Transformational Science with ALMA: Through Disks to Stars and Planets

Distributions of Hot Molecules in Young Circumstellar Disks

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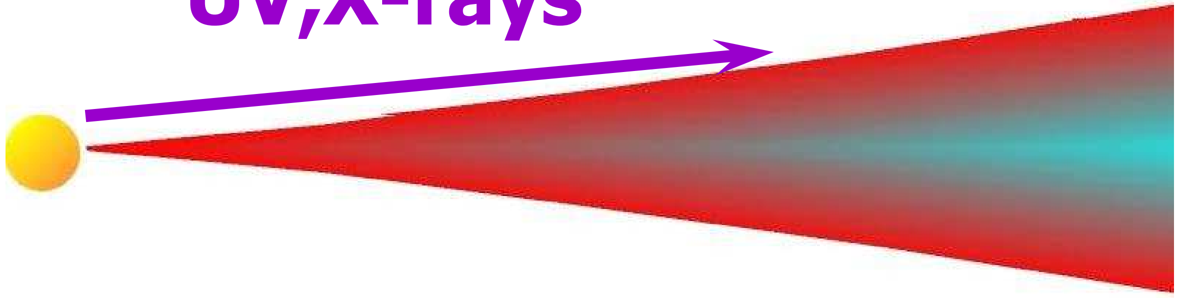
1 Introduction

Chemical Structure of Young Disks



Optical,
UV,X-rays

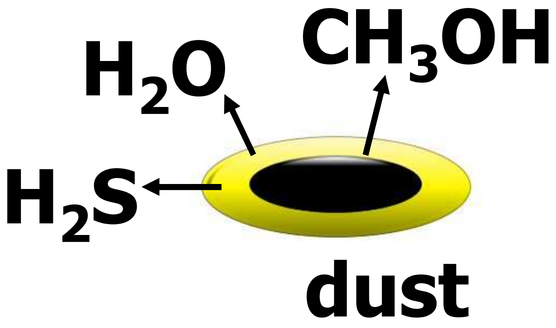
dust & gas
heating

outer disk
gas-phase

CN, C_2H
HCN, H_2CO
H_3^+, H_2D^+
etc.

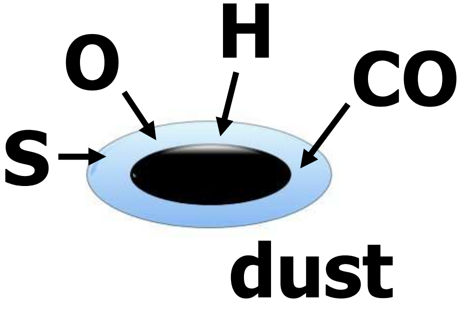
surface
↕
midplane

inner disk
hot



→ ALMA observations

outer disk
near midplane
cold, dense

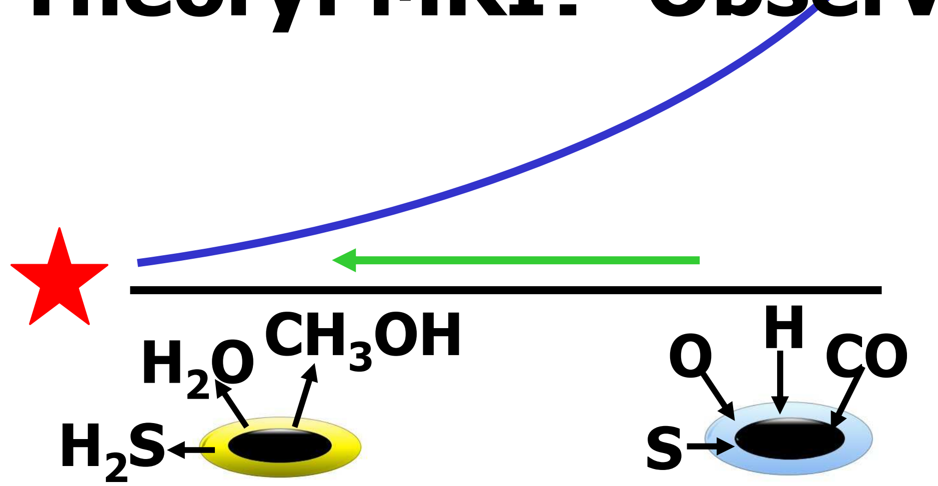


Disk Accretion & Chemistry

Disk Accretion:

gas disk dispersal
gaseous planet formation,
migration of (proto)planets

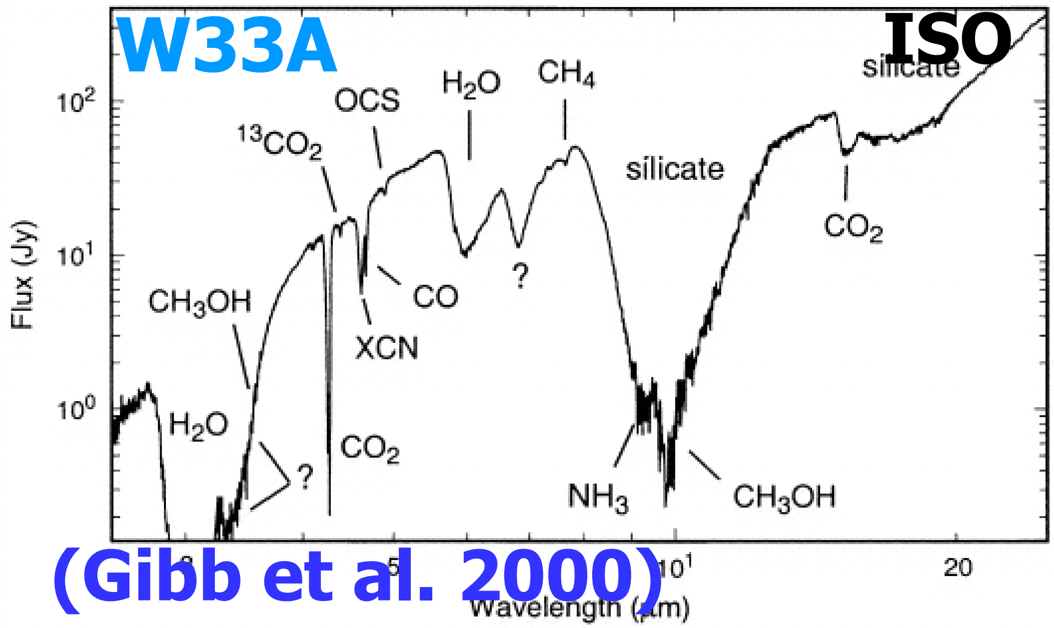
⟷ **Theory: MRI? Observation?**



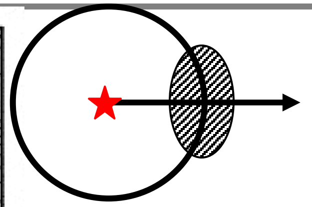
Icy mantle evaporation ⟶

observational diagnosis of disk accretion?

Obs. of Solid & Gas-Phase Molecules

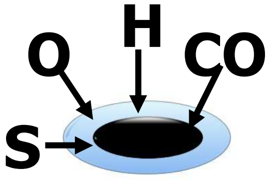


(Gibb et al. 2000)



Obs.

cold, dense

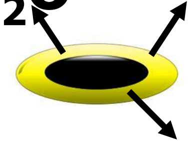


$O \xrightarrow{H} H_2O$

$S \rightarrow H_2S$

$CO \rightarrow CH_3OH$

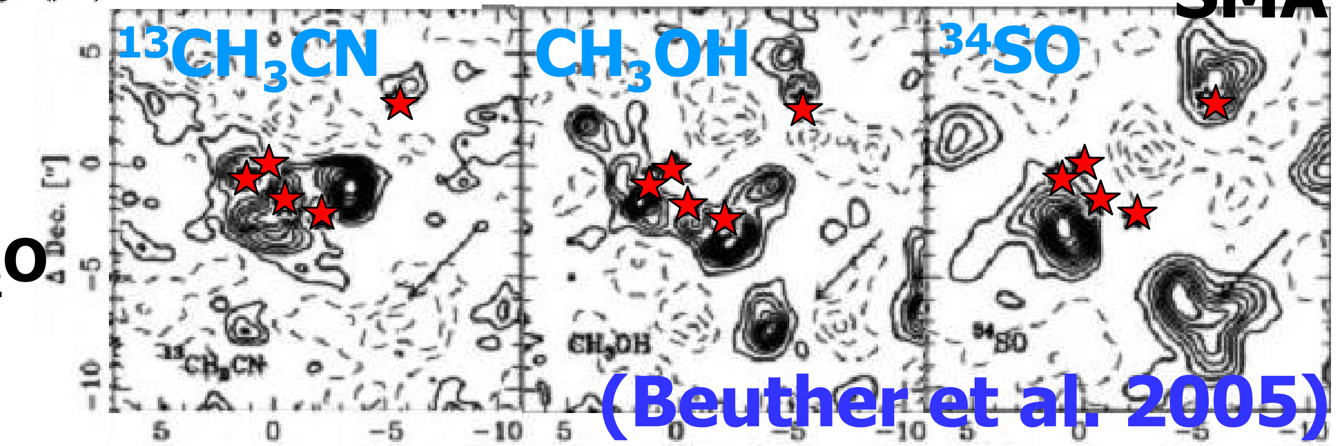
hot



H_2O

$CH_3OH \rightarrow (CH_3)_2O$

$H_2S \rightarrow SO, SO_2$



(Beuther et al. 2005)

NH_3, H_2S, CH_3OH, HCN, SO, SO_2, $(CH_3)_2O$: abundant

Obs. of Molecular Abundances

Molecules	Orion Hot Core	AFGL 2591	TMC1
H_2O	1.0(-5)	3.6(-5)	
H_2S	$\leq$ 5.0(-6)	$\leq$ 1.0(-4)	2.5(-10)
SO	1.5(-7)	2.0(-8)	2.5(-9)
SO_2	9.4(-8)	6.3(-7)	5.0(-10)
NH_3	1-10(-6)	2.0(-8)	1.0(-8)
HNC	3.0(-7)	3.0(-7)	1.0(-8)
CH_3CN	7.8(-9)	2.0(-8)	5.0(-10)
CH_3OH	1.0(-6)	8.0(-8)	1.0(-9)

(from Charnley et al. ‘92, Charnley ‘97, Ikeda et al. ‘01, Doty et al. ‘02, Lee et al. ‘96)

