Disks in Young Stellar Objects

- IR excess due to disk emission

lack of correlation $A_V \leftrightarrow$ IR excess
near-IR excess correlation with accretion
indicator: veiling
HST images: proplyds and silhouettes in Orion
scattered light images
HST images: flared disks
mm images, dust
mm images, molecules, Keplerian velocity
$\Rightarrow$ disk in central potential of star

Millimeter observations and models

- Disk masses from mm observations and parametric models

Assumptions

absorption and emission due to dust particles
(same dust/gas ratio as ISM, $\approx$ 1 %)
optically thin
vertically isothermal

$T = T_0 (R/R_0)^{-q}$
$\Sigma = \Sigma (R/R_0)^{-p}$, p $=3/2$ (Hayashi)

Millimeter observations

Flux from annulus at R inclined by i to the line of sight at distance d

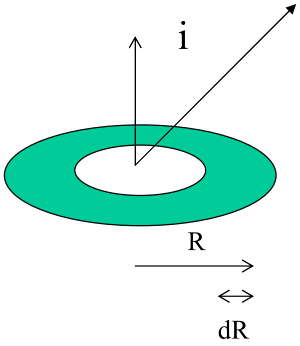
$$dF_\nu = I_\nu d\Omega = I_\nu \left(\frac{2\pi R dR}{d^2}\right) \cos i$$

where the specific intensity is

$$I_\nu = B_\nu(1 - e^{-\tau_\nu/\cos i}) \sim B_\nu \tau_\nu / \cos i$$

and the optical depth

$$\tau_\nu = \kappa_\nu \Sigma$$



Millimeter observations

Total flux is

$$F_\nu = \frac{2\pi}{d^2} \int_{R_1}^{R_2} B_\nu(T(R))\Sigma(R)\kappa_\nu R \mathrm{d}R$$

- Dependence on frequency: B_ν and → dust opacity κ_ν

- With the disk mass,

$$M_d = \int_{R_1}^{R_2} 2\pi \Sigma R \mathrm{d}R$$

$$\nu F_\nu = \frac{4k\nu^3}{c^2}\kappa_\nu M_d T(R_d)\left(\frac{2-p}{2-p-q}\right)$$

with $R_2 = R_d$ and $R_1 << R_2$.

Millimeter observations

$$\nu F_\nu = \frac{4k\nu^3}{c^2}\kappa_\nu M_d T(R_d)\left(\frac{2-p}{2-p-q}\right)$$

- $F_\nu, \kappa_\nu, p, q \rightarrow M_d$
- If $\kappa_\nu = \kappa_0(\nu/\nu_0)^\beta = \kappa_0(\lambda_0/\lambda)^\beta$,

$$\nu F_\nu \propto \nu^{3+\beta}$$

$\Rightarrow$ slope of the SED in the mm $\rightarrow$ frequency dependence of dust opacity

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Millimeter observations and models

- Most used (Beckwith et al 1990) dust opacity $\kappa_0 = 0.1\text{cm}^2\text{gr}^{-1}$ at $\lambda_0 = 250\mu\text{m}$
- $M_d \sim 0.01 - 0.1\text{M}_\odot$
- Surface density (for $p = 3/2$)

$$\Sigma = 3.5(M_d/0.05\text{M}_\odot)(\text{R}_\text{d}/100\text{AU})^{-2}$$

- How valid are assumptions?

Accretion disks

- Disks in YSO are accreting → use theories of accretion disks

- If steady accretion (constant $\dot{M}$), $T(R)$

$$T_{vis} = \left(\frac{3GM_* \dot{M}}{8\pi\sigma R^3} \left[1 - \left(\frac{R_*}{R} \right)^{1/2} \right] \right)^{1/4}$$

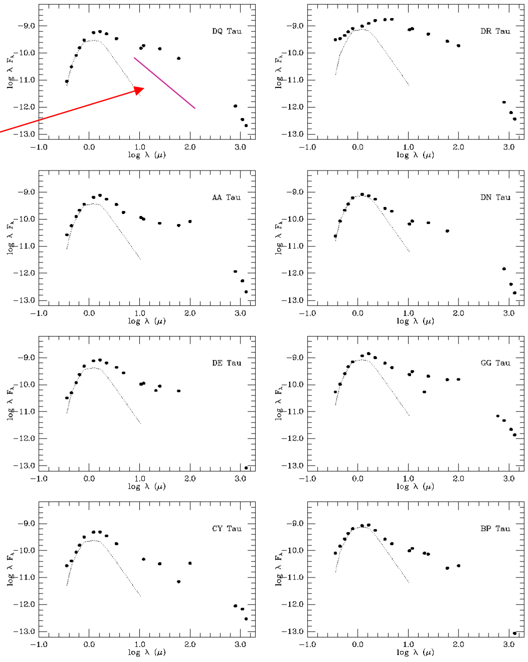
$T_{vis} \propto R^{-3/4}, R >> R_*$

- If disk is optically thick, SED is

$$\lambda F_\lambda \propto \lambda^{-4/3}$$

- SEDs of CTTS are flatter than expected from accretion disks

IR excess



$\lambda F_\lambda \; \alpha \; \lambda^{-4/3}$

Irradiated accretion disks

with $\dot{M} \sim 10^{-8} M_\odot yr^{-1}$, $L_{acc} < 0.1 L_\odot$

$\Rightarrow L_{acc} << L_*$

$\rightarrow$ stellar irradiation important heating agent

$\rightarrow$ irradiated accretion disks

- For flat disk, irradiation flux

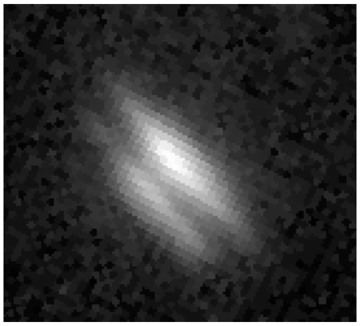
$$F_{irr} \sim I_* \Omega_* \cos\alpha \sim \frac{I_* \pi R_*^2}{R^2} \frac{h}{R} \propto I_* \left(\frac{R_*}{R}\right)^3$$

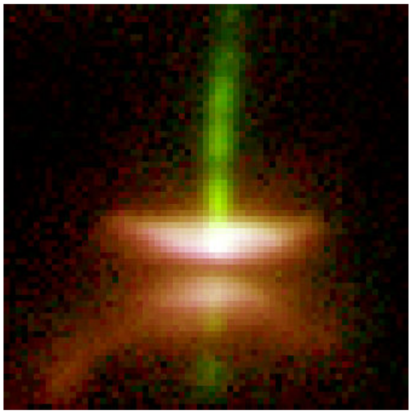
α = angle from surface to R
h = height

with $I_* \sim \sigma T^4 \Rightarrow T \propto R^{-3/4}$

Disks are flared

- But disks of CTTS are flared (Kenyon & Hartmann 1997) $\Rightarrow$ can capture more stellar radiation than flat disks





Density in the isothermal approximation

Hydrostatic equilibrium in vertical direction

$$\frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}z} = -\frac{GM_* z}{R^3}$$

where $\rho(z,R)$ and $p(z,R)$ are the density and pressure at height z and radius R

if isothermal disk

$$p = \rho c_s^2 = \rho(2kT/m)^{1/2}$$

c_s = isothermal sound speed, m = mass of the particle. In this approximation

$$\rho(z,R) = \rho_c e^{-\frac{z^2}{2H^2}}$$

where H is the scale height:

$$H = \frac{c_s}{(GM_*/R^3)^{1/2}} = \frac{c_s}{\Omega_K} \propto T^{1/2}$$

Flatter SED with irradiation

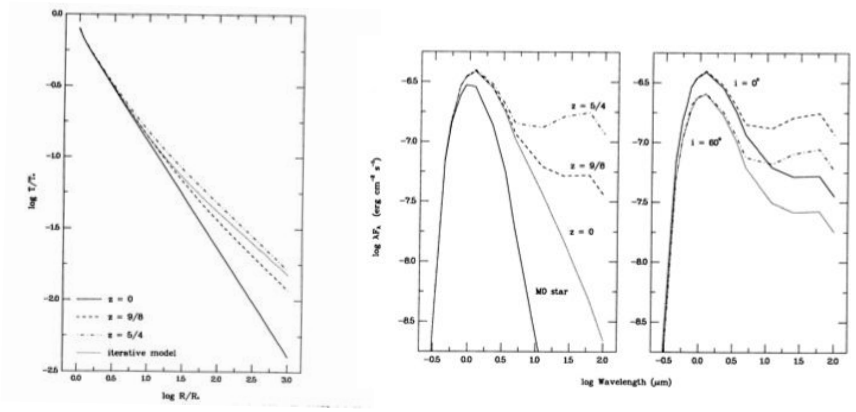
$$H = \frac{c_s}{(GM_*/R^3)^{1/2}} = \frac{c_s}{\Omega_K} \propto T^{1/2}$$

- if $T \uparrow \rightarrow$ cross section to capture of stellar photons $\uparrow \rightarrow$ disk gets heated

stable solution for the disk surface → flared surface

$T(R) \rightarrow R^{-1/2} \Rightarrow$ flatter SEDs

Irradiated disks are hotter



Kenyon & Hartmann 1987

Vertical structure

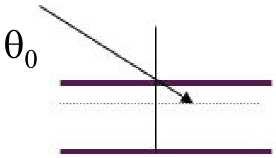
- Disks are not vertically isothermal

Stellar radiation enters the disk at an angle θ_0 to the local normal, → energy captured

$$F_{irr} \sim (\sigma T_*^4/\pi)(R_*/R)^2\mu_0$$

with

$$\mu_0 = \cos\theta_0$$



- a fraction $d\tau_*/\mu_0$ of the stellar flux absorbed at each z

τ_* = vertical optical depth at the wavelength of the stellar radiation

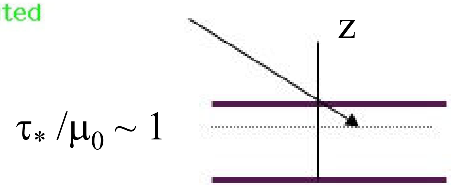
Stellar energy deposited in upper layers

- a fraction $d\tau_*/\mu_0$ of the stellar flux absorbed at each z

τ_* = vertical optical depth at the wavelength of the stellar radiation

- the larger the inclination $\leftrightarrow \mu_0 \downarrow$

$d\tau_*/\mu_0 \uparrow$
$z(\tau_*/\mu_0 \sim 1) \uparrow$
$\Rightarrow$ stellar energy is deposited in higher layers



Malbet & Bertout 1991

Wavelength effects

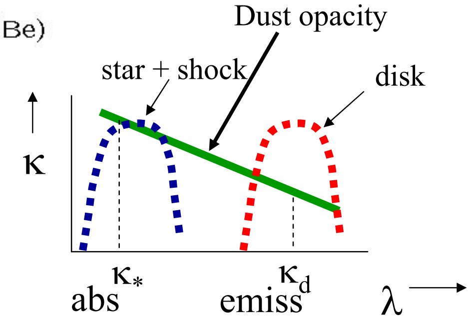
τ_* = vertical optical depth at the wavelength of the stellar radiation

