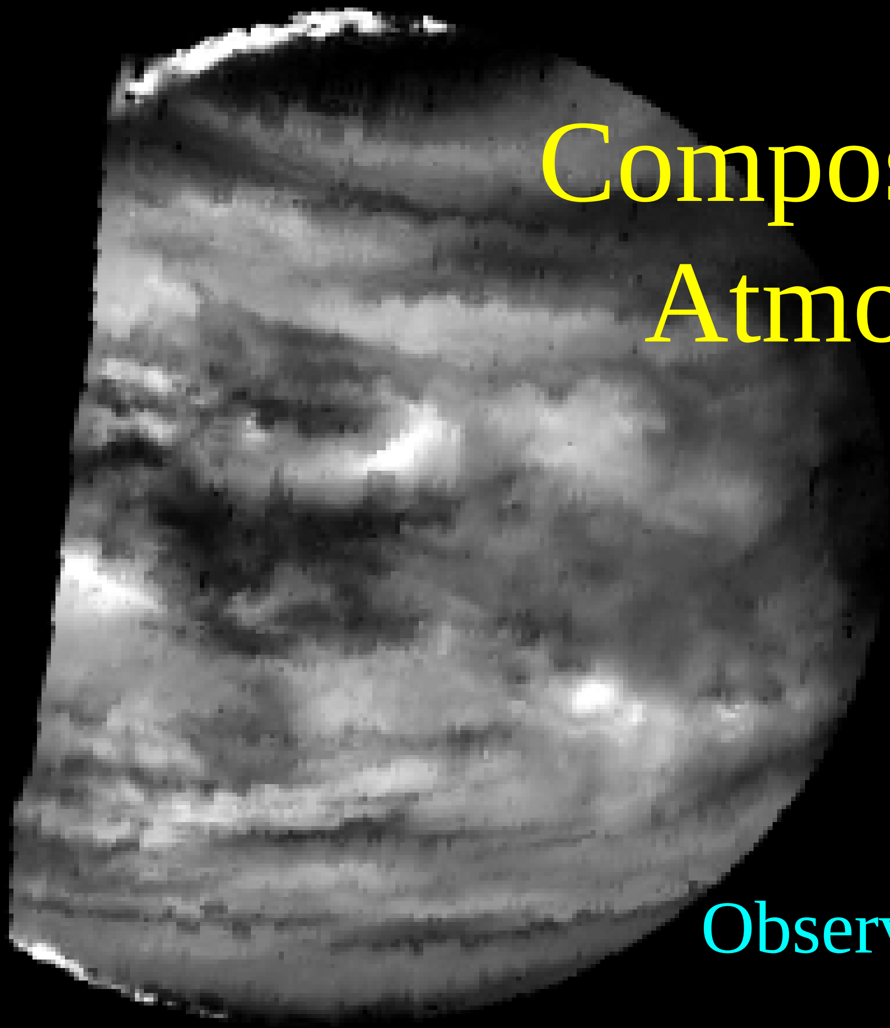
Composition of the Lower Atmosphere of Venus



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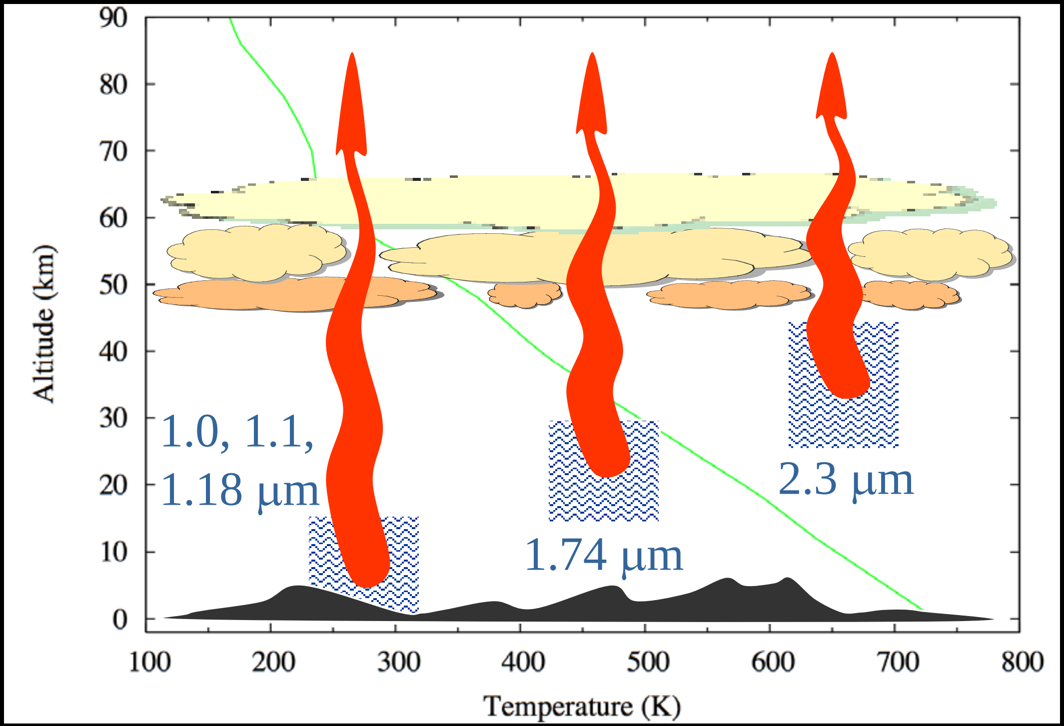
Lower atmosphere measurements

- *In situ* measurements
  - Mass spectrometry, gas chromatography
    - Venera 11-12, Pioneer Venus Large probe
  - Spectroscopy
    - *Visible + infrared*: Venera 11, 13, 14 → H_2O
    - *Ultraviolet*: Vega 1, 2 → SO_2
- Microwave remote sensing
  - Multi-frequency observations
    - Ground-based (VLA) → H_2SO_4, SO_2
  - Radio occultation
    - Mariner, Pioneer Venus, Magellan → H_2SO_4, SO_2

