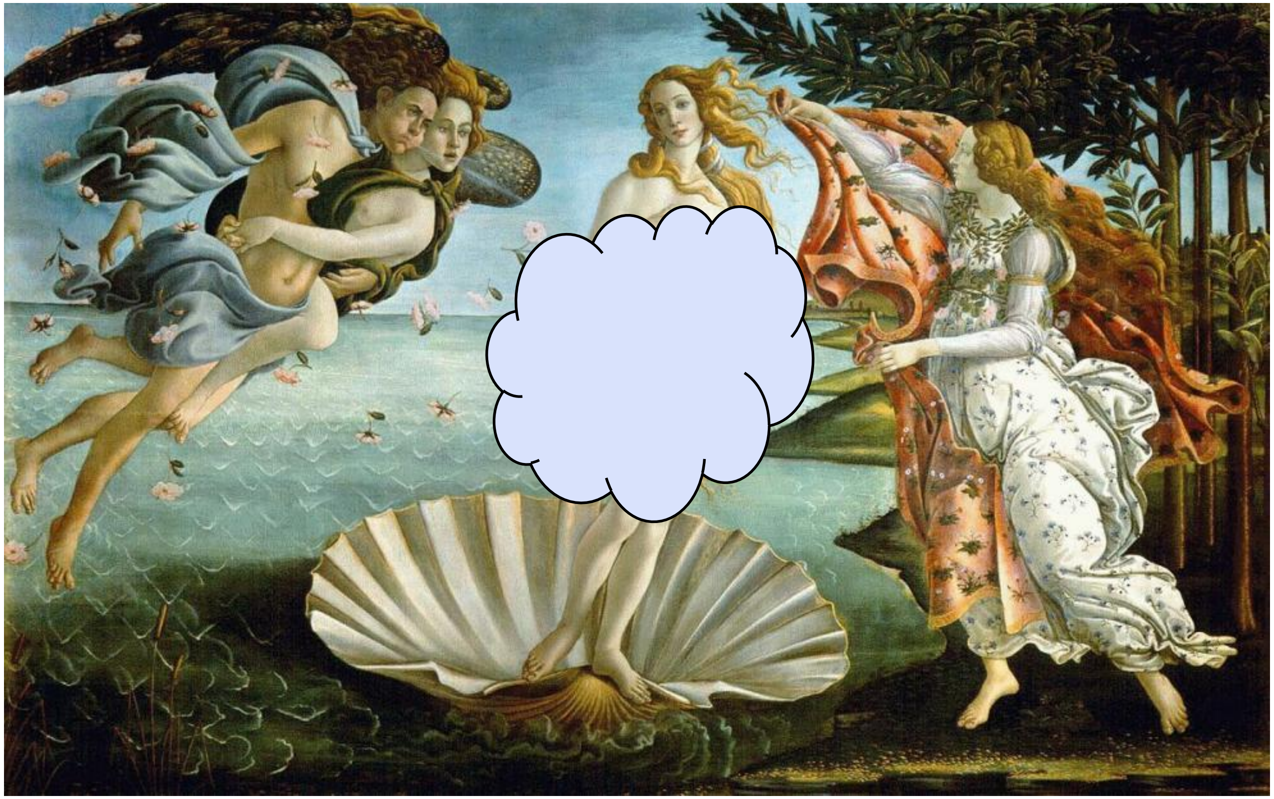
The cloudy veil of Venus



Colin Wilson

True-colour image of Venus
(Mariner 10, 1974)

UV image of Venus
(Pioneer Venus, 1979)

Summary

- **Introduction – past missions & Venus Express**

- **Radiative Balance & Vertical Structure**

- **Lower Clouds**

- **Chemistry & Upper Clouds**

- **Winds & polar vortex**

- **Hunting for active volcanoes**

Why Venus?

- **Venus is our nearest neighbour.**
- **Venus should be the most Earthlike planet we know.**
  - ***Created at roughly the same time (4.4 billion years ago)***
  - ***Apparently similar bulk composition***
  - ***Roughly the same size & density***
- **Early Venus was probably much like early Earth**
  - ***Hot dense atmosphere rich in CO_2 and water***
  - ***On Earth, CO_2 was sequestered in carbonate rocks***
  - ***On Venus, CO_2 is all still in atmosphere – 92 bar surface pressure***
  - ***If Earth's carbonates were evaporated, Earth's atmosphere would have similar atmospheric CO_2 and N_2 abundances as Venus.***
- **Venus also illustrates the probable fate of the Earth.**
  - ***In ~ 1 billion years, with a brighter sun, sunlight level at Earth may be similar to that at Venus today.***
  - ***Will we be able to avoid the runaway greenhouse warming that is found at Venus?***

Why Venus (II)?

- **Venus is the same size as Earth, but rotates more slowly.**
  - ***Planet rotates once every 243 Earth days***
  - ***One Venus year = 223 Earth days***
  - ***However, atmosphere at cloud-tops rotates once every 5 days,***
    - ***50x faster than solid planet***
  - ***How does atmospheric circulation on slowly-rotating planets work?***
    - ***Relevance to Titan & exoplanets***

- **Venus today has a climate very different from the Earth**
  - ***92 bar CO_2 leads to intense greenhouse warming***
  - ***Surface temperatures exceed 450 °C***
  - ***Main cloud-forming volatile is sulphuric acid, rather than water***

- **Venus atmosphere is optically thick**
  - ***Thick cloud layer covers whole planet***
  - ***95% of sunlight absorbed at cloud deck, not at/near surface as on Earth***

Venus missions 1961 - 1972

Name	country	Type†	Success	Launch / Arrival	Remarks
Sputnik 7	USSR		×	04.02.1961	4th stage failed, stayed in Earth orbit
Venera 1	USSR	F	×	12.02.1961	Contact lost
Mariner 1	USA		×	22.07.1962	Launch failure
Sputnik 19	USSR	F	×	25.08.1962	Escape stage failed, stayed in Earth orbit
Mariner 2	USA	F	✓	27.08.62/14.12.62	IR and μwave radiometers reveal hot surface.
Sputnik 20	USSR	F	×	01.09.1962	Escape stage failed, stayed in Earth orbit
Sputnik 21	USSR	F	×	12.09.1962	3rd stage failed
Cosmos 21	USSR	F	×	11.11.1964	Escape stage failed
Venera 1964A	USSR	F	×	19.02.1964	Failed to reach Earth orbit
Venera 1964B	USSR	F	×	01.03.1964	Failed to reach Earth orbit
Cosmos 27	USSR	F	×	27.03.1962	Failed to reach Earth orbit
Zond 1	USSR	F	×	02.04.1964	Contact lost
Venera 2	USSR	F	×	12.11.1965	Contact lost
Venera 3	USSR	L	×	16.11.1965	Impacted Venus; no data
Cosmos 96	USSR	L?	×	23.11.1965	Exploded in Earth orbit
Venera 1965A	USSR	F	×	23.11.1965	Launch failure
Venera 4	USSR	P	✓	12.06.67/18.10.67	Atmospheric and magnetic data
Mariner 5	USA	F	✓	14.06.67/19.10.67	Particles & fields data
Cosmos 167	USSR	P	×	17.07.1967	Failed to leave Earth orbit
Venera 5	USSR	P	✓	05.01.69/16.05.69	405 kg descent probe
Venera 6	USSR	P	✓	10.01.69/17.05.69	405 kg descent probe
Venera 7	USSR	L	✓	17.08.1970	Returned data during descent and from surface.
Cosmos 359	USSR	L	×	22.08.1970	Failed to leave Earth orbit
Venera 8	USSR	L	✓	27.03.72/22.07.72	Returned data during descent and from surface.
Cosmos 482	USSR	L	×	31.03.1972	Escape stage failed

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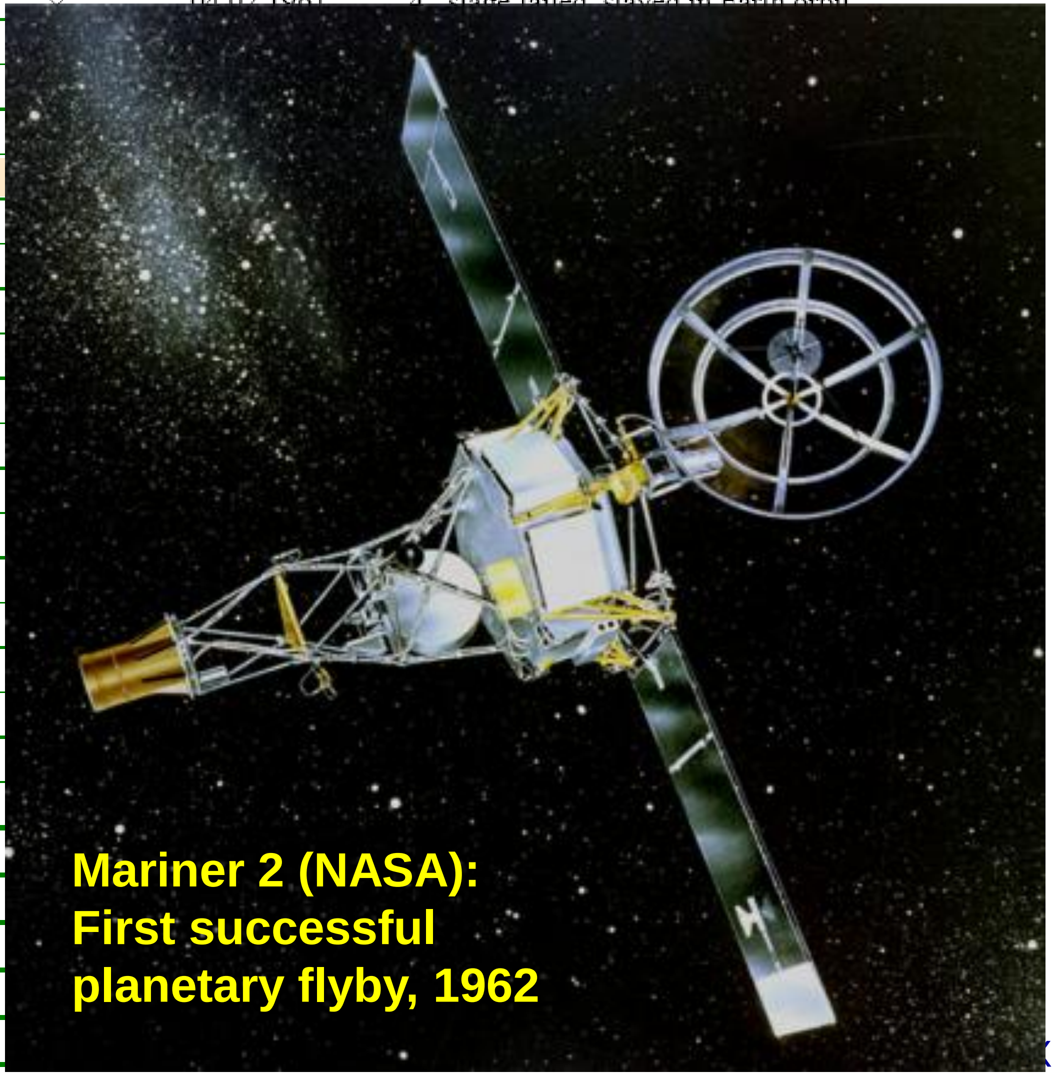
Sputnik 7	USSR		×	04.02.1961	4th stage failed, stayed in Earth orbit
Venera 1	USSR	F			
Mariner 1	USA				
Sputnik 19	USSR	F			
Mariner 2	USA	F			
Sputnik 20	USSR	F			
Sputnik 21	USSR	F			
Cosmos 21	USSR	F			
Venera 1964A	USSR	F			
Venera 1964B	USSR	F			
Cosmos 27	USSR	F			
Zond 1	USSR	F			
Venera 2	USSR	F			
Venera 3	USSR	L			
Cosmos 96	USSR	L?			
Venera 1965A	USSR	F			
Venera 4	USSR	P			
Mariner 5	USA	F			
Cosmos 167	USSR	P			
Venera 5	USSR	P			
Venera 6	USSR	P			
Venera 7	USSR	L			
Cosmos 359	USSR	L			
Venera 8	USSR	L			
Cosmos 482	USSR	L	×	31.03.1972	Escape stage failed



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First in situ analysis of another planet's atmosphere, 1967

Venus missions 1961 - 1972

Name	country	Type†	Success	Launch / Arrival	Remarks
Sputnik 7	USSR		×	04.02.1961	
Venera 1	USSR	F	×	12.02.1961	
Mariner 1					
Sputnik 1					
Mariner 2				.62	
Sputnik 2					
Sputnik 2					
Cosmos 2					
Venera 19					
Venera 19					
Cosmos 2					
Zond 1					
Venera 2					
Venera 3					
Cosmos 9					
Venera 19					
Venera 4				.67	
Mariner 5				.67	
Cosmos 1					
Venera 5	USSR	P	✓	.69	
Venera 6	USSR	P	✓	10.01.69/17.05.69	405 kg descent probe
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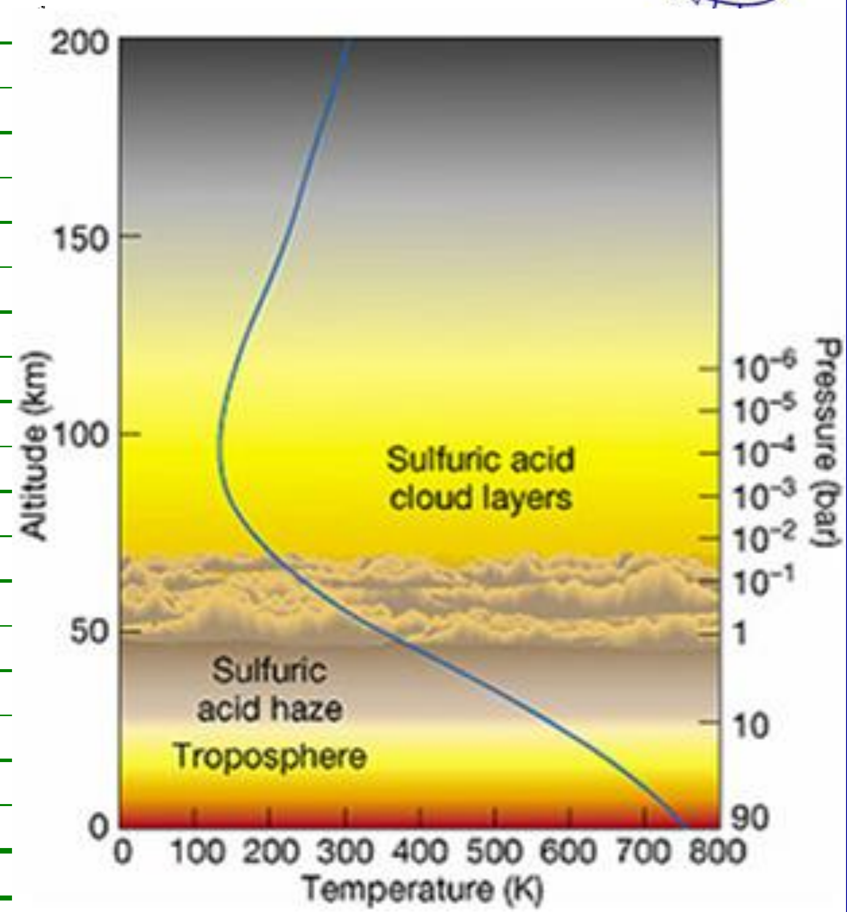


Venus missions 1972 - present

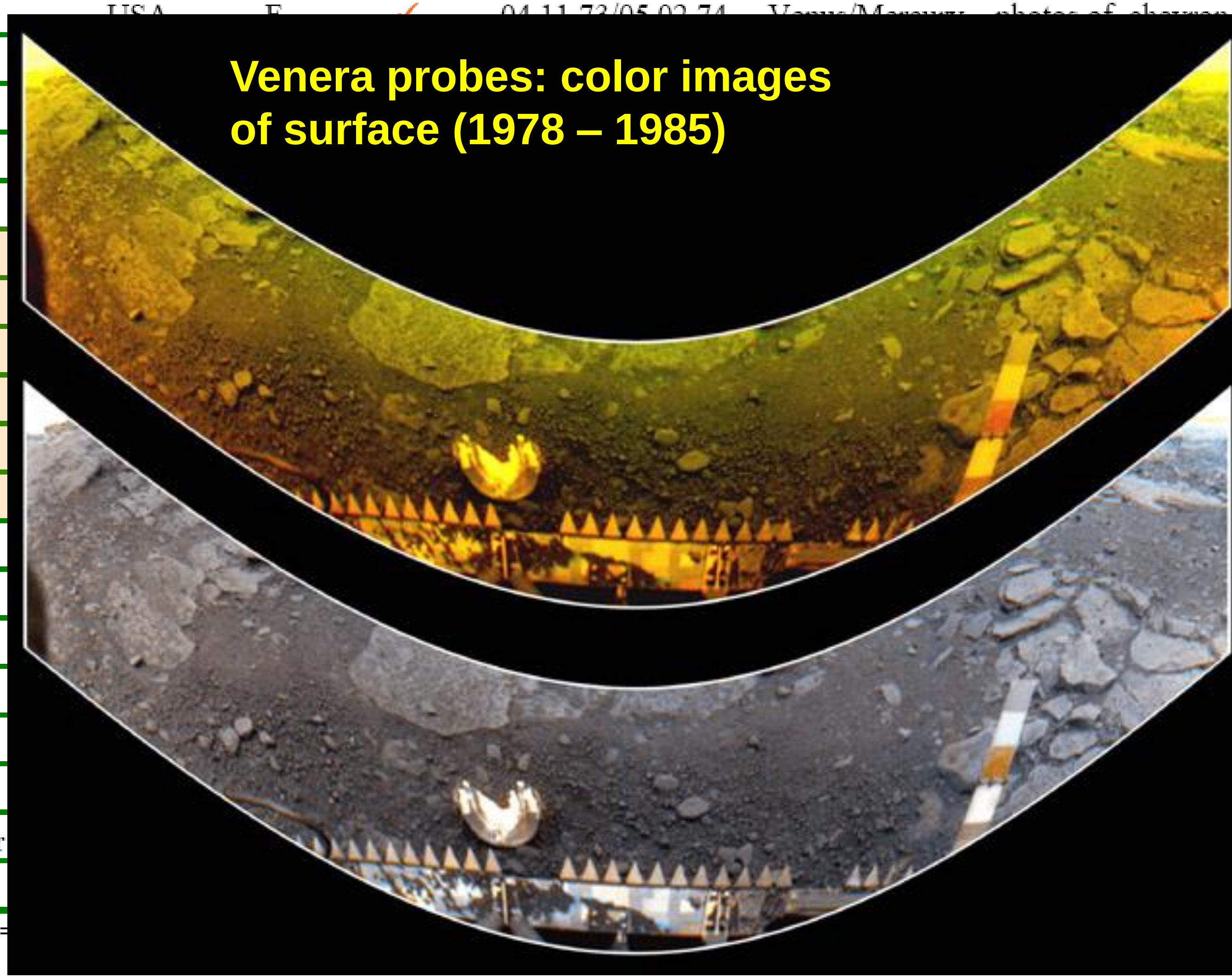
Mariner 10	USA	F	✓	04.11.73/05.02.74	Venus/Mercury – photos of chevron clouds
Venera 9	USSR	O/L	✓	08.06.75/22.08.75	First photo of surface; cloud structure
Venera 10	USSR	O/L	✓	14.06.75/25.08.75	
Pioneer Venus 1	USA	O	✓	20.05.78/04.12.78	Including IR radiometer
Pioneer Venus 2	USA	Probes	✓	08.08.78/09.12.78	4 x descent probes
Venera 11	USSR	O/L	✓	09.09.78/25.12.78	Reported observation of lightning & thunder?
Venera 12	USSR	O/L	✓	14.09.78/21.12.78	As above
Venera 13	USSR	O/L	✓	30.10.81/01.03.82	First colour photo of surface
Venera 14	USSR	O/L	✓	04.11.81/05.03.82	As above; also analysed basalt on surface.
Venera 15	USSR	O	✓	02.06.83/10.10.83	Synthetic aperture radar mapping
Venera 16	USSR	O	✓	07.06.83/14.10.83	Synthetic aperture radar mapping
Vega 1	USSR	L/B	✓	15.12.84/11.06.85	Balloon floated at 50 km on nightside
Vega 2	USSR	O/L	✓	21.12.84/15.06.85	As above, also probe/lander
Magellan	USA	O	✓	04.05.89/10.08.90	Radar mapping of surface
Galileo	USA	F	✓	18.10.89/10.02.90	Jupiter orbiter (Venus Flyby)
Cassini	USA	F	✓	15.10.97/24.06.99	Saturn orbiter (Venus Flyby)
Venus Express	Europe	O	✓	9.11.05 / 11.04.06	Polar orbit, apoapsis above South Pole
Mercury Messenger	USA	F	✓	03.08.05	Two Venus flybys: 24.10.06 & 06.06.07
Akatsuki	Japan	O		May 2010	Equatorial orbit, equatorial cloud tracking

† F = flyby, O = Orbiter, L = lander, B = balloon

Venus missions 1972 - present

Mariner 10	USA F 04.11.73/05.02.74	Venus/Mercury – photos of chevron clouds
Venera 9		
Venera 10		
Pioneer Venus 1		
Pioneer Venus 2		
Venera 11		hunder?
Venera 12		
Venera 13		
Venera 14		face.
Venera 15		
Venera 16		
Vega 1		
Vega 2		
Magellan		
Galileo		
Cassini		
Venus Express		e
Mercury Messenger		07
Akatsuki		king

† F = flyby, O =



Venus missions 1972 - present

Mariner 10	USA	F	✓	04.11.73/05.02.74	Venus/Mercury – photos of chevron clouds
Venera 9	USSR	O/L	✓		
Venera 10	USSR	O/L	✓		
Pioneer Venus 1	USA	O	✓		
Pioneer Venus 2	USA	Probes	✓		
Venera 11	USSR	O/L	✓		
Venera 12	USSR	O/L	✓		
Venera 13	USSR	O/L	✓		
Venera 14	USSR	O/L	✓		
Venera 15	USSR	O	✓		
Venera 16	USSR	O	✓		
Vega 1	USSR	L/B	✓		
Vega 2	USSR	O/L	✓		
Magellan	USA	O	✓		
Galileo	USA	F	✓		
Cassini	USA	F	✓		
Venus Express	Europe	O	✓		
Mercury Messenger	USA	F	✓		
Akatsuki	Japan	O			

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Vega Balloons deployed on Venus (1985)

Venus missions 1972 - present

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Venera 9	USSR	O/L	✓	08.06.75/22.08.75	First photo of surface; cloud structure
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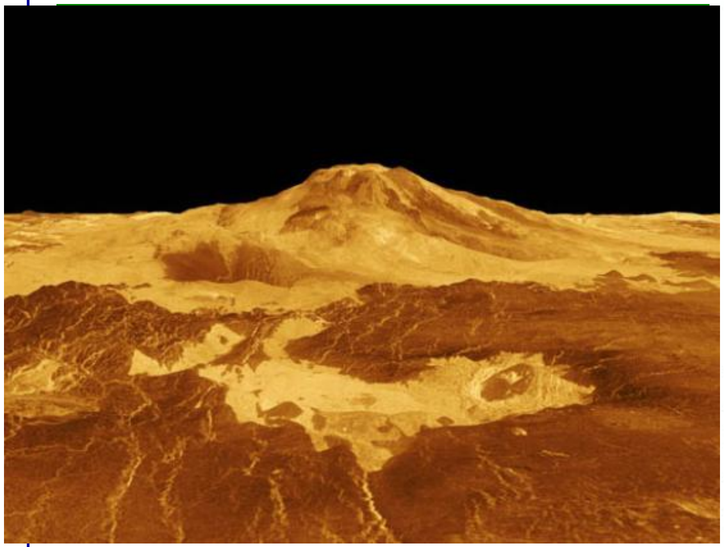
Ve			✓	14.09.7	
Ve			✓	30.10.8	
Ve			✓	04.11.8	on surface.
Ve			✓	02.06.8	ng
Ve			✓	07.06.8	ng
Ve			✓	15.12.8	htside
Ve			✓	21.12.8	
Ma			✓	04.05.8	
Ga			✓	18.10.8	
Ca			✓	15.10.9	
Ve			✓	9.11.05	th Pole
Me			✓	03.	06.06.07
Ak				Ma	d tracking

American Pioneer Venus orbiter & probes (1978 -)

Venus missions 1972 - present

Mariner 10	USA	F



Vega 1	USSR	L/B
Vega 2	USSR	O/L
Magellan	USA	O
Galileo	USA	F
Cassini	USA	F
Venus Express	Europe	O
Mercury Messenger	USA	F
Akatsuki	Japan	O

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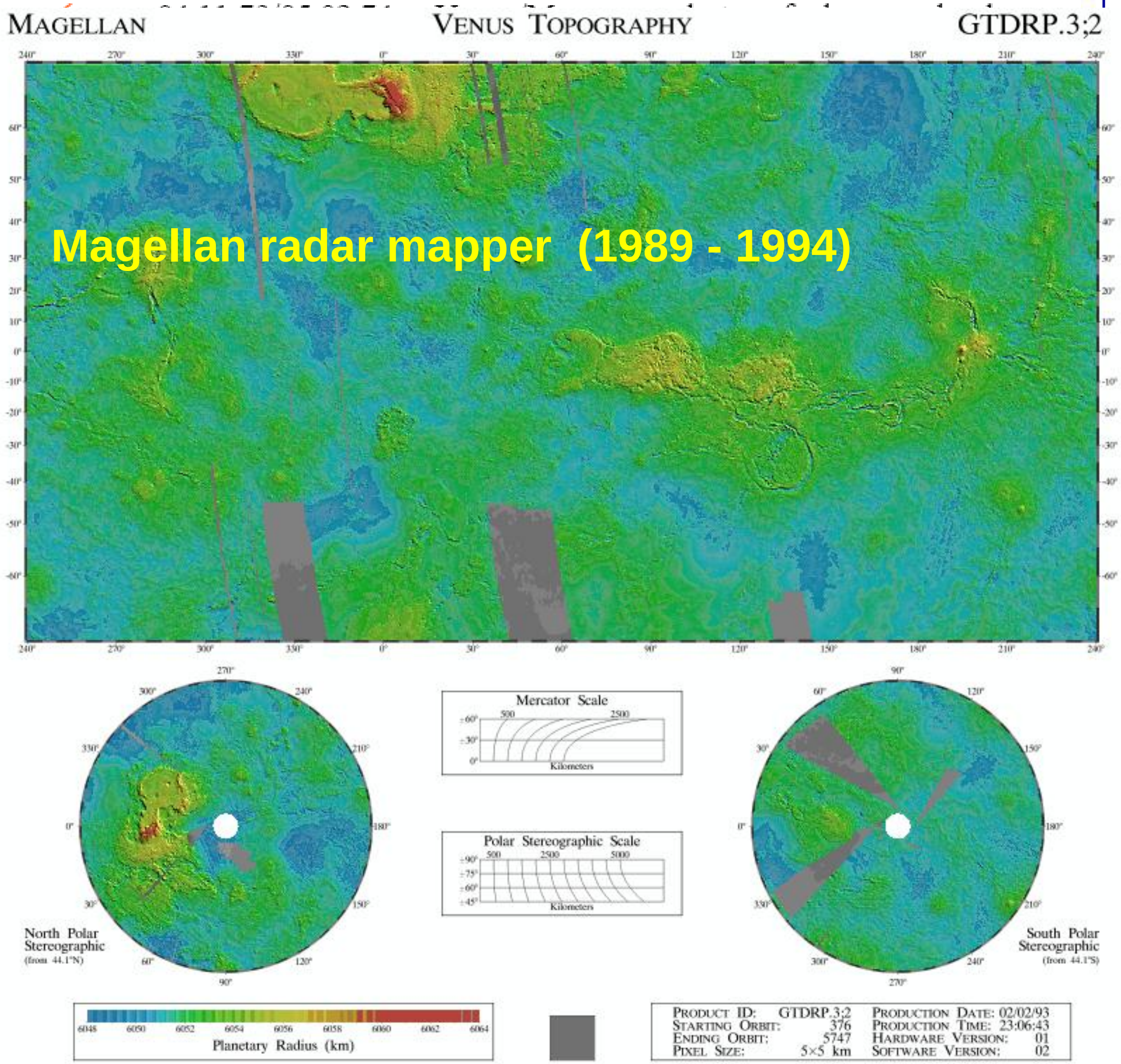