Disk Accretion & Chemistry

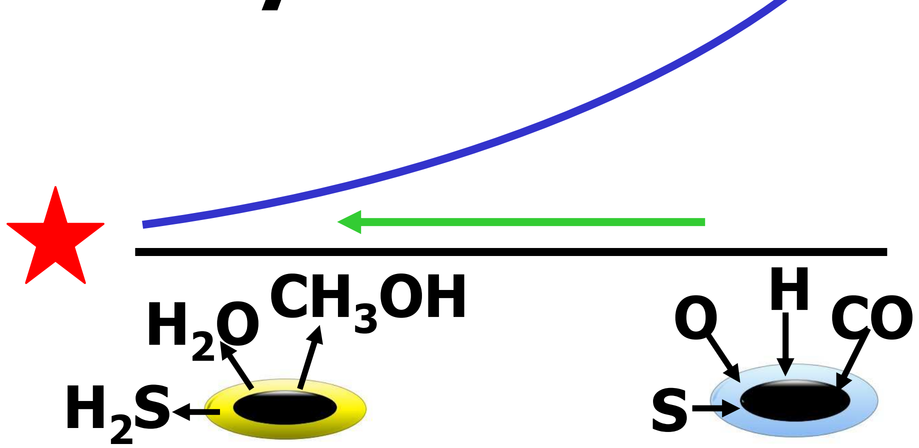
Disk Accretion:

gas disk dispersal

gaseous planet formation,

migration of (proto)planets

↔ Theory: MRI? Observation?



Icy mantle evaporation →

observational diagnosis of disk accretion?

2 Models

Gas, dust temp. & density profiles

gas dens.: **hydrostatic equilibrium**

($M_* = 2.5\ M_s$)

surface dens.: steady accretion model

$dM_{acc} = (0.5\text{-}20) \times 10^{-8} M_s/yr$ (=const.)

gas temp.: **local thermal equilibrium**

Γ_X : X ray heat., Γ_{pe} : FUV heat., Λ_{line} : radiative cooling, L_{gr} : gas-grain collisions

dust temp.: **local radiative equilibrium**

(irradiation($T_* = 10000K$), viscous heating)

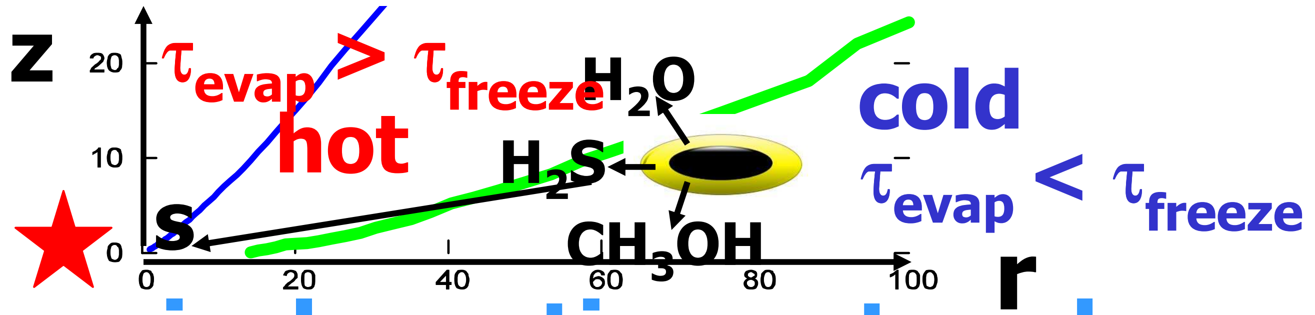
dust dens.: **coagulation equation for settling dust particles**

(Nomura et al. 2007)

Chemical Model

Chemical kinetic models

$$\frac{d\left(n_{\alpha} v_{\alpha}\right)}{ds} = \sum_{\beta} A_{\alpha\beta} n_{\beta} + \sum_{\beta,\gamma} B_{\alpha\beta\gamma} n_{\beta} n_{\gamma}$$



Chemical reaction network :