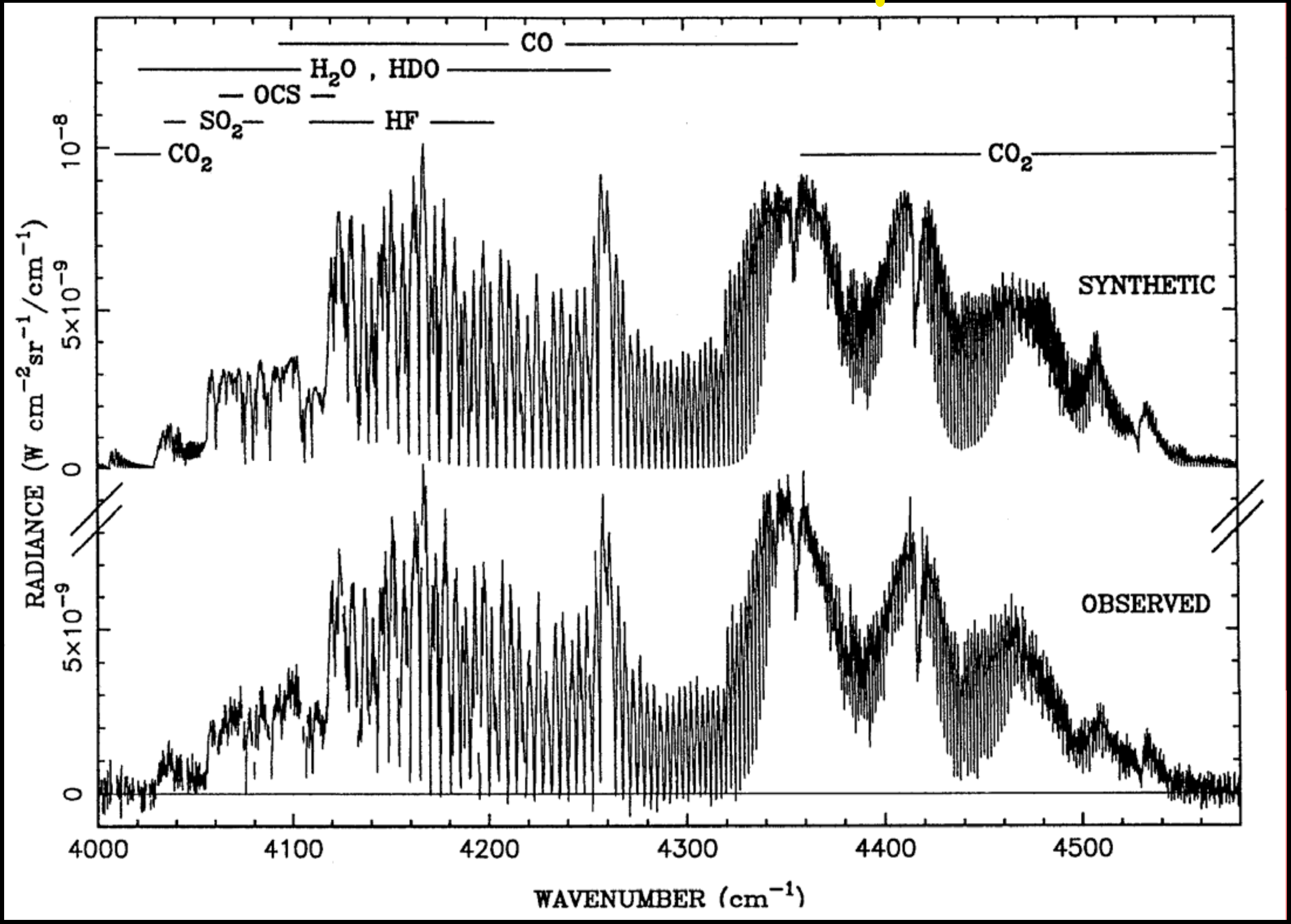
Lower atmosphere measurements

- Nightside observations
  - Near infrared spectroscopy
    - Spectral windows: 0.9, 1.0, 1.1, 1.18, 1.27, 1.74 and 2.3 µm
    - Ground-based, Galileo, Venus Express



→ H_2O, HDO, CO, OCS, SO_2, HF, HCl

Venus nightside windows: 2.3 μm

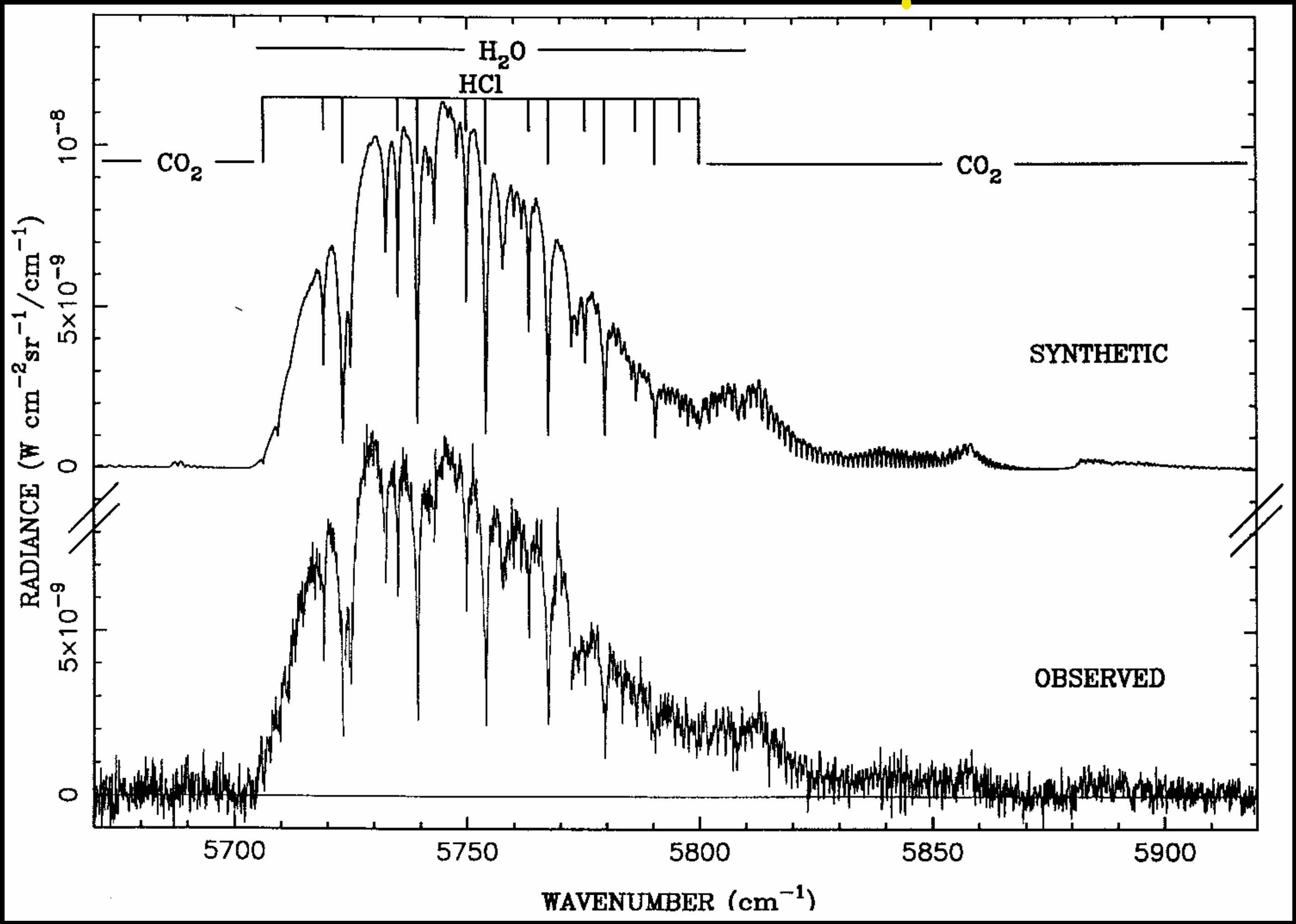


CFHT/FTS observations
Res = 0.15 cm^{-1}

(Bézard *et al*. 1990, Taylor *et al*. 1997)

