Grain Evolution

Formation of Grains

Atoms → diatomic molecules (e.g., CH, CO, CN)
→ 10-20 atoms as condensation nuclei
→ growth by accretion

In HI clouds, n_H~10-100 cm^{-3} → molecules form too slow

Grains likely formed in (1) atmospheres of cool stars and (2) dark molecular clouds

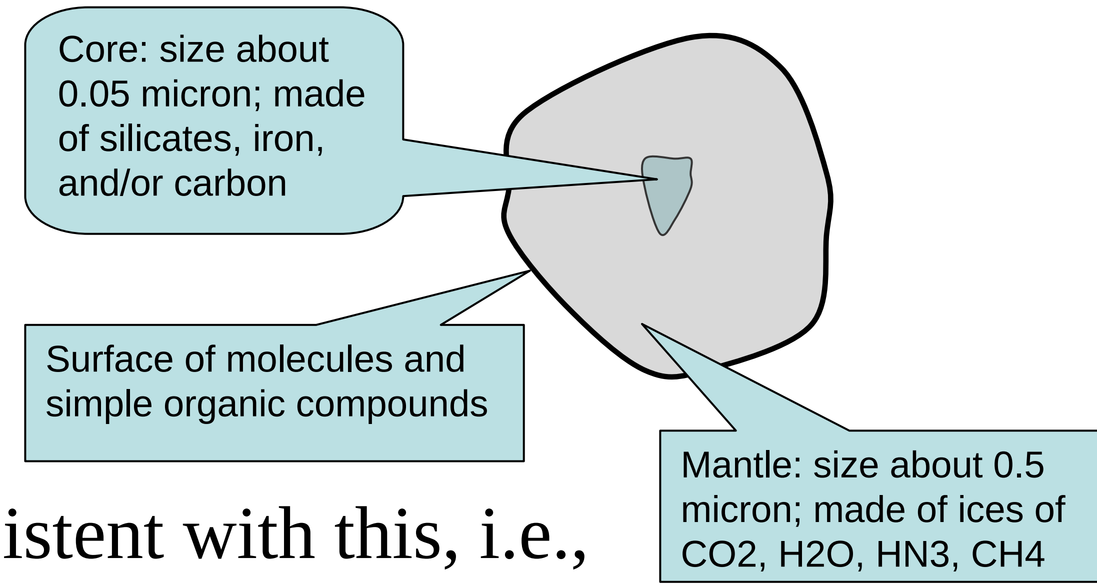
IR observations detected grains in both.

Generally, depletion of elements → grain formation
Those with higher condensation temperatures condense first, so condense/deplete more

With condensation nuclei (small, refractory particles), volatile materials such as CO_2, CH_4, NH_3, H_2O condense as mantles

http://cosmos.swin.edu.au/entries/dustgrain/dustgrain.html

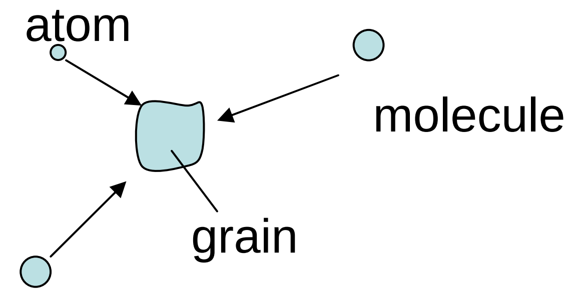
Dark clouds show grain size (> 1 μm) larger than typical ISM < 0.2-0.5 μm



C, N, O depletion consistent with this, i.e., they are locked into ices on the grains