- re-emerges at wavelength of local radiation

- $\kappa_*/\kappa_d >> 1$ (d = local radiation)

continuum from $z(\tau_d \sim 1)$
dust opacity increases as λ decreases
$\lambda_* \sim 1\mu$m (CTTS), $\sim 0.3\mu$m (Herbig Ae/Be)
$\lambda_d >> \lambda_*$
$\Rightarrow z(\tau_*/\mu_0 \sim 1) >> z(\tau_d \sim 1)$, $(\tau_* = \frac{\kappa_*}{\kappa_d}\tau_d)$
$\Rightarrow$ stellar energy is deposited in higher layers the hotter the star

$\Rightarrow$ Upper layers get heated



Temperature structure

- Conservation of energy → $T(z)$

$$\int \kappa B_\nu(T) \mathrm{d}\nu = \int \kappa J_d \mathrm{d}\nu + \frac{\mathrm{d}F_d}{\mathrm{d}z}$$

J_d = mean intensity of the local radiation.

$$\frac{\mathrm{d}F_d}{\mathrm{d}z} = \Gamma_* = 4\pi\kappa^* \rho J_{*,0} e^{-\tau_*/\mu_0}$$

Γ_* = stellar heating (no viscous heating)
κ^* = opacity at stellar wavelength
$J_{*,0}$ = mean intensity entering the disk

Temperature structure

With

$$J_{*,0} = 1/4\pi \int I \mathrm{d}\Omega \sim I_* \Omega_* / 4\pi$$

$$\kappa_P(T) \frac{\sigma T^4(z)}{\pi} = \kappa_P(T) J_d(z) + \kappa_P(T_*) \frac{\sigma T_*^4}{\pi} \left(\frac{R_*}{R}\right)^2 e^{-\tau_*/\mu_0}$$

κ_P = Planck mean opacity
$\kappa^* \sim \kappa_P(T_*)$

Calvet et al 1991, 1992

Upper layers

At surface, $J_d << J_{*,0}$, $\tau_*/\mu_0 << 1$,

$$\kappa_P(T)T^4(z) \sim \kappa_P(T_*)T_*^4\left(\frac{R_*}{R}\right)^2$$

surface temperature → optically thin limit

→ the “hot layer” temperature in the 2-level approximation (Chiang & Goldreich 1997)

but T decreases as z decreases

Disk surface

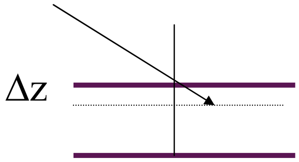
- $T(z,R) \leftrightarrow \mu_0 \leftrightarrow$ surface of the disk $z_s(R)$

- where $\tau_*/\mu_0 \sim 1$ and most of the stellar energy deposited

- size of upper optically thin region above the surface is given by

$$\Delta z \sim \mu_0/\kappa_*$$

the more inclined the surface → the smaller the region



Isothermal approximation

- with more detailed calculation for stellar flux intersected by disk by surface $z_s(R)$

$$F_{irr}(R, z_s) \sim \frac{2\sigma T_*^4}{\pi}\left[\frac{1}{3}\left(\frac{R_*}{R}\right)^3 + \pi\left(\frac{R_*}{R}\right)^2 \frac{\mathrm{d}z_s}{\mathrm{d}R}\right]$$

for $R >> R_*$

for $z_s = nH \rightarrow z_s = z_s(T)$

$$\frac{\mathrm{d}z_s}{\mathrm{d}R} = \frac{1}{2}\frac{z_s}{T}\frac{\mathrm{d}T}{\mathrm{d}R}\frac{3}{2}\frac{z_s}{R}$$

With $F_{irr} = \sigma T^4 \rightarrow$ system for $T(R)$ in the isothermal approximation

$\rightarrow T(R) \propto R^{3/7}$

Solutions for the vertical structure

- But disks are not isothermal, and $z_s \neq nH$ $\rightarrow$ solution of vertical structure equations for more accurate results

Several groups and approaches. Here, results from D'Alessio et al. Analytical solution of disk vertical structure equations, including irradiation and viscous heating. Iterative approach: find solution for given F_{irr}, i.e., $z_s(R)$, calculate new $z_s(R)$.

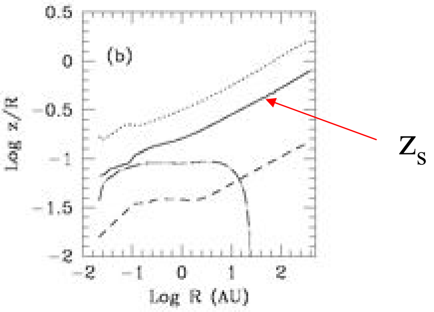
- Results for typical CTTS parameters:
$M_* = 0.5\mathrm{M}_\odot, \mathrm{R}_* = 2\mathrm{R}_\odot, \dot{\mathrm{M}} = 10^{-8}\mathrm{M}_\odot\mathrm{yr}^{-1}$

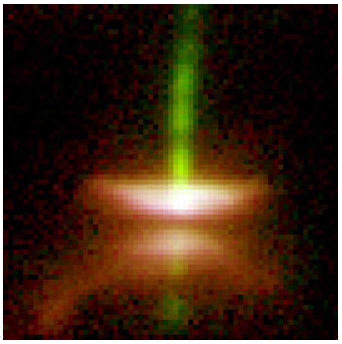
Extent of the flared surface

$*$ Since κ_* high → surface is flared out to a few hundred AU

$*$ although disk becomes optically thin to its own radiation ($\tau_{\rm R} < 1$) at ~ few × 10 AU

$\tau_{\rm R}$ = Rosseland mean opacity





T (z,R) in optically thick annuli

$*$ Three characteristic temperatures:
T_0 (surface)
T_{mid} (midplane)
T_{phot}, at photoshere, $\tau_d \sim 1$, only defined if disk is optically thick at its own radiation ($\tau_{\rm R} > 1$)

$*$ $T_{mid} >> T_{phot}$ if $\tau_{\rm R} >> 1$ (inner disks regions)

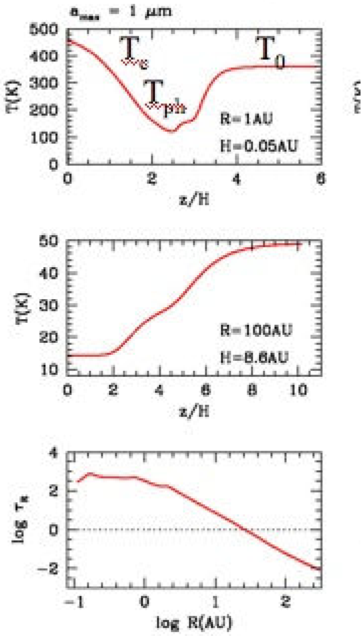
In the diffusion approximation

$$\frac{{\rm d}J_d}{{\rm d}z} = -\frac{3}{4\pi}\chi_R \rho F_d$$

or

$$\Delta(\sigma T^4) \sim \frac{3}{4\pi}\tau_R F_d$$

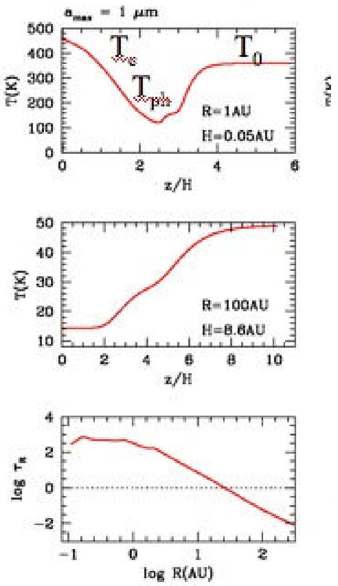
so, $\tau_R >> 1 \rightarrow T_c > T_{phot}$. T gradient allows viscous flux to escape



T(z,R) in optically thin annuli

When $\tau_R << 1$, inner disk $\sim$ isothermal

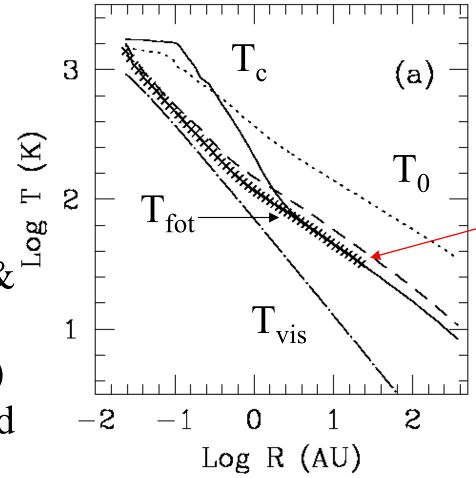
- $T \propto 1/R^{1/2}$, $R >> R_*$
- but still hot upper layers



Properties of disk structure

$T_c > T_{fot}$

$T_c \sim T_{dust}$
"thermostat effect" (Cassen & Wollum 1999)
H(disk) ~ H(rim)
=> rim not puffed up



$T_c \sim T_{fot}$ α $1/R^{1/2}$

D'Alessio et al 1999

Implications of hot upper layers

*Strong features (CO,Silicate)
in emission even if disk optically thick
*Molecules can exist in upper layers, even
if they are adsorbed on grain surface near
midplane

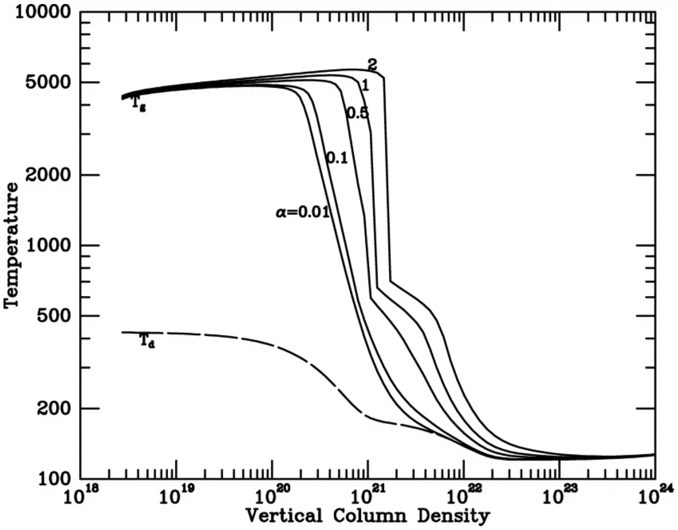
Implications of hot midplane in inner disk

$T_c \sim T_{dust}$, T_{dust} = dust destruction temperature
"thermostat effect"

$H \sim H(T_{dust})$ in inner disk ~ H("rim")

Rim is not significantly "puffed up"
=> inner disks are not shadowed

Gas T different from dust T



X-ray heating of gas in upper less dense layers

Glassgold et al 2004

Surface density

- Surface density self-consistently calculated from disk equations. For a steady viscous disk,

$$\Sigma = \frac{\dot{M}}{4\pi\nu}\left[1 - \left(\frac{R_*}{R}\right)^{1/2}\right]$$