Altitude range probed:
26-45 km

Venus nightside windows: 1.74 μm

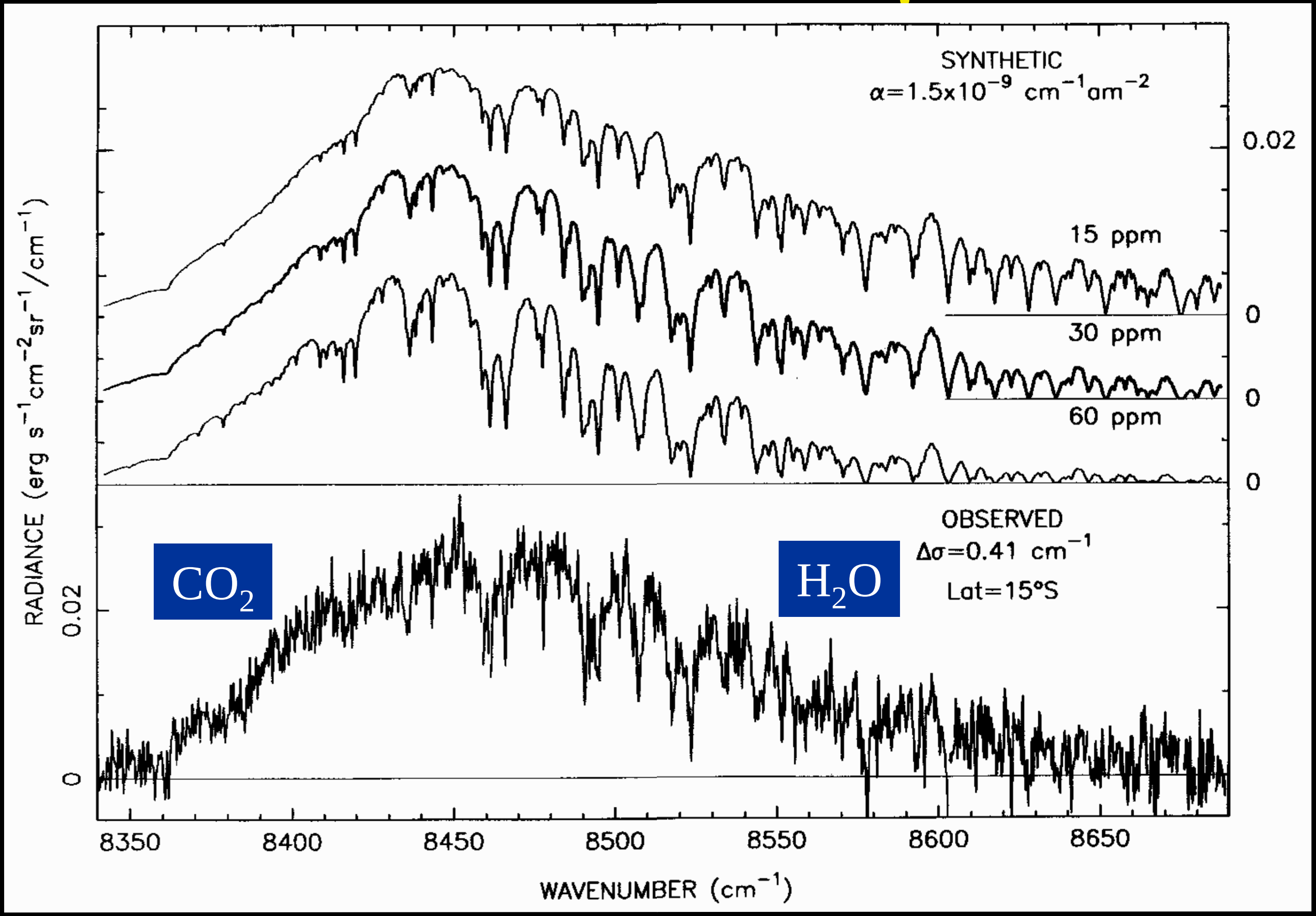


CFHT/FTS observations
Res = 0.15 cm^{-1}

(Bézard *et al*. 1990, Taylor *et al*. 1997)

Altitude range probed:
15-30 km

Venus nightside windows: 1.18 µm



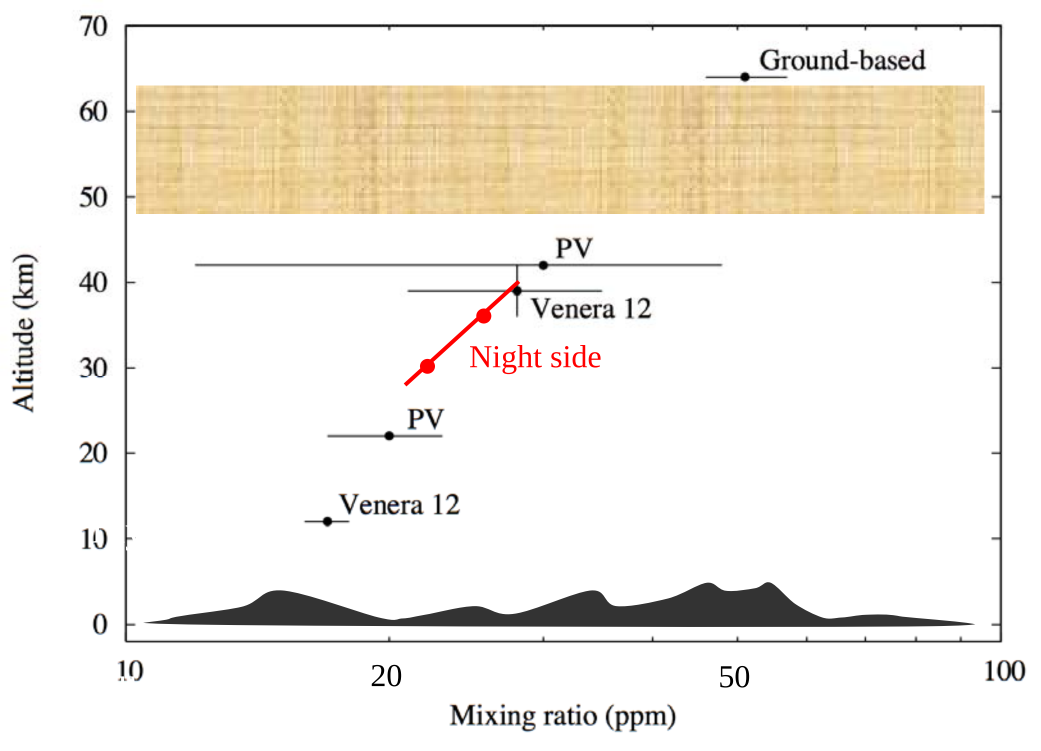
CFHT/FTS observations
Res = 0.41 cm^{-1}

(de Bergh *et al.* 1995)