Venus missions 1972 - present

Mariner 10	USA	F
Venera 9	USSR	O/L
Venera 10	USSR	O/L
Pioneer Venus 1	USA	O
Pioneer Venus 2	USA	Prob
Venera 11	USSR	O/L
Venera 12	USSR	O/L
Venera 13	USSR	O/L
Venera 14	USSR	O/L
Venera 15	USSR	O
Venera 16	USSR	O
Vega 1	USSR	L/B
Vega 2	USSR	O/L
Magellan	USA	O
Galileo	USA	F
Cassini	USA	F
Venus Express	Europe	O
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Akatsuki	Japan	O

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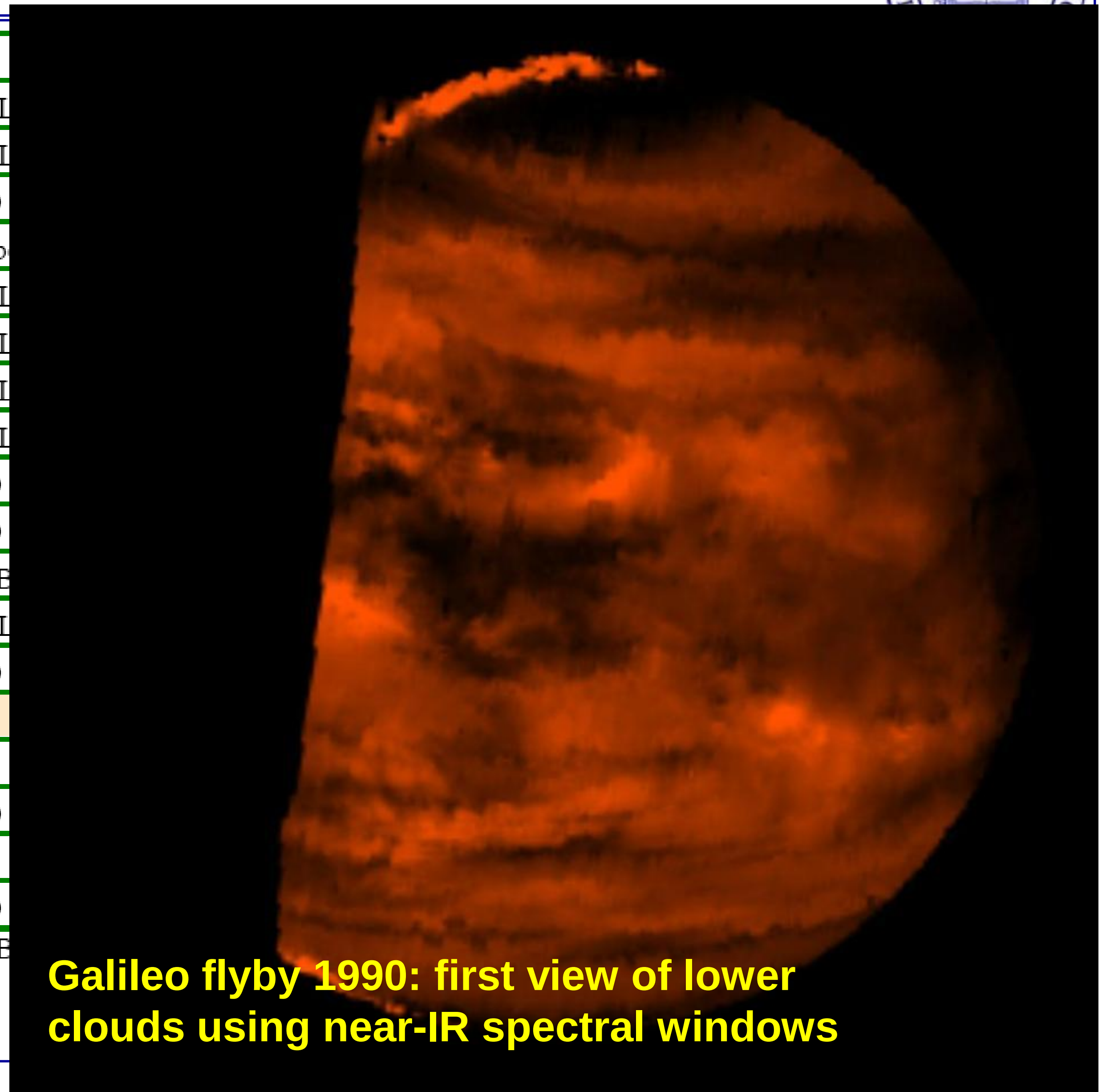


Venus Express

PFS – spectrometer, 2 – 25 μm

VIRTIS – imaging spectrometer, 0.25 – 5 μm

SPICAV – UV / nIR spectrometer, primarily for solar / stellar occultation

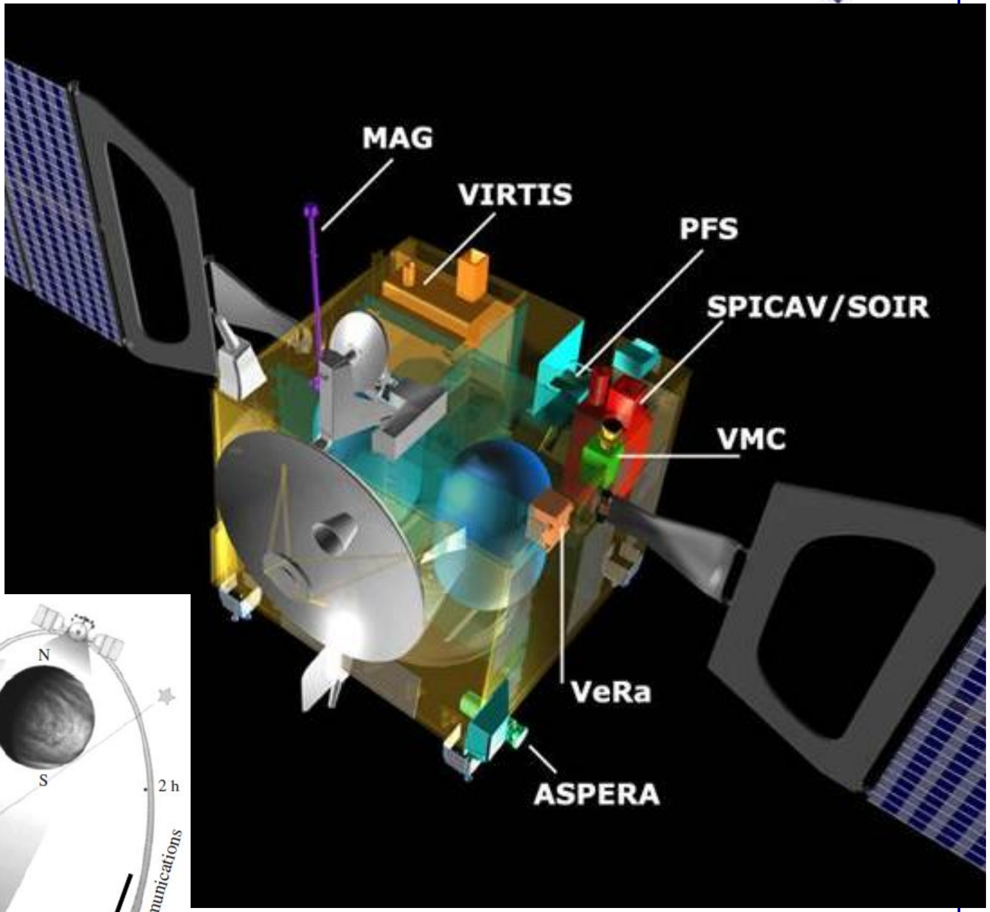
VMC – wide-angle camera with 4 spectral channels

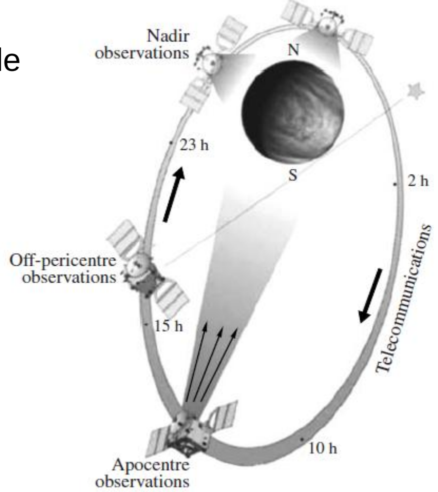
VeRa – radio occultation & bistatic radar

MAG – magnetometer

Aspera – in situ ion & neutral species

- Launched Nov 2005
- In Venus orbit since 11 April 2006
  - Orbit is polar, apocentre above S pole
- Mission extended until end 2014
- Fuel runs out in 2015 ?





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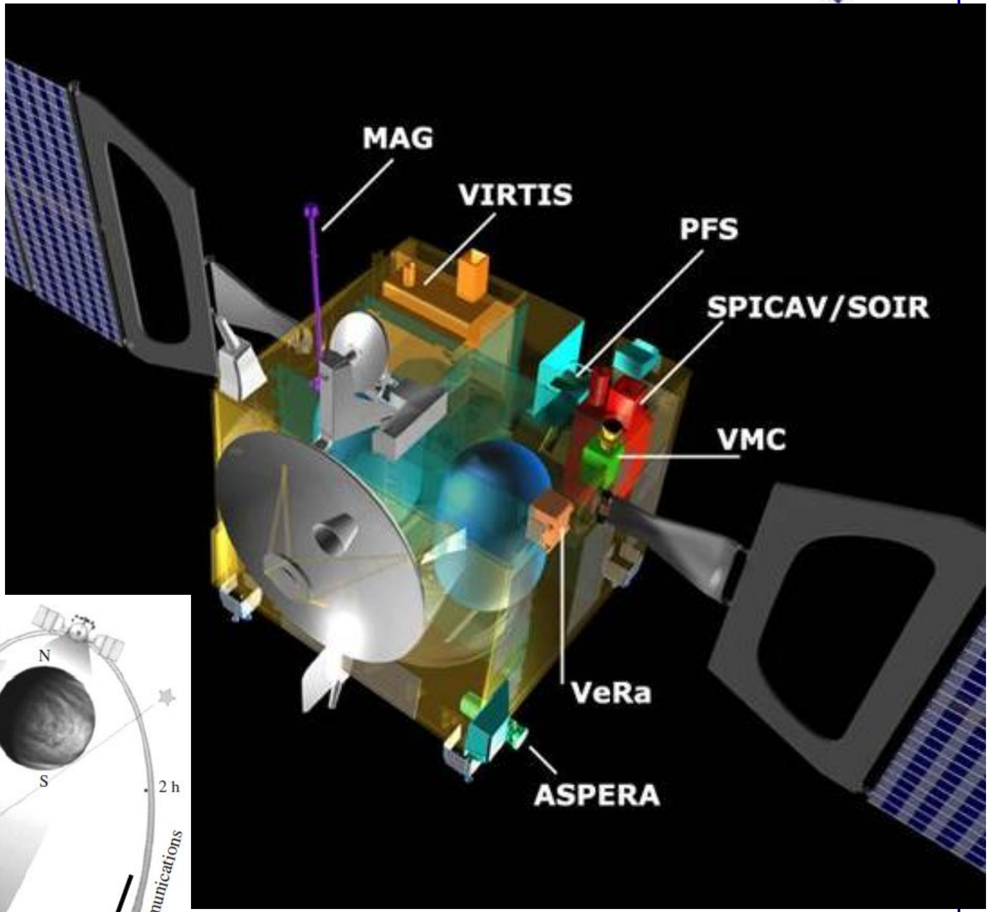
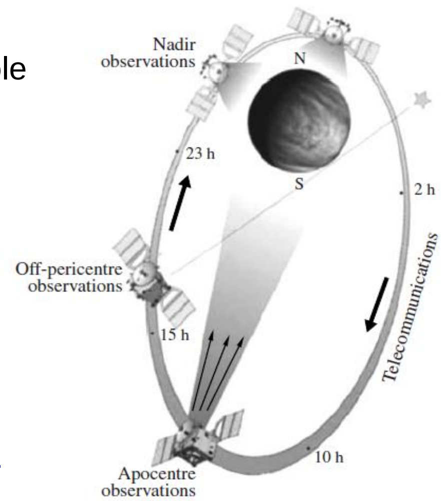




Summary

- **Introduction – past missions & Venus Express**

- **Radiative Balance & Vertical Structure**

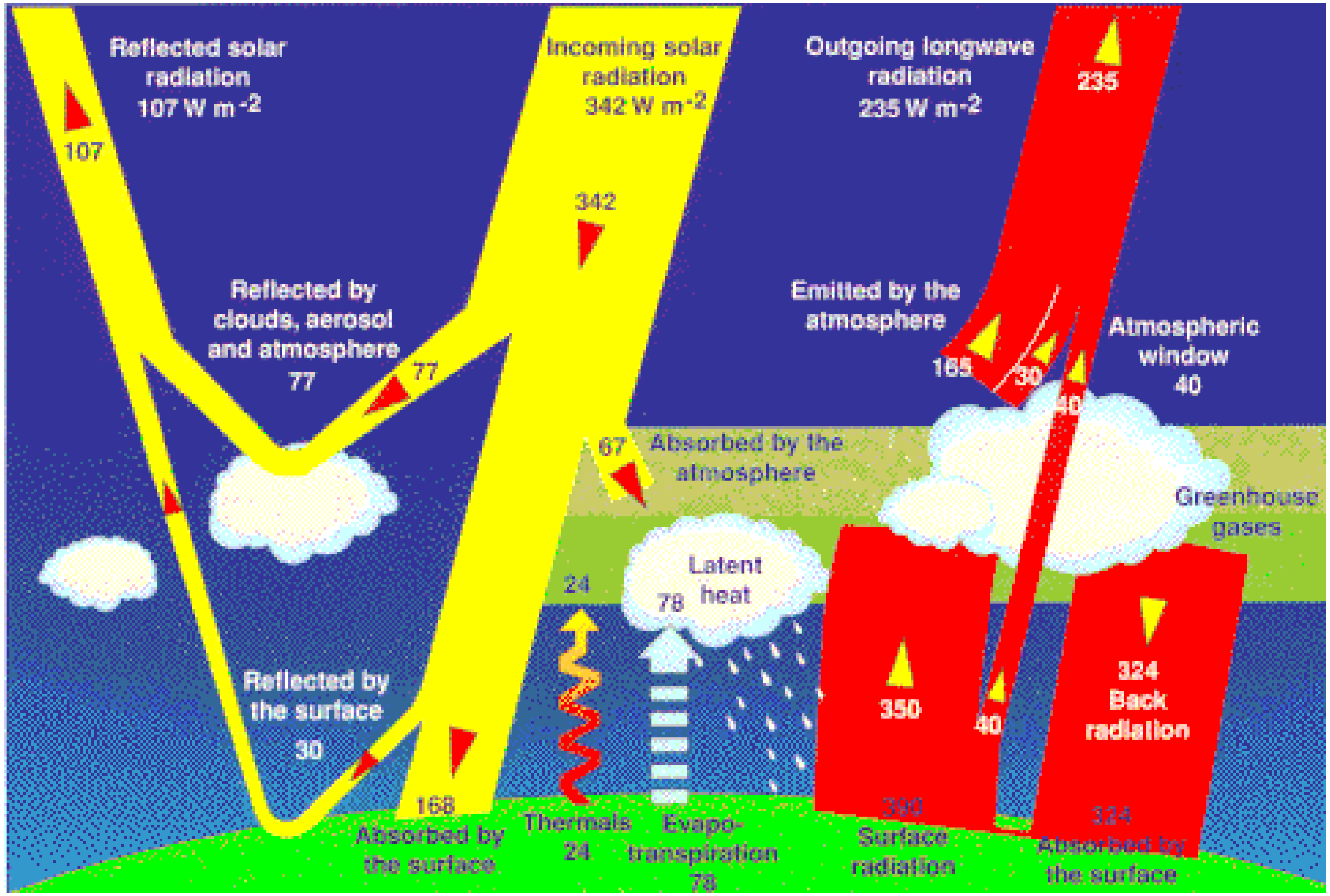
- **Lower Clouds**

- **Chemistry & Upper Clouds**

- **Winds & polar vortex**

- **Hunting for active volcanoes**

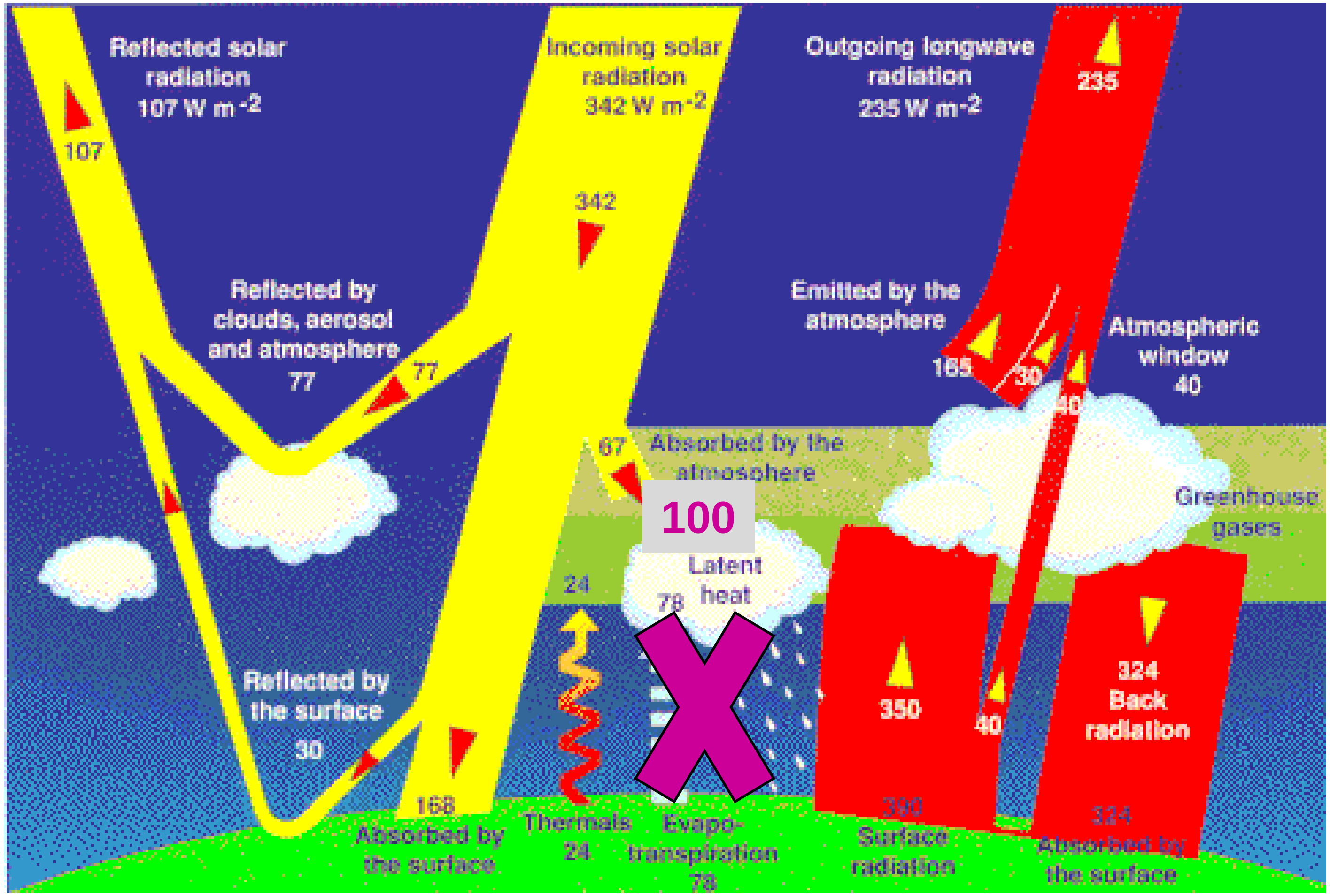
Radiation budget on Earth



NASA/LARC

Radiation budget on Venus

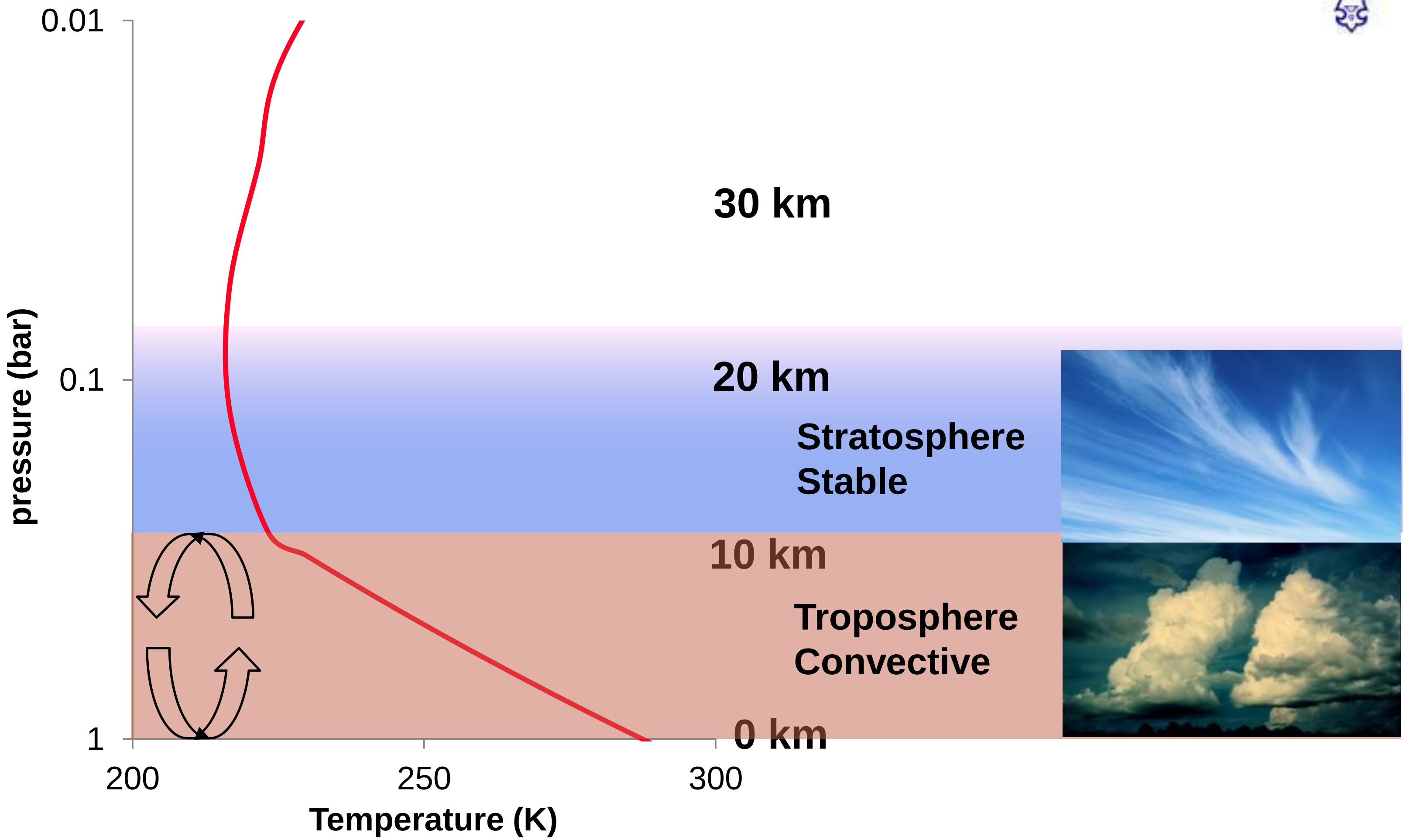
475 W/m^2 625 W/m^2 150 W/m^2



20 W/m^2 absorbed at surface

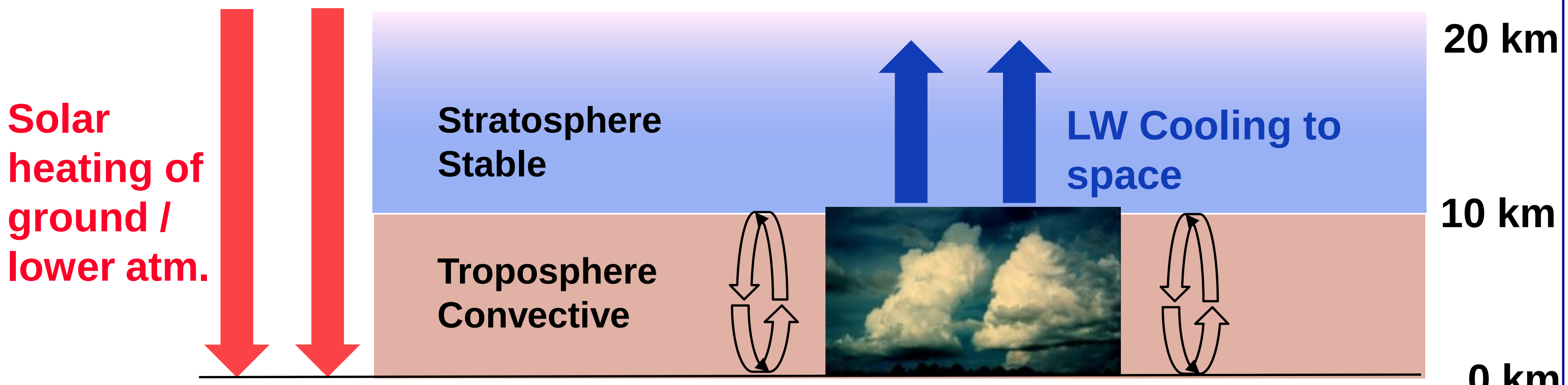
Titov et al., 2007

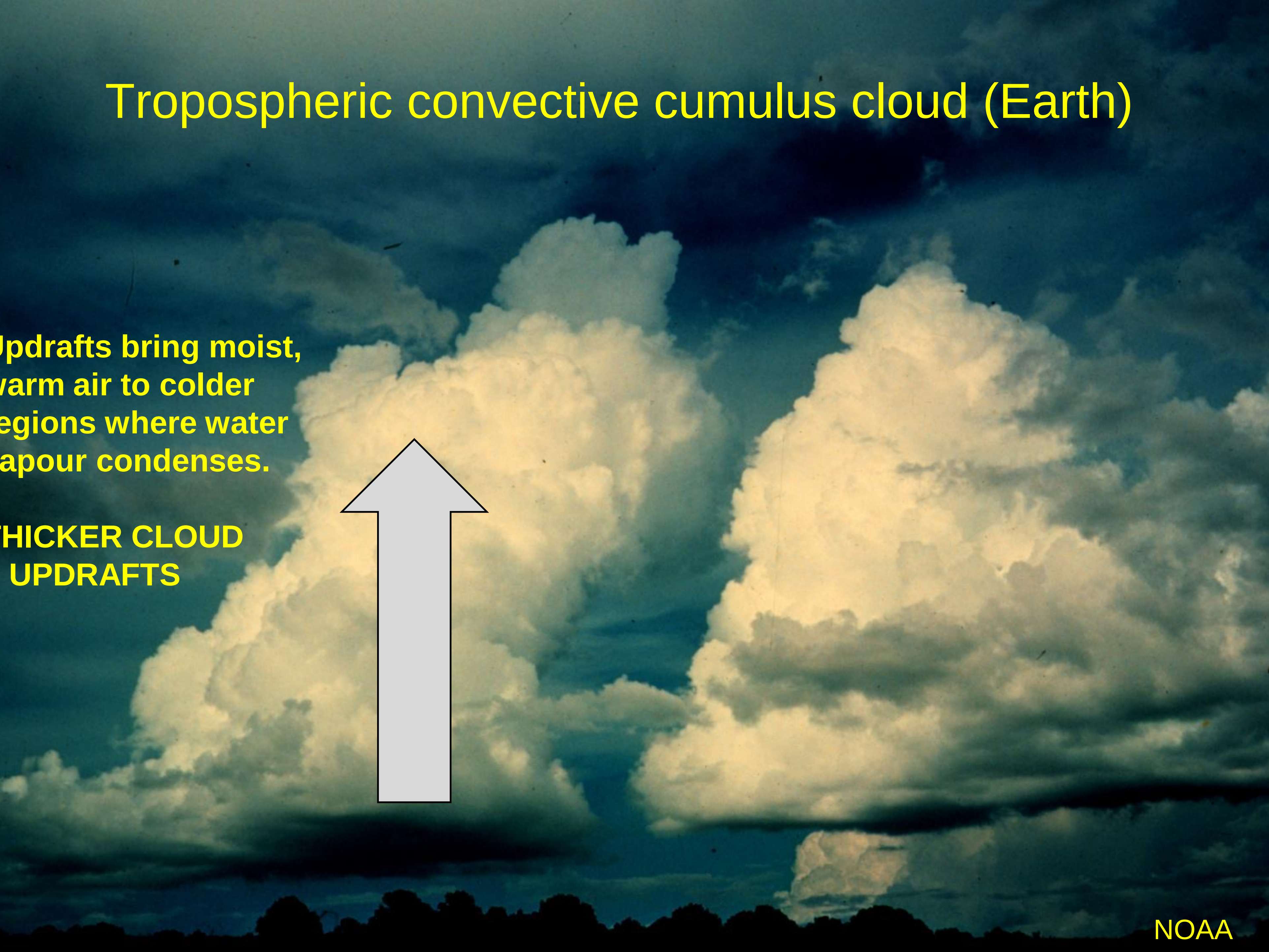
Temperature structure (Earth)



Temperature structure (Earth)

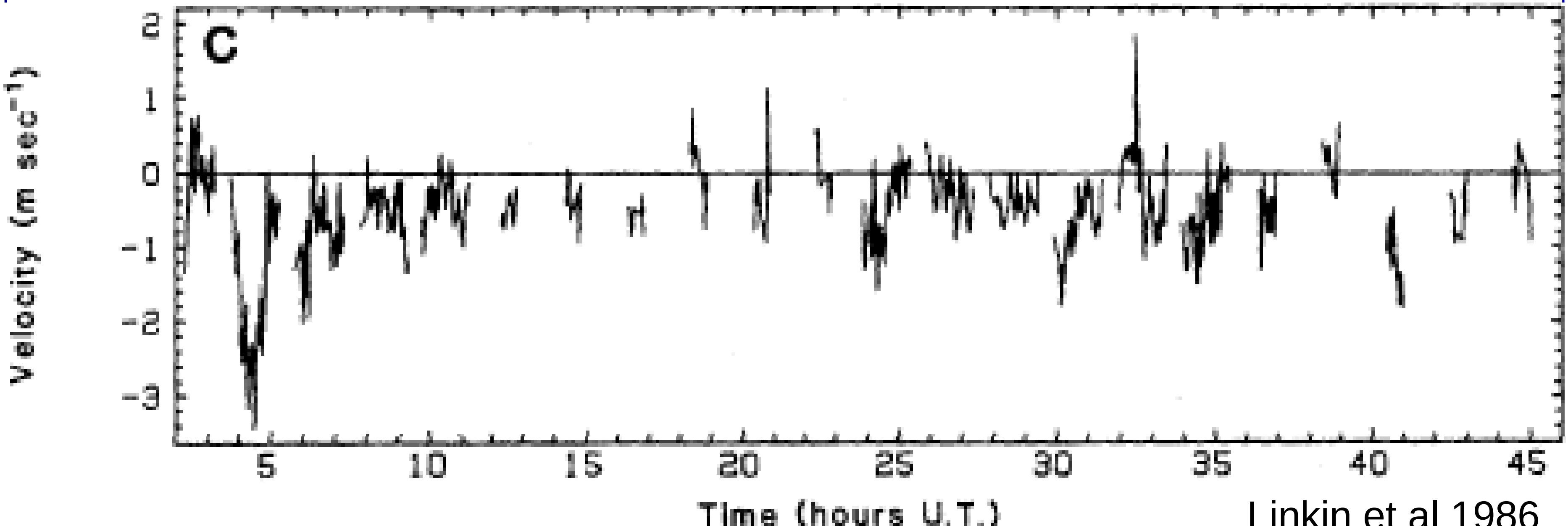
What drives cloud-level convection?