ν = viscosity

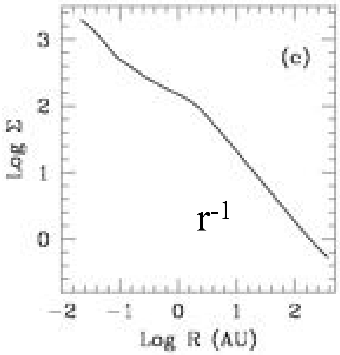
With (SS93) $\nu = \alpha c_s H = \alpha c_s^2/\Omega_K$
$c_s \propto T^{1/2} \propto R^{-1/4}$
$\Omega_K \propto R^{-3/2}$
at large R

$$\Sigma \sim 2\left(\frac{\alpha}{0.005}\right)^{-1}\left(\frac{T_{100AU}}{10K}\right)^{-1}\left(\frac{R}{100AU}\right)^{-1} \text{gr cm}^{-2}$$

α consistent with CTTS models

- $\Sigma \propto 1/R$ (flatter then $p =$ 3/2)

- confirmed by observations



Disk Mass

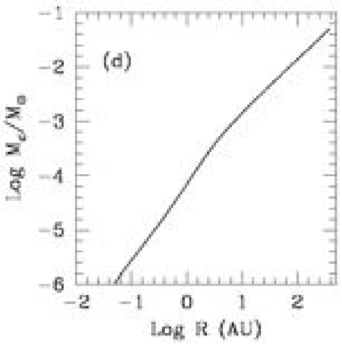
Assuming this dependence,

$$M_{disk} = 0.016 \left(\frac{\dot{M}}{10^{-8} M_{\odot} yr^{-1}}\right) \left(\frac{\alpha}{0.005}\right)^{-1} \left(\frac{M_*}{0.5 \mathrm{M}_{\odot}}\right)^{-1/2} \left(\frac{T_{Rdisk}}{10K}\right)^{-1} \left(\frac{R_{disk}}{200AU}\right)^{1/2} \mathrm{M}_{\odot}$$

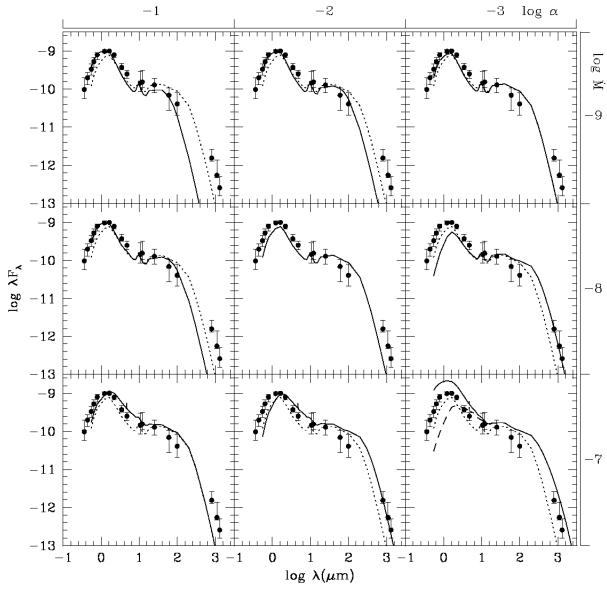
$\sim$ dust mm measurements

If $\dot{M}$ known, M_{disk} and α complementary

- M_{disk} consistent with $\dot{M}$



SEDs



SED @ IR similar for low dM/dt – dominated by irradiation

F_{mm} increases with $\Sigma \sim dM/dt / \alpha$

D'Alessio et al 1999

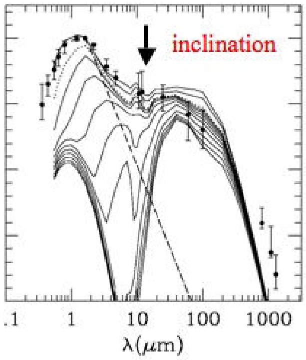
Disk self-absorption

- Expression for disk flux

$$F_\nu = \frac{2\pi}{d^2}\int_{R_1}^{R_2} B_\nu(T(R))\Sigma(R)\kappa_\nu R\mathrm{d}R$$

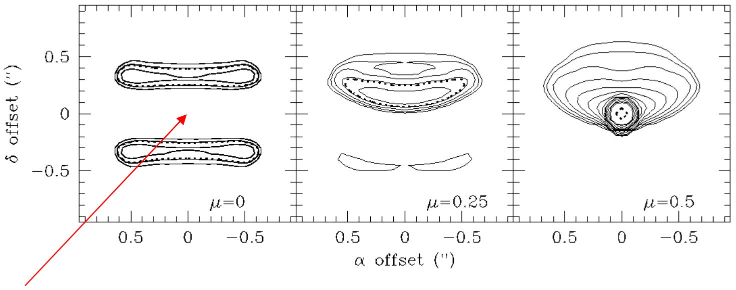
→ simplification

Assumes disk isothermal
Ignores self-absorption of disk emission
by outer regions



- Effects of inclination. Edge-on disks self-absorbed. Stellar scattered light

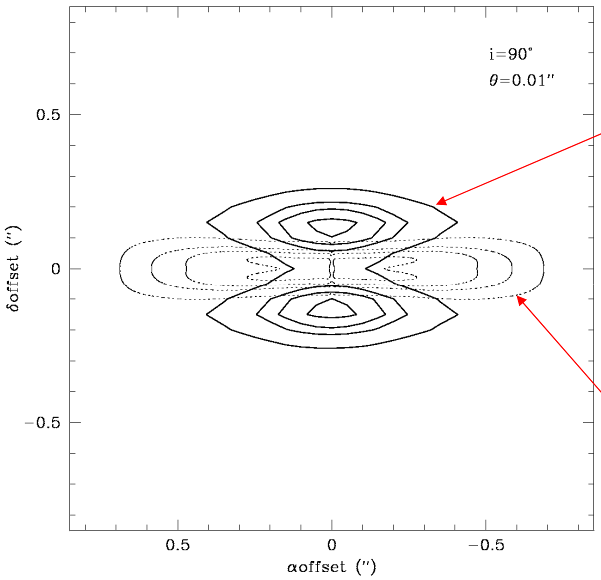
Images



Dark lane: optically thick
disk layers near mid-plane

D’Alessio et al 1999

Optical/mm



Optical/near IR scattered light (upper layers)

mm emission (midplane, most mass)

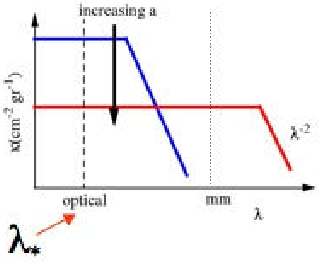
Dust opacity: single grain

For spherical single grain of radius a

$$\sigma \approx Q\pi a^2, \lambda < 2\pi a$$
$$\sigma \propto \lambda^{-2}, \lambda > 2\pi a$$
$$\kappa(\mathrm{cm^2 gr^{-1}}) = \sigma(\mathrm{cm^2})/(4/3\pi\rho_g a^3(\mathrm{gr}))$$
$$\kappa \propto 1/a$$

If a↑

$\kappa \downarrow$ at short λ
$\kappa \uparrow$ at long λ



Dust opacity: mixture of sizes

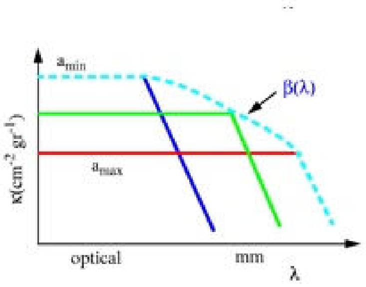
Dust: mixture of grain sizes

$$n(a)da = a^{-p}da$$

between a_{min} and a_{max}

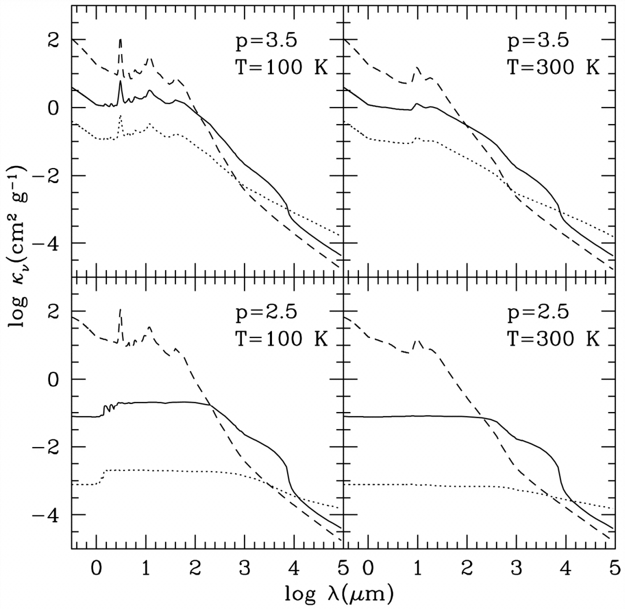
$p = 3.5$ (ISM), $p = 2.5$ (coagulation)

transition from flat to λ^{-2} regimes over a range of $\lambda \Rightarrow \beta = \beta(\lambda)$



More realistic dust opacities

a_{max}= 10μm, 1mm, 10cm

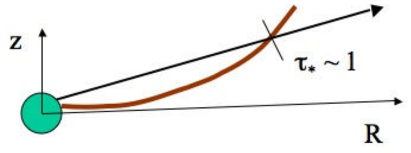


D’Alessio et al 2001

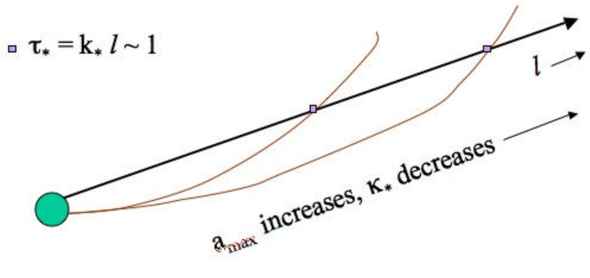
Effect of dust opacity on heating

- Location of disk surface depends on dust opacity at stellar wavelengths

- For dust uniformly distributed in the disk and with a given mixture of grain sizes, the location of the disk surface depends on a_{max} (with fixed a_{min})



Dependence on a_{max}



If $a_{max} \uparrow$

  $\kappa_* \downarrow$
  $z_s \downarrow$
  $\Rightarrow$ less stellar energy captured
  $\Rightarrow$ lower T
  $\Rightarrow$ less IR emission

also

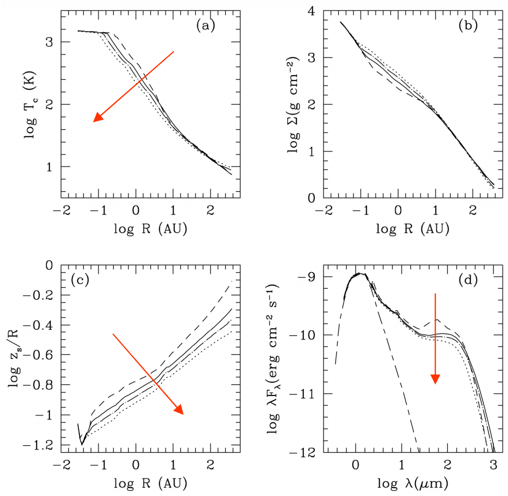
  $\kappa(\text{mm}) \uparrow$
  $\Rightarrow$ higher mm fluxes

