Microphysics and Dynamics of Venusian Clouds

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Clouds of Venus

- Determining the planetary albedo (Cloud planet)
- Serving as a high-altitude (45-70 km) heat source, influencing atmospheric dynamics

Schubert (1983)
Microphysical properties

- $\text{H}_2\text{SO}_4-\text{H}_2\text{O}$ droplets with radii $r < 5 \ \mu m$
- Smallest mode (including sub-cloud haze) might be condensation nuclei whose composition is unknown.
- Size distribution is variable.

![Graphs showing size distribution of droplets](image)

**Pioneer Venus LCPS (54 km)**

**Vega ISAV (48-52 km)**

Mode 1

Mode 2

Mode 3
Three-layered structure – Different dynamical and chemical regimes at different altitudes?

Pioneer Venus LCPS (Knollenberg and Hunten, 1980)

The bulk of the mass exists in Mode 2 ($r \approx 1 \mu m$)

Static stability measured by entry probes

(Von Alvensleben and Hunten, 1983)
Traditional 1D model
(Krasnopolsky & Pollack 1994; James et al. 1997)

- Photochemical production of $\text{H}_2\text{SO}_4$ from $\text{SO}_2$ and $\text{H}_2\text{O}$
- Sedimentation of $\text{H}_2\text{SO}_4$-$\text{H}_2\text{O}$ droplets
- Evaporation (Cloud base)
- Downward diffusion of $\text{H}_2\text{SO}_4$ vapor
- Thermal decomposition of $\text{H}_2\text{SO}_4$ into $\text{SO}_2$ and $\text{H}_2\text{O}$

70km
60km
50km
40km
30km
1D model result of James et al. (1997)

Soluble nuclei are included

Observation (incl. mode 3)
Observation (excl. mode 3)

Size distribution at 50 km altitude
Cloud-Level Hadley Circulation?

Cloud-top poleward flow (UV images) (Rossow et al., 1990)

Hot poles and cool tropics due to adiabatic heating (Temperatures measured by IR spectroscopy and radio science) (Taylor et al., 1983)

Cloud-base poleward flow (Near-IR images) (Belton et al., 1991)

Enhancement of subcloud CO (Near-IR spectroscopy) (Collard et al., 1993)
Sedimentation vs. Hadley circulation

- Sedimentation velocity of typical droplets in the upper cloud ($r \sim 1 \mu m$)
  \[ W_{\text{sedimentation}} \sim 0.1 \text{ mm/s} \]
- Time constant of Hadley circulation
  - From cloud drift ($v \sim 1 \text{ m/s}$), $\tau = 6050 \text{ km} / v \sim 70 \text{ Earth days}$
  - From thermal structure, $\tau \sim 90 \text{ Earth days}$
  \[ W_{\text{Hadley}} = H/\tau \sim 1 \text{ mm/s} \]

Droplets DO NOT fall. They are transported by Hadley circulation. (Imamura & Hashimoto 1998; Yamamoto & Tanaka 1998)
2D condensation/transport model

- Transport and condensation of H$_2$SO$_4$ and H$_2$O
- Particle radius is fixed:
  - $r = 1.15 \mu$m for $z > 58$ km
  - $r = 3.65 \mu$m for $z < 58$ km
- H$_2$SO$_4$ production at 60-64 km
Result of 2D model

Cloud Mass Loading

Advection

Precipitation

Unit: 10^{-6} \text{ kg m}^{-3}

H_{2}SO_{4} Vapor

Advection/Diffusion

Evaporation

Advection

Unit: ppm
Latitude dependence of cloud thickness

2.3μm Images (Crisp et al. 1991)

Clouds are optically thinner in the mid-latitude.

Okayama Astronomical Observatory, Japan
H$_2$SO$_4$ vapor profiles

H$_2$SO$_4$ vapor is concentrated near the equatorial cloud base.
Proposed $\text{H}_2\text{SO}_4$ cycle

- Droplets
- $\text{H}_2\text{SO}_4$ vapor

Upwelling, Convection, Photochemical production, Condensation, Sedimentation, Evaporation, Diffusion, Thermal decomposition.

Stagnant region

Equatorward advection, Poleward advection.
1D microphysical model for the tropics
(Imamura & Hashimoto, *J. Atmos. Sci.*, 2001)

- Phase transition of H$_2$SO$_4$ and H$_2$O
- Coagulation
- Sedimentation / Diffusion

Eddy diffusion coefficient

Convection at 49-57 km

H$_2$SO$_4$ = 4 ppm, H$_2$O = 30 ppm,
Condensation nuclei = 40 cm$^{-3}$ at the bottom
Calculated cloud mass distribution

- Upward transport
- Condensation
- Sedimentation
- Evaporation
Importance of transience

• In steady state, condensation occurs only on existing large droplets in the lower cloud region, since Kelvin effect (Higher saturation pressure over smaller particles) prevents condensation onto bare nuclei.

→ Bimodal size distribution

• The nuclei can overcome the Kelvin barrier with adiabatic cooling in medium updraft, which have been observed by several entry probes.

→ Various size distribution
Mixing in a convective cell
Mixing in a convective cell

Two identical columns (Nominal model result)

Updraft (1 m/s x 10 min) and Downdraft (1 m/s x 10 min)

Merge two columns at each altitude
Size distributions in updraft

Initial state

Updraft=1 m/s, 30 sec

Updraft=1 m/s, 1 min

Updraft=1 m/s, 10 min
Size distributions after mixing

Size distribution depends on the history of each air parcel.
Development of near-IR opacity

2.3 μm image by Galileo NIMS
Other vertical transport processes

Y-feature
- Kelvin wave?

‘Cells’ near sub-solar region
Convection cells near subsolar?

Amplitude of the diurnal component of solar heating (K/day) (Crisp 1986)

Cloud-top water vapor observed by Pioneer Venus (Koukouli et al. 2005)
Unsolved questions

• Detailed structure of meridional circulation both above and below clouds
• Diurnal variation of cloud structure
• Composition and sources of condensation nuclei
• Relationship between UV markings and cloud structure/vertical transport
• Feedback of cloud variation to atmospheric motions
Longwave IR camera onboard Venus Climate Orbiter (PLANET-C)

10-μm thermal images for detailed cloud-top structure and cloud-tracked winds on both dayside and nightside.

Talk on the mission: Thursday afternoon.
1-D H$_2$SO$_4$ Cycle Near the Equator

- Upward advection of vapor
- Upward diffusion of vapor
- Upward advection of droplets
- Upward diffusion of droplets
- Downward diffusion of vapor
- Downward diffusion of droplets
- Precipitation

Diagram shows the distribution of liquid, vapor, and droplets across different cloud layers and their interactions with H$_2$SO$_4$ flux.
Conclusions

- H$_2$SO$_4$ cycle in the Venusian cloud system is governed by Hadley circulation.
- Effect of winds can explain:
  - Latitude dependence of cloud thickness
  - Accumulation of H$_2$SO$_4$ vapor near the tropical cloud base
  - Variability of particle size distribution
- Transient atmospheric motions cause large opacity variations in the lower cloud region.
- Middle cloud is caused by convective mixing.