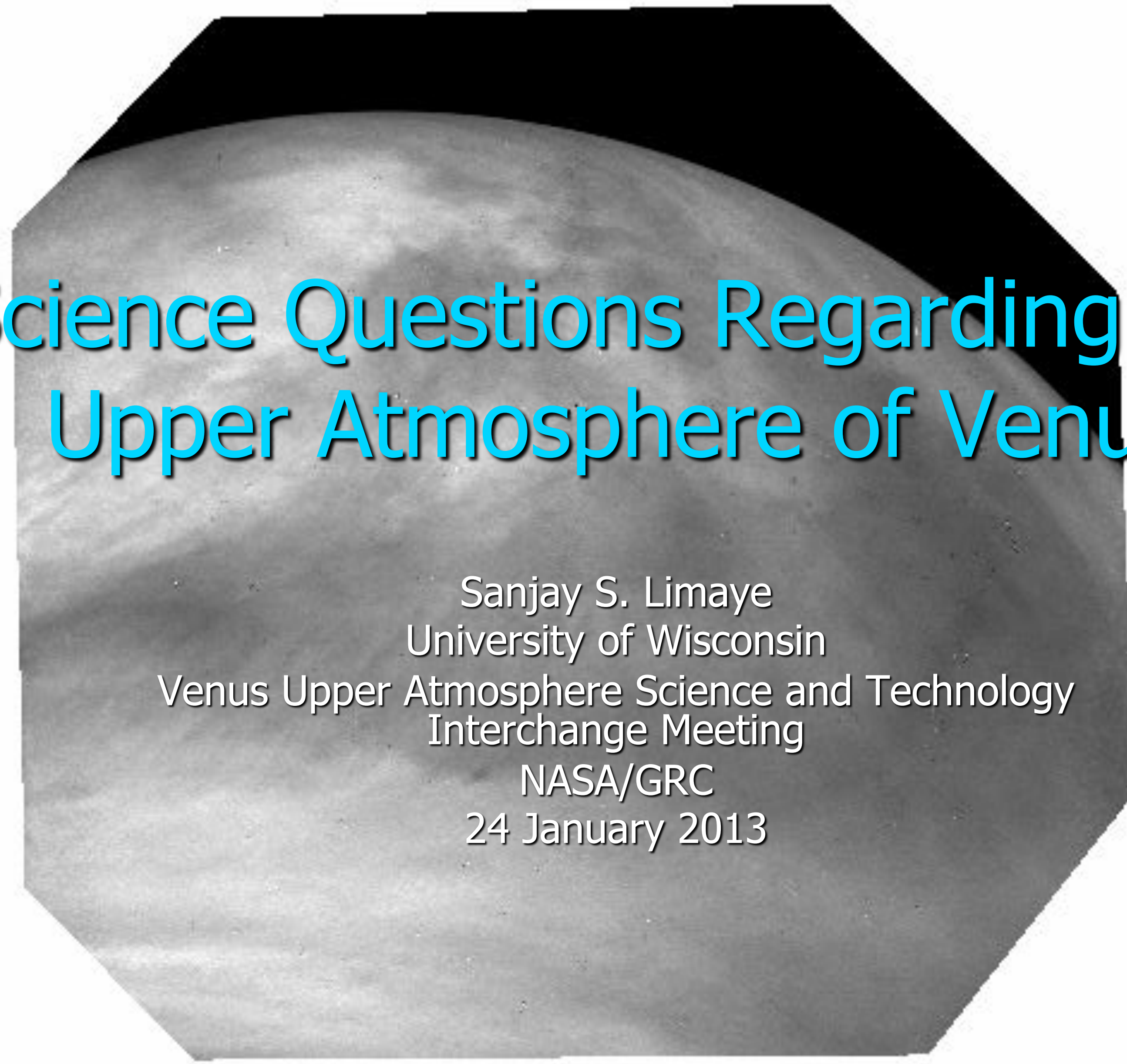
Science Questions Regarding the Upper Atmosphere of Venus



Sanjay S. Limaye
University of Wisconsin

Venus Upper Atmosphere Science and Technology Interchange Meeting

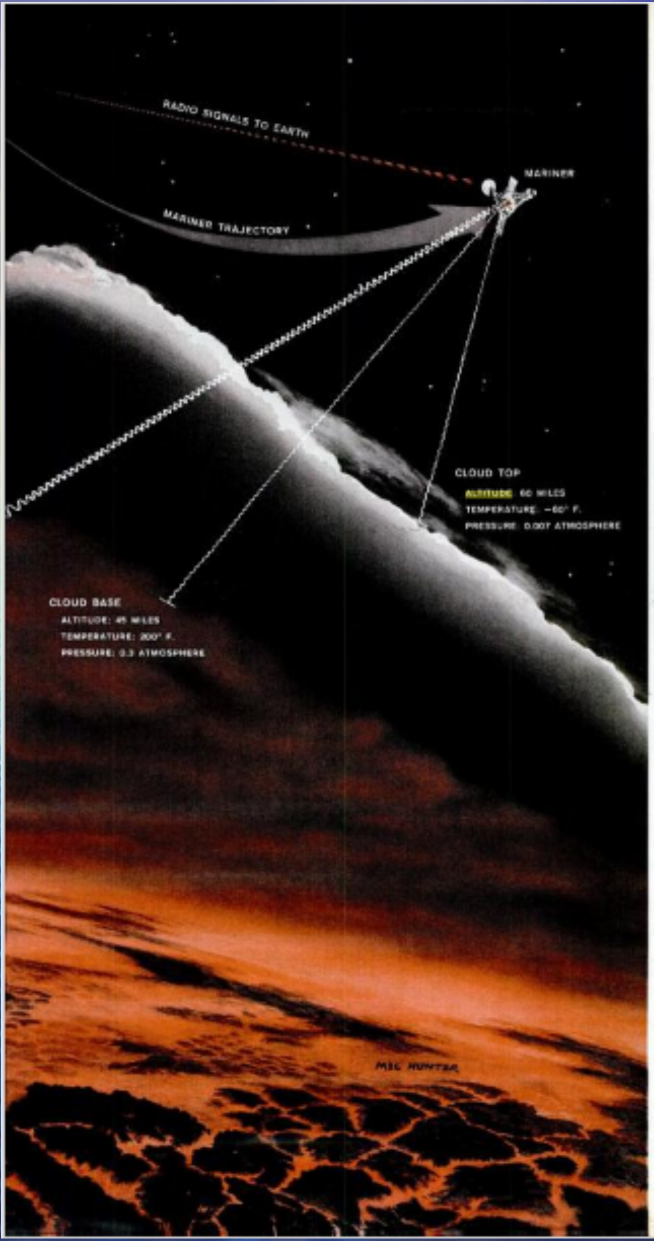
NASA/GRC

24 January 2013

Today’s Measeting

It is being recognized that the thick atmosphere of Venus plays a key role in the current state of Venus. The presence of the atmosphere makes it unlikely that Venus was ever in a 1:1 spin orbit resonance and the interplay between the thermal and the gravity tides lead to the present retrograde state of Venus (Correia and Laskar, Nature, 411, 767-770, 2001).

- Focus on regions of the Venus atmosphere that have not been sampled at all by in-situ measurements or where sampling is inadequate
- What tools/platforms are available to make the needed measurements?
- What technology developments are desired and should be undertaken?



NEWSFRONTS
CONTINUED

VENUS GLOWS IN MARINER PORTRAIT

This is a landscape of the planet Venus. In the past any such portrayal would have been based on the speculations of science-fiction writers, backed by meager spectrographic and radar readings. But this fiery scene is solidly based on data transmitted across 36 million miles from the U.S. spacecraft Mariner II. Now, after ten weeks of decoding at Caltech's Jet Propulsion Laboratory, where Mariner II was designed and built for NASA, the data can be interpreted.

The surface temperature of Venus, according to Mariner, is about 800° F., about 180° higher than the melting point of lead. This makes it seem highly unlikely that any life exists there. If it did, it would have to live on air that consisted of 10% carbon dioxide and (scientists guess) 90% nitrogen, and under an atmospheric pressure 10 times the pressure at sea level on earth. Venus wears an unbroken cloud cover. The earth's cloud cover ends about 10 miles up, but Venus' begins at 45 miles. At that altitude its atmosphere is about a thousand times as dense as earth's at the same altitude.

As it flew by, Mariner took Venus' temperature by measuring radiation (wavy lines in drawing) at different wavelengths from various points on the surface and in the atmosphere. At one point in the clouds Mariner detected a "cold spot" where the temperature took a 20° drop. Radar from earth had also detected a surface irregularity. Scientists believe both may be due to the presence of a mountain range (*at left, on horizon*).

Scientists also believe that Venus rotates so slowly that it may take 225 earth days from one Venusian sunrise to the next. This means that, like the moon, Venus has a "dark side" turned away from the sun for long periods of time. The moon's dark side is incredibly cold, but scientists think that Venus is so well insulated by its dense cloud cover that the surface is just as hot on the dark side as it is on the side facing the sun.

35

General Venus Atmosphere Science Investigations and Questions

- Spatial/Temporal variations in trace species throughout the atmosphere below 100 km
- Above the clouds
  - Breakdown of the cyclostrophic balance when the equator-pole temperature gradient reverses sign resulting in a transition zone for the atmospheric circulation (95 – 110 km)
  - Air glow (~ 95 km) due to NO
  - Higher D/H ratio than below the clouds – loss/escape mechanisms
- In the cloud layer
  - Major deposition of solar energy
  - Cloud physics/chemistry
  - Change in the static stability of the atmosphere from neutral to stable at ~ 50 km
  - Change in the dynamical regime of the atmospheric circulation
  - "Lightning" ?
- Below the clouds
  - Critical point of CO2 is reached (@ 74.8 bar)
  - Kinetic energy and Angular Momentum density peaks occur at ~ 20 km altitude
  - Exchange process at the surface-atmosphere boundary – mass, momentum, heat

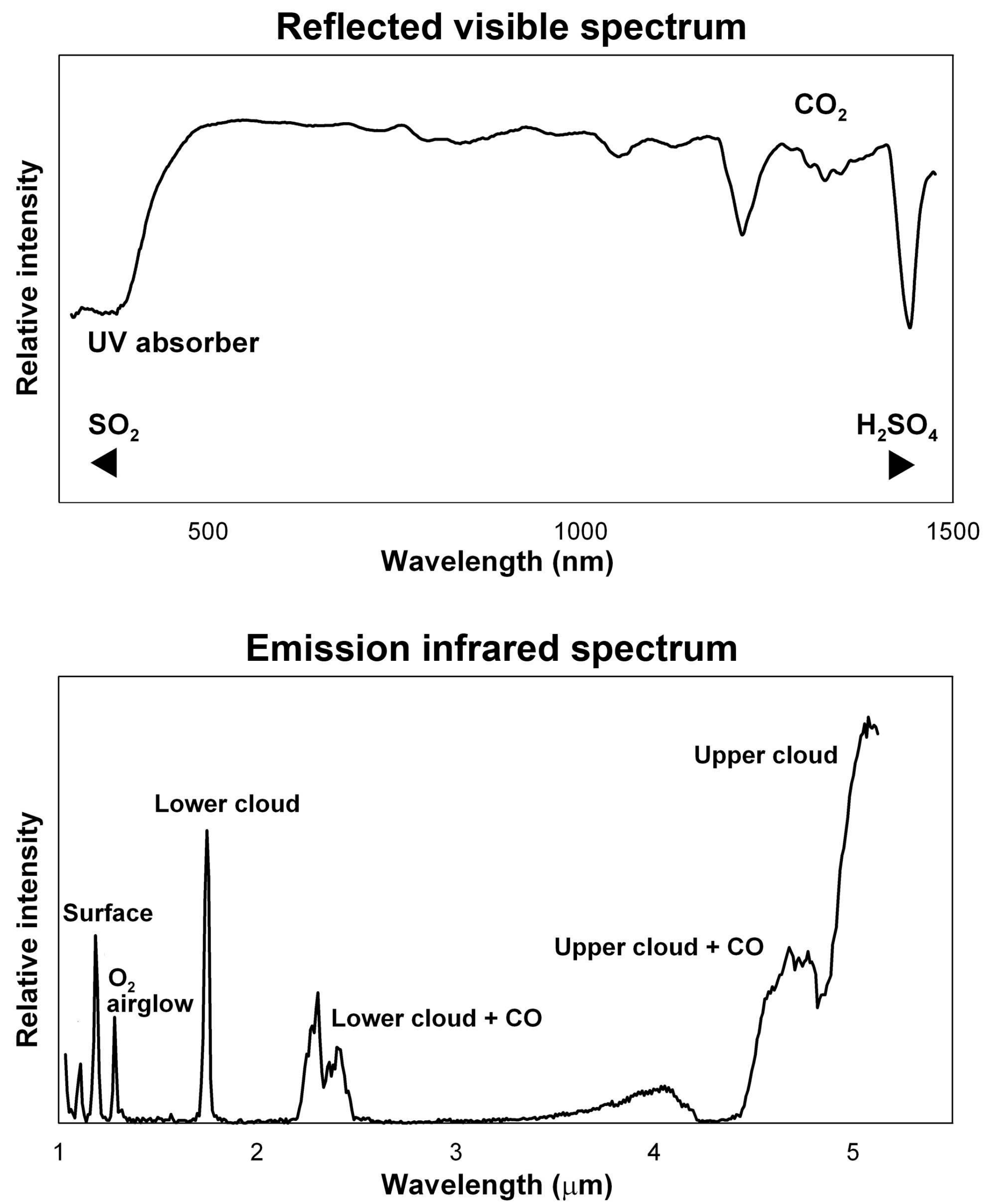
What level are we interested in?

- From Venera and Pioneer Venus entry probes, clouds are believed to reach as deep as 48 km and above the highest level where the measurements began ~ 65 km above the surface (6117 km radius)
- Orbiter measurements of cloud tops range from ~ 75 km in equatorial latitudes to ~ 67 km in polar regions
- Near Infrared observations from Earth and Venus Express reveal significant variations in the cloud opacity regionally and locally
- Clouds are responsible for the dominant fraction of solar energy absorbed by the Venus atmosphere which drives the superrotation
- A major fraction of this energy deposition is due to the presence of an ultraviolet absorber whose properties have yet to be conclusively determined and is likely to be present in the upper most layers of the cloud
- Significant variation in the presence of the ultraviolet absorber from equator to pole

Clouds of Venus

Venus reflected and emitted spectrum. The top panel shows the spectrum in reflected light on the day-side in the vicinity of 1 μm with a mean albedo of 76%.

The bottom panel shows the infrared emission spectrum obtained by VIRTIS on the night-side of the planet with particular observation windows identified.



Almost everything we know about Venus clouds and have based our models on is based on this SINGLE measurement from the Pioneer Venus Large Probe!

