Tropospheric Clouds on Jupiter

- Cloud-Forming Molecules
  assuming solar $\% A, NH, 8\% H$ ratios
  $\Rightarrow H_2O, NH_3, H_2S$
  + deeper "rocks"

- "dew points"
  - phase diagram
  - on heavy line, vapor & solid or liquid are in equilibrium, $\Rightarrow$ saturation vapor (partial) pressure.
  - Temperature profile & saturation vapor pressures

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**FIG. 8.** Temperature profile and saturation curves. The $H_2O$ and $NH_4SH$ curves are based on $2\times$ solar abundances of oxygen, sulfur, and nitrogen. The effect of variations in the abundance of $NH_3$ is also shown.
• intersection is where cloud bottom is.
• pressure depends on molecular mixing ratio.
  if abundance increases, \( \Rightarrow \) partial pressure increases
  \( \Rightarrow \) equilibrium temp increases \( \Rightarrow \) cloud base lowers
• cloud height still not determined by this.

- Assuming solar mixing ratios, 3 cloud decks:
  \( \text{NH}_3 \sim 600 \text{ mbar} \)
  \( \text{H}_2\text{S} \) (\( \text{NH}_4\text{SH} \) actually) \( \sim 2 \text{ bars} \)
  \( \text{H}_2\text{O} \sim 6 \text{ bars} \)

- Observed Mixing ratios

- Probe Mass spectrometer
  \( \text{H}_2\text{O} \sim 4 \times 10^{-4} \text{ solar} @ \sim 3 \text{ bar} \)
  \( \lesssim 0.35 \text{ solar} @ \sim 15 \text{ bar} \)
  \( \text{H}_2\text{S} \sim 3 \times 10^{-2} \text{ solar} @ \sim 3 \text{ bar} \)
  \( \sim 2.5 \text{ solar} @ \sim 15 \text{ bar} \)
  \( \text{NH}_3 \lesssim 10 \text{ solar} @ \sim 15 \text{ bar} \)

- Is this representative? Hotspot = desiccated.

  rising air \( \rightarrow \) saturation pressure \( \rightarrow \) condensate forms
  \( \rightarrow \) condensates segregated (e.g. precipitation) \( \Rightarrow \) dried air
  \( \Rightarrow \) descending air anomalously dry.
• If deep mixing ratios of O, N, S are 
  ~2× solar
  ⇒

  standard theoretical cloud model:
  \(NH_3\) cloud ~ 700 mbar
  \(NH_3SH\) cloud ~ 2 bars
  \(H_2O\) cloud ~ 6 bars
Cloud Layers

Visible Cloud layers

Plutochemical hazes

CH4

NH3

H2O
Heat Transfer Processes

Heated by "smog", aerosols, photochemistry & waves from below

Set by equilibrium radiation to space

Radiative

Convection

Isentropic
Figure V.11 Cloud structure deep in Jupiter's atmosphere. The approximate condensation locations of a number of species in a solar-composition model of Jupiter's upper troposphere, from the water clouds (base at about 6 bar) on down. The atmosphere is by no means transparent in the intercloud regions because of the opacity contributed by Rayleigh scattering and collision-induced absorption.
Reflectivity Spectra

absorbing gas (well mixed, e.g., CH₄) + scattering aerosols

\[ \frac{dI_i}{dz} = I_i - I_i' \]

\[ \mu = \cos \theta_m \]
\[ \mu_i = \cos \theta_i \]

Assume simple scattering (i.e., particles and aerosols are small)

\[ J_0 = \frac{\mu_i}{\mu} P(x) F(x) e^{-\mu x} \]

\[ dI_i = (n_0 \sigma_{g_i} + n_0 \sigma_{s_i}) dz \]

\[ \mu_i = n_0 \sigma_{g_i} \vec{v}_i + n_0 \sigma_{s_i} \vec{v}_i \]

\[ I_i = \frac{I_0}{4} \int_0^\infty P_i(z) \vec{v}_i e^{-(\mu + \mu_i) \vec{v}_i} \frac{dz}{\mu} \]
\[ I_i = \frac{F_i}{4} \int_0^\infty P_i(a) \eta_p \sigma_p \omega_p e^{-\frac{(a+\omega)p}{\mu}} \, da \]

unknown

- linear problem... invert w/ matrix approach
Figure 8.8 Angular distribution of radiation scattered from (a) small particles (of radius $a << \lambda$), which is representative of Rayleigh scattering of SW radiation by air molecules (Sec. 9.4.1), and (b) large particles ($a >> \lambda$), which is representative of Mie scattering of SW radiation by cloud droplets (Sec. 9.4.1). Phase function $P$ is plotted in terms of the scattering angle $\Theta$ and in (b) for a scattering population with the refractive index of water and an effective size parameter $x_e = 2\pi(a_e/\lambda) = 5$. Note: The compressed scale in (b) implies that energy redirected by large particles is dominated by forward scattering. Larger particles produce even stronger forward scattering (compare Fig. 9.27). Data in (b) courtesy of F. Evans (U. Colorado).
Galileo SSI

- Coverage: much of planet in ~30,000 km x 30,000 km patches
  - Feature tracks
  - lightning
  - Aurora
  - high phase

- Resolution: ≤30 km/pix
  ⇒ high-res!

