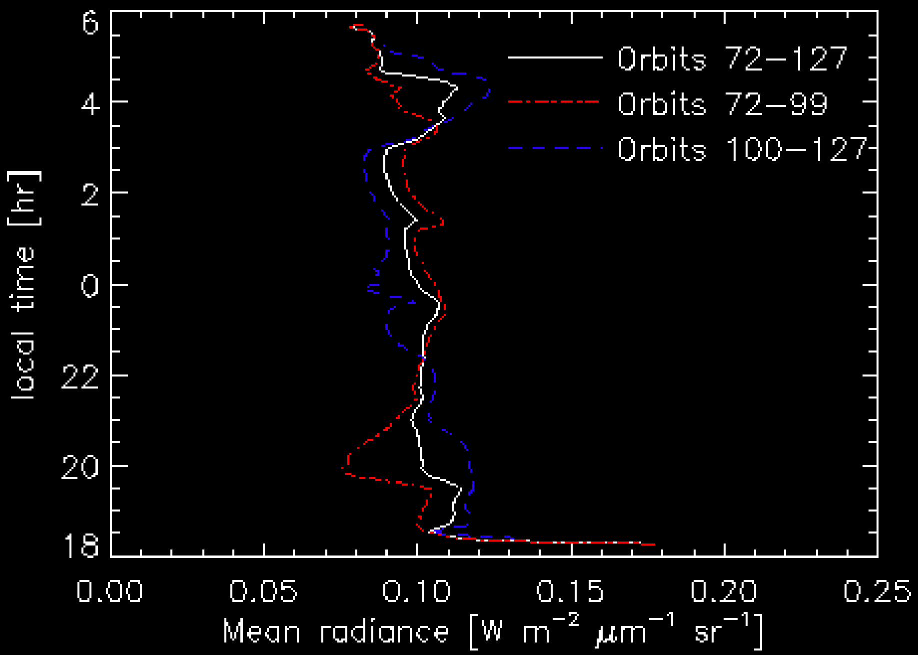
Radiative Heating rates in the Venus condensational clouds



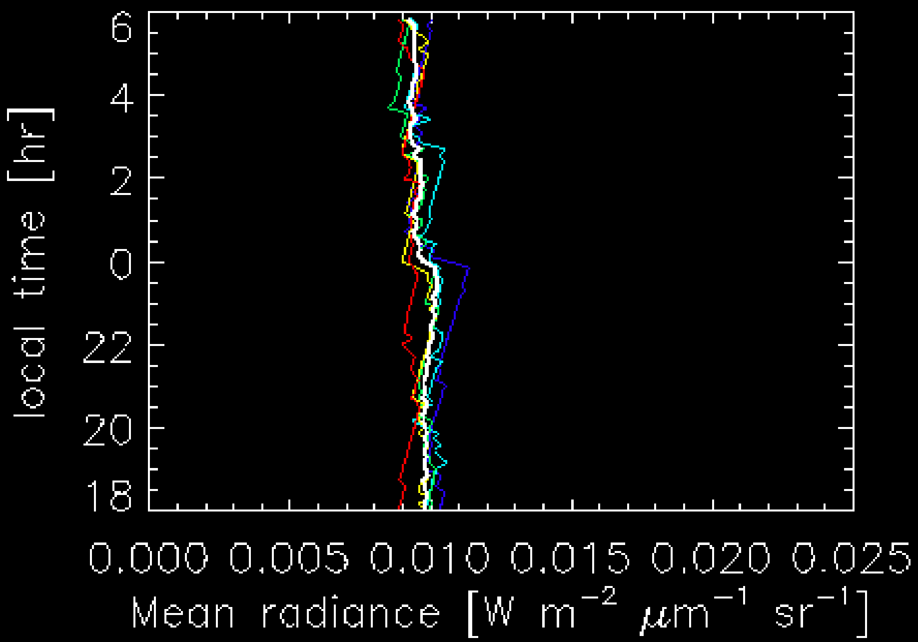


Radiance Variation versus Solar Time

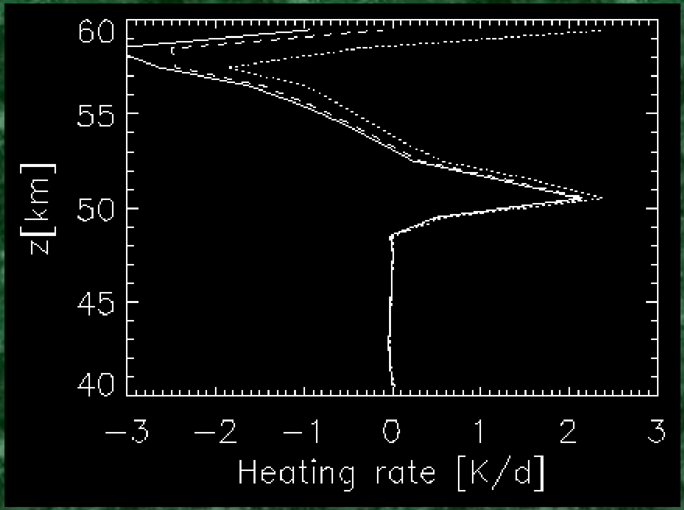
Observation (VIRTIS)

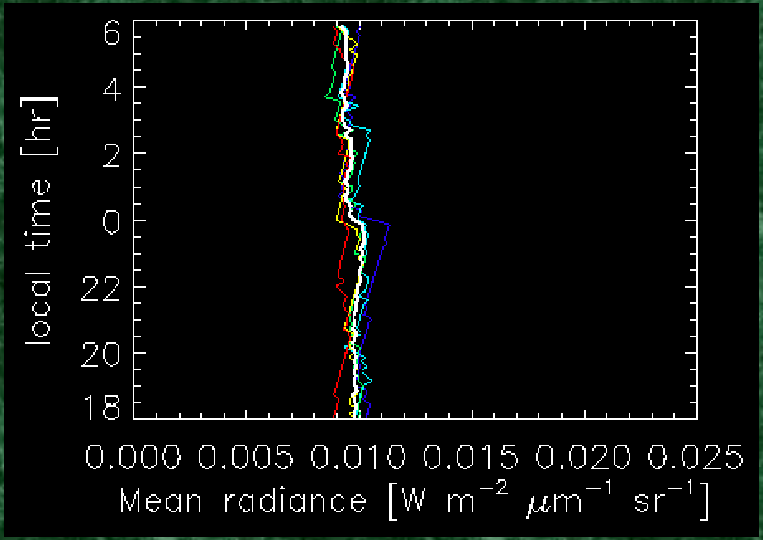


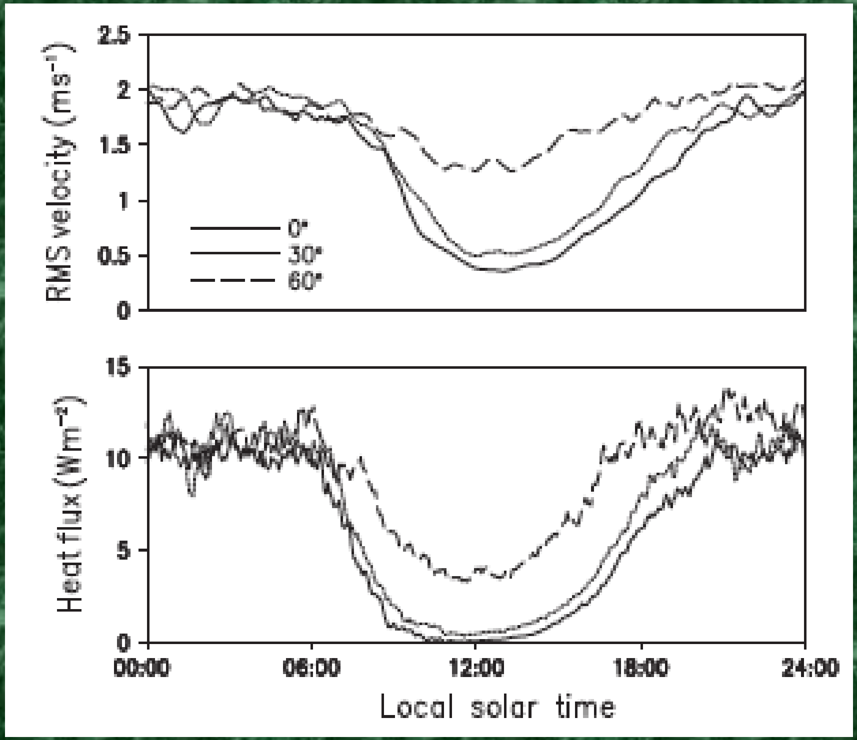
Simulation (CARMA)



Mixing Variation versus Solar Time

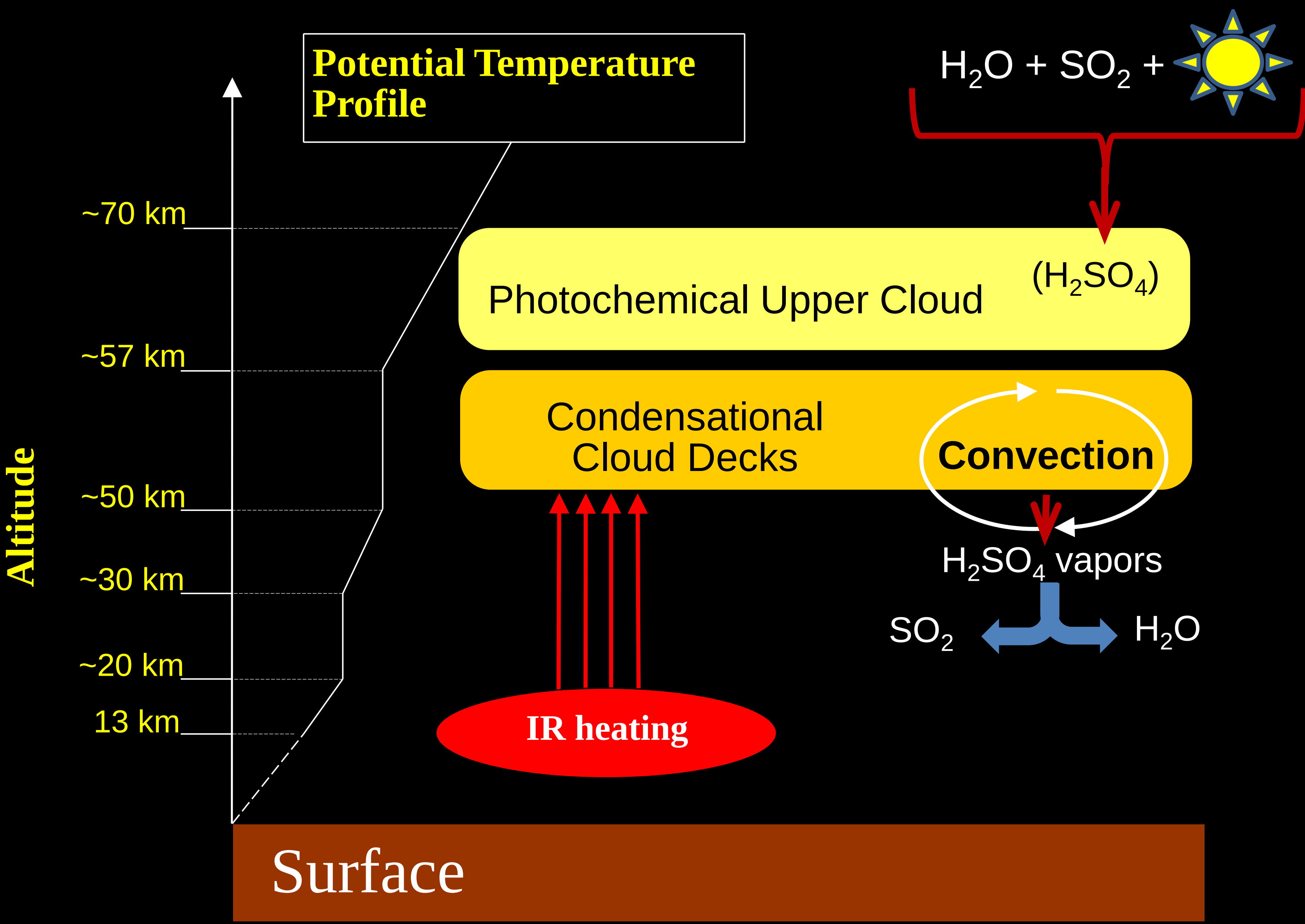




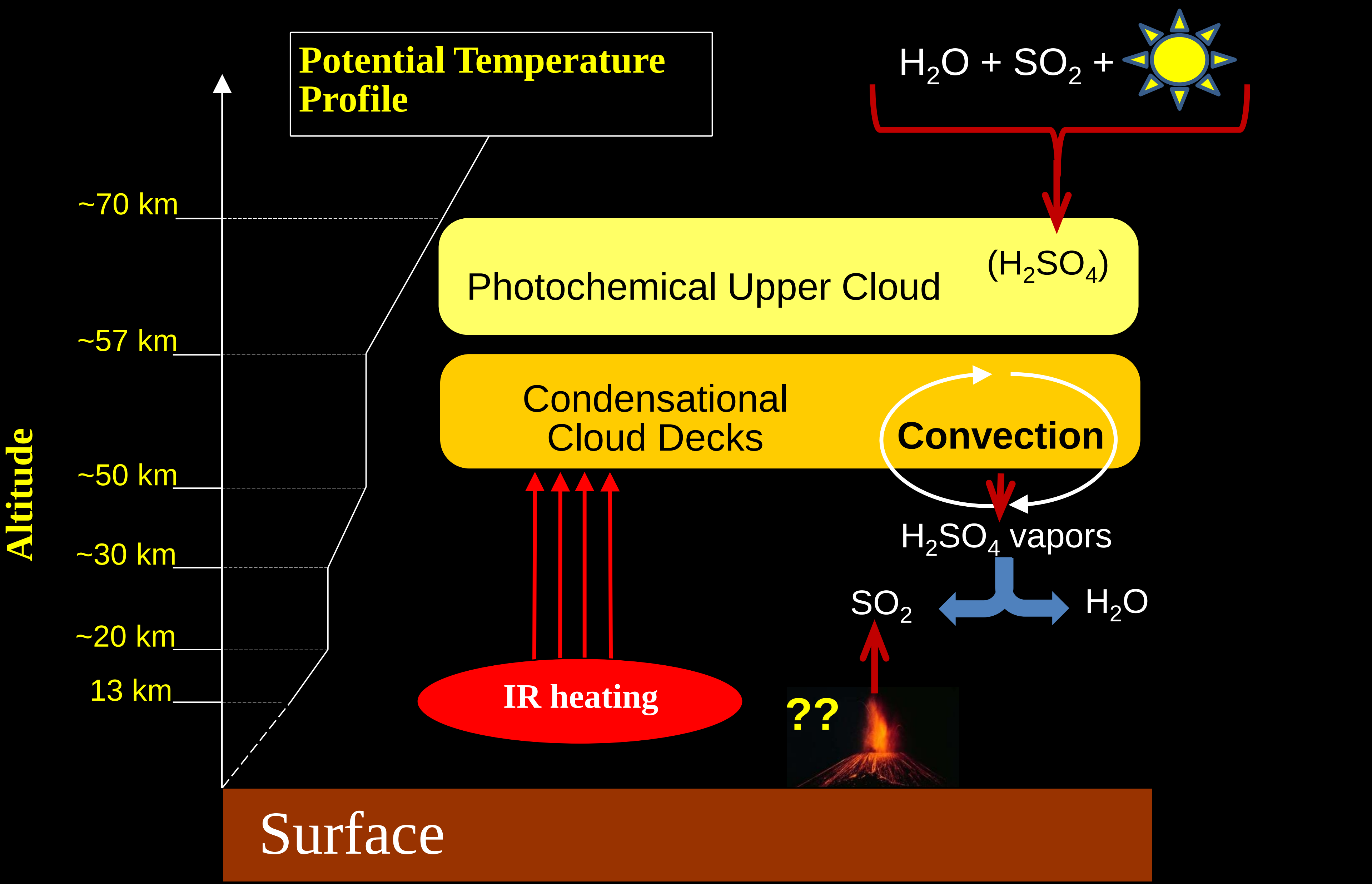


Imamura et al 2014 Icarus. 228:181.

The Venusian Cloud Decks



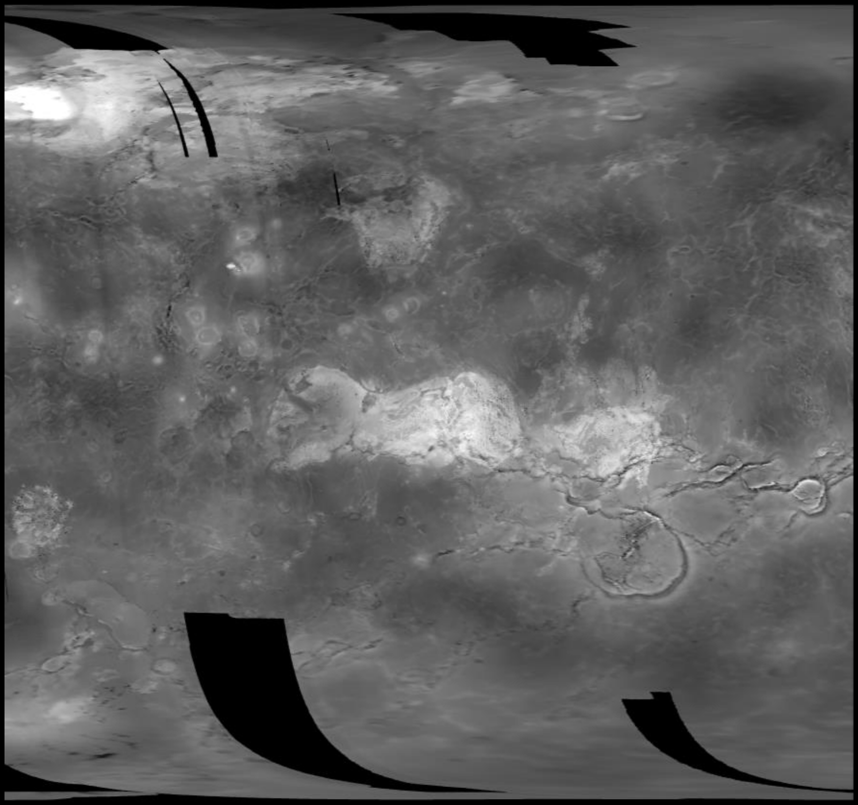
The Venusian Cloud Decks



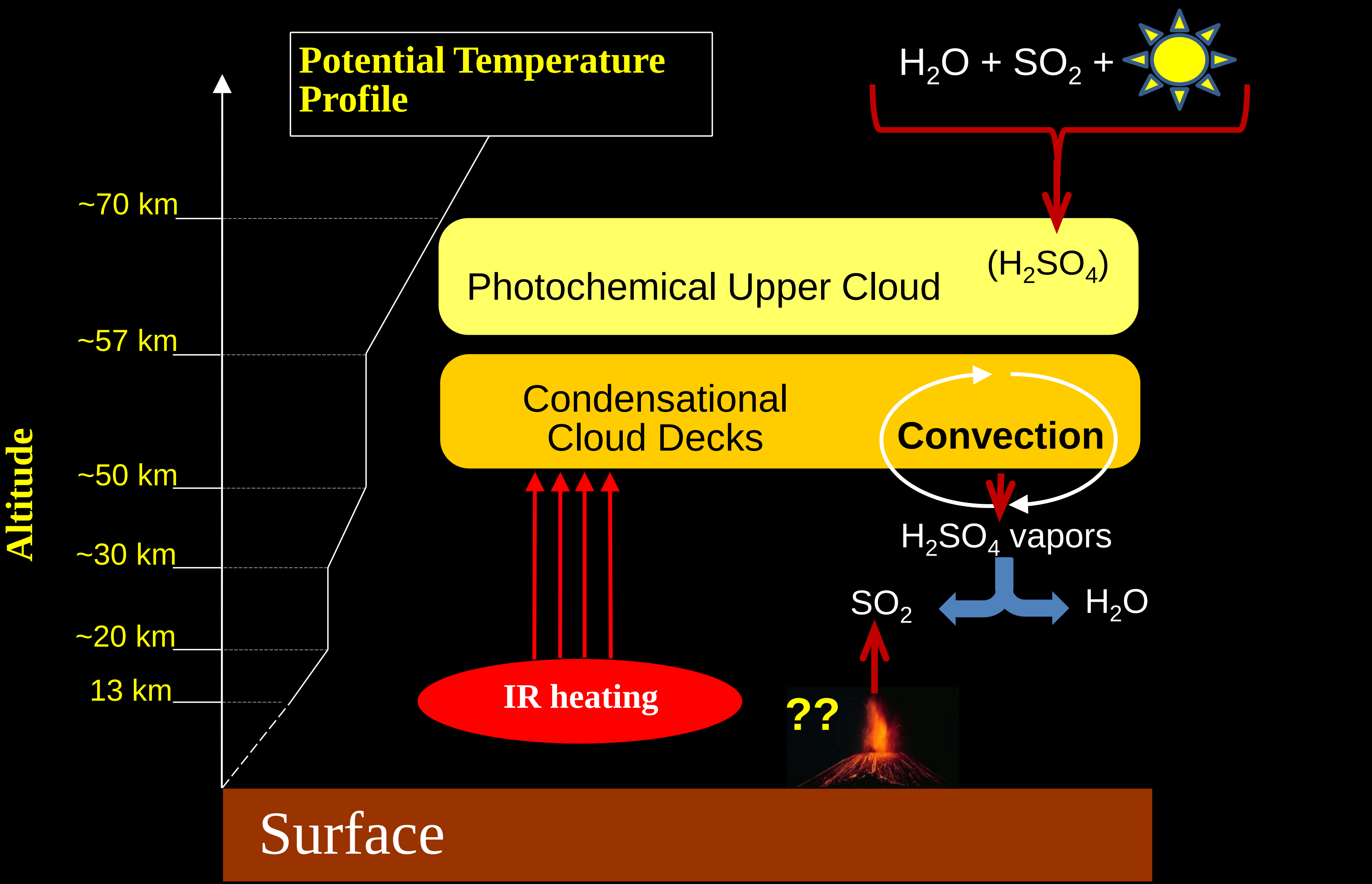
Magellan topography and radar emissivity