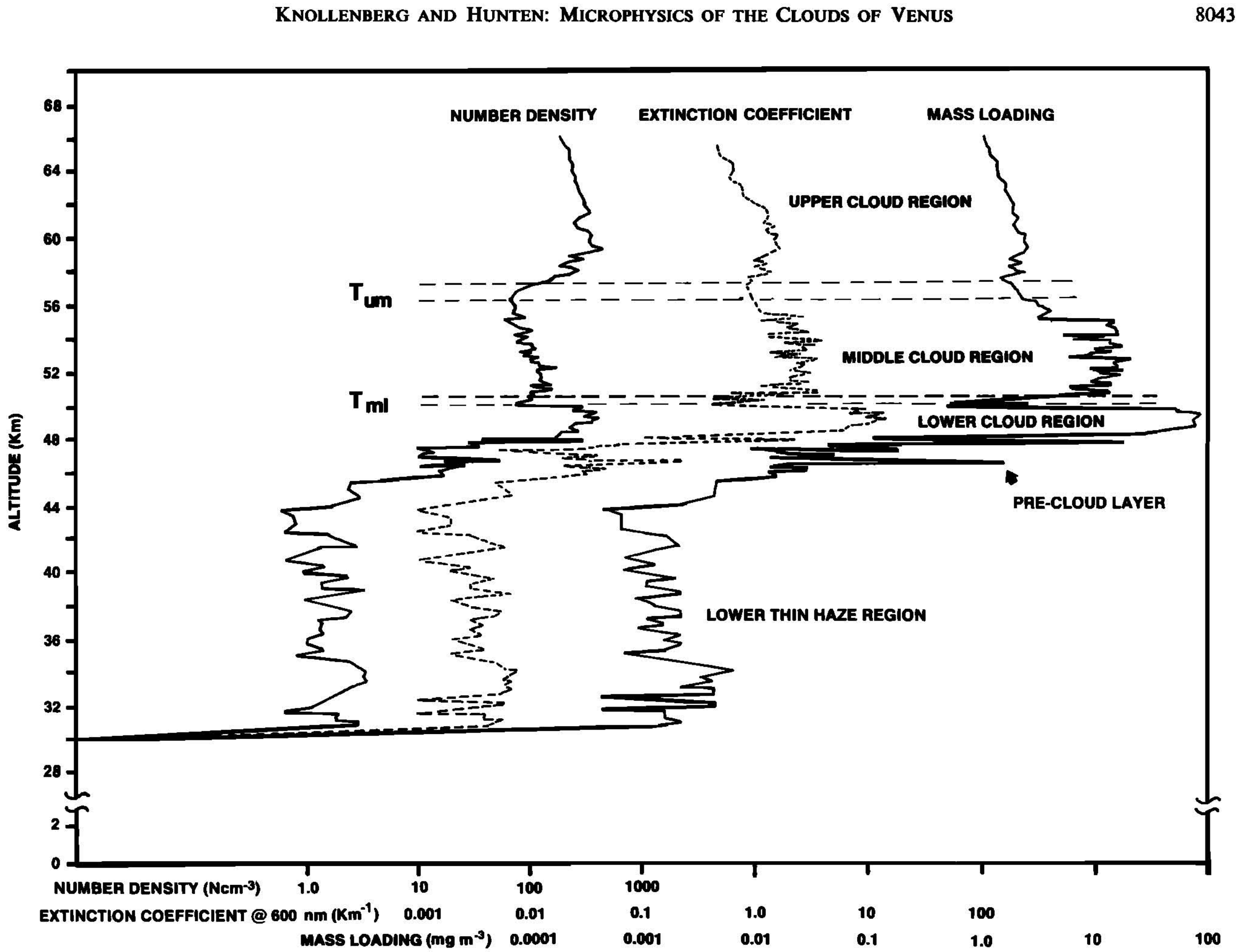


Fig. 4. Vertical structure of Venus cloud system. The above data represent direct computations from the LCPS data. No allowance has been made for particles smaller than the 0.6 μm lower limit of size sensitivity or above the largest sizes actually measured. A density of 2 g cm^{-3} was assumed for mass loading computations. The thickness of T_{um} is about 1 km while T_{ml} is several hundred meters thick.

The vertical cloud structure is found to consist of three primary cloud regions of approximately 20 km total thickness suspended within an ubiquitous aerosol haze which extends more than 10 km above and below it.

The three cloud regions are separated by sharp transition regions where both particle chemistry and microphysics exhibit change.

The size distributions are multimodal in all cloud regions. Three size modes are observed in the middle and lower cloud region which are composed of aerosol, H2SO4 droplets, and crystals. The crystals likely could be either sufates or chlorides.

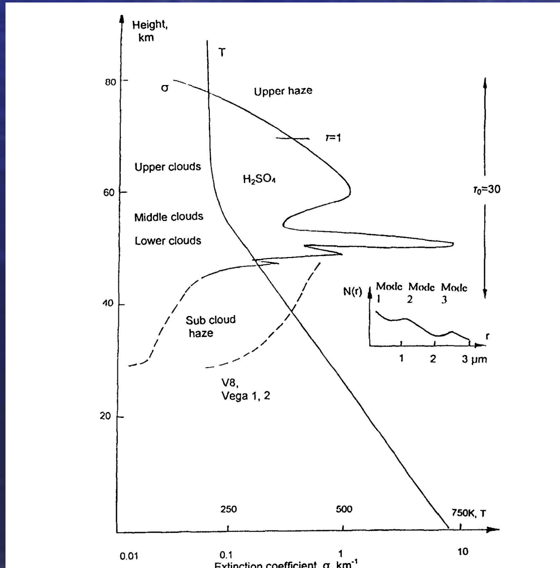
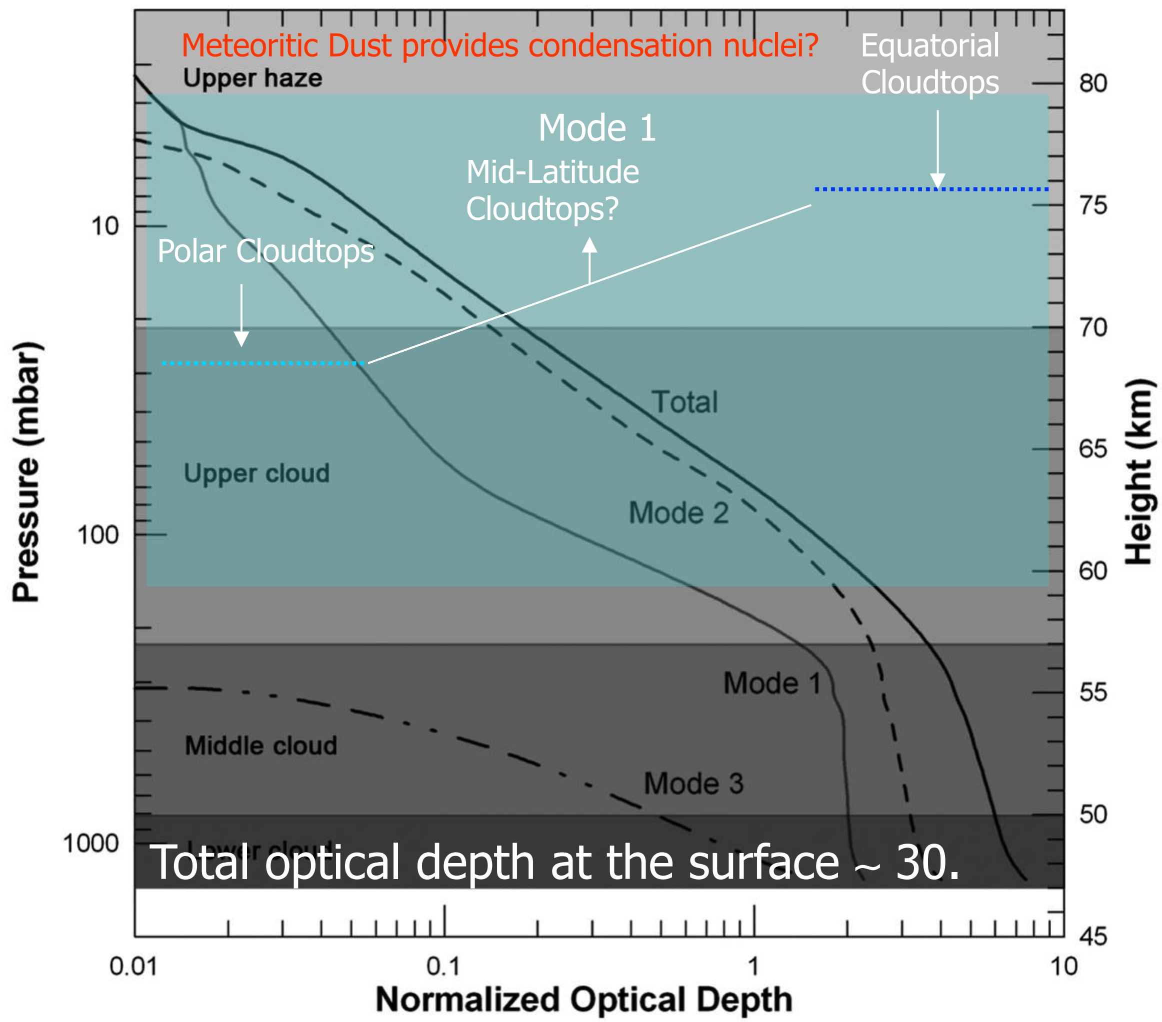


Fig.3. A scheme of the vertical structure of the aerosol medium in the atmosphere of Venus.

Vertical distribution of particles in Venus atmosphere. Shaded areas mark the extension of the three cloud decks and the haze above. Lines show the contribution to the total optical thickness normalized to the value at 630 nm for an isotropic scatterer. Modes represent different particle sizes.

CO_2: Critical Point: 304.19 K , 73.8 bar



Mode 1: smallest particles with radii around 0.1 μm. These are dominant in the upper part of the atmosphere and probably have their origin in the photochemical processes taking place in even higher locations of the atmosphere

Modes 2 (radii ~ 1.0μm)

Mode 3 (radii around 3.0 – 5.0μm)

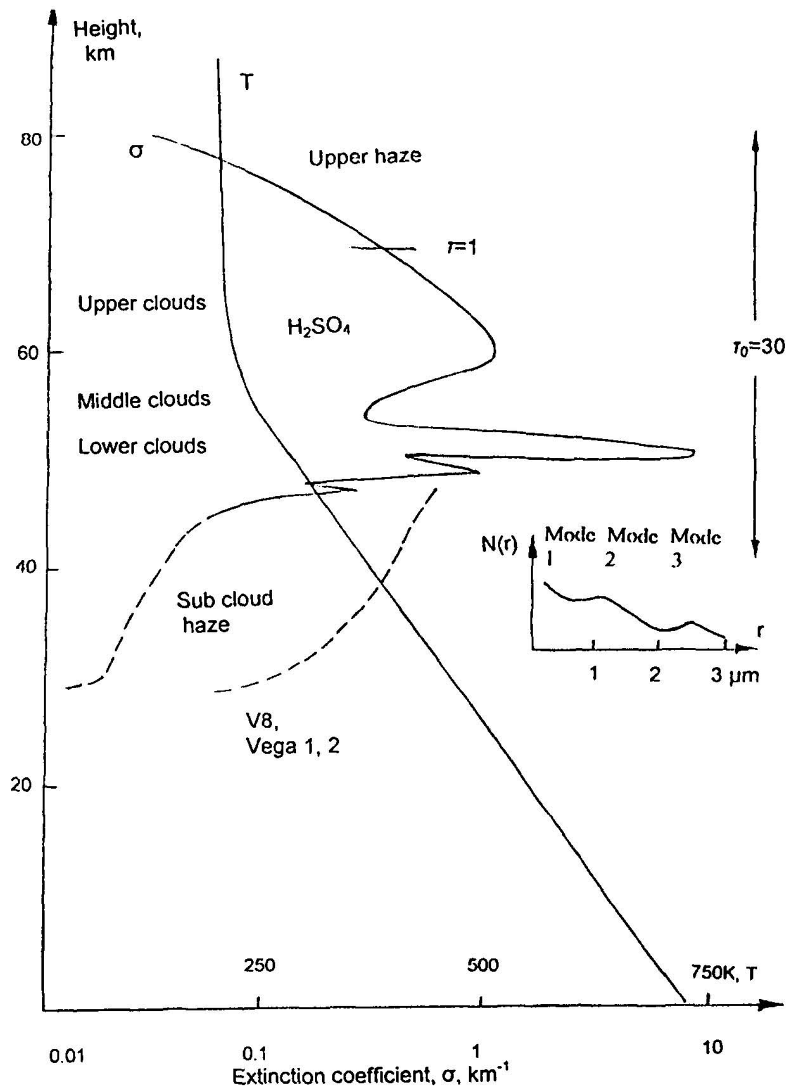


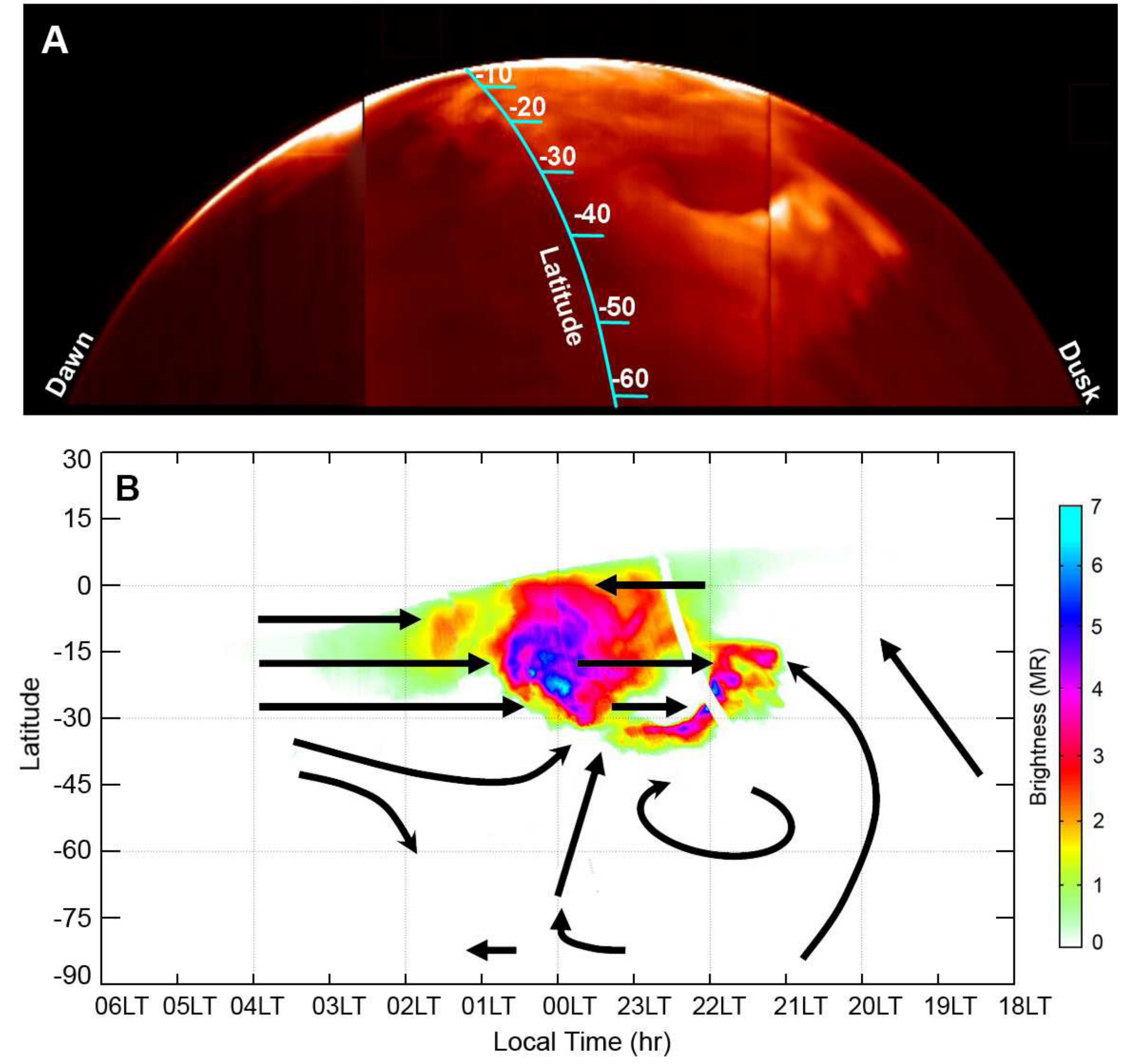
Fig.3. A scheme of the vertical structure of the aerosol medium in the atmosphere of Venus.