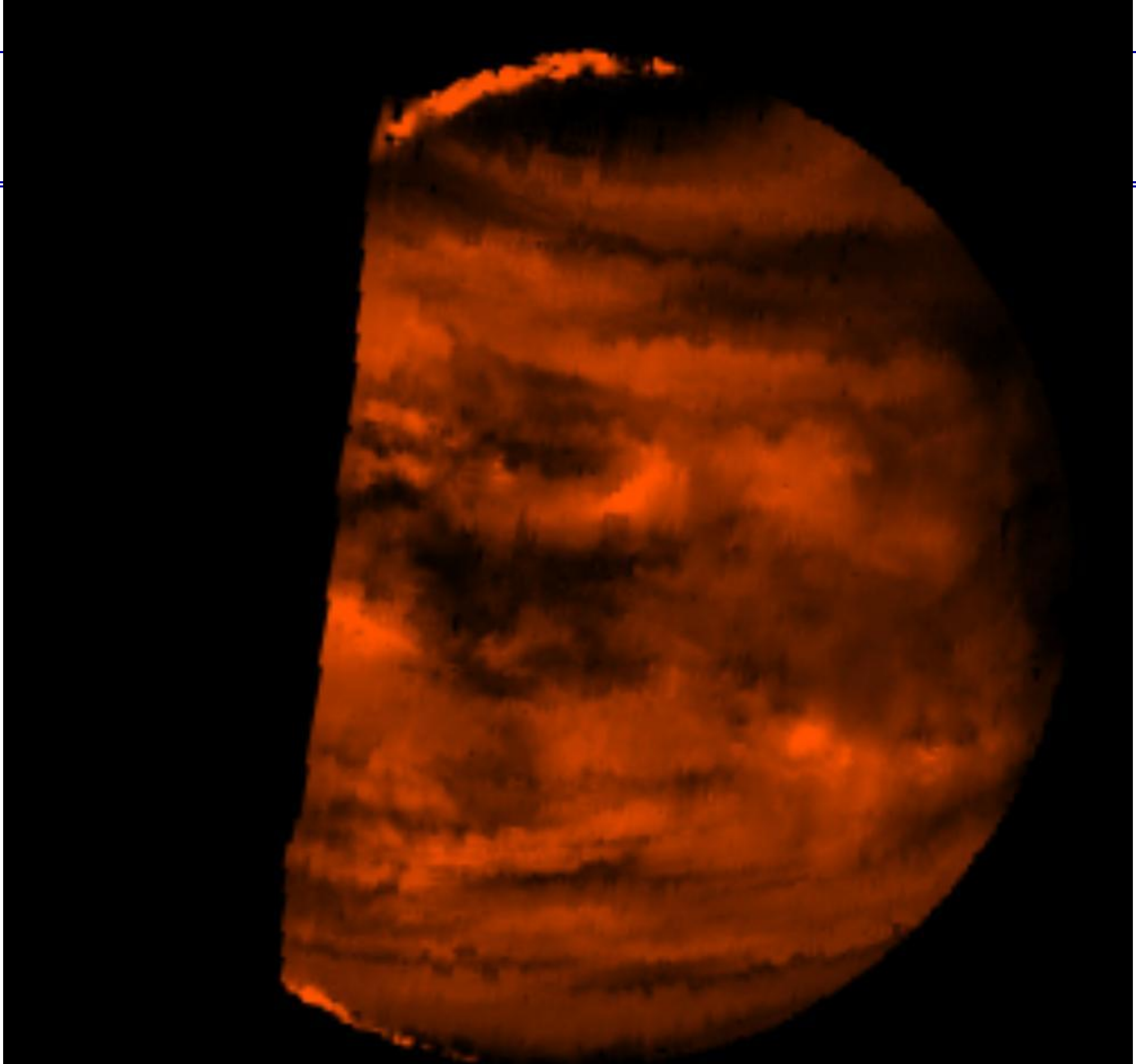

Tropospheric convective cumulus cloud (Earth)
pdrafts bring moist,
arm air to colder
egions where water
apour condenses.
HICKER CLOUD
UPDRAFTS
NOAA

Convective clouds on Venus?

Vega balloon vertical velocities at 55 km altitude

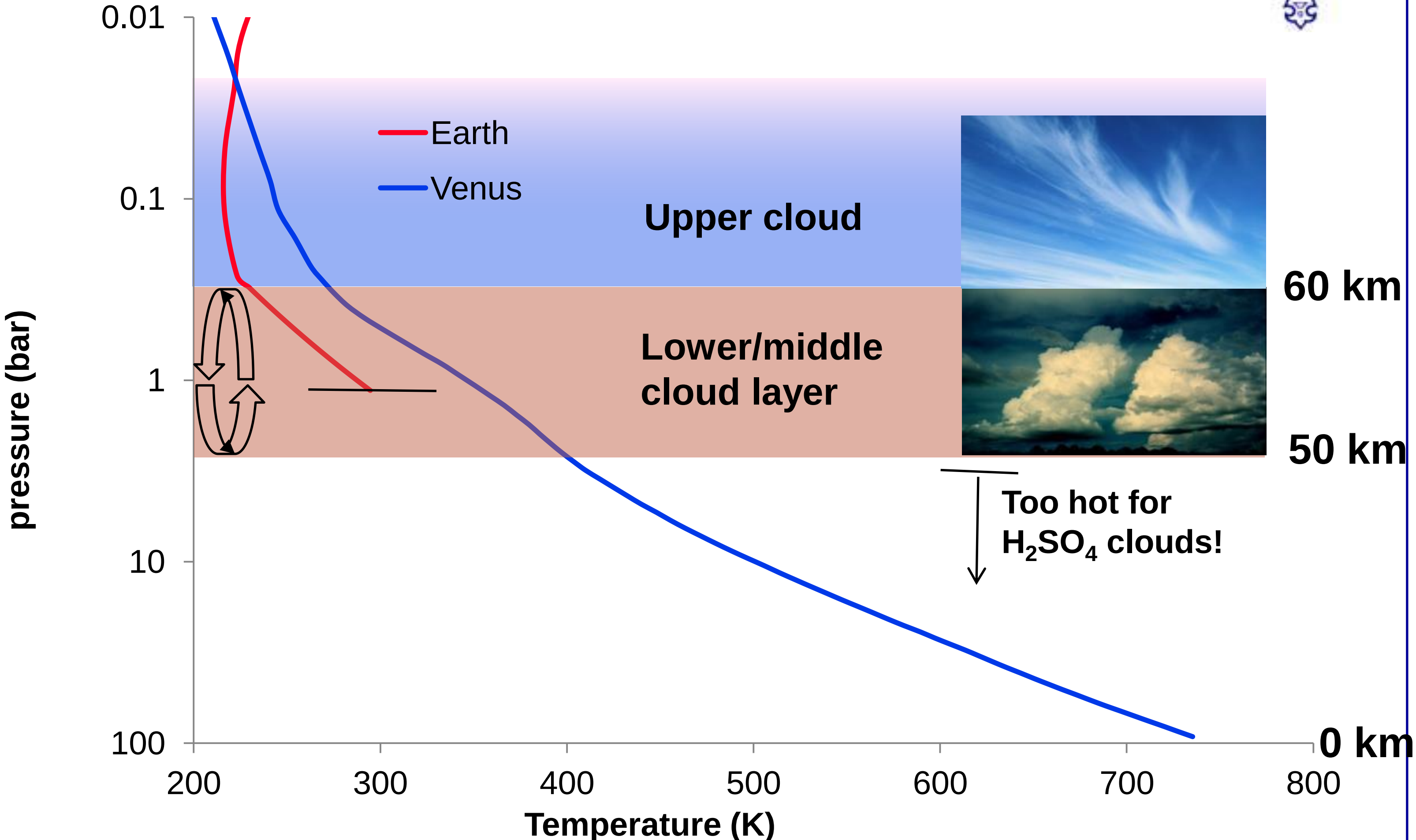


Linkin et al 1986



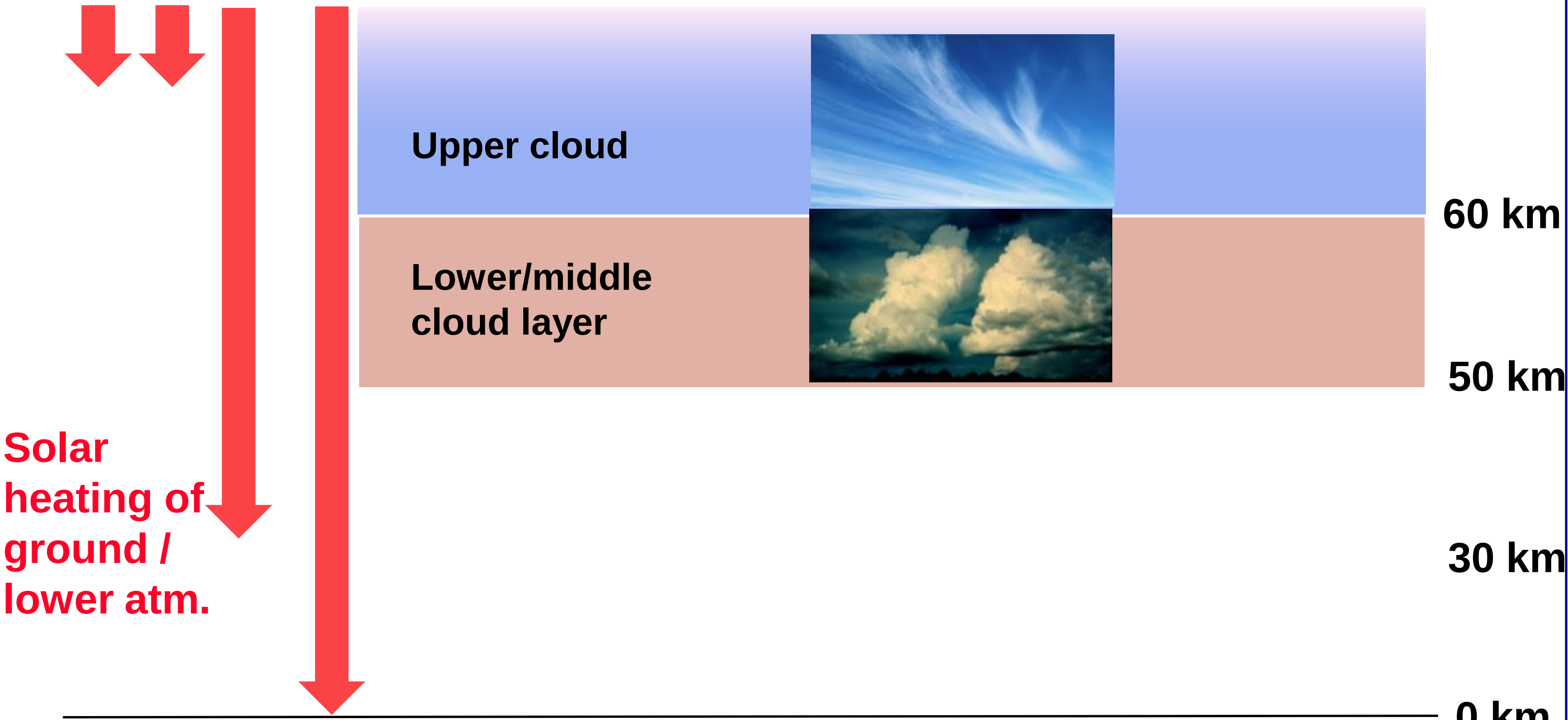
Galileo Venus flyby image 1990 – nightside near-IR emission

Temperature structure (Venus)



Temperature structure (Venus)

What drives cloud-level convection?



Temperature structure (Venus)

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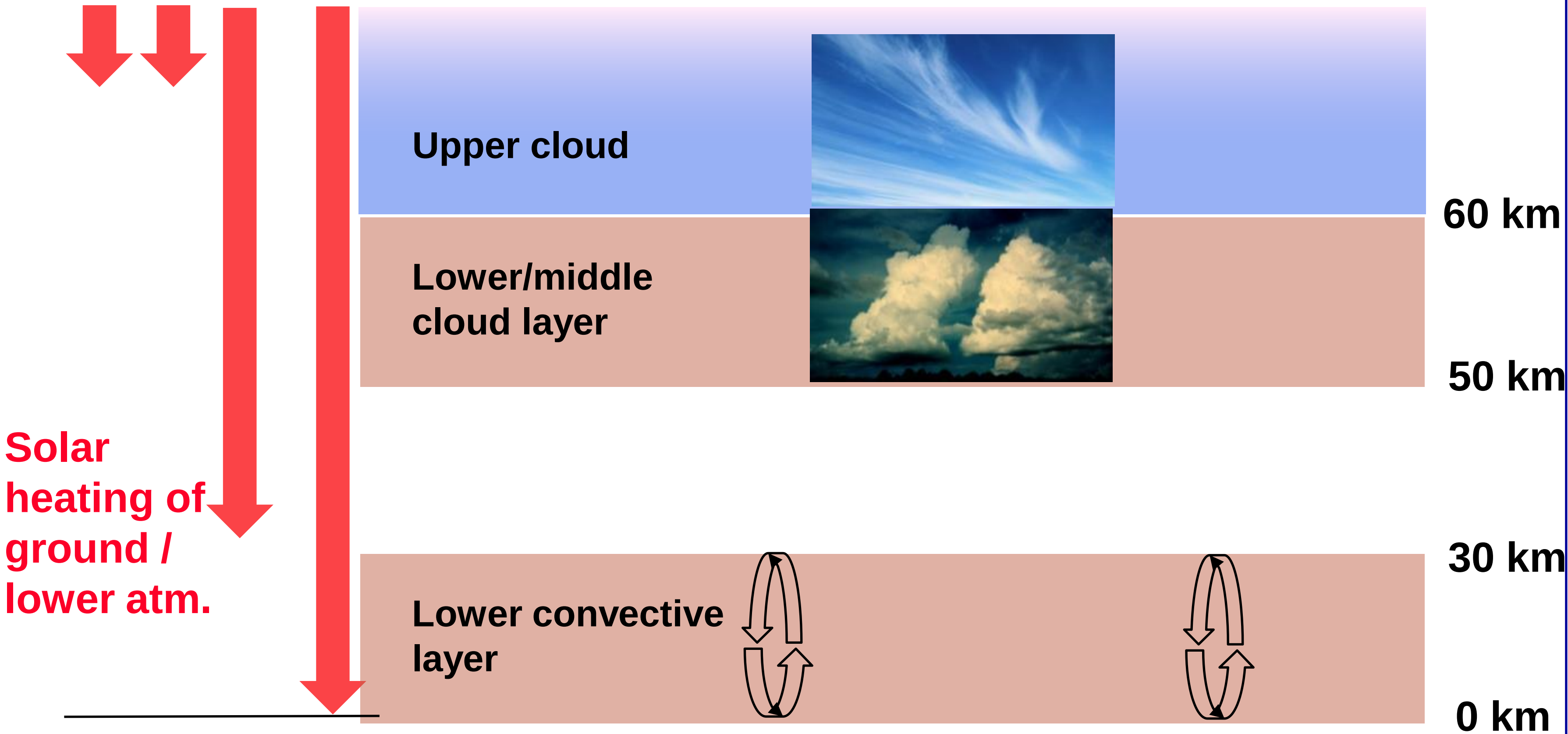

Temperature structure (Venus)

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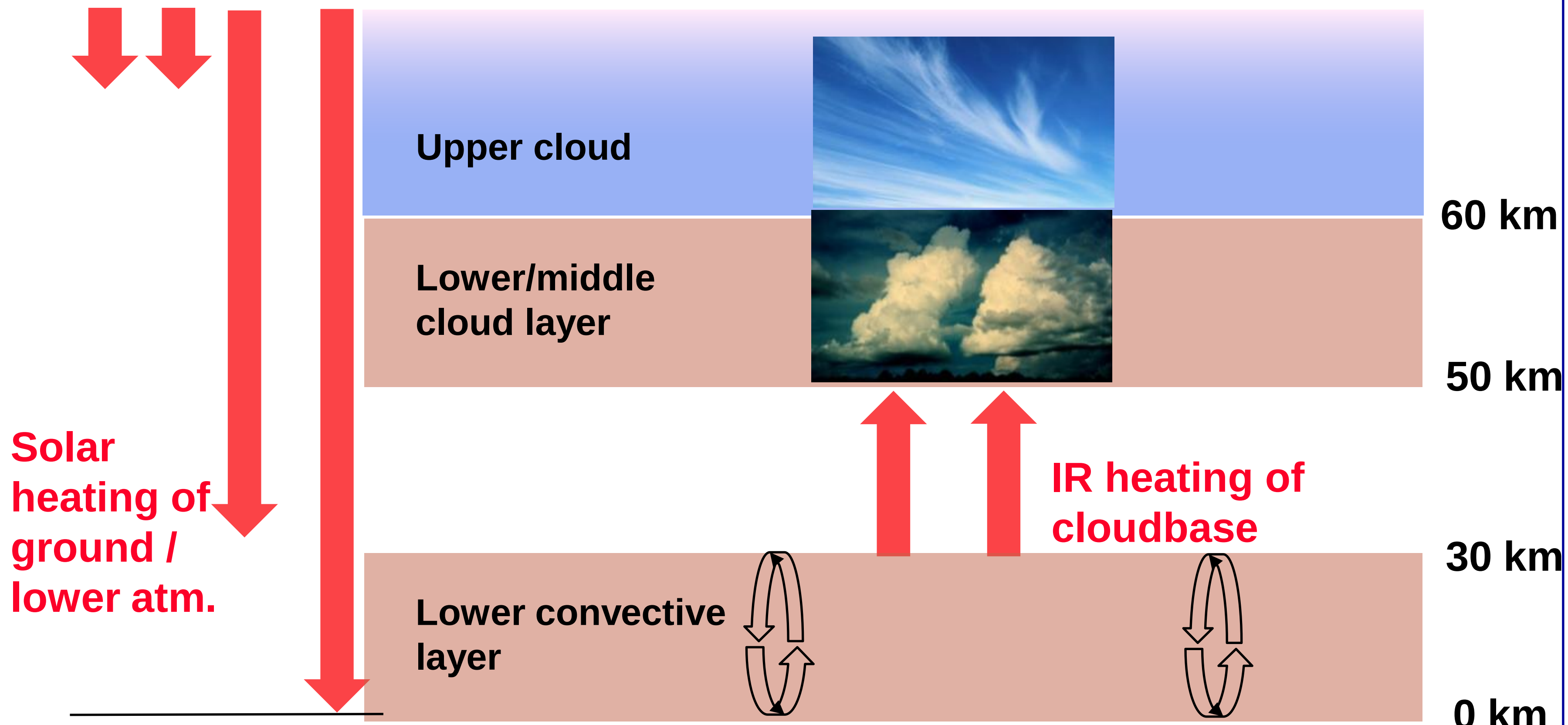

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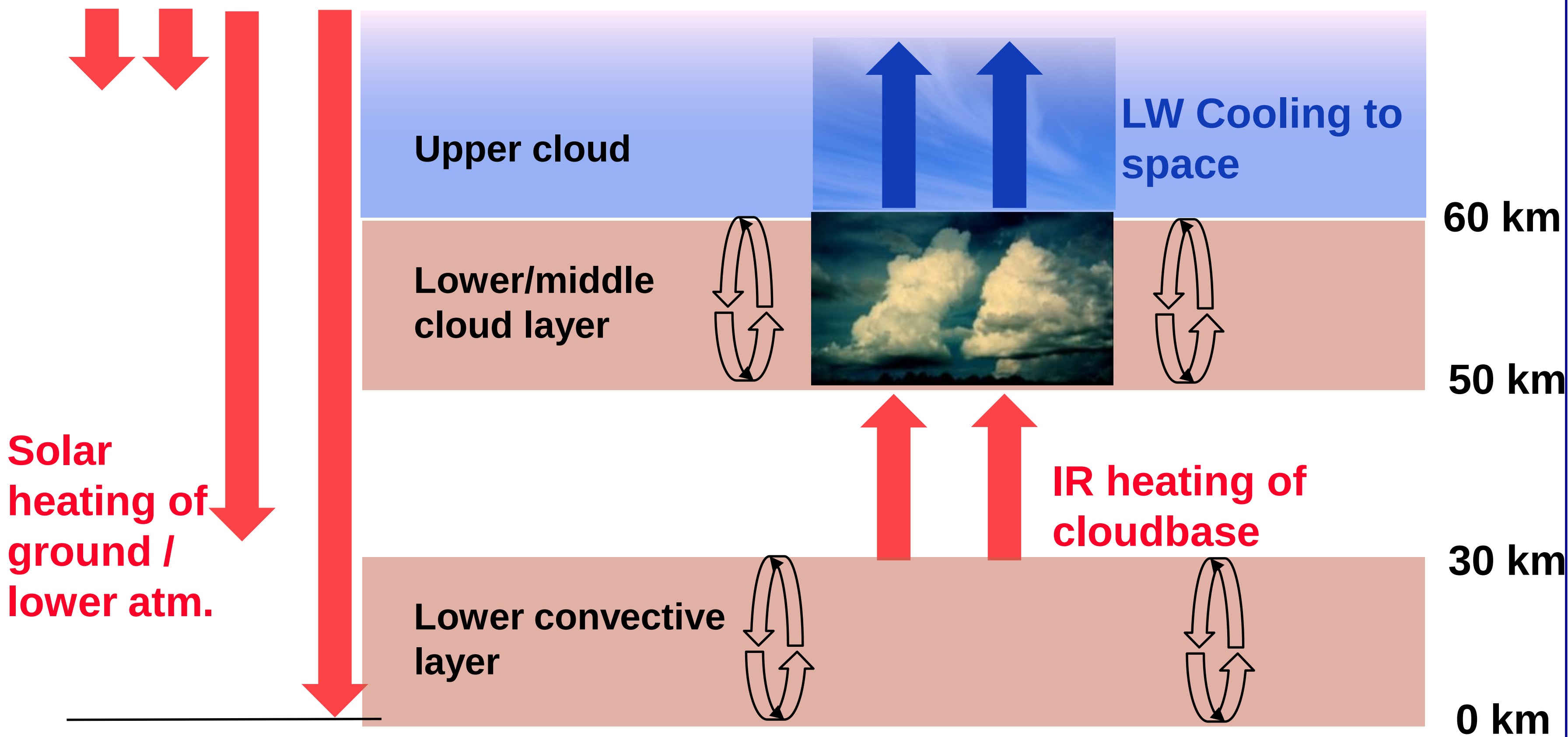
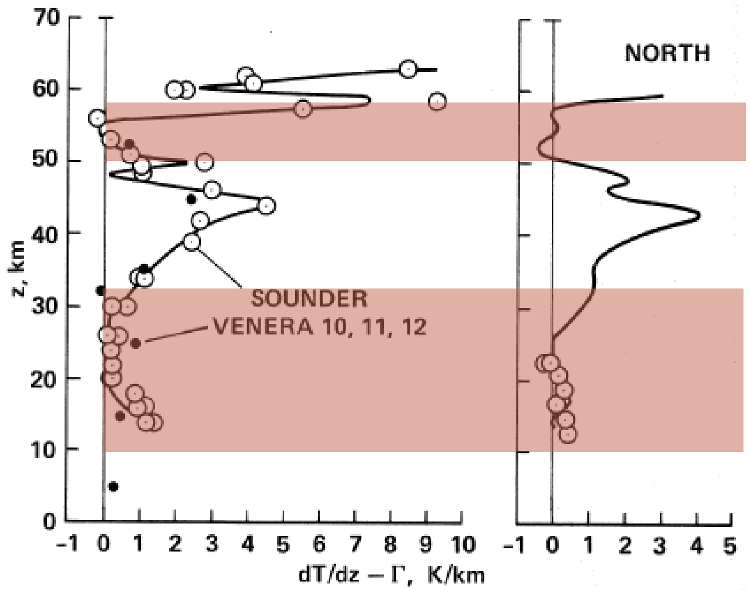


Temperature structure from descent probes

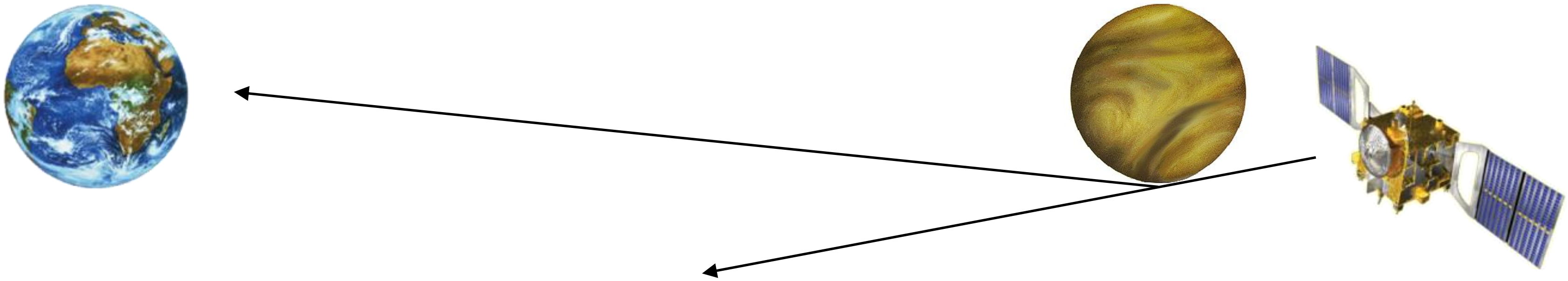
Static stability measures deviation of measured dT/dz from adiabatic lapse rate
Static stability near 0 indicates convection.