- Viewing Geometry:
  Feature tracks from 3 angles

- Wavelengths:
  756 - continuum IR
  727 - weak Methane
  889 - strong methane
  410 - Blue continuum

- not all wavelengths for all views.
Galileo Primary Mission
Feature Track Observations
Aurora: C03, G07, C10, E11, C20

Lightning: C03, C10, E11, C20, C22

High Phase: C03, E04, C09
Discrete, narrow filters in CH₄ absorptions

& nearby continuum.

Gas Absorption

889 nm sensitive to upper troposphere & stratosphere aerosols

727 nm sensitive to troposphere (P < 3 bars) aerosols

[619 (Cassini only) sensitive to troposphere (P < 10 bars) aerosols]

756 nm continuum, deep sensitivity.
Gas Absorption ( & Rayleigh)

Pressure (bars)

Transmissivity

0.01

0.1

1.0

10.0

889 nm

727 nm

(Rayleigh 756)

756 nm
G1 Great Red Spot observation geometries
- regional coverage (e.g., GRS, Hotspot, OVals) most regions now imaged.
- High spatial resolution (~30 km/pixel)
- Usually obtained @ 3 different geometries (different gas path lengths => more vertical info)
Limb-darkening Fits

- Excellent fits $\chi^2 \leq 1$
- non-unique at bottom
- well constrained above $\chi \sim 3$
  angular information lost below that.
- Results very consistent with
  upper hazes from earlier studies

Exploit high spatial and spectral resolution
of Galileo imaging to resolve
ambiguity at the bottom.
- Smallest-scale features change in ~hours
  ⇒ probably in unstable troposphere (P≥600 mbar)

- Smallest-scale features plot on a line between
  CH₄ absorption channels & continuum.
  ⇒ features are optical depth variations
  in a "sheet cloud".

- Slope of line is sensitive to sheet cloud pressure

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**Model Schematics**

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<td>τ₃</td>
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**756–727 scatter plot**

- Likely NH₃ condensate cloud.
- Typically sheet cloud @ ~600 mbar → 950 mbar (NH₃) hints of contrast @ 1-2 bars (NH₄SH) but rare & tenuous ... perhaps covered?

- Localized events showing deep (p>4 bars) sheet cloud (H₂O), usually seen w/ "cumulus towers" (to ~450 mbar) & lightning. ⇒ Convective water thunderstorms.

Blue = 889
Green = 727
Red = 756
deep cloud (p>4 bars) ⇒ red
high thin cloud ⇒ blue
high thick cloud ⇒ white
Water Cloud NW of GRS

400 mb

700 mb

5 bars

← 1000 km → ← 800 km →

Total height exceeds 60 km
From Voyager Area \( \sim 10,000 \text{ km} \times 5000 \text{ km} \)
if \( P_0 \sim \Delta P \sim 1 \text{ bar} \)
\[
Q = \frac{A \rho c_p \Delta T}{g} \sim 10^{22} J
\]
From Voyager \( \Delta t \sim 10 \text{ days} \)
\[
\therefore \quad P \sim 10^{16} \text{ W}
\]
→ Same as internal energy in 5° latitude band!
FIG. 3. Lightning storms amid moonlit clouds. These two C10 images (s0416083400 on the left and s0416090800 on the right) were taken on Jupiter's night side 1 h 15 min apart. These false-color renditions are simple cylindrical projections, with equal increments of latitude and longitude up and across the page, respectively. The bottom of each image is at the equator, while the top is at a latitude of $\sim 50^\circ$. The planet's clouds, which appear in various shades of black (low DN) and red (moderate DN), are dimly lit by reflected light from Jupiter's moon Io. The images' brightest pixels appear white, and correspond to lightning. Storms 7, 8, and 10 are visible on the left, while Storms 5, 11, 13, and 15 are visible on the right.
- Generally:
  stratospheric haze, $\tau \approx 0.1$
  upper tropospheric haze, $\tau \approx 3$
  sheet cloud @ $\sim 650-950$ mbar, $\tau \sim 0-20$
  occasional deeper contrast ($1.5 \rightarrow >4$ bars)

sheet cloud thick in zones, thin in belts.
sheet cloud higher in zones, lower in belts.
(surprising if belts are dry $\Rightarrow$ higher cloud level...
but sheet cloud pressure is probably top
of cloud, not bottom.)

- Still Controversial. NIMS retrievals
  show cloud mostly $\sim 1.8$ bars $\Rightarrow$ NH$_4$SH dominates,
  perhaps only NH$_3$ hazes.
Is it "raining"?

Cloud particle growth processes must be fast enough so that particles grow large enough that fall speeds exceed diffusive motion speeds, all before they fall out.

\[
\text{if } \text{cloud } \sim \frac{1}{10} \text{H} = \text{Hdeep}, \text{ oddy diffusivity } \sim 2 \times 10^5 \text{ cm}^2/\text{s}
\]

\[
\Rightarrow \text{diffusivity } \sim \frac{L^2}{K} \sim 3 \times 10^5 \text{ s (3 days)}
\]

If fallout is the fastest process, and its faster than \( \sim 3 \times 10^5 \text{ s} \) timescale, it rains otherwise, just a cloud.

**Fig. 2.** The variation of the microphysical time constants with mean particle radius for an NH\(_3\) cloud on Jupiter, an example of the relations in a weakly precipitating system.

**Fig. 3.** The variation of the microphysical time constants for a solar abundance H\(_2\)O cloud on Jupiter, an example of a moderately precipitating system.

light rain, drops \( \sim 1 \text{ mm} \)

real rain, drops \( \sim 1 \text{ cm} \)