Mode	Effective radius (μm)	σ
Mode 1	0.30	0.44
Mode 2	1.00	0.25
Mode 2′	1.40	0.21
Mode 3	3.65	0.25

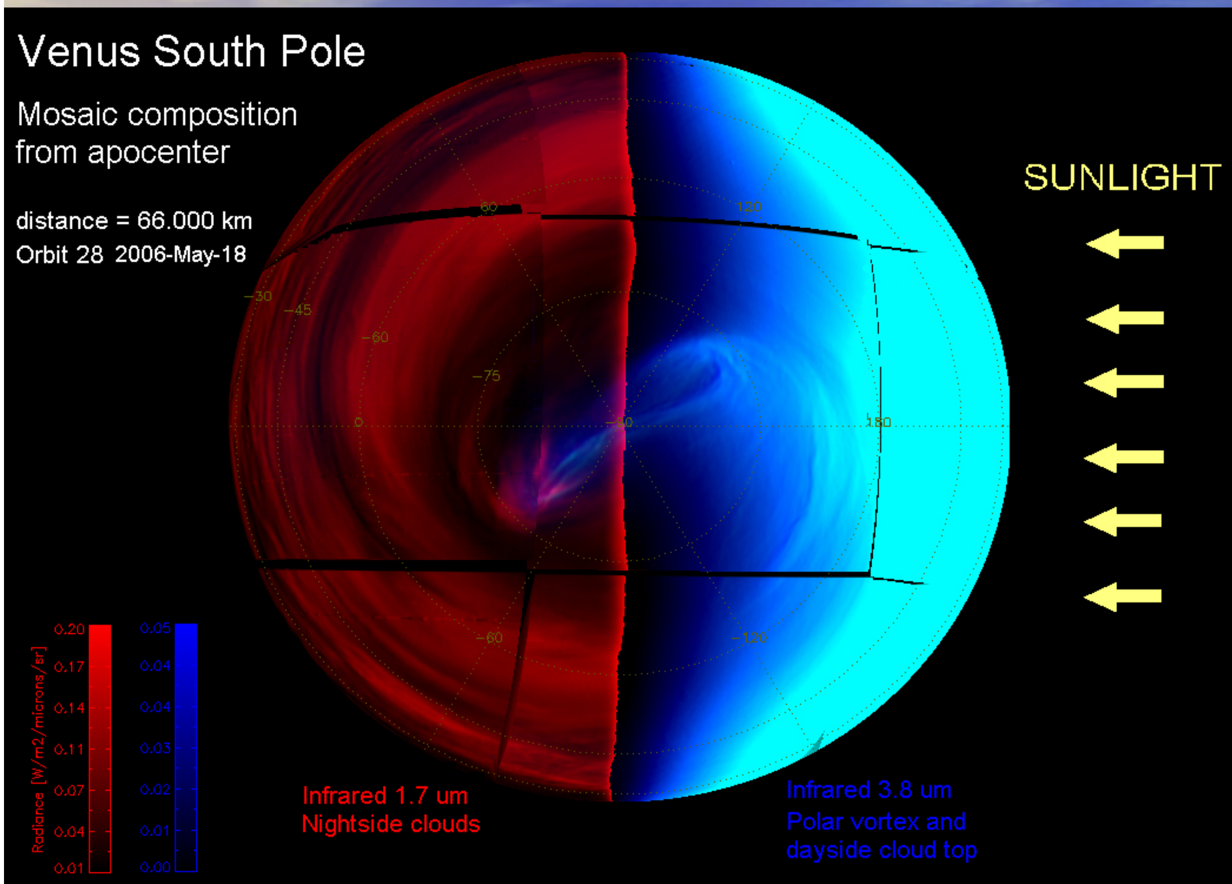
Pollack et al. Near-infrared light from Venus' nightside: A spectroscopic analysis Icarus, 103 (1993), pp. 1–42.

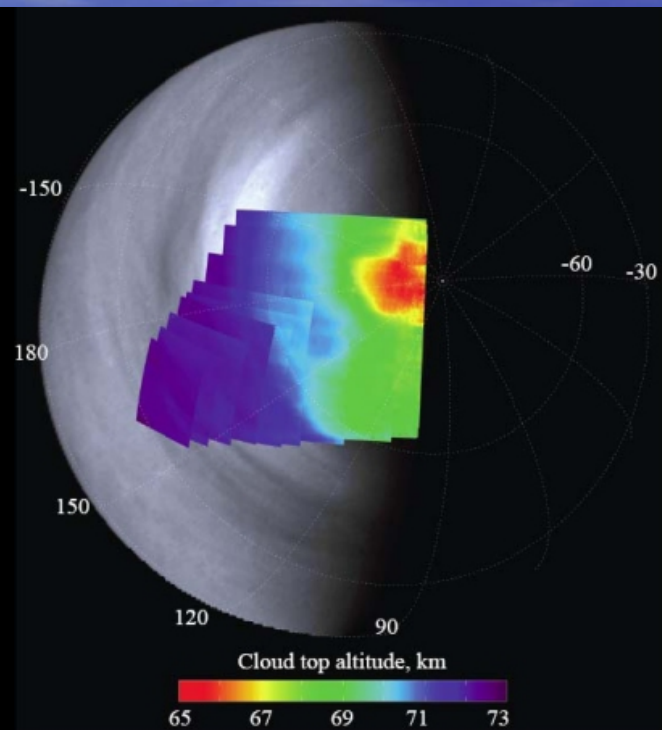
Results from Venus Express

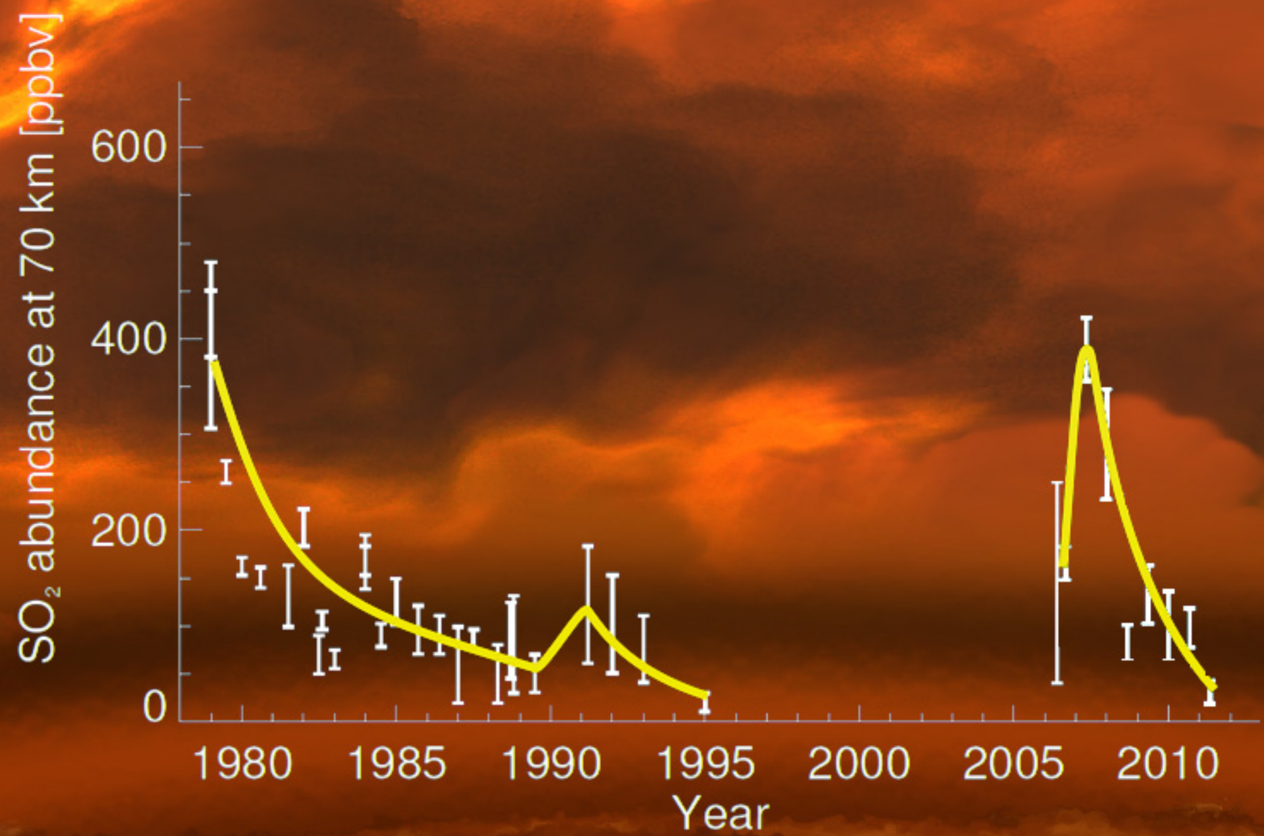
Airglow structures (bright patches) and average derived motions averaged over several Venus Express orbits. The airglow intensity largely increases at equatorial latitudes and specially at the antisolar point.



(Bougher, S. W., Rafkin, S. and Drossart, P. 2006, Planet. Space Sci. 54, 1371)

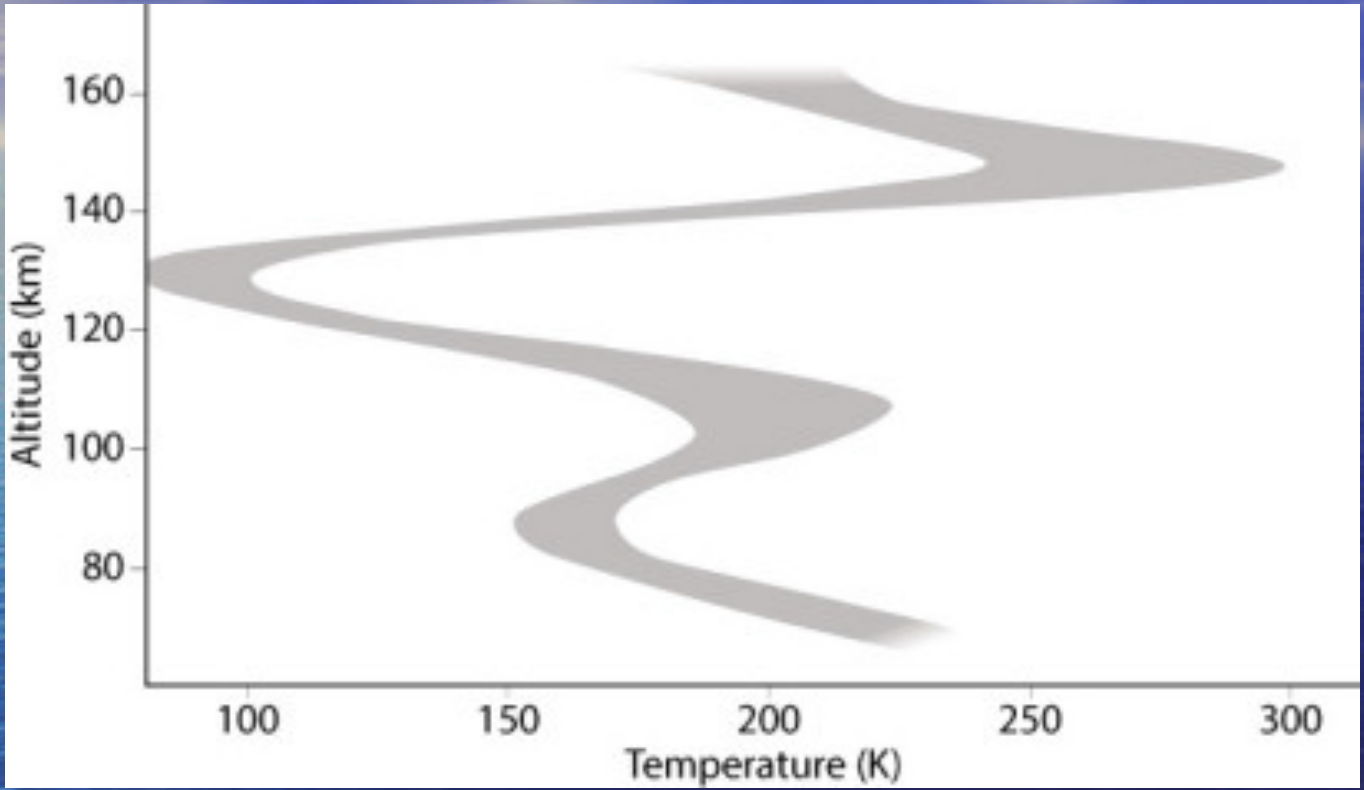

Venus South Pole
Mosaic composition from apocenter
distance = 66.000 km
Orbit 28 2006-May-18
SUNLIGHT
Infrared 1.7 um
Nightside clouds
Infrared 3.8 um
Polar vortex and
dayside cloud top


-150
180
150
120
90
-60
-30
Cloud top altitude, km
65
67
69
71
73



SO2 abundance at 70 km [ppbv]
600
400
200
0
1980
1985
1990
1995
2000
2005
2010
Year

It gets very cold on Venus at ~ 130 km between 77 – 89 S latitude!



Densities and temperatures in the Venus mesosphere and lower thermosphere retrieved from SOIR on board Venus Express: Carbon dioxide measurements at the Venus terminator," by A. Mahieux et al. is published in the Journal of Geophysical Research - Planets, vol 117, E07001, 2012. DOI:10.1029/2012JE004058