Radar Emissivity

Surface Topography



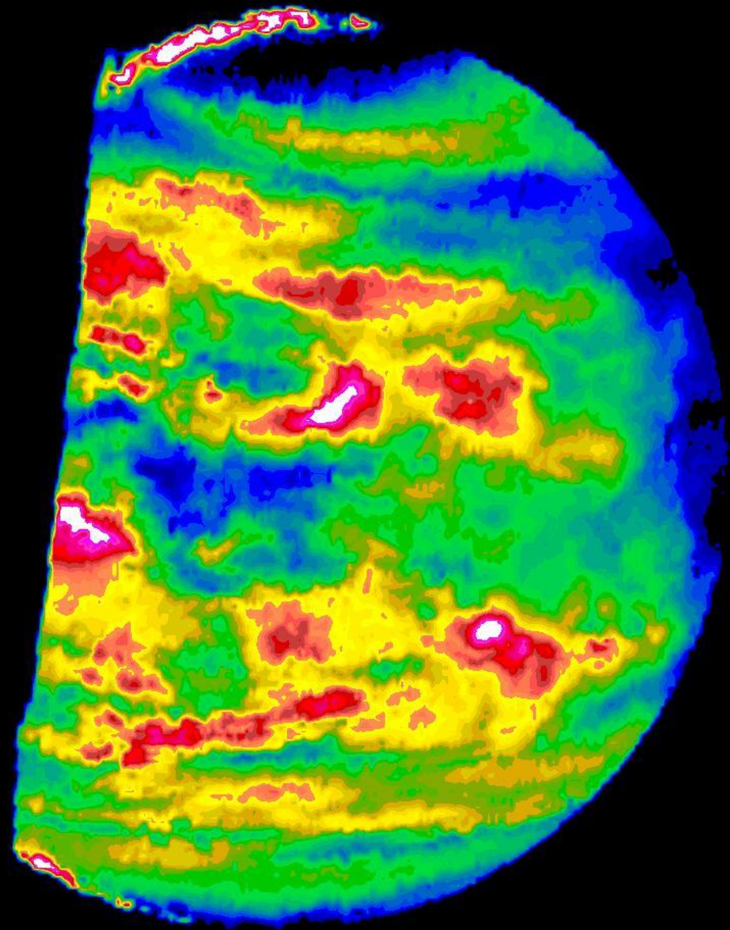
The Venusian Cloud Decks



Venus in Visible wavelengths

NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington (MESSENGER spacecraft)

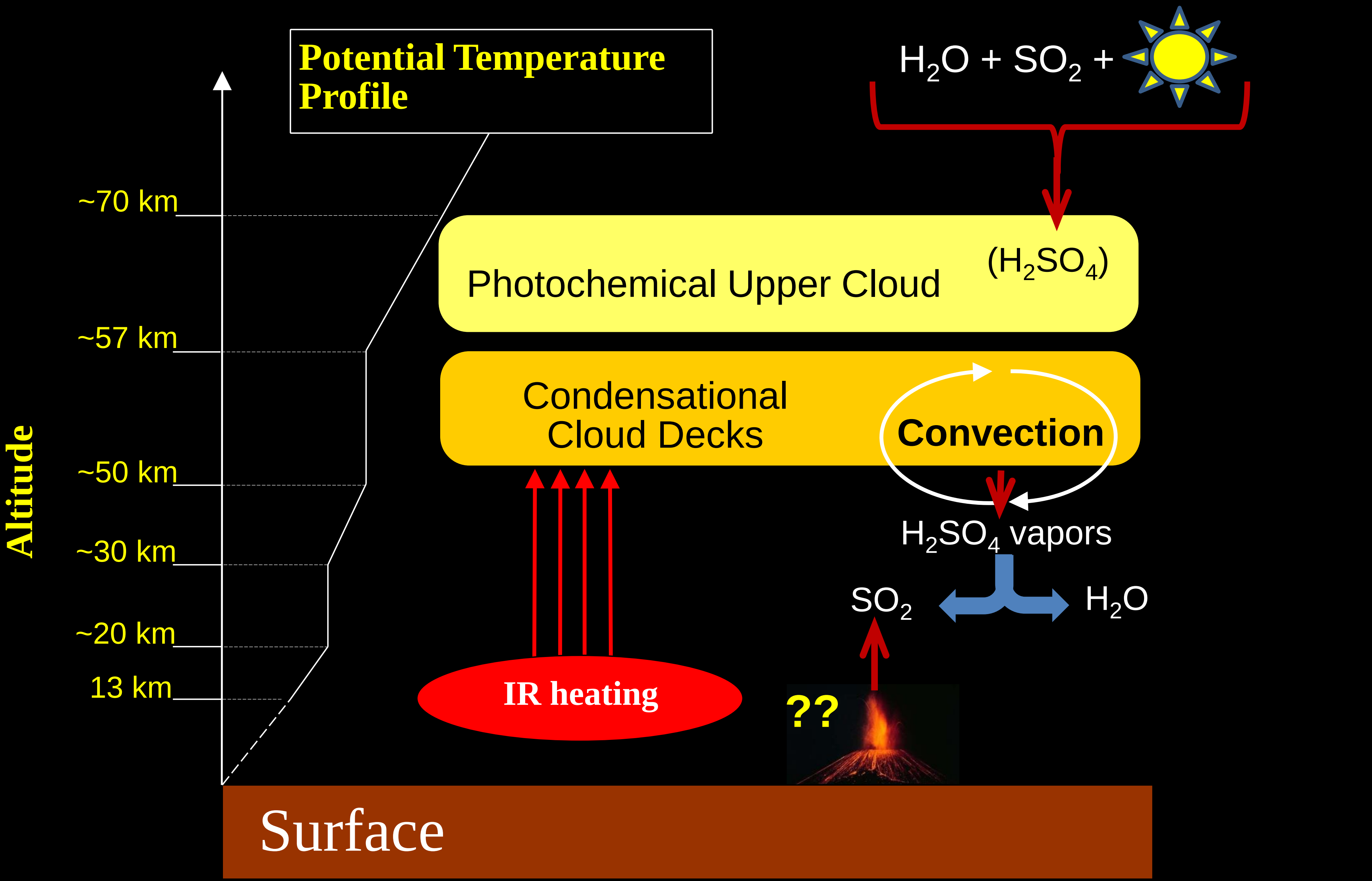
Venus in Visible wavelengths



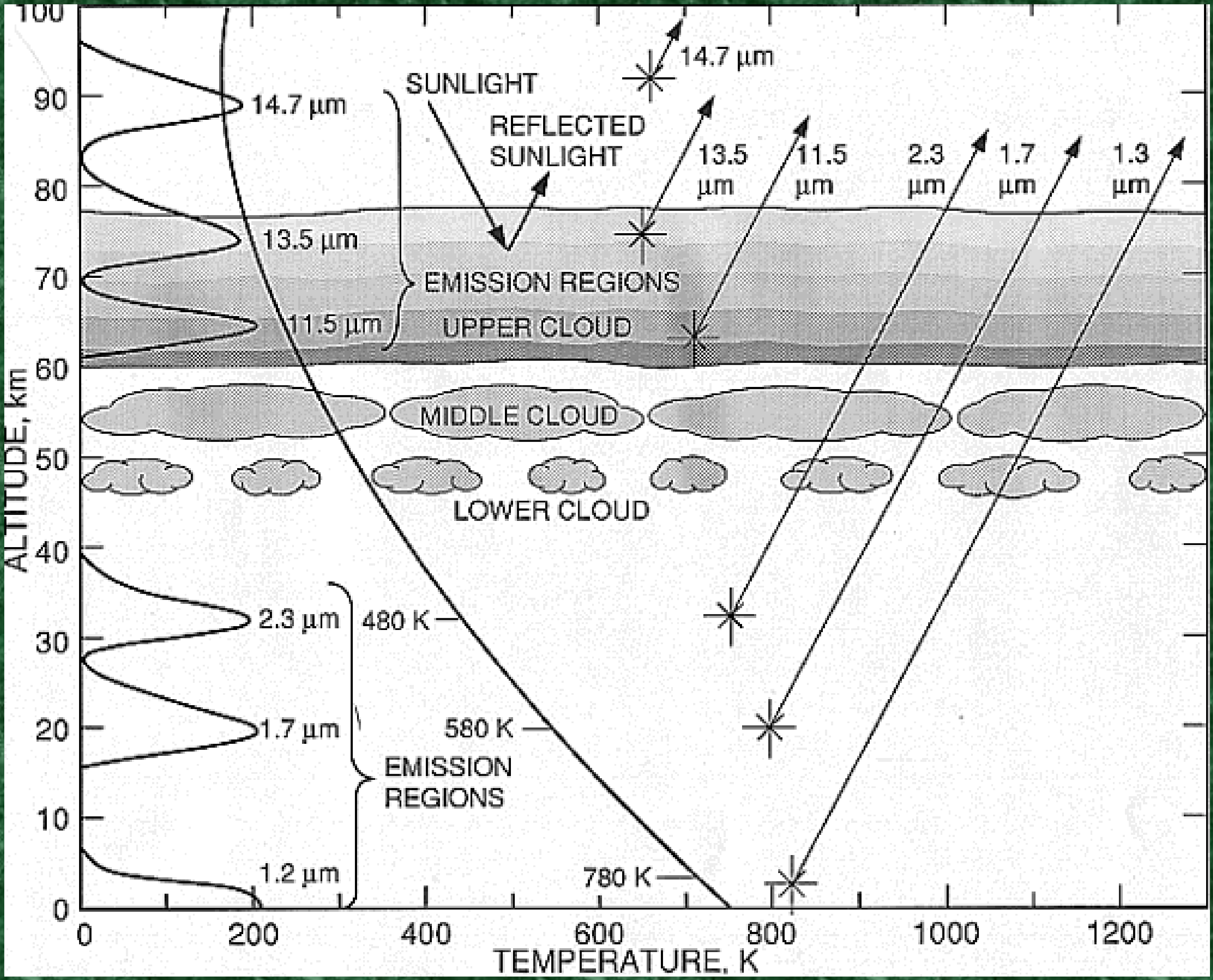
NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington (MESSENGER spacecraft)

Image Courtesy NASA

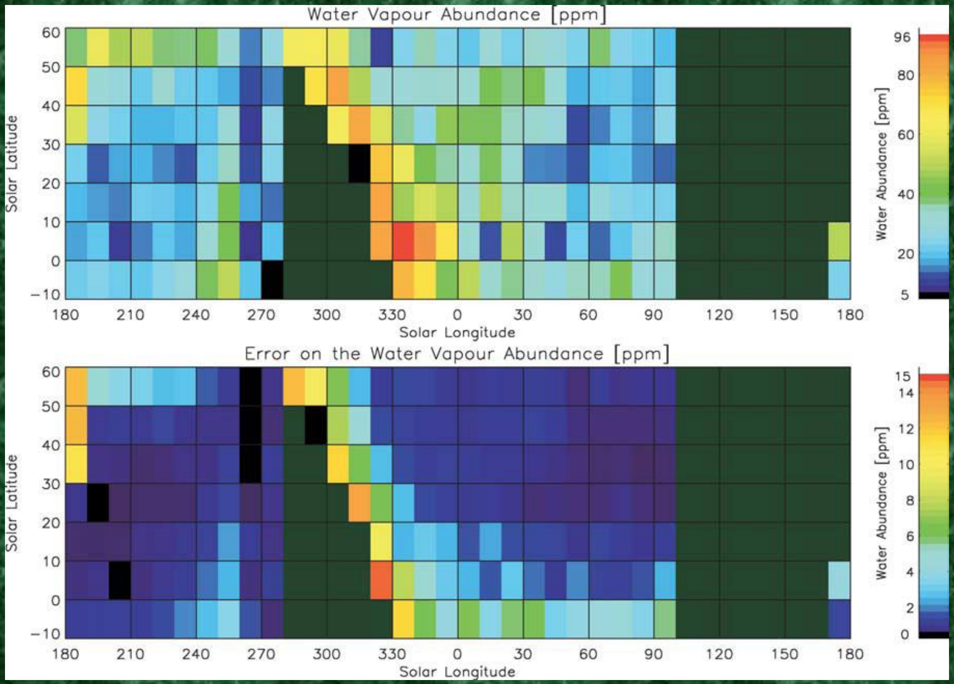
The Venusian Cloud Decks



Venus lower atmosphere spectral windows



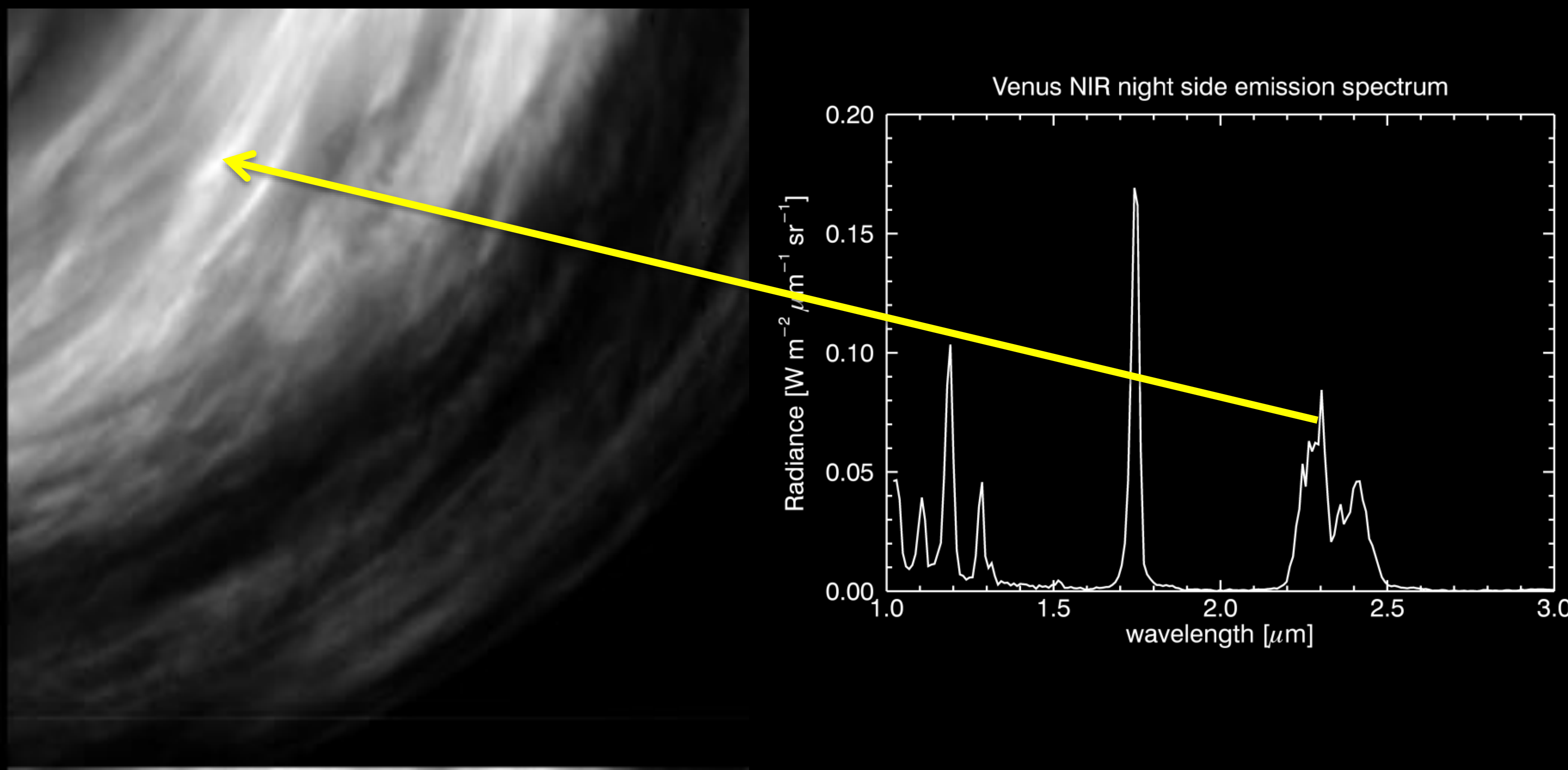
Upper atmosphere Water Vapour Variations from Pioneer Venus OIR



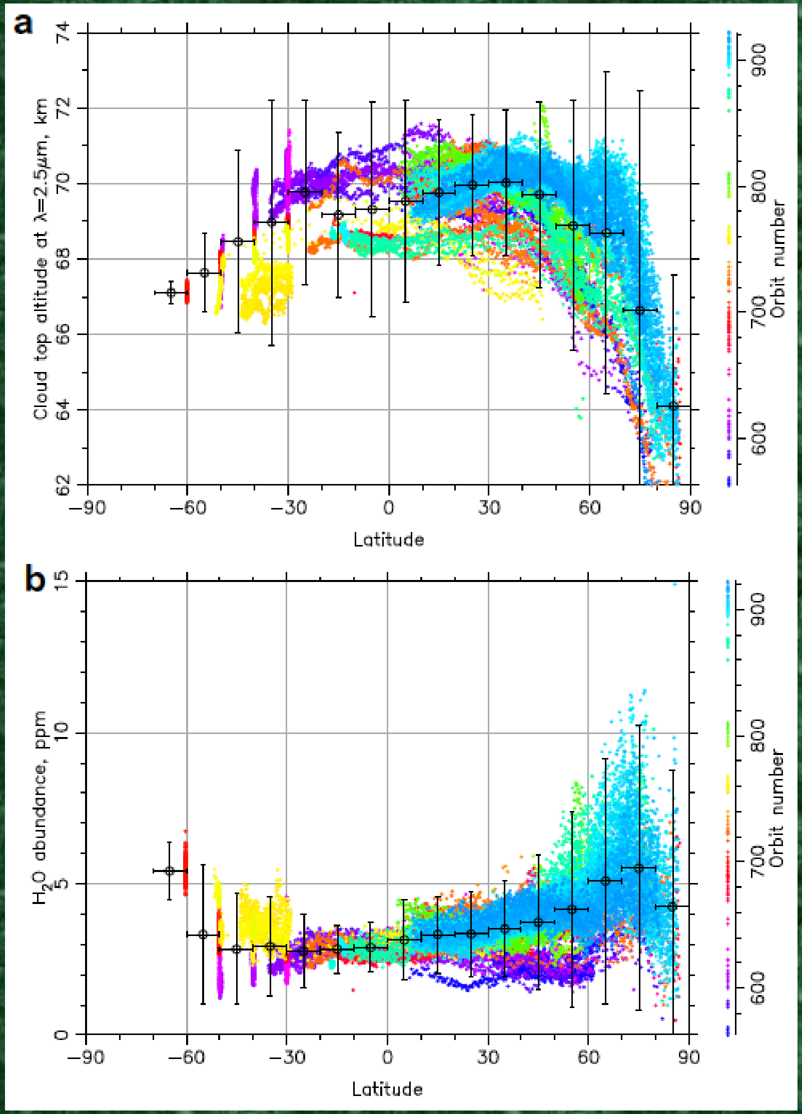
- Retrieved water vapour concentrations varying between 5ppmv and 100ppmv above the cloud tops.
- Local maximum seen just after local noon.