Dependence on a_{max}

p=3.5

→

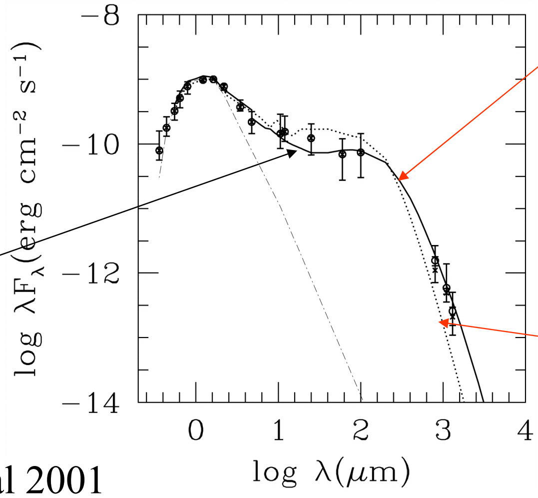
a_{max} from 10 µm to 10 cm



D'Alessio et al 2001

Comparison with Taurus median

- Median SED of Taurus explained better with a_{max} = 1mm than with ISM dust, a_{max} = 0.3μm ⇒ grain growth



a_{max} = 1mm

median 50% obs inside quartiles

a_{max} = 0.3µm (ISM)

D'Alessio et al 2001

Spitzer/IRS data of Taurus (1-2 Myr)

Silicate emission

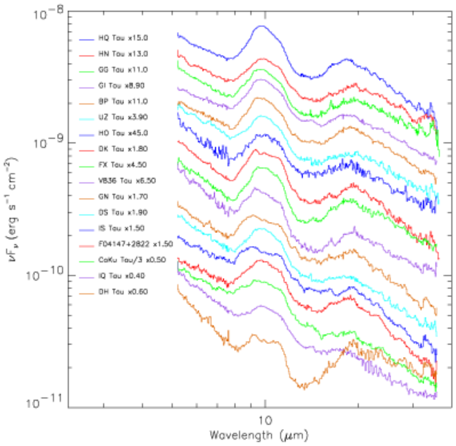


Fig. 5.— Morphological sequence of Class II objects: Group C.

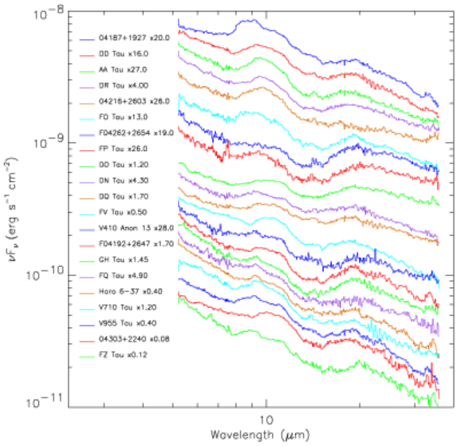


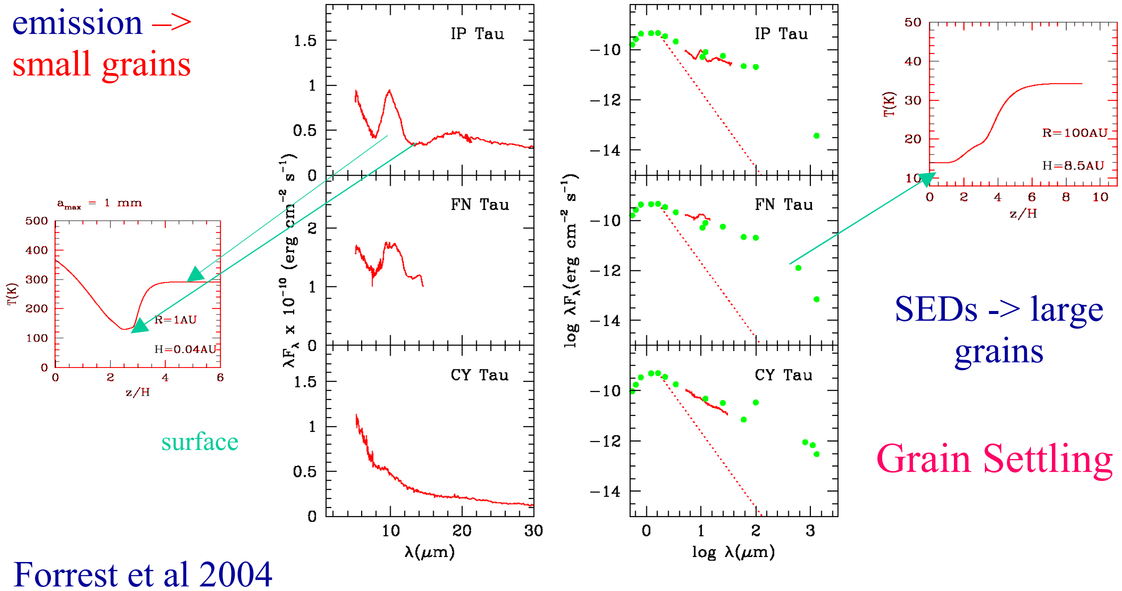
Fig. 6.— Morphological sequence of Class II objects: Group D.

Furlan et al. 2006

Large range of properties at one age

Spitzer/IRS spectra of T Tauri stars

silicate feature
emission –>
small grains



surface

SEDs -> large
grains

Grain Settling

Forrest et al 2004

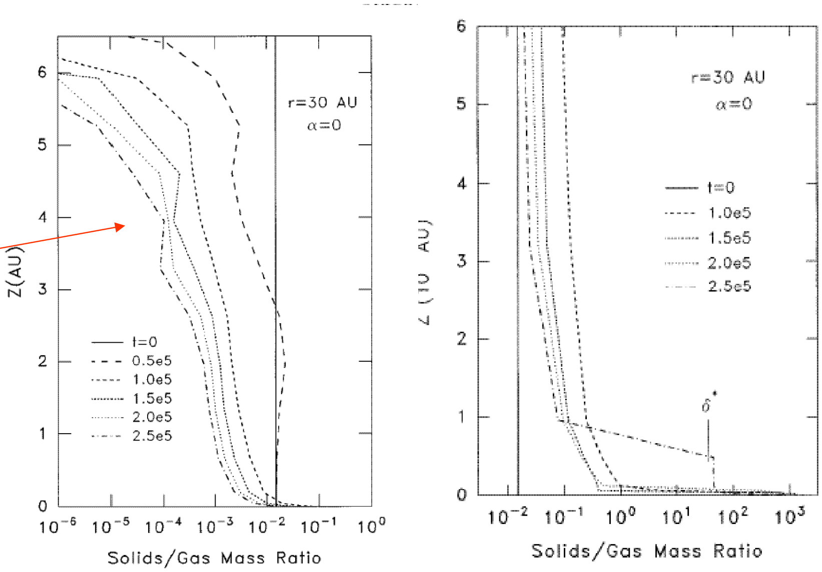
Dust growth and settling

Gas in disk subject to radial pressure gradient dp/dR => $V_{orb} < V_K$
Dust tends to rotate at V_K

- ⇒Small particles coupled to gas, large particles rotate at V_K
- ⇒Intermediate particles feel gas drag, loose J
- ⇒Differences in orbital and radial velocities
- ⇒Particules shock, stick together, grow in size
- ⇒Gravity tends to settle particles to midplane
- ⇒Faster at small radii (large Ω)

Weidenschilling 1997; Dullemond & Dominik 2004

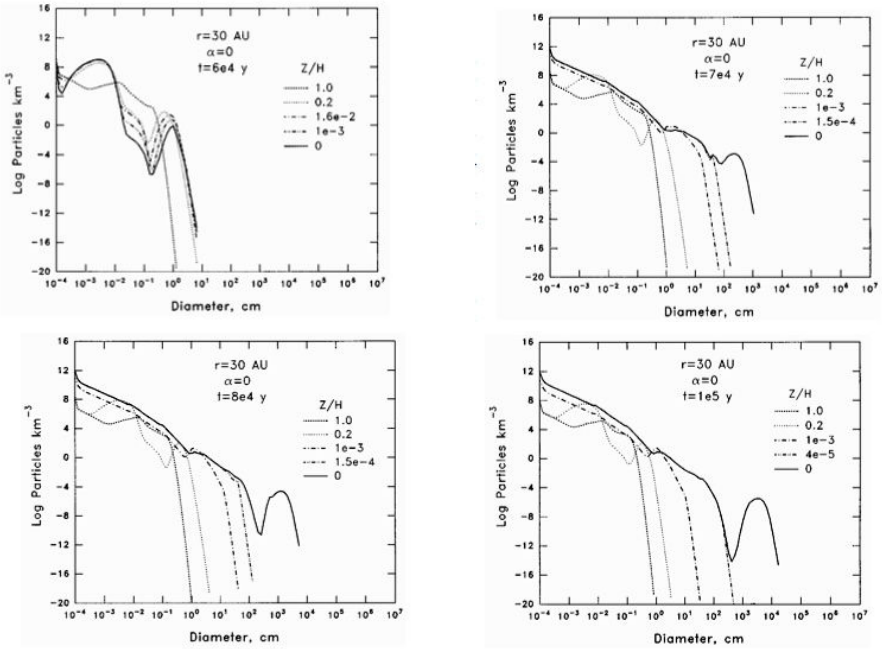
Dust growth and settling



Upper layers get depleted

Weidenschilling 1997; Dullemond & Dominik 2004

Evolution of particle sizes



Vertical optical depth

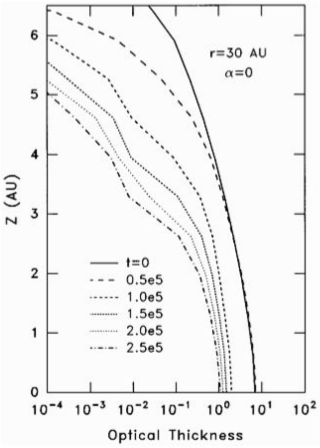
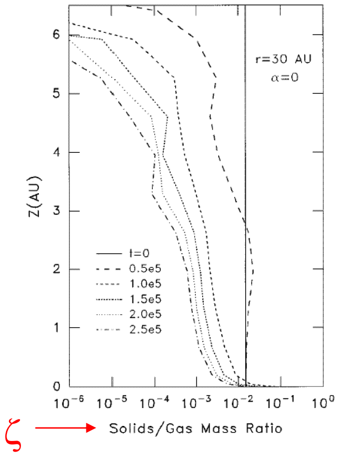


FIG. 5. Integrated optical thickness above height *z*, computed using Rosseland mean opacity for the mass loading and size distribution of particles at each level. Vertical distribution changes because of settling; total optical thickness decreases due to particle growth.

