Last Week - Chemistry

- Cycles: ozone, CO, SO₂
- Photodissociation and loss (CH₄, H₂O etc.)
- D/H ratios and water loss
- Noble gas ratios and atmospheric loss (fractionation)
- Outgassing (⁴⁰Ar, ⁴He)
- Dynamics can influence chemistry
- Non-solar gas giant compositions
- Titan’s problematic methane source
This Week – Clouds, Hazes, Dust

• Physics of cloud formation
  – Vapour pressure, nucleation

• Clouds in practice
  – Mars \((\text{CO}_2 + \text{H}_2\text{O})\), Venus \((\text{SO}_2)\), Earth \((\text{H}_2\text{O})\)
  – Titan \((\text{CH}_4)\), Gas giants, Exoplanets

• Dust

• Guest lecture (Patrick Chuang)
Schematic cloud formation

Clouds may consist of either solid or liquid droplets. Lapse rate gets smaller when condensation begins - why?

\[ g \, dz = C_p \, dT + L_H \, df \]

\( L_H \) is the latent heat.
Vapour pressure

• Condensation occurs when the partial pressure of vapor in the atmosphere equals a particular value (the saturation vapor pressure $P_s$) defined by the phase boundary given by the Clausius-Clapeyron relation:

$$\frac{dP_s}{dT} = \frac{L_H P_s}{RT^2}$$

• This gives us $\ln(P_s) = a - b/T$

• As condensation of a species proceeds, the partial pressure drops and so $T$ will need to decrease for further condensation to proceed

• What happens when you boil water at high altitude?
Phase boundary

\[ P_{vap} = C_L \exp\left( - \frac{L_H}{RT} \right) \]

E.g. water \( C_L = 3 \times 10^7 \) bar, \( L_H = 50 \) kJ/mol
So at 200K, \( P_s = 0.3 \) Pa, at 250 K, \( P_s = 100 \) Pa
Nucleation

• Liquid droplets can form spontaneously from vapour (*homogeneous* nucleation), but it can require a large degree of supercooling.

• In practice, nucleation is much easier if there are contaminants (e.g. dust) present. This is *heterogeneous* nucleation.

• In real atmospheres, nucleation sites (cloud condensation nuclei, CCN) are usually present.

• On Earth, pollution is one major source of CCN.

• CCN are much smaller than raindrops (~0.1 μm).
Earth Clouds

- Crudely speaking, air picks up water from the ocean and deposits it on land.
- Equatorial easterly winds mean that western sides of continents tend to be cloud-free and very dry.

What causes the equatorial easterlies (trade winds)?
Albedo and feedback

- Clouds can have an enormous impact on albedo and hence surface temperature
- E.g. Venus $A=0.76$ Earth $A=0.4$
- Venus receives less incident radiation than Earth!
- Clouds are typically not resolved in global circulation models – but can be very important
- Sea surface warming will lead to more clouds, partly offsetting the warming effect
- “cloud feedbacks remain the largest source of uncertainty in climate sensitivity estimates” (IPCC 2007)
- How much extra cloud cover would be required to offset a 2K increase in temperature?
Venus

Thermal breakdown at 400K

\[ H_2SO_4 \rightarrow SO_3 + H_2O \]

Clouds consist mostly of \( H_2SO_4 \) droplets
These break down at high temperatures – lower atmosphere is cloud free
Mars Clouds

Observed in spacecraft images
Most clouds observed are water ice (very thin, cirrus-like)
Do not have significant effect on global energy budget (unlike Earth)
CO$_2$ ice clouds have also been observed
Mars clouds

- CO$_2$ clouds form only when cold – either at high altitude (~100 km) or near poles
- H$_2$O is not abundant (few precipitable microns)
- But H$_2$O clouds are common where there is a source of water (e.g. polar caps in spring)
Clouds consist mostly of CH$_4$ ice & droplets

Haze is a by-product of methane photochemistry high in the atmosphere (long-chain hydrocarbons), ~0.1 μm
Clouds & rain on Titan

- Tropospheric methane clouds
- North pole, 2009 (equinox)
- Speeds ~ 5 m/s

- Patches of surface look darker after clouds form – suggests rainfall took place
- Distribution of clouds is observably changing with seasons (moving past equinox)
- Titan has a dynamic “hydrological” cycle

PIA12811_full_movie.mov
Giant planet clouds

Different cloud decks, depending on condensation temperature

Colours are due to trace constituents, probably sulphur compounds
Exoplanet Clouds

- I – Ammonia (<150 K)
- II – Water (<250 K)
- III – Cloudless (>350 K)
- IV – Alkali Metals (>900 K)
- V – Silicate (>1400 K)

Different classes of exoplanets predicted to have very different optical & spectroscopic properties depending on what cloud species are present
Dust on Mars

Dust has major control on energy budget of atmosphere
Dust lofting & settling

Global dust storms on Mars result from feedback: dust means more energy absorbed in atmosphere, local increase in wind strength, more dust lofted and so on . . .

Why don’t we get global dust storms on Earth?
- Oceans
- Wet atmosphere helps particles flocculate

Sinking timescale: \( t \approx \frac{\eta H}{g r^2 \Delta \rho} \)

Where does this come from?

How do we calculate the viscosity of a gas? \( \eta \sim \frac{v \mu}{N_A r^2} \)

For Mars, \( \eta \sim 10^{-3} \) Pa s, \( H \sim 15 \) km, \( r \sim 10 \mu m \) so \( t \sim \) few months
Dust Devils on Mars

Phoenix image

10 December 2003

22 July 2003

Helpful in cleaning solar cells!
Moving dunes on Mars

Bridges et al. *Nature* 2012
Thermal effect of dust

\[ T^4(z) = T_{eq}^4 \left(1 + \frac{3}{4} \tau(z)\right) \]

Tropospheric \( T_{eq} = 160 \) K
Tropospheric warming due to dust gives \( T = 240 \) K (see diagram)
Implies \( \tau \sim 5 \) (a bit high)

\[ \tau = \frac{3d \rho}{4r \rho_s} \]

If \( d = 20 \) km and \( r = 10 \) \( \mu \)m, \( \rho \sim 10^{-5} \) kg m\(^{-3}\). What surface thickness does this represent?
\( 0.2 \) kg/m\(^2\) = 0.1 mm (not a lot!)

* We’ll discuss \( \tau \) next week (radiative transfer)
Key concepts

- Saturation vapour pressure, Clausius-Clapeyron
- Moist vs. dry adiabat
- Cloud albedo effects
- Giant planet cloud stacks
- Dust sinking timescale and thermal effects

\[ \frac{dP_s}{dT} = \frac{L_H P_s}{RT^2} \]

\[ t \approx \frac{\eta H}{gr^2 \Delta \rho} \]
End of lecture
• Could talk about Zahnle style water atmosphere and radiative heat loss 300 W/m²?
Giant planet atmospheric structure

- Note position and order of cloud decks