209 species, 2203 gas-phase reactions

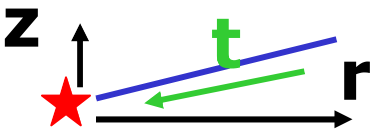
Initial condition: ice evaporation

CH_4, C_2H_2, C_2H_4, C_2H_6, CO, CO_2, O_2,
H_2O, H_2CO, CH_3OH, C_2H_5OH, N_2,
NH_3, H_2S, OCS

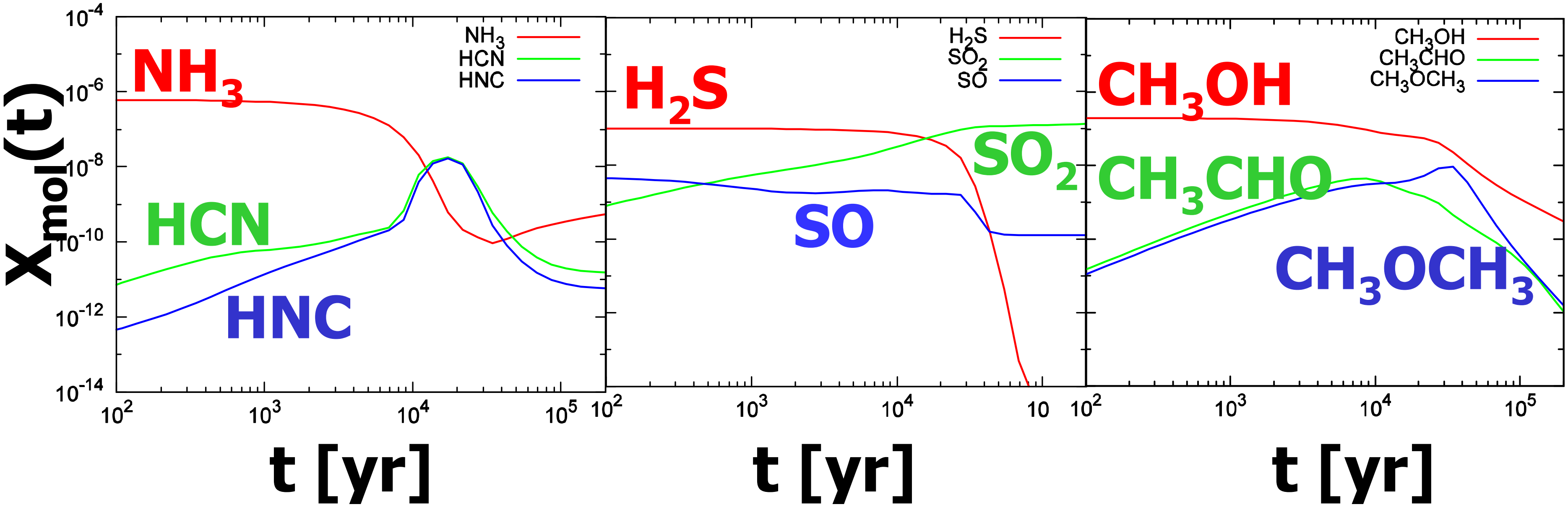
(Nomura & Millar 2004)

3 Results

Time evolution of Mol. Abundances



$dM_{acc}=1x10^{-8}Ms/yr$, z=1.5H



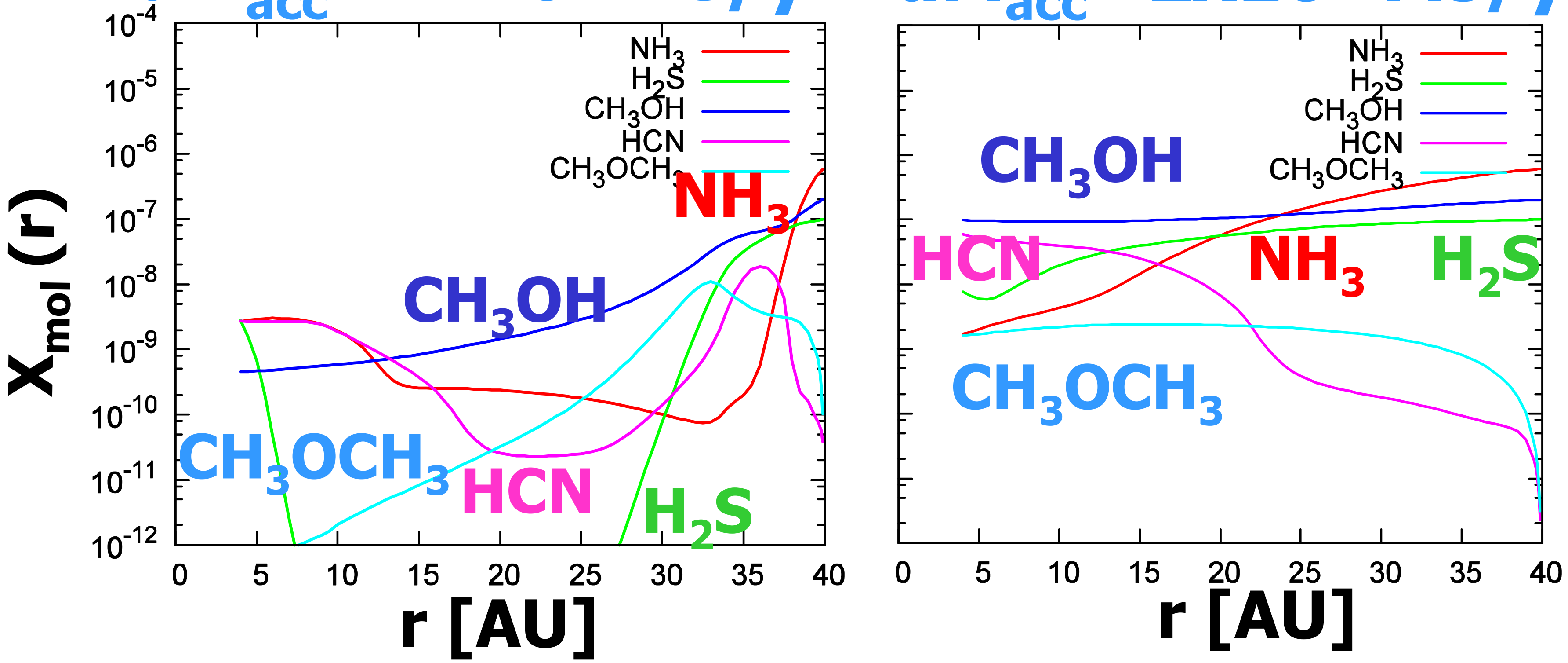
Parent species(CH_3OH, H_2S)