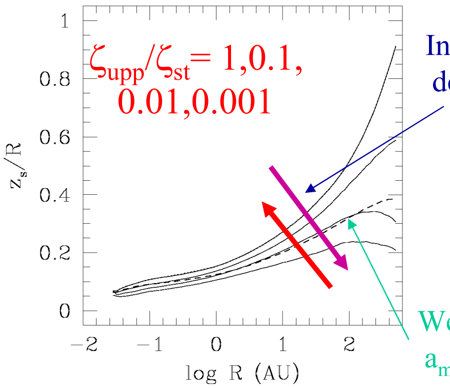
Settling – dust evolution in solar nebula

Decrease of dust/gas in upper layers



Weidenschilling 1997

Lower surface even with small grains in upper layers



ζ_{upp}/ζ_{st} = 1,0.1, 0.01,0.001

Increasing depletion

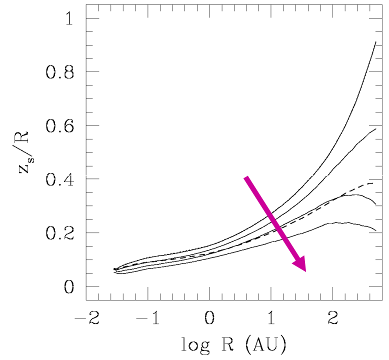
Well mixed a_{max}=1mm

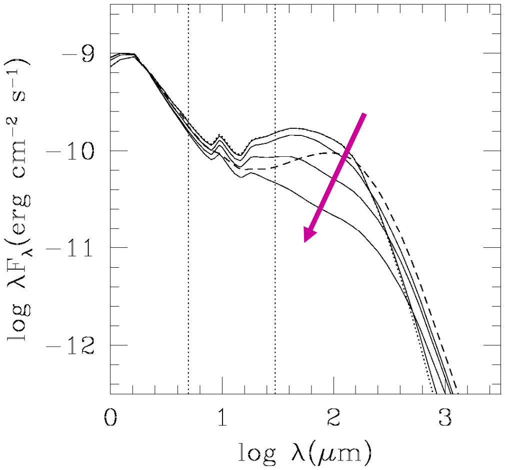
D'Alessio et al. 2006

Settling of solids toward midplane

$\varepsilon = \zeta_{upp}/\zeta_{st} = 1,0.1, 0.01,0.001$

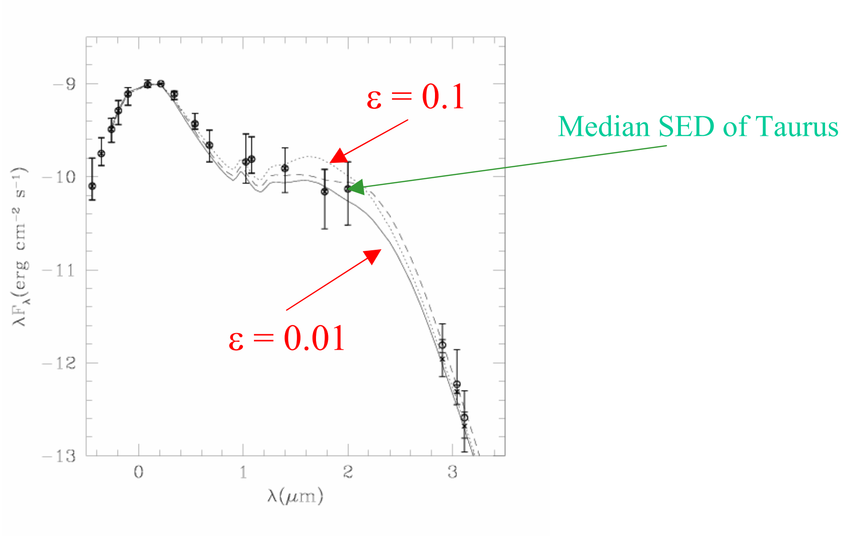
Lower IR and silicate emission





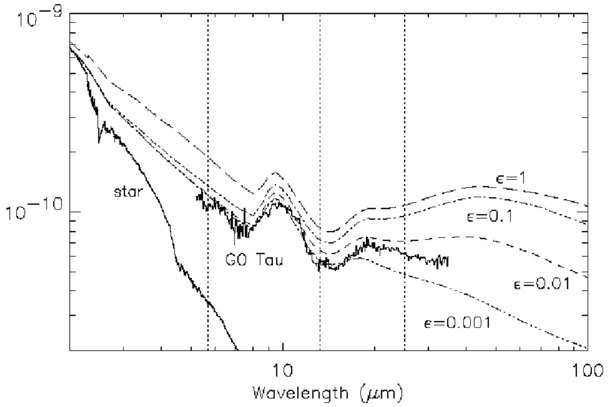
D'Alessio et al. 2005

Comparison with observations



D'Alessio et al. 2006

Settling of solids toward midplane

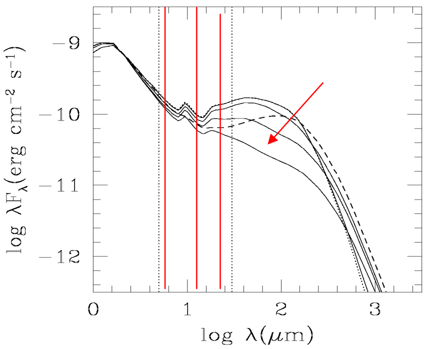


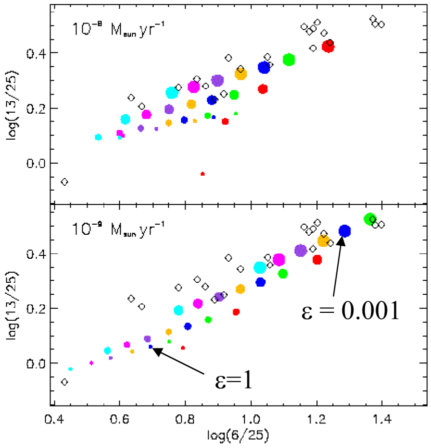
Furlan et al. 2005

Settling of solids towards the midplane: effects on SED

Model slopes for a range of ε and inclinations compared to measured slopes in IRS spectra of Taurus stars

Depletion of upper layers: $\varepsilon = \zeta_{upp}/\zeta_{st}$





Furlan et al 2005

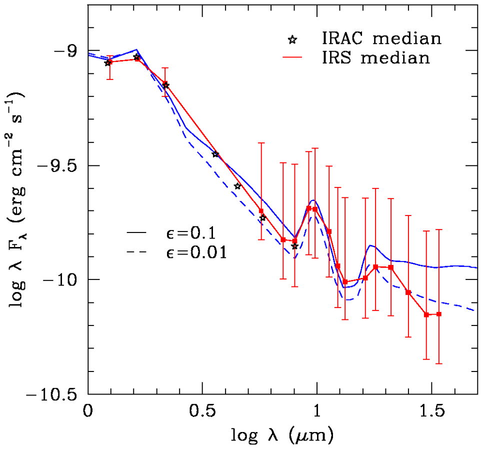
Settling of solids toward midplane

Median of Taurus from IRAC fluxes for 60 stars (Hartmann et al 2005) and IRS spectra of ~75 objects (Furlan et al 2005)

ε~ 0.1 – 0.01

Olivines

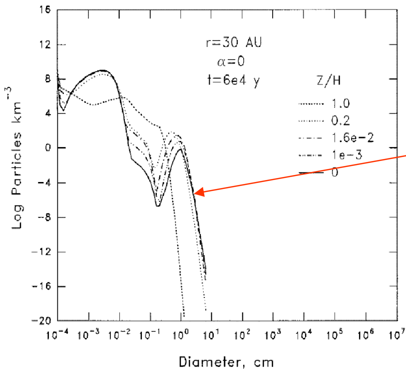
No settling in wall



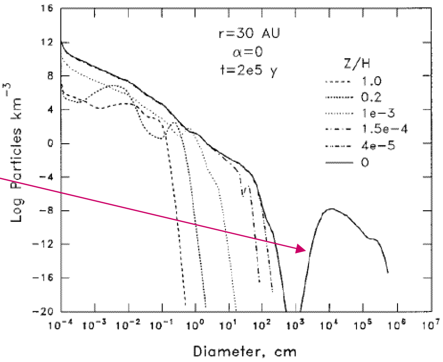
Depletion of upper layers: $\varepsilon = \zeta_{upp}/\zeta_{st}$

Furlan et al 2006

Dust growth and settling

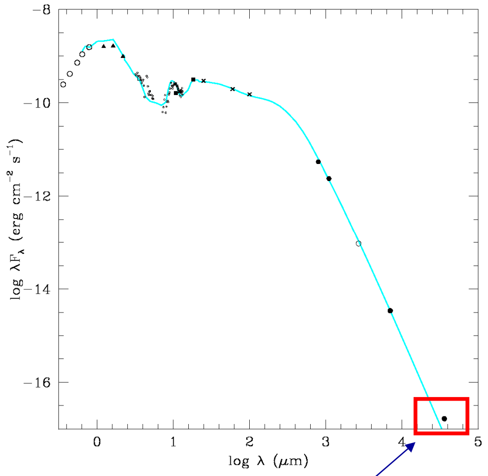


Population of big grains at midplane



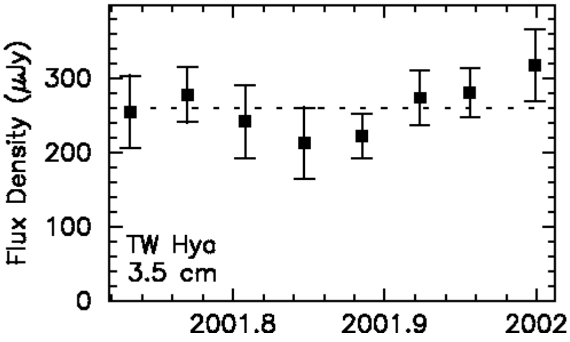
Weidenschilling 1997

Settling of solids: TW Hya



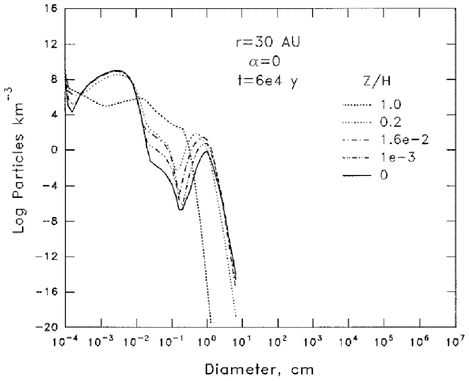
Jet/wind?
Northermal emission?