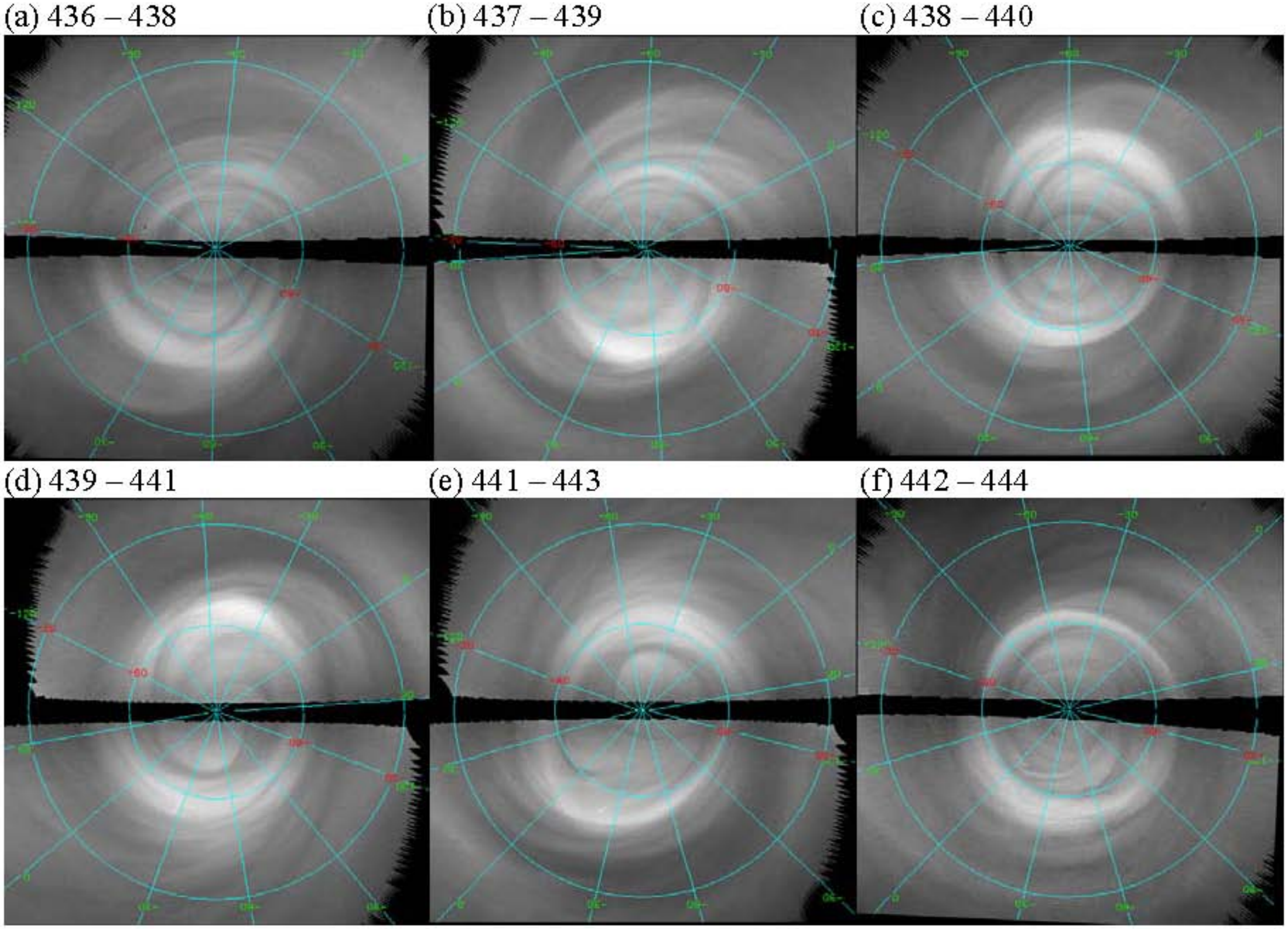
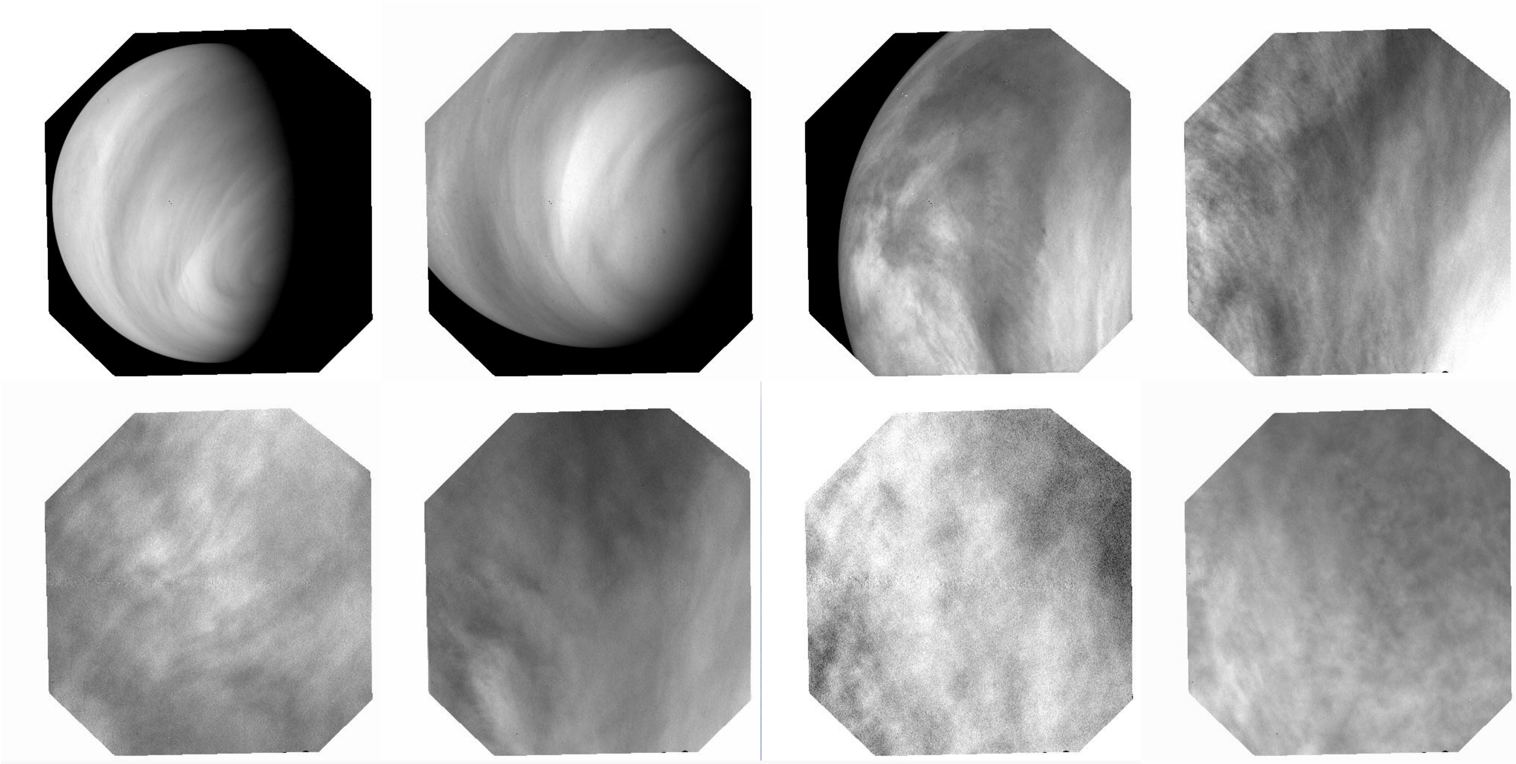
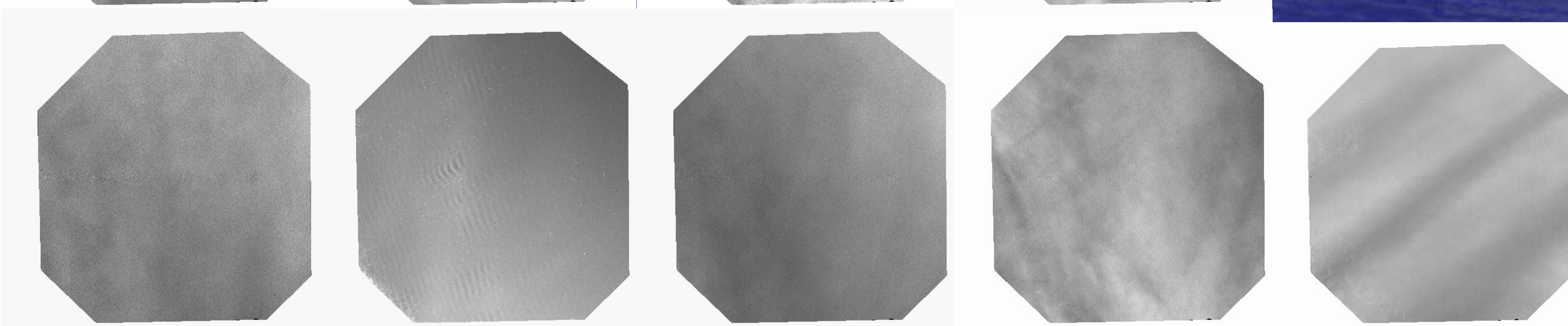


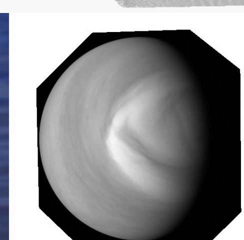
Figure 1. Space-time composite view of the southern hemisphere of Venus from polar stereographic projections of UV imagery taken by VMC on Venus Express over a seven-day period. Only two images separated by two orbit numbers are used per panel. In each panel, the succeeding image is rotated by about 180° in two-days time in order to use the approximate four-day rotation period for adequate matching of spiral bands and/or inner-core asymmetries.

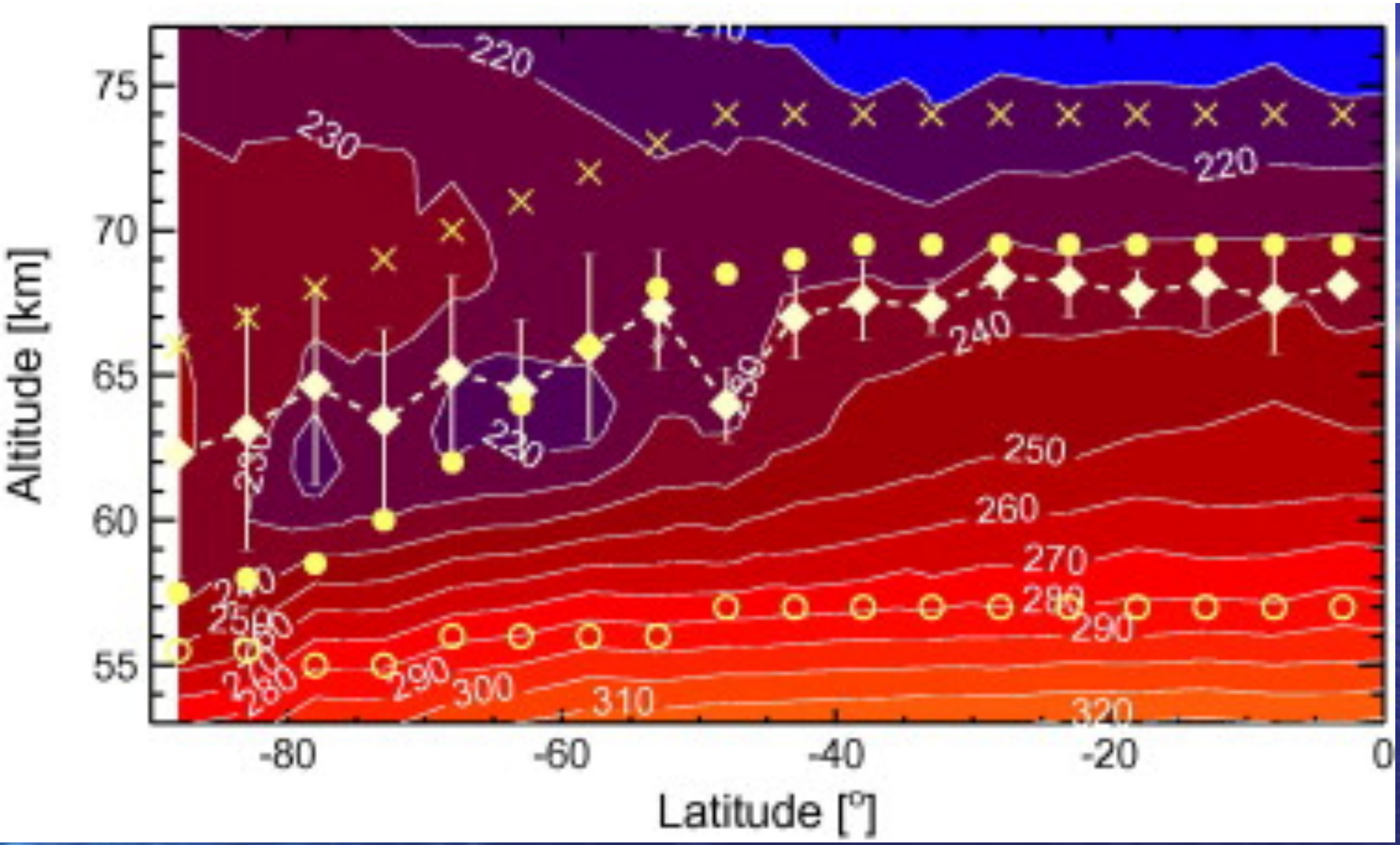


UV absorber is highly variable on Venus as thse images show.

At other wavelengths contrast is much lower, but detectable







Latitude dependence of the cloud top altitude overplotted on the VeRa latitude–altitude temperature field: diamonds – this study (4–5 μm); crosses – VIRTIS spectroscopy in the 1.6 μm CO2 band (Ignatiev et al., 2009); filled and open circles – approximate Venera-15 Fourier spectroscopy in the 8.2 and 27.4 μm, respectively (Zasova et al., 2007).

Lee t al., Icarus, Volume 217, Issue 2, February 2012, Pages 599–609

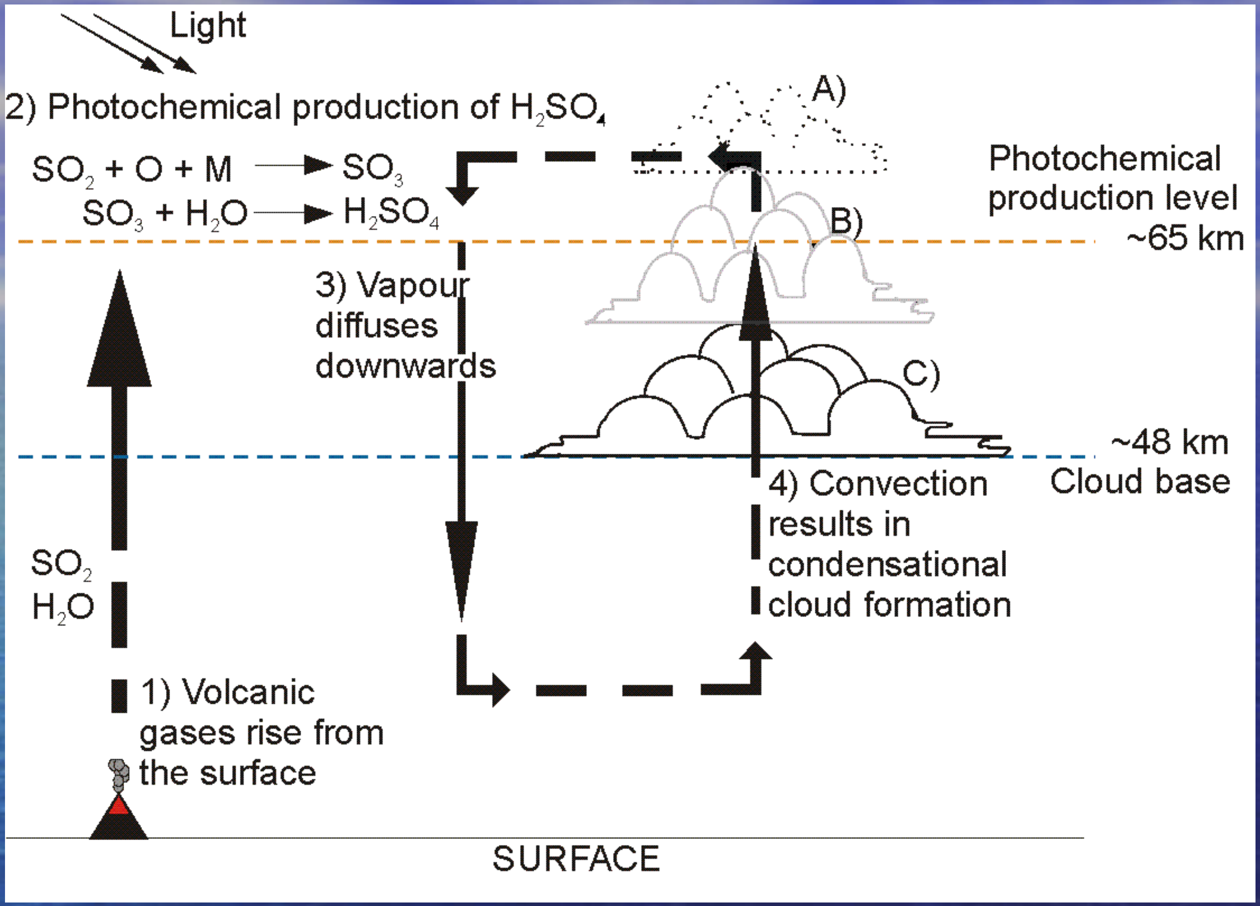


Figure 4: A simple schematic of how sulphuric acid clouds may form on Venus. A) marks the upper haze, B) is the upper cloud composed of mode 1, mode 2 and UV absorber particles, and C) is the lower cloud made mostly of mode 2′ and mode 3 particles, as described by Crisp (1986) and Pollack et al. (1993).

