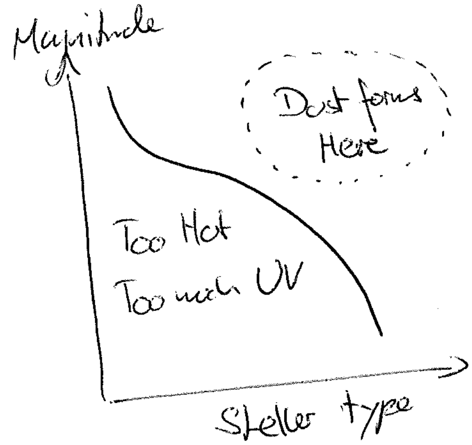
Circumstellar Dust & Cloud Formation

Motivation

1. Where does all the dust come from?
2. What drives Stellar winds in evolved Stars?
3. What type of clouds form in substellar atmospheres?

Where do we find dust & Clouds:

- Red Giants
- Asymptotic Giant Branch (AGB) Stars
- Brown Dwarfs
- Exoplanets
- nova Shells
- Super nova

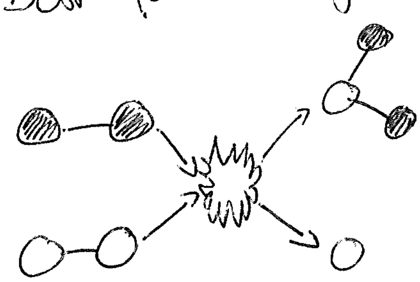


What do we need to form dust?

1. Cool Temperatures
2. High densities

Kinetic Chemistry

Dust forms through chemical reactions so lets start with that.



$$H_2 + O_2 \xrightarrow{R^+} H_2O + O$$

Reaction rate:

$$R^+ = k^+ n_{H_2} n_{O_2}$$

-> k^+: reaction rate coefficient

-> n: number densities

Arrhenius equation

$$k^+ = A \exp\left(\frac{-E_a}{k_B T}\right)$$

-> E_a: Activation Energy

-> A: fitting factor

Backward reaction

→ In chemical equilibrium: $\left.\begin{aligned} R^- = R^+ &= k^+ \mathring{n}_{H_2} \mathring{n}_{O_2} \\ &= k^- \mathring{n}_{H_2O} \mathring{n}_{O} \end{aligned}\right\} \Rightarrow \underbrace{k^- = \frac{\mathring{n}_{H_2} \mathring{n}_{O_2}}{\mathring{n}_{H_2O} \mathring{n}_{O}} k^+}_{\text{Also valid in Chem. Diseq!}}$

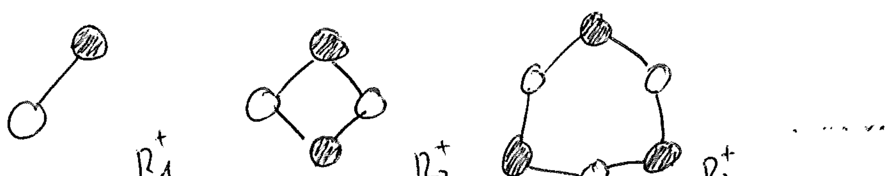
Typicall chemical reaction Networks:

→ hundreds of species (H, C, N, O)

→ thousands of reactions (Thermal, photochemistry, 3-Body reactions)

Nucleation

Phase transition from gas to solid → Form Cloud Condensation Nuclei (CCNs) a.k.a. aerosols



$$\underset{\text{monomer}}{SiO} \underset{R_1^-}{\overset{R_1^+}{\rightleftarrows}} \underset{Si_2O_2}{(SiO)_2} \underset{R_2^-}{\overset{R_2^+}{\rightleftarrows}} \underset{Si_3O_3}{(SiO)_3} \underset{R_3^-}{\overset{R_3^+}{\rightleftarrows}} \dots$$

Forward Reaction

$$R_i^+ = \underbrace{\int_0^\infty \sigma_\nu \alpha_\nu \nu f_\nu \, d\nu}_{k^+} \, n_i n_1$$

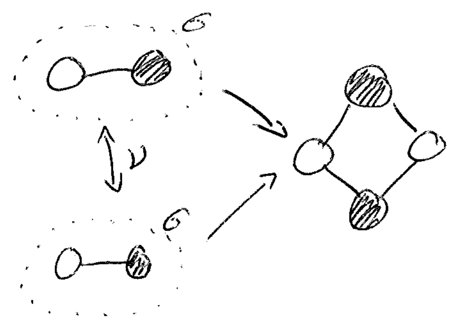
→ σ_ν: Cross section

→ α_ν: sticking coeficient

→ ν: relativ velocity

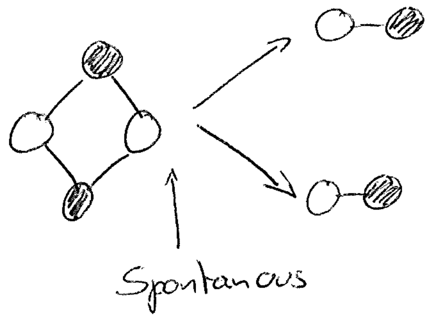
→ n_1: monomer number density

→ f_ν: Velocity distributions e.g. Boltzmann Dist.



