The Clouds of Venus in Global Context: A Multispectral Tour

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University of North Dakota
Department of Space Studies
• 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

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 dunes driven by East → West winds

NB, even these, at km-scale, are too small to be noted in Magellan topography
• 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”
Retrieval of 1.18 micron surface emissivity variations from Galileo NIMS

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

- 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
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.

1.74 micron window again
The Venusian Cloud Decks

Surface

~70 km

H₂O + SO₂ → (H₂SO₄)

Altitude
The Venusian Cloud Decks

$\text{H}_2\text{O} + \text{SO}_2 + \text{sun} \rightarrow \text{Photochemical Upper Cloud (H}_2\text{SO}_4\text{)}$

\[ \sim 70 \text{ km} \]
The Venusian Cloud Decks

Photochemical Upper Cloud ($\text{H}_2\text{SO}_4$)

$\text{H}_2\text{O} + \text{SO}_2 \rightarrow \text{H}_2\text{SO}_4$

Altitude

- ~70 km
- ~57 km
- ~50 km

Surface
The Venusian Cloud Decks

Surface

~70 km

~57 km

~50 km

~40 km

H$_2$O + SO$_2$ + (H$_2$SO$_4$)

Photochemical Upper Cloud

H$_2$SO$_4$ vapors

SO$_2$ ↔ H$_2$O
The Venusian Cloud Decks

Photochemical Upper Cloud

\[ H_2O + SO_2 \rightarrow (H_2SO_4) \]

IR heating

H$_2$SO$_4$ vapors

SO$_2$ ↔ H$_2$O

~70 km

~55 km

~50 km

~40 km
The Venusian Cloud Decks

Potential Temperature Profile

- IR heating
- Condensational Cloud Decks
  - Convection
  - H$_2$O + SO$_2$ + \( \rightarrow (\text{H}_2\text{SO}_4) \)
  - H$_2$SO$_4$ vapors
  - SO$_2$ ↔ H$_2$O

Altitude

- ~70 km
- ~57 km
- ~50 km
- ~30 km
- ~20 km
- 13 km

Surface
Radiative Heating rates in the Venus condensational clouds
Radiance Variation versus Solar Time

Observation (VIRTIS)

Simulation (CARMA)
Mixing Variation versus Solar Time

The Venusian Cloud Decks

Potential Temperature Profile

Condensational Cloud Decks

Photochemical Upper Cloud

\( H_2O + SO_2 + \) → \( (H_2SO_4) \)

Convection

\( H_2SO_4 \) vapors

SO2 ↔ H2O

IR heating

Surface
The Venusian Cloud Decks

Potential Temperature Profile

Photochemical Upper Cloud

Condensational Cloud Decks

Convection

H$_2$O + SO$_2$ + \cdot \cdot \cdot$

H$_2$SO$_4$ vapors

SO$_2$ \leftrightarrow H$_2$O

IR heating

Surface
Magellan topography and radar emissivity

Radar Emissivity

Surface Topography
The Venusian Cloud Decks

Potential Temperature Profile

Condensational Cloud Decks

Photochemical Upper Cloud

IR heating

Surface

H₂O + SO₂ + \(\rightarrow\) (H₂SO₄)

H₂SO₄ vapors

SO₂ \(\leftrightarrow\) H₂O

??

13 km

~20 km

~30 km

~50 km

~57 km

~70 km
Venus in Visible wavelengths

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

The Venusian Cloud Decks

Potential Temperature Profile

Photochemical Upper Cloud $(\text{H}_2\text{SO}_4)$

Condensational Cloud Decks

Convection

IR heating

$\text{H}_2\text{O} + \text{SO}_2 + \text{??}$

$\text{H}_2\text{SO}_4$ vapors

$\text{SO}_2 \leftrightarrow \text{H}_2\text{O}$

Surface

Altitude

~70 km

~57 km

~50 km

~30 km

~20 km

13 km
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.

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)

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.
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.
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.