→Daughter species (CH_3OCH_3, SO_2 etc.)

timescale : t~10^{4-5}yr

Spatial Distributions of Molecules

z=1.5H



$dM_{acc}=1x10^{-8} Ms/yr$ $dM_{acc}=2x10^{-7} Ms/yr$

$dM_{acc}=1x10^{-8} Ms/yr$ ($\tau_{acc} > \tau_{react}$)

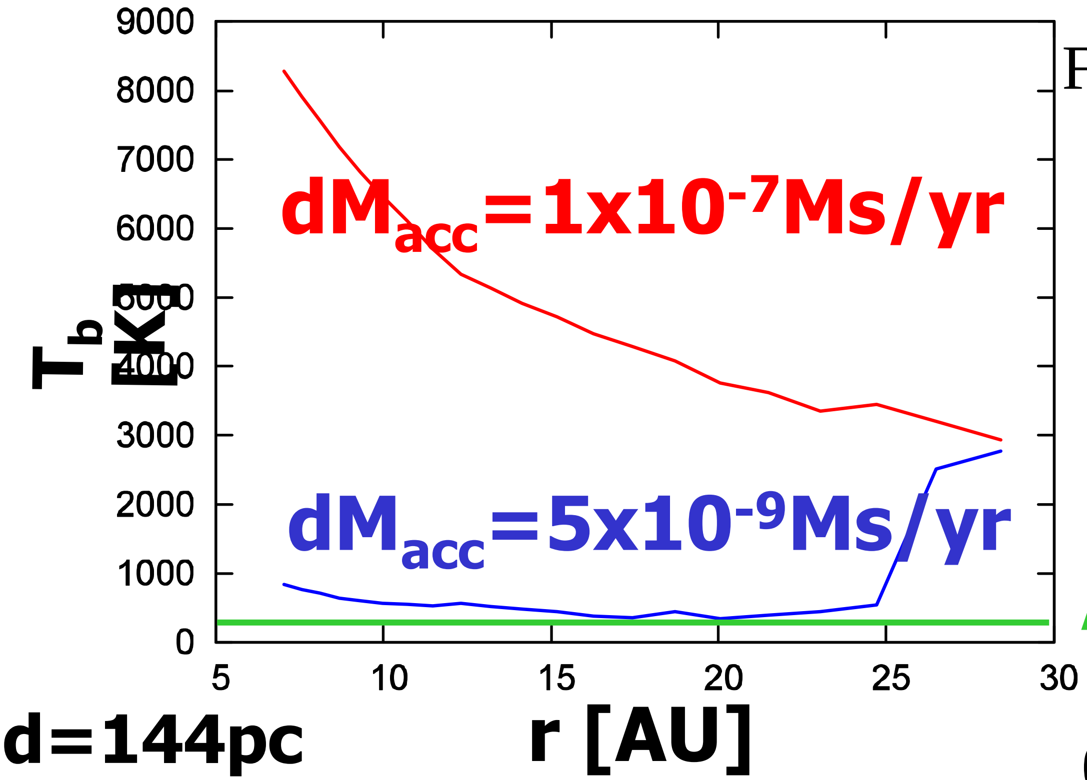
: high abundances only at large r

$dM_{acc}=2x10^{-7} Ms/yr$ ($\tau_{acc} < \tau_{react}$)

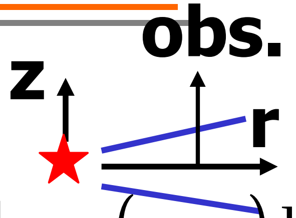
: parents: uniform, daughter: high at inner

Spatial Distribution of Line emission

CH_3OH: $J_K=7_{-1} \rightarrow 6_{-1}$ @338GHz



d=144pc



$$F_{ul,r} = \int_{-z_\infty}^{z_\infty} n_u A_{ul} \frac{h\nu_{ul}}{4\pi} \exp(-\tau_{ul}) dz$$

n_u: LTE distribution

(Hogerheijde & van der Tak 2000, Schoier et al. 2005)

ALMA 5σ detections

10 antennas, 1km/s, 0".1, 600s

Dependence of spatial distribution of line emission on accretion rate

→ Observable by ALMA

Spatial Distribution of Line emission

$$F_{\mathrm{ul,obs}} = \frac{1}{\pi \Theta^2_{\mathrm{beam}}} \int 2\pi\, r\, F_{\mathrm{ul,r}} \exp\left(-r^2/\Theta^2_{\mathrm{beam}}\right) dr$$

CH_3OH: $J_K=2_1 \longrightarrow 1_1$@97GHz

Θ_{beam}=12".5 (~1800AU)

T_b~3.1mK (r<30AU)