Altitude range probed:
0-15 km

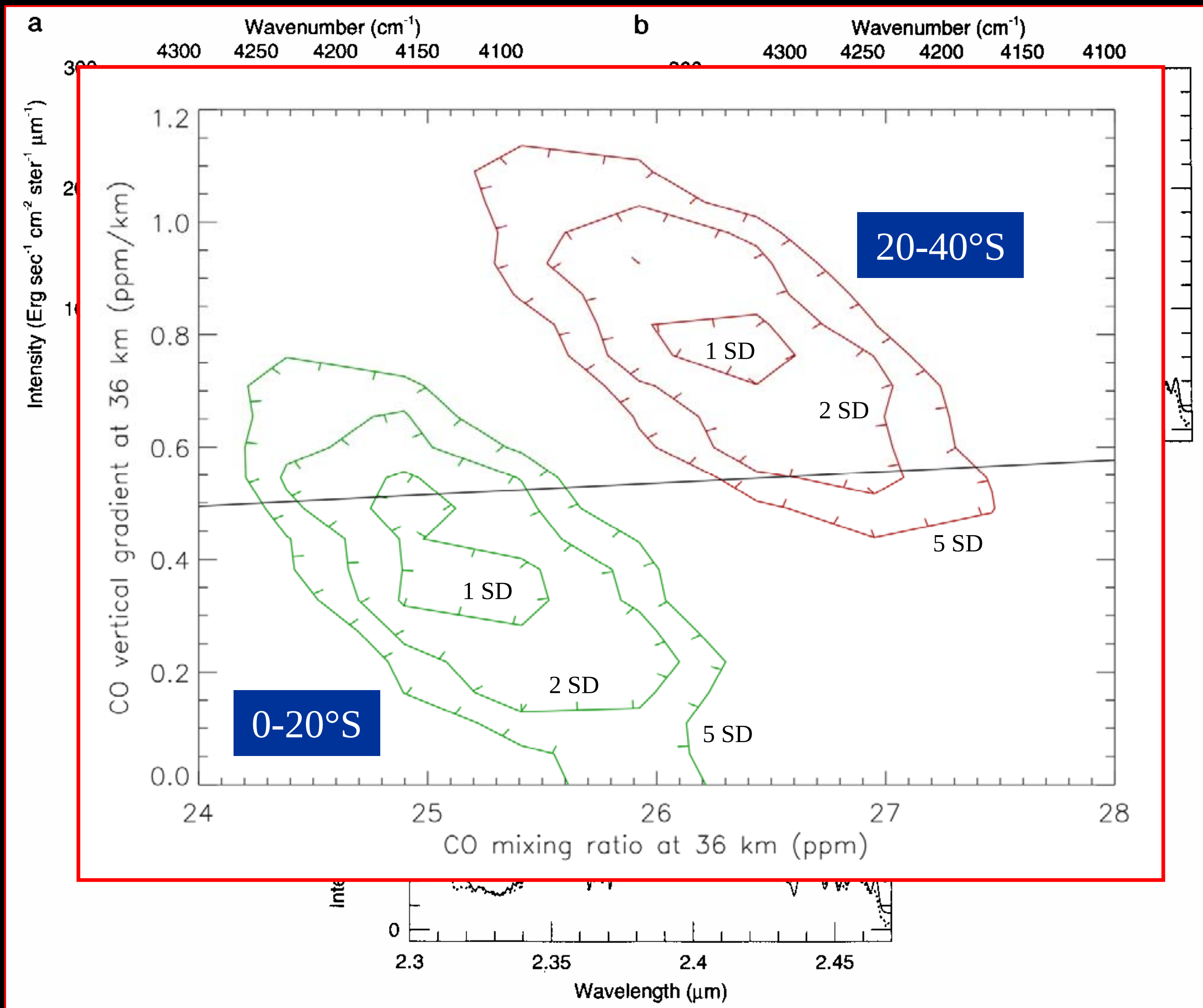
Carbon monoxide: CO

- *In situ* measurements
  - Pioneer Venus GC (Oyama *et al.* 1980)
    - 20 ± 3 ppm at 22 km
    - 30 ± 18 ppm at 42 km
  - Venera 12 GC (Gel'man *et al.* 1979)
    - 28 ± 7 ppm at 36-42 km
    - 17 ± 1 ppm at 12 km
- Ground-based nightside spectroscopy
  - Mole fraction at 36 km
    - 26 ± 5 ppm
      (Pollack *et al.* 1993, Bézard 1994, *et al.* 1997, Marcq *et al.* 2006)
  - Vertical gradient (28-42 km)
    - 1.2 ± 0.5 ppm /km
      et al. 1993)
    - 0.6 ± 0.4 ppm /km
      (Bézard 1994, Taylor *et al.* 1997, Marcq *et al.* 2006)



⇒ *CO increases with altitude*

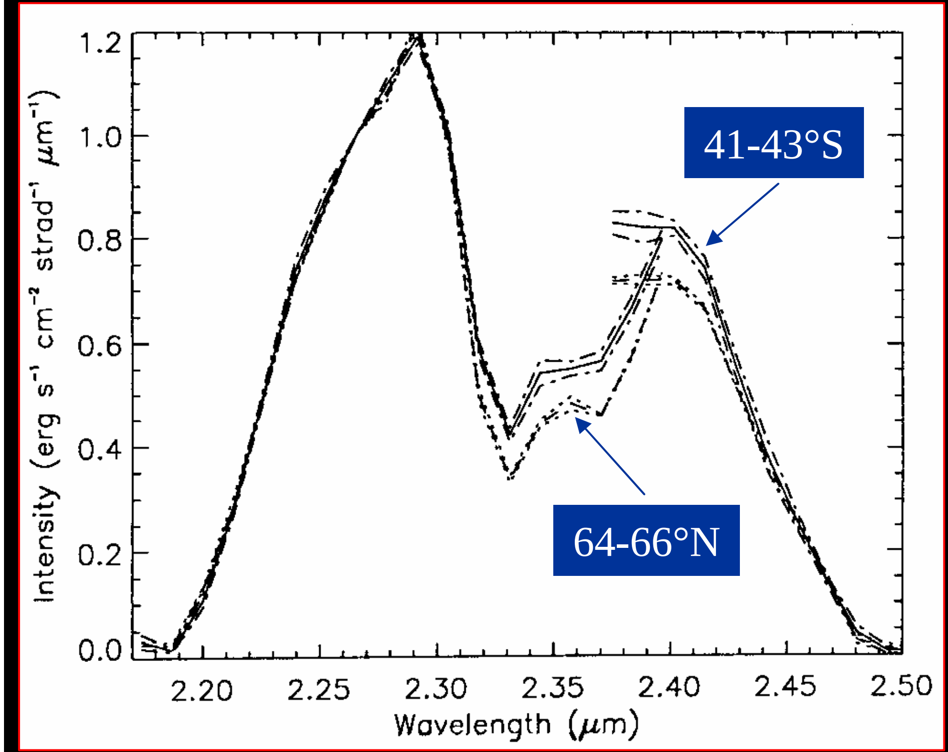
CO: vertical gradient

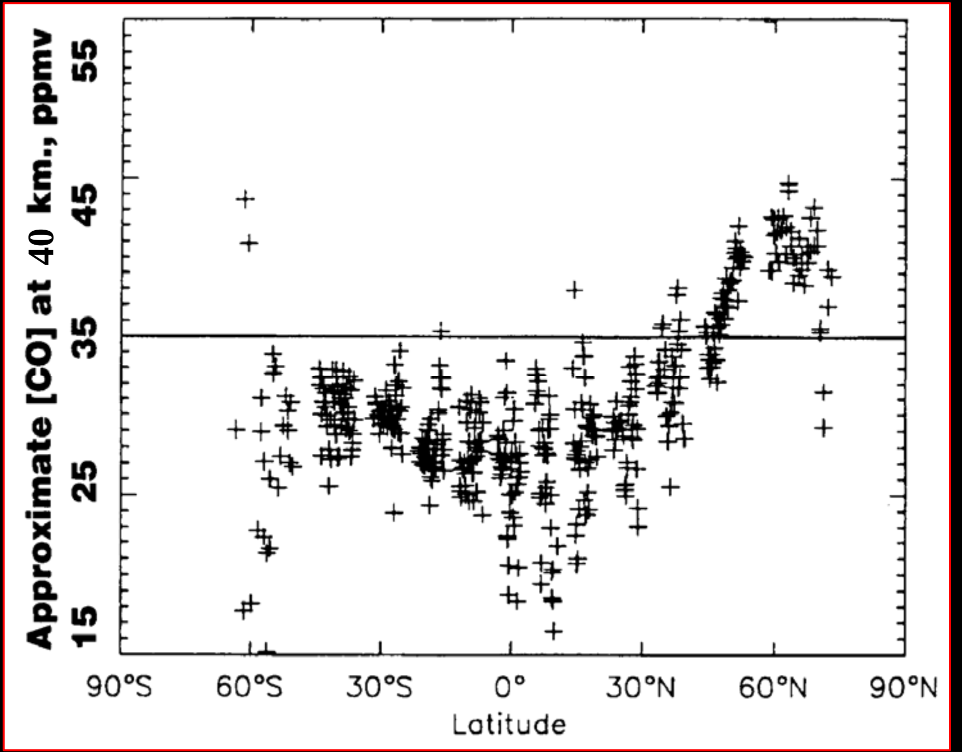


IRTF/SpeX observations
R = 2000
(Marcq *et al.* 2006)

AAT spectra
R = 1600
(Pollack *et al.* 1993)