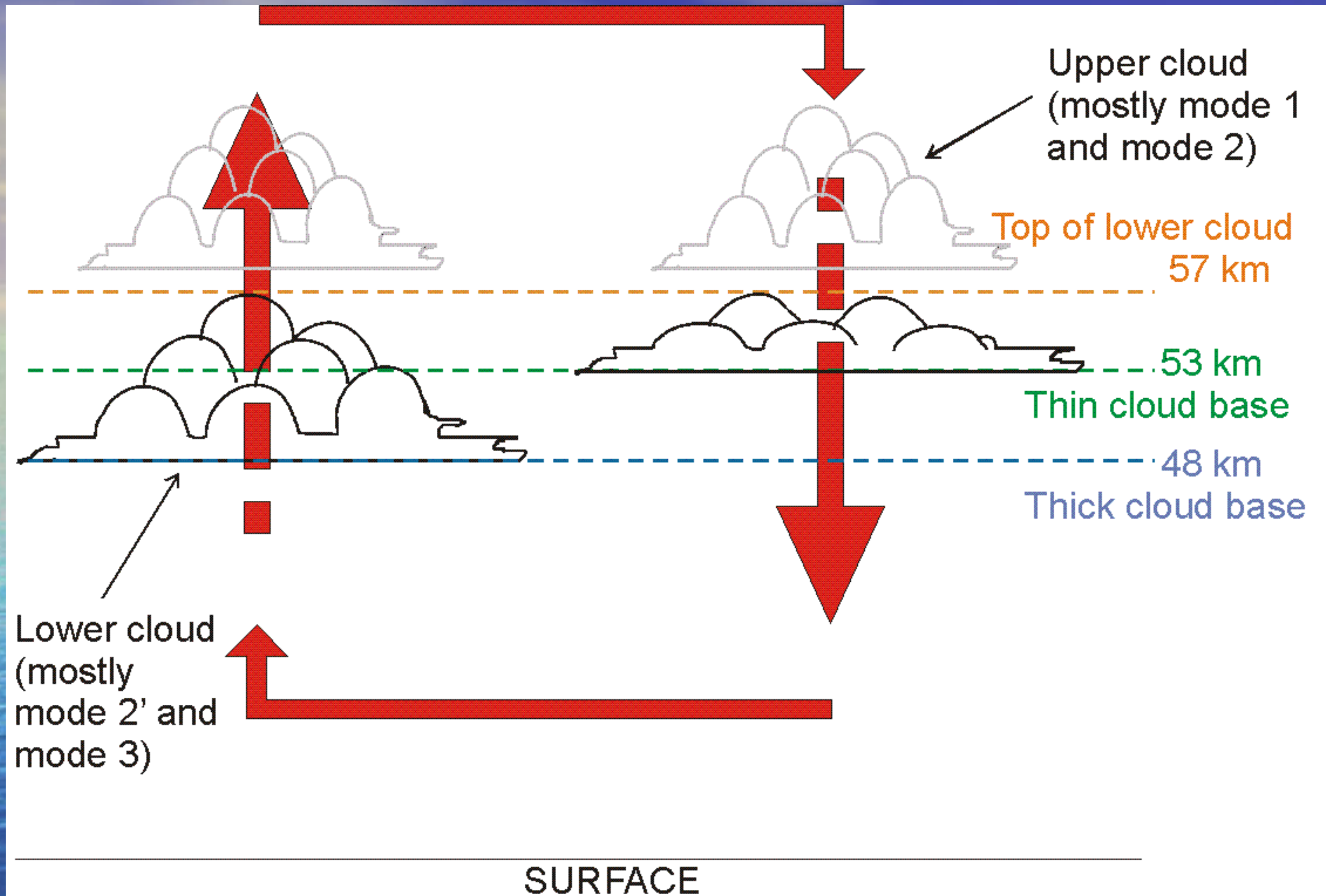
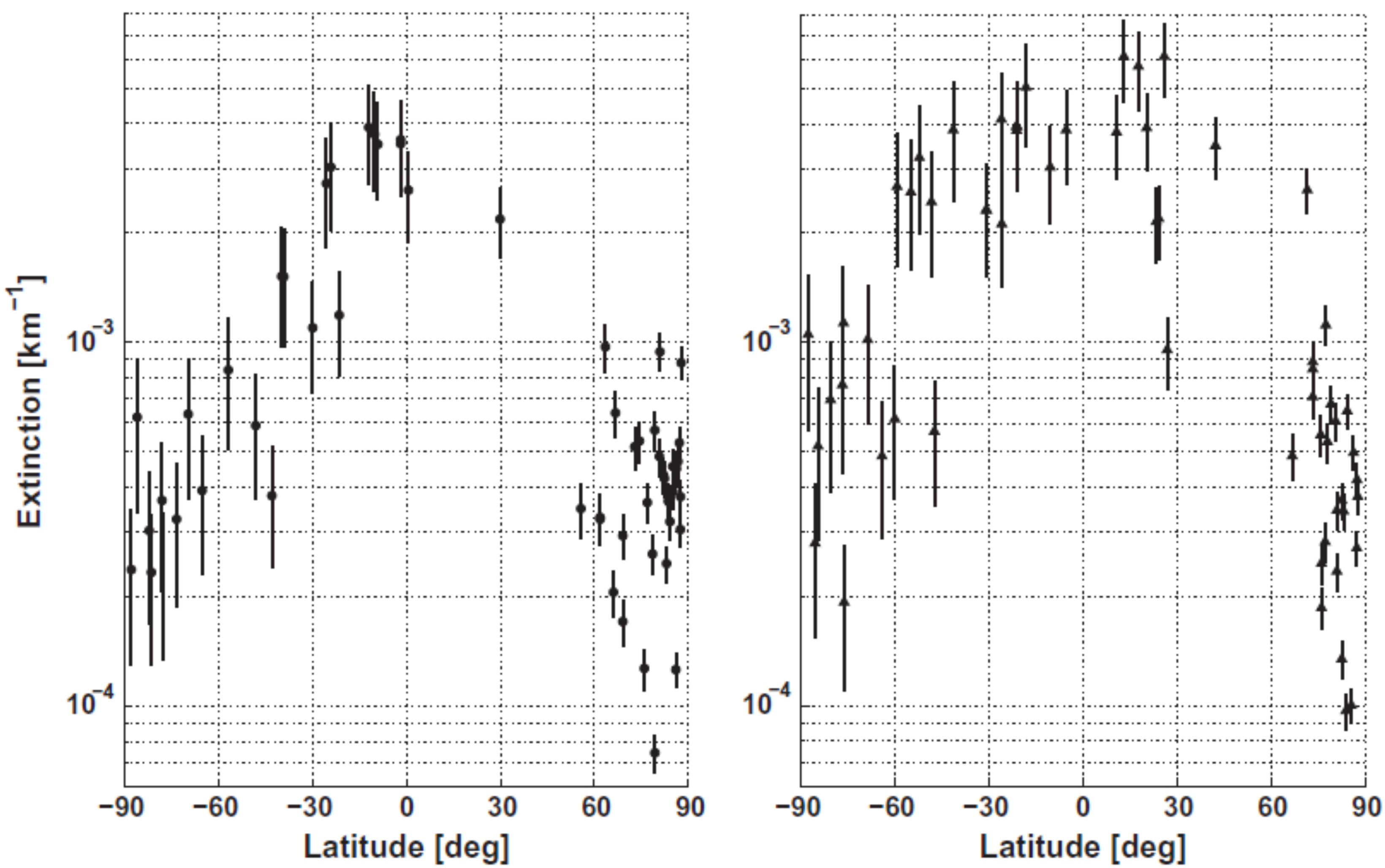


Figure 16: A simple representation of how cloud base variations may occur on Venus. Arrows indicate the presence of a convection cell. Thick cloud forms in regions of upwelling as H2SO4 vapour is transported upwards and Condenses (Barstow, 2007, Thesis)

Latitudinal variations of the extinction at 80 km of altitude for the all data set. On the left-hand panel, the values of the extinction for SO at the morning terminator (●) are plotted as a function of the latitude and on the right-hand panel, for observations at the evening terminator (▲). The vertical bars represent the error on retrieved b.

V. Wilquet et al. / Icarus 217 (2012) 875–881



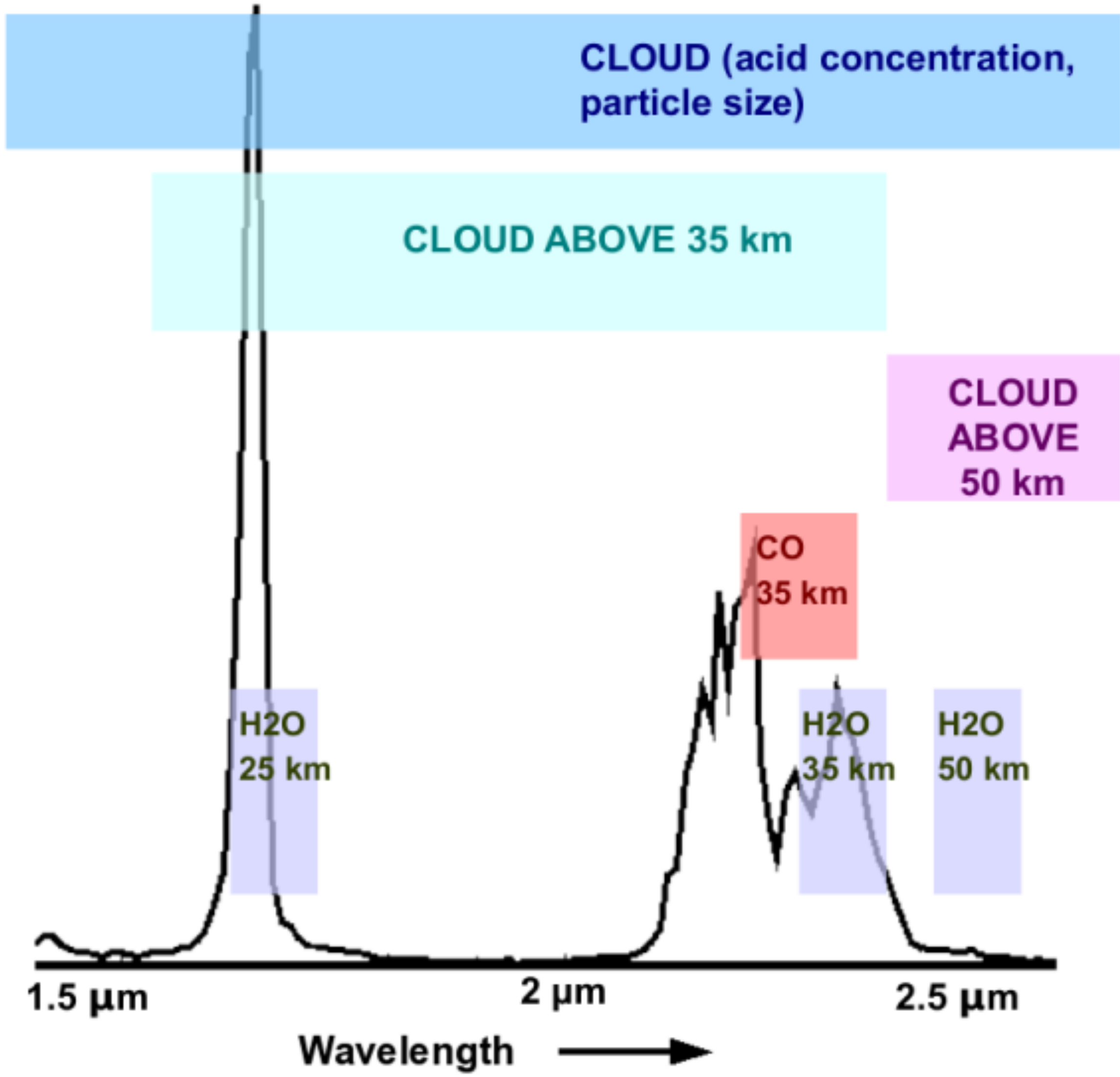
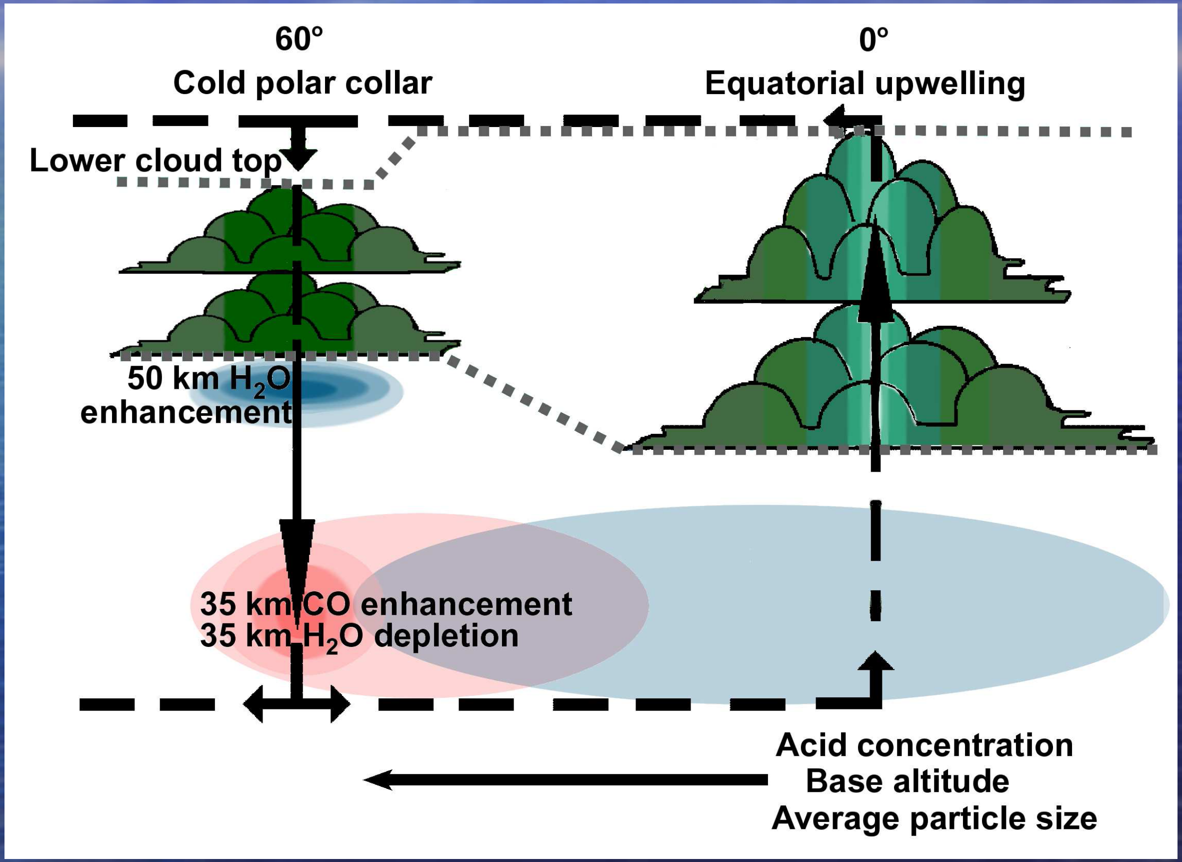


Figure 7: Sensitivity to the acid concentration, mode 3 abundance, base altitude and CO and H_2O between 1.6 and 2.6 µm.

