The Role of Clouds in Planetary and Exoplanetary Atmospheres

Robert West
Jet Propulsion Lab,
Caltech
‘The atmospheres of substellar objects contain clouds of oxides, iron, silicates and other refractory condensates. Water clouds are expected in the coolest objects. The opacity of these ‘dust’ clouds strongly affects both the atmospheric temperature–pressure profile and the emergent flux. Thus, any attempt to model the spectra of these atmospheres must incorporate a cloud model.’ (Ch. Helling et al., *Mon. Not. R. Astron. Soc.* **391**, 1854–1873 (2008))
Outline*

• Thermochemical Equilibrium Theory for Condensates – Chemical abundances, P,T profiles, condensate cloud bases
• Examples from our solar system and beyond
• Beyond the cloud base – Cloud microphysics and dynamics
• Cloud effects on radiative transfer and remote sensing
• Photochemical Haze
• Cloud effects in Cool stars

*See the embedded notes pages for references and notes
Condensation Vapor Pressure

\[
\ln(P_V) = \ln(C) + \frac{1}{R_V} \left[ - \frac{L_0}{T} + \Delta \alpha \ln T + \frac{\Delta \beta}{2} T + O(T^2) \right].
\]

Sánchez-Lavega, Pérez-Hoyos, and Hueso

\[ P_V \] = Vapor pressure in equilibrium with the condensate

\[ T \] = Temperature

\[ \frac{1}{R_V} \] = Specific gas constant for the vapor

From Sánchez Lavega et al., 2003
## Empirical Constants*

*For hot Jupiters and cool dwarfs see papers by Lodders and Fegley and colleagues

<table>
<thead>
<tr>
<th>Component</th>
<th>$\ln(C)$ (C in bars)</th>
<th>$L_0$ (J g$^{-1}$)</th>
<th>$\Delta \alpha$ (J g$^{-1}$ K$^{-1}$)</th>
<th>$\Delta \beta/2$ (J g$^{-1}$ K$^{-2}$)</th>
<th>Reference</th>
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</table>

From Sánchez Lavega et al., 2003

*For hot Jupiters and cool dwarfs see papers by Lodders and Fegley and colleagues
Phase Diagram – H₂O

From Sánchez Lavega et al., 2003
# Planetary Condensates

## I. Terrestrial Planets

From Sánchez Lavega et al., 2003

<table>
<thead>
<tr>
<th>Cloud and planet</th>
<th>$X_c$ (l)</th>
<th>$\mu_c$</th>
<th>P (bar)</th>
<th>T (K)</th>
<th>H (km)</th>
<th>$H_c$ (km)</th>
<th>$H_c/H$</th>
<th>Density (g cm$^{-3}$)</th>
<th>$\Gamma_s$ (K km$^{-1}$)</th>
<th>$\Gamma_s/\Gamma_a$</th>
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<tr>
<th>Mole Fraction</th>
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<th>Scale Height</th>
<th>Lapse Rate</th>
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From Sánchez Lavega et al., 2003
# Planetary Condensates

## II. Jupiter, Saturn

Table III. Planetary atmospheres condensates (l=liquid, s=solid) and cloud characteristics. The quantities are defined in Sec. IV.

<table>
<thead>
<tr>
<th>Cloud and planet</th>
<th>$X_c$</th>
<th>$\mu_c$</th>
<th>P</th>
<th>T</th>
<th>H</th>
<th>$H_c$</th>
<th>$H_c/H$</th>
<th>Density (g cm$^{-3}$)</th>
<th>$\Gamma_s$ (K km$^{-1}$)</th>
<th>$\Gamma_s/\Gamma_a$</th>
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<td>$\text{H}_2\text{O}$ (Solar) (s)</td>
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<td>50.0</td>
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<td>MgSiO$_3$ (s)</td>
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<td>0.59</td>
<td>0.987</td>
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</tbody>
</table>
Condensation Levels
I. Terrestrial Planets

Solid curves: planetary representative P/T relations
Dashed curves: ‘Nominal’ Pv(T) for noted constituents

Note: multiple cloud levels
Are expected due to meteorology

From Sánchez Lavega et al., 2003
Condensation Levels
II. Giant Planets, Titan, HD 209458b

From Sánchez Lavega et al., 2003
Condensate Layers on the Giant Planets – Thermochemical Equilibrium Theory

From Atreya and Wong

From de Pater et al., 1991

R. West
Theoretical Cloud Density Profiles

From Ackerman and Marley, 2001
Observationally Derived Cloud Structure for Jupiter

From West et al., 2004
Particle Nucleation and Growth

The change in Gibbs Free Energy determines if a particle grows or evaporates. For a liquid drop in equilibrium with vapor

$$
\Delta G = 4\pi a^2 \sigma - \frac{4}{3} \pi a^3 n_l K T \ln(e/e_l)
$$

Where $a$ = drop radius
$\sigma$ = surface tension of the liquid
$n_l$ = number density of molecules in the liquid
$e$ = vapor pressure
$e_l$ = saturation vapor pressure