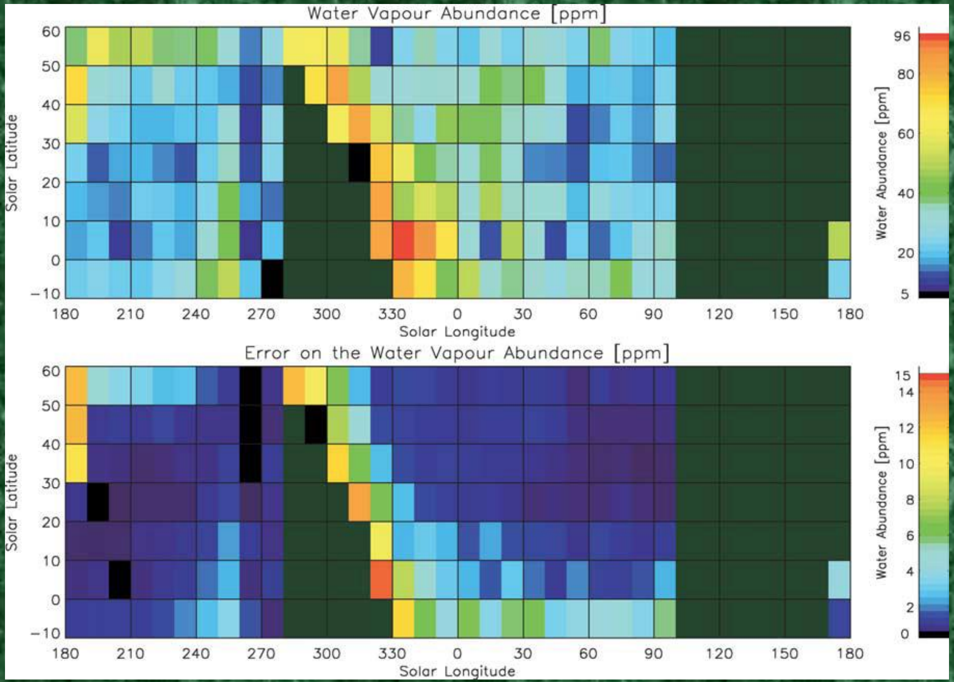
Koukouli et al. 2005. Icarus 173:84.

2.20-2.60 micron spectral window



Upper atmosphere Water Vapour Variations from Pioneer Venus OIR





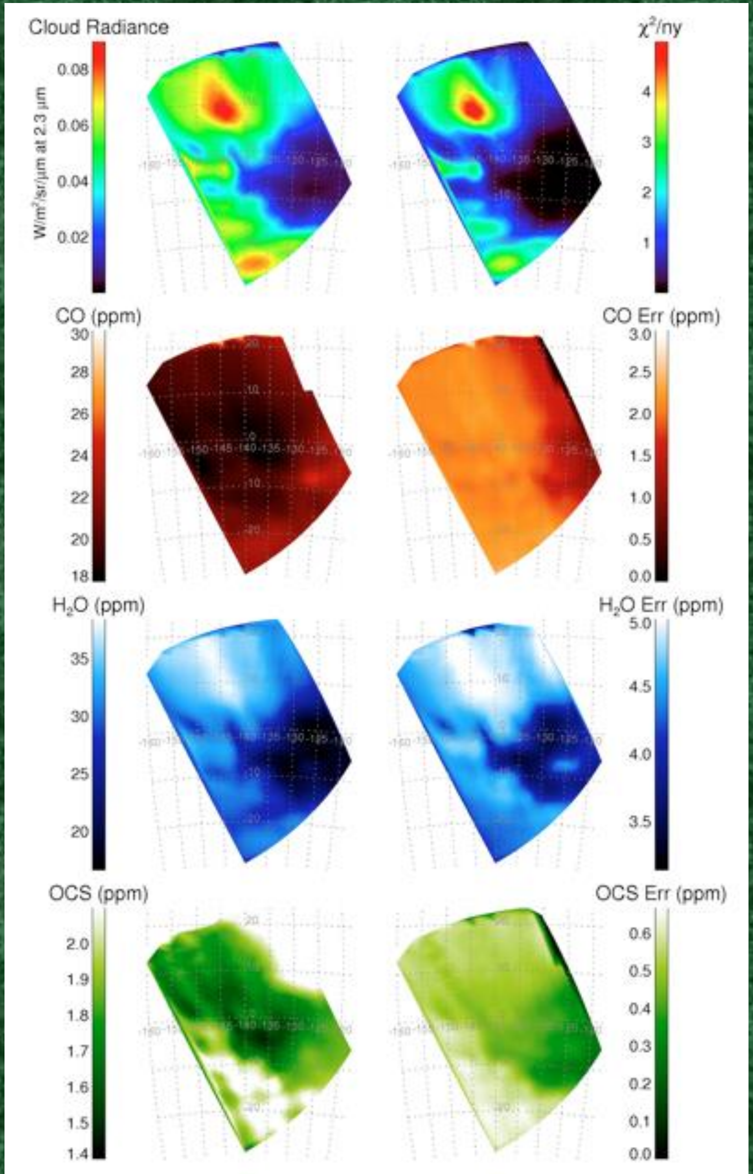
- **PV-OIR (15-45 micron) Inconsistent with VEx-VIRTIS observations (2.48-2.60 micron)**

Cottini et al. 2012 Icarus 217:561.

Koukouli et al. 2005. Icarus 173:84.

Lower atmosphere Water Vapour Variations from VIRTIS-M-IR

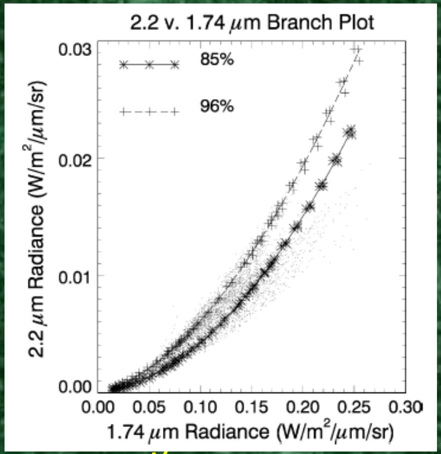
- Retrieved water vapour concentrations varying between 20ppmv and 40ppmv below the clouds.
- Possible correlation with cloud opacity.
- Retrieval likely affected by cloud acidity variations.

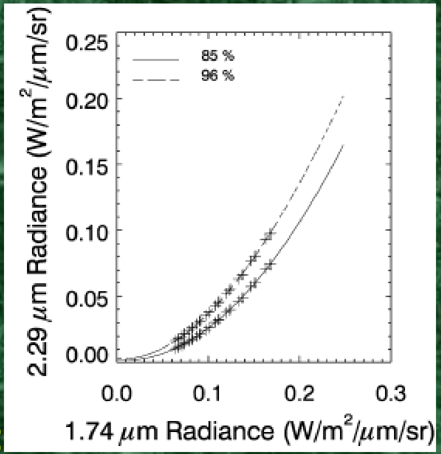


Tsang et al 2010 GRL 37:L02202.
Barstow et al 2012. Icarus 217:542.

Lower atmosphere Water Vapour Variations from VIRTIS-M-IR

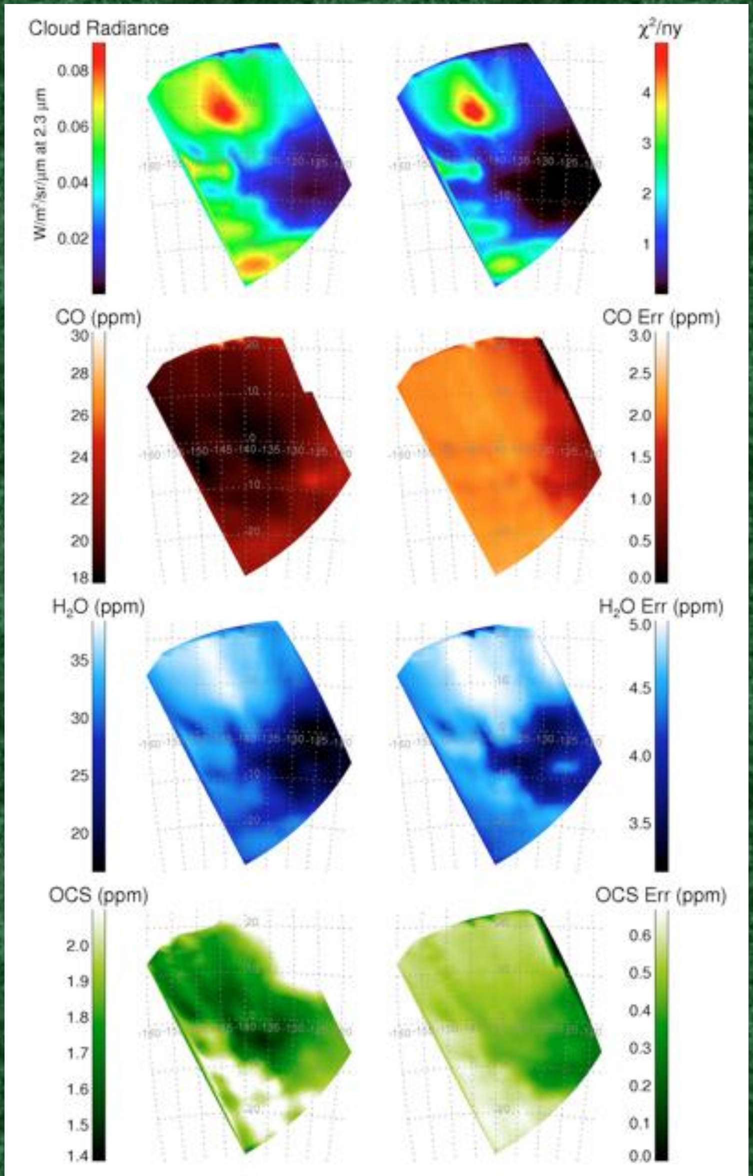
- Retrieved water vapour concentrations varying between 20ppmv and 40ppmv below the clouds.
- Possible correlation with cloud opacity.
- Retrieval likely affected by cloud acidity variations.



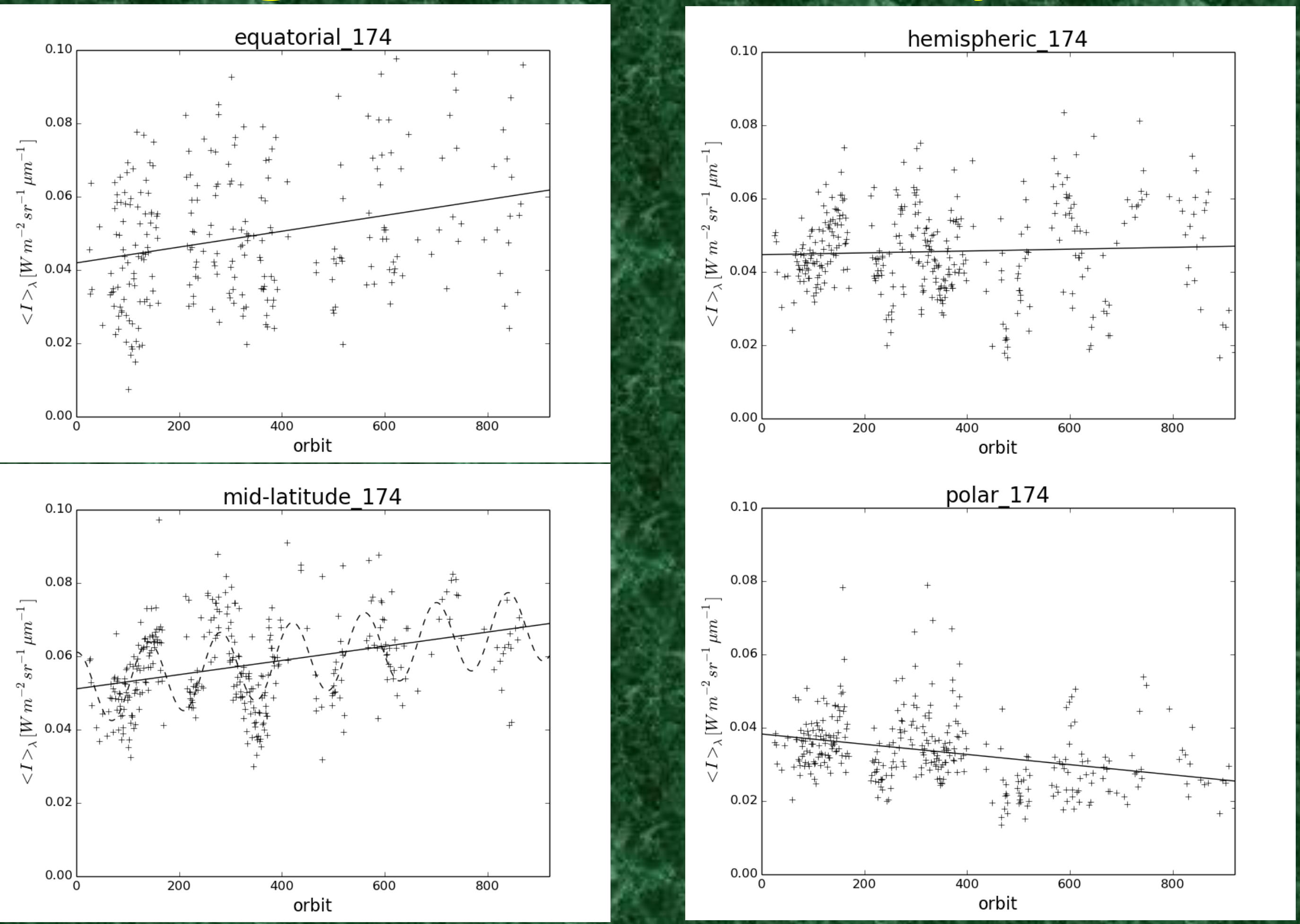


37:

Barstow et al 2012. Icarus 217:542.



Long term variability in Venus clouds

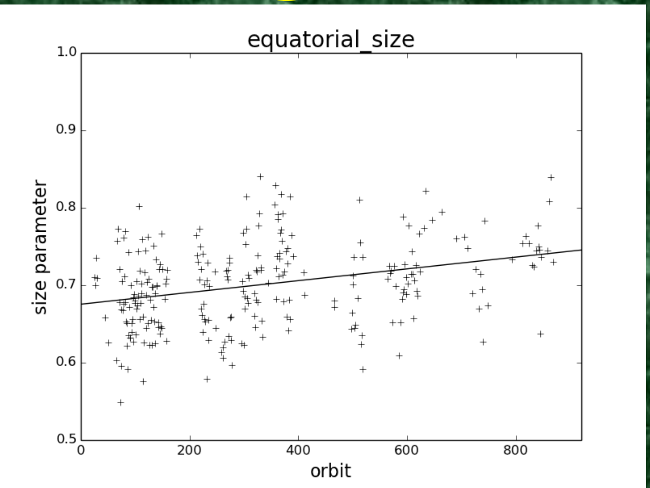


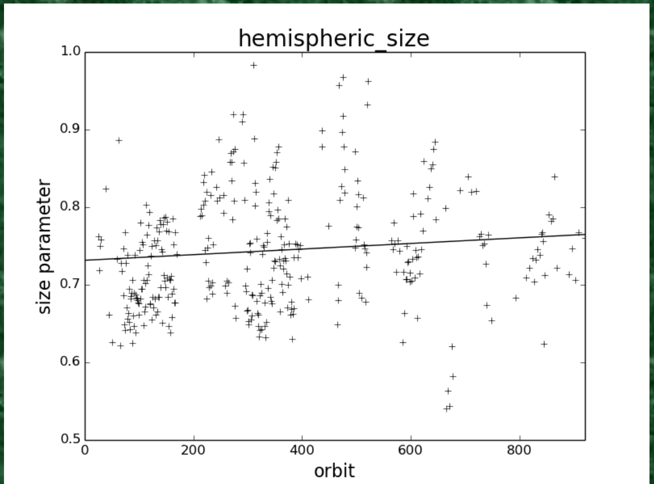
- 1.74 micron variations
  - i.e., clouds
- See long-term trend exceeding variability
- Possibly see mid-latitude oscillation with ~140d period.

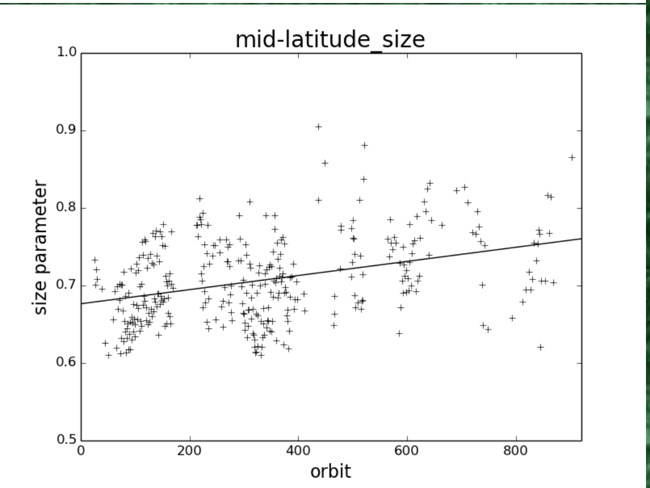
region	δI_0(x10^{-3})	dI/dt(x10^{-3})	dI/dt x Δt(x10^{-3})
pol	2.85	-0.0139	-12.8
mid	4.96	+0.0193	+17.8
equ	3.55	+0.0216	+19.9
hem	3.63	+0.0251	+2.3

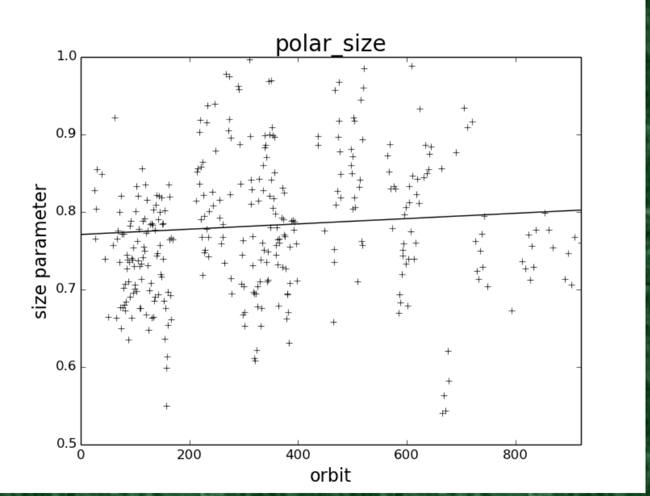
McGouldrick et al. (2015) In Prep.