Main Convective layer is at ~ 50 – 60 km altitude

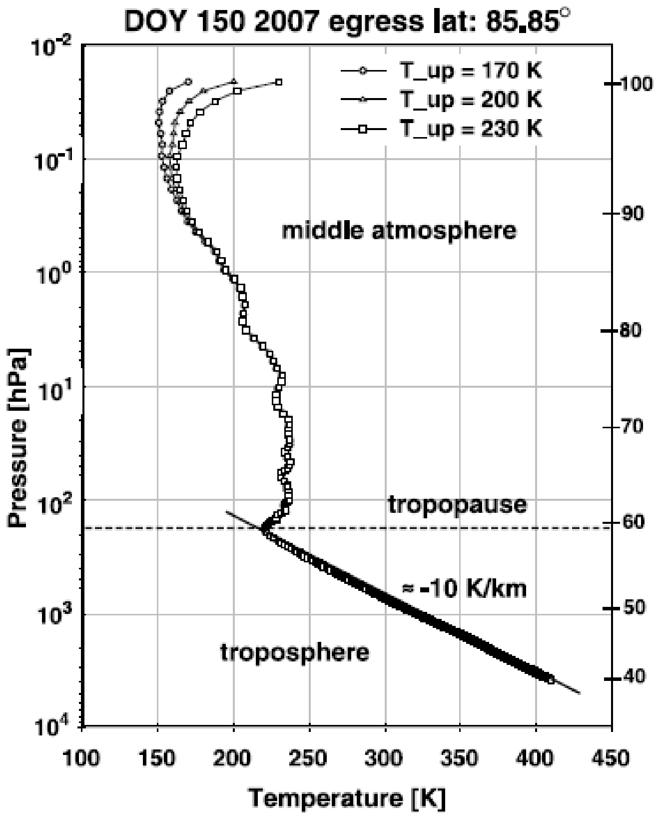
Upper cloud (60 – 70 km altitude) is very stable

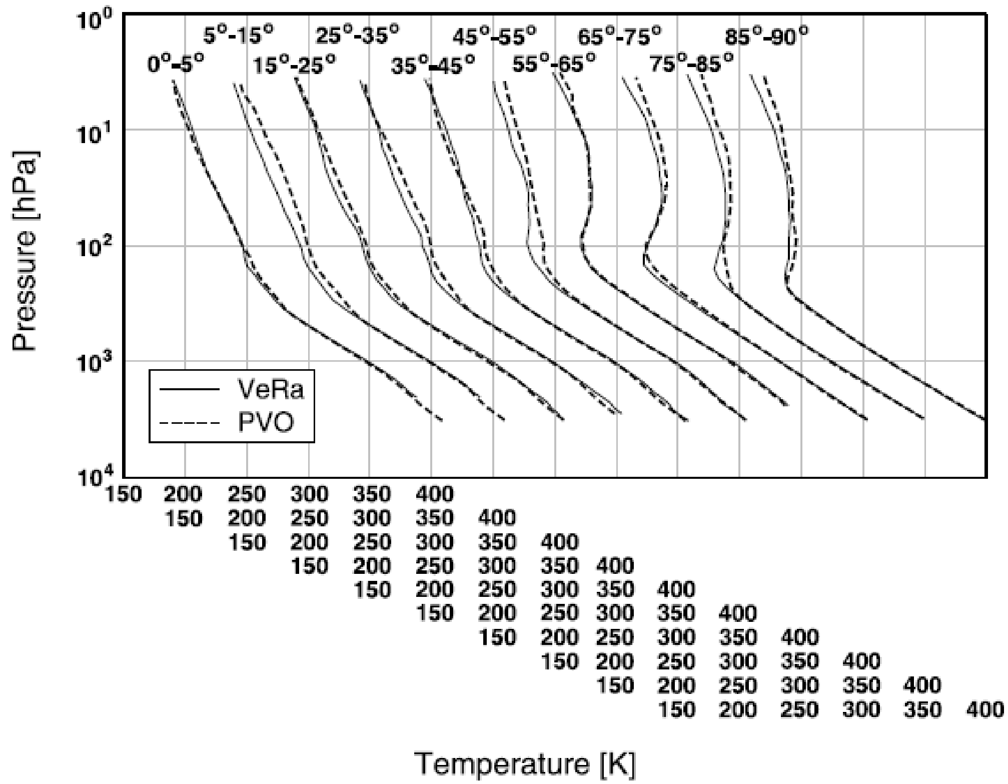
Temperature structure - VEx radio occultation



- As VEx sets behind Venus, radio signal is bent by atmosphere of Venus.
- Examining **Doppler shift** of signal yields
  - profile of refractive index gradients
  - density, pressure and temperature profiles 40 – 90 km
- Examining **absolute magnitude** of signal reveals losses, due to
  - beam spreading
  - **absorption in atmosphere - assumed to be H_2SO_4**
  - *any* other loss processes

Temperature structure - VEx radio occultation



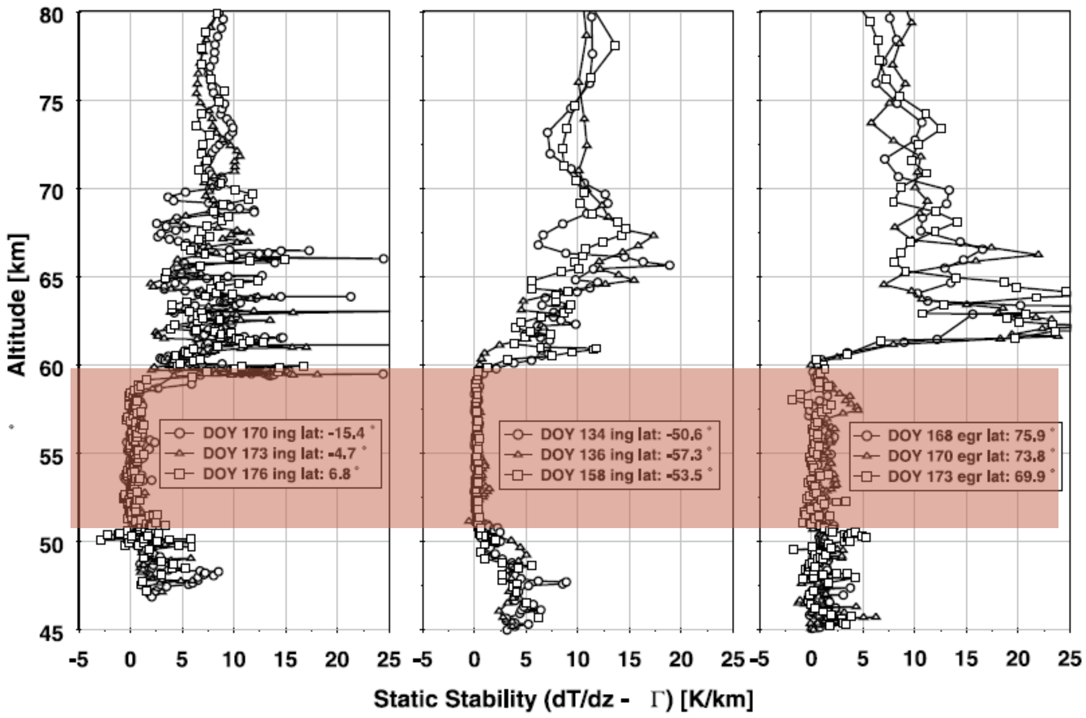


Tellmann et al., JGR 2009

VEx radio occultations have been returning data showing latitude and local time dependence of stability profiles

Temperature structure - VEx radio occultation

Venus Express measures temperature profiles from 40 – 90 km using radio occultation (>300 profiles to date)



Tellmann et al., JGR 2009

VEx radio occultations appear to show that polar regions may have far deeper convection than previously thought.

Venus clouds – Sulphur cycle

60 - 75 km
Stratosphere

Net H_2SO_4 source (photochemical)

$$SO_2 + CO_2 + H_2O \rightarrow H_2SO_4 + CO,$$
$$SO_2 + 2CO \rightarrow 2CO_2 + S.$$

H_2SO_4:H_2O clouds

Net transports:

↑ **SO_2, H_2O, OCS**

↓ **H_2SO_4, S_x, CO**

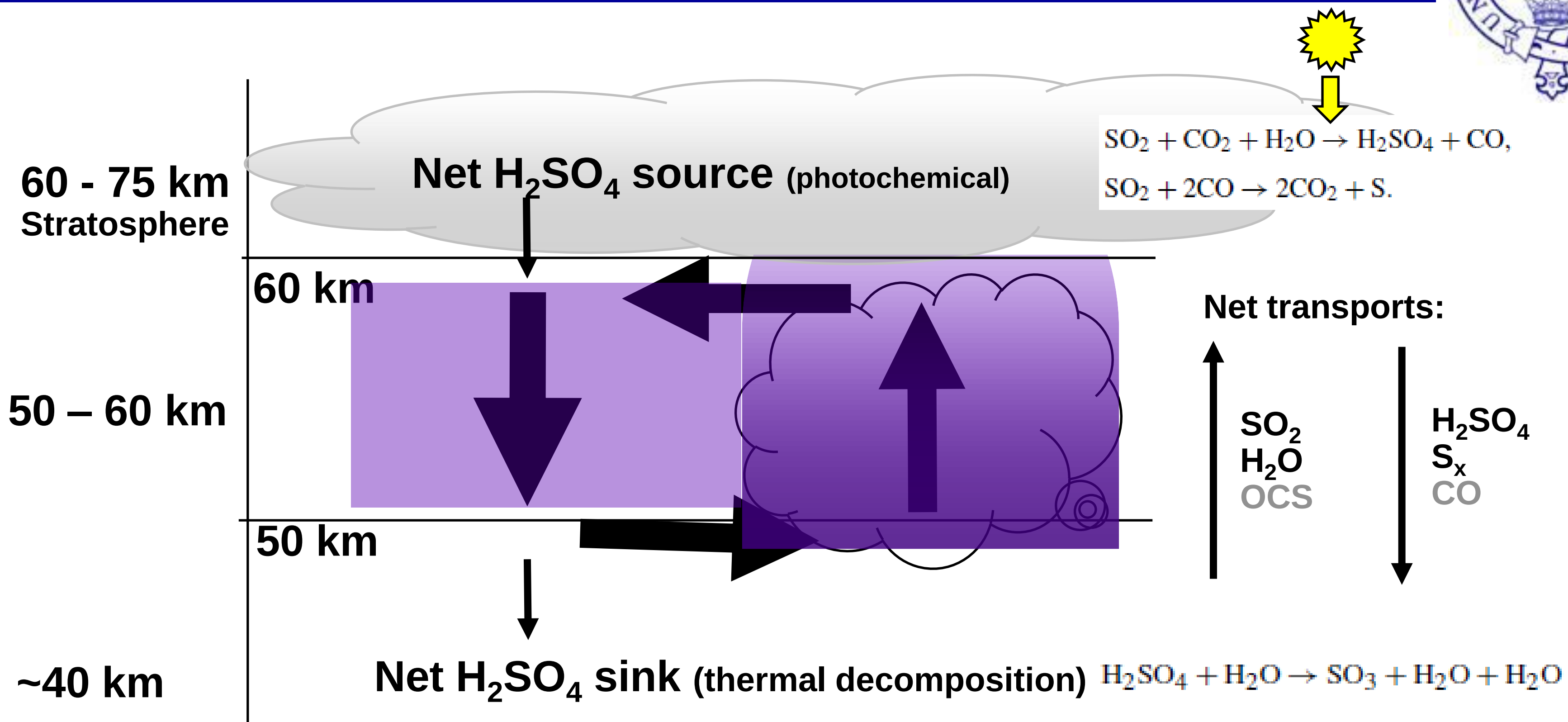
~40 km

Net H_2SO_4 sink (thermal decomposition)

$$H_2SO_4 + H_2O \rightarrow SO_3 + H_2O + H_2O$$

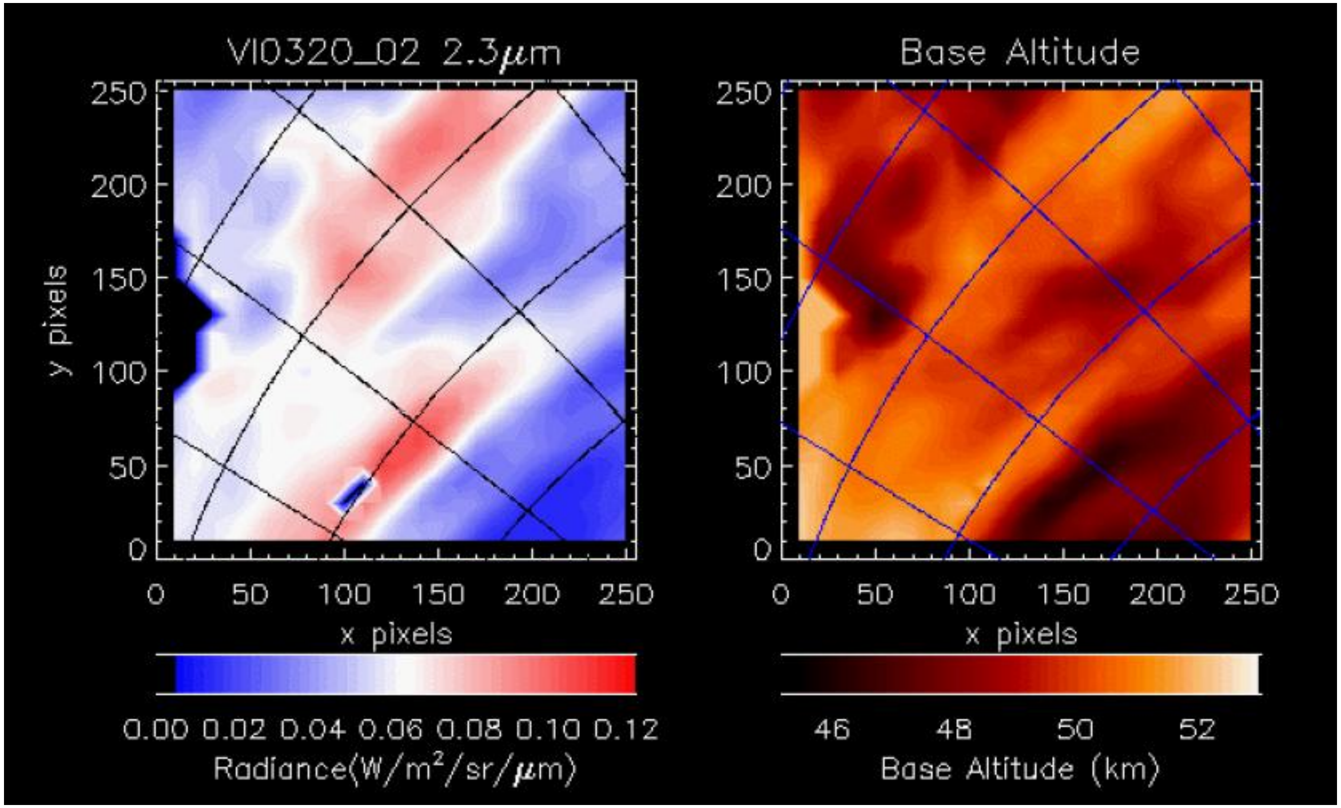
- **SO_2 & H_2O : volcanic source?**
- ***H_2SO_4 & S_x : cloud-forming agents***

Venus clouds – Sulphur cycle



- **SO_2 & H_2O : volcanic source?**
- ***H_2SO_4 & S_x : cloud-forming agents***

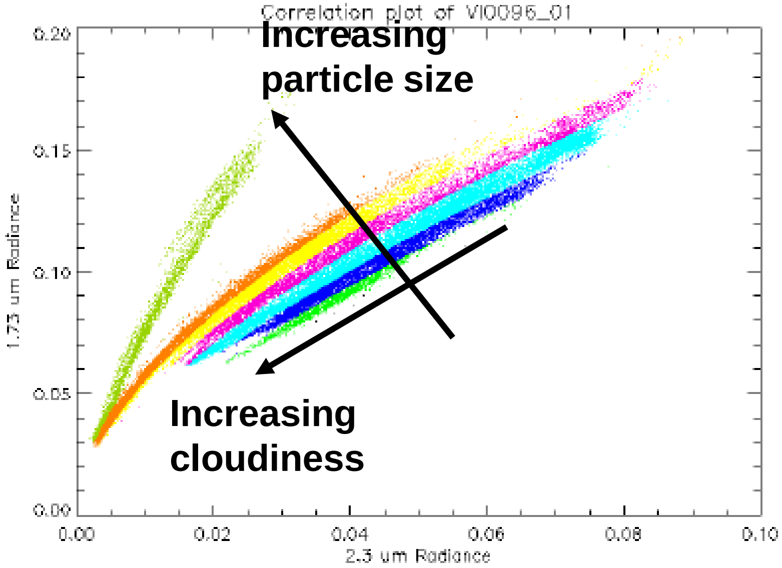
Lower clouds – constraints on cloud base altitude



- **Regions of thicker cloud have a slightly *lower cloudbase altitude*, and *higher acid concentration*, than regions of thin cloud. (Barstow et al., 2012).**

Lower clouds – particle size

- Wavelength dependence of scattering depends on particle size, so wavelength ratios give *rough* indication of particle size
- No consistent correlation of particle size with cloud thickness!
  - (unlike Earth thunder clouds)
- However, large particles found towards polar vortex



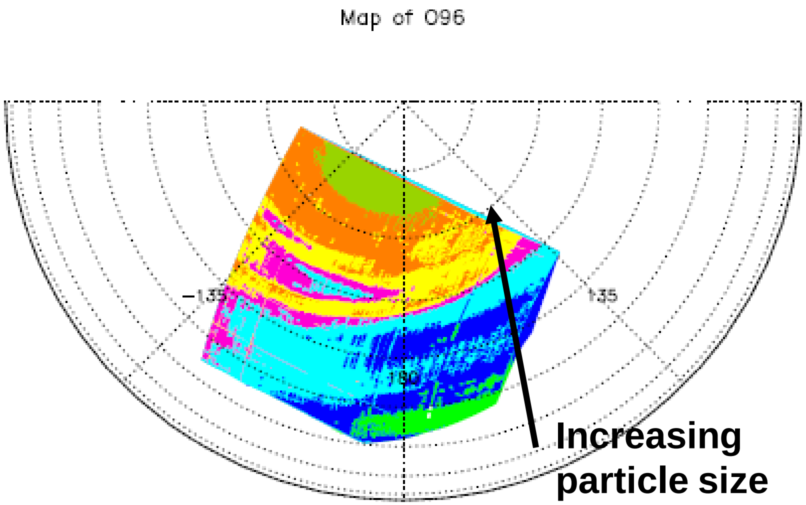
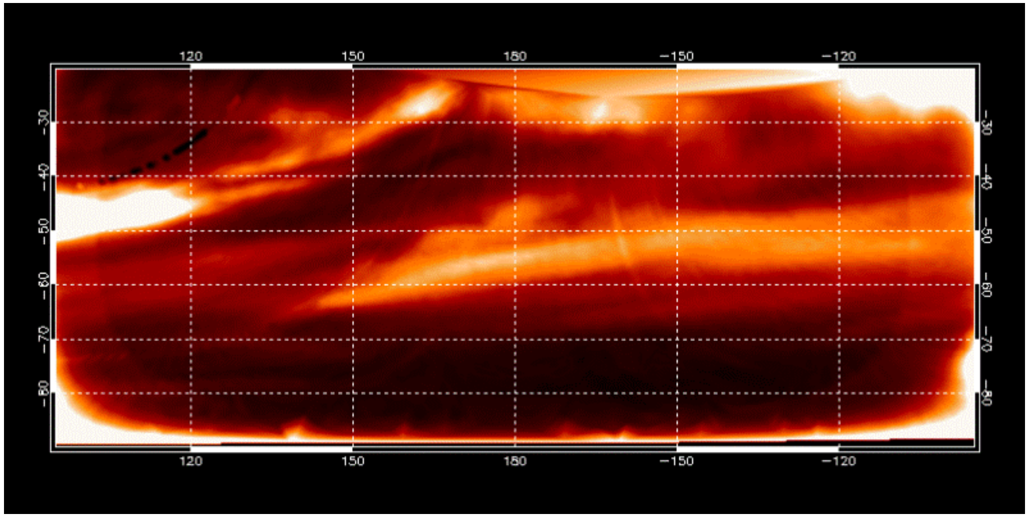


Image: Sandrine Guerlet

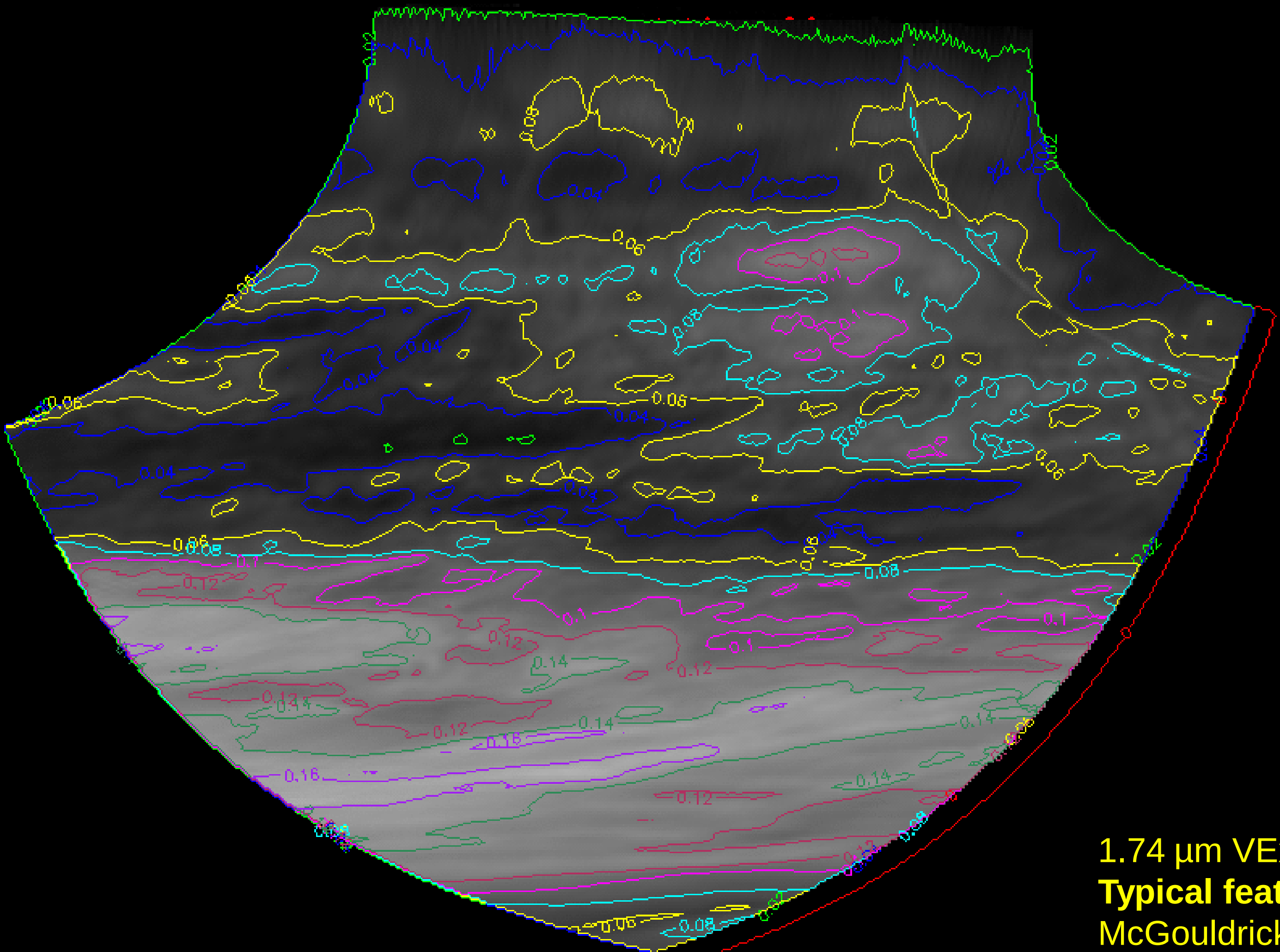
Lower clouds – temporal evolution

- Individual cloud features can be tracked in image sequences from Venus Express / VIRTIS imagery



- **Features evolve with a time constant of approximately 1 Earth day.**
- **Features at lower latitudes evolve more quickly.**

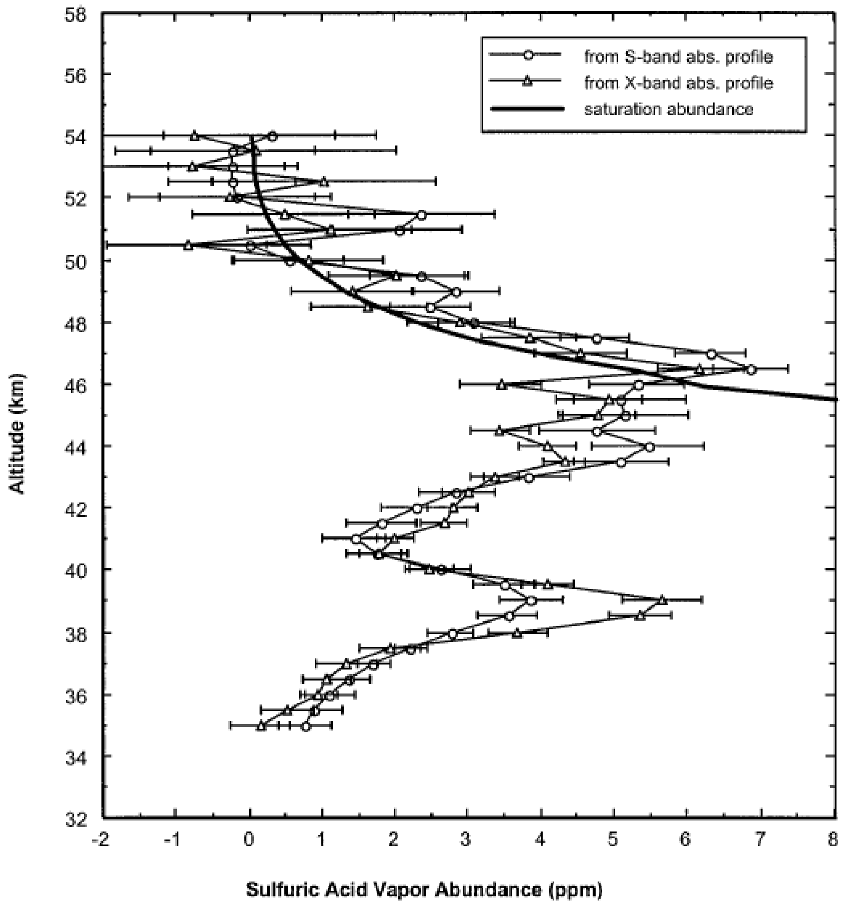
Lower clouds –
temporal evolution of lower clouds



1.74 µm VEx/VIRTIS images
Typical feature lifetime ~ 1 Earth day
McGouldrick et al, 2012

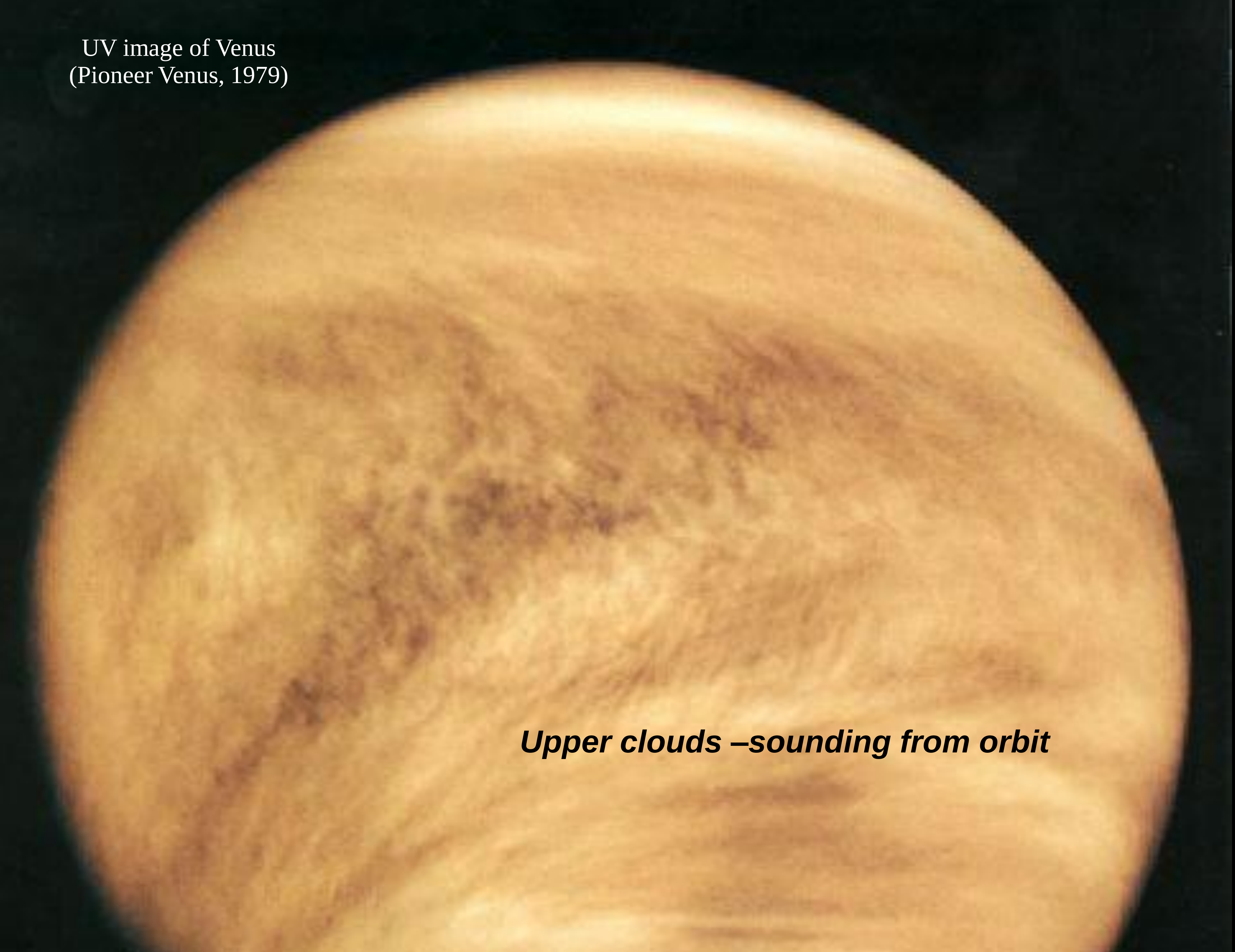
Sulfuric acid profiles - VEx radio occultation

Analysis of VEx profiles is in progress!