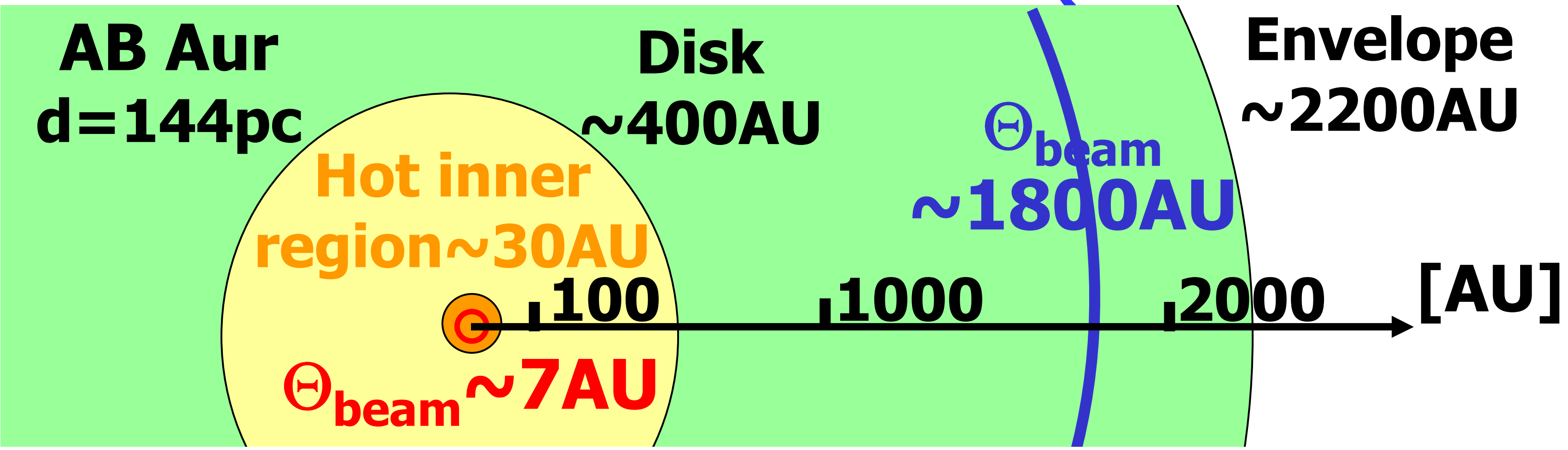
↔ **Non-detection with IRAM30m**

Θ_{beam}=0".05 (~7AU)

T_b~130K

Beam dilution effect

(Semenov et al. 2005)



4 Summary

Distribution of hot molecules in inner region of young circumstellar disks

(evap. of ice + gas-phase reactions)

Timescale of chemical reactions: ~$10^{4\text{-}5}$yr

accretion time > $10^{4\text{-}5}$yr

→high abundances only at large r

accretion time < $10^{4\text{-}5}$yr

→parents: uniform, daughter: high at inner

Dependence of accretion rate on spatial distribution of line intensity

→ Observable by ALMA ?

Chemical Model

Initial Condition

Inject mantle molecules into gas

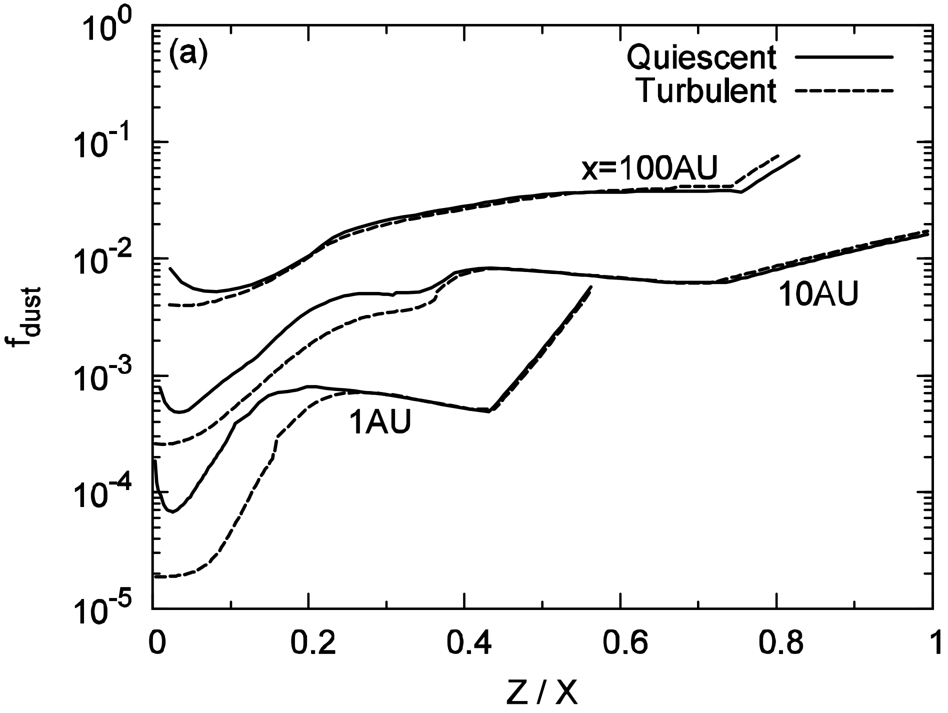
if $\tau_{\mathrm{evap},\, i} < \tau_{\mathrm{freeze},\, i}$;