⚠ No 2nd Body to take away Binding E.

Backward reaction



In equilibrium: $R_+^i = R_-^i$ → Detailed Balance

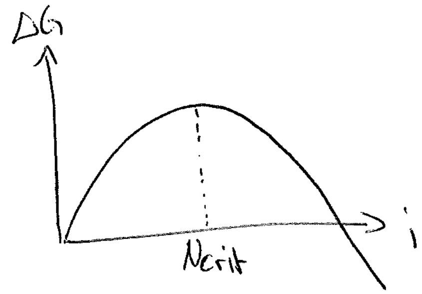
$$k_i^- = k_i^+ \frac{\mathring{n}_1 \mathring{n}_i}{\mathring{n}_{i+1}} = k_i^+ K$$

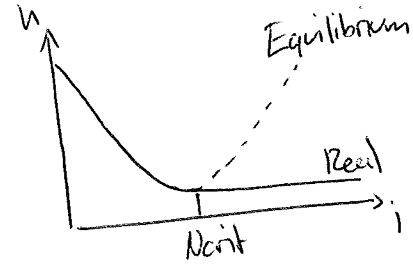
$$K = \frac{\bar{p}}{k_B T} \exp\left[\frac{1}{k_B T}\left(\overline{\Delta G}_{i+1} - \overline{\Delta G}_i - \overline{\Delta G}_1\right)\right]$$

→ K: Equilibrium Constant
→ $\overline{\Delta G}_i$: Gibbs free energy at standard pres.
→ $\bar{p}$: standard pres. 10^5 PA

Non-Classical Nucleation

$$J_* = \left(\sum_{i=1}^{N_{max}} \frac{1}{k_i^+ n_i n_1}\right)^{-1}$$ ≈ slowest growth step





⚠ Requiers clusterdata up to critical cluster size N_{crit}
Species with good data: Al_2O_3, TiO_2, SiO, KCl
Stars — Planets / Brown Dwarfs

Classical Nucleation Theory

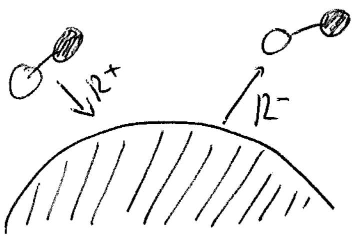
Idea: Approximate cluster properties with Bulk properties

$$J_* = k^+_{crit} \mathring{n}_{crit} \mathring{n}_1 Z \exp\left[(N_{crit} - 1)\ln(S) - \theta_\infty (N_c - 1)^{2/3}\right]$$

→ Z: Zeldovich factor ≈ probability that a N_{crit} cluster grows
→ S: Supersaturation
→ N_{crit}: Critical cluster size

Accretion

Often called condensation even if not liquid



⚠ Materials that cannot nucleat can still accret

→ e.g. $MgSiO_3$, ZnS

$$R = R^+ - R^-$$

Growth

$$G^+ = \underbrace{4\pi r^2 \alpha \nu n_r}_{n^+} n_{cl}$$

→ $4\pi r^2$: cross section

→ n_{cl}: number density cloud particle

→ n_r: number density reactant

$$\Rightarrow G = 4\pi r^2 \alpha \nu n_{cl} \left(1 - \frac{\mathring{n}_r}{n_r}\right)$$

(*) Size distributions & Cond. Curves

Evaporation

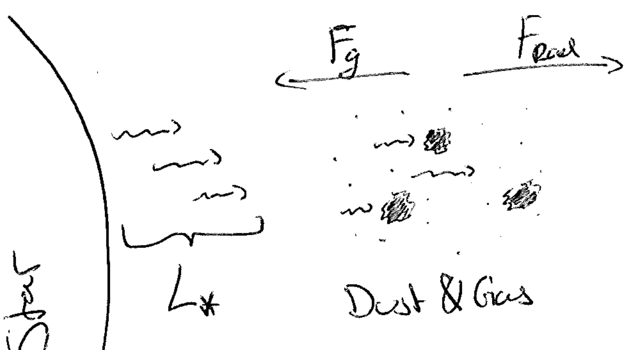
In phase equilibrium $G^+ = G^-$

$$\Rightarrow G^- = 4\pi r^2 \alpha \nu \mathring{n}_r n_{cl}$$

→ $\frac{\mathring{n}_r}{n} = \frac{1}{S}$: Supersaturation ratio

→ $S = \frac{p_r}{p_{vap}}$ ← Partial pressure, ← Vapor pressure

Dust driven Winds



⇒ Dust carries momentum over to gas!

Ratio of radiative and gravitaional acceleration:

$$\Gamma = \frac{(\kappa_d + \kappa_g) L_*}{4\pi c G M_*}$$

→ κ_d: Dust opacity (Planck mean op.)