Kolodner & Steffes, 1998

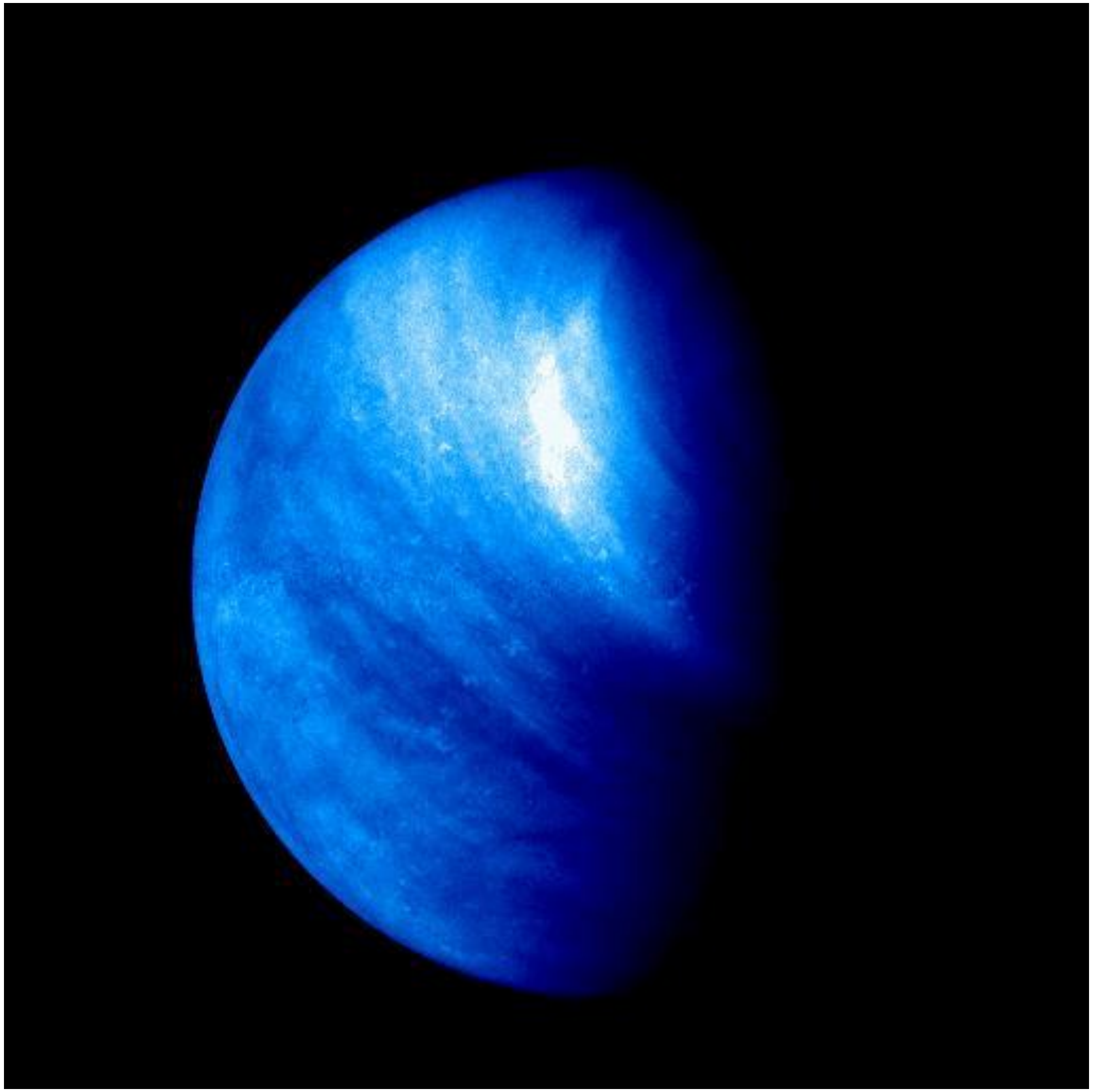
using Magellan data



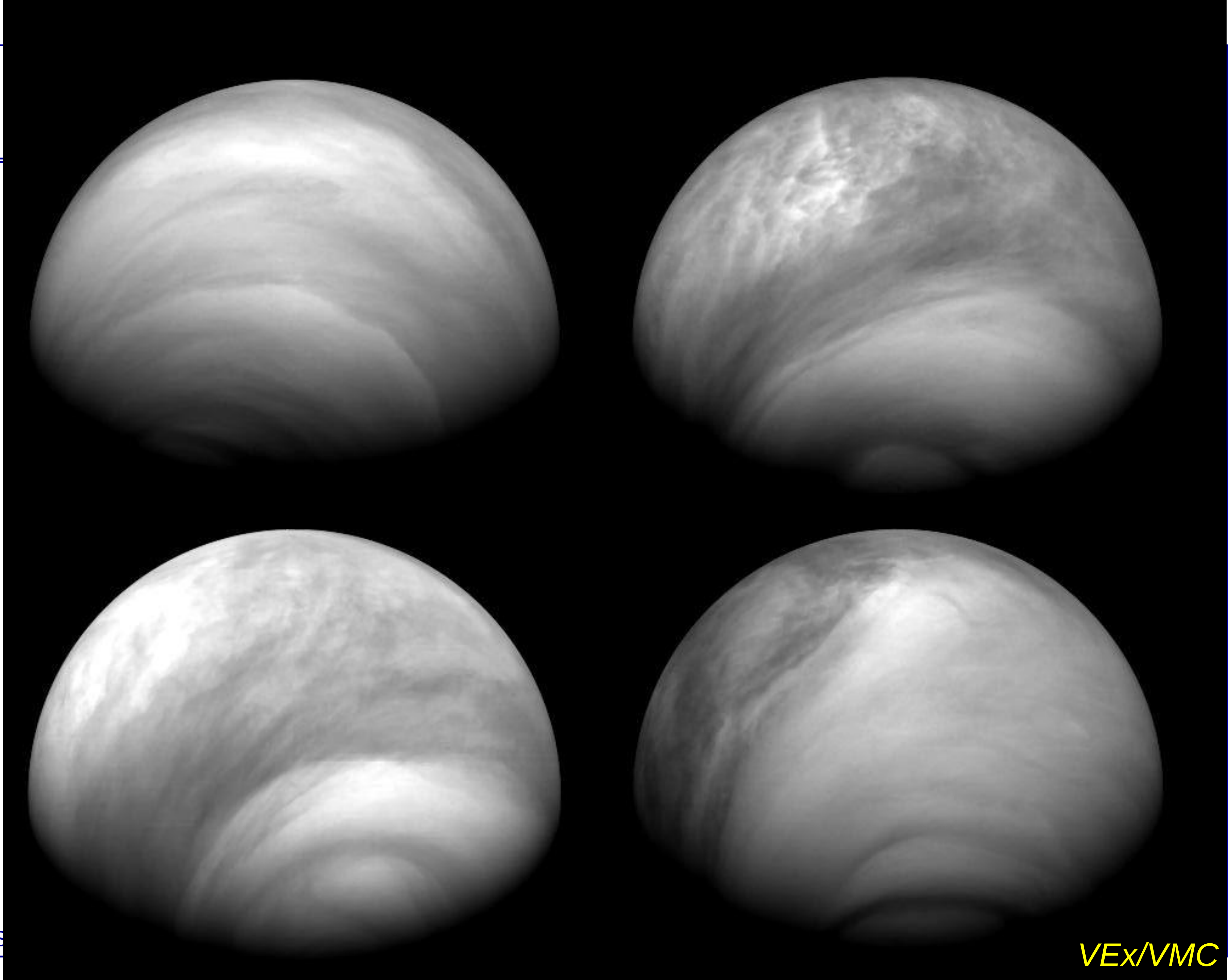
UV image of Venus
(Pioneer Venus, 1979)

Upper clouds –sounding from orbit

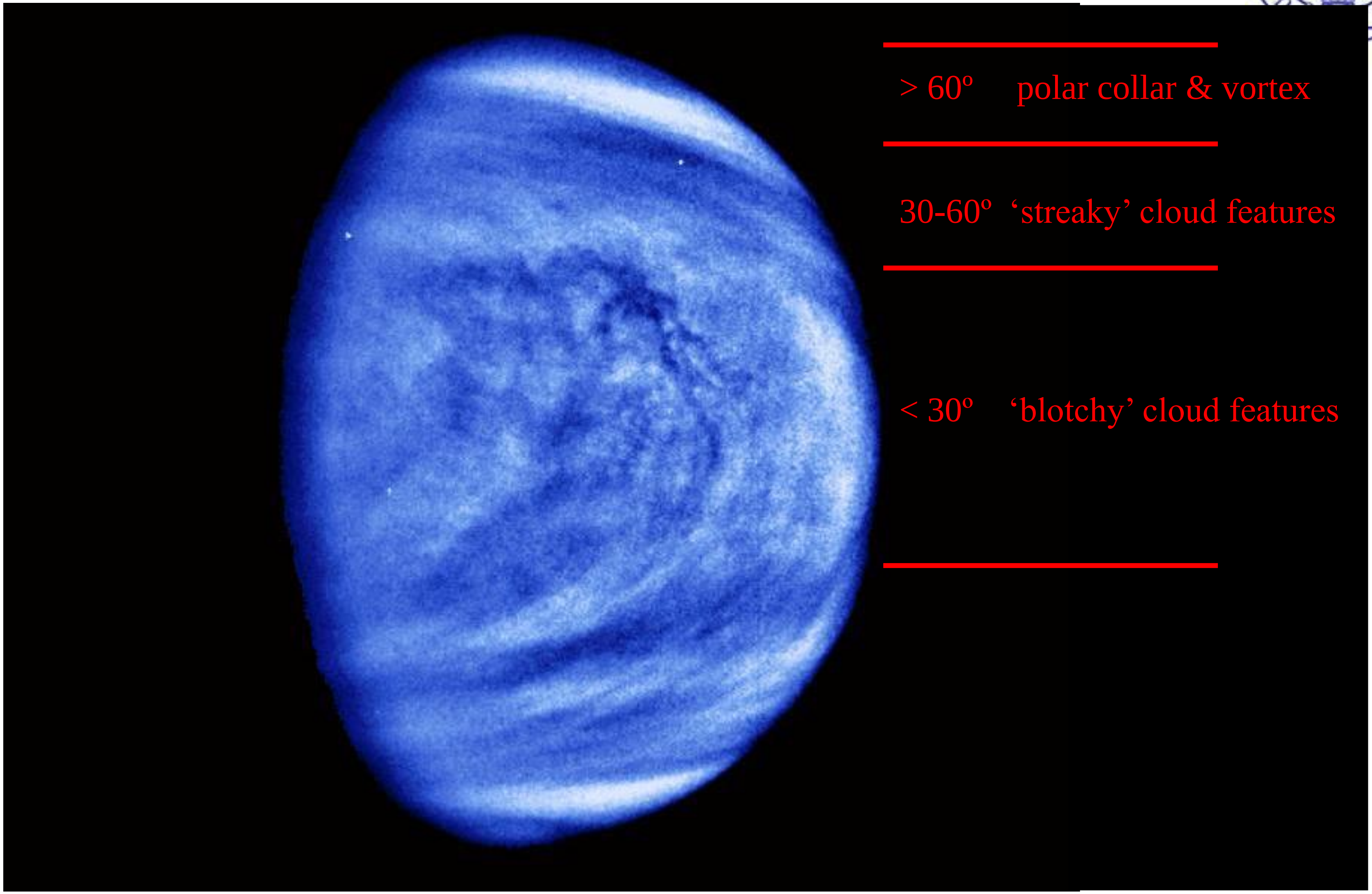
VEx/VMC images of upper clouds



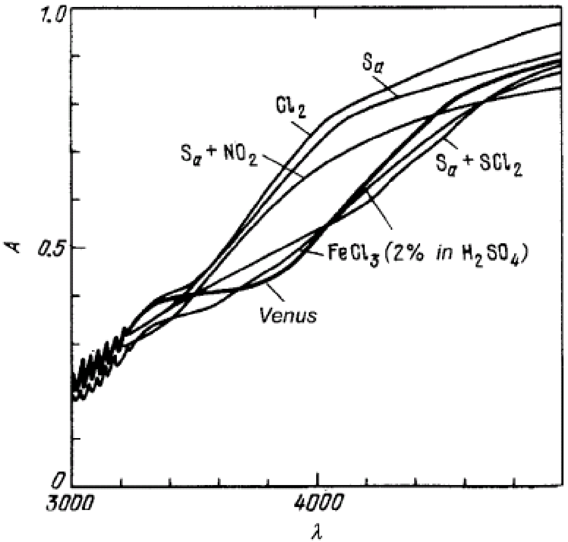
VEx/VMC


VEx/VMC

Upper clouds - morphology



But what causes UV contrast?



Suggestions include:

- Formaldehyde CH2O
- Carbon suboxide C3O2
- Nitrosylsulfuric acid NOHSO4
- Nitrogen dioxide NO2 and nitrogen tetroxide N2O4
- Ammonium nitrite NH3NO2
- Ammonium pyrosulfate (NH4)S2O5
- Amides
- Chlorine Cl2
- Sulfur dichloride, SCl2
- Iron chloride FeCl3
- Perchloric acid HClO4
- Disulfur monoxide S2O
- AND
- Elemental sulfur allotropes (S_3 , S_4 , S_8 , ...)

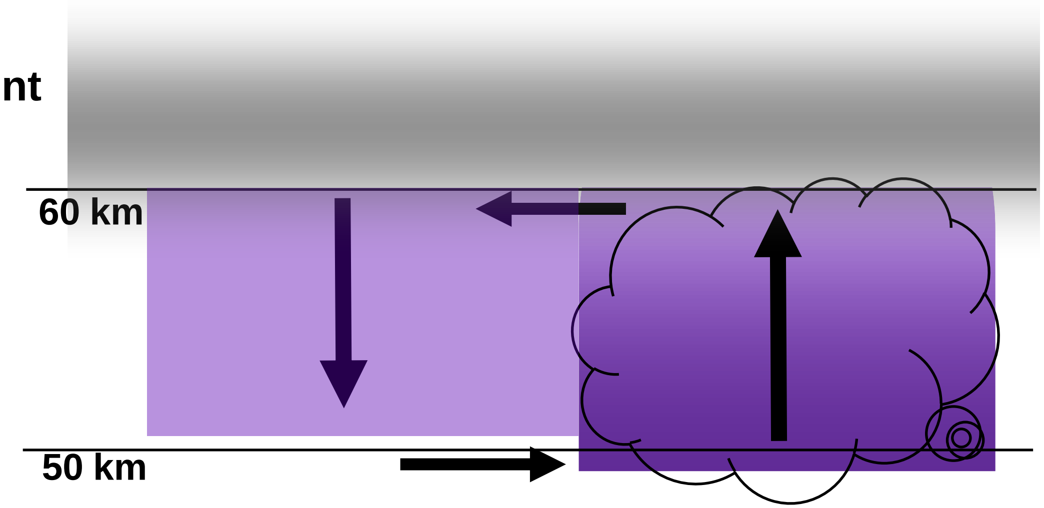
Can VEx resolve this dilemna?

How do UV features arise?

60 -70 km : atmosphere has high convective stability – not consistent with convective cells!

50 - 60 km : convective region

from VeRa observations



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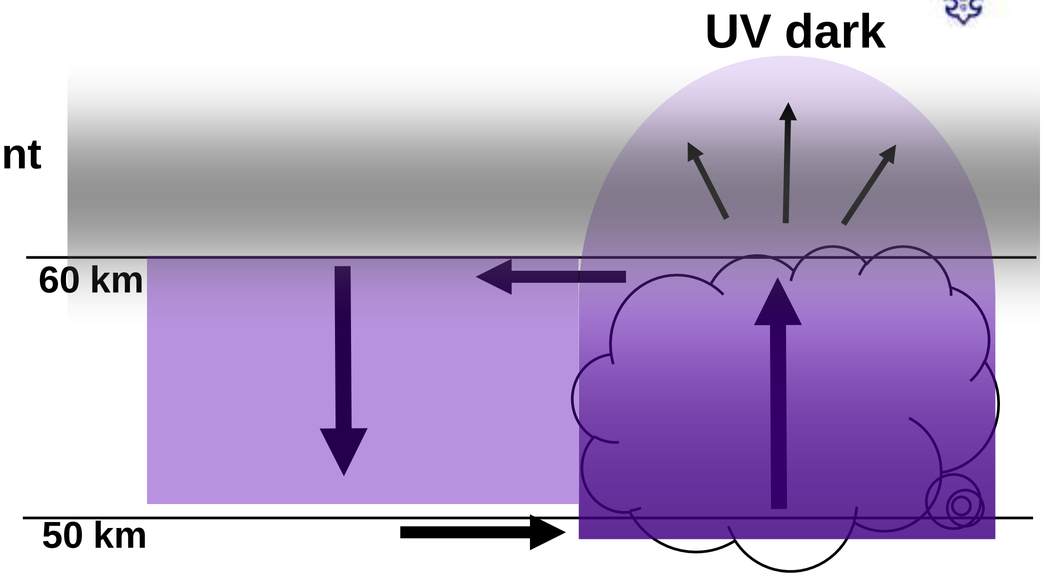

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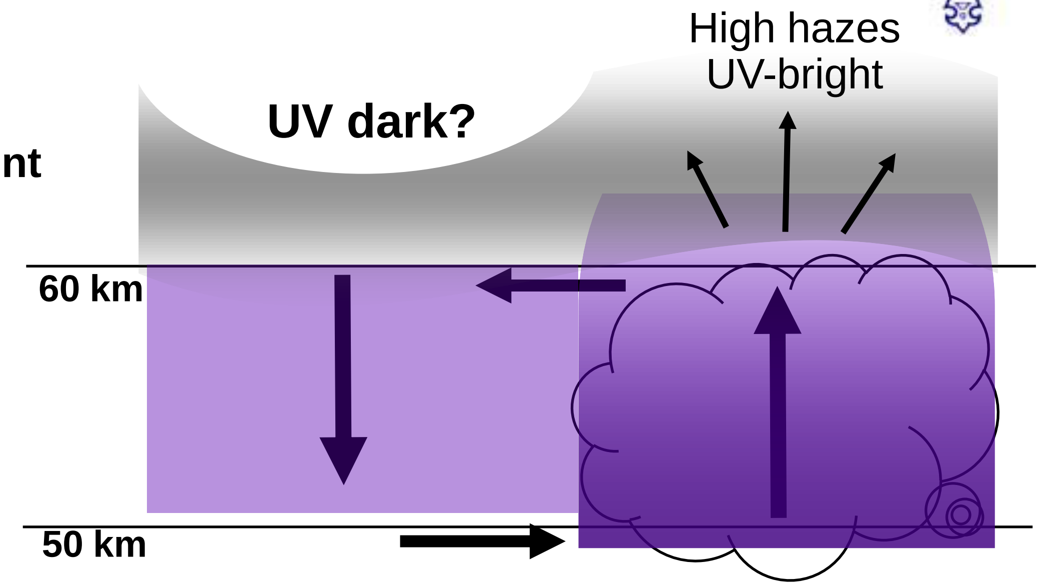
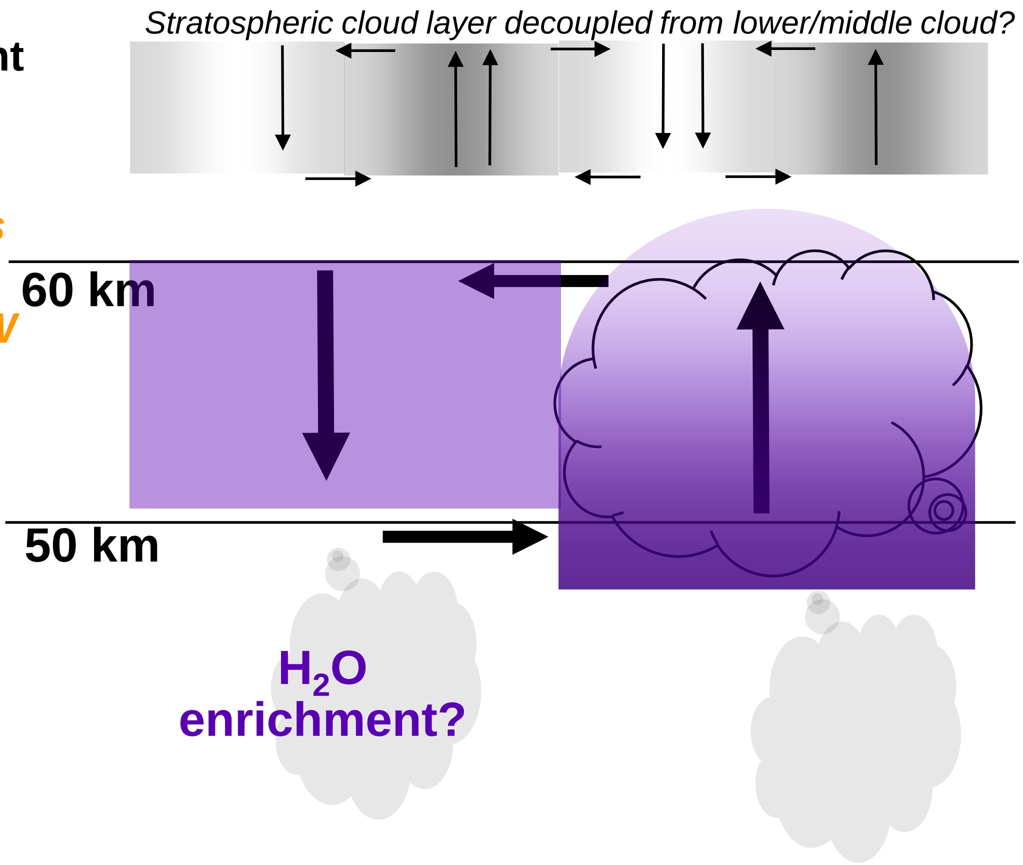


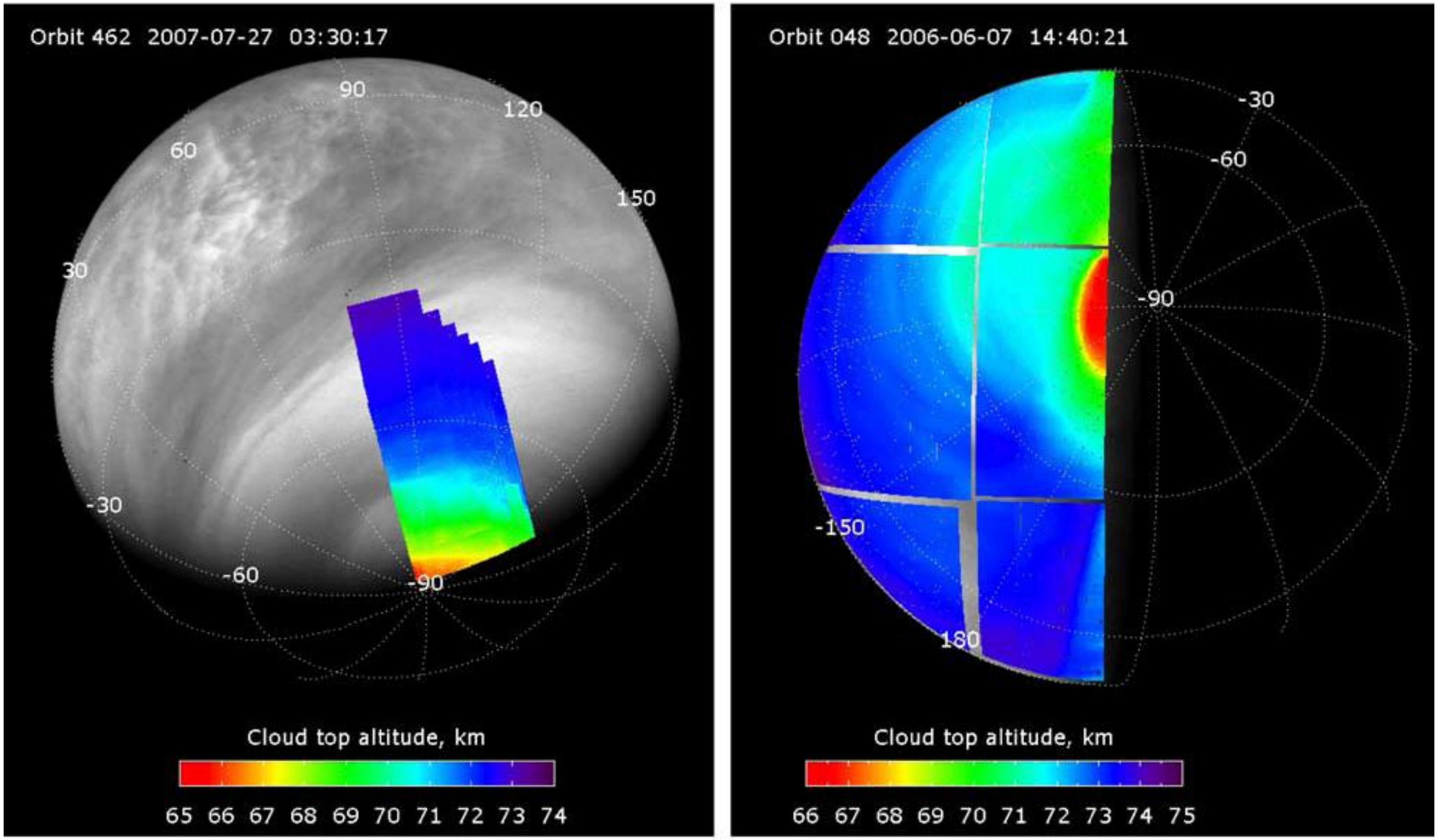
How do UV features arise?

60 -70 km : atmosphere has high convective stability – not consistent with convective cells!