Long term variability in Venus clouds







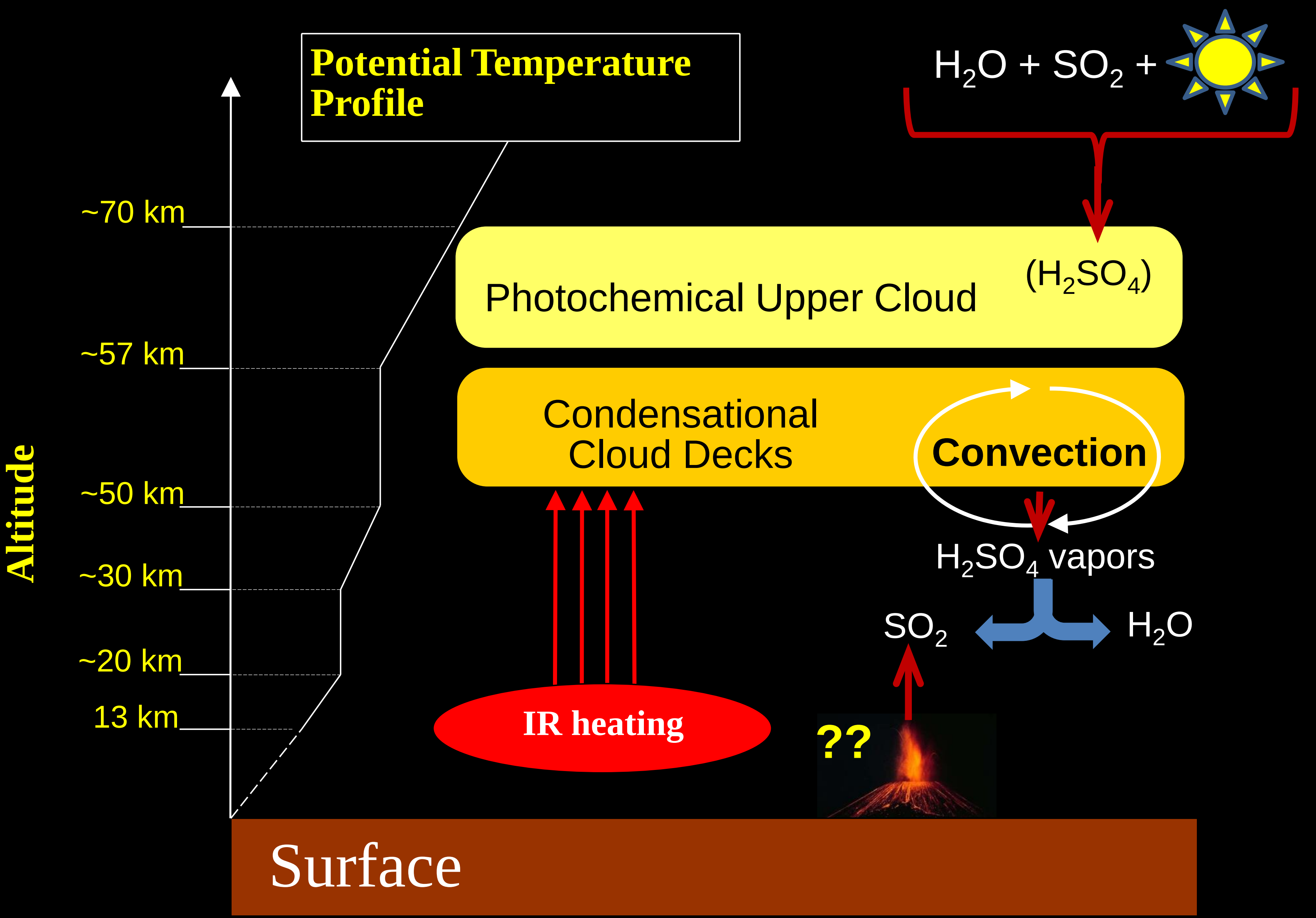


region	δm(x10^{-3})	dm/dt(x10^{-3})	dm/dt x Δt(x10^{-3})
pol	3.58	+0.0342	+31.5
mid	2.73	+0.0911	+83.9
equ	2.84	+0.0760	+70.0
hem	4.30	+0.0361	+33.3

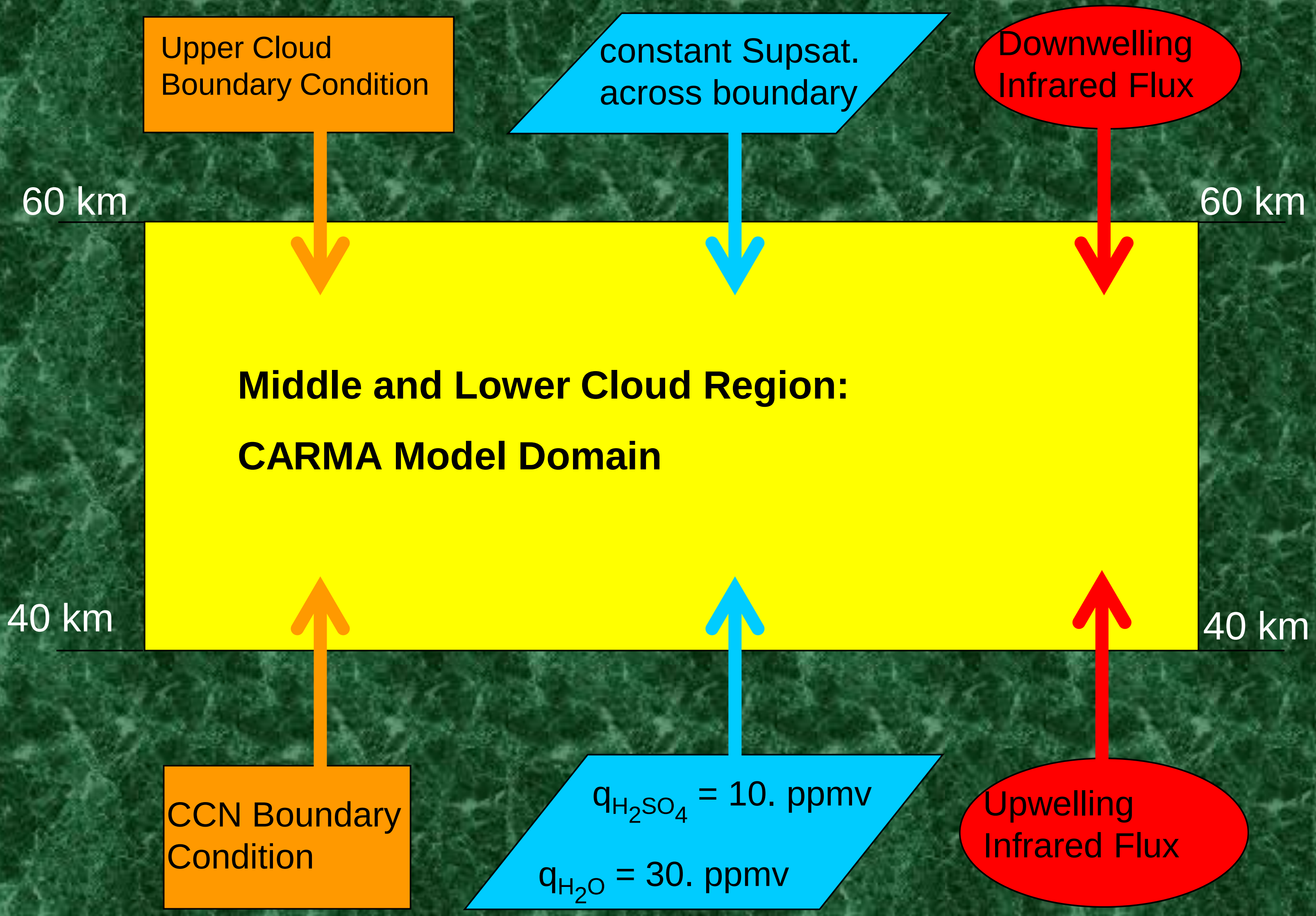
- Size parameter
  - $I_{1.74}/I_{2.32}^{0.53}$
- Larger size parameter can indicate larger particles
- See a trend of increasing size parameter at the 5-10% level, especially at low latitudes.

McGouldrick et al. (2015) In Prep.

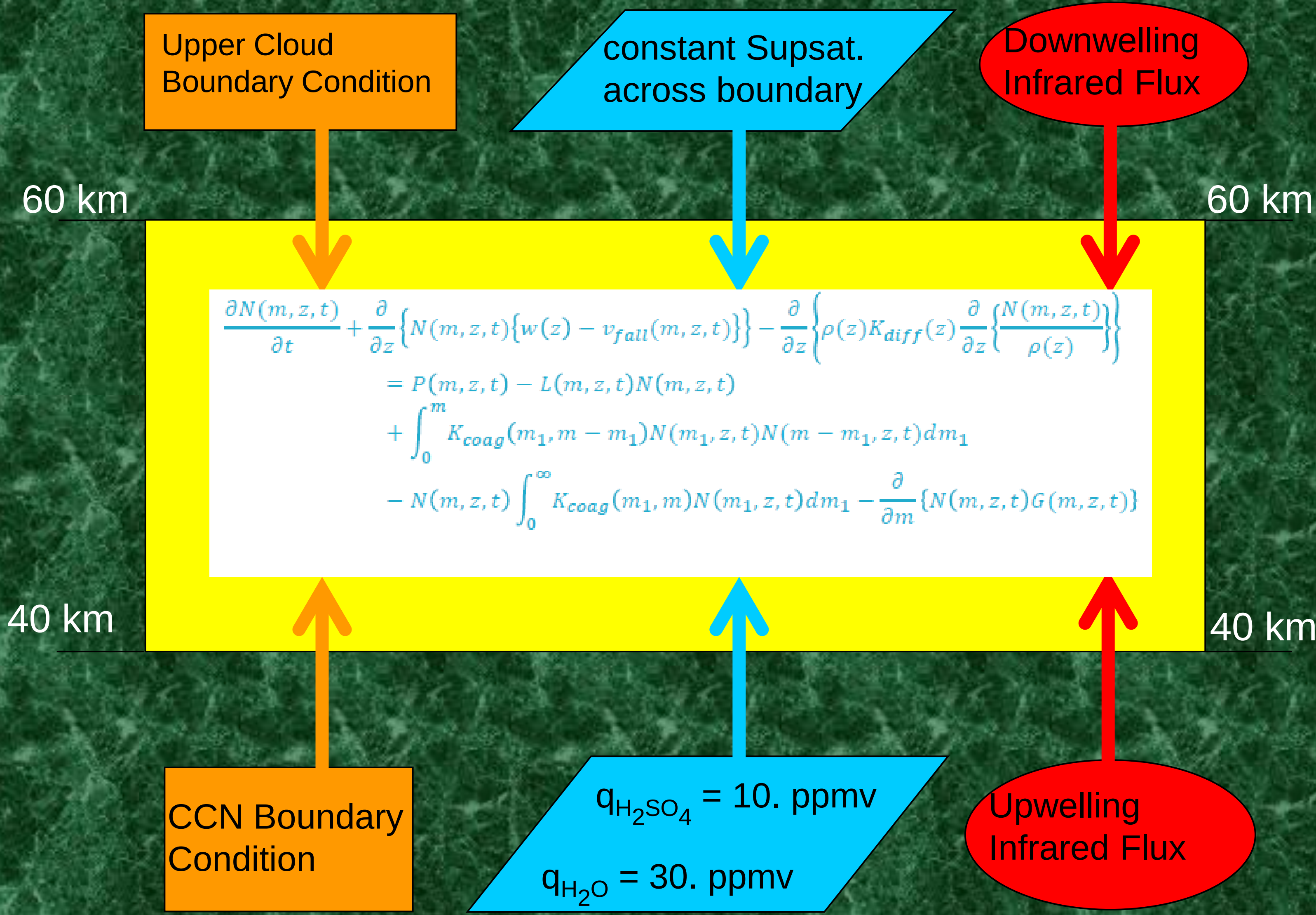
The Venusian Cloud Decks



Microphysics, Chemistry, and Radiation cloud model

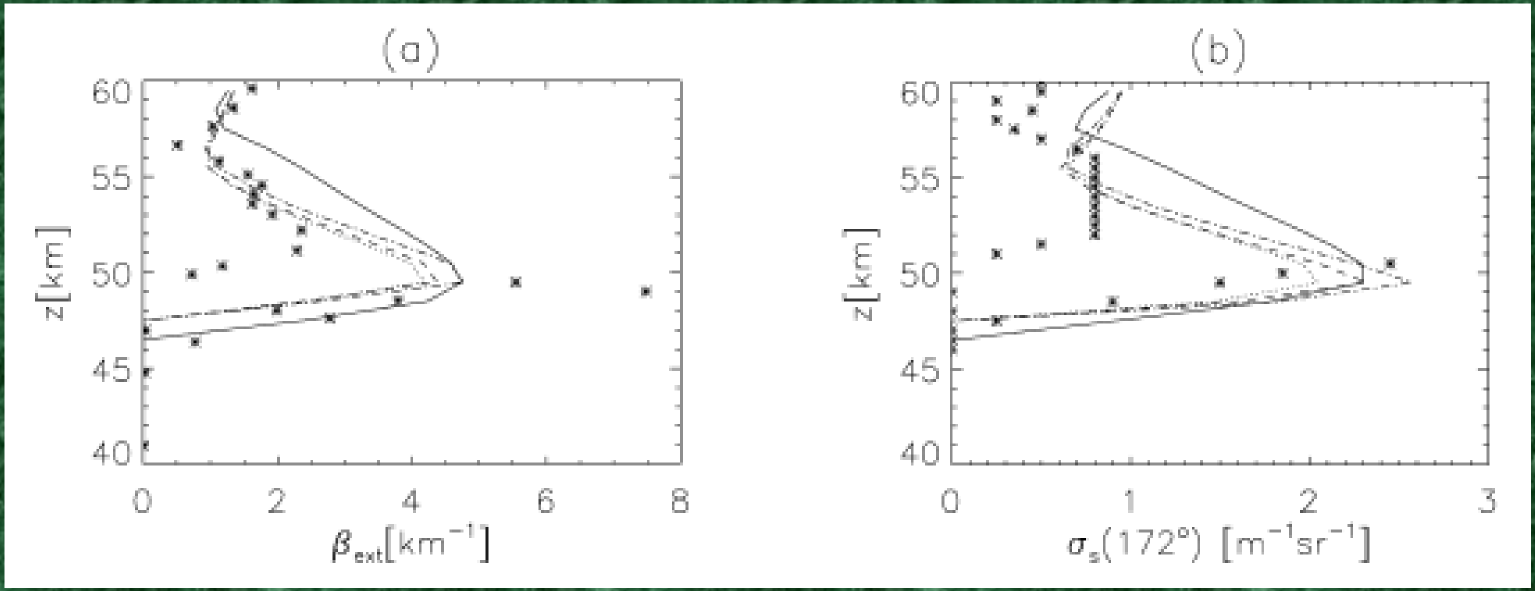


Microphysics, Chemistry, and Radiation cloud model



$$
\begin{aligned}
\frac{\partial N(m,z,t)}{\partial t} &+ \frac{\partial}{\partial z}\left\{N(m,z,t)\{w(z) - v_{fall}(m,z,t)\}\right\} - \frac{\partial}{\partial z}\left\{\rho(z)K_{diff}(z)\frac{\partial}{\partial z}\left\{\frac{N(m,z,t)}{\rho(z)}\right\}\right\} \\
&= P(m,z,t) - L(m,z,t)N(m,z,t) \\
&+ \int_0^m K_{coag}(m_1, m - m_1)N(m_1,z,t)N(m - m_1,z,t)dm_1 \\
&- N(m,z,t)\int_0^\infty K_{coag}(m_1,m)N(m_1,z,t)dm_1 - \frac{\partial}{\partial m}\{N(m,z,t)G(m,z,t)\}
\end{aligned}
$$

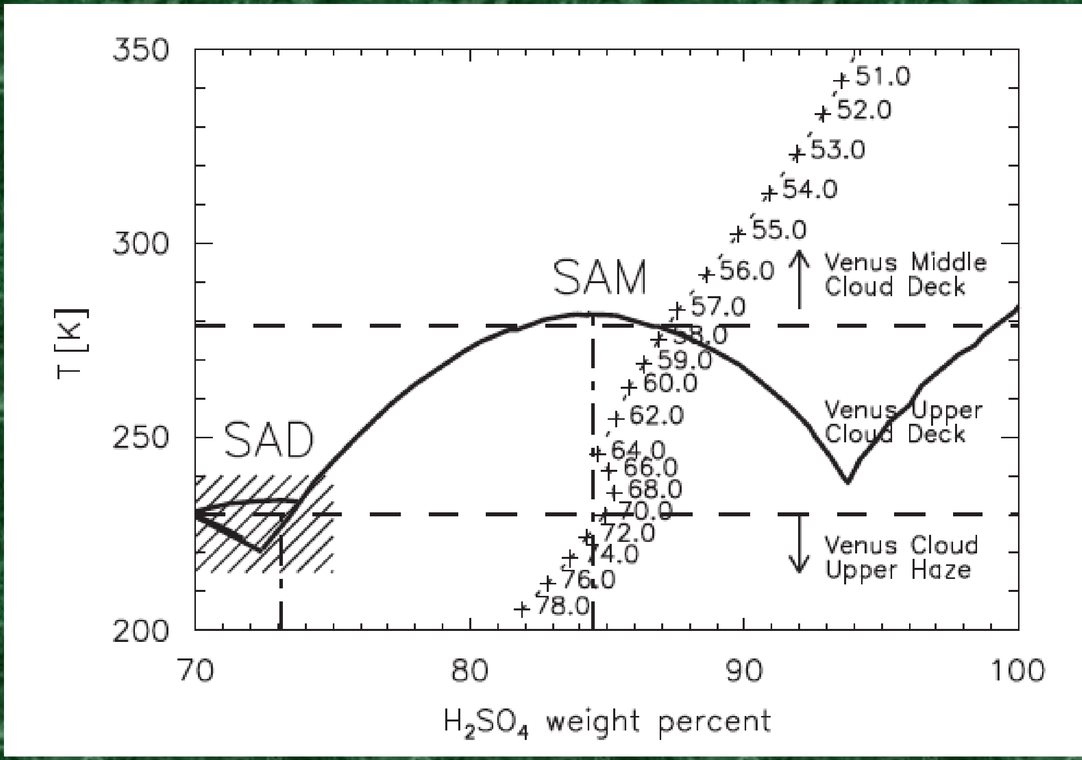
Results from Radiative Dynamical Feedback Simulations



- Solid line in each plot is a constant (with time) eddy diffusion profile dictating vertical motions other than sedimentation
- The three broken lines are simulations with varying parameters affecting the calculation of a variable eddy diffusion profile that responds to the lapse rate.
- Symbols represent values derived from LCPS in situ observations.