3.5 cm flux ~ constant =>
Dust emission



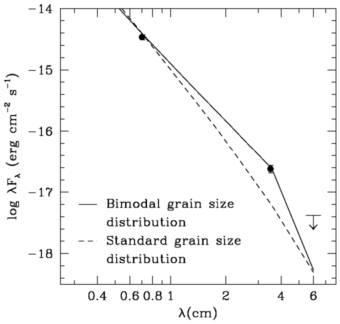
Wilner et al. 2005

Settling: bimodal grain size distribution

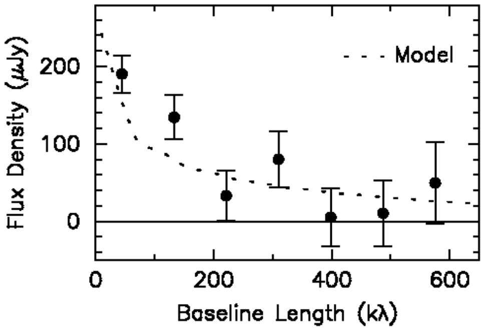


Weidenschilling 1997

Wilner et al. 2004



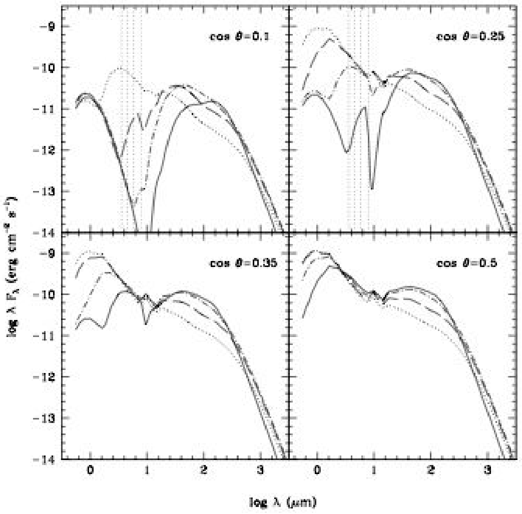
Small +
5-7mm



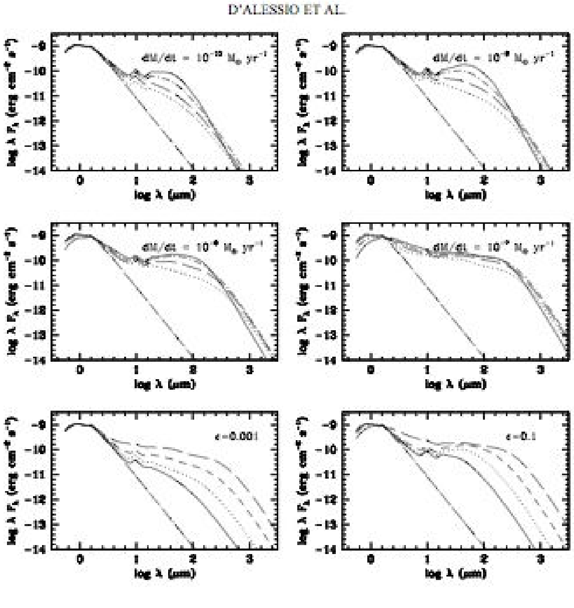
~ 1/R

Inclination effects in settled disks

Increasing settling
=> less self-absorption



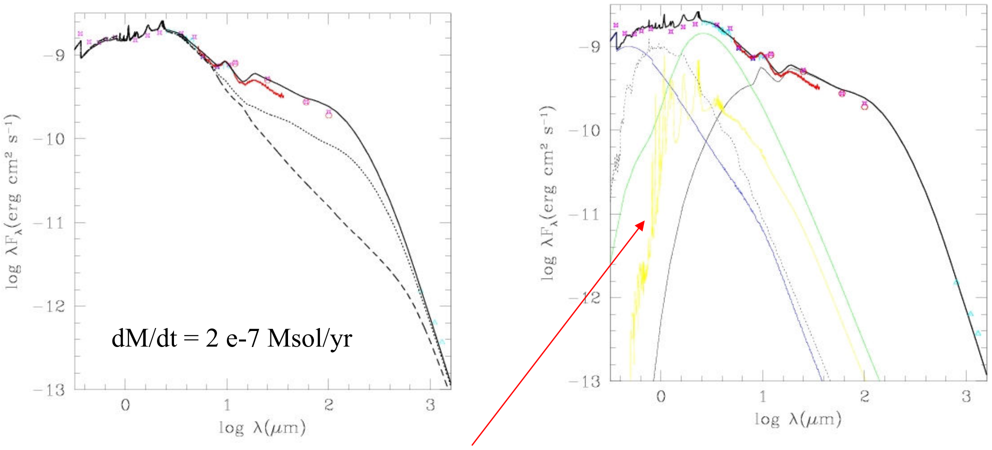
Settling and mass accretion rate effects



D'Alessio et al. 2006

High accretors: DR Tau

Silicate emission and high far-IR flux because of irradiation by high energy radiation from accretion shock



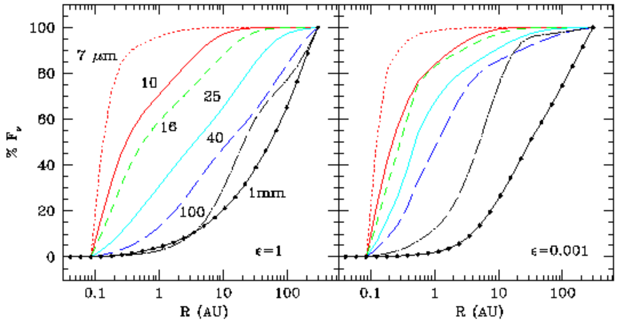
dM/dt = 2 e-7 Msol/yr

Optically thick gas disk

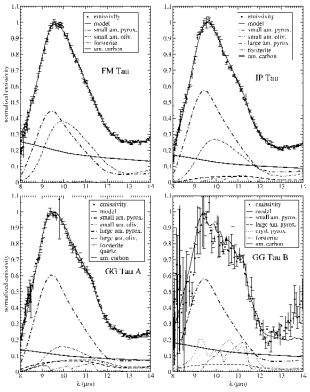
D'Alessio et al 2006c

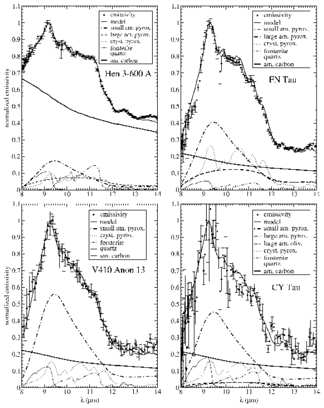
Emitting region decreases with settling

- As degree of settling increases, disk flux comes from a smaller region of the disk



Settling of dust toward midplane: small grains in upper layers

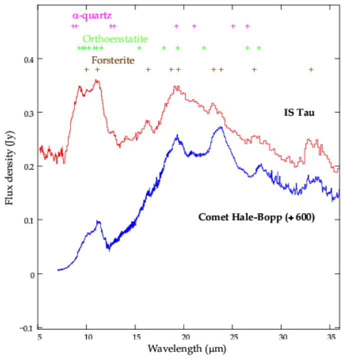


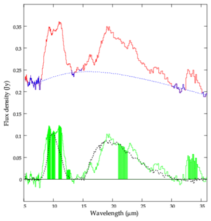


- Silicate emission feature formed in hot upper inner disk layers
- Small grains in upper layers, consistent with settling
- Crystalline components

Sargent et al 2006

Crystallinity





Processing of dust

Watson et al 2006

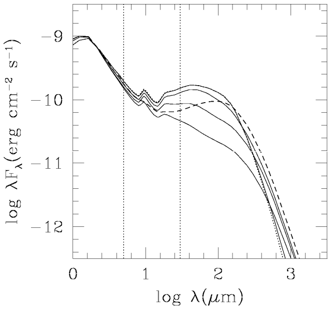
Crystallinity indices:

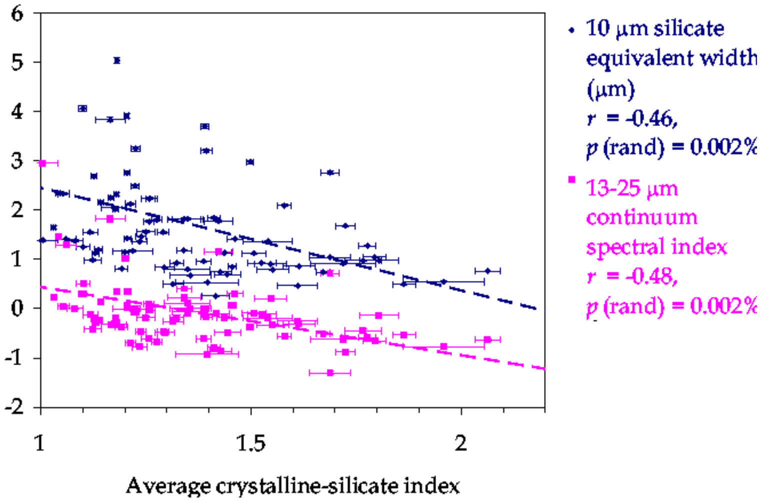
No correlation with

- stellar luminosity
- stellar mass
- dM/dt
- disk mass

(similar to HerbigAe/Be, Van Boekel et al 2005)

Crystallinity increases as SEDs become steeper

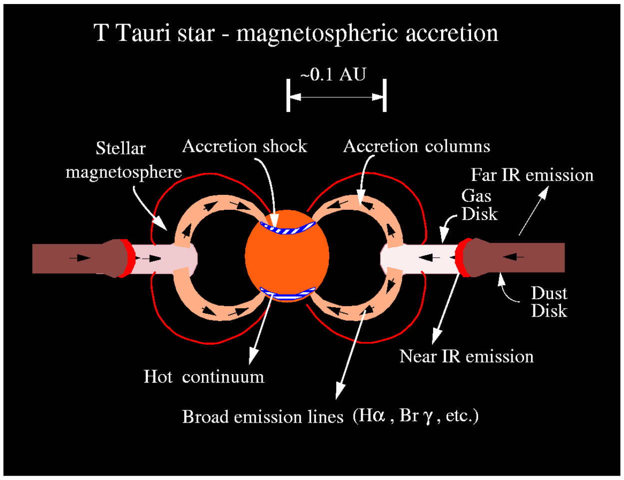




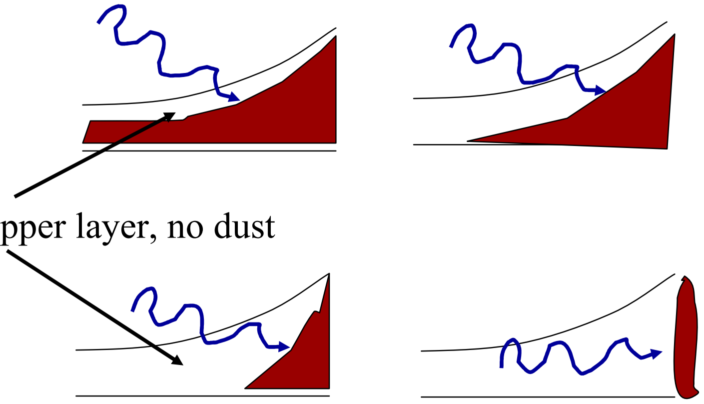
Watson et al 2006

Present picture of inner disk

Near-IR emission mostly from wall at dust destruction radius



Wall at dust sublimation radius



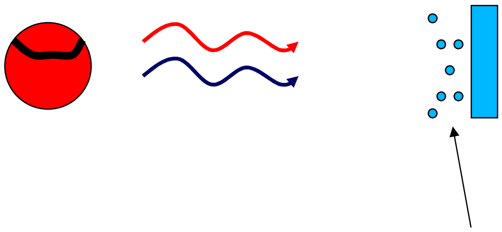
Hot upper layer, no dust

Optically thin T = dust sublimation T

Natta et al 2001

Location of wall

$$R_{wall}=[(L_{*}+L_{acc})/16\ \sigma_R\ \ (2+\kappa^{*}/\kappa^{d})]^{1/2}/\ T_{sub}^{2}$$