CO: horizontal variations

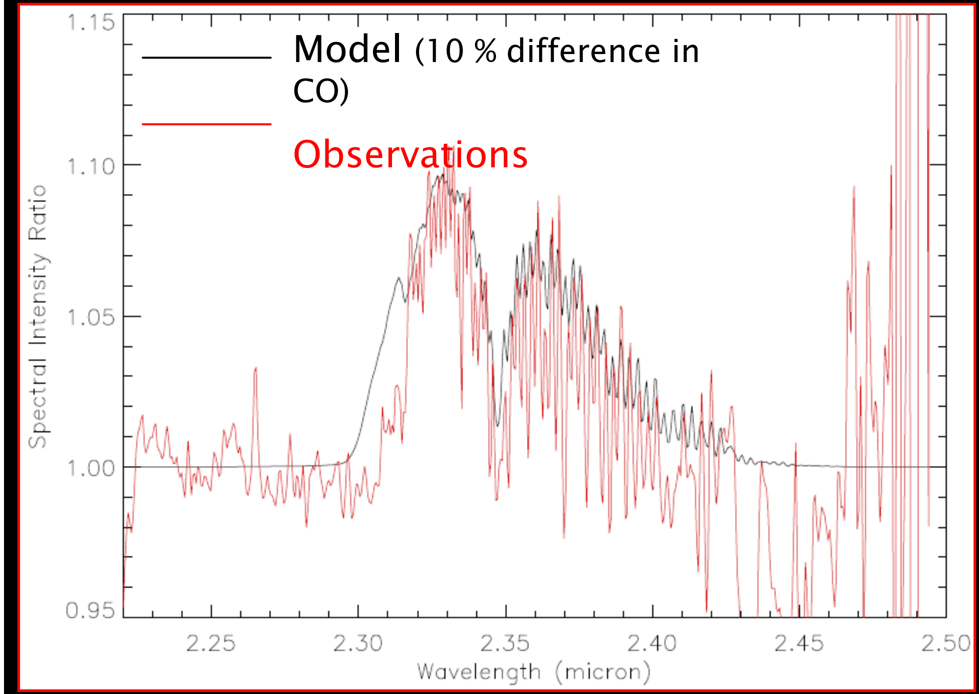


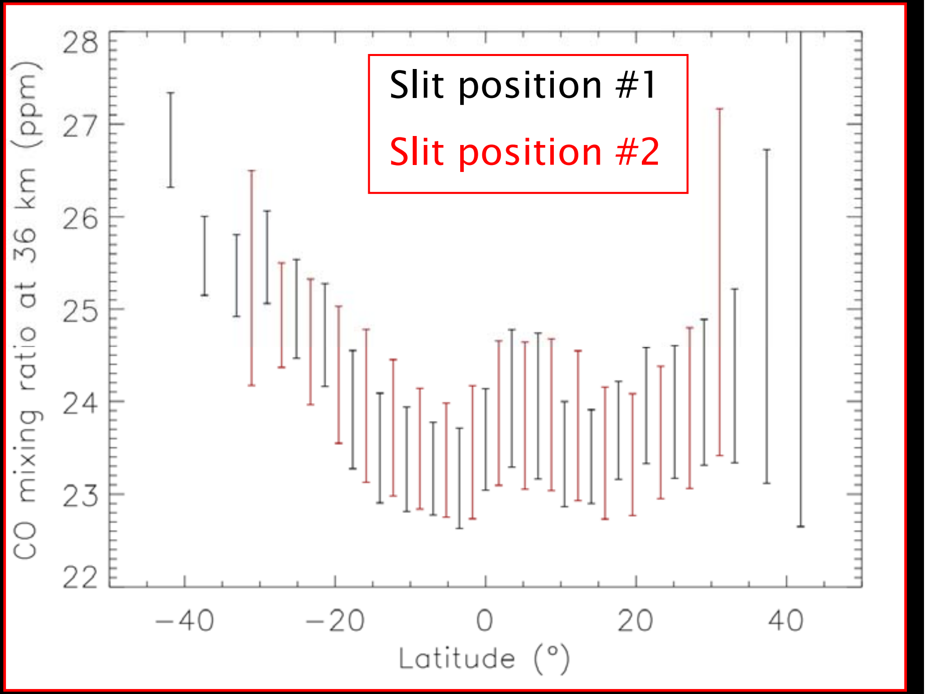


⇒ CO increases by ~35% beyond 47°N

Galileo/NIMS observations
R = 100
(Collard *et al.* 1993)

CO: horizontal variations





⇒ CO increases northward and southward of equatorial latitudes (~10-15% at 40°N or S)

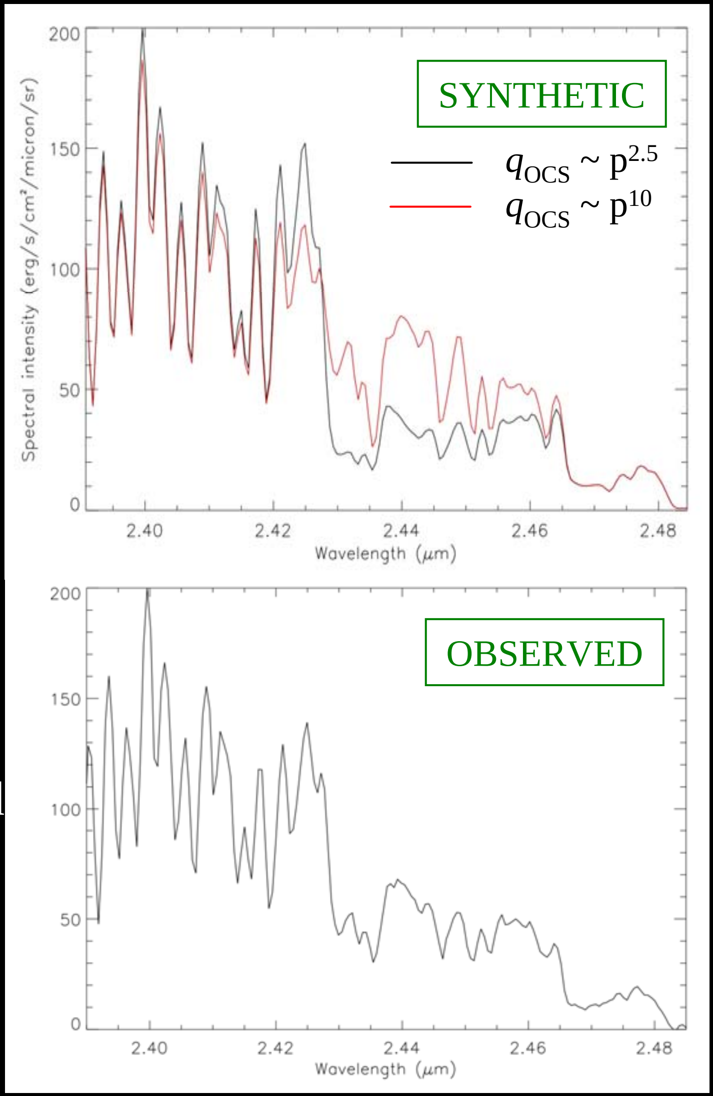
IRTF/SpeX observations
R = 2000
(Marcq *et al*. 2005, 2006)