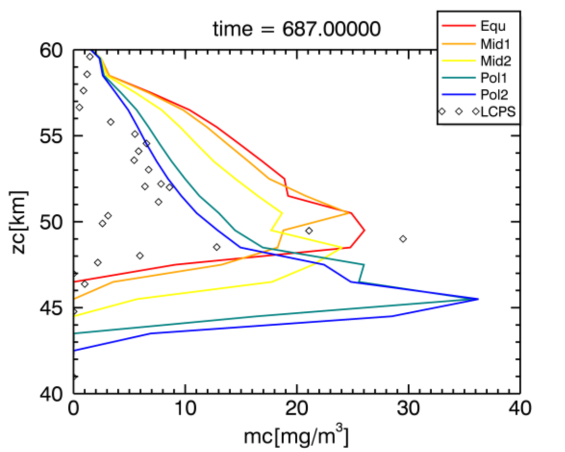
Low temperature behavior of sulfuric acid

- Sulfuric acid tends to supercool rather than freeze
- But, in the Venus atmosphere, the melting point of H_2SO_4 occurs at about the transition between upper and middle clouds.

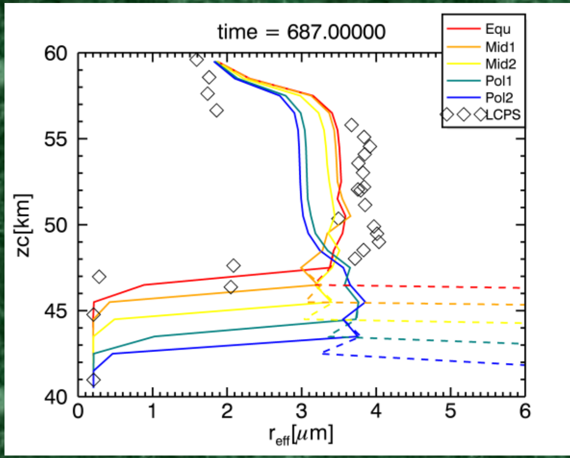


Coalescence Sensitivity Test

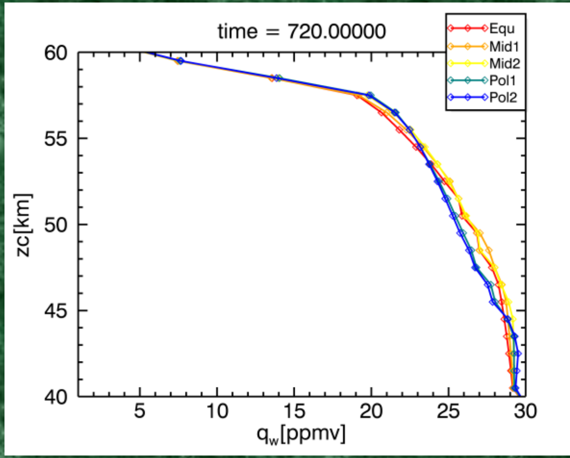
Coag T: Mass loading



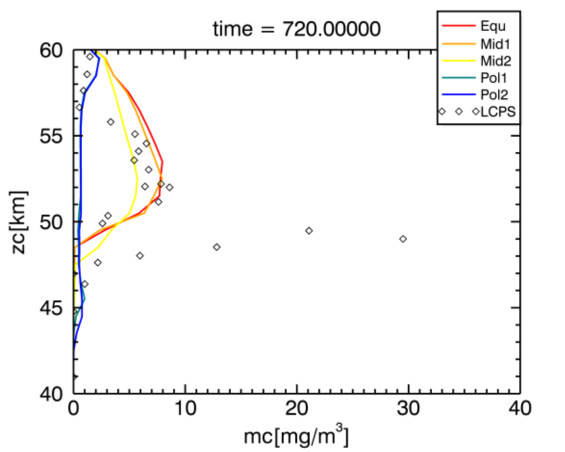
Effective radius

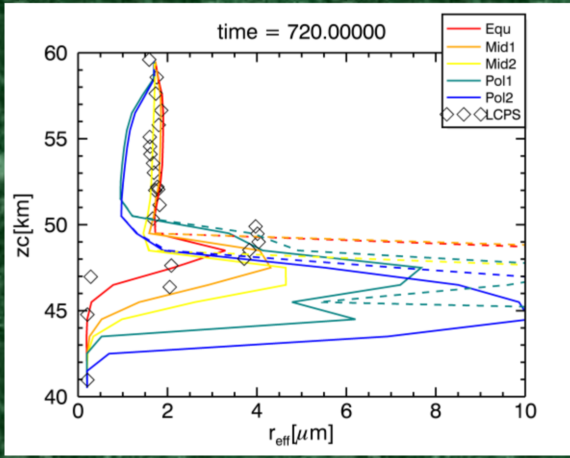


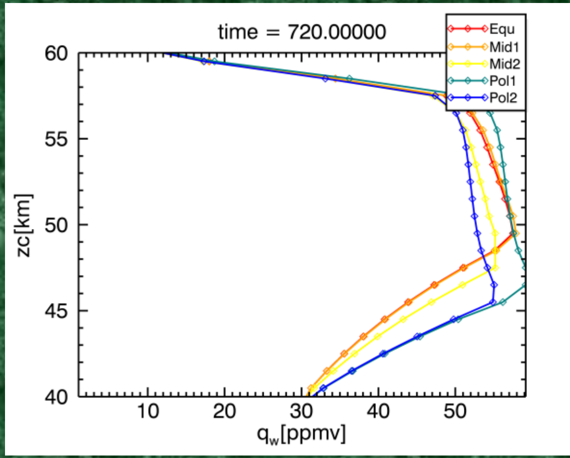
Water vapor



Coag F:





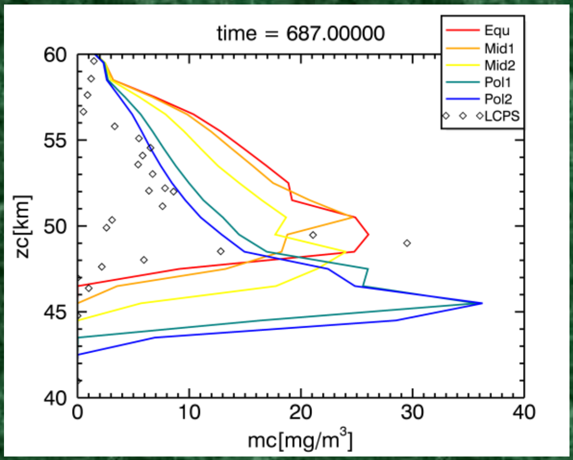


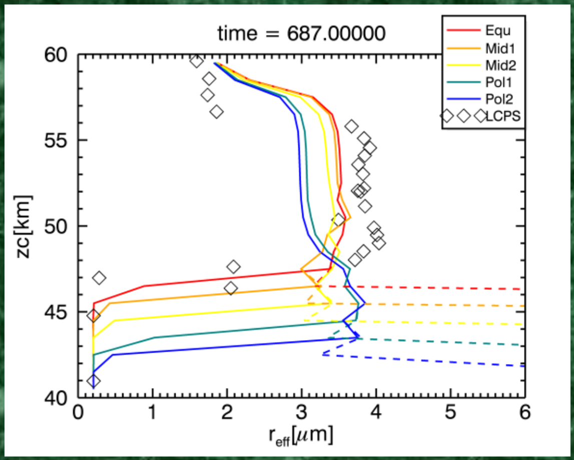
Coalescence Sensitivity Test

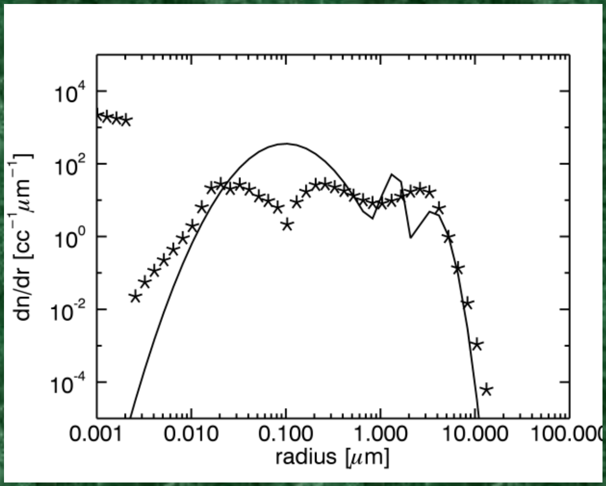
Coag T: Mass loading

Effective radius

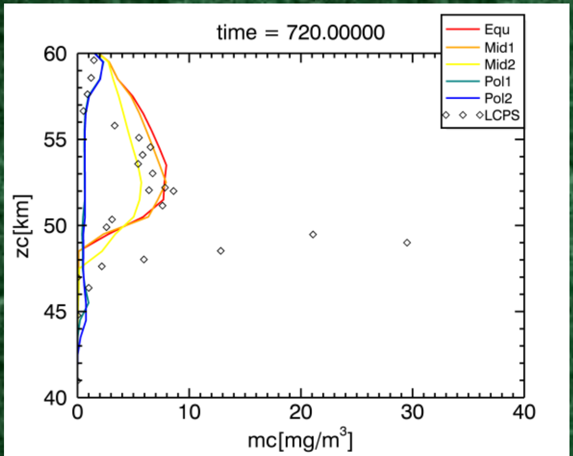
Water vapor

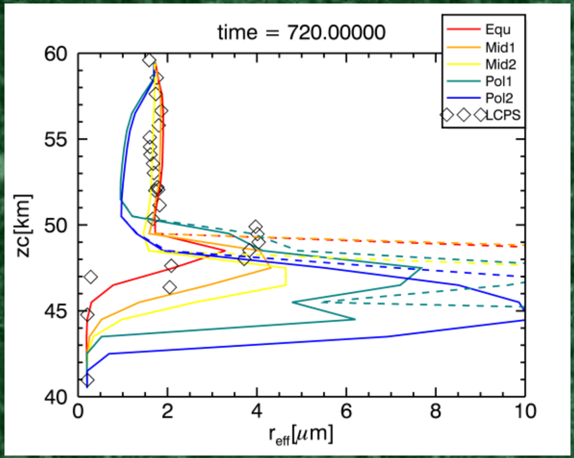


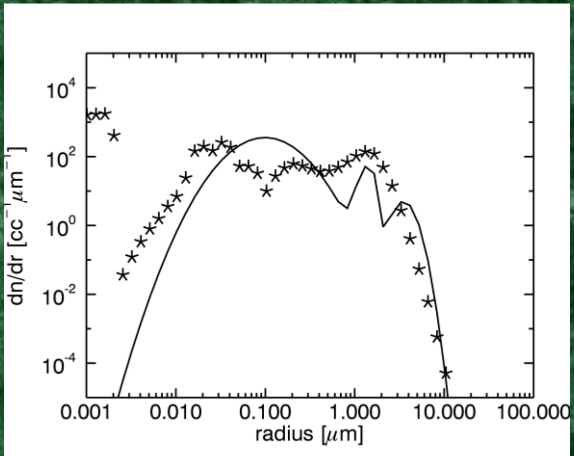




Coag F:







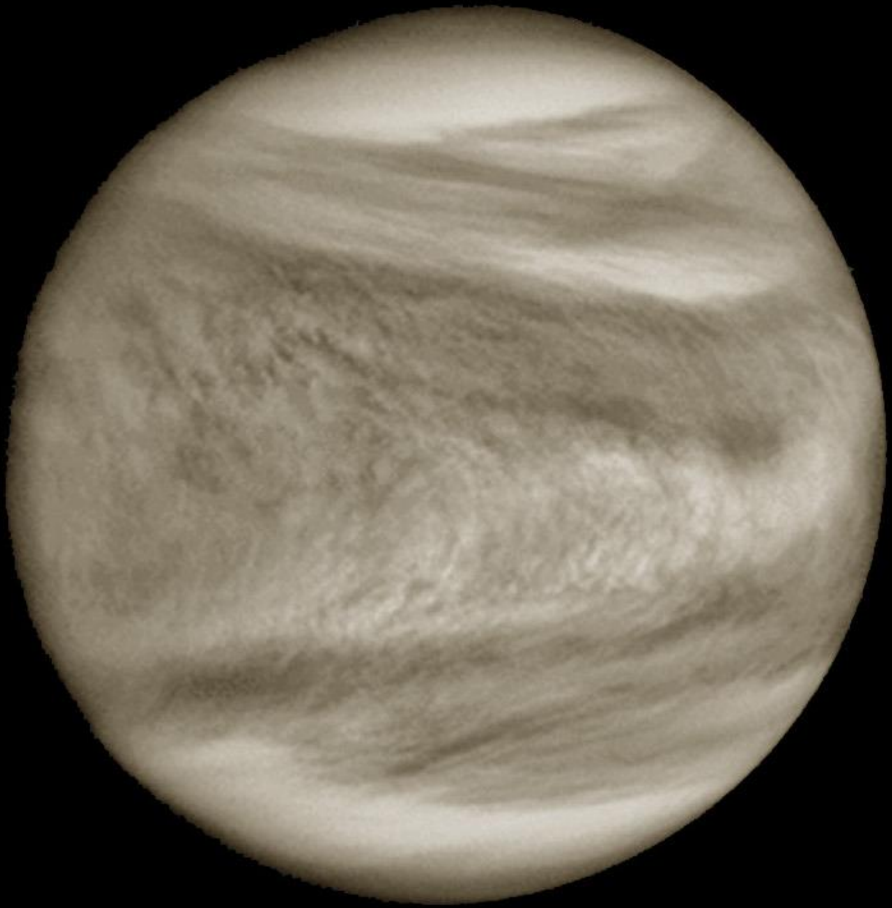
Cloud size parameter comparison

- More consistent with observations when coalescence included
- Not a surprise, since coalescence is important in the lower clouds
- May have significant effect if applied to upper clouds only

Table 1: Size parameter: $I(1.74)/I(2.3)^{0.53}$

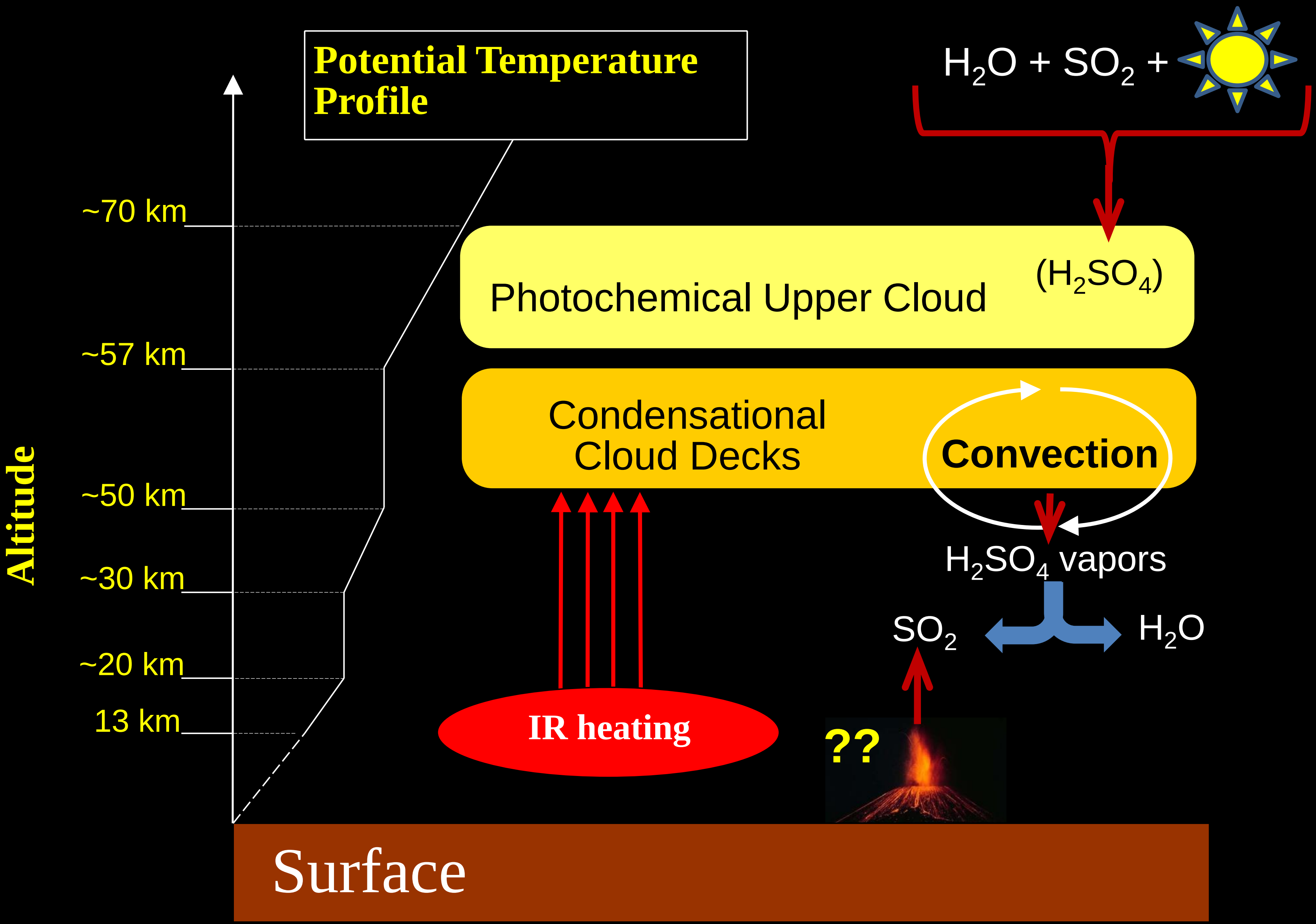
Latitude	No coalescence	With coalescence	Wilson et al. (est)
0-30	0.294	0.615	0.6
30-45	0.231	0.658	0.65
45-60	0.191	0.676	0.7
60-75	0.273	0.550	0.65
75-85	0.251	0.545	0.8

Venus in Ultraviolet wavelengths

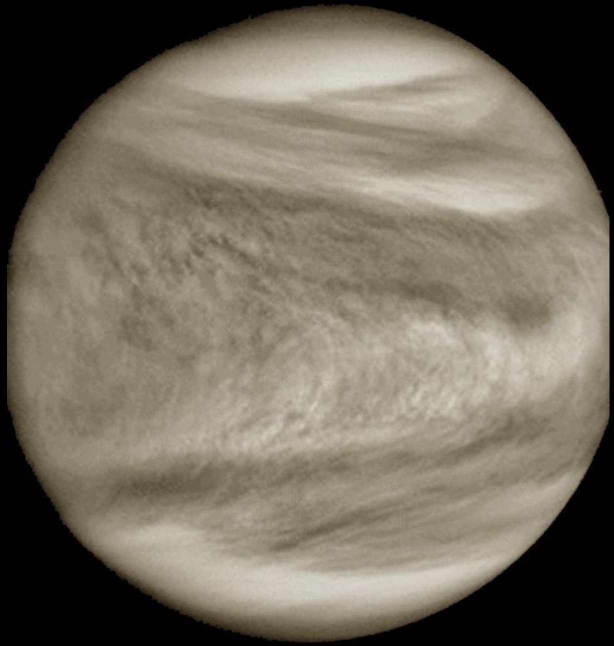


NASA (Pioneer Venus spacecraft – PV Orbiter
Cloud PhotoPolarimeter – 365nm)