ISM grain (nuclei, mantles) → grain growth → planetesimals

Grain Growth Rate



$$\frac{dm}{dt} = (\frac{1}{4} n\bar{v})(m_H\, A)\, \xi\, (4\pi a^2)$$

Sticking coefficient (probability) $\xi \lesssim 1$

$$\frac{dm}{dt} = \rho_s 4\pi a^2 \frac{da}{dt}$$

$$\begin{aligned}
\frac{da}{dt} &= \frac{(1/4) n\bar{v} m_H A\, \xi}{\rho_s} \\
&= \frac{v\rho_H}{4\rho_s} A\xi \\
&= \frac{10^5\, 1.6 \times 10^{-24}}{4 \cdot 1} A\xi \\
&= 4 \times 10^{-20}\, \mathrm{cm\ s^{-1}}\, A\xi \\
&= 15 \times 10^{-13}\, \mathrm{cm\ yr^{-1}}\, A\xi
\end{aligned}$$

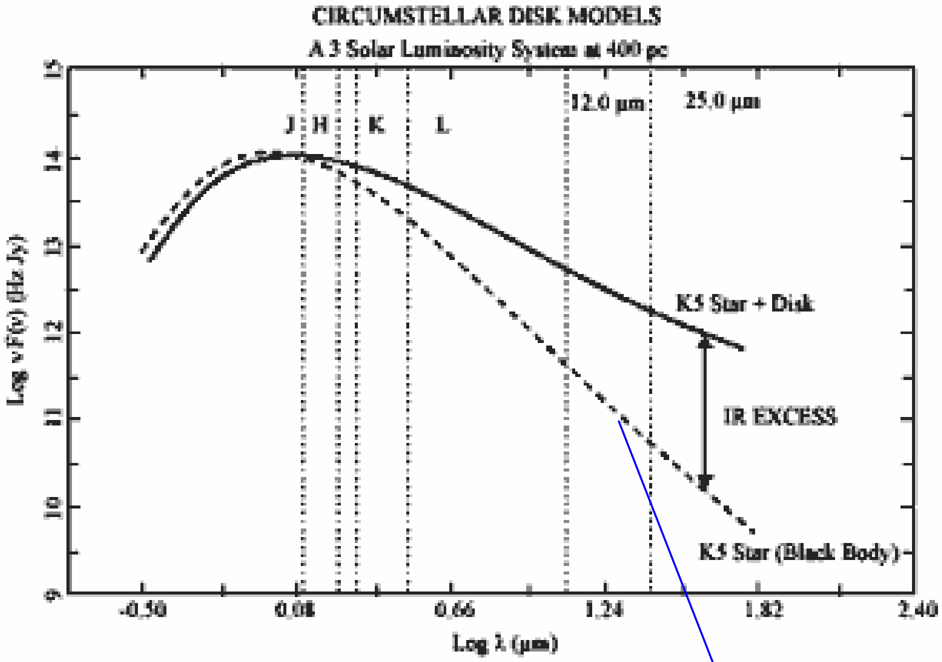
$$t = \frac{a}{da/dt} \sim \frac{10^{-5}}{1.5 \times 10^{-12} A\xi} \sim \frac{10^7}{1.5 A\xi}$$

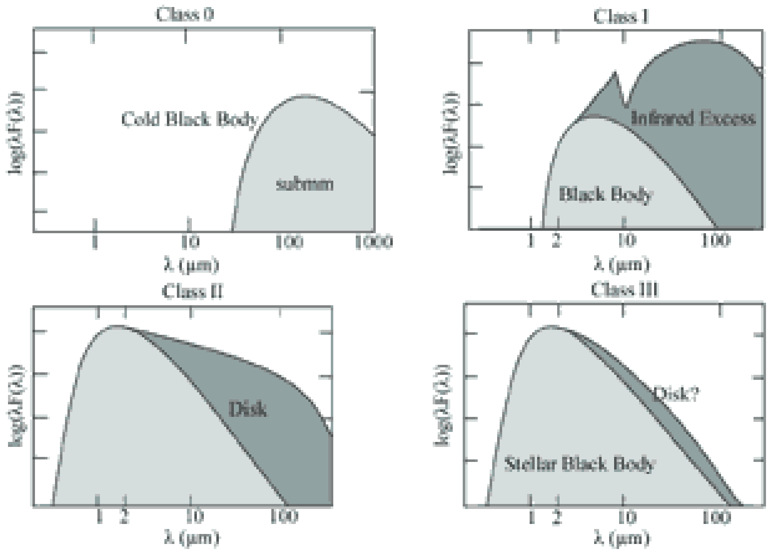
Take $A = 1$, $\xi = 1$, then $t = 10^7$–10^9 yr to grow to 0.1μm.