→ κ_g: Gas opacity (")

→ L_*: luminosity

→ G: Gravitational constant

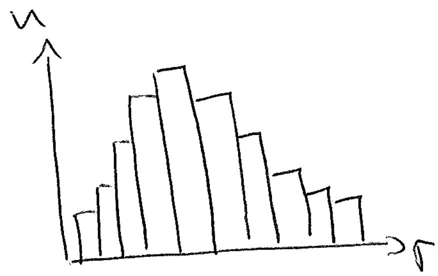
→ c: speed of light

→ M_*: Mass of the Star

*

Size distributions

Binning Method



→ Solve for each bin

→ Accurate but slow

Moment Method

$$\rho L_j = \int_{V_{min}}^{\infty} V^{j/3}\, \chi(V)\, dV$$

→ L_j: j^{th} moment

→ $\chi(V)$: Size distribution

$$\begin{cases} \rho L_0 = n_{cl} & \sqrt[3]{\frac{3}{4\pi}}\,\frac{L_1}{L_0} = \langle r \rangle \\ \sqrt[3]{36\pi}\,\frac{L_2}{L_0} = \langle A \rangle & \frac{L_3}{L_0} = \langle V \rangle \end{cases}$$

Commonly assumed size distributions

→ log-normal

→ gamma distribution

→ Monodisperse

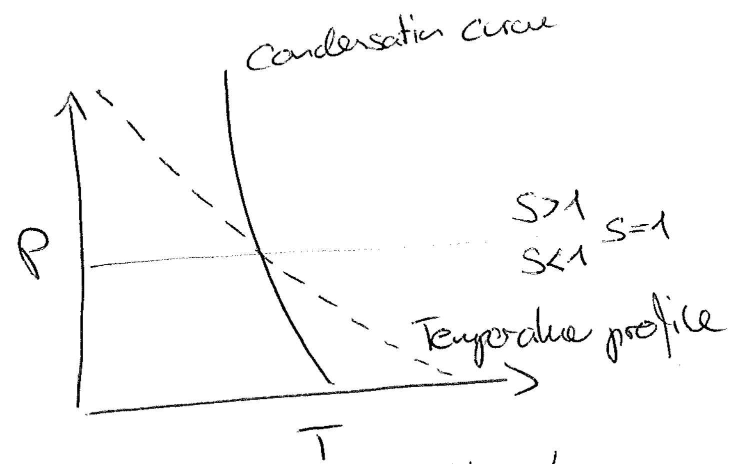
Condensation Curves

Recall: $S = \frac{P_r}{P_{vap}}$

→ $S > 1$: clouds form

→ $S = 1$: static

→ $S < 1$: Clouds evaporate



Once clouds can form they deplete the gas phase. Higher layers have less material to form clouds.

*: Show condensation curves

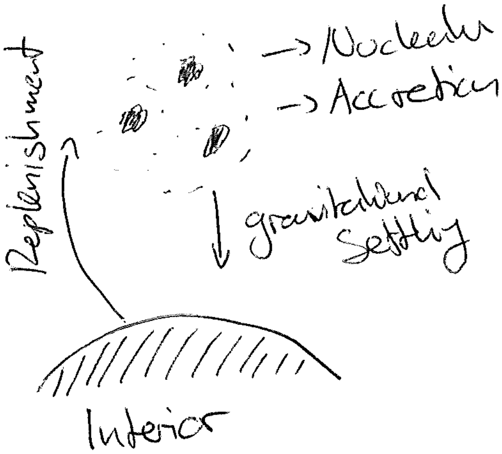
Dust transfers momentum onto the gas phase

$\Rightarrow$ Allows gas to surpass escape velocity

Important Materials: Al_2O_3, C, (TiO_2), Mg_2SiO_4

* show images of AGB Winds

Cloud formation in substellar atmospheres



Basic Equations:

$$\rho_a \frac{dq_c}{dt} - \frac{\partial}{\partial z} q_c \rho_a v_{dr} + \frac{\partial}{\partial z} K_{zz} \frac{\partial q_c}{\partial z} = m_n J_* + m_1 G$$

$$\rho_a \frac{dq_n}{dt} - \frac{\partial}{\partial z} q_n \rho_a v_{dr} + \frac{\partial}{\partial z} K_{zz} \frac{\partial q_n}{\partial z} = m_n J_*$$

$$\rho_a \frac{dq_v}{dt} + \frac{\partial}{\partial z} K_{zz} \frac{\partial q_n}{\partial z} = -m_n J_* - m_1 G$$

-> q_c: Mass Mixing Ratio (MMR) of clouds

-> q_n: MMR of CCNs

-> q_v: MMR of cloud material in gas

-> K_{zz}: Diffusion Constant

-> ρ_a: density of the atmosphere

-> v_{dr}: Settling velocities of cloud particle

-> m_n: Mass of 1 CCN

-> m_1: Mass of 1 addition during accretion

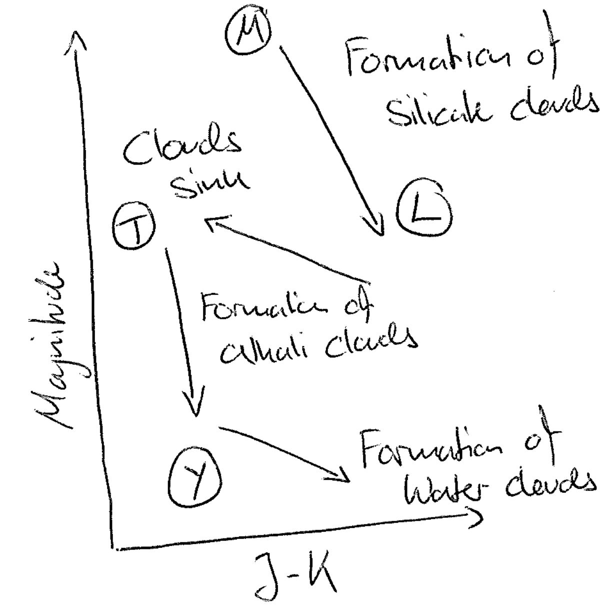
Important Materials:

-> Hot: TiO_2, VO, Fe, SiO, $MgSiO_3$, Mg_2SiO_4

-> Temperate: KCl, ZnS, Na_2S

-> Cold: H_2O, NH_3, CH_4, H_2S

L-T Transition



→ M: Star ⇒ no clouds

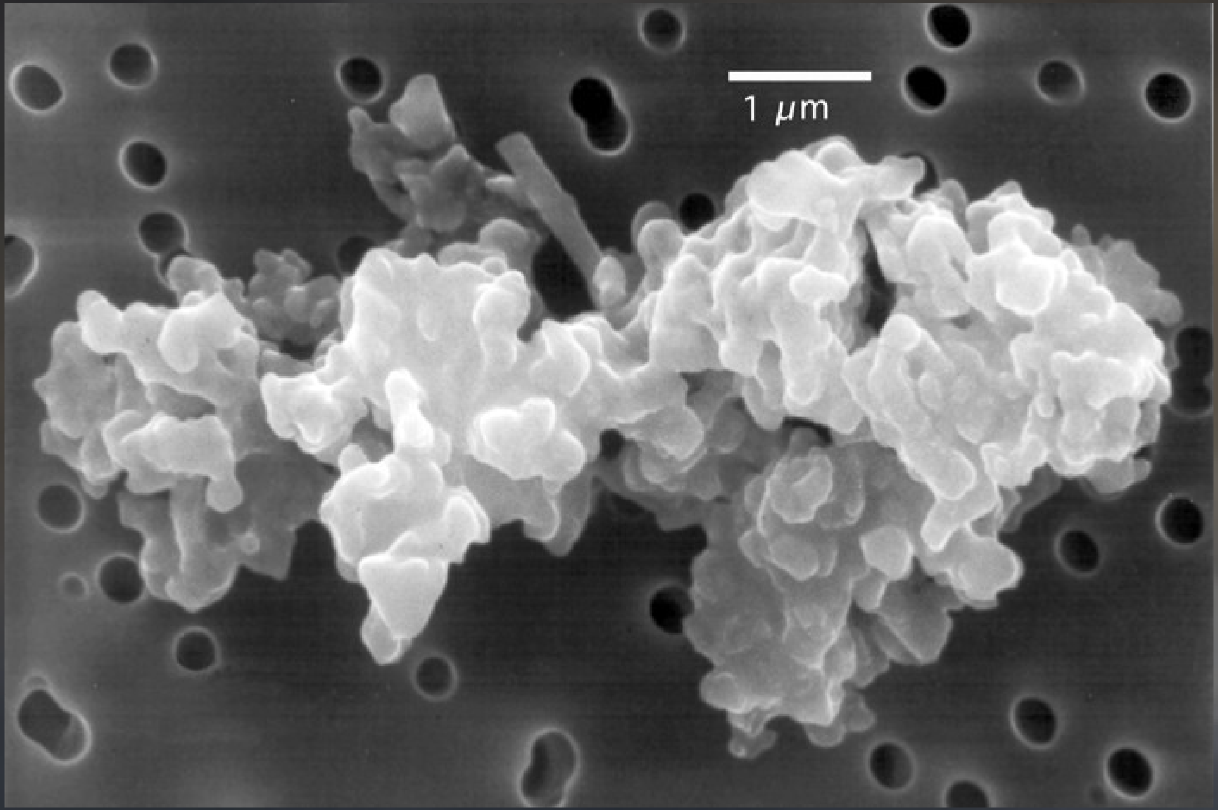
→ L: Brown dwarf with silicate clouds (Si)

→ T: Cloud free brown dwarf

→ Y: Brown dwarf with alkali clouds (Na, K)