Carbonyl sulfide: OCS

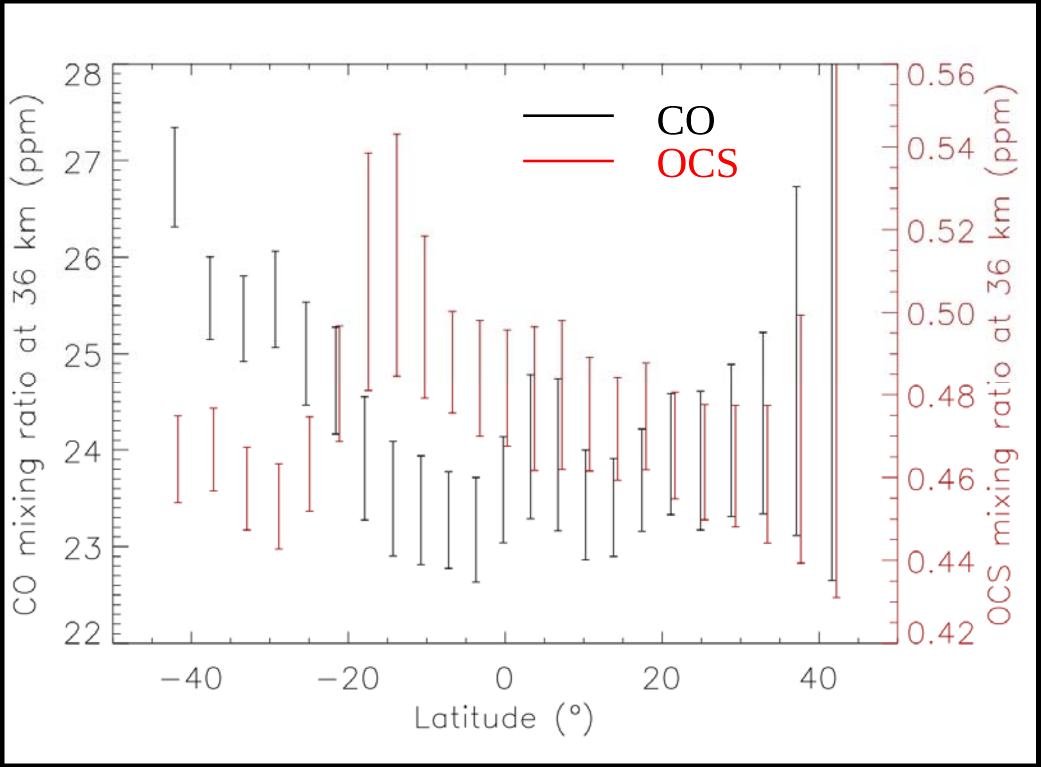
- Ground-based nightside spectroscopy
  - OCS vertical profile
    (review by Taylor *et al.* 1997)
    - 0.35 ± 0.1 ppm at 38 km
    - 10-20 ppm at 30 km
    - q_{OCS} varies as $p^{5\pm1}$ (Marcq *et al.* 2006)

⇒ *strong decrease of OCS with altitude*

- Thermochemical models
    - OCS is destroyed by reaction with SO_3 to yield CO (Krasnopolsky & Pollack 1994)
    - Can explain the decrease of OCS and the increase of CO in the range 30-40 km



OCS: horizontal variations



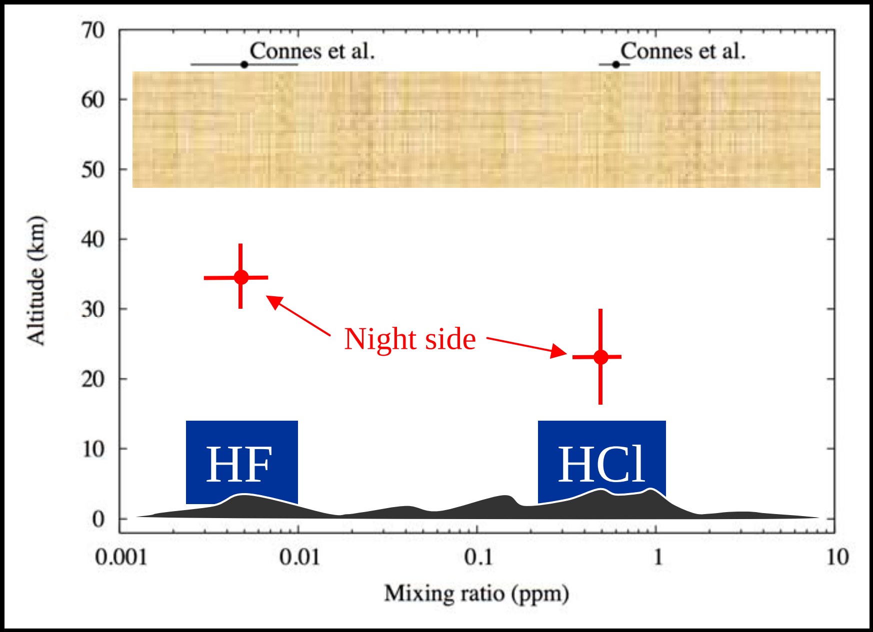
IRTF/SpeX observations
R = 2000
(Marcq *et al*. 2005, 2006)

- OCS is less abundant (~10%) at 40°S than at equatorial latitudes
- Latitudinal variations anticorrelated with CO

⇒ *consistent with upward motion at the equator and subsidence at high latitudes*

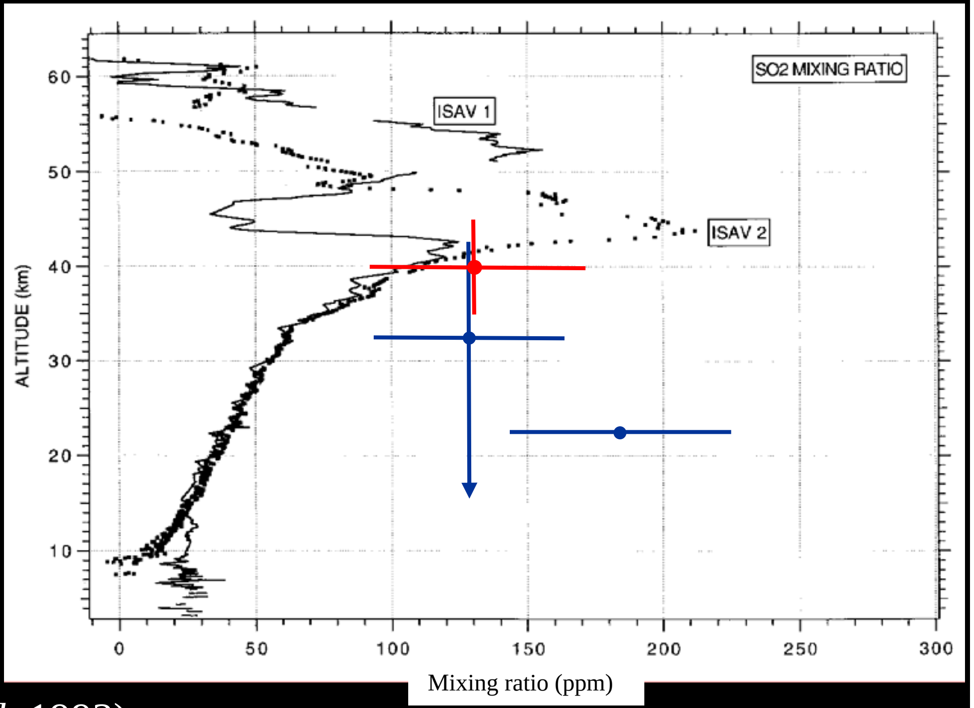
Halides: HCl and HF

- Ground-based nightside spectroscopy
  - HCL
    - 0.5 ± 0.15 ppm at 15-30 km (from 1.74-µm window) (Bézard *et al.* 1990, Pollack *et al.* 1993, Taylor *et al.* 1997)
  - HF
    - 0.005 ± 0.002 ppm at 30-40 km (from 2.3-µm window) (Bézard *et al.* 1990, Taylor *et al.* 1997)
- Abondances virtually identical to those measured at cloud tops, 20 years before (Connes *et al.* 1967)
- HCl and HF are likely in chemical equilibrium with alkaline minerals at the surface (Fegley & Treiman 1992)



Sulfur dioxide: SO_2

- *In situ* measurements
  - Pioneer Venus GC (Oyama *et al.* 1980)
    - 185 ± 43 ppm at 22 km
  - Venera 12 GC (Gel'man *et al.* 1979)
    - 130 ± 35 ppm below 42 km
  - Vega 1 and 2 ISAV (Bertaux *et al.* 1996)
    - Profiles peak at 42-43 km (120 and 200 ppm), decrease below
    - 38 ± 2 ppm at 22 km
    - 20-25 ppm at 12 km