In a much denser environment, e.g., dark clouds, or the envelope of a cool star, the time scale is considerably shorter.

The initial nucleation is extremely slow; general diffuse ISM cannot do it ➔ Need high densities (1) star-forming regions (2) cool stellar atmospheres, (3) (super)novae or PNe: expanding gas shells

We indeed see evidence of dust in all these objects.





Stellar photosphere

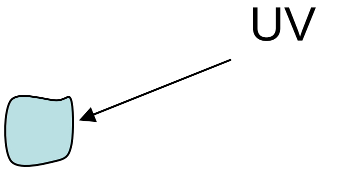
IR excess: reradiation of stellar radiation by heated circumstellar dust

A distribution of T_{dust} → superposition of bb spectra

Destroy of Grains

1) ***Evaporation***
CH_4: 20 K; NH_3: 60 K; H_2O: 100 K

2) ***Sputtering***
Maybe important in diffuse clouds; grains better shielded in dense clouds

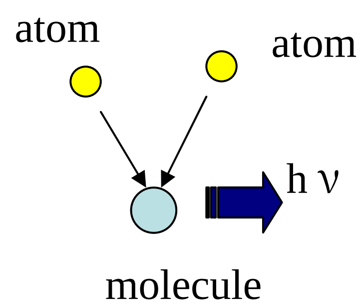


3) ***Grain-grain collision***
kinetic energy (a few km/s) → dust heated and evaporated; important in shocked media; may not be important in ISM otherwise

4) ***Heating***

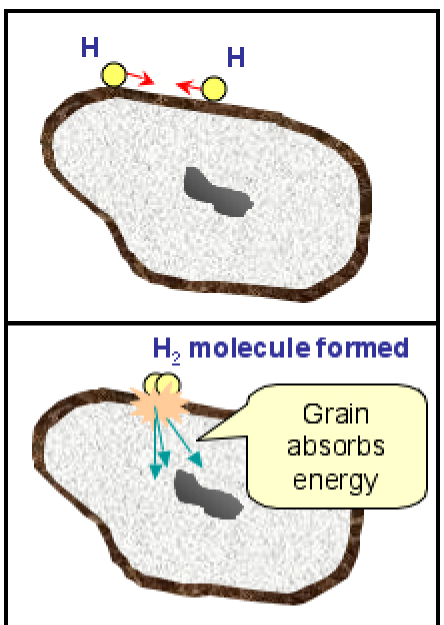
Formation of Molecules

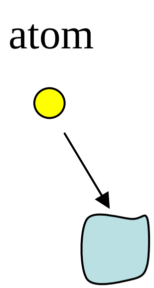
Grains catalyzes the reactions between atoms which otherwise do not meet together.



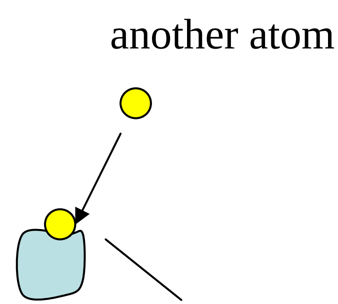
Two-body collision unlikely in ISM

Cannot form H_2 (no dipole)





Sticking, need ~ 1 keV to expel, which > general E_{kin} in HI clouds



Molecules form on surface; heated, binding energy = 4.47 eV

Take H_2 as an example (Ref: Hollenbach & Salpeter, 1971, ApJ, 163, 155)