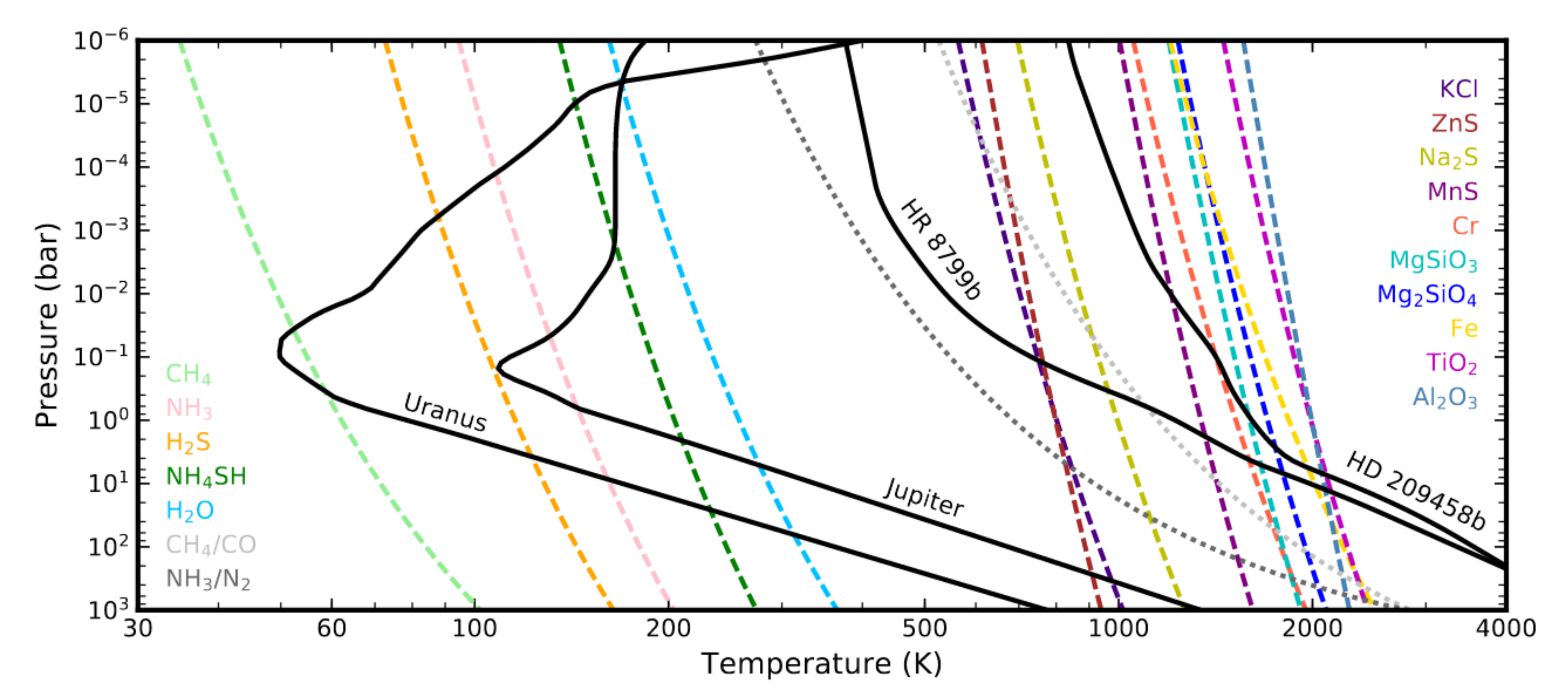
* Show images of Brown dwarf clouds

Cosmic dust



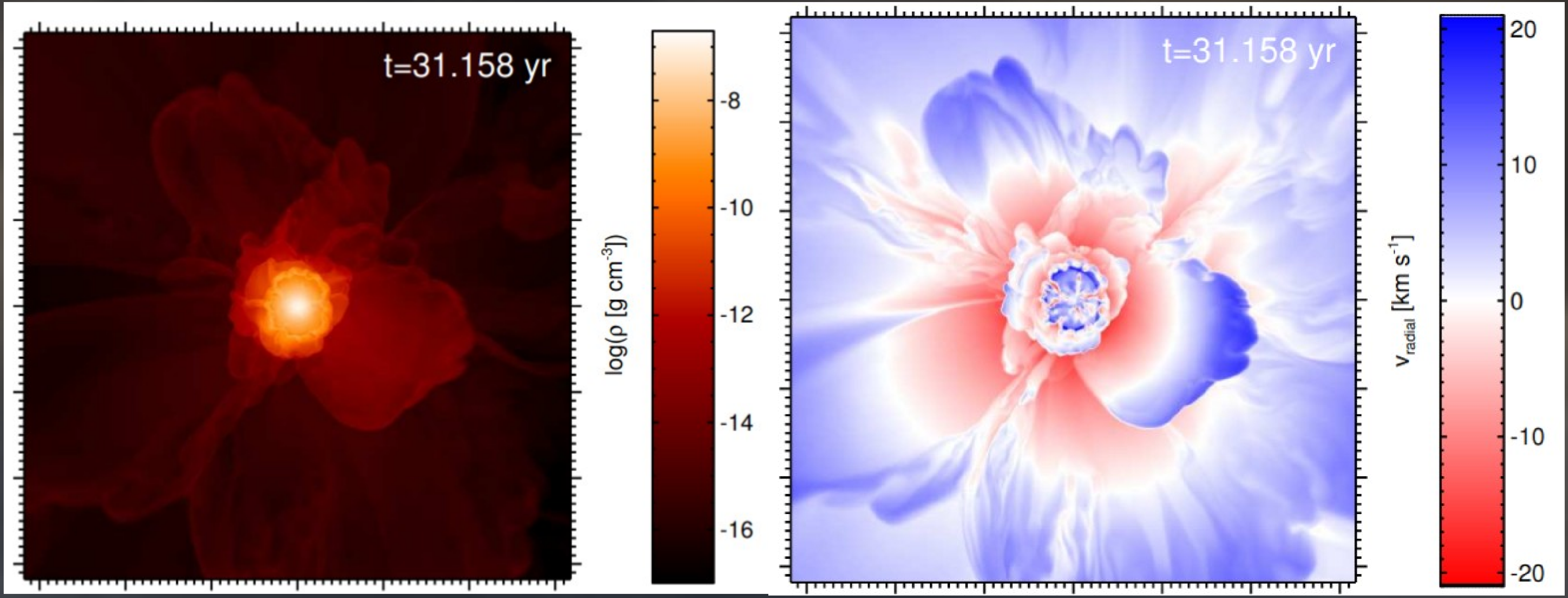
Jessberger et al. 2001

Condensation curves