- ***Almost half of solar energy input is absorbed by the UV absorber (Crisp, Icarus, 1986).*** *This is* ***~ 400 W m^{-2}*** *at sub-solar point.*



UV contrast & cloud-top height (VEx/VIRTIS)



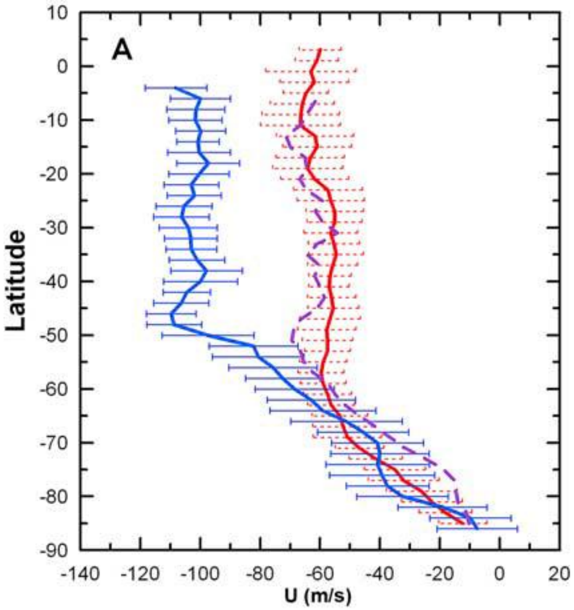
Ignatiev et al., 2009

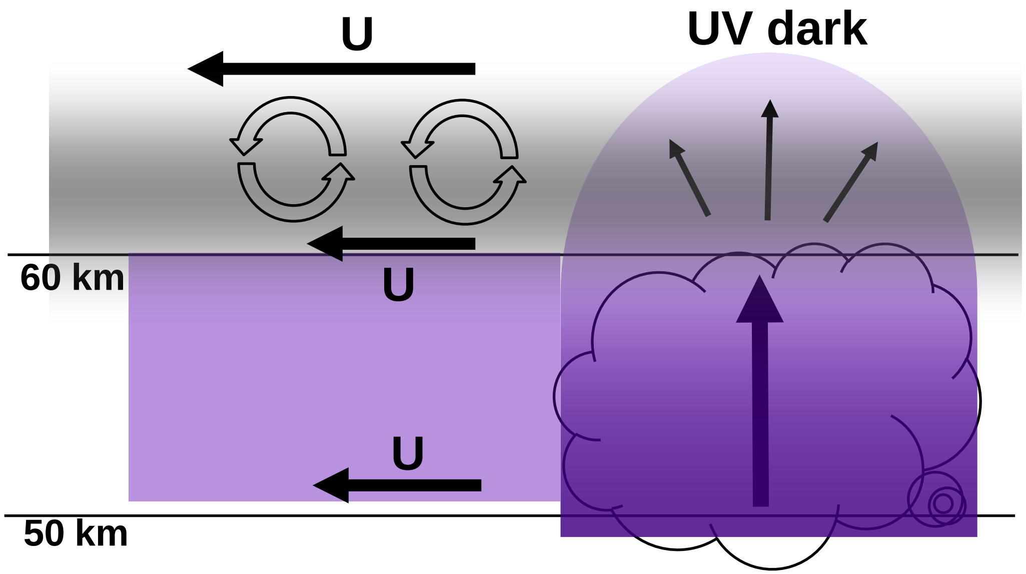
- Cloud-top height measured on the dayside by measuring depth of CO_2 absorption line in reflected sunlight (Ignatiev et al., 2007)
- No variation at low latitudes; decrease of ~7 km toward poles

3-D Wind fields reveal strong vertical shear

Using multiple wavelengths including near-IR channels, VEx measures the drift speed of clouds.

Sanchez-Lavega et al., 2008



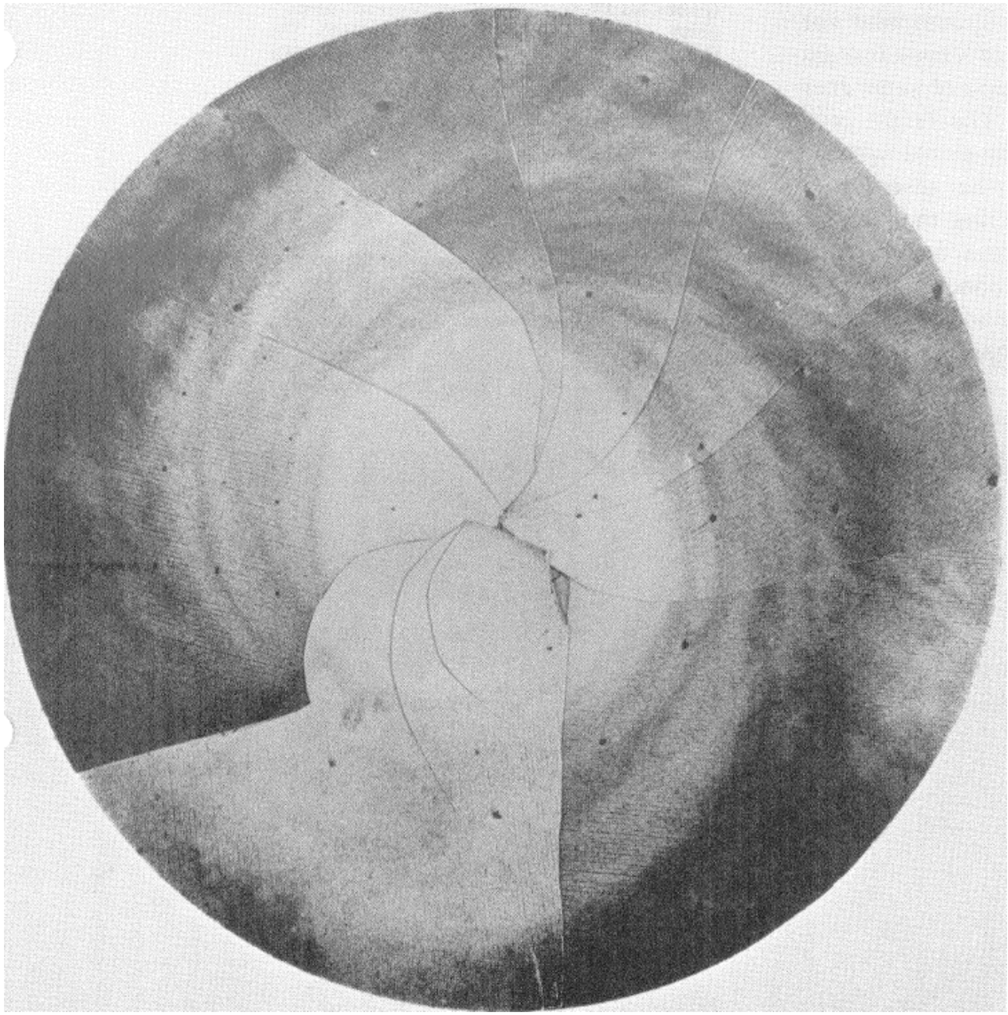


E-W wind speed at 70 km, 60 km, 50 km altitude

(Sanchez-Lavega et al. 2008)

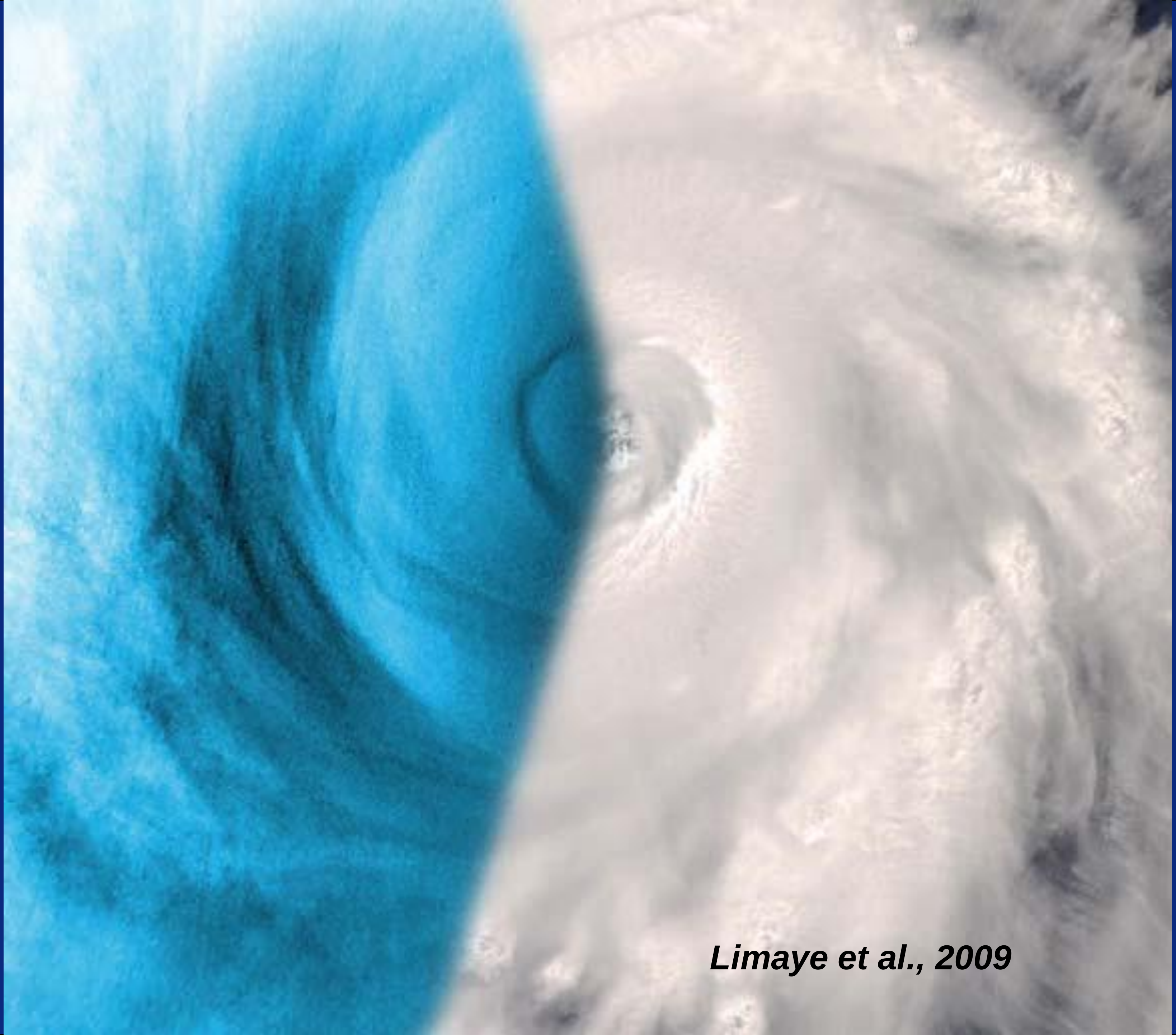
- Very strong vertical wind shear at 60-70 km!
- Casues turbulent mixing despite stratification.

Polar Vortex



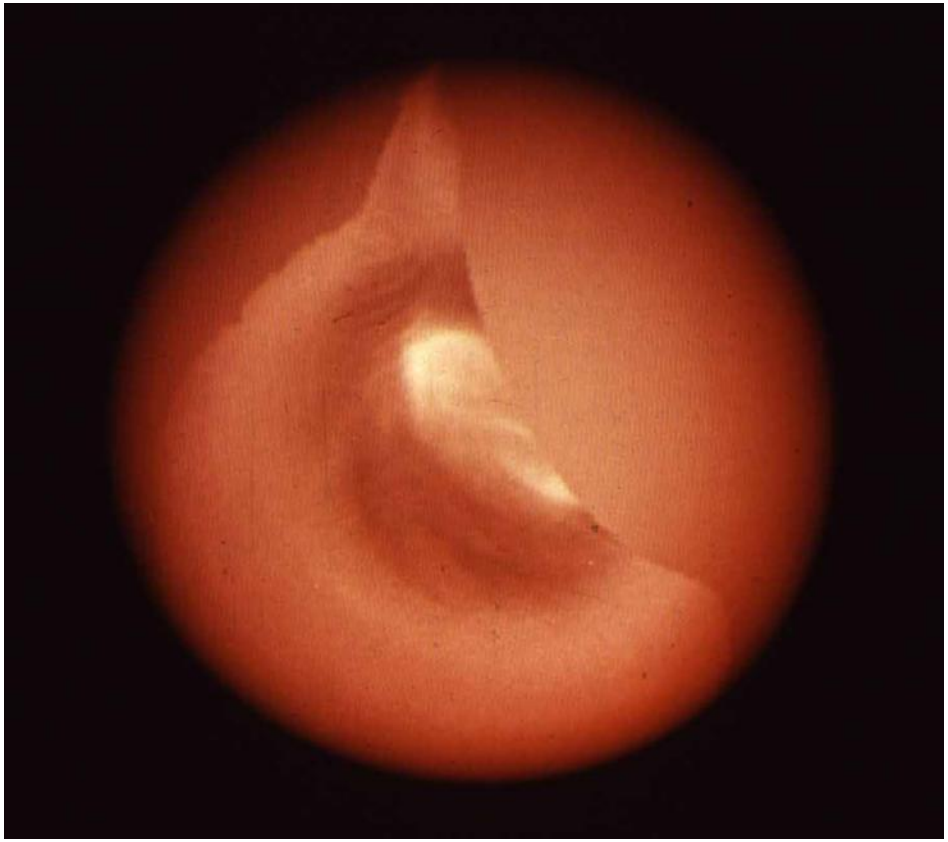
[Suomi and Limaye, 1978-S. hemisph., Mariner 10]

Venus – VEx / VMC



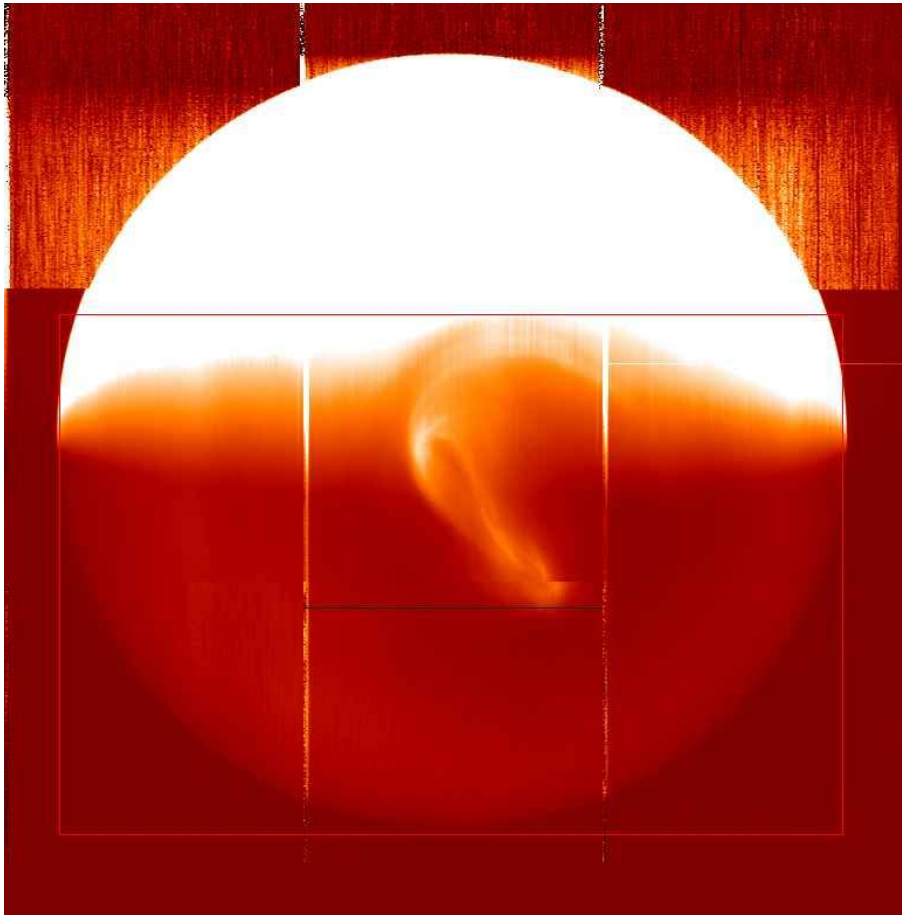
Earth - hurricane Frances

Upper cloud – thermal IR imagery



- Polar view of N pole of Venus at 15 μm wavelength, Pioneer Venus (Taylor et al.1979)
- Little variation at low latitudes but curious ‘double vortex’ at pole

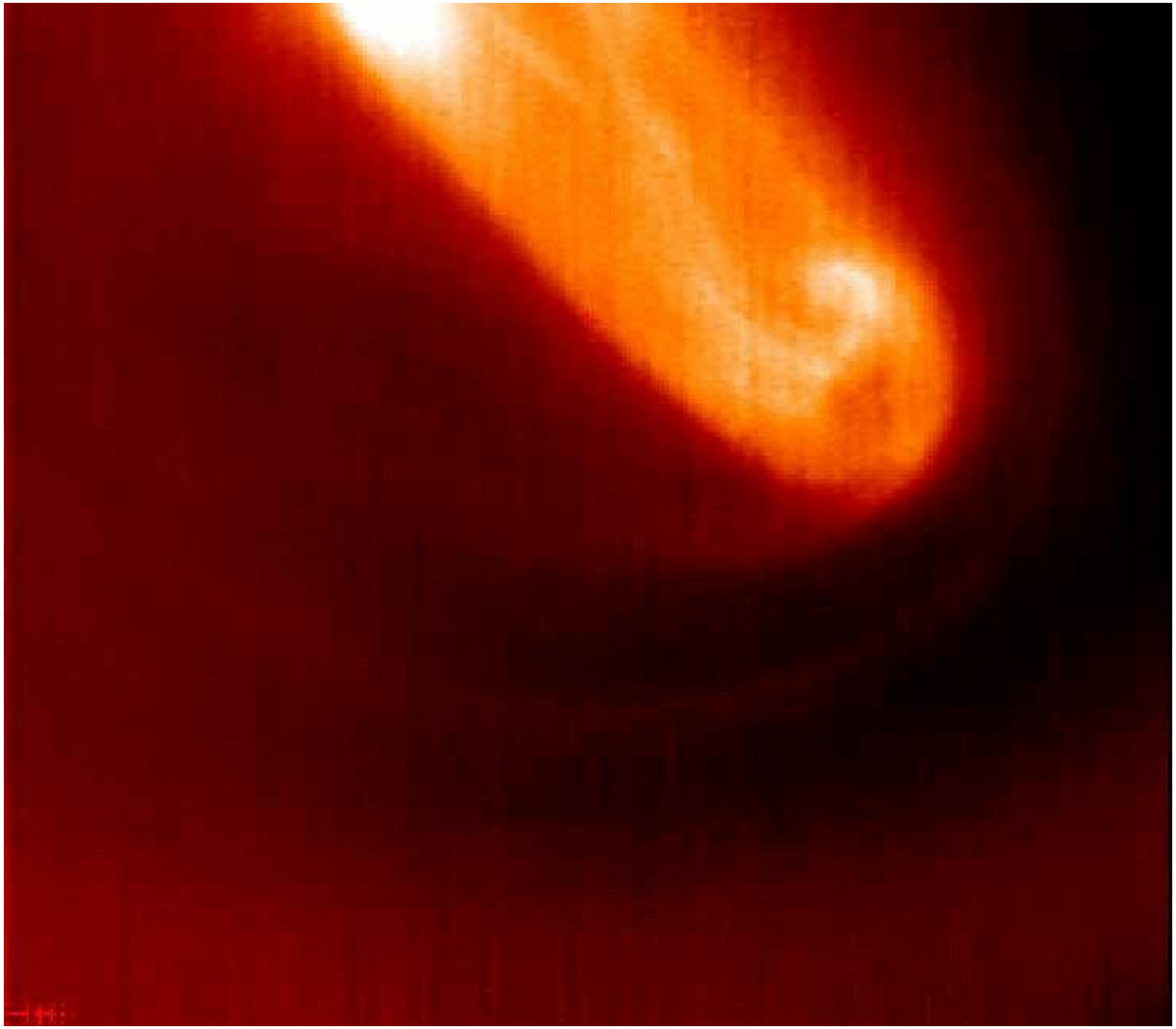
Upper cloud – thermal IR imagery



VEX/VIRTIS

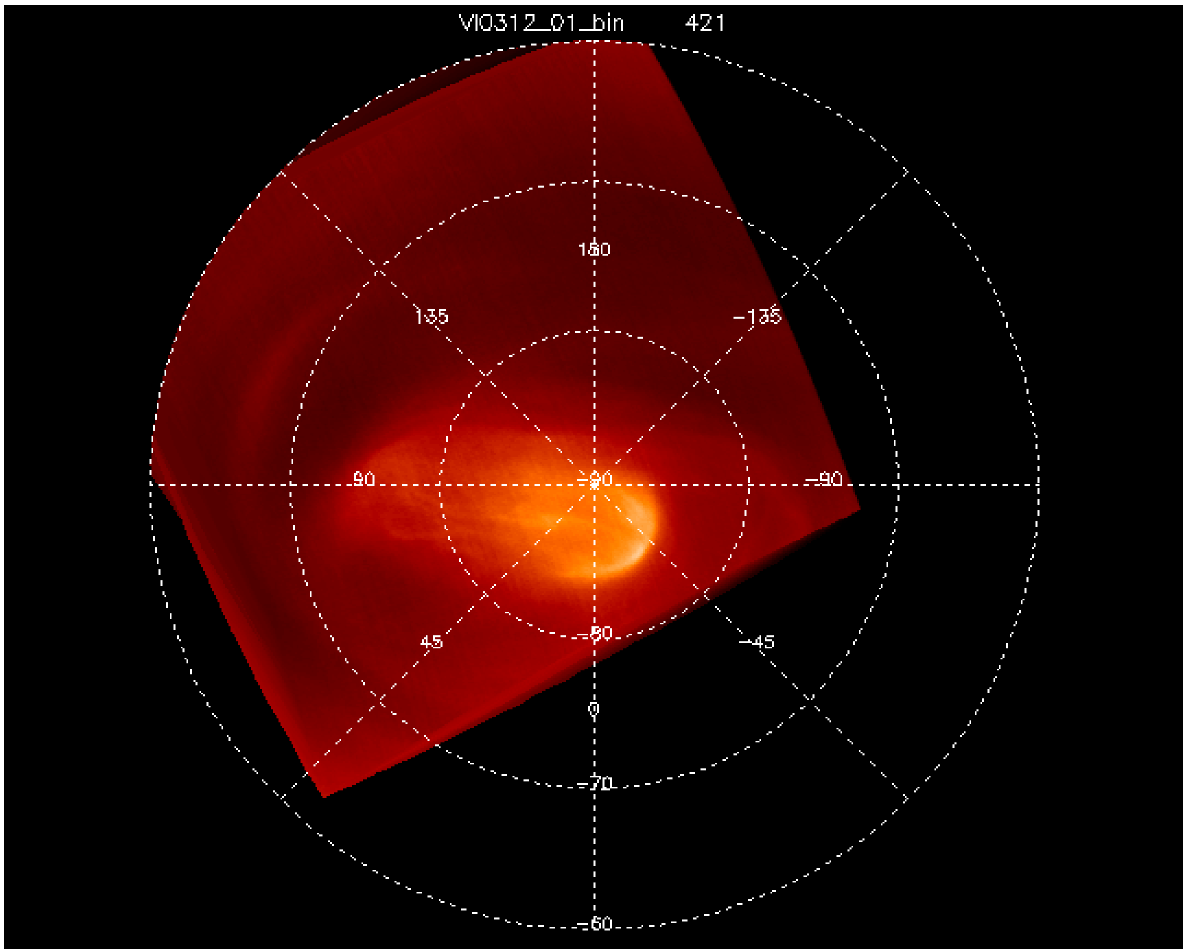
- Polar view of S pole of Venus, with sun to the top
- Thermal infrared image at 3.7 µm (VIRTIS/VEx, from orbit 28)

Upper cloud – thermal IR imagery



VEx/VIRTIS

Upper cloud – thermal IR imagery

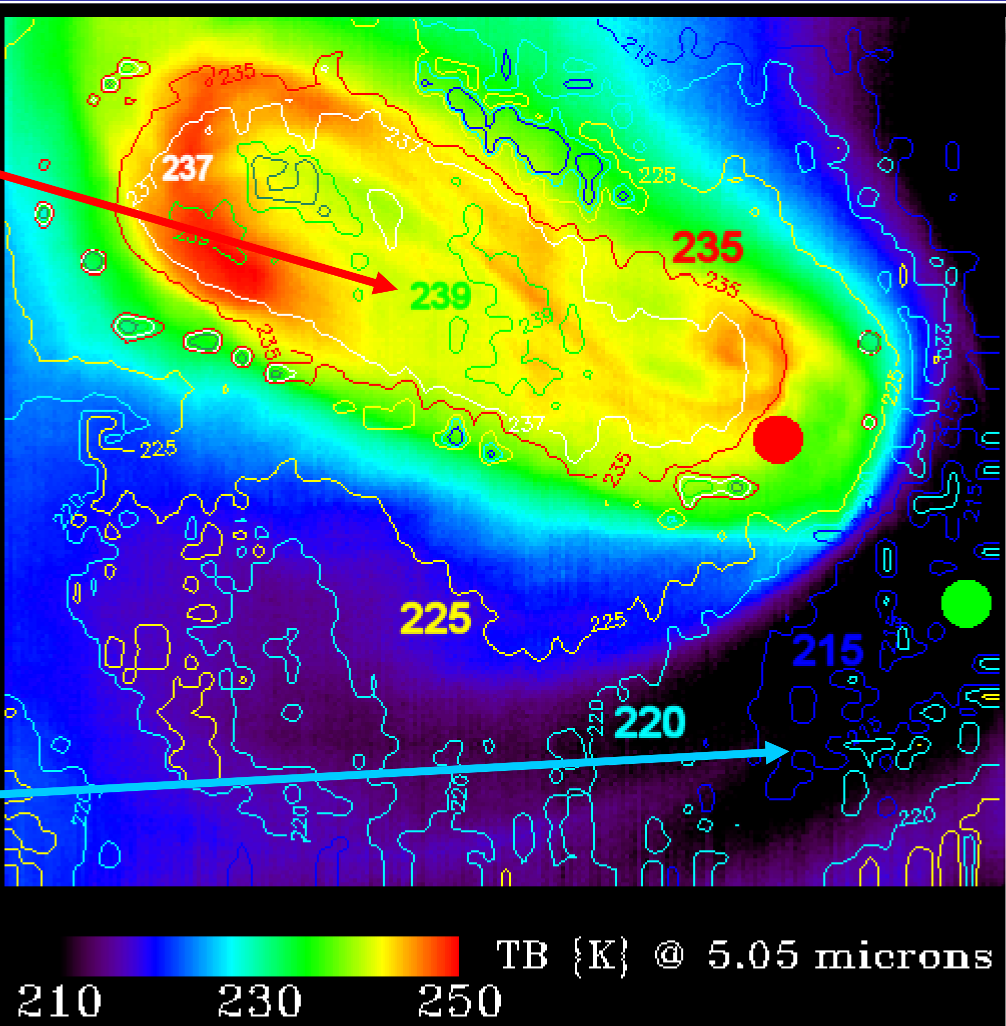


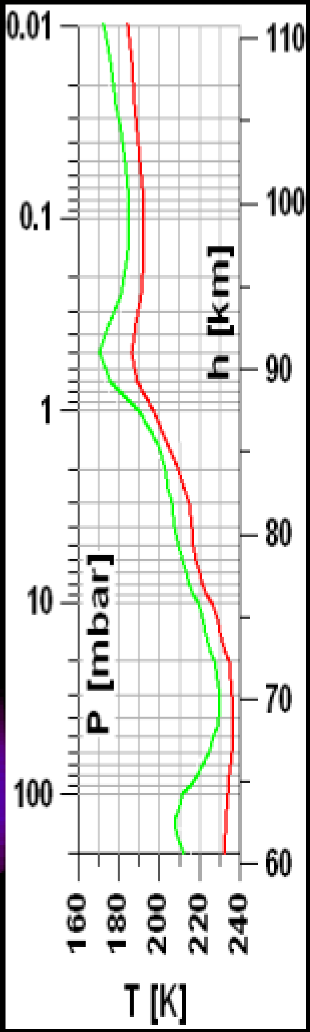
VEx/VIRTIS

Upper cloud – thermal IR imagery

"High" temperature region is within the vortex

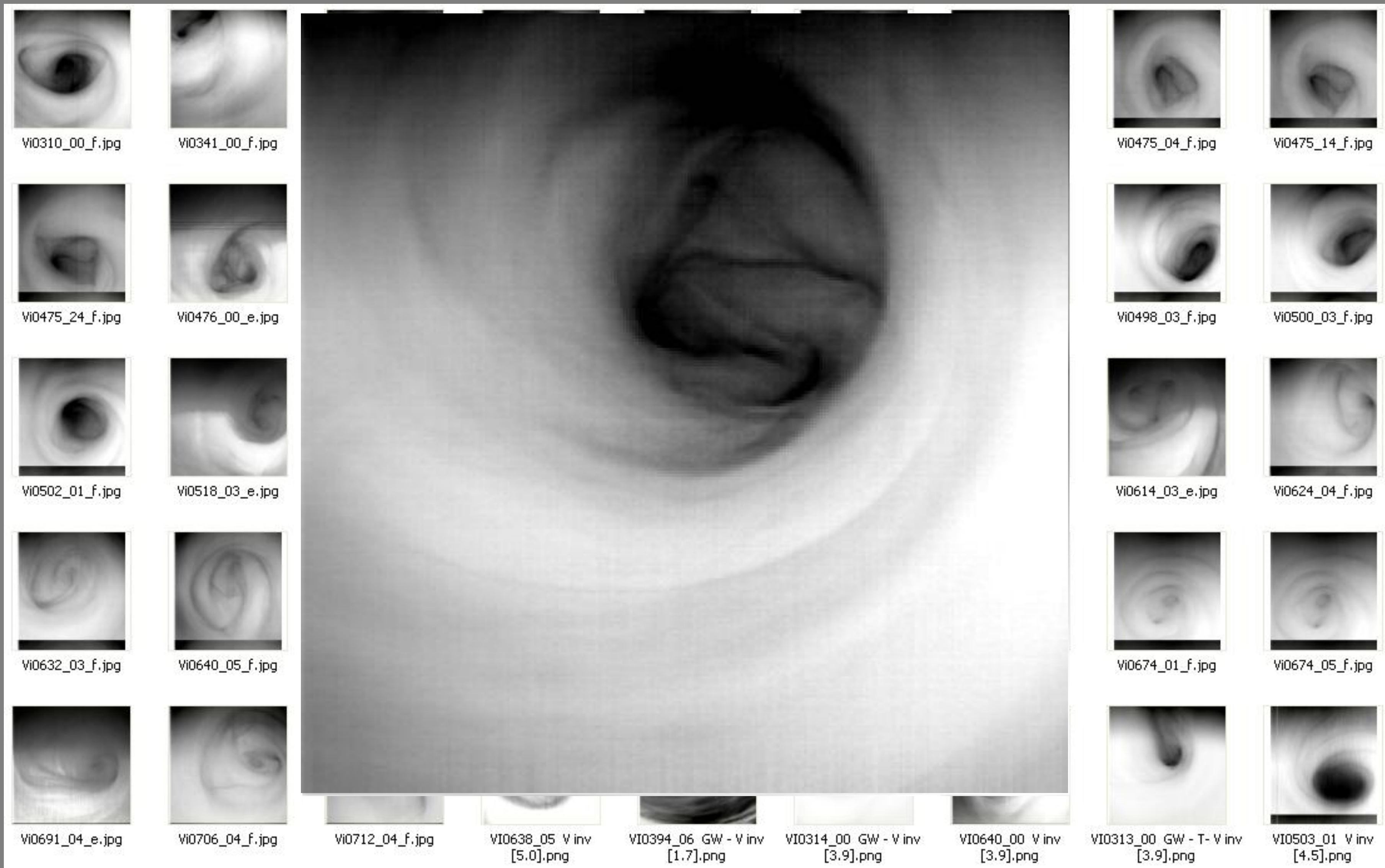
"Low" temperature region is just outside, sorrounding the vortex