- Ground-based nightside spectroscopy
    - 130 ± 40 ppm at 35-45 km (Bézard *et al.* 1993)

- Reaction with surface minerals cannot buffer SO_2 in the lower atmosphere (Fegley & Treiman 1992)

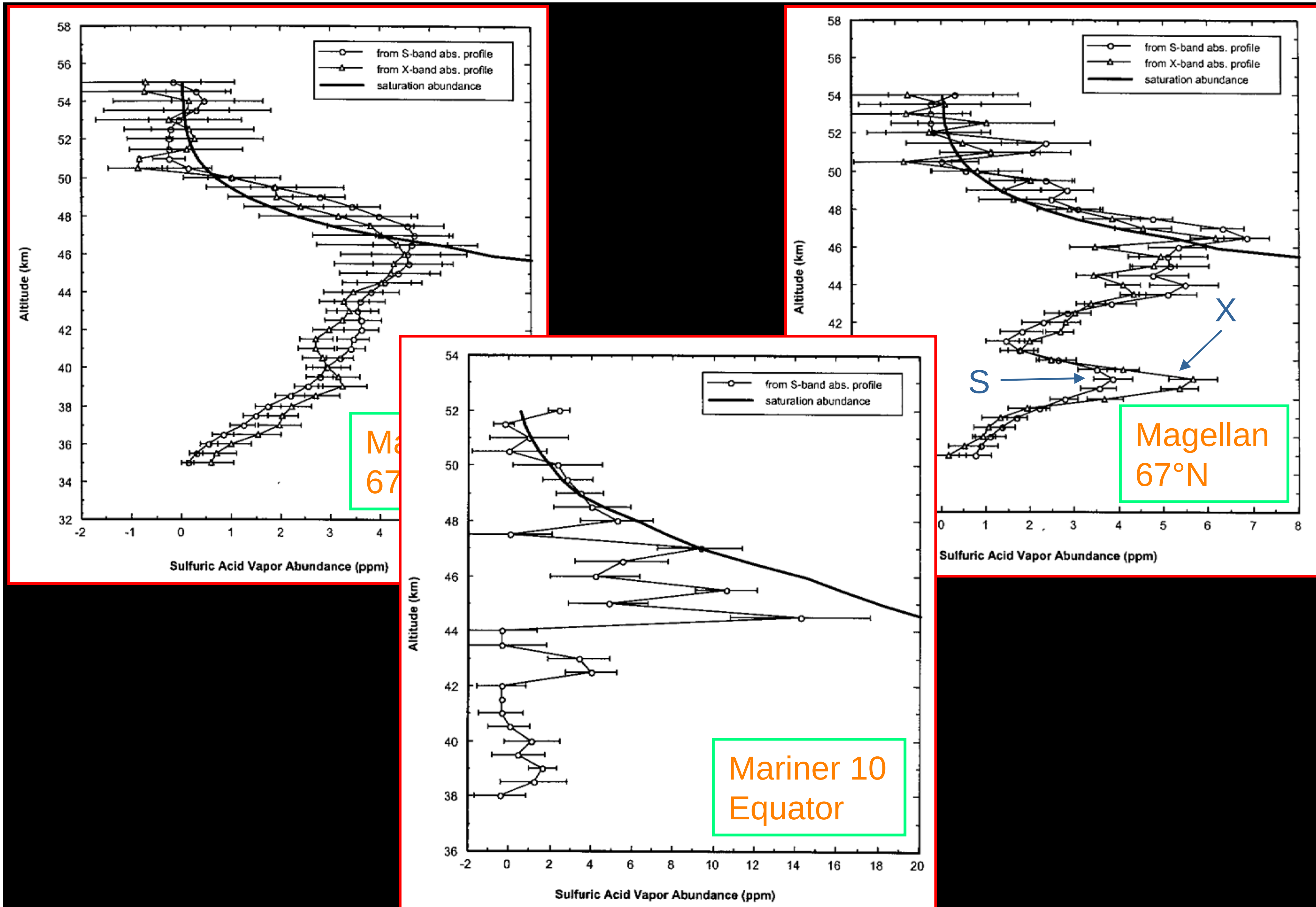
- VEGA profiles cannot be explained by existing thermochemical equilibrium models ⇒ *need to be confirmed!*

Sulfuric acid vapor: H_2SO_4

- Radio occultation measurements
  - Pioneer Venus (Jenkins & Steffes 1991)
    - Large error bars
  - Magellan (Jenkins *et al.* 1994; reanalysis by Kolodner & Steffes 1998)
    - 3-7 ppm below 47 km cloud base at 67°N
    - Sharp drop off below 39 km
    - 6-10 ppm below 44 km cloud base at 88°S
  - Mariner 10 (Kolodner & Steffes 1998)
    - 10-14 ppm below 48 km cloud base at equator
    - Sudden drop off below 45 km

$\Rightarrow$ *evidence for thermal decomposition of H_2SO_4 a few km below cloud base*

  - Missing opacity in X band at some locations
    - Large amounts of SO_2?

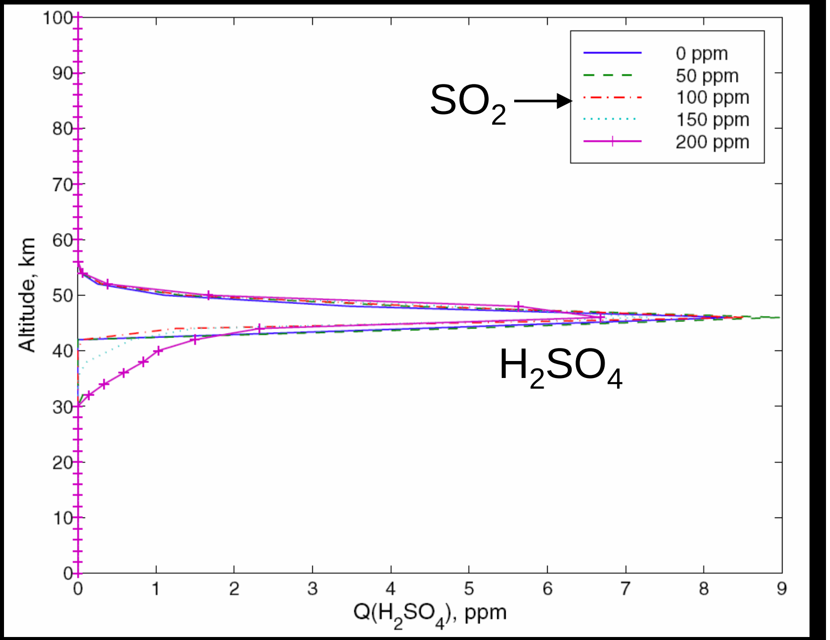

from S-band abs. profile
from X-band abs. profile
saturation abundance
Altitude (km)
Sulfuric Acid Vapor Abundance (ppm)
from S-band abs. profile
from X-band abs. profile
saturation abundance
Altitude (km)
Sulfuric Acid Vapor Abundance (ppm)
X
S
Magellan
67°N
from S-band abs. profile
saturation abundance
Altitude (km)
Sulfuric Acid Vapor Abundance (ppm)
Mariner 10
Equator

Sulfuric acid vapor: H_2SO_4

- Microwave observations

  VLA maps at 1.3 and 2 cm (Jenkins *et al*. 2002)

  – At high latitudes (> 45°):
    - H_2SO_4 peaks at 46 km (~ 8 ppm)
    - Decays rapidly away from this altitude
    - Consistent with Magellan profiles



  – At low latitudes
    - No significant H_2SO_4 observed (< 2.5 ppm)
    - Much less than measured by Mariner 10