Fraction of H atoms that stick: s

……………………… move across and find another H: ξ

…………………….... react: ζ

………………………. come off the grains: η

Overall, rate γ : fraction that hit and then make an H_2

$$\gamma = s \; \xi \; \zeta \; \eta$$

In the lab, $s \sim 1/3$, and for H, ξ , ζ , η all ~ 1

[# of H_2 formed s^{-1} cm^{-3}] = R $n_H\, n_H$

$$= (1/2) \quad \gamma\, n_H\, n_d\, v\, \pi a^2$$

2 atoms

where R [$cm^3\ s^{-1}$]

$$n_d \frac{4}{3}\pi a^3 \rho_s = \rho_d = \frac{\rho_{gas}}{100} = \frac{10 \times 1.6 \times 10^{-24}}{100}$$

$$R = (1/2) \quad \gamma\, n_d / n_H\, v\, \pi a^2$$

$$= (1/2)\ 1/3\ (4 \times 10^{-12})/10\ (10^5)\ \pi\ (2 \times 10^{-5})^2$$
$$= 10^{-17}\ cm^3\ s^{-1}$$

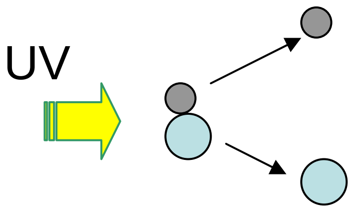
Time scale for H_2 formation is $(R\, n_H)^{-1} = 10^{17}/n_H$ [s]

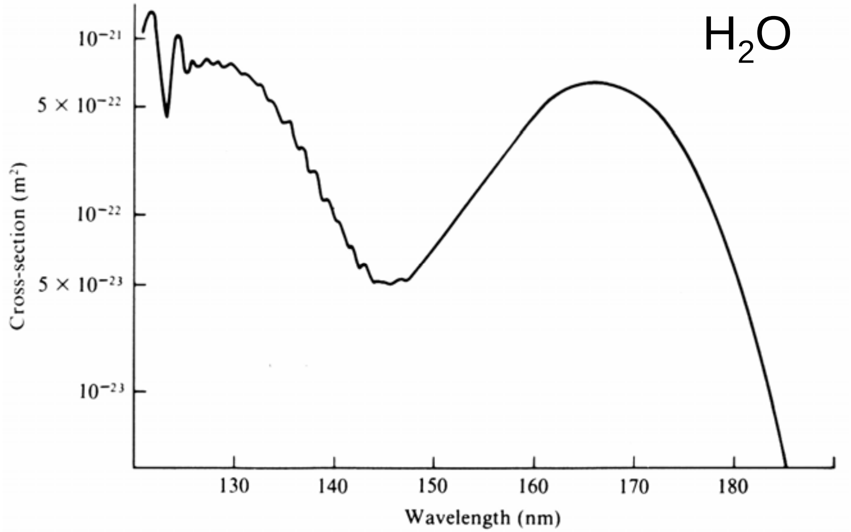
$= 3 \times 10^9/n_H$ [yr]

e.g., for $n_H = 100\ cm^{-3}$, then $(R\, n_H)^{-1} \sim 3 \times 10^7$ yr

Ref: Kaplan & Pikelner

Dissociation of Molecules





$$\sigma_{dis} \sim 10^{-20} - 10^{-18}\ \mathrm{cm}^2$$

General ISM stellar radiation is equivalent to 10,000 K diluted by $W \sim 10^{-14}$

$$I = W\,\sigma_B\,T^4$$

# of photons s^{-1} cm^{-2} = $\dfrac{I}{h\nu} = \dfrac{W\,\sigma_B\,T^4}{h\nu}$

# of dissociation s^{-1} = $\dfrac{W\,\sigma_B\,T^4}{h\nu}\sigma_{dis} \approx (1/3) \times 10^9\ \mathrm{s}^{-1}$

$\tau_{dissociation} \sim 3 \times 10^9$ s ~ 100 yrs

So it takes some 10^7 years to form an H_2 molecule, but it get destroyed in 100 years.

➔ need shielding!