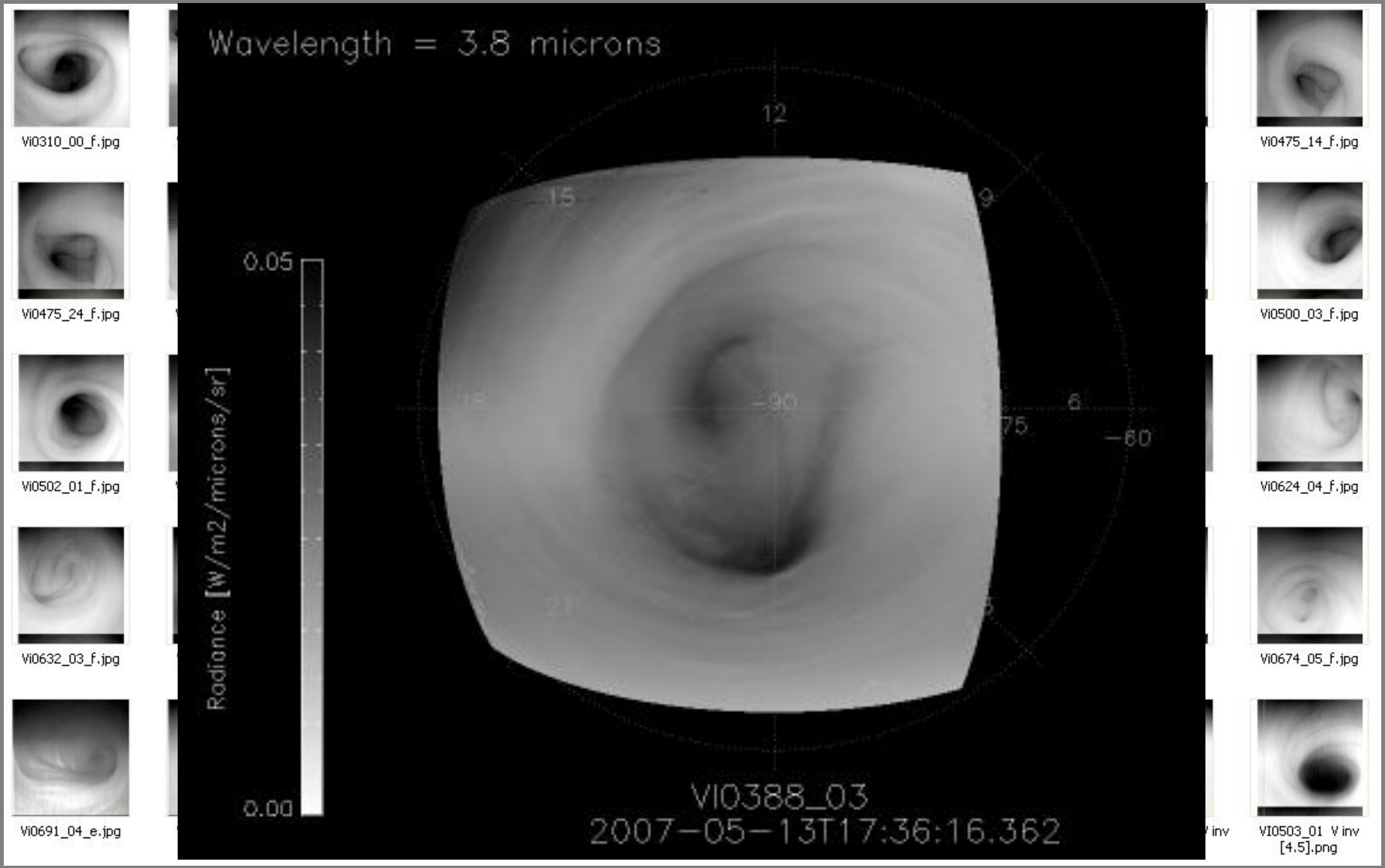
G. Piccioni et al., Nature 29 November 2007

The many many faces of the vortex

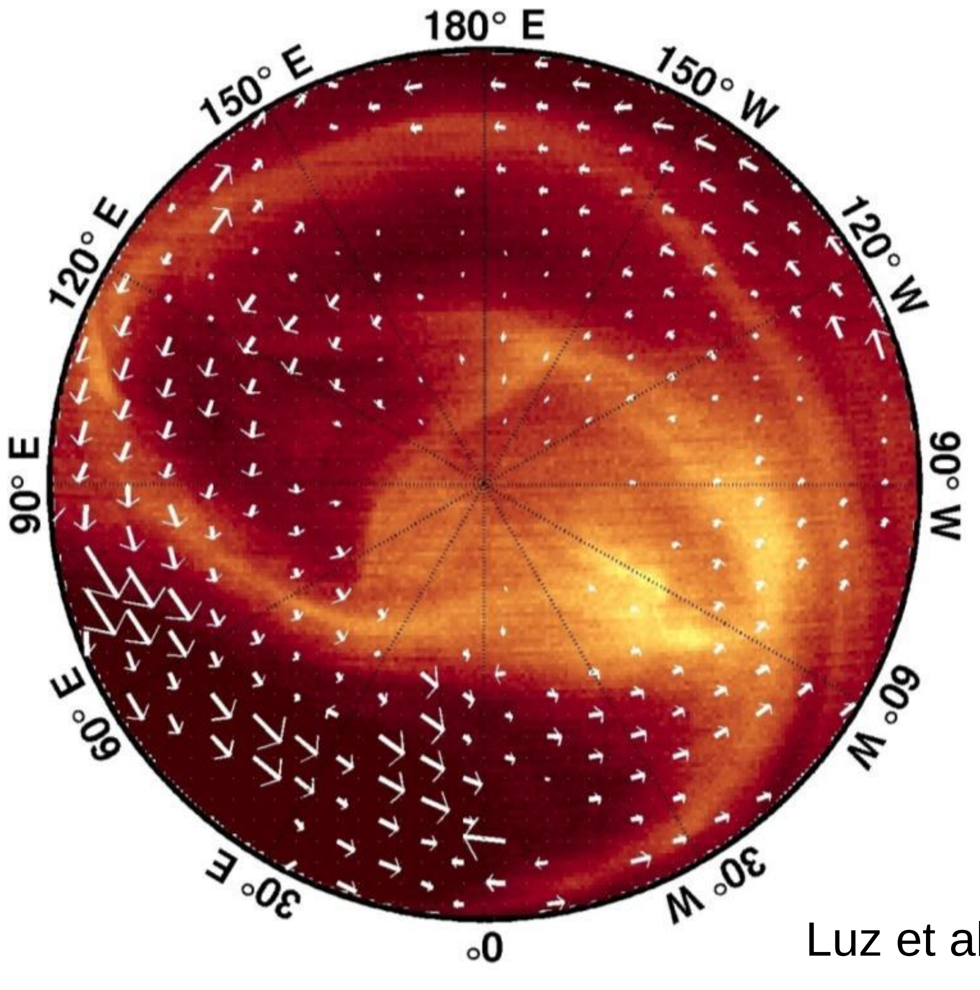


Inverted thermal images from VEx/VIRTIS:
Darker means deeper and higher temperature

The many many faces of the vortex

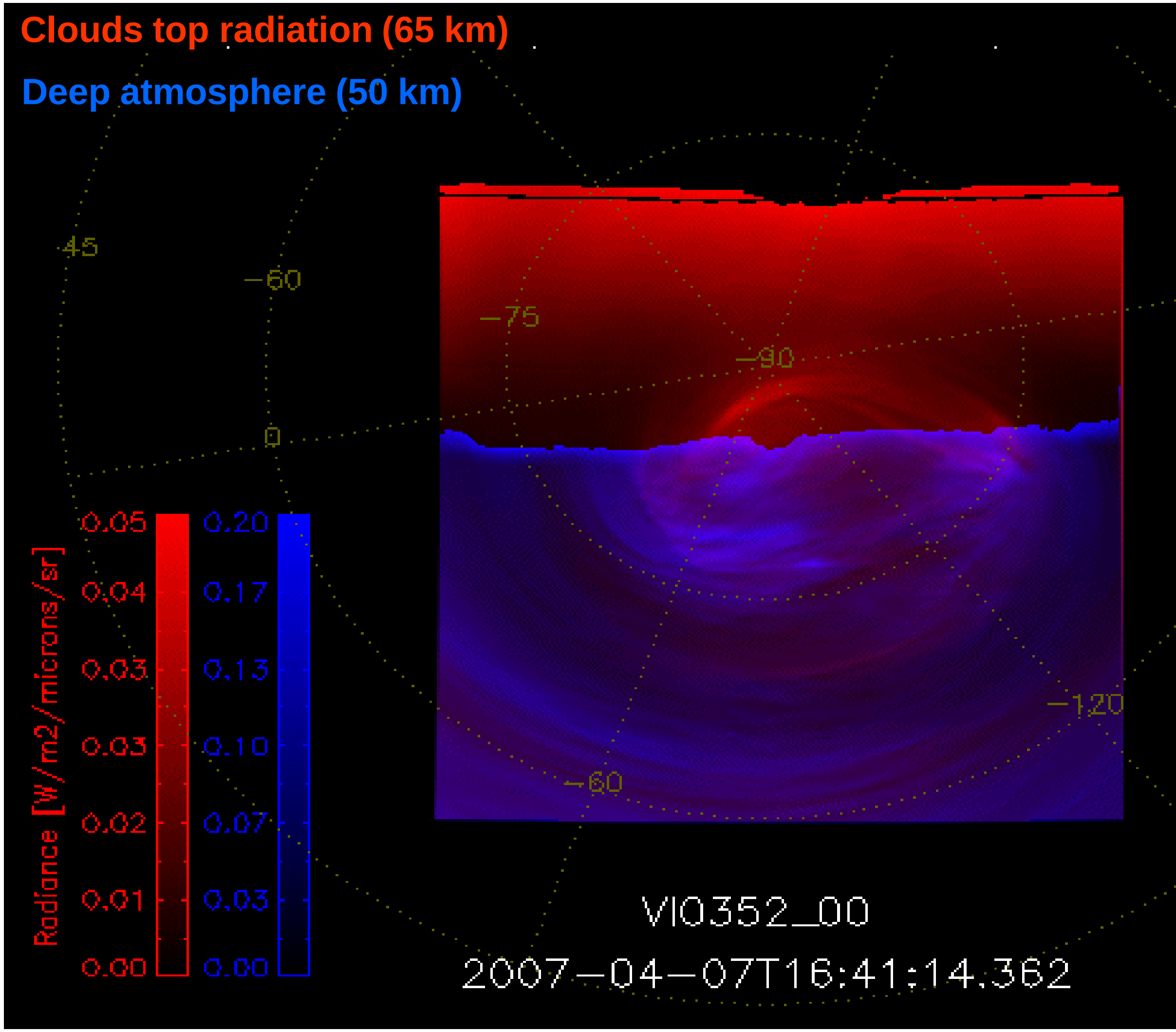


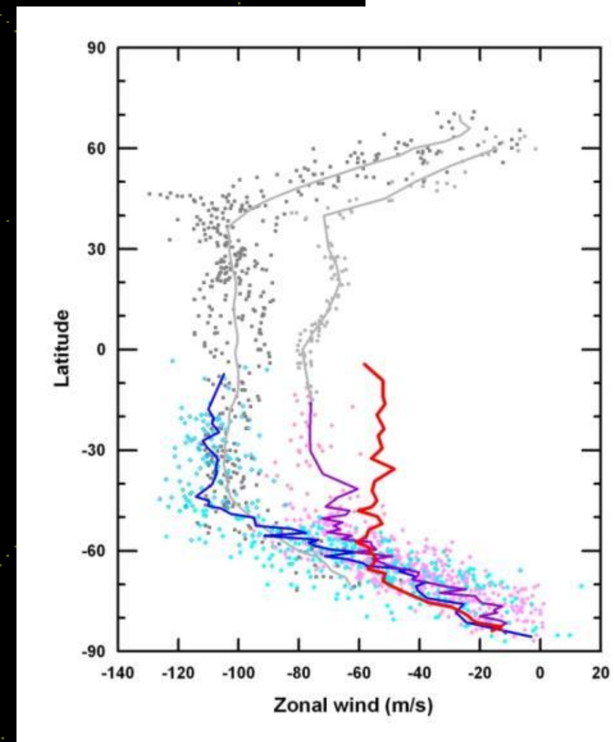
Inverted thermal images from VEx/VIRTIS: Darker means deeper and higher temperature



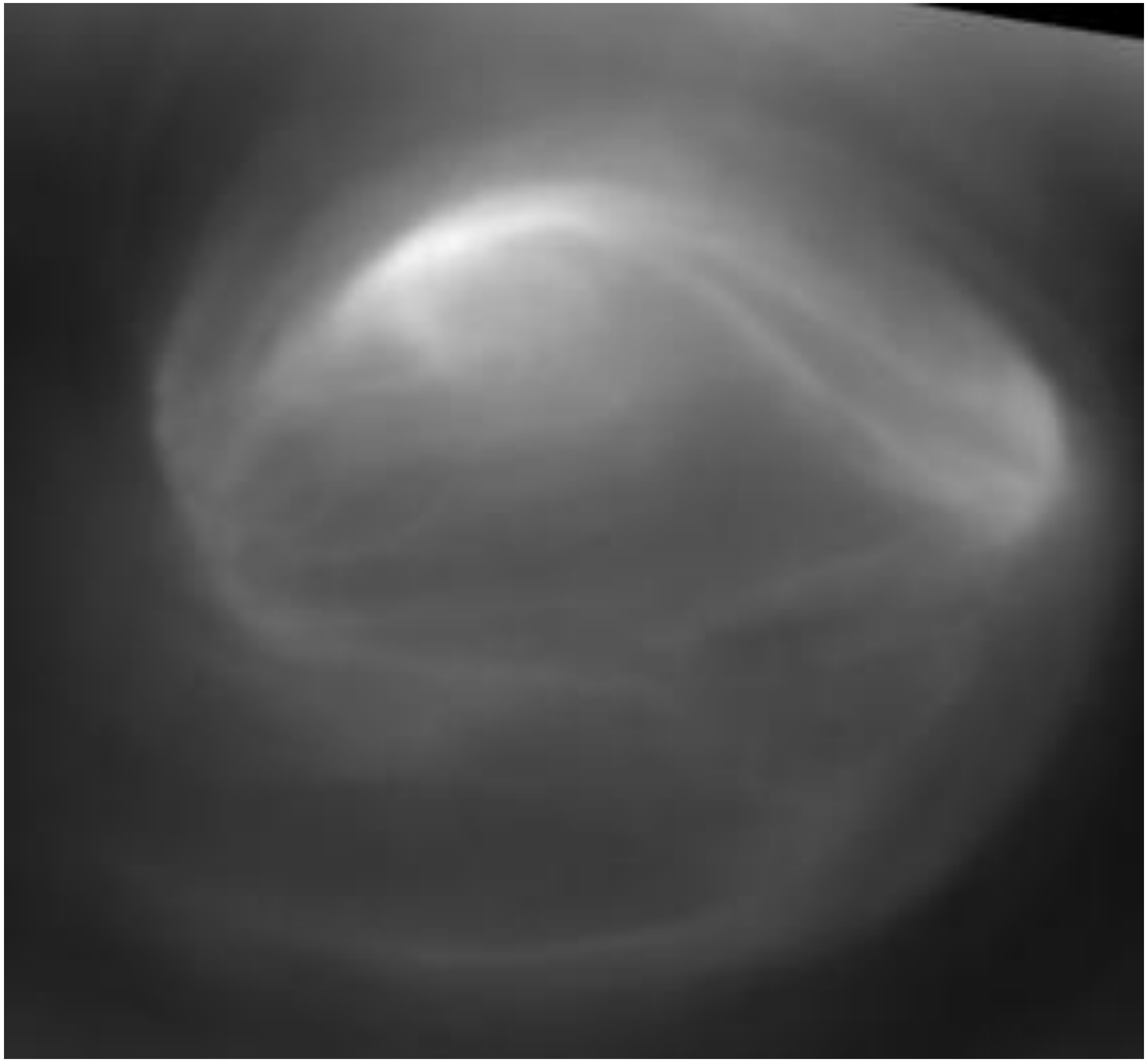
Luz et al., 2011

On average, the vortex is in solid-body rotation...

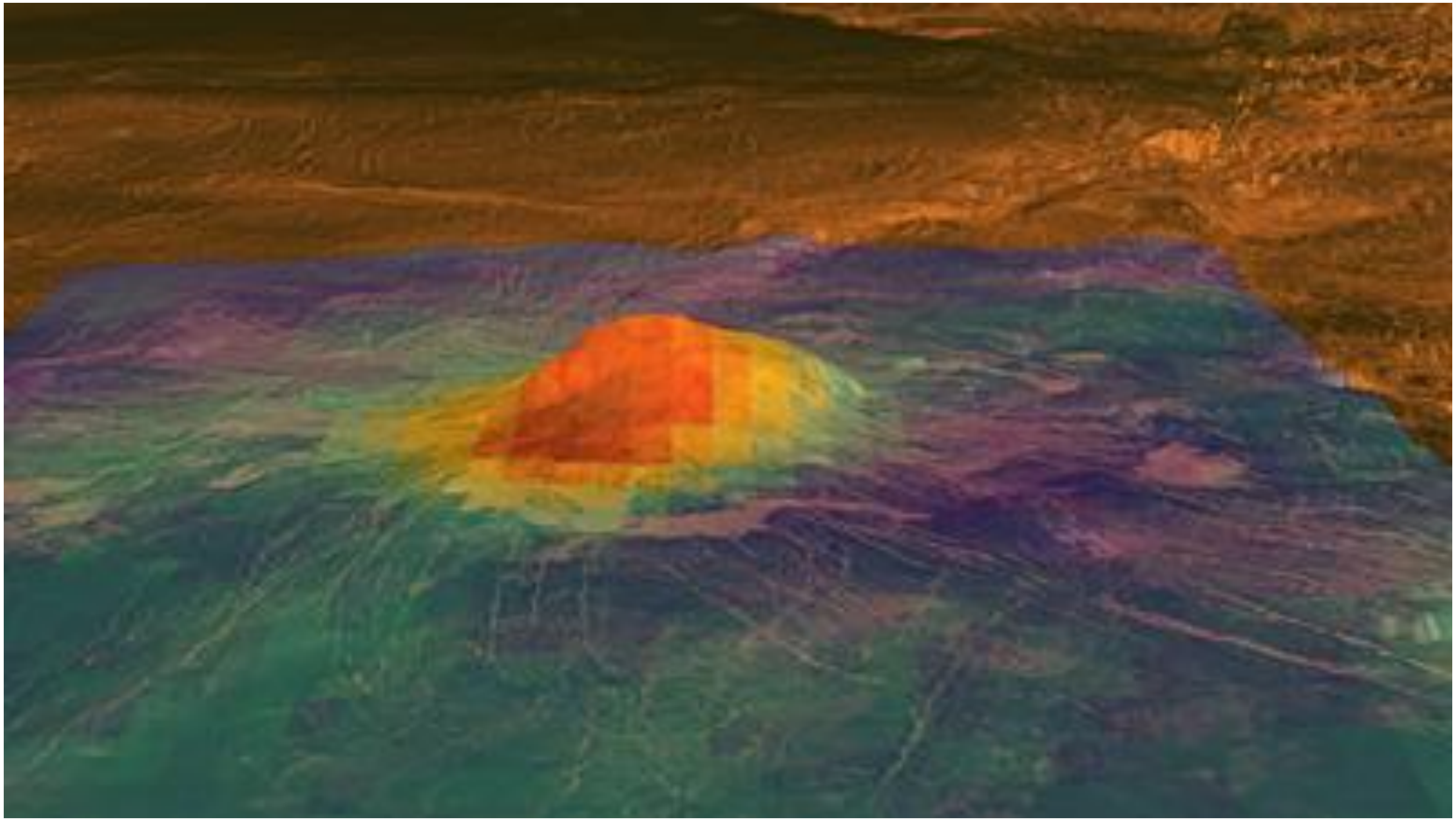




... But viewed in detail, the flow is extremely complex.

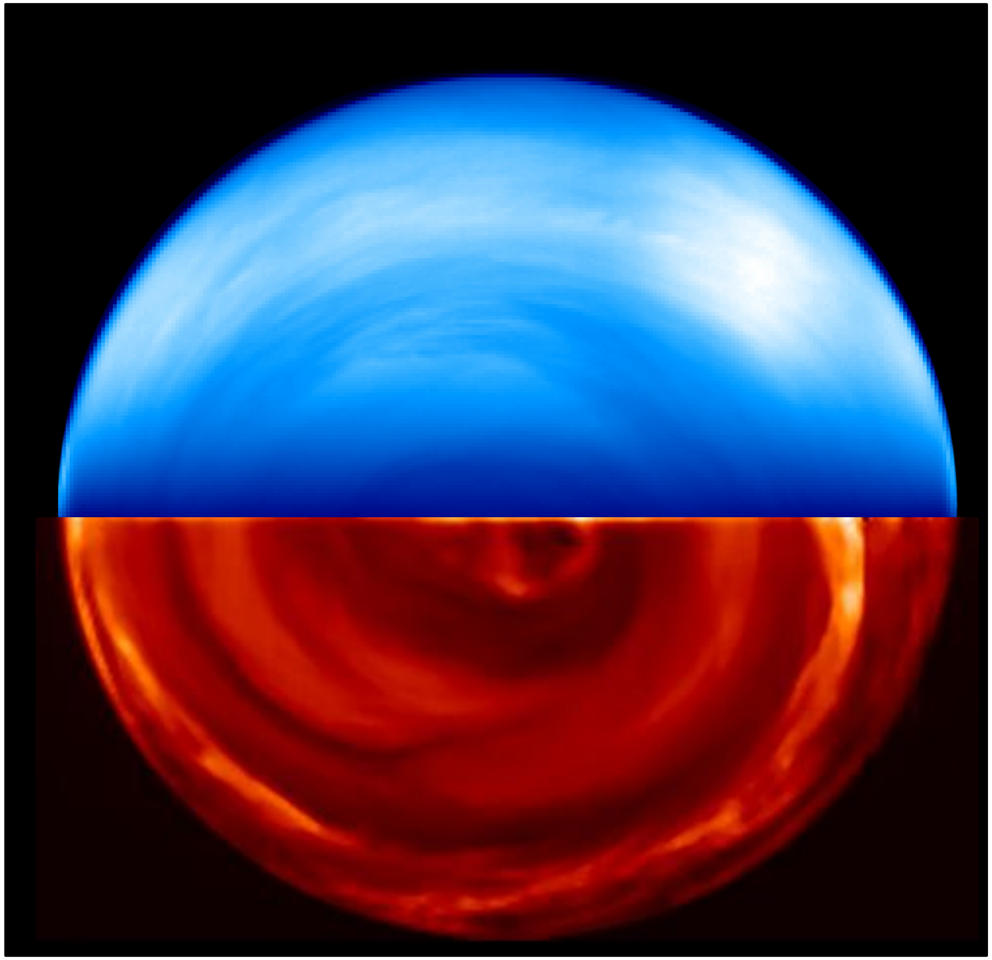


Hunting active volcanoes



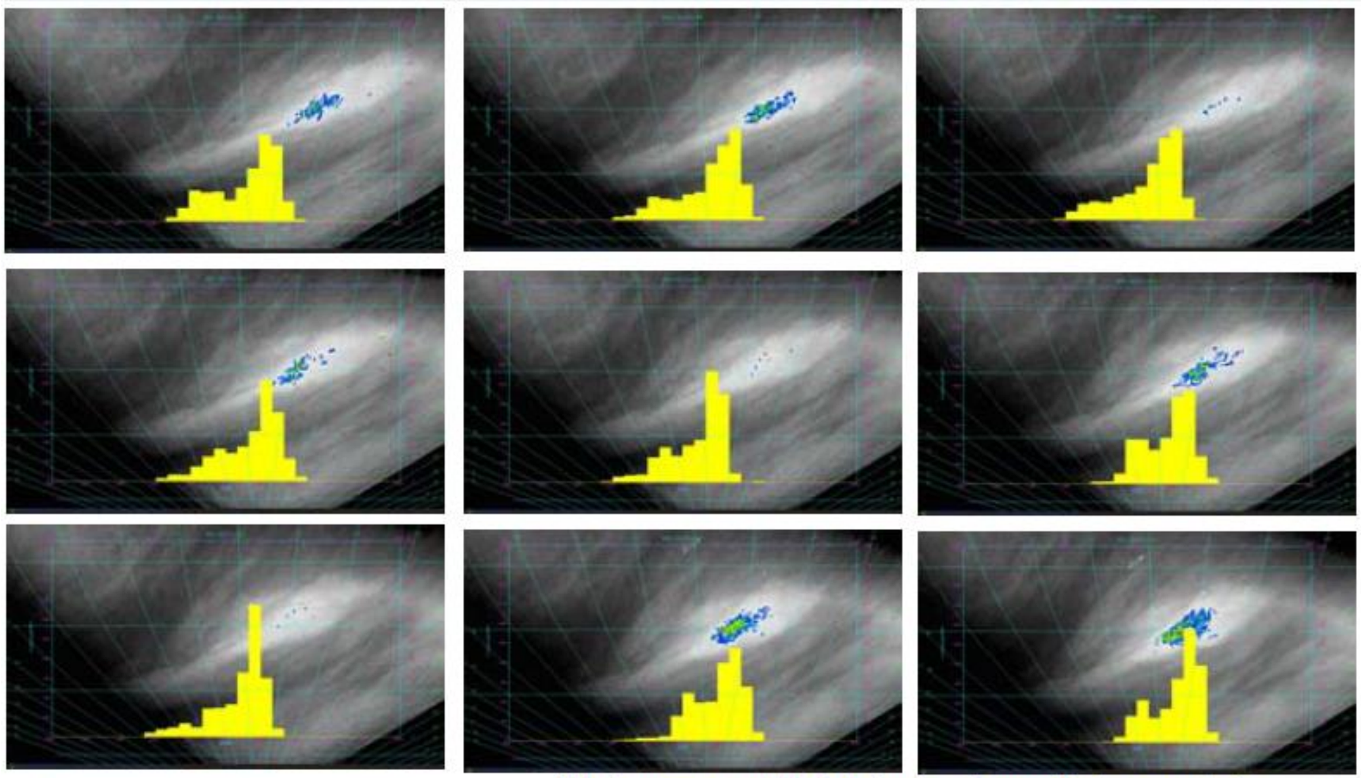
Smrekar et al.