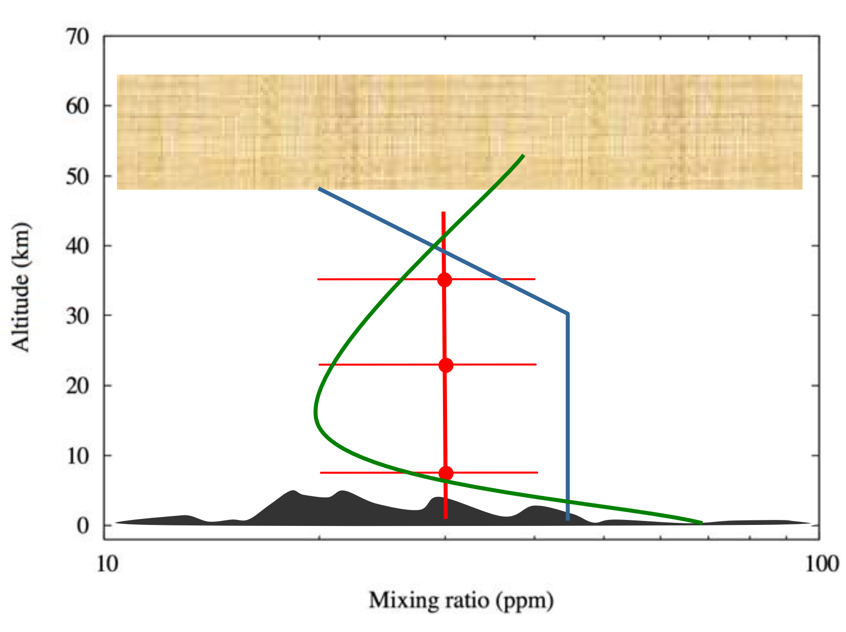
  – Suggests < 100 ppm of SO_2 at low latitudes and < 50 ppm in polar regions

Water vapor: H_2O

- Ground-based nightside spectroscopy
  - H_2O vertical profile (review by Taylor *et al.* 1997)
    - 30 ± 10 ppm from 0 to 45 km, using the 2.3-, 1.7- and 1.18-μm windows
    - Much drier than indicated by the GCMS probe measurements

⇒ *Approximately constant from the*
to the cloud base (~30 ppm)

  - Vertical variations? (Meadows & Crisp 1996)
    - 20 ppm at cloud base;
      ppm from 0 to 30 km

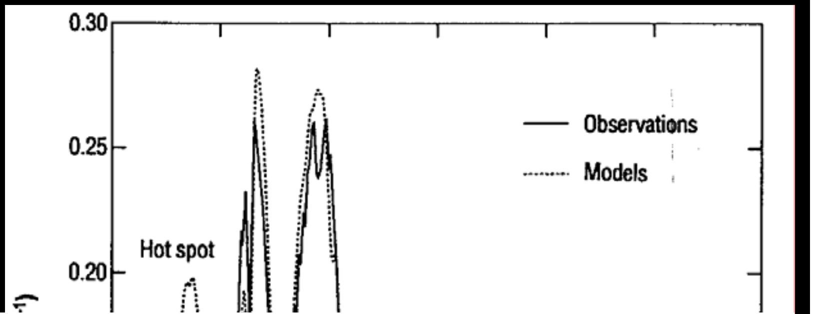


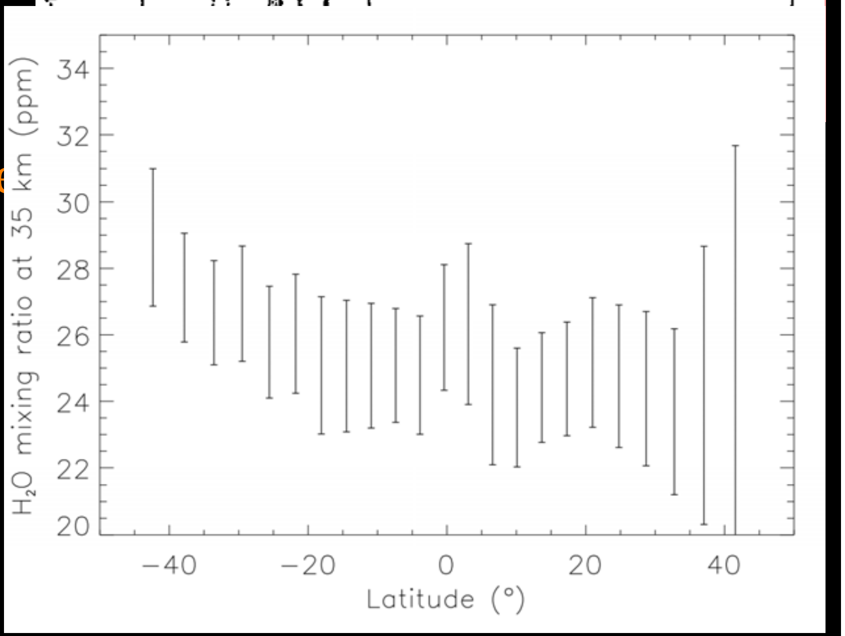
- Venera 11 spectrophotometers
  - Vertical variations? (Ignatiev *et al.* 1997)
    - H_2O possibly decreases from 40 ppm in the clouds to 20 ppm at 10-20 km
    - Likely 50-70 ppm below 5 km

H_2O: horizontal variations

- No variations exceeding 20% at 0-15 km
  (Drossart *et al.* 1993)
  - NIMS/Galileo data at 1.18 µm
  - Limited areal coverage but large latitude range (40°S-50°N)
- No variations exceeding 20% at 30-45 km
  (Marcq *et al.* 2006)
  - SPeX/IRTF spectra at 2.3 µm
  - Latitude range: 40°S-40°N
- Localized enhancement of the H_2O abundance
  (Bell *et al.* 1991)
  - CGS/IRTF spectra at 2.3 µm
  - Factor of ~5 over a low cloud opacity spot
  - Strong downdraft associated with evaporation of H_2SO_4 droplets?
  - Never seen in subsequent measurements

  ⇒ *needs to be confirmed!*





D/H ratio

- Ground-based nightside spectroscopy
  - D/H = 120 ± 40 ⊕ (de Bergh *et al*. 1991); 130 ± 20 ⊕ (Marcq *et al*. poster)
  - Agrees with Pioneer Venus measurements (Mc Elroy *et al*. 1982, Donahue *et al*. 1982)
- Enhancement due to removal of water through dissociation and H-escape
- Interpretation depends on lifetime of H_2O vapor in the atmosphere
  - Signature of a lost primordial ocean (Mc Elroy *et al*., Donahue *et al*.) *or:*
  - Steady state with H_2O supplied by:
    - Impacting comets (Grinspoon & Lewis 1988)
    - Volcanic outgassing (Grinspoon 1993)

Conclusions

Gas	Altitude range	Mixing ratio (ppm)	Comment
CO	36 km Below	26 ± 5 12 + 0.38 × Z(km)	Latitudinal variations
OCS	38 km 30 km	0.35 ± 0.1 10-20	Latitudinal variations
SO_2	35-45 km Below	130 ± 40 Conflicting results	
HCl	15-30 km	0.5 ± 0.15	
HF	30-40 km	0.005 ± 0.002	
H_2SO_4	46 km Below 39 km	4-10 ~ 0	Horizontal variations
H_2O	0-45 km	30 ± 10	Possibly varies with altitude
D/H	30-40 km	120 ± 40	

- *Venus Express* will map and monitor these compounds
  - Large-scale circulation
  - Meteorology of H_2SO_4 clouds
  - Possible volcanic activity
- Other quantities important for the sulfur cycle would require *in situ* measurements
  - SO_2, OCS near the surface
  - SO_3, H_2S, SO, elemental sulfur
  - …