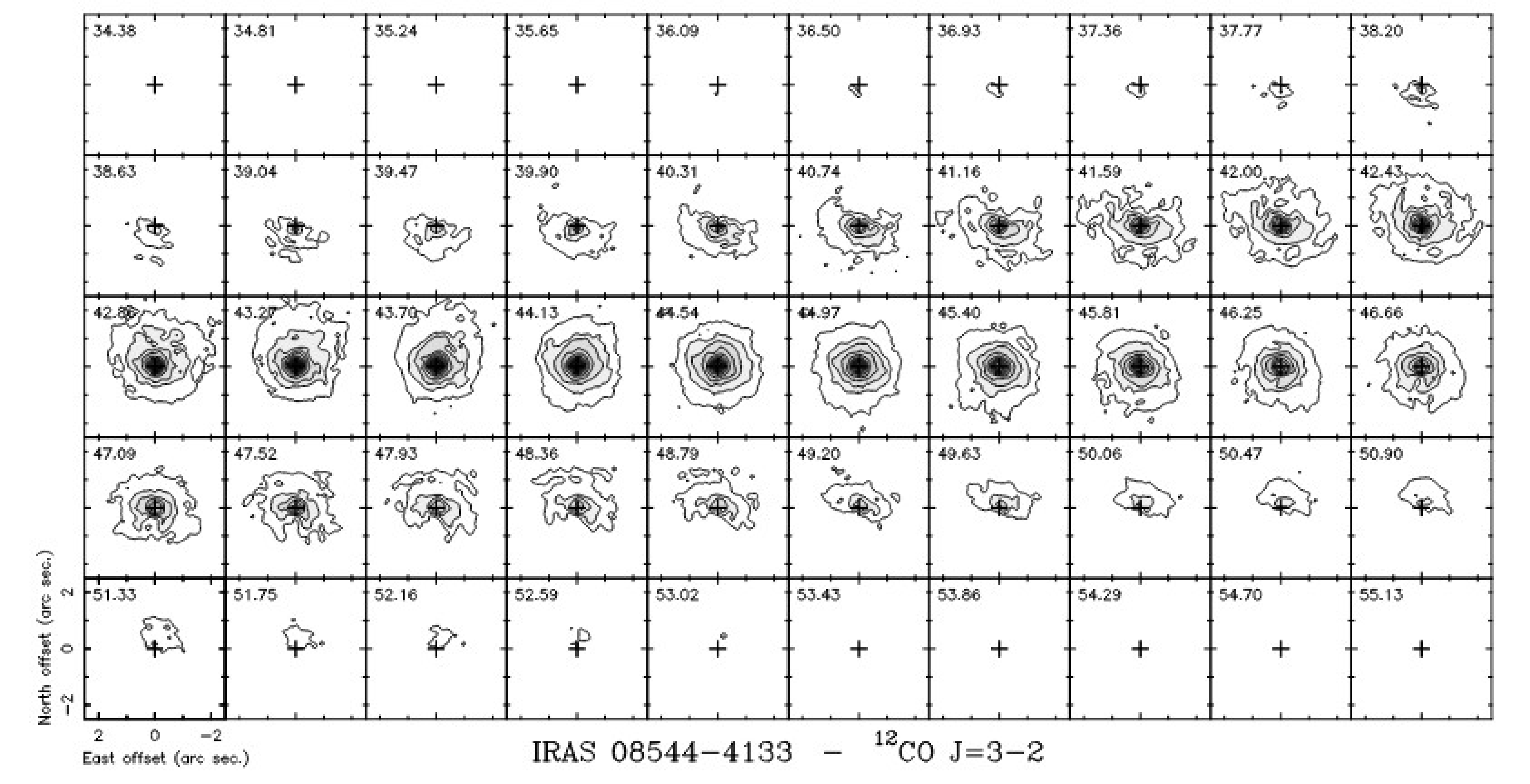
Gao et al. 2018

Simulations of AGB winds



Freytag & Höfner (2023)

Observations of AGB winds



Bujarrabal et al. (2018)