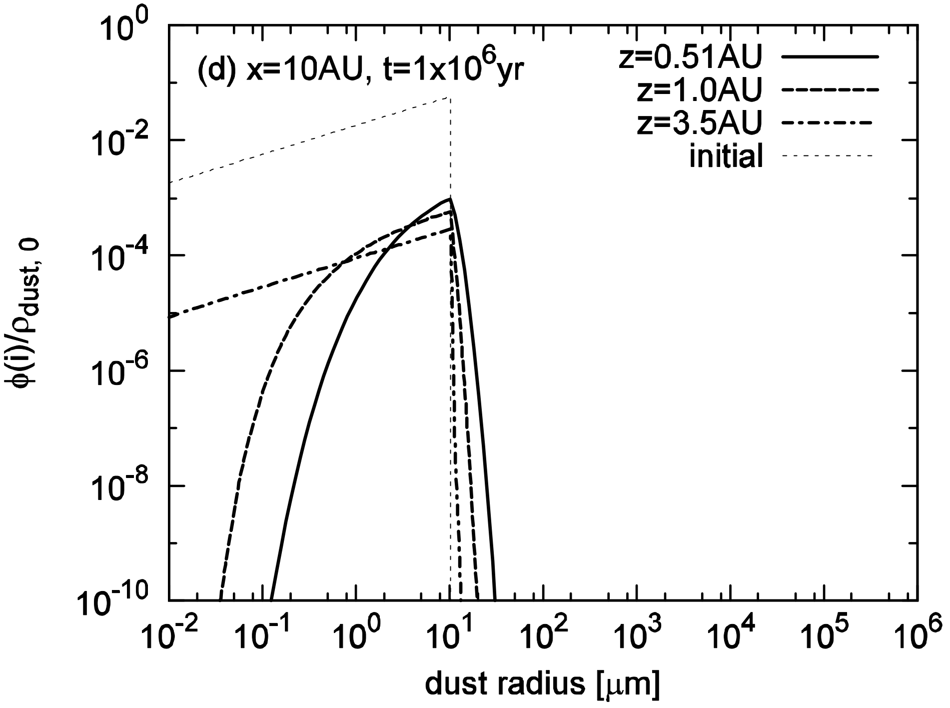
$$\tau_{\mathrm{evap},\, i} = \nu_{0,i}^{-1} \exp(E_{b,i}/kT_d)$$

$E_{b,i}$: binding energy

$$\tau_{\mathrm{freeze},\, i} = (S\pi a^2 d_g n v_i)^{-1}$$
$$\sim 10^9\ \mathrm{yr} / n\ [\mathrm{cm}^{-3}]$$