The Venusian Cloud Decks

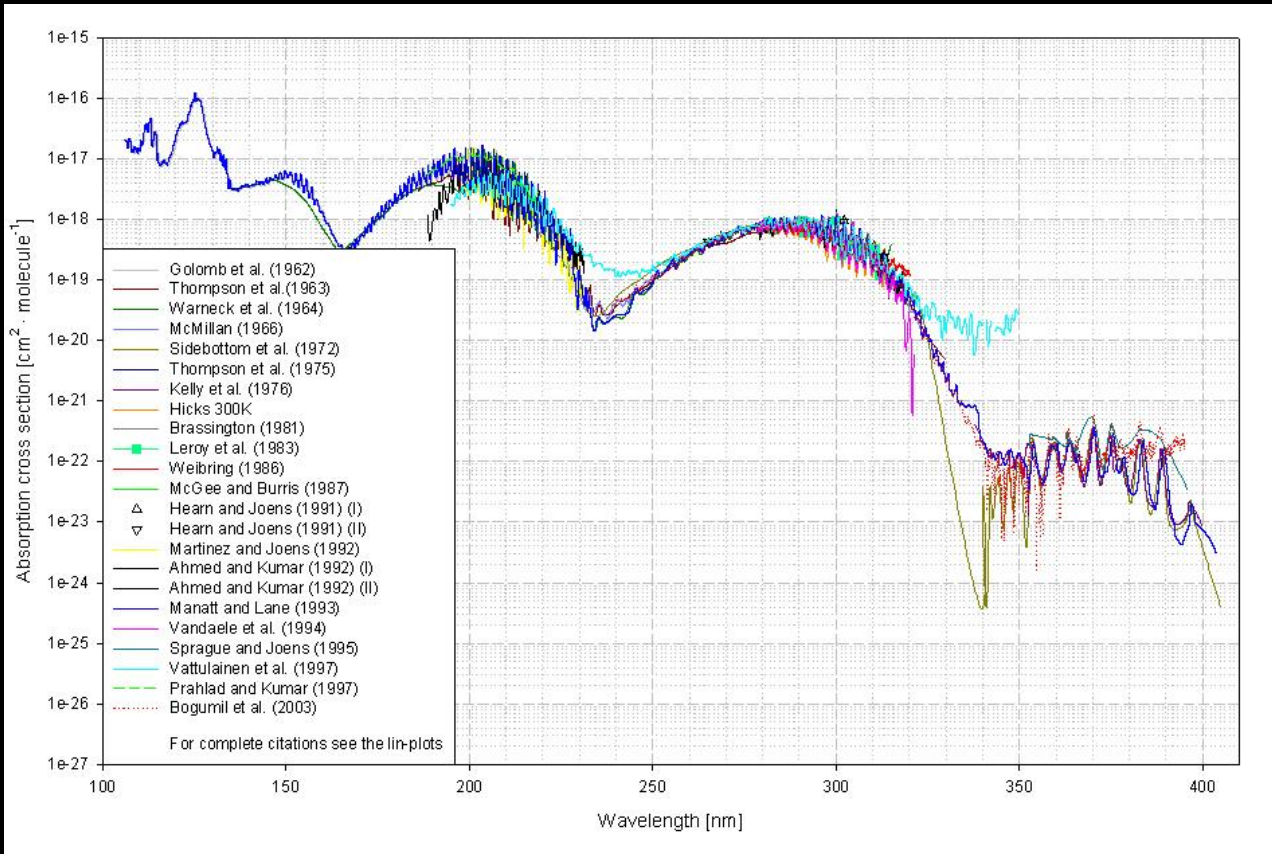


Venus in Ultraviolet wavelengths



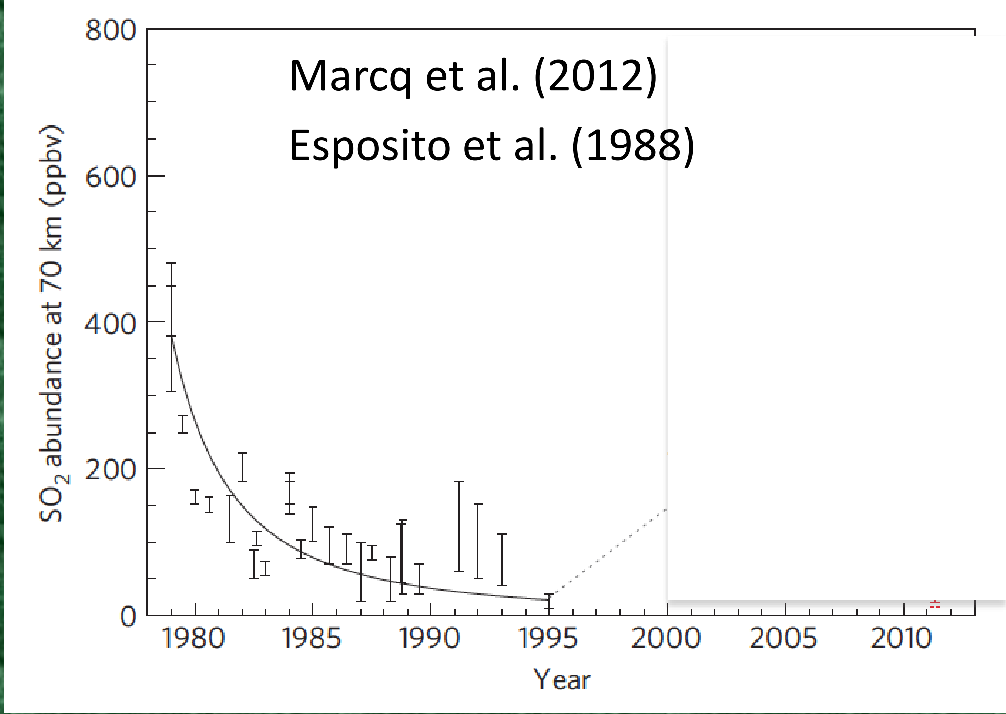
NASA (Pioneer Venus spacecraft – PV Orbiter Cloud PhotoPolarimeter – 365nm)

SO_2 absorption cross section

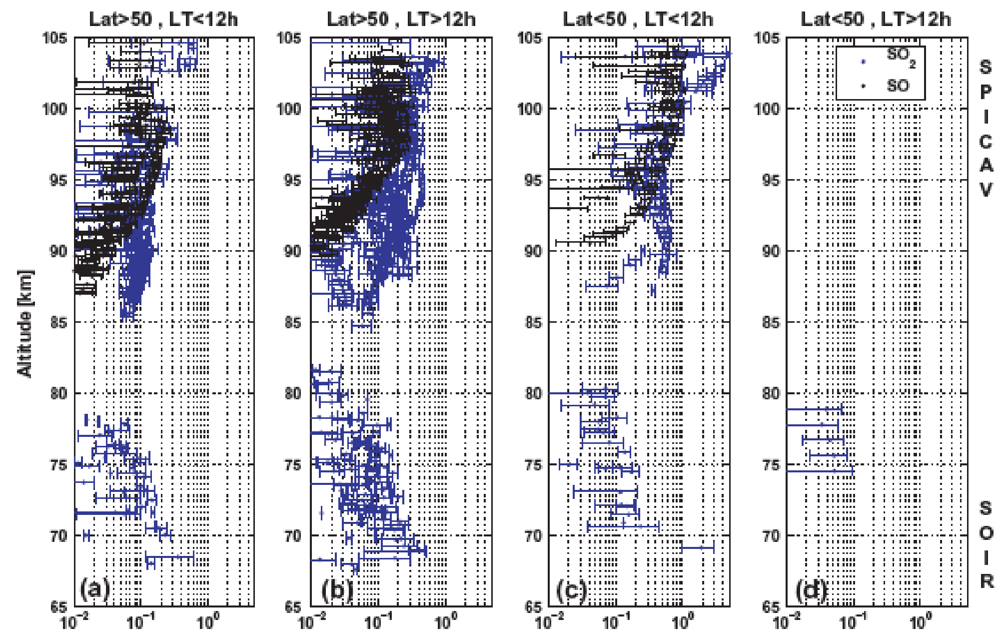


Low- and medium resolution absorption cross sections of sulfur dioxide SO_2 at room temperature (106-405 nm)

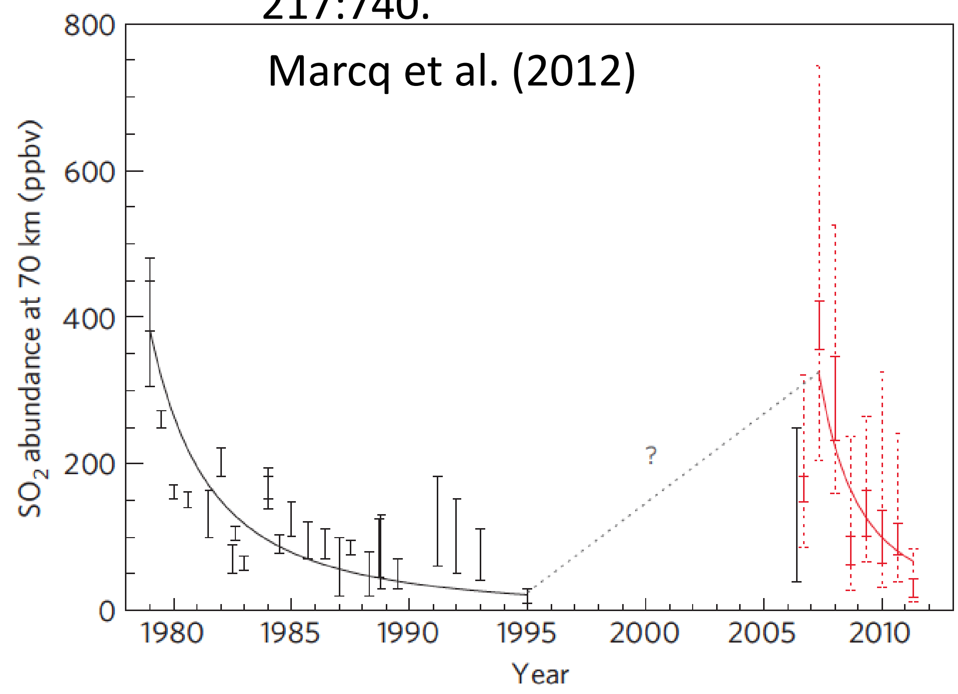
Long-term (years to decades) variation in SO_2: from the 1970s to today



Long-term (years to decades) variation in SO_2: from the 1970s to today

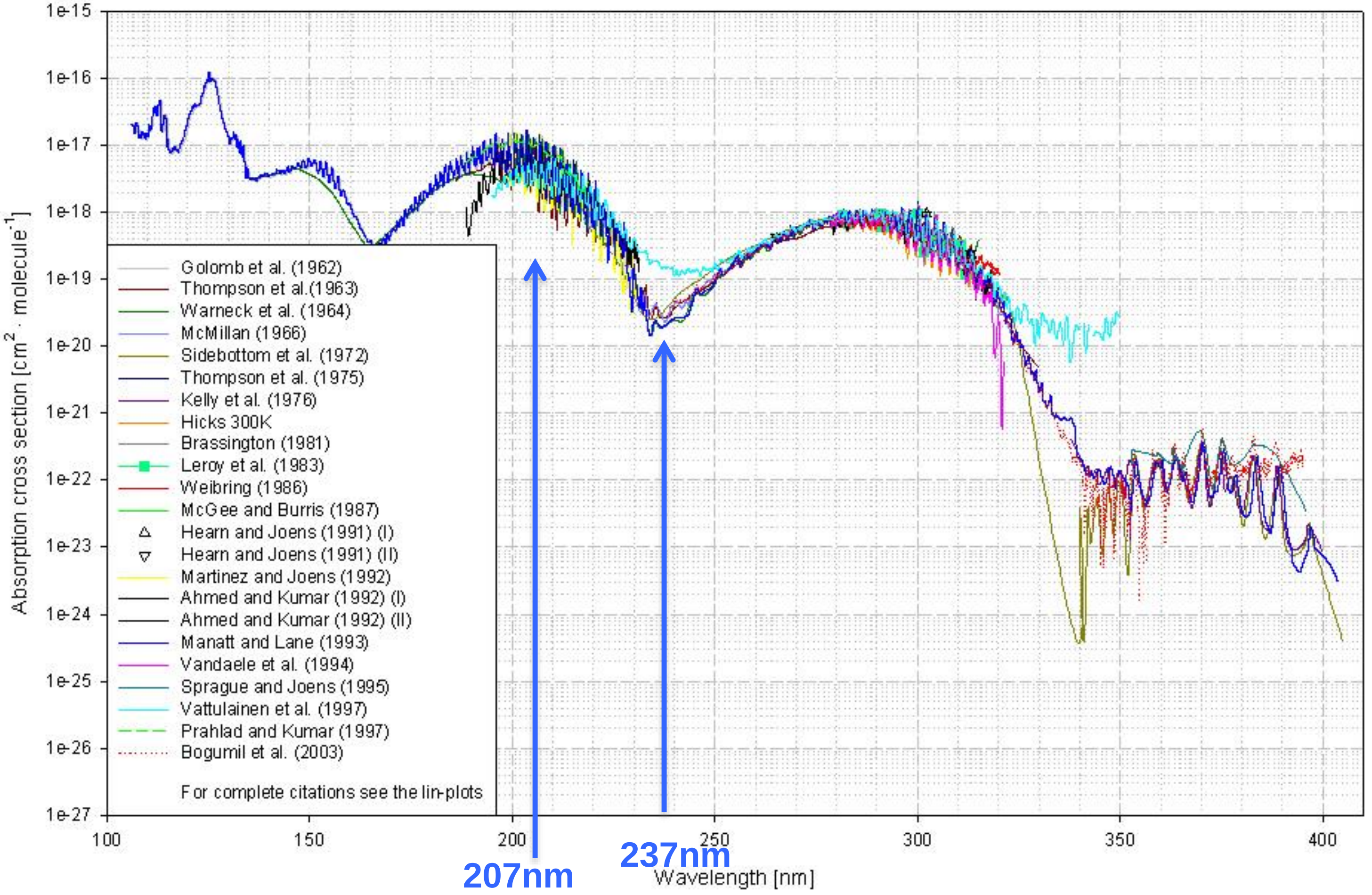


Belyaev et al. (2012) Icarus 217:740.



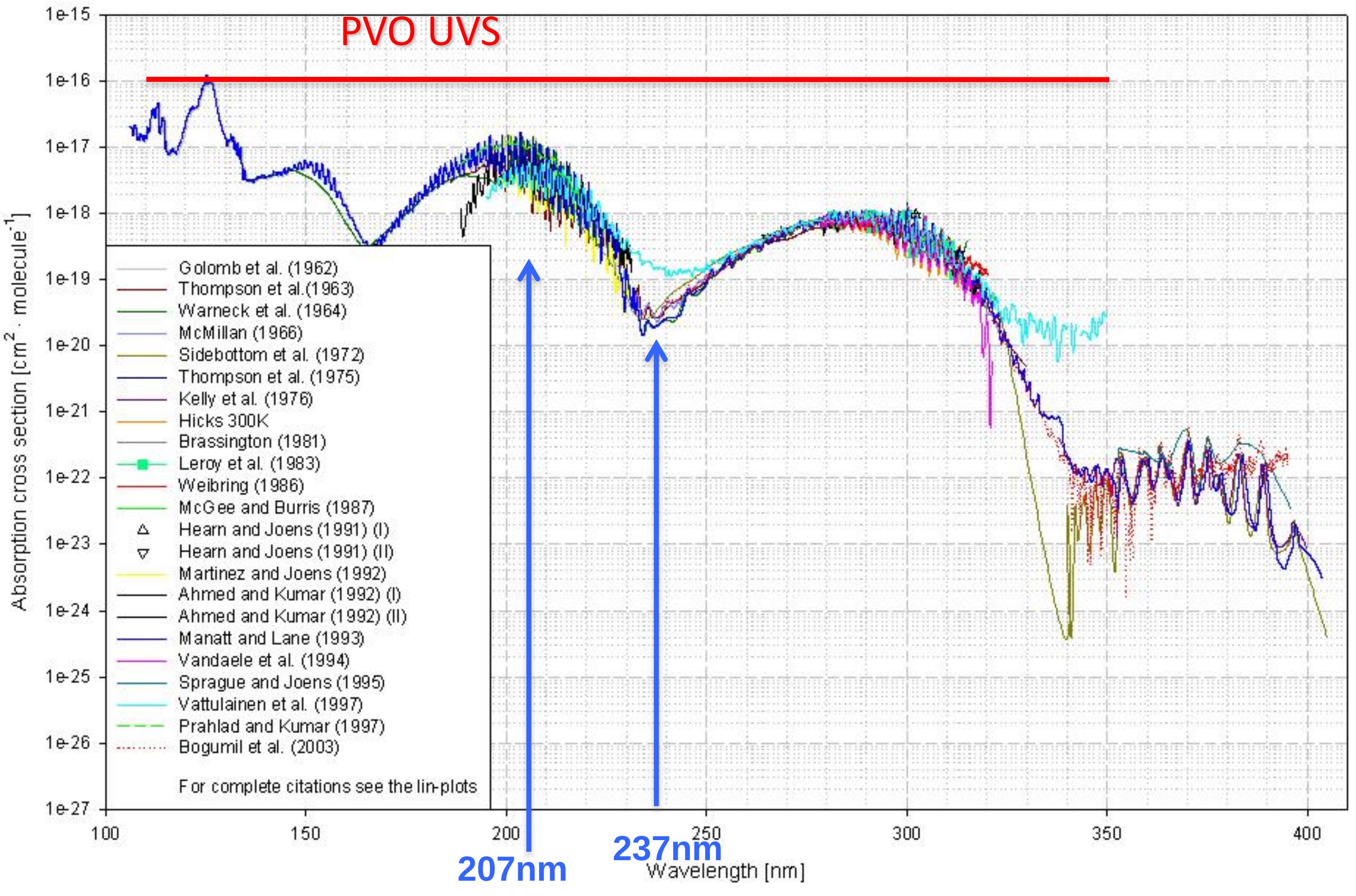
Marcq et al. (2012)

SO_2 UV absorption coefficient



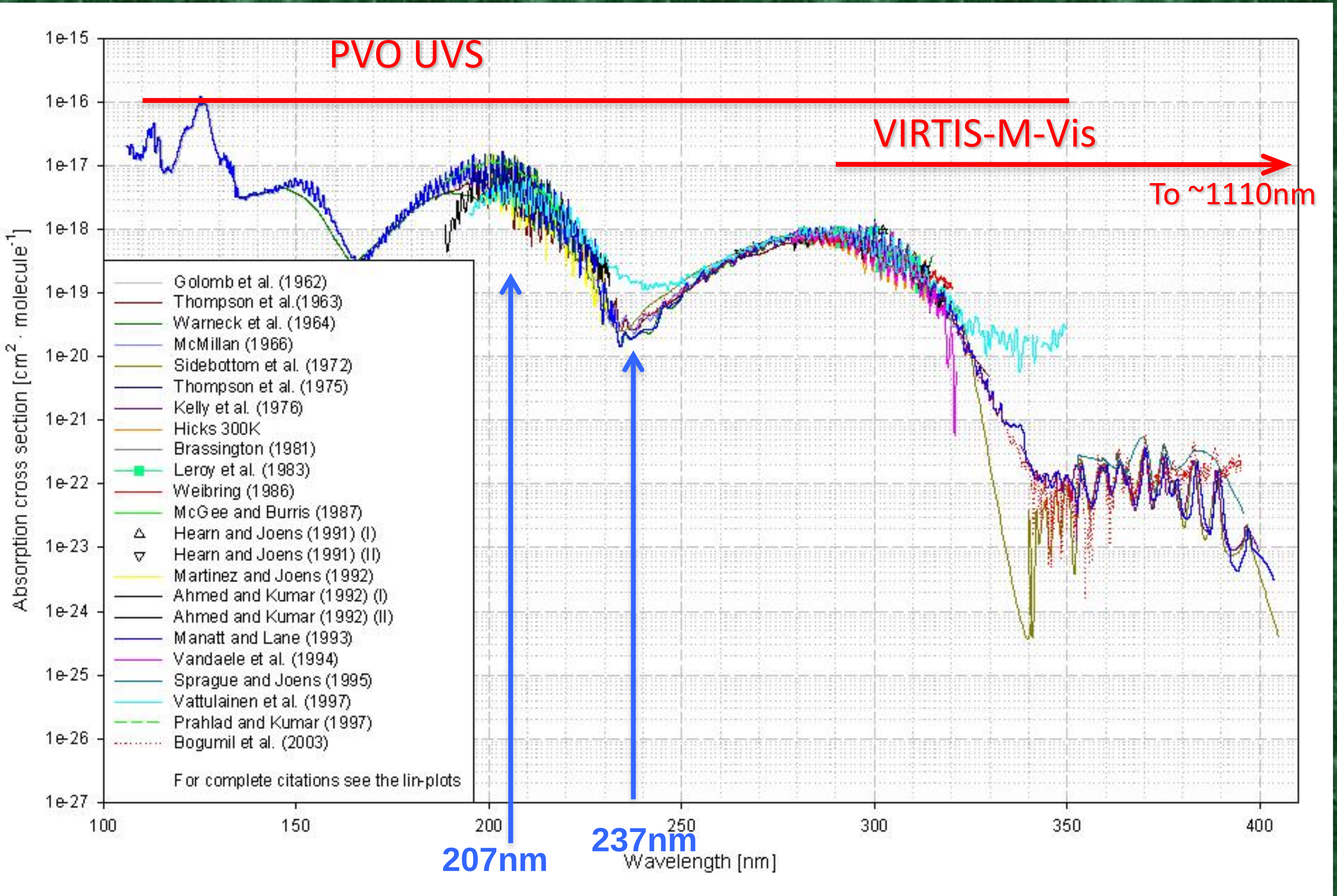
Low- and medium resolution absorption cross sections of sulfur dioxide SO_2 at room temperature (106-405 nm)