Observations of brown dwarf clouds

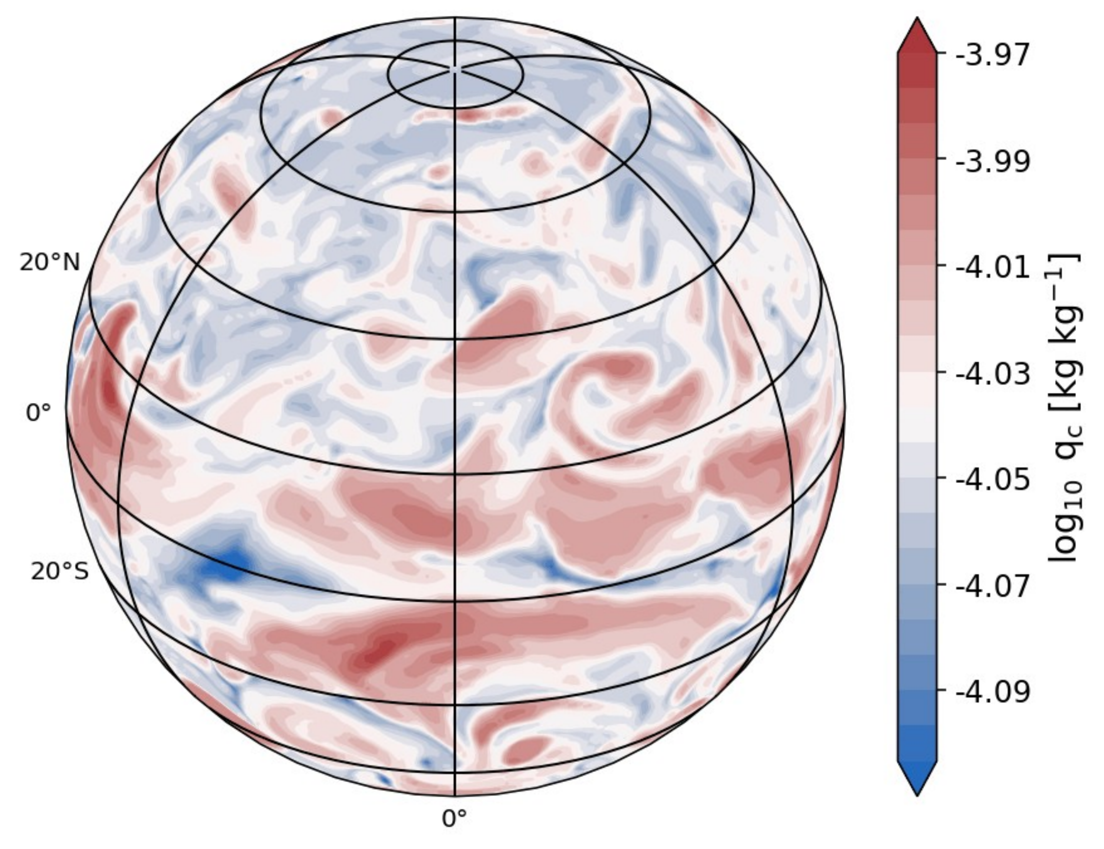
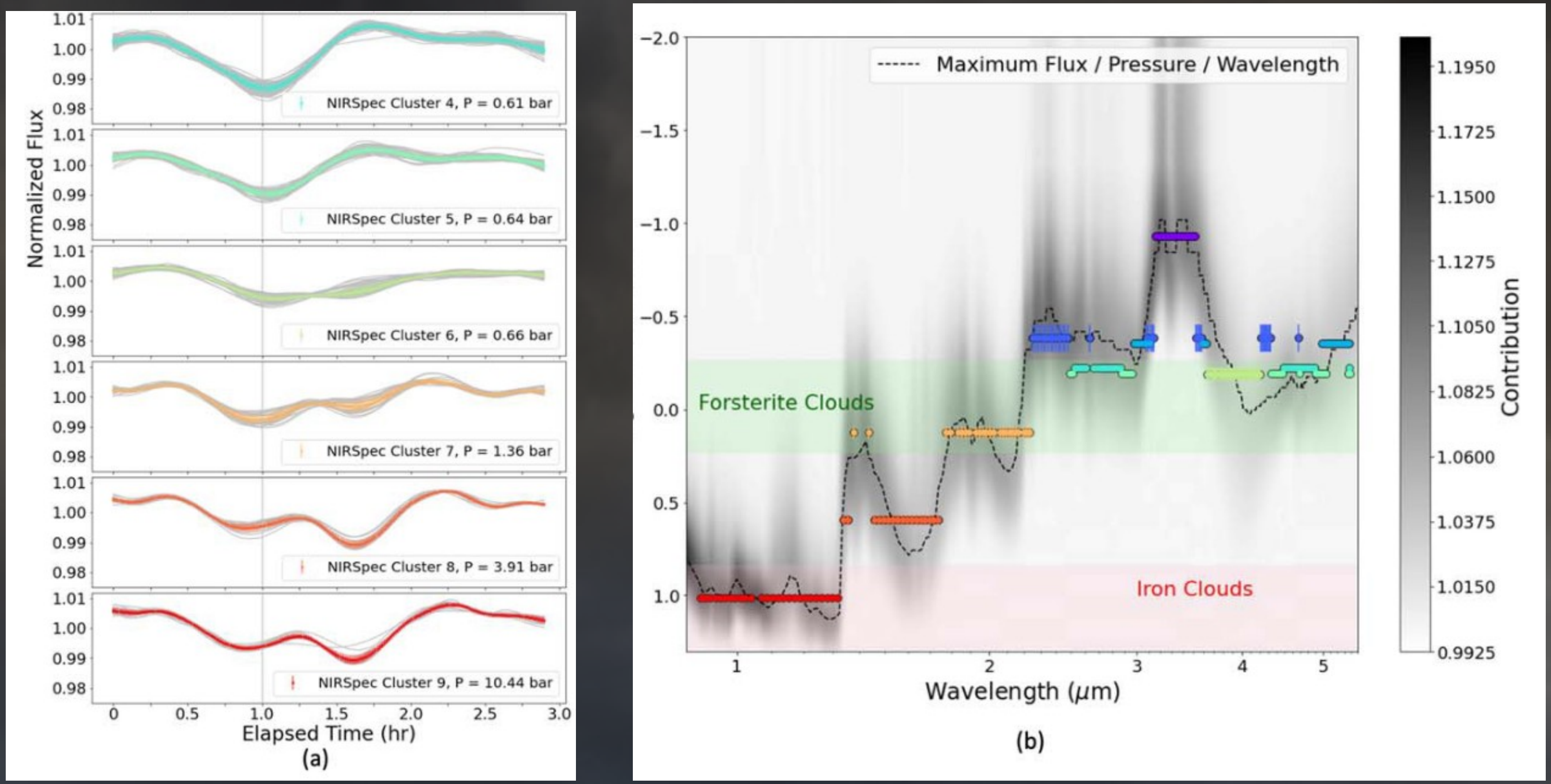