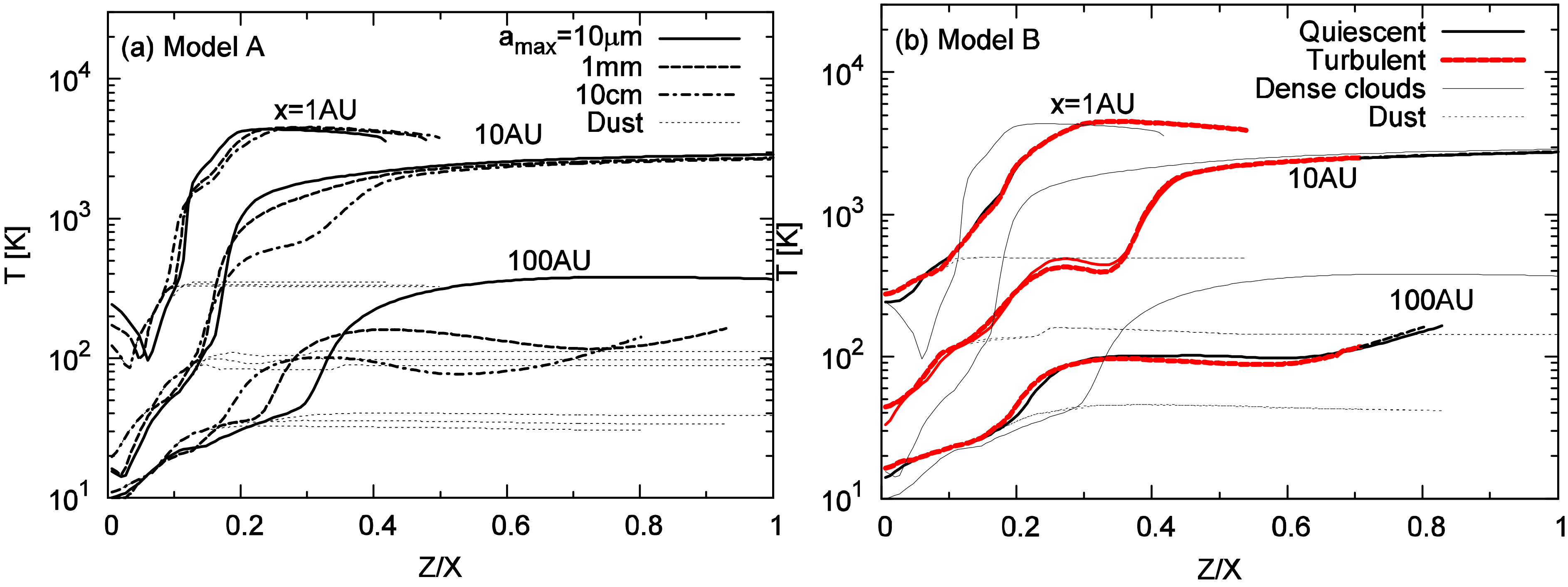
Dust Distribution





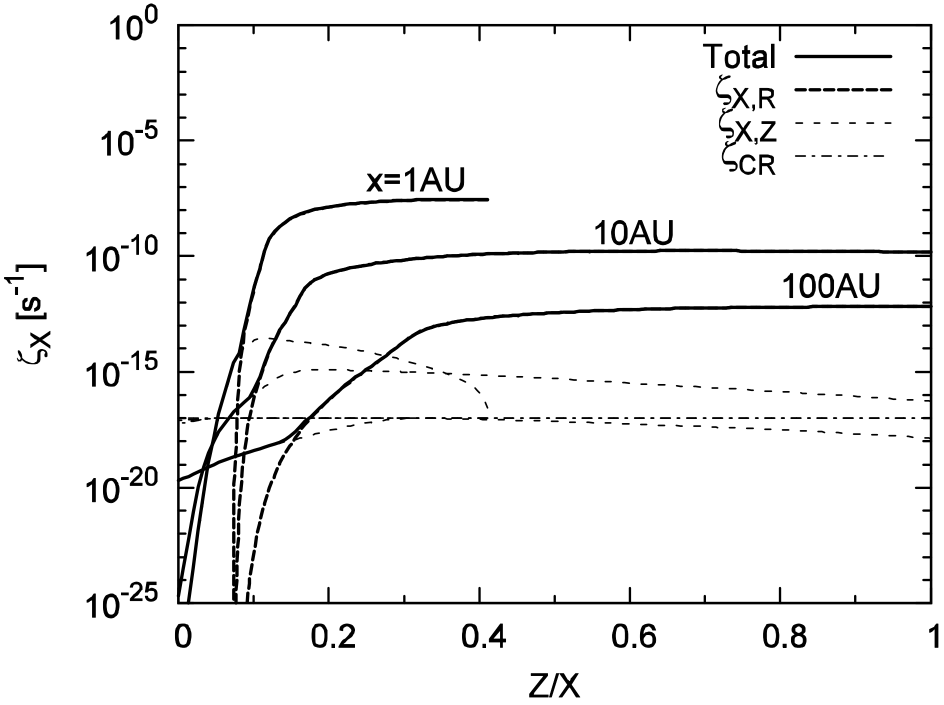
(Nomura et al. 2007)

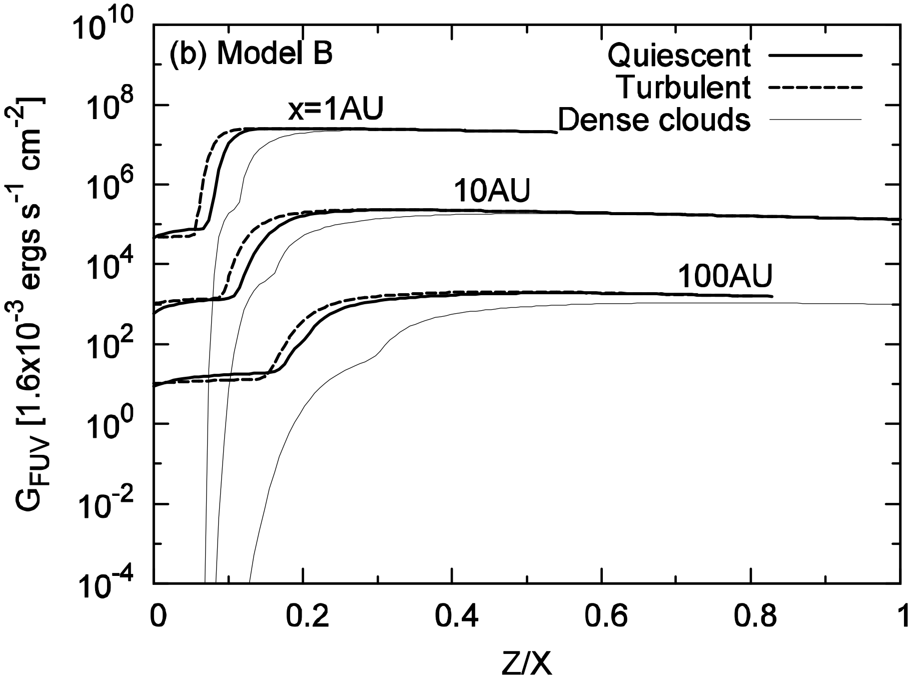
Temperature Profiles



(Nomura et al. 2007)

X-rays & UV radiation fields





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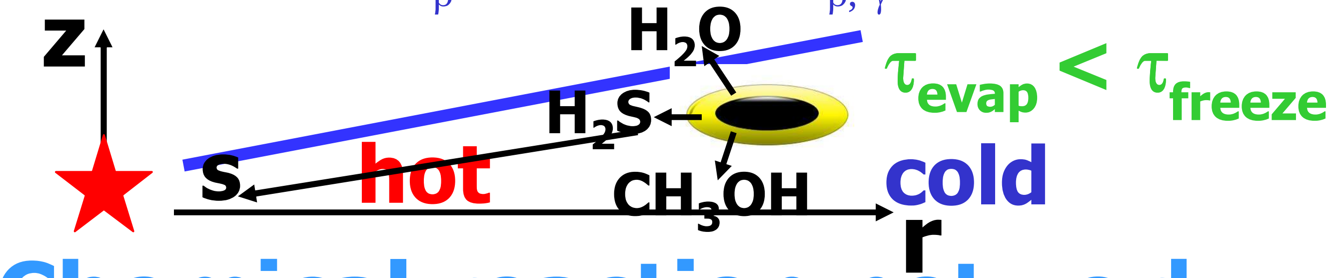

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