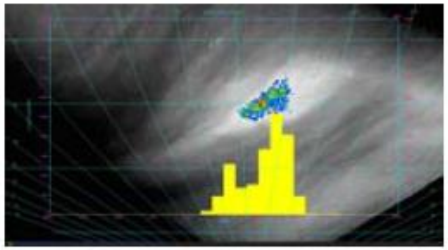
Venus clouds – volcanic source?



- **Lower clouds: No correlation of clouds or SO_2 / H_2O / CO with topographic features has (yet) been found.**

Upper clouds – did we see a volcanic eruption?





Histograms of brightness (raw data counts) distribution in a region containing the bright spot in normalized UV images on 19 July 2009 shown on each equal area projection of the respective image.

The change in the the area above a certain brightness value in the core region over time may indicate overshooting plume, consistent with penetrative convection due to a buoyant plume.

Limaye et al., EGU 2010

Long-term variability of SO_2 and haze particles

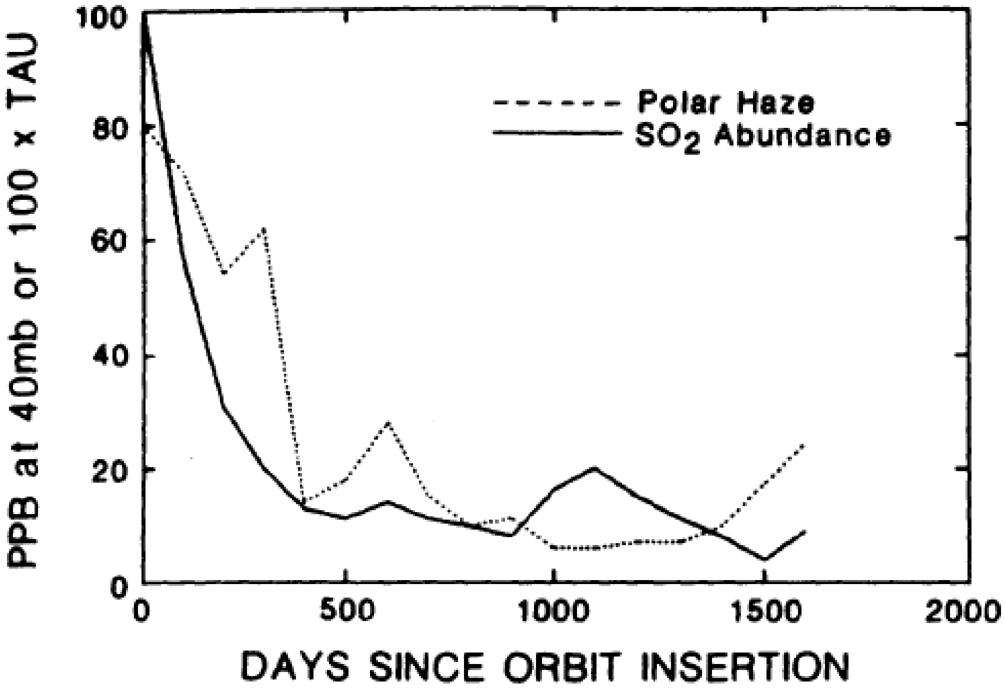


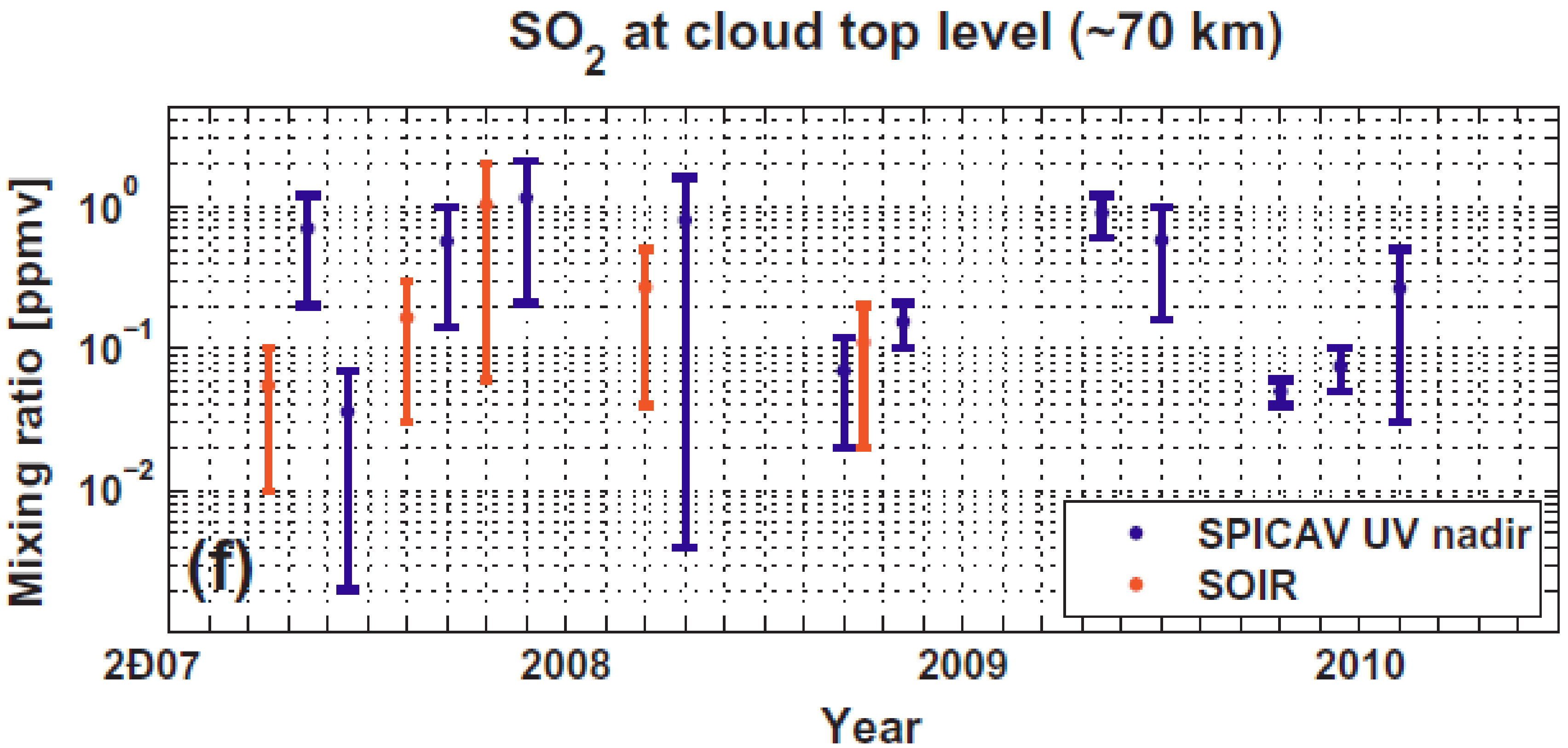
Figure 3. Intercomparison of Pioneer Venus observed SO_2 abundance (solid line, UVS) and haze optical thickness (dashed line, CPP)

Esposito, *Adv. Spa. Res.,* 1985

- **Episodic vulcanism?**

Evolution SO_2 mixing ratio above Venus' clouds

(From Denis Belyaev et al., SPICAV/SOIR teams)



Evolution SO_2 mixing ratio above Venus' clouds

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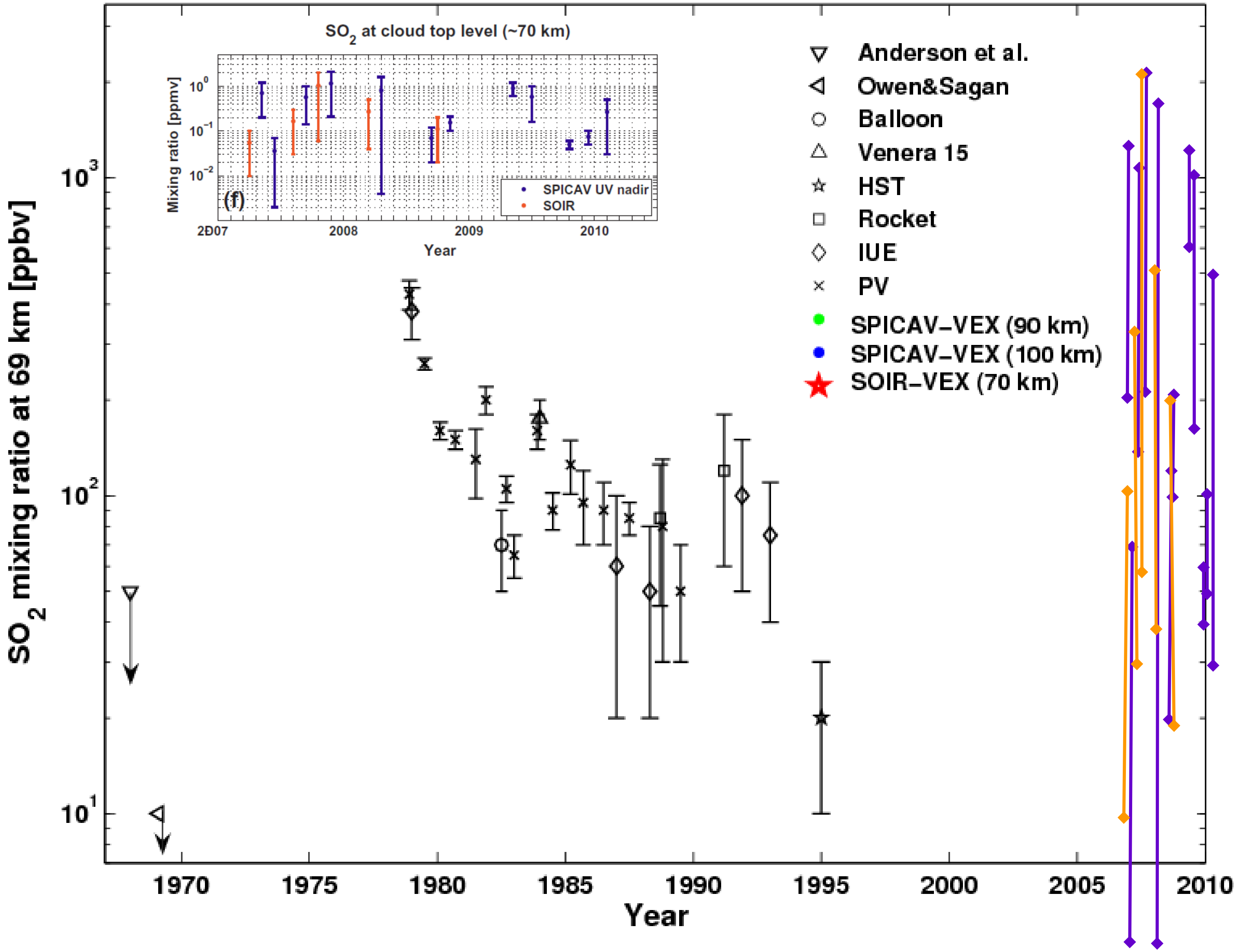
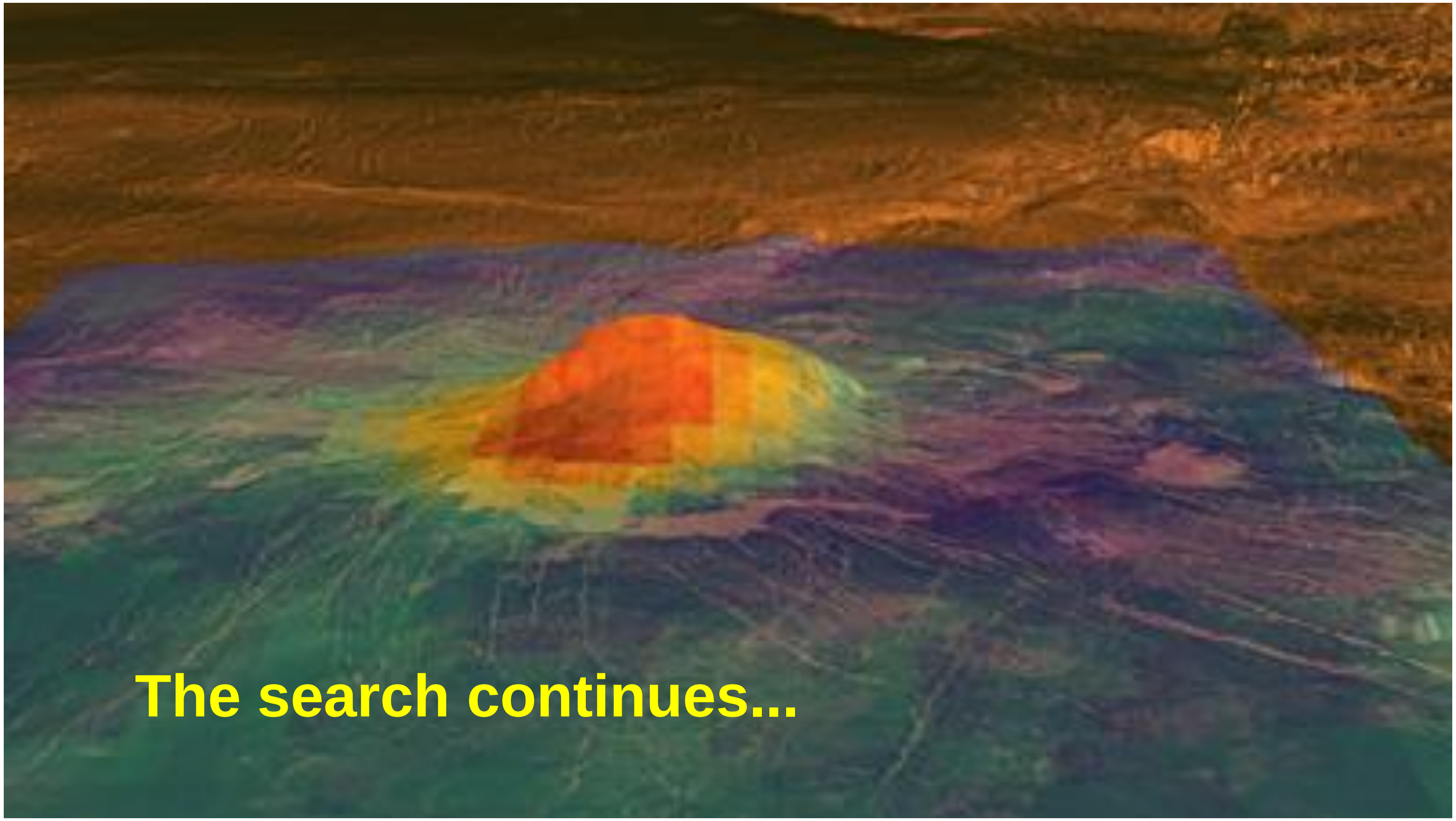
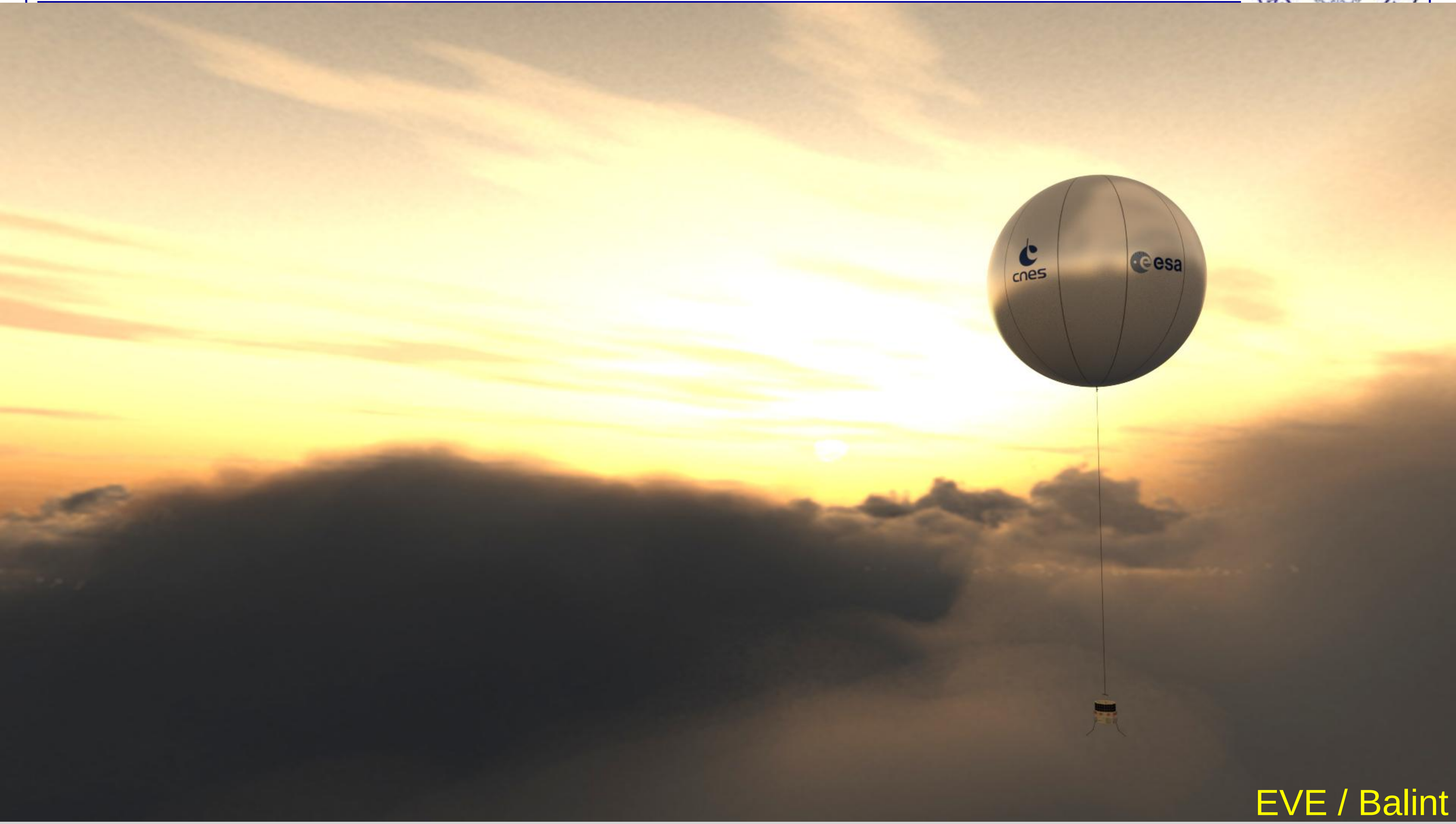


Hunting vulcanogenic clouds



Smrekar et al.

The end



Thanks for your attention

Future missions

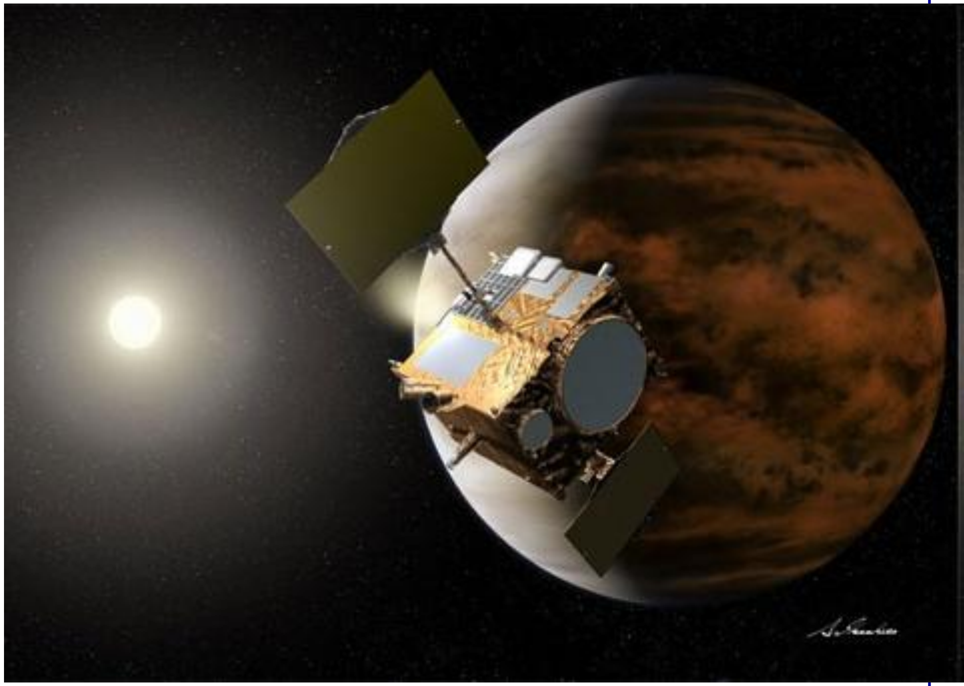
Venus Express is making the clouds of Venus ever more familiar...

Akatsuki (*aka* Venus Climate Orbiter)

- **Launched May 2010**
- **Failed VOI December 2010**
- **To attempt VOI 2015/2016 using AOCS thrusters**

- **Payload:**
  6 cameras – UV, vis, near IR, lightning
  50 kHz imaging at 777 nm oxygen line

- **Equatorial orbit to follow cloud features**



This mission has a strong focus on dynamics

Lack of spectrometers means little new constraints on composition.

Cloud-level balloon mission

Compatible with ESA M-class mission opportunity

- At 55 km, T=20°C, p=0.5 bar
- Explore heart of convective cloud layer
- Full circumnavigation of planet in <1 week.
- Long duration allows sensitive measurement of noble gas isotopes => clues to early evolution of planet

Balloon-deployed microprobes

- With ESA and UK funding, we have undertaken a pair of studies into balloon deployed probes weighting from 100 – 2000 g.

- Probes, deployed from balloon at ~60 km altitude, would provide access to surface and low atmosphere
  - Balloon is carried around the planet in ~4-5 days, allowing good spatial coverage

- Microprobes weigh 100 g, 46 mm ∅ x 110 mm L

-Wind profiles derived from tracking microprobes (from balloon)

- *Micro*probes measure pressure, temperature, upwards & downwards light flux using 10 g science payload.

- Design is technologically conservative, feasible using today's technology

-Slightly larger (200 g) microprobes would allow chemistry payload

- Even larger (1-2 kg) probes would allow surface imaging

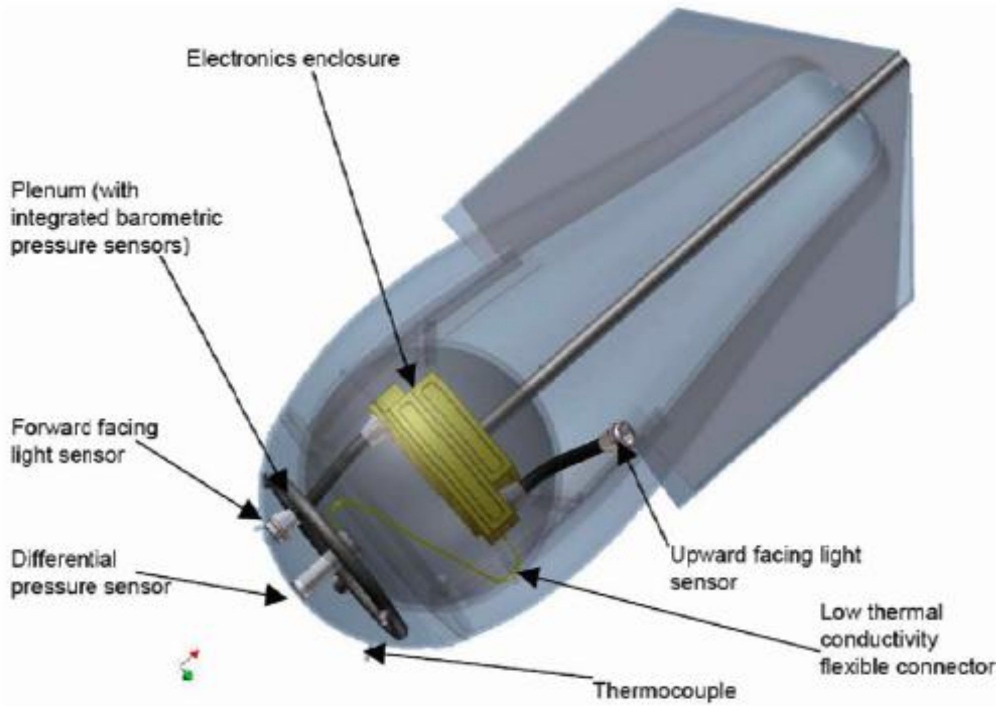


Image credit: Oxford Univ. / Qinetiq / ESA

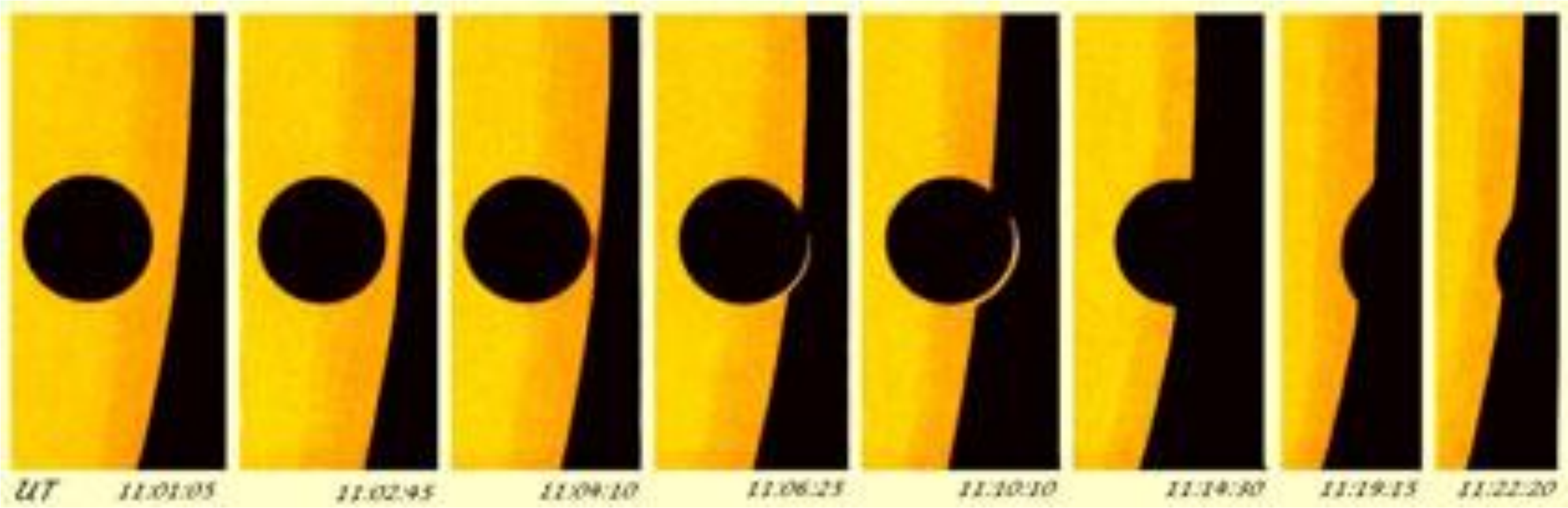
Could be provided as a UK-provided, high visibility, UKSpace - branded subsystem

Fixed-wing aircraft to study upper cloud?

GAP project, Scripps

Transit of Venus

Transit of Venus : 6 June 2012 at 00:04
Information day at ESAC : 9 May 2012 at 14:00



M. Frassati