Wall atmosphere

Dust destruction radius: optically thin expression

$$R_p=[L_*/4\,\pi\,\sigma\ \kappa_i/\kappa_d]^{1/2}/\ T_{sub}^2$$

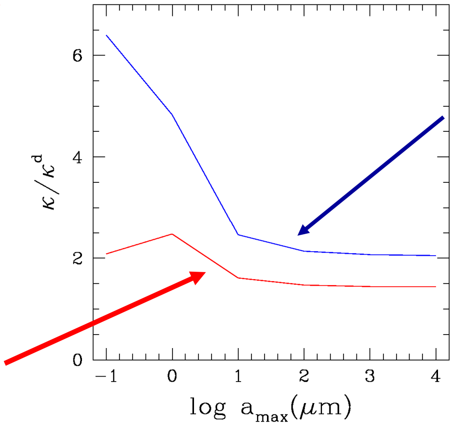
Including accretion shock emission and local radiation field:

$$R_p=[(L^*+L_{acc})/4\,\pi\,\sigma\ (2+\kappa_i/\kappa_d)]^{1/2}/\ T_{sub}^2$$

Muzerolle et al 2005

$$R_p=[(L_*+L_{acc})/4\,\pi\,\sigma_R\ (2+\kappa^i/\kappa^d)]^{1/2}/\ T_{sub}^2$$

$q = \kappa^i/\kappa^d$ depends on dust size and irradiating flux



T=8000K
shock or HAeBe

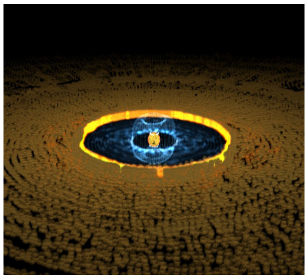
T=4000K
CTTS

$n(a)da = C\ a^{-p}da,\ \{a_{min},a_{max}\}$

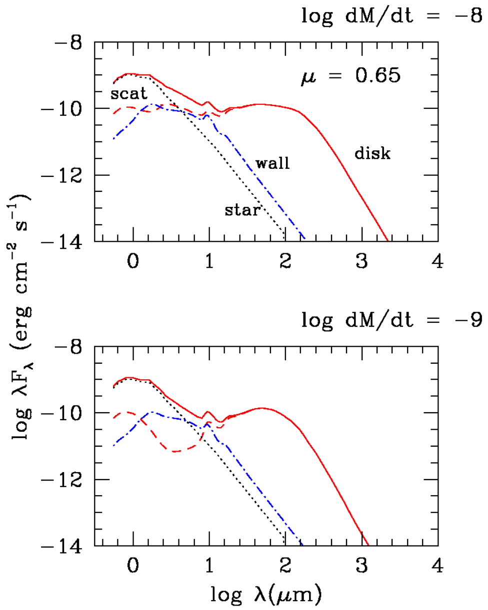
And shape of wall! Isella & Natta

Wall emission in near-IR

- •large contribucion from wall to near-IR



Art by Luis Belerique & Rui Azevedo

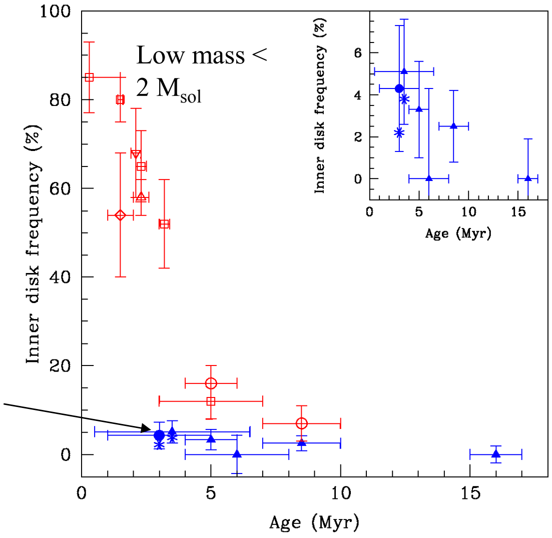


D'Alessio et al 2006

Dust evolution in inner disk

Hernandez et al 2004

Mass dependence: Inner disks of more massive stars dissapear faster

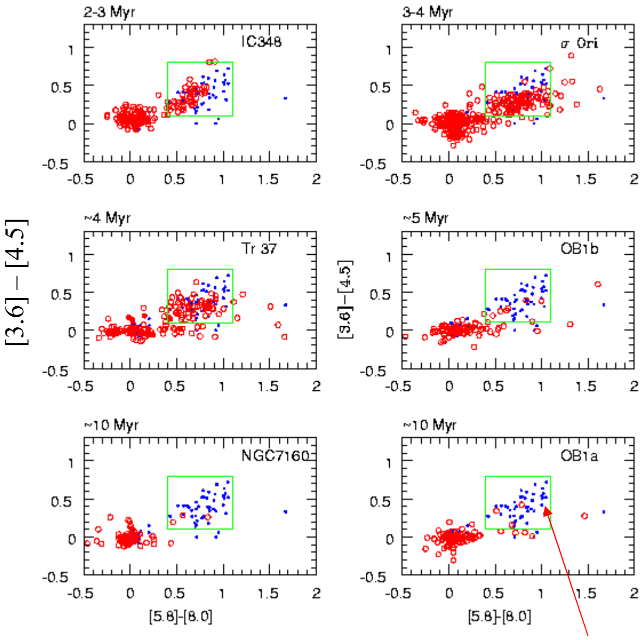


High mass 2-8 Msun

SED evolution:comparison at different ages

IRAC data for a number of clusters and associations with ages 1 – 10 Myr: Gradual decrease of excess emission

Data from
Hartmann et al 2005
Sicilia-Aguilar et al 2005
Lada et al 2006
Hernandez et al 2006a



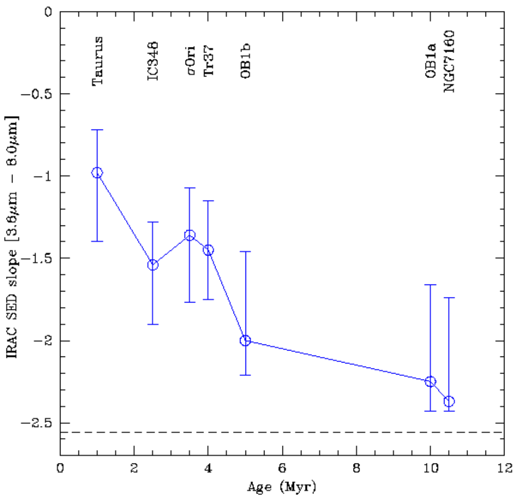
Taurus

Hernandez et al 2006b

SED evolution: inner disk

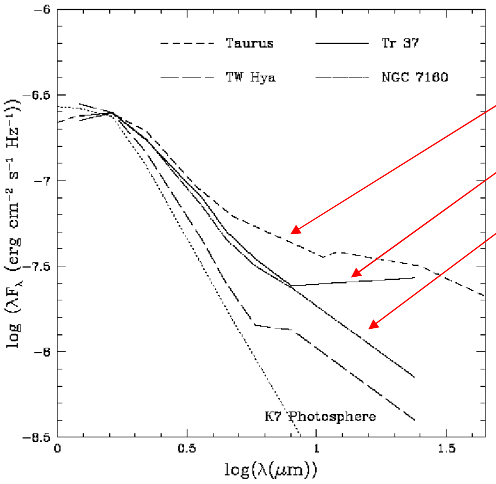
Decrease of median slope with age: consistent with decrease of dM/dt and dust settling in inner disk

Hernandez et al 2006b



SED evolution

Evolution of the median SED from IRAC and MIPS 24 measurements:
Gradual decrease of emission, increased settling



Taurus 1-2 Myr

Tr 37 3 Myr

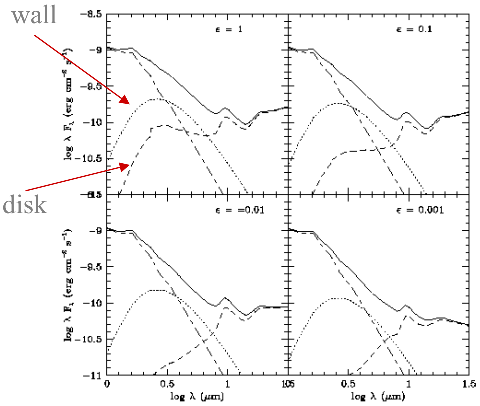
NGC 7160 10 Myr

Sicilia-Aguilar et al 2005

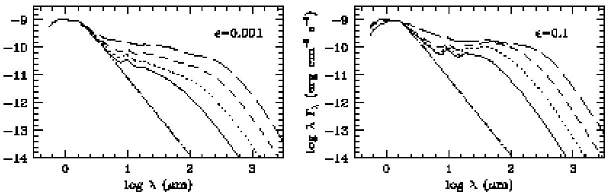
SED evolution

Slope becomes stepper - less excess as

Degree of settling increases



Accretion rate decreases



log dM/dt= -10, -9, -8, -7

Σ decreases

SED evolution

Present evidence:

As a given population ages, the fraction of remaining disks tend to have lower accretion rates and their dust more settled towards the midplane

But fraction of remaining disks decreases with time. What happened to the other disks?

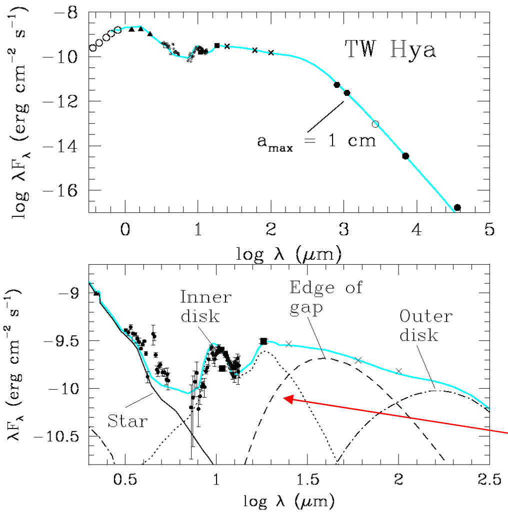
Transition disks

Transition disks?

- Lack of significant excess flux below 10 μm
- But flux comparable to the median of Taurus at longer wavelengths

Model:
- Clearing of the innermost, hotter disk regions
- Truncated outer optically thick disk
- Wall at truncation radius illuminated frontally by star

Transition disks



- Weak or absent near-IR excess in TW Hya: clearing of inner disk regions
- 'Wall' at ~ 4 AU – edge of outer disk
- Inner disk: gas and small amount of micron-size dust
- Large solids - with low near-IR opacity - may be in inner disk

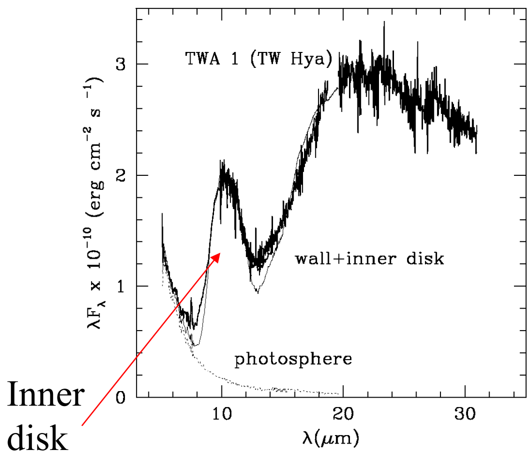
Wall emission, T~ 130K

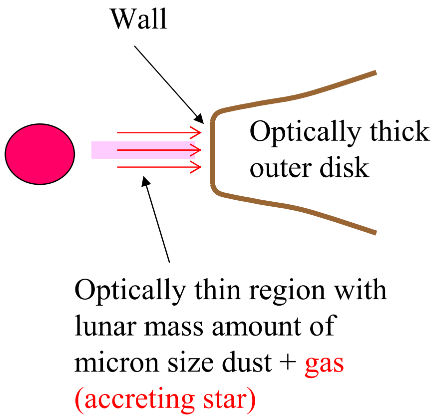
Calvet et al 2002

Inner disk clearing

Spectra from IRS on board SPITZER

TW Hya, ~ 4 AU
~ 10 Myr




Wall

Optically thick outer disk

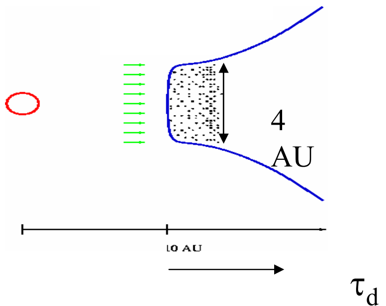
Optically thin region with lunar mass amount of micron size dust + gas (accreting star)

Uchida et al. 2004

Inner disk clearing

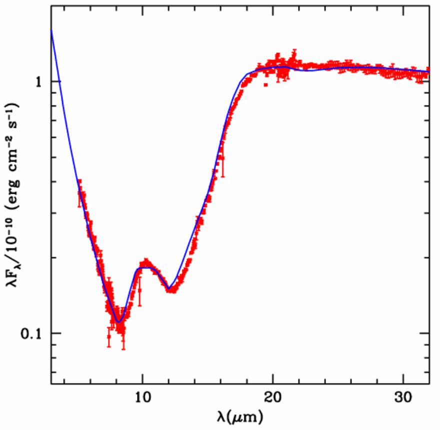
Spectra from IRS on board Spitzer

CoKu Tau 4, ~ 10 AU
~ 2 Myr



No inner disk, silicate from wall atmosphere

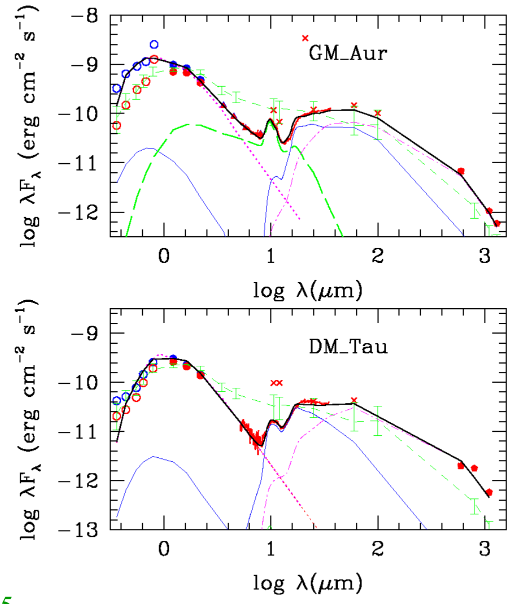
Non-accreting star



Forrest et al. 2004;
D'Alessio et al. 2005

More disks in transition in Taurus

IRS spectra finely maps wall region

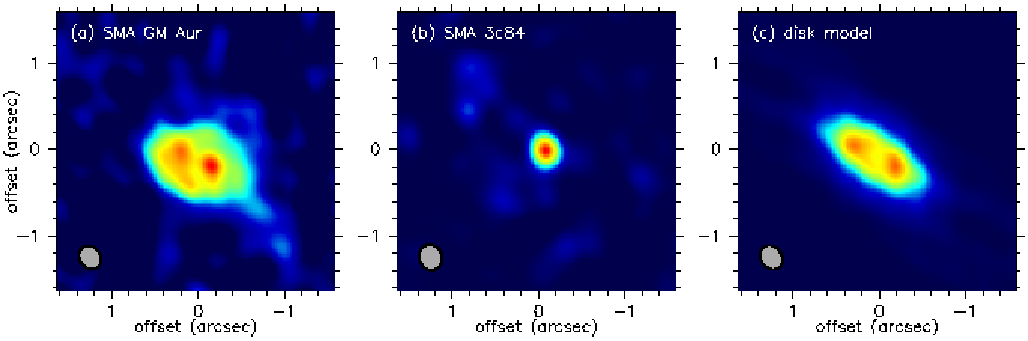


R_w ~ 24AU
outer disk +
inner disk with
little dust + gap
(~ 5-24AU)

Rw ~ 3 AU
only external
disk but
accreting star

Calvet et al 2005

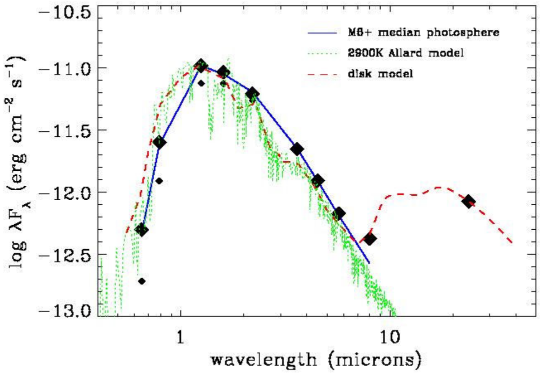
Detection of predicted hole on GM Aur with SMA



$R_w \sim 24\text{AU}$

Wilner et al 2006

Transition Disk in a Brown Dwarf



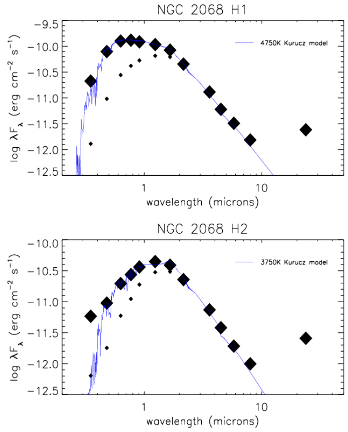
$R_w = 1\text{AU}$

Muzerolle et al 2005
Model: Lucia Adame

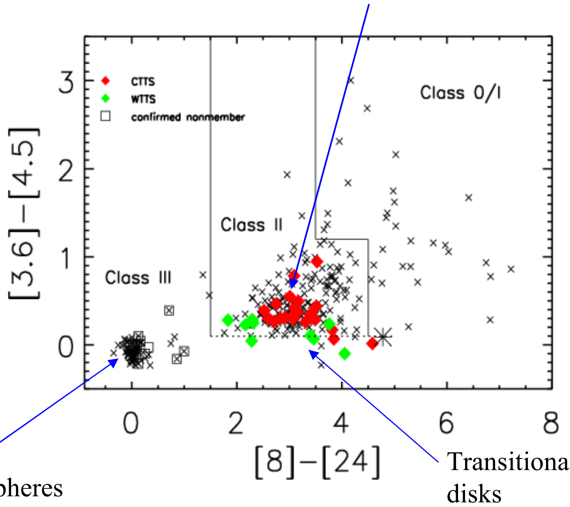
No significant UV

Inner disk clearing

Search of transitional disks in large populations: IRAC-MIPS 24 observations of clusters in a range of ages



Muzerolle et al 2005



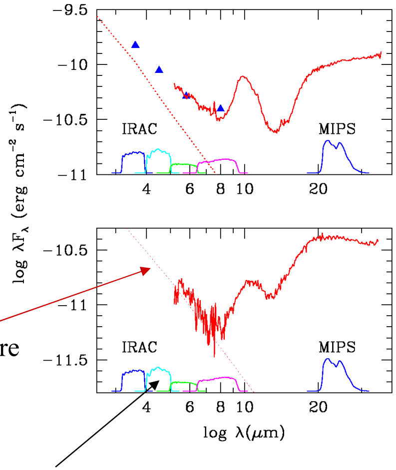
Accreting disks (Allen et al 2004)

Photospheres

Transitional disks

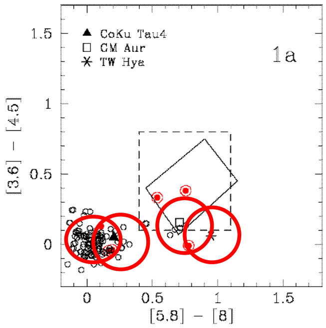
IRAC colors of transition disks

Wall (and optically thin inner disk) emission effect in IRAC colors



Photosphere

Filter transmissions

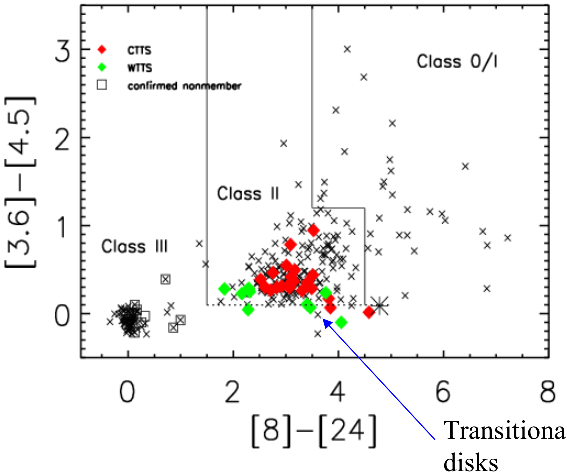


Inner disk clearing

Search of transitional disks in large populations: IRAC-MIPS 24 observations of clusters in a range of ages

Fraction of objects with signatures of inner disk clearing increases with age, from 1% at 1 Myr to 13% at 3 Myr

Muzerolle et al 2005

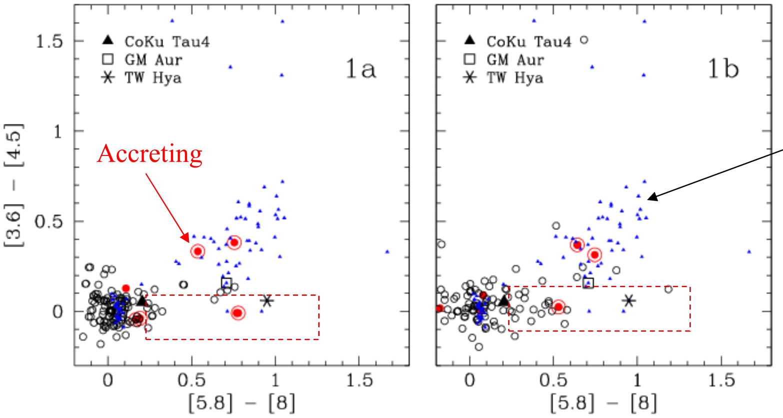


Transitional disks

Inner disk clearing

Ori OB1a: 10 Myr, 7%

Ori OB1b: 5 Myr, 13%



Taurus (Hartmann et al 2005)

Fraction of accreting transitional disks ~ 1%

Briceno et al 2005

Inner disk clearing

Observations of transition disks in populations of ages 1-10 Myr indicate

timescale $\sim N_{transition}/N_{total}$ x age ~ few 10^5 yrs