Figure 24: Variation of cloud properties with latitude. (Barstow)



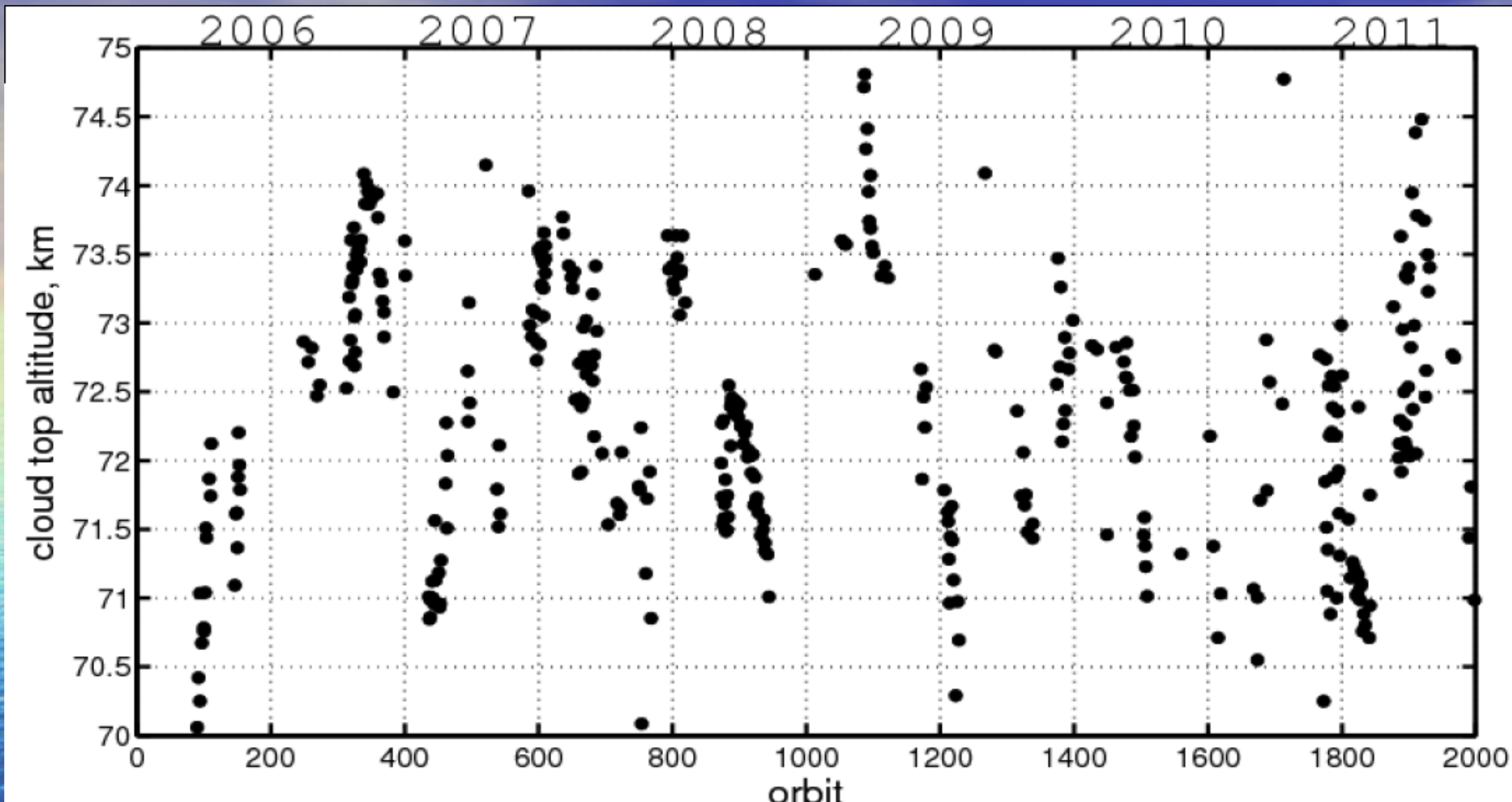


Figure 4: Variations of the cloud top with orbit. The values were averaged within the latitude range of 40°S-40°N, local time 8:00-16:00 hours and emission angle below 30°. (Fedorova et al., EPSC, 2012)

Maps of the SO2 abundance on Venus at the cloud level during three consecutive nights (January 10, 11 and 12, 2012), obtained from the line depth ratio of two weak neighbouring lines of SO2 and CO2. The maximum mixing ratio of SO2 varies from 75 10-9 (Jan. 10) to 125 10-9 (Jan. 11) with an intermediate value on Jan. 12. These values are compatible with Venus Express results. T. Encrenaz, et al.,, Astron Astrophys. 543, A153(2012)

SO2 highly variable locally and on short term (~ day)

Maps of the water vapor abundance (measured through its proxy HDO) and the sulfur dioxide SO2 have been measured during three successive nights. The abundances are measured from the line depth ratio of HDO and SO2 versus CO2, the major atmospheric component. H2O and SO2 are the two key elements involved in the condensation and saturation of the sulfuric acid present in the clouds.

globally uniform, shows little variation on a timescale of 48 hours, the SO2 map (Fig. 2) shows local variations up to a factor 10 and very strong temporal variations on a timescale of 24 hours. These variations cannot be due to dynamical motions as they would imply very fast winds at the cloud level, not compatible with the wind speeds measured by Venus Express. More likely, the SO2 variations are due to the very short photochemical lifetime of sulfur dioxyde.

SO_2/CO_2 maps

Jan 10 & 12: SO_2 @ 1350.16 cm^{-1}, CO_2 @ 1350.4 cm^{-1}

Jan 11: SO_2 @ 1366.43 cm^{-1}, CO_2 @ 1366.36 cm^{-1}

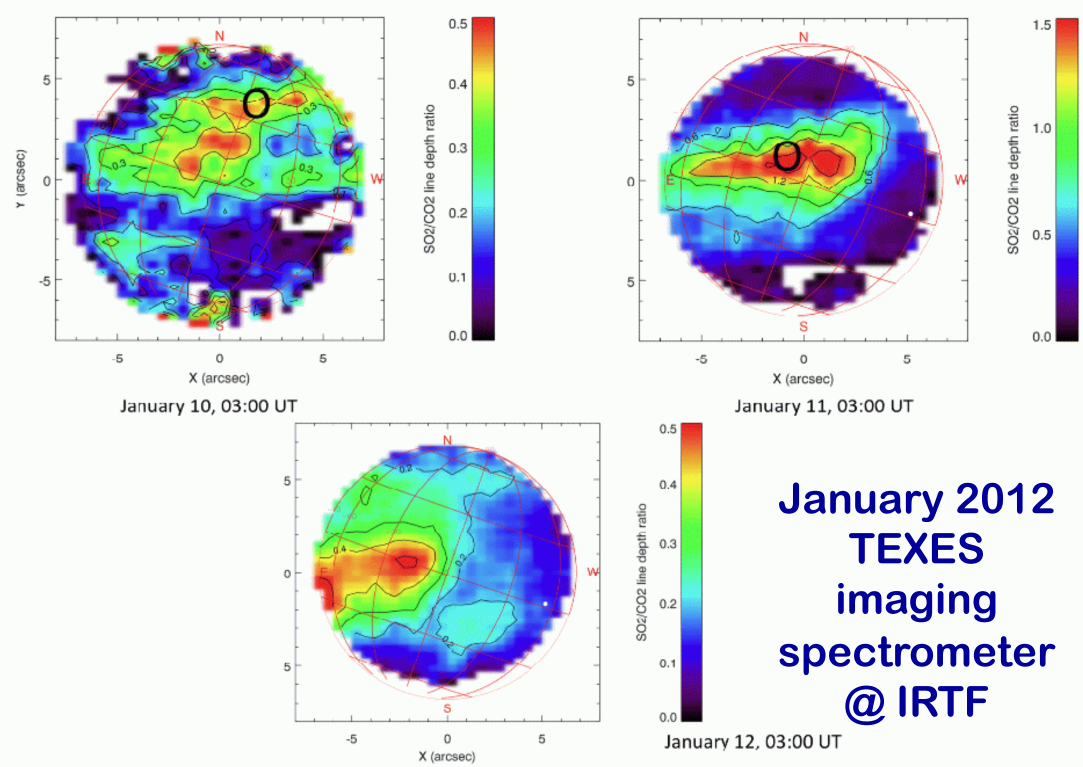
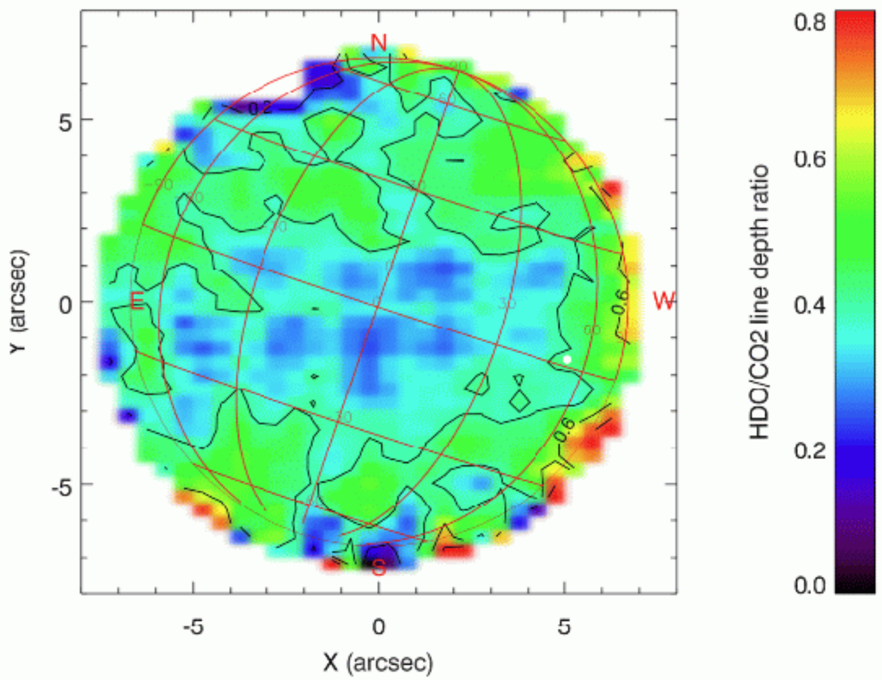


Figure 1: *Maps of the HDO abundance at the cloud level, obtained from the line depth ratio of two weak neighbouring lines of HDO and CO2. Left: 10 January 2012; Right: 12 January 2012. Assuming a D/H ratio of 200 times the terrestrial value (as measured by Venus Express), the mean mixing ratio of water is 1.5 10**-6**, in agreement with Venus Express measurements.*

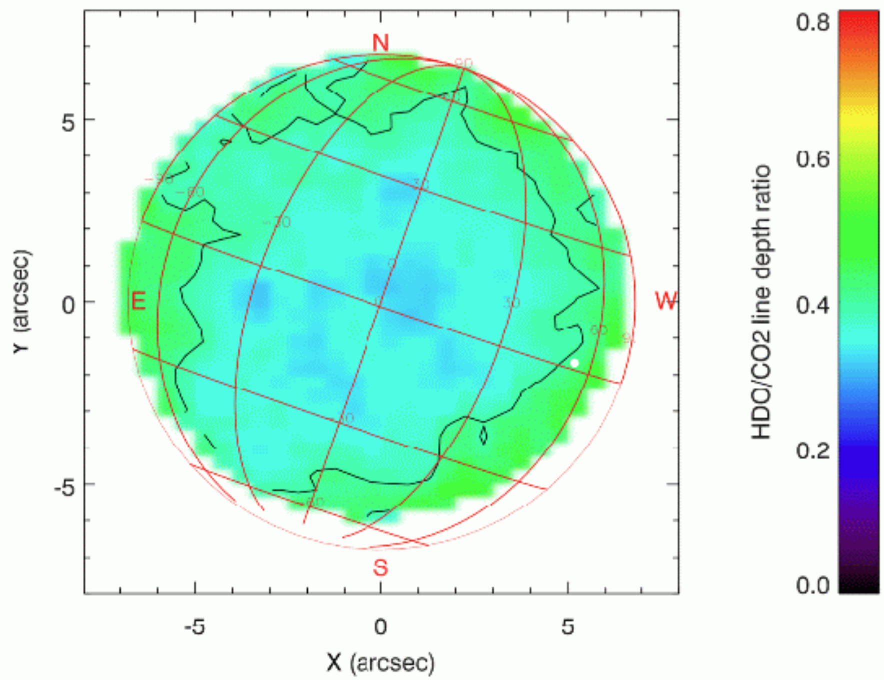
HDO/CO_2 maps

HDO @ 1350.3 cm^{-1}, CO_2 @ 1350.4 cm^{-1}

January 10, 03:00 UT



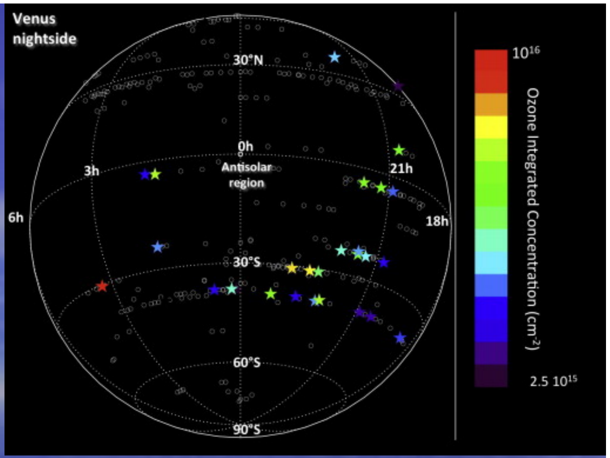
January 12, 03:00 UT



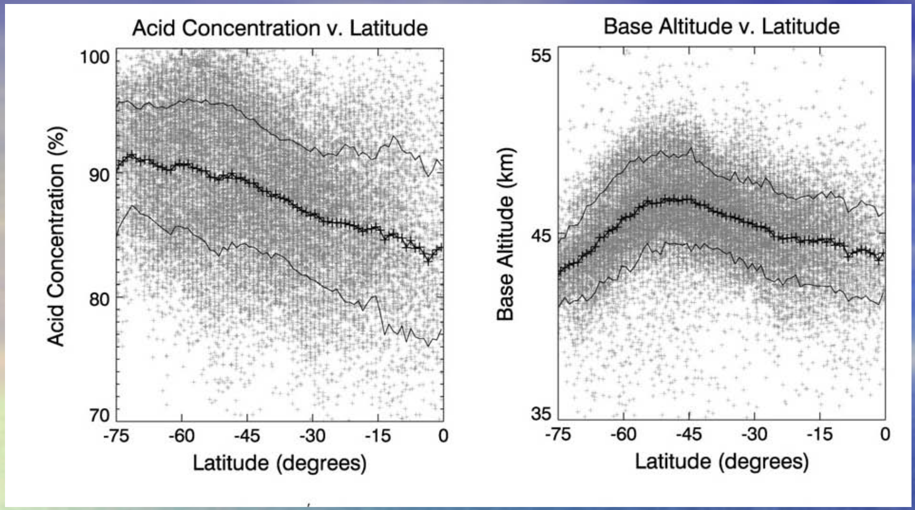
Detection of Ozone

Nightside view of Venus showing the ozone detections of SPICAV. Positive identifications are indicated by stars with a color code scaled to the ozone abundance integrated along the line of sight (molecules cm−2). Empty circles point the location of all successful occultation performed between April 2006 and July 2010, without positive detection. As noted for the observations of the OH emission with VIRTIS (Piccioni et al., 2008, Migliorini et al., 2010 and Soret et al., 2010), ozone shows no obvious maximum in column abundance in the antisolar region where the thermospheric

circulation subsides and the O2 airglow emission concentrates.