<table>
<thead>
<tr>
<th>region</th>
<th>$\delta l_0 \times 10^{-3}$</th>
<th>$dl/dt \times 10^{-3}$</th>
<th>$dl/dt \times \Delta t \times 10^{-3}$</th>
</tr>
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<tbody>
<tr>
<td>pol</td>
<td>2.85</td>
<td>-0.0139</td>
<td>-12.8</td>
</tr>
<tr>
<td>mid</td>
<td>4.96</td>
<td>+0.0193</td>
<td>+17.8</td>
</tr>
<tr>
<td>equ</td>
<td>3.55</td>
<td>+0.0216</td>
<td>+19.9</td>
</tr>
<tr>
<td>hem</td>
<td>3.63</td>
<td>+0.0251</td>
<td>+2.3</td>
</tr>
</tbody>
</table>

Long term variability in Venus clouds

- Size parameter
  \[ \frac{l_{1.74}}{l_{2.32}}^{0.53} \]
- Larger size parameter can indicate larger particles
- See a trend of increasing size parameter at the 5-10% level, especially at low latitudes.

<table>
<thead>
<tr>
<th>region</th>
<th>( \delta m \times 10^{-3} )</th>
<th>( \frac{dm}{dt} \times 10^{-3} )</th>
<th>( \frac{dm}{dt} \times \Delta t \times 10^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>pol</td>
<td>3.58</td>
<td>+0.0342</td>
<td>+31.5</td>
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<tr>
<td>mid</td>
<td>2.73</td>
<td>+0.0911</td>
<td>+83.9</td>
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<tr>
<td>equ</td>
<td>2.84</td>
<td>+0.0760</td>
<td>+70.0</td>
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<tr>
<td>hem</td>
<td>4.30</td>
<td>+0.0361</td>
<td>+33.3</td>
</tr>
</tbody>
</table>

The Venusian Cloud Decks

Potential Temperature Profile

- Photochemical Upper Cloud: (H$_2$SO$_4$)
- Condensational Cloud Decks
- Convection
- IR heating

Altitude:
- ~70 km
- ~57 km
- ~50 km
- ~30 km
- ~20 km
- 13 km

Surface
Microphysics, Chemistry, and Radiation cloud model

**Middle and Lower Cloud Region:**
CARMA Model Domain

- **Upper Cloud Boundary Condition**
- **CCN Boundary Condition**
- **Concentration** $q_{H_2SO_4} = 10. \text{ ppmv}$
- **Concentration** $q_{H_2O} = 30. \text{ ppmv}$
- **Constant Supsat. across boundary**
- **Downwelling Infrared Flux**
- **Upwelling Infrared Flux**

Dimensions:
- 60 km
- 40 km
- 60 km
- 40 km
Microphysics, Chemistry, and Radiation cloud model

Upper Cloud Boundary Condition

constant Supsat. across boundary

Downwelling Infrared Flux

60 km

Upper Cloud Boundary Condition

\[
\frac{\partial N(m, z, t)}{\partial t} + \frac{\partial}{\partial z} \left\{ N(m, z, t) \left[ w(z) - v_{\text{fall}}(m, z, t) \right] \right\} - \frac{\partial}{\partial z} \left\{ \rho(z) K_{\text{diff}}(z) \frac{\partial}{\partial z} \left\{ \frac{N(m, z, t)}{\rho(z)} \right\} \right\}
\]

\[
= P(m, z, t) - L(m, z, t) N(m, z, t)
\]

\[
+ \int_{m}^{m_{1}} K_{\text{coag}}(m, m_{1}) N(m_{1}, z, t) N(m - m_{1}, z, t) \, dm_{1}
\]

\[
- N(m, z, t) \int_{0}^{\infty} K_{\text{coag}}(m_{1}, m) N(m_{1}, z, t) \, dm_{1} - \frac{\partial}{\partial m} \left\{ N(m, z, t) G(m, z, t) \right\}
\]

CCN Boundary Condition

Downwelling Infrared Flux

40 km

\( q_{\text{H}_2\text{SO}_4} = 10. \text{ ppmv} \)

\( q_{\text{H}_2\text{O}} = 30. \text{ ppmv} \)

Upwelling Infrared Flux

40 km
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 $\text{H}_2\text{SO}_4$ occurs at about the transition between upper and middle clouds.
Coalescence Sensitivity Test

Coag T: Mass loading

Effective radius

Water vapor

Coag F:

(time = 687.000000)

(time = 720.000000)

(time = 720.000000)
Coalescence Sensitivity Test

**Coag F:**

- **Mass loading**
- **Effective radius**
- **Water vapor**

**Coag T:**

- Mass loading
- Effective radius
- Water vapor
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: $I(1.74)/I(2.3)^{0.53}$

<table>
<thead>
<tr>
<th>Latitude</th>
<th>No coalescence</th>
<th>With coalescence</th>
<th>Wilson et al. (est)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>0.294</td>
<td>0.615</td>
<td>0.6</td>
</tr>
<tr>
<td>30-45</td>
<td>0.231</td>
<td>0.658</td>
<td>0.65</td>
</tr>
<tr>
<td>45-60</td>
<td>0.191</td>
<td>0.676</td>
<td>0.7</td>
</tr>
<tr>
<td>60-75</td>
<td>0.273</td>
<td>0.550</td>
<td>0.65</td>
</tr>
<tr>
<td>75-85</td>
<td>0.251</td>
<td>0.545</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Venus in Ultraviolet wavelengths

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

Potential Temperature Profile

Altitude

~70 km
~57 km
~50 km
~30 km
~20 km
13 km

Surface

IR heating

Photochemical Upper Cloud

(H$_2$SO$_4$)

Condensational Cloud Decks

Convection

H$_2$O + SO$_2$ +

H$_2$SO$_4$ vapors

SO$_2$ ↔ H$_2$O

??
Venus in Ultraviolet wavelengths

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

Marcq et al. (2012)
Esposito et al. (1988)
Long-term (years to decades) variation in SO$_2$: from the 1970s to today


Marcq et al. (2012)
SO$_2$ UV absorption coefficient

Low- and medium resolution absorption cross sections of sulfur dioxide SO$_2$ at room temperature (100-405 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$_2$SO$_4$ 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).

The Varied Clouds of Venus

Image Courtesy NASA
The Varied Clouds of Venus
Venus clouds movie
### Summary of Cloud and Hole Evolution timescales

<table>
<thead>
<tr>
<th>VIR0383</th>
<th>VIR0384</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Timescale</strong></td>
<td>-13.2 hr</td>
</tr>
<tr>
<td><strong>Mean Absolute Timescale</strong></td>
<td>32.2 hr</td>
</tr>
<tr>
<td><strong>Mean Timescale (Holes only)</strong></td>
<td>+17.8 hr</td>
</tr>
<tr>
<td><strong>Abs. Timescale (Holes only)</strong></td>
<td>35.6 hr</td>
</tr>
<tr>
<td><strong>Mean Timescale (Clouds only)</strong></td>
<td>+6.4 hr</td>
</tr>
<tr>
<td><strong>Abs. Timescale (Clouds only)</strong></td>
<td>27.0 hr</td>
</tr>
<tr>
<td><strong>Mean Timescale</strong></td>
<td>-13.7 hr</td>
</tr>
<tr>
<td><strong>Mean Absolute Timescale</strong></td>
<td>34.5 hr</td>
</tr>
<tr>
<td><strong>Mean Timescale (Holes only)</strong></td>
<td>-26.6 hr</td>
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<tr>
<td><strong>Abs. Timescale (Holes only)</strong></td>
<td>36.5 hr</td>
</tr>
<tr>
<td><strong>Mean Timescale (Clouds only)</strong></td>
<td>+12.2 hr</td>
</tr>
<tr>
<td><strong>Abs. Timescale (Clouds only)</strong></td>
<td>30.4 hr</td>
</tr>
</tbody>
</table>

- 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...

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...

### Summary of Cloud and Hole Wind Speed Effects

<table>
<thead>
<tr>
<th>Point</th>
<th>VIR0383</th>
<th>VIR0384</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Edge</td>
<td>-50 m/s</td>
<td>-57 m/s</td>
</tr>
<tr>
<td>East Edge</td>
<td>-55 m/s</td>
<td>-71 m/s</td>
</tr>
<tr>
<td>Peak rad</td>
<td>-64 m/s</td>
<td>-65 m/s</td>
</tr>
</tbody>
</table>

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

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