There is a critical radius where $\Delta G$ becomes negative. If the particle is larger than the critical radius it will grow.
Particle Microphysics - I

• Homogeneous and heterogeneous nucleation
• Heterogeneous nucleation requires cloud condensation nuclei (CCN) but these are abundant in most environments
  – Hydrophobic or hygroscopic nuclei influence particle density and size.
  – Abundant hygroscopic CCN lead to a high density of small particles (eg. ship tracks)
  – The opposite is true when hygroscopic CCN are absent
Ship Tracks over the Atlantic

http://earthobservatory.nasa.gov/IOTD/view.php?id=3275
Particle Microphysical Processes

- **Growth from vapor (+ CCN)**
  - Depends on abundance, contact parameter of CCN and relative humidity of the vapor

- **Particle collisions and coagulation**
  - Depends on particle size distribution n(r), number density, and sticking coefficient (which in turn depends on particle electrical charge and composition)
  - Modifies n(r,z) where r = radius, z = altitude

- **Sedimentation**
  - Depends on particle size and density, atmospheric density, gravity

- **Transport by advection and eddies**
  - Can lead to holes and enormous heterogeneity
  - Cloud particles can be distant from source vapor

- **Mixed phase and mixed compositions complicate the simulation**
Ramifications of Microphysics and Atmospheric Dynamics
Particle Microphysics: Size and Shape

- Particle size distribution is usually monomodal but can be bimodal, evolves as the cloud evolves
  - Parameters are effective size, and variance
  - Mie theory can be used to calculate optical properties
- Typical mean sizes are sub-micron to 10s of microns, sometimes larger
- If particles are liquid the shape is spherical; if not the shape can be a crystal or aggregates of many small (50 nm) monomers. Most planetary cloud particles are solid
Remote Sensing: Particle Size and Shape Diagnostics: Spectra

• Spectra of reflected, emitted, or transmitted light
  – Large particles have a flat spectral dependence, except near absorption features
  – Absorption features are broad for large particles, narrow for small particles
  – Mie theory for spheres is sometimes not appropriate
Reflection Spectra of the Giant Planets

Note: Spectra of Jupiter and Saturn are much darker than Uranus and Neptune at short wavelengths due to chromophores. The reverse is true at longer wavelengths due to methane absorption.

Karkoschka, 1998
ISO Spectra – IR Whole Disk

Fig. 1. The SWS grating spectrum of Jupiter between 2 and 16 µm. The resolving power is about 1500. The Uranus spectrum only shows the \( \text{C}_2\text{H}_2 \) band at 13.7 µm, about 3 times weaker than on the Neptune spectrum. Uranus and Neptune are not detected below 7 µm with SWS.
Crystals and Aggregates

Do not use Mie theory

Ammonia Ice absorptions
From West et al., 1989

Photochemical or auroral-generated haze particles in Jupiter/Saturn auroral regions are aggregates
Photochemical/Auroral Haze Revealed by UV and near-IR Images

From the Cassini ISS instrument at Jupiter Porco et al., 2003

The polar stratospheric haze is concentrated near the few-mbar pressure level, well above the condensate cloud deck
Photochemical Haze Production on Planets Near Stars

• Stratospheric haze production can be prodigious
• On the giant planets the composition can be organic, $N_2H_4$ (hydrazine), $P_2H_4$ (diphosphene)
• Tidal locking will influence static stability, photochemical production rates and lifetimes
• Dynamical regime will be unfamiliar probably leading to a highly asymmetric distribution of absorbing haze.

• Does this explain the low albedo for HD 209458b? See paper by Rowe et al., *Ap. J.* 689, 2008
Cloud Heterogeneity is Important for Emitted Radiation

Ground-based 5-μm image from J. Spencer
Jovian Hot Spot Spectra and Models

Data from the Voyager IRIS instrument.

Models having cloud opacity at the water base or high above the water base. If the cloud is at the water base the spectrum is much too flat.

From West et al., 1986.
Clouds in Dwarf Stars

Marley et al., 2002
Effective Temperatures for Three Models – Cloud or no Cloud

Marley et al., 2002
Color Diagram for L, T Dwarfs with/without Clouds

Marley et al., 2002
Conclusions from Cool Star Models

• Condensate layers have a profound effect on the P/T profile, and models would be in disagreement with observation if all available cloud opacity were in play. Sedimentation and/or cloud heterogeneity are important in limiting cloud opacity. (Marley et al., 2002)

• Condensate layers have a significant effect on the observed spectrum (as much as 2 magnitudes in the color diagram)
Further reading*


*A separate text file bibliography, including abstract for dwarf stars is available