- Ozone detected on Venus by SPICAV (Montmessin et al., Icarus, Volume 216, Issue 1, November 2011, Pages 82–85).
- The observed ozone concentrations are consistent with values expected for a chlorine-catalyzed destruction scheme, indicating that the key chemical reactions operating in Earth’s upper stratosphere may also operate on Venus



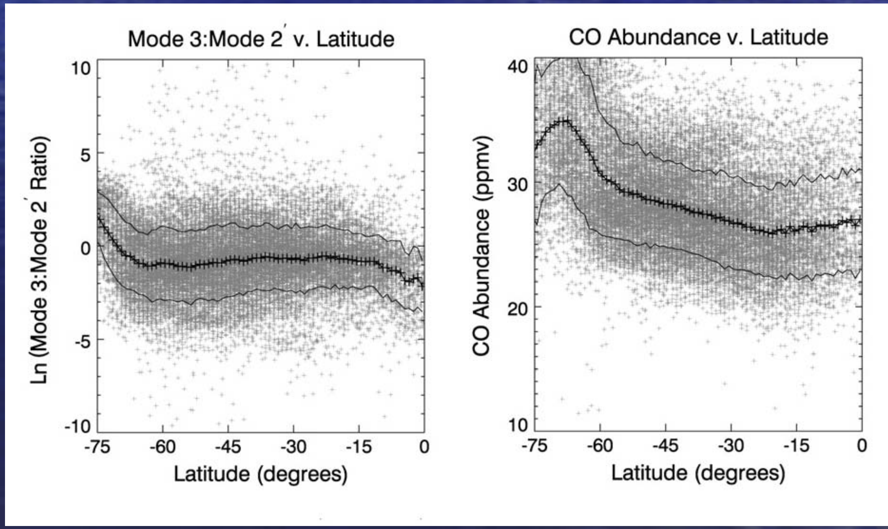
The acid concentration is higher in regions of optically thick cloud, where it ranges from ~90 to 100 wt%, than in thin cloud where it is between 75 and 85 wt%. It also increases from ~80 wt% at low latitudes to 90 wt% polewards of −60°.

Wilson et al. (2008) found that the relative number of large cloud particles increases towards the pole, and this result is reproduced here. Wilson et al. (2008) postulate that the downwelling at the poles removes the more volatile smaller particles from the cloud and results in their evaporation. Barstow et al. suggest that the composition of the cloud particles changes towards the poles. This is still an open question and a conclusive explanation for this phenomenon is deferred until the next in situ Venus mission.

The altitude of the cloud base falls from 46 at −50° latitude to 42 km at −75°, and this behaviour correlates with a strong decrease in the abundance of water vapor at 35 km, from 40 to 30 ppmv.

The abundance of sub-cloud water vapor is also ~10 ppmv lower in regions of very thick cloud compared to moderately cloudy regions.

Little variation in cloud structure is observed as a function of local solar time and longitude..



Variation of Cloud Height with Latitude *(Ignatiev et al., 2009)*

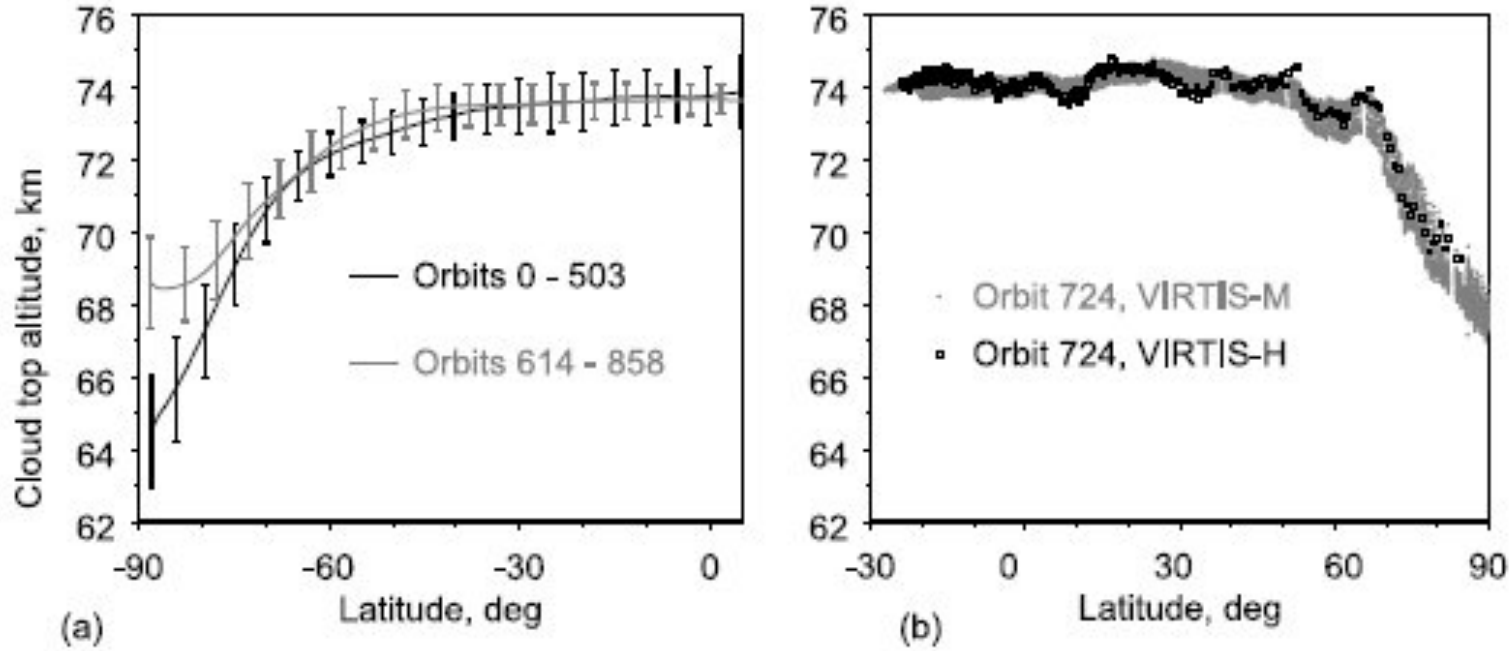
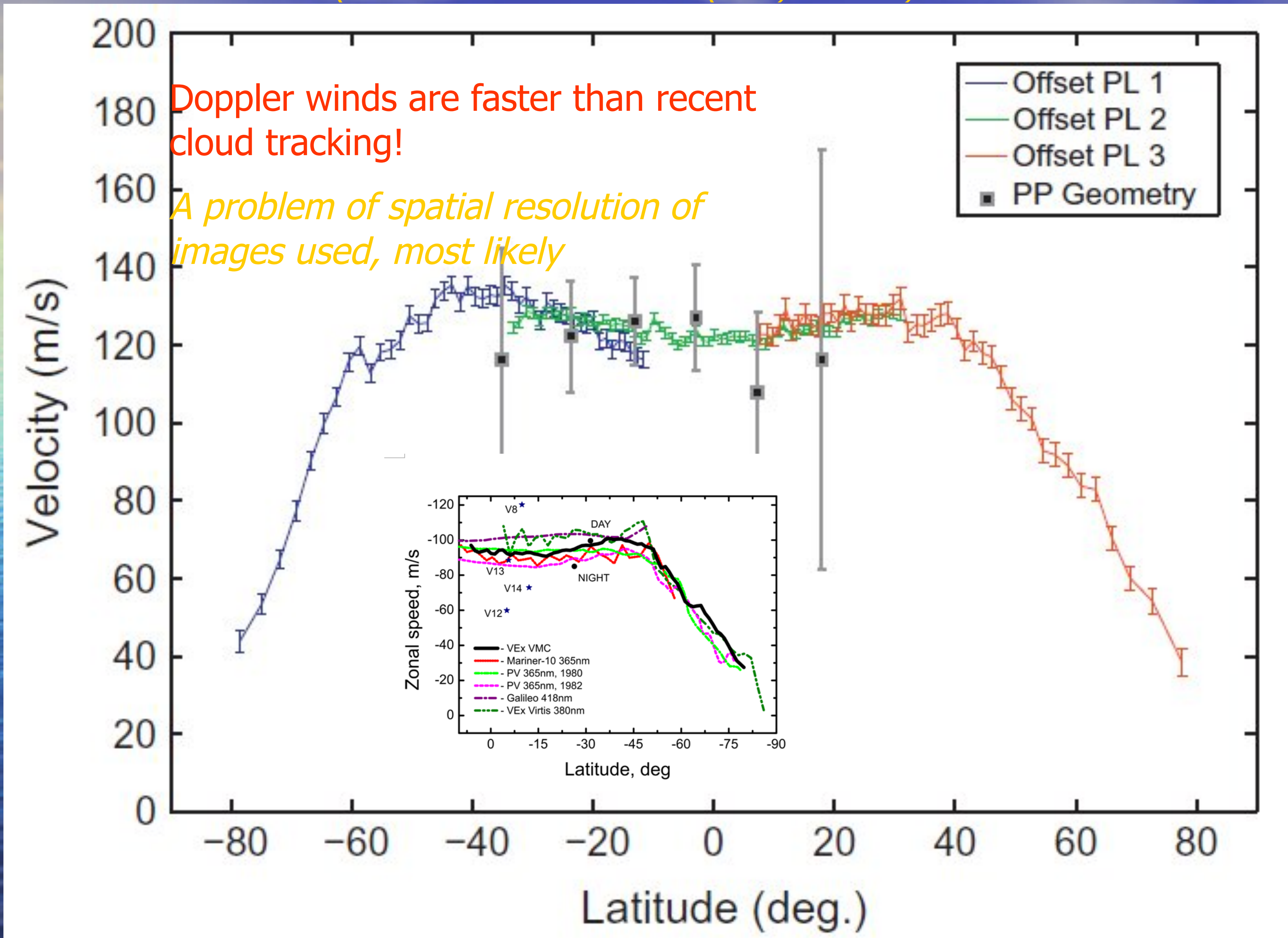


Figure 8. Latitudinal behavior of the cloud top altitude. (a) Mean value in the southern hemisphere for two periods: from April 2006 to September 2007 (orbits 0–503) (black) and from December 2007 to August 2008 (orbits 614–858) (gray). The curves are moving averages with 5° latitude window. Error bars represent scattering of individual measurements due to both temporal variations and instrumental errors. (b) Observations in the northern hemisphere in orbit 724 with by VIRTIS-M (dots) and VIRTIS-H (squares).

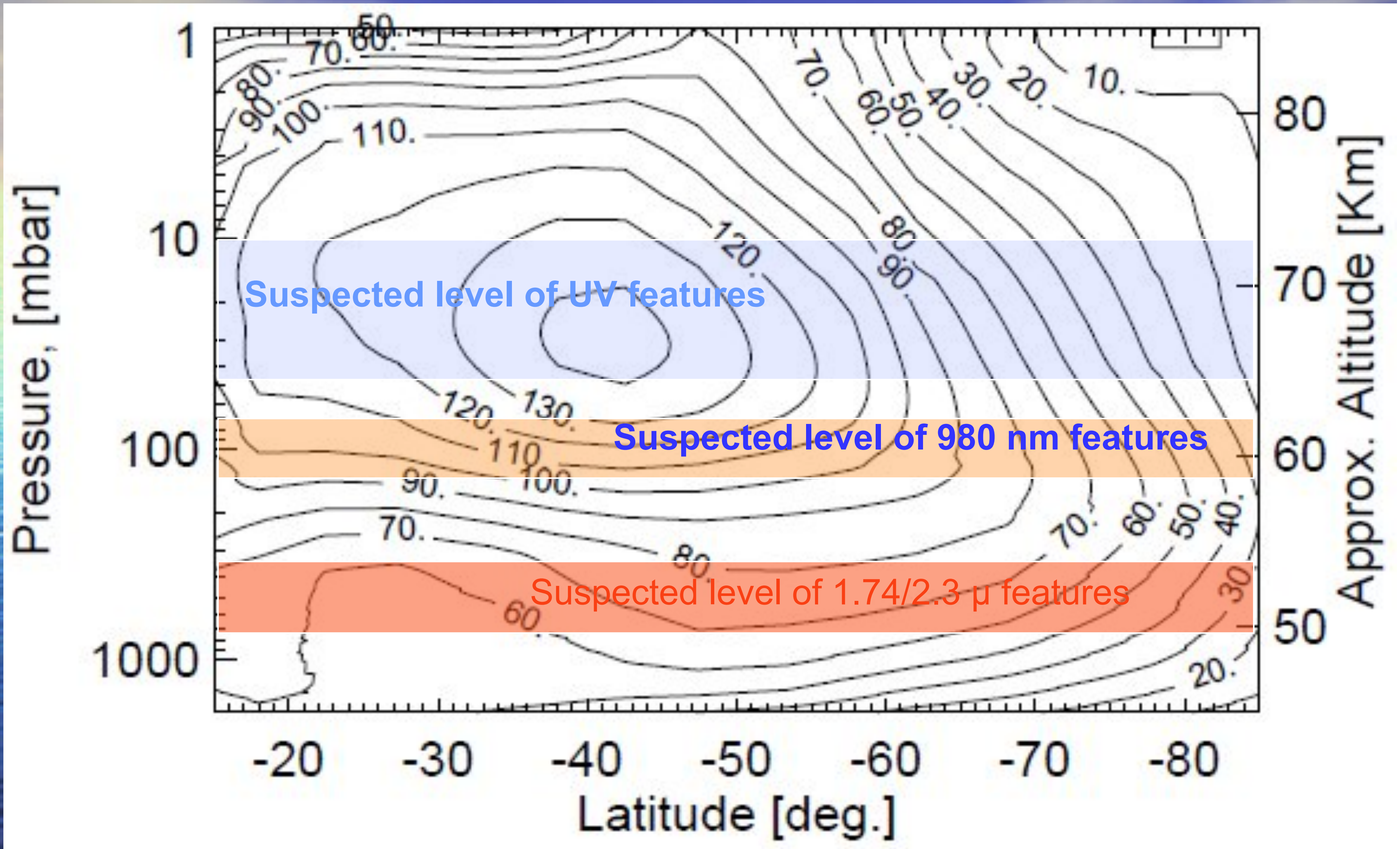
Cloudtop Winds by Doppler Tracking from Ground Based Telescope

(P. Machado et al. Icarus 221 (2012) 248–261)

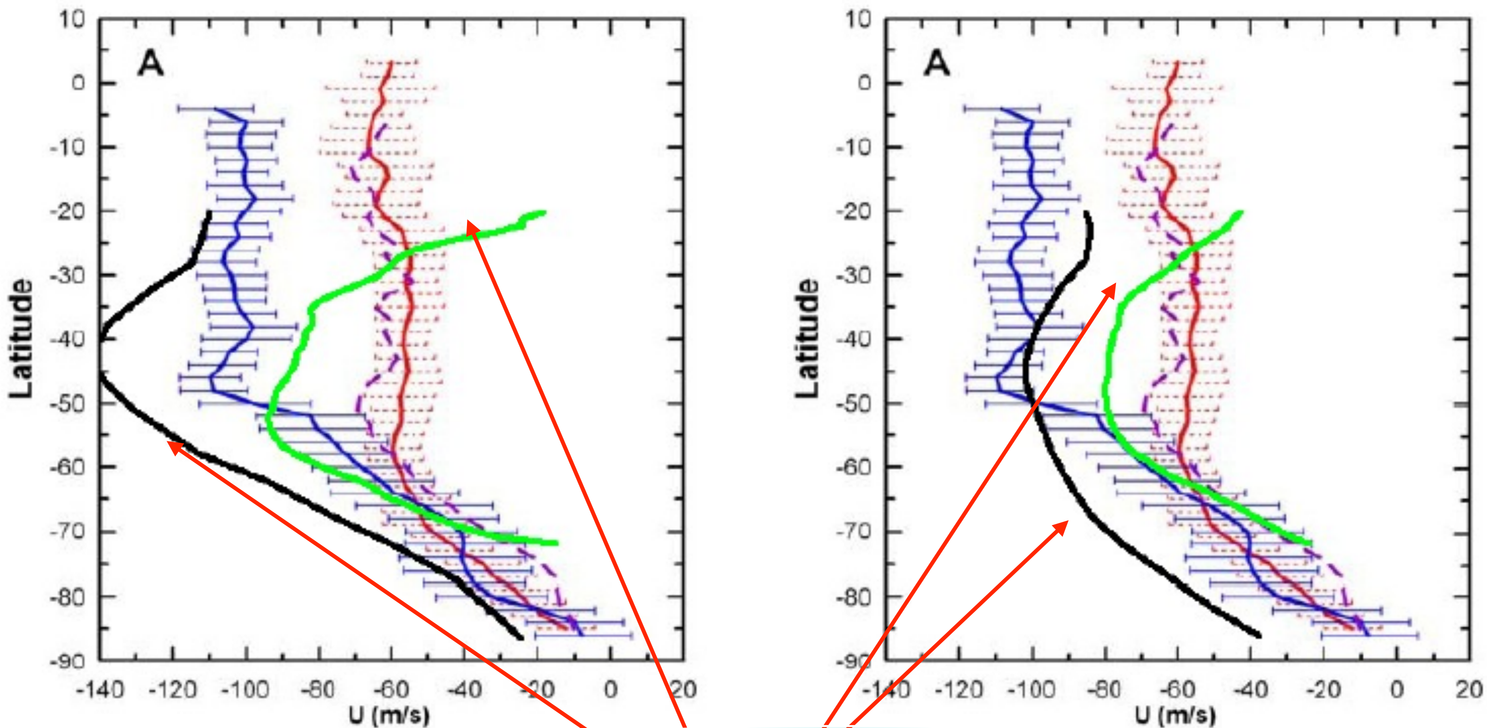


VIRTIS and VMC zonal component profiles not quite consistent with the thermal support for the flow