Image credit: Elsie Lee

Observations of brown dwarf clouds

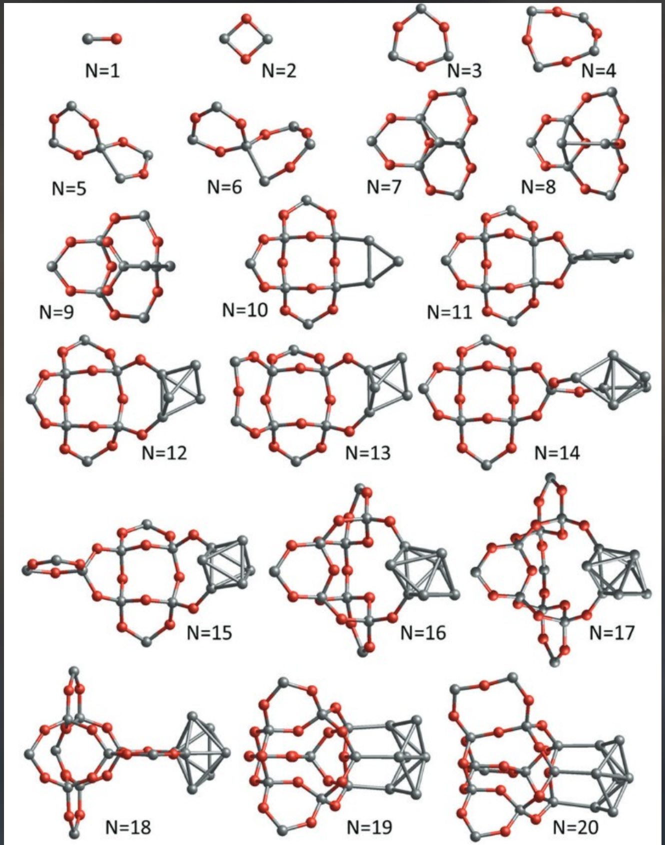


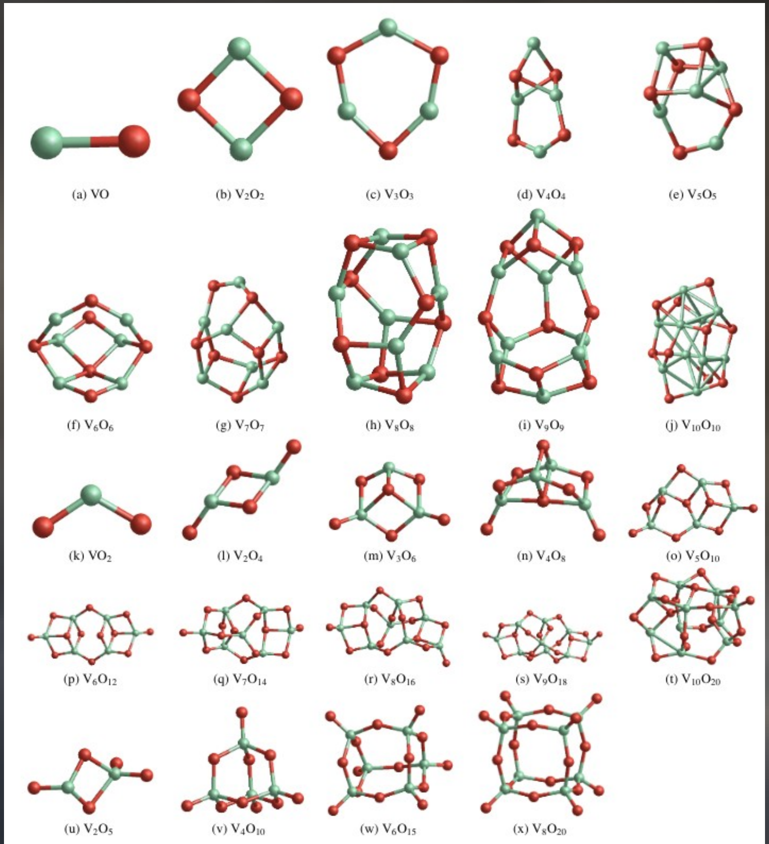
McCarthy et al. (2025)

Observations of Jupiter clouds

Image Credit: NASA / JPL-Caltech / SwRI / MSSS / Gerald Eichstadt / SEAN Doran

Cluster geometries





Bromley et al. 2016 // Lecoq-Molinos et al. 2024