SO_2 UV absorption coefficient



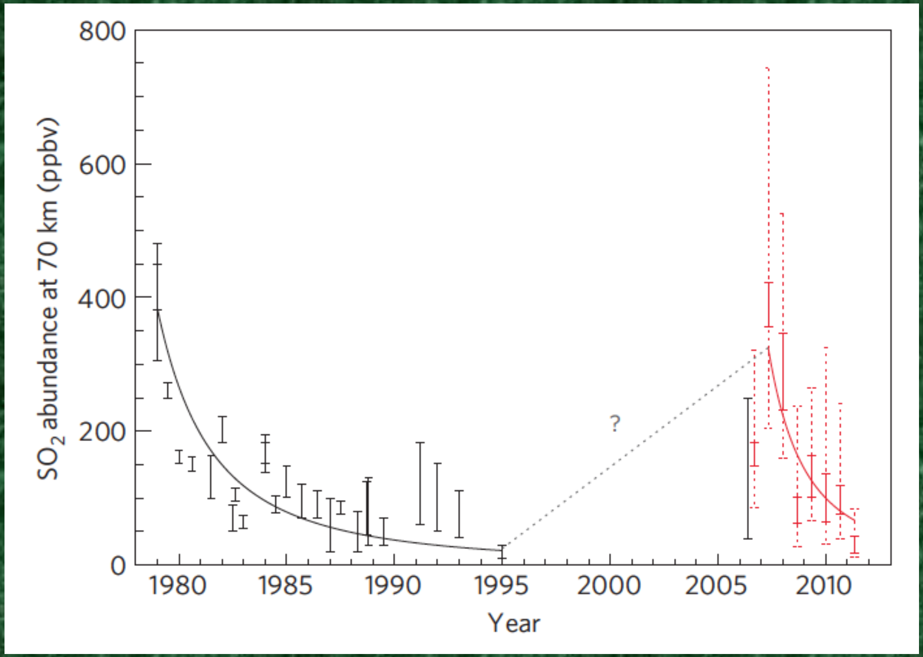
Low- and medium resolution absorption cross sections of sulfur dioxide SO_2 at room temperature (106-405 nm)

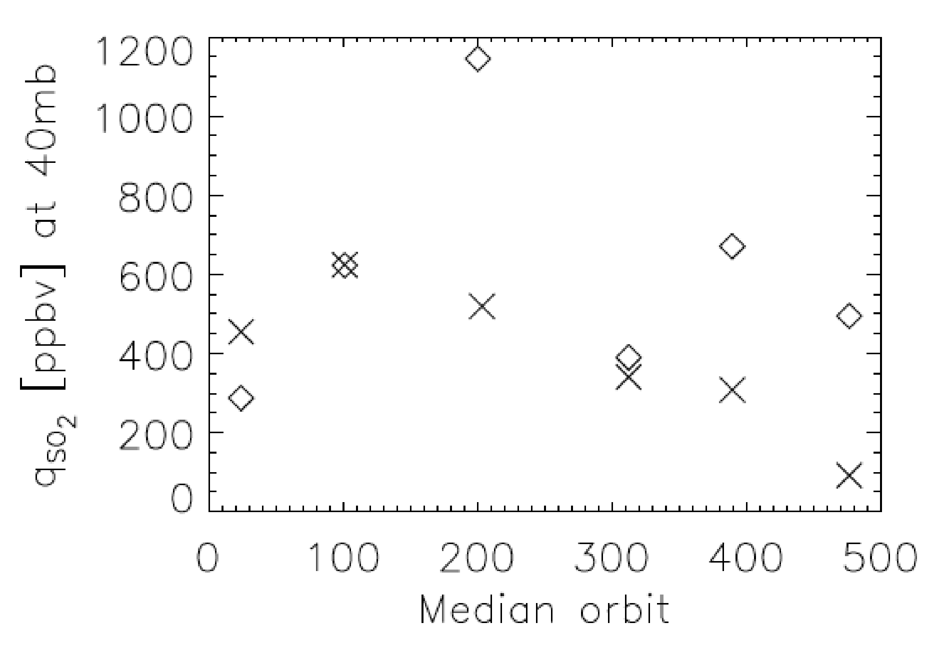
SO_2 UV absorption coefficient



Low- and medium resolution absorption cross sections of sulfur dioxide SO_2 at room temperature (106-405 nm)

Comparison with previous work

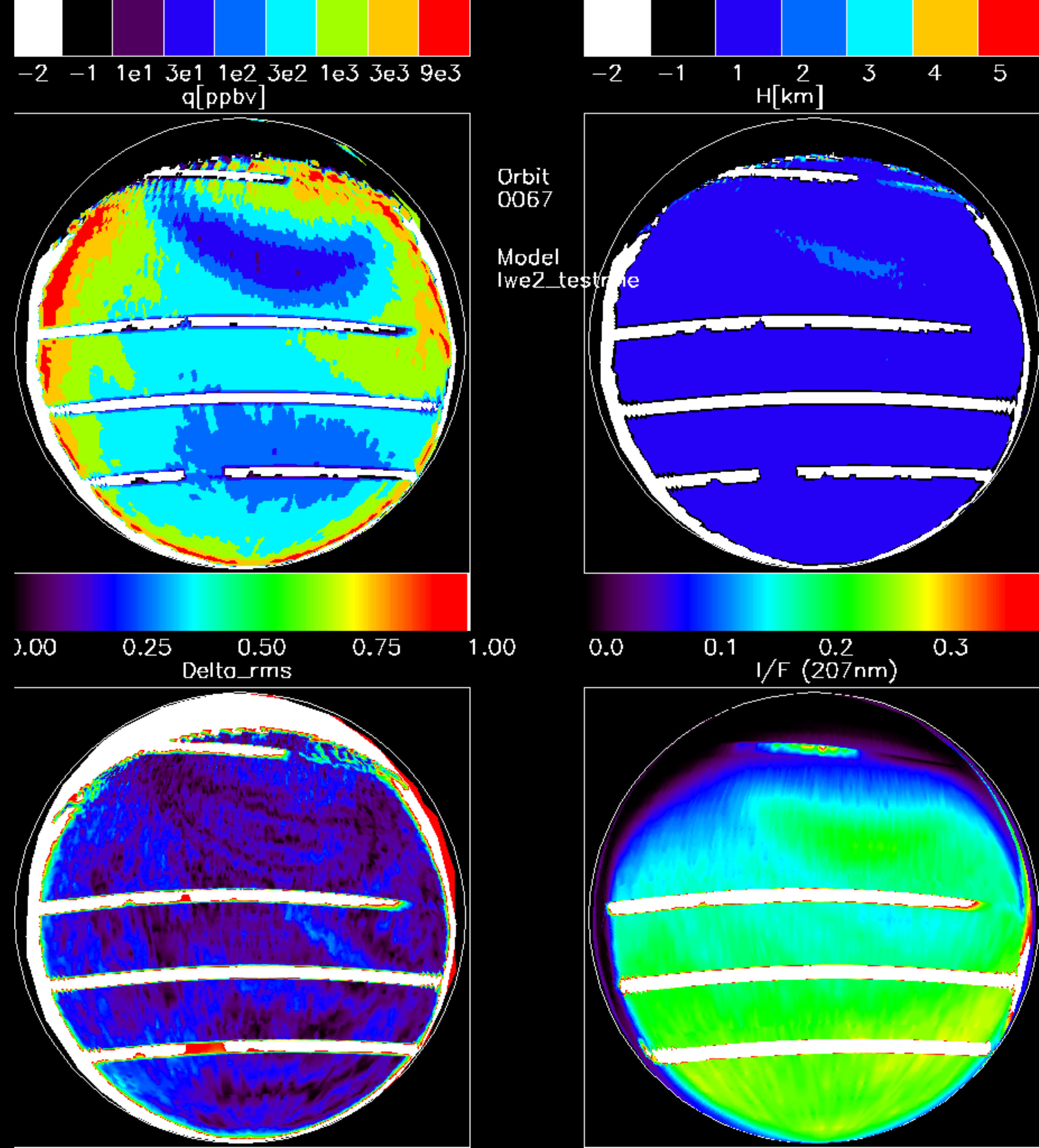




- Crosses represent analysis making the same assumptions as Esposito et al 1988
  - Good match
- Diamonds represent analysis using laboratory calibration only.

Spatial variations of SO_2

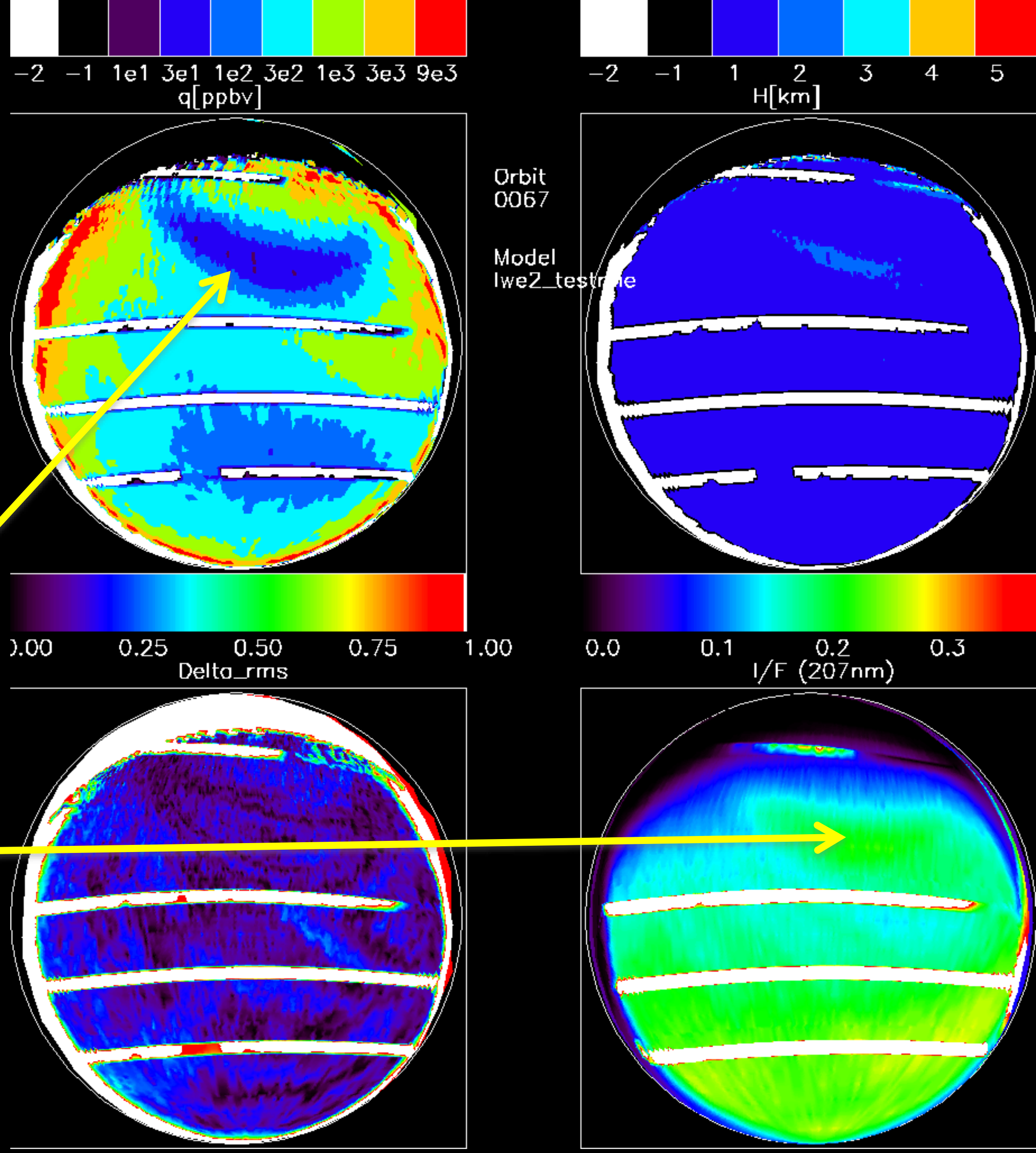
- Order of magnitude variations in retrieved SO_2 over the observed disk of the planet



Spatial variations of SO_2

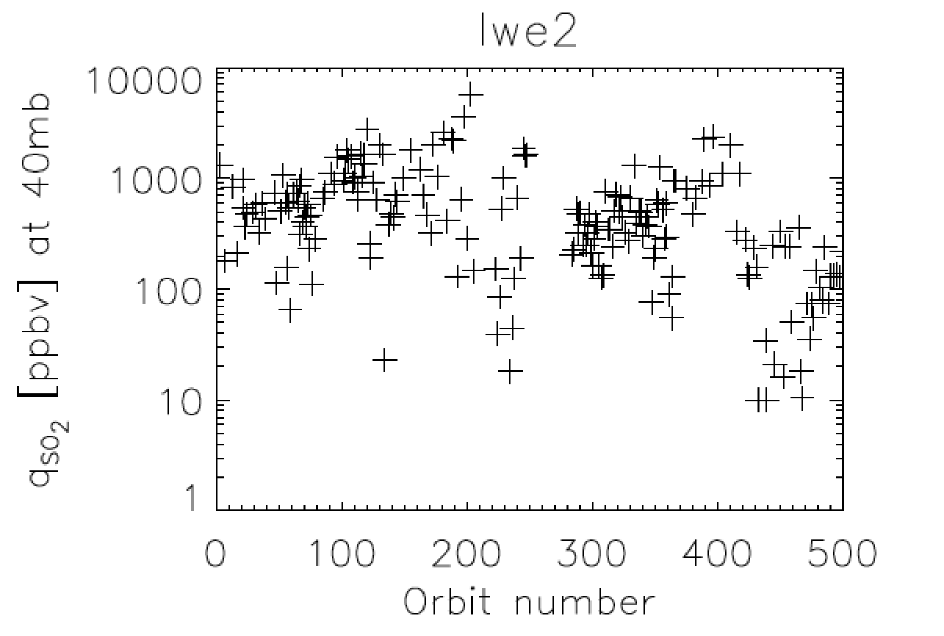
- Order of magnitude variations in retrieved SO_2 over the observed disk of the planet

- Some can be explained by discrepancies in assumed haze properties or concentrations



Temporal variations of SO_2

- Order of magnitude variations in retrieved SO_2 over timescales ranging from days to years.



Photolysis of H_2SO_4 in upper atmosphere

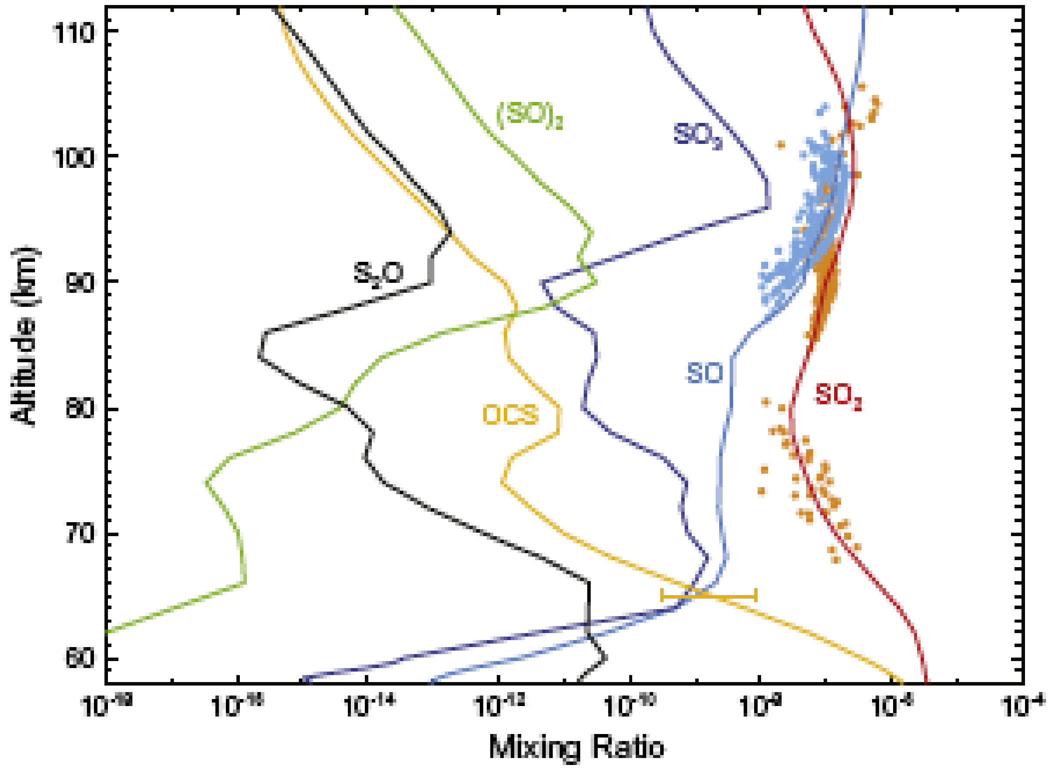


Fig. 8. Same as Fig. 2, for the sulfur oxides. The SO_2 and SO observations with errorbars are from the Belyaev et al. (2012). The temperature at 100 km is 165–170 K for the observations. The OCS measurement (0.3–9 ppb with the mean value of 3 ppb) is from Krasnopolsky (2010).

Zhang et al. (2012) Icarus 217:714.

The Varied Clouds of Venus

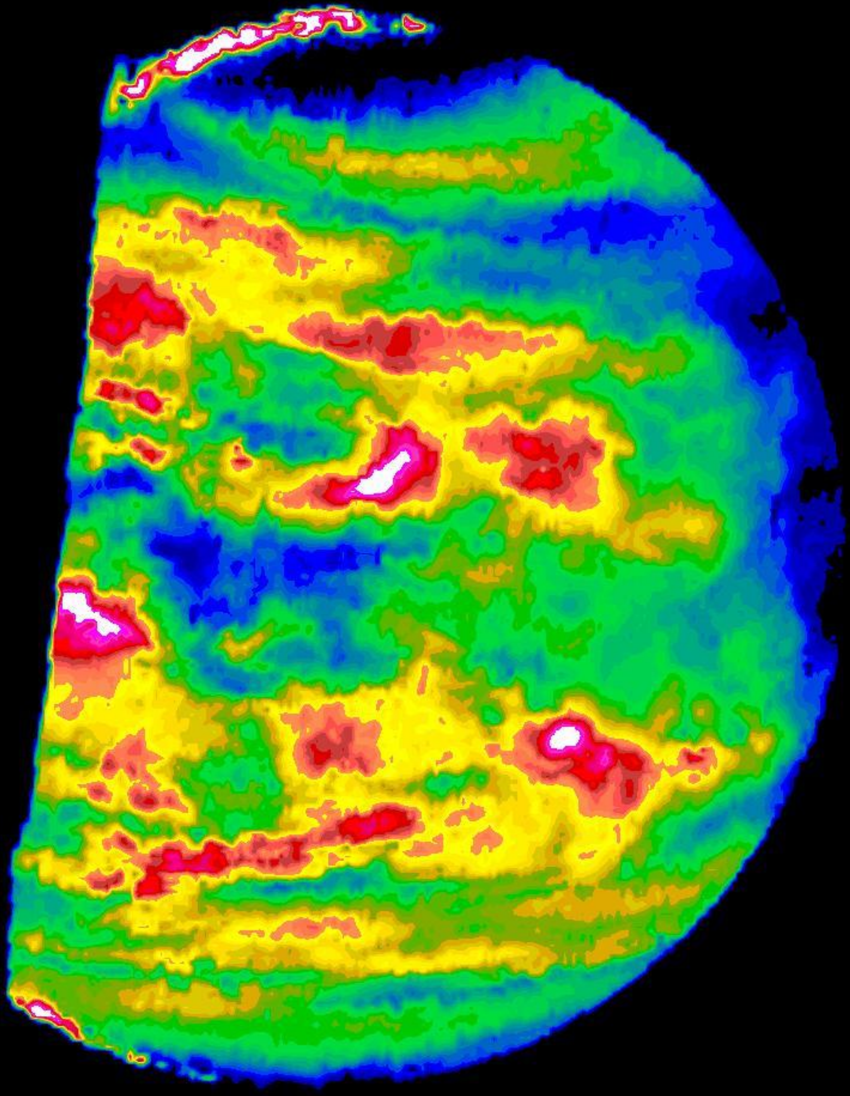
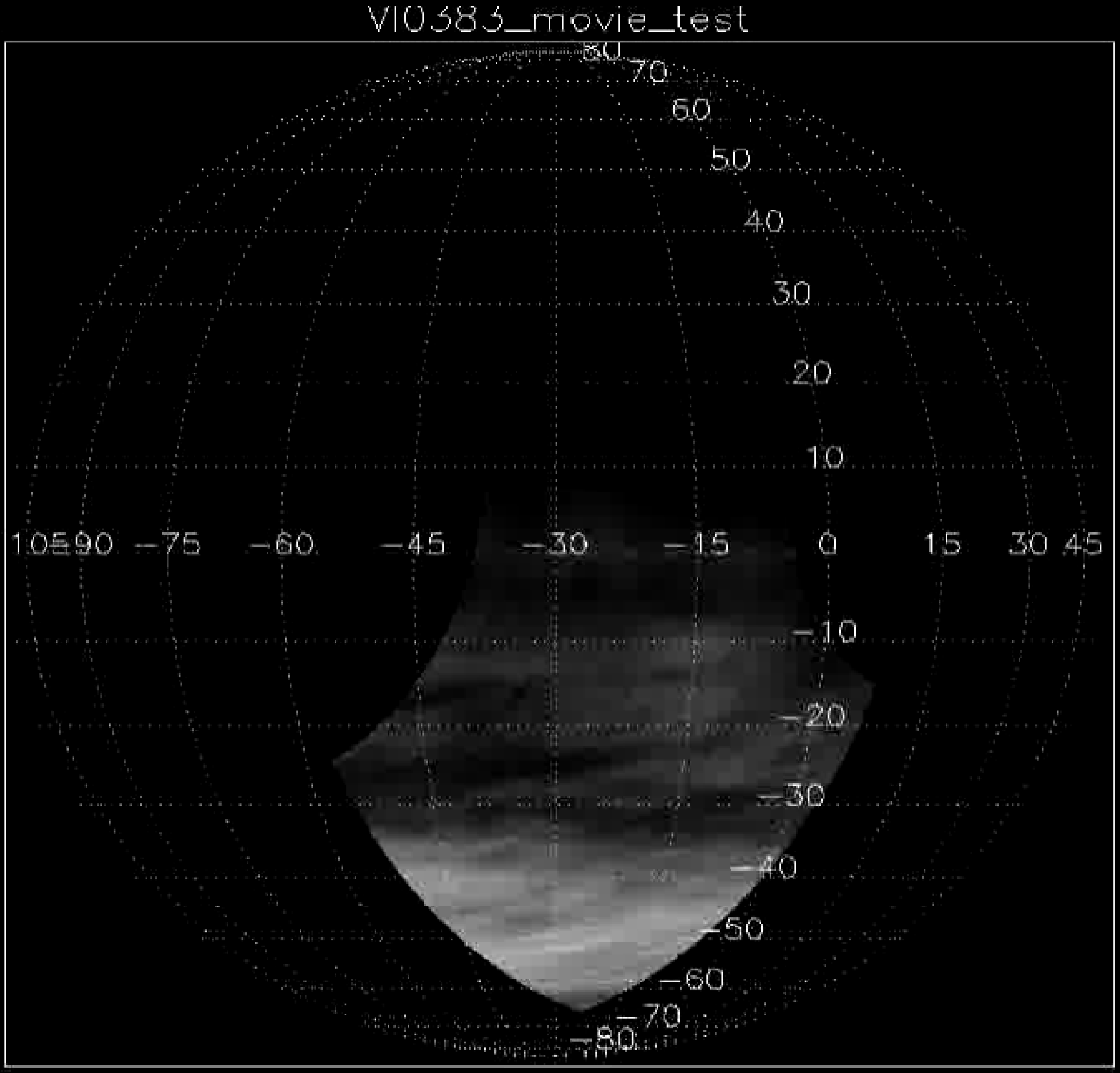
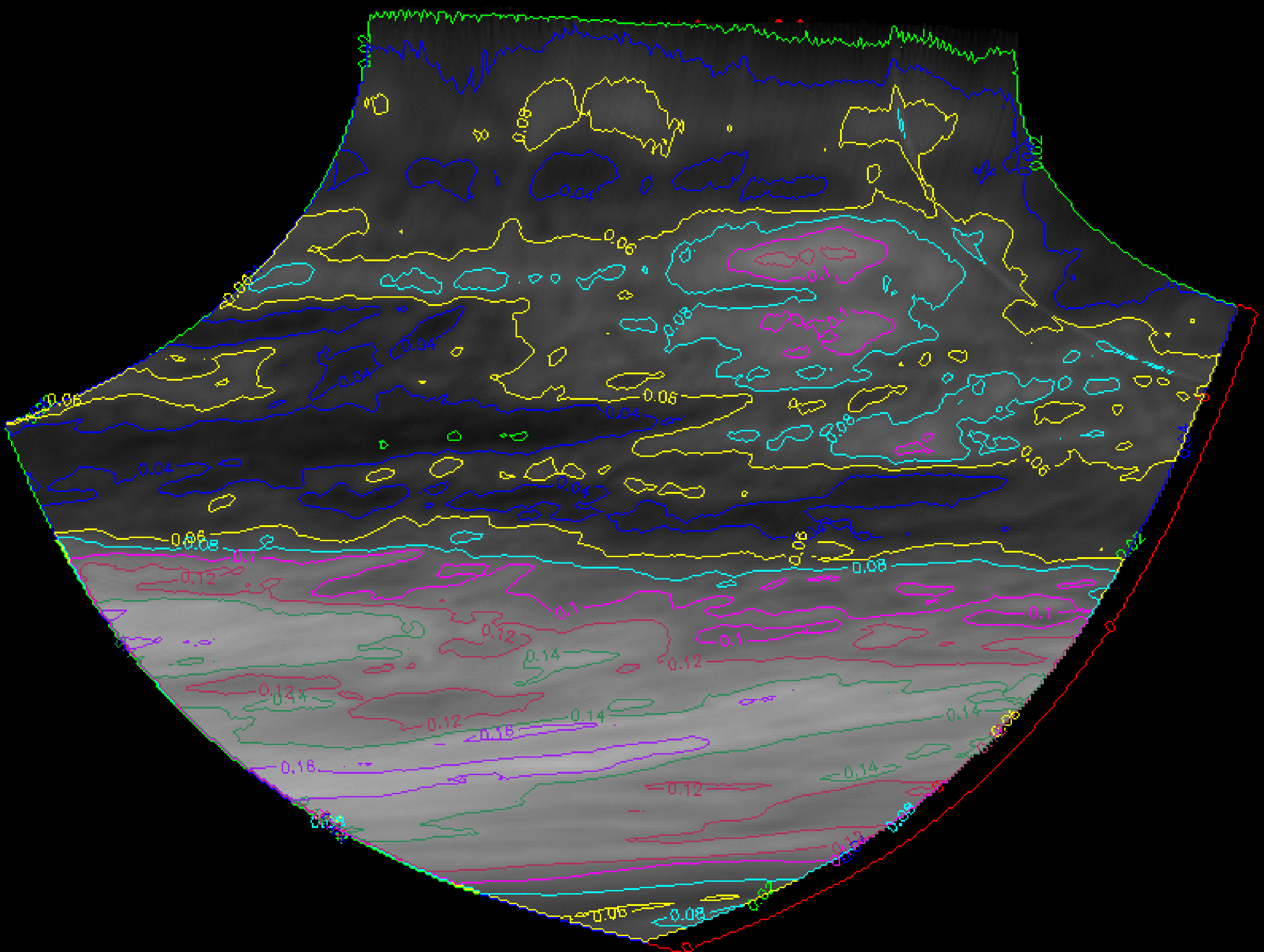


Image Courtesy NASA

The Varied Clouds of Venus



Venus clouds movie



Summary of Cloud and Hole Evolution timescales

VIR0383

Mean Timescale	-13.2 hr
Mean Absolute Timescale	32.2 hr
Mean Timescale (Holes only)	+17.8 hr
Abs. Timescale (Holes only)	35.6 hr
Mean Timescale (Clouds only)	+6.4 hr
Abs. Timescale (Clouds only)	27.0 hr

VIR0384

Mean Timescale	-13.7 hr
Mean Absolute Timescale	34.5 hr
Mean Timescale (Holes only)	-26.6 hr
Abs. Timescale (Holes only)	36.5 hr
Mean Timescale (Clouds only)	+12.2 hr
Abs. Timescale (Clouds only)	30.4 hr

- Typical timescale is about 30 hours, ignoring direction.
- In each case, the locally dark features tended to evolve more quickly than the locally bright features.
- The bright features in the observation of orbit 383 tend to be growing brighter with time, while those from orbit 384 are growing dimmer.

- Positive vorticity appears to be correlated with negative divergence (i.e., convergence) among holes and vice versa.
- This is consistent with holes being caused by downdrafts, and winds tracked near cloud base.
- However, just as on Earth, divergence (convergence) aloft must be balanced by convergence (divergence) below.
- Tracking same feature at different altitudes can measure this…

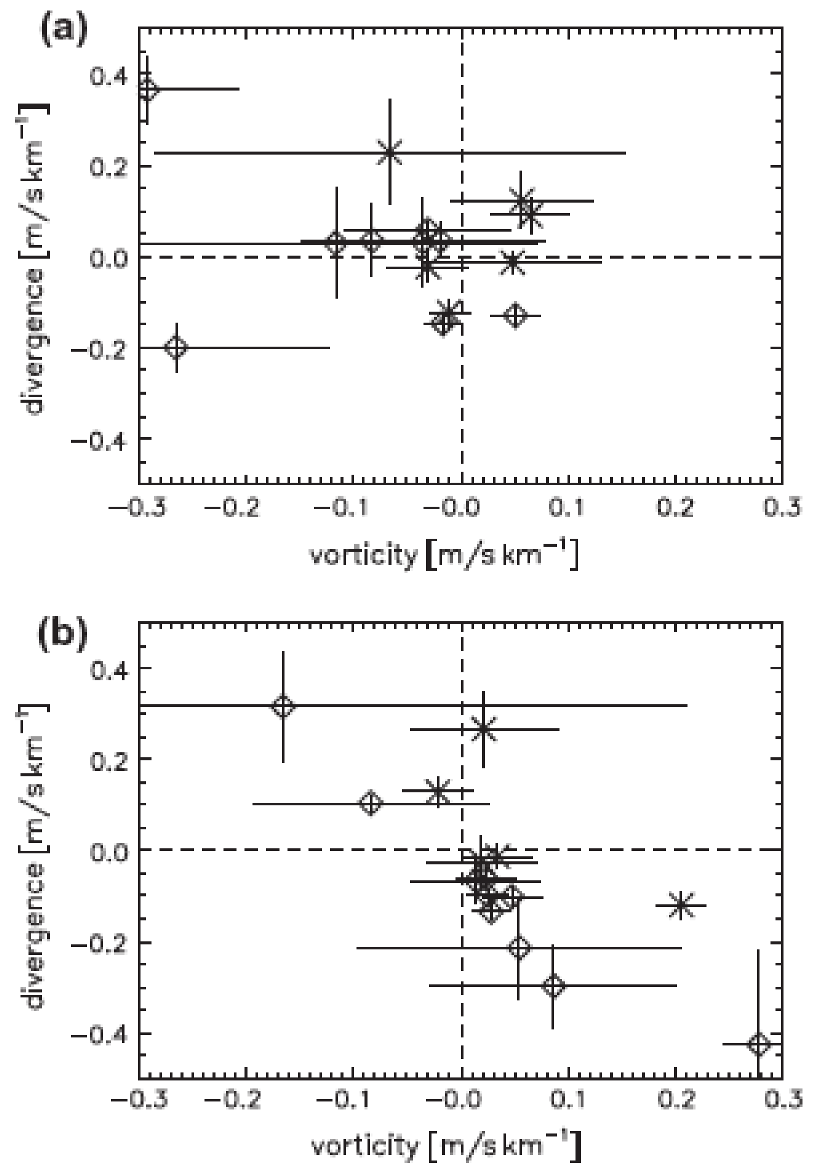
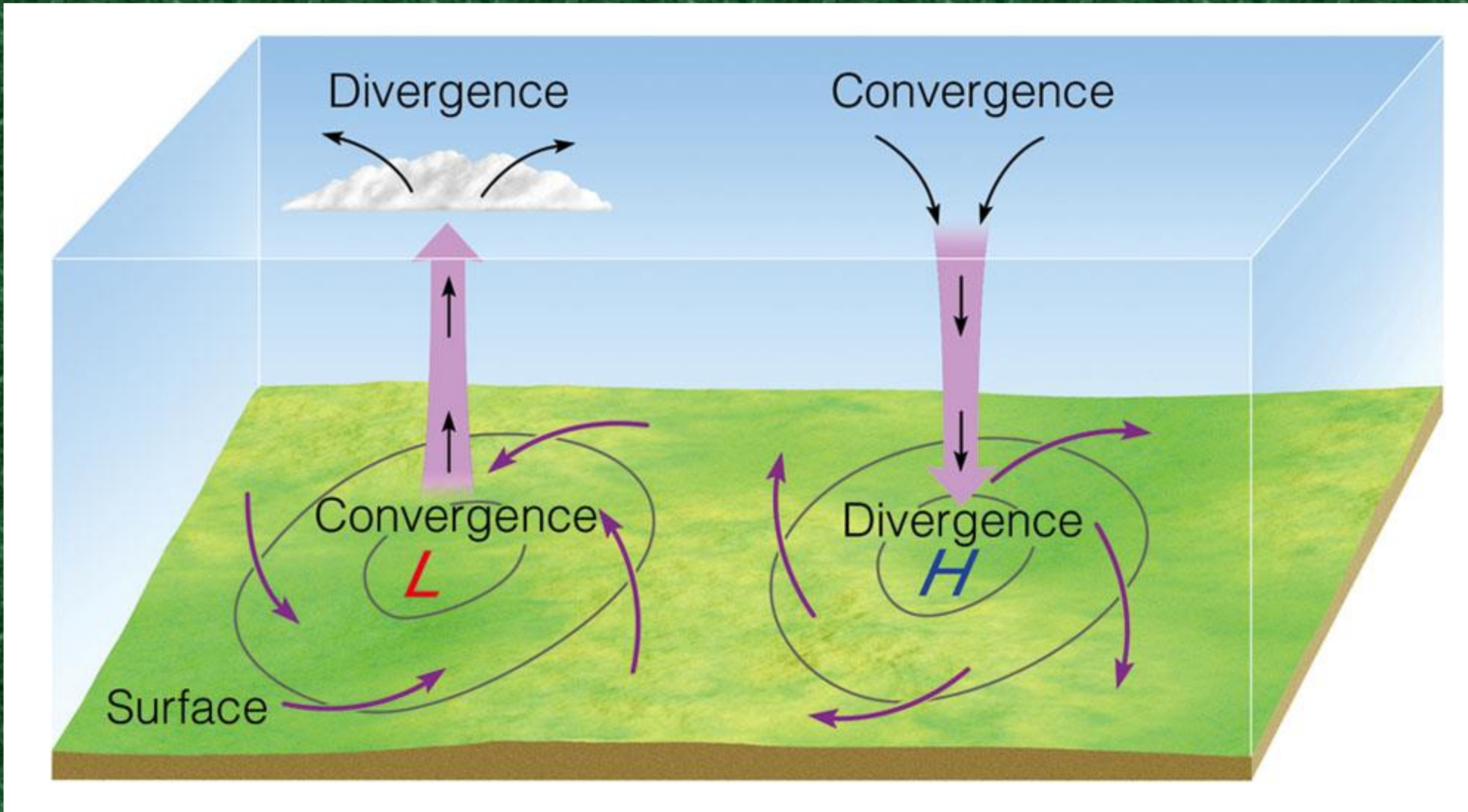


Fig. 14. Divergence versus vorticity. Holes are indicated by (◇), clouds are indicated by (×). The lines associated with each feature indicate error bars calculated from the standard deviation of the best fit to the constituent winds.

McGouldrick et al. (2012) Icarus 217:615.



- Tracking same feature at different altitudes can measure this…

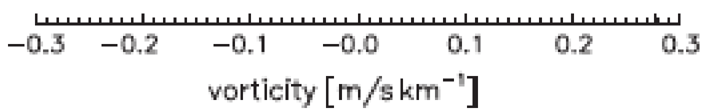


Fig. 14. Divergence versus vorticity. Holes are indicated by (◇), clouds are indicated by (×). The lines associated with each feature indicate error bars calculated from the standard deviation of the best fit to the constituent winds.

McGouldrick et al. (2012) Icarus 217:615.

Summary of Cloud and Hole Wind Speed Effects

VIR0383

Point	<U>	<V>
West Edge	-50 m/s	+1.0 m/s
East Edge	-55 m/s	+7.0 m/s
Peak rad	-64 m/s	+2.6 m/s

VIR0384

Point	<U>	<V>
West Edge	-57 m/s	+3.9 m/s
East Edge	-71 m/s	-0.3 m/s
Peak rad	-65 m/s	+2.4 m/s

- On average, for these two orbits, the western edge is measured to be slower than the eastern edge.
    - But the speed of the location of the peak in the radiance in each feature seems to be about the same across the two orbits.

The Clouds of Venus in Global Context: A Multispectral Tour