Cyclostrophic Flow from VeRa Thermal Structure (Piccialli et al., Icarus, 2012)



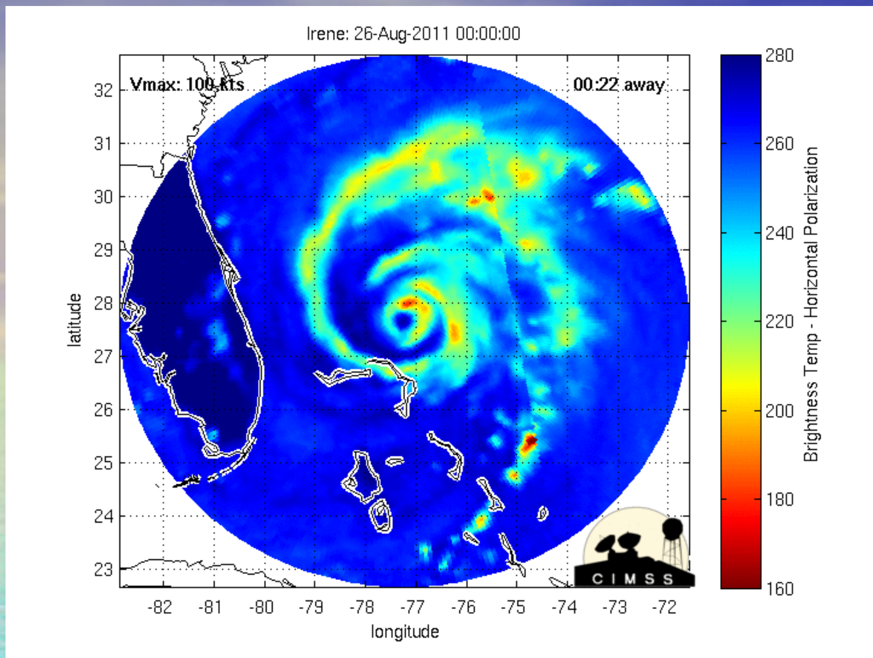
Comparison of Cyclostrophic Flow and Cloud Tracking Results (VIRTIS)



(a) 66 km (b) 61 km

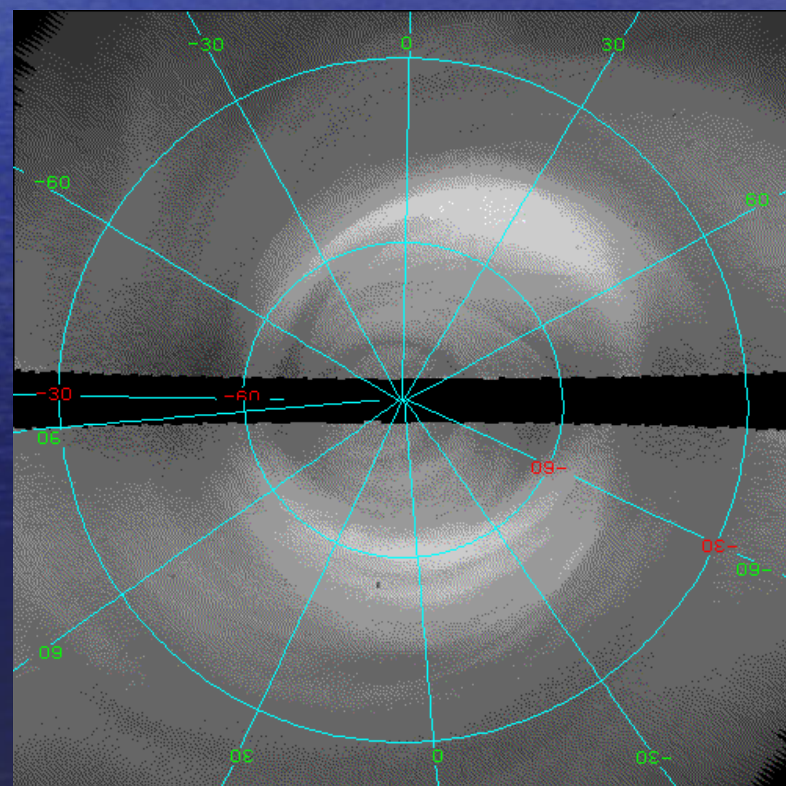
Huge discrepancy between balanced flow and observations for that level

Figure 5.4: VIRTIS cloud-tracked winds observed at different altitudes: (blue) ∼ 66 km; (violet) ∼ 61 km; and (red) ∼ 48 km. Zonal thermal winds derived from VIRTIS (green) and VeRa (black) vertical temperature profiles are shown for comparison (Sánchez-Lavega et al., 2008).

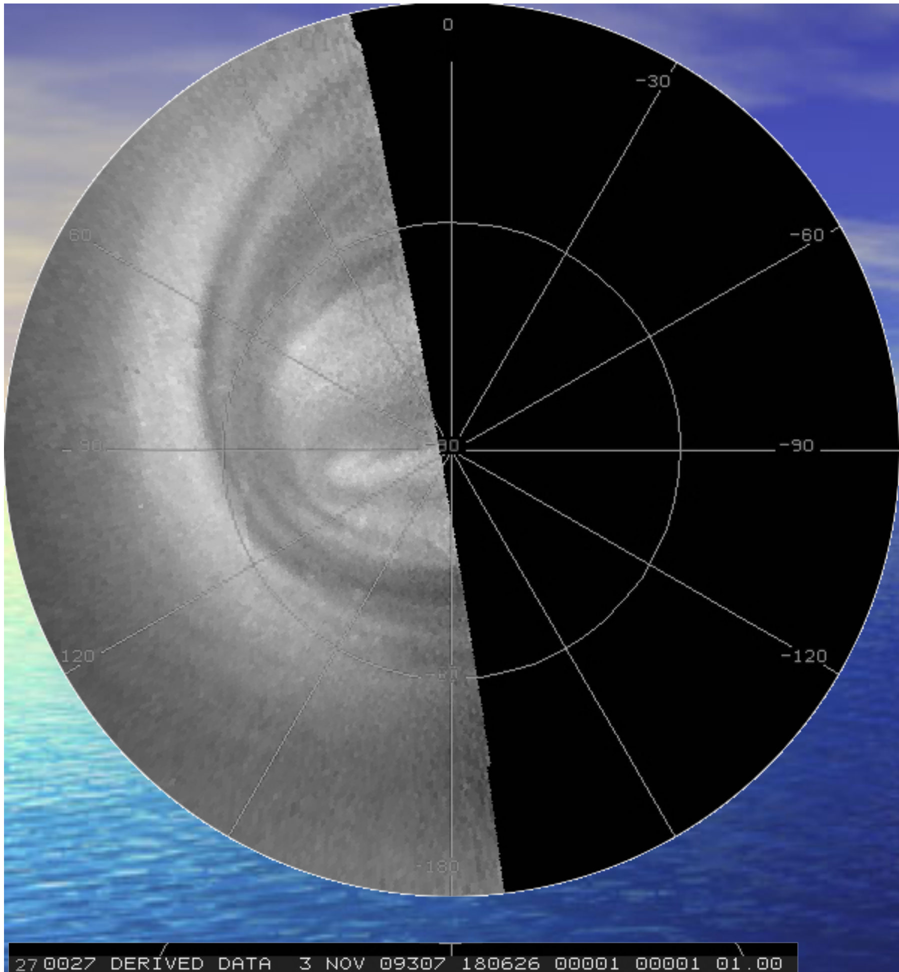


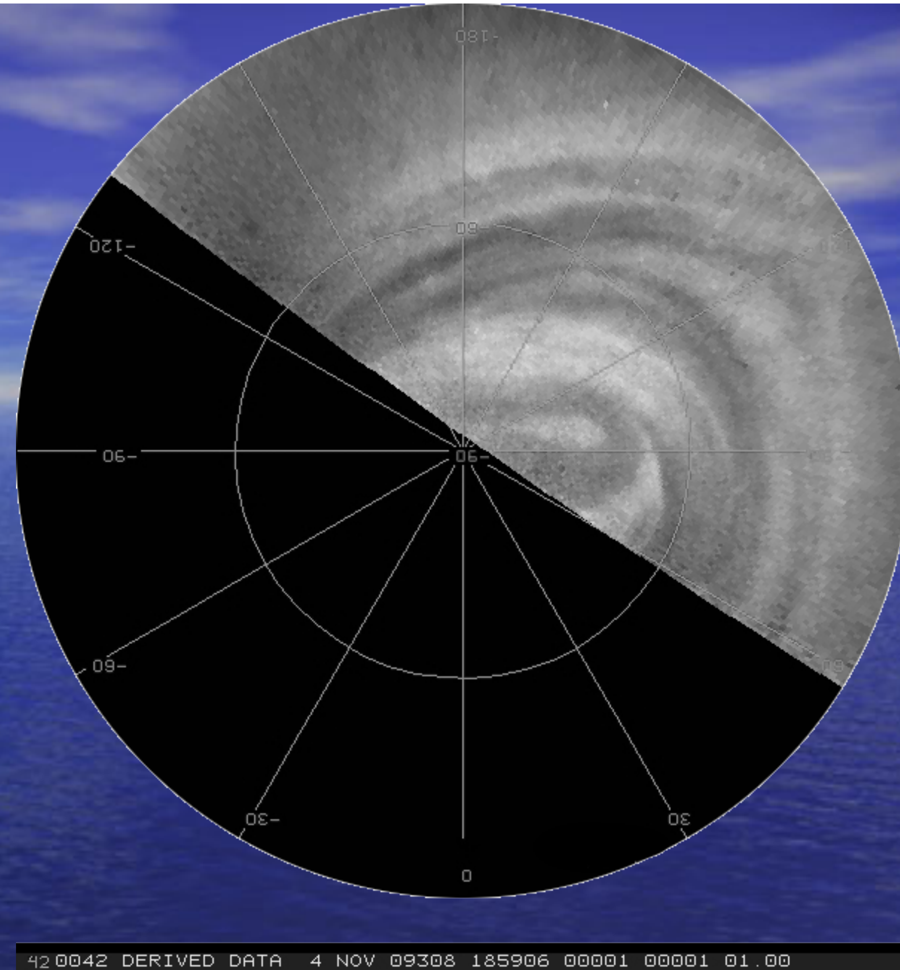
The spiral bands of a tropical cyclone are vortex Rossby waves and are regions of strong convection (left).

By analogy the bright spiral arms of the Venus hemispheric vortex (below) are also Rossby waves and move slower than ambient flow and may indicate convective regions (Limaye et al. GRL, 2009)



The hemispheric vortex is asymmetric as seen in this composite view animation of time-lapse composites of polar projections of VMC uv filter images. The grid overlay is disjointed at times on account of the vortex asymmetry





"Frozen" view of the two halves of the Venus vortex - the linear instability feature is held fixed, showing relative motions of the bands

Lightning as summarized by Krasnopolsky *(Plan. And Space Sci., 54, 1352-1359, 2006)*

- Electrical signals detected by Venera 11-14 landers and Pioneer Venus Orbiter
- Galileo Fly-by results from PWS also interpreted as due to lightning (Russel 1991, Grebowsky et al., 1997)
- Cassini Fly-by results from an improved PWS DID NOT detect any electrical signals attributable to lightning (*D. A. Gurnett, et al., Non-Detection at Venus of High-Frequency Radio Signals Characteristic of Terrestrial Lightning, Nature, 409, 313-315, 2001*)
- Venera 9 and Venera 10 optical spectrometers revealed one flashing region (Krasnopolsky, Planet. Space Sci., 31, 1363-1369, 1983). Mean energy (2 x 10^7 J) comparable to flashes on Earth, spectrum agrees with simulated with no significant depletion below 550 nm by Rayleigh extinction, ruling out lightning below 20 km
- VeGa 1 and VeGa 2 photometers did not detect any flashes during the combined 60 hour duration of the two flights on the night side (Sagdeev et al., Science, 231, 1411-1414.
- Ground based observations of Venus night side indicated seven flashes over ~ 4 hours (Hansell, et al., Icarus, 117, 345-351, 1995; Borucki et al., .
- Detection of NO in the lower atmosphere of Venus (Kranspolsky, Icarus, 182, 80-91) is a convincing and independent proof of lightning

Venus Express Plasma Instrument has detected electrical activity indicative of lightning, but no optical detection (*Russell, C., Leinweber, H., Zhang, T., Daniels, J., Strangeway, R., & Wei, H. (2012) Electromagnetic waves observed on a flight over a Venus electrical storm. Geophysical Research Letters. DOI: 10.1029/2012GL054308*)

Questions: *As summarized by V. Moroz (Adv. Space Res., vol 29, No, 2, pp 215-225, 2002)*

- Minor constituents, including atmospheric/surface exchange and noble gases
- Heat transfer , greenhouse effect
- Dynamics – especially superrotation
- Aerosols, clouds and hazes, their chemical composition at different heights
  - Vertical profiles distributed in latitude-longitude and time
  - Chemical composition of particles
  - Size distribution of cloud and haze particles
  - Ultra Violet absorber – best done by “A” and “B” type missions*

*A: aircraft. B: Balloon

More Questions

- Is the lightning/electrical activity restricted to lower cloud only?
- What is the level of the optical activity and is it correlated with electrical and acoustical activity?
- What are the > 1 μ radius particles and do they exist within and below the cloud level?
- What is the nature of turbulence different below at different levels in the cloud layer?

Questions about the cloud particles

- What are the physical shapes of the larger particles? Are they crystals ? Are they irregular as expected?
- What is the chemical composition of the UV absorber(s)?
- Why is the UV absorber not well mixed?
- What are the sources and sinks of the UV absorber?
- what is the nature of CCN? Do meteoritic dust particles act as CCN in the clouds and above the clouds?

- In the clouds - is homogeneous nucleation and growth of ice aerosols? Presumably these would be necessary for lightning.
  - Below the clouds: hazes, metallic salt aerosols (i.e. FeCl2)

Questions about the circulation above the cloud top level

- What is the nature of the Sub-Solar – Anti-Solar flow? *– Is there flow over the poles? Analysis and observations of the flow to date have been severely inadequate.*
- *The cloud tracking results from low resolution imaging are NOT detecting the atmospheric flow, so need better characterization of the flow and local variability*
- it it possible that there's vorticity in the downwelling near the antisolar point?
- to be able to correctly reproduce the thermal environment in the 45-100 km region at any latitude. That means we need to know this temperature field (more and more data available from VIRTIS and VeRa), but also the opacity sources (particle distributions) and the radiative fluxes in solar radiation and in thermal emissions. Constraining the distribution of opacity sources is a key point to get the fluxes (and the temperatures) right in the GCMs.

What measurements are needed?

- Trace species composition (SO2, NO, CO, H2O, etc.
- Cloud particle measurements of:
  - Particle size distribution including exact shape
  - Chemical composition including nucleation species

at a many different latitudes/longitudes at different times