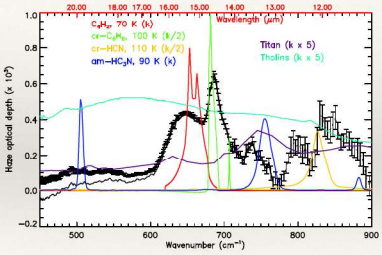
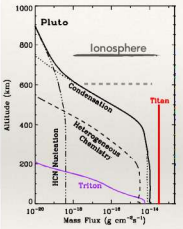
JWST Results: Organic ices are present



Lellouch et al. 2025

How much Titan-type haze could be present ?



Based on Titan observations, ionospheric chemistry driven by EUV on Pluto could generate $7x10^{-16}$ g cm^{-2}s^{-1}.

However, on Titan, the mass flux generated by EUV is only 10% of the total haze mass flux observed. Further particle growth through neutral processes between 1000 and 500 km.

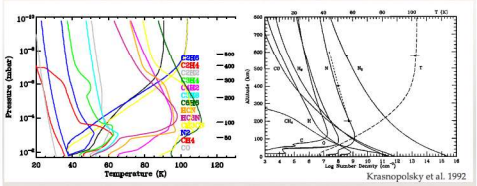
How efficient could the corresponding growth on Pluto be between ~750 km and ~600 km ?

Assuming no condensation and a 30% yield (Titan), the maximum mass flux could reach $6x10^{-15}$ g cm^{-2}s^{-1}.

Voyager II
Visible wavelengths
1989

RADIUS: 1352.4 km
COMPOSITION: N_2, CH_4(1.5x10^{-2}), CO(6x10^{-4})
GRAVITY: 0.78 m/s²
TEMPERATURE: 38 K
SURFACE PRESSURE: ~16 mbar
ORBIT: 30.3 AU

Condensation Curves | Chemical composition



Krasnopolsky et al. 1992

Temperature colder than Pluto's in the lower atmosphere and all photochemical products condense

Methane is chemically lost above ~200 km thus limiting molecular growth through ion chemistry

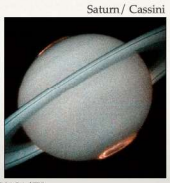
Comparison

	Titan	Pluto	Triton
Formation Mode	Molecular growth	Condensation / Molecular Growth	Condensation
Particle Composition	Tholin-type	Organic ice (tholin-type cores)	Organic ice
Mass Flux (g cm^{-2} s^{-1})	$3x10^{-14}$	~$1x10^{-14}$	~$6x10^{-15}$

Titan and Triton define the extremes of haze formation between molecular growth and condensation. Pluto, during the New Horizons observations is closer to the Triton case but along its orbit the situation could become more Titan-like when the atmosphere is warmer.

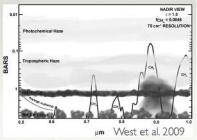
Giant Planets

Jupiter /Juno | Saturn/ Cassini



NASA/JPL

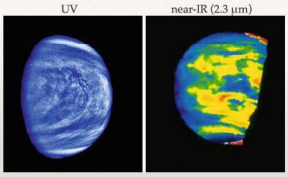
Haze opacity detected at high latitudes, related to auroral energy input (Koskinen et al. 2016).



West et al. 2009

Venus

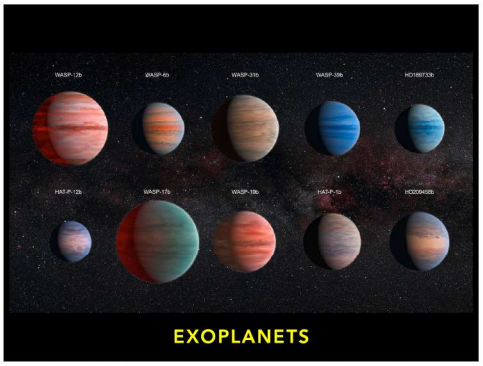
UV | near-IR (2.3 μm)



Galileo

H_2SO_4 clouds (~60 km) | Atmosphere (30 km)

Encrenaz& Coustenis 2017

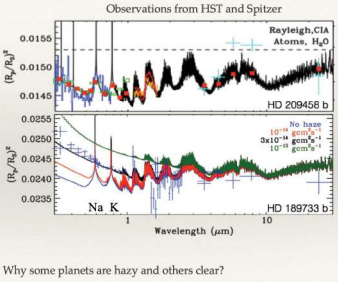


THE USUAL SUSPECTS

Observations from HST and Spitzer

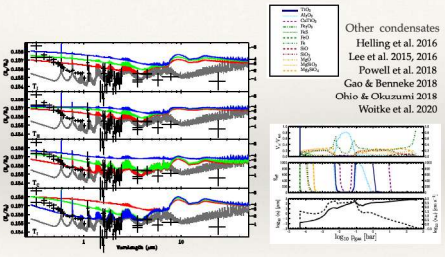
HD 209458 b
Mass: 0.66 MJ
Radius: 1.38RJ
SM-Axis: 0.04747AU
Star: G0 V
(Sing et al. 2016)

HD 189733 b
Mass: 1.238 MJ
Radius: 1.138RJ
SM-Axis: 0.03142AU
Star: K1-K2
(Pont et al. 2013)



Why some planets are hazy and others clear?

SILICATE CLOUDS

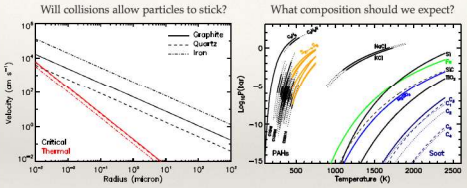


Other condensates
Helling et al. 2016
Lee et al. 2015, 2016
Powell et al. 2018
Gao & Benneke 2018
Ohio & Okuzumi 2018
Woitke et al. 2020

Clouds not consistent with primary transit observations

ARE PHOTOCHEMICAL HAZES POSSIBLE?

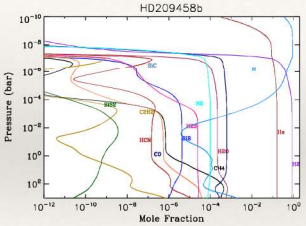
Will collisions allow particles to stick? | What composition should we expect?



$$\frac{\partial n_g}{\partial t} = -\frac{1}{r^2}\frac{\partial (r^2 \Phi(v_g))}{\partial r} + \frac{1}{2}\sum_{i=1}^{i-1} K_B(u_i, v_g - u_i) n(u_i) n(v_g - u_i) - n_g \sum_{i=1}^{N_{max}} K_B(u_i, v_g) n(u_i) + \frac{\partial n(v_g)}{\partial t}\Big|_{PC} - \frac{\partial (\dot{m} n_g)}{\partial m}$$

Transport | Coagulation | Production (Photochemistry) | Ablation

Disequilibrium Chemistry



photochemistry

atmospheric mixing

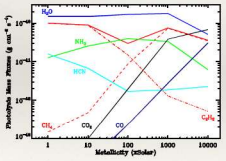
thermochemical balance

Moses et al. 2011, Line et al. 2012, Venot, et al. 2013, Lavvas et al.,2014, Tsai et al. 2018

Haze Production

A fraction of the mass flux generated from the photolysis of the main haze precursors will produce photochemical hazes.

Main Haze precursors:
CH_4, C_2H_2, N_2, NH_3, HCN



At low metallicities C_2H_2 provides the major contribution along with NH_3 and HCN.

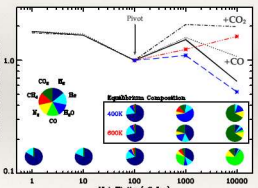
As metallicity increases CH_4 survives to lower pressures and dominates the production.

At very high metallicities CO/CO_2 become major atmospheric components and have significant photolysis mass fluxes.

For 10% yield mass fluxes of ~10^{-11} g cm^{-2} s^{-1} are possible.

Haze Production

Although metallicity changes by 4 orders of magnitude haze production rates remain remarkably unaffected with changes of a factor of few (~3).

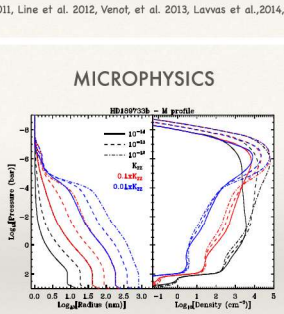


Lavvas et al. 2019

Lab experiments suggest a similar small relative variability across metallicity (He et al. 2018, Horst et al. 2018 Fleury et al. 2019).

For the first time there is a direct connection between the starting point of haze production (photolysis rates) and the end product (haze mass measured).

MICROPHYSICS

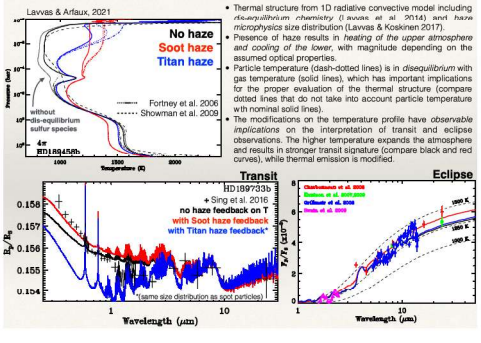


Lavvas & Koskinen 2017
Kawashima & Ikoma 2018
Adams et al. 2019
Ohno & Kawashima 2020

Large production —> Larger size
Stronger mixing —> Smaller size
High temperature —> Loss of particles

Impact of hazes on exoplanet thermal structure & observations

Lavvas & Arfaux, 2021



- Thermal structure from 1D radiative convective model including *disequilibrium chemistry* (Lavvas et al. 2014) and *haze microphysics* size distribution (Lavvas & Koskinen 2017).
- Presence of haze results in *heating of the upper atmosphere and cooling of the lower*, with magnitude depending on the assumed optical properties.
- Particle temperature (dash-dotted lines) is in *disequilibrium* with gas temperature (solid lines), which has important implications for the proper evaluation of the thermal structure (compare dotted lines that do not take into account particle temperature wth nominal solid lines).
- The modifications on the temperature profile have *observable implications* on the interpretation of transit and eclipse observations. The higher temperature expands the atmosphere and results in stronger transit signature (compare black and red curves), while thermal emission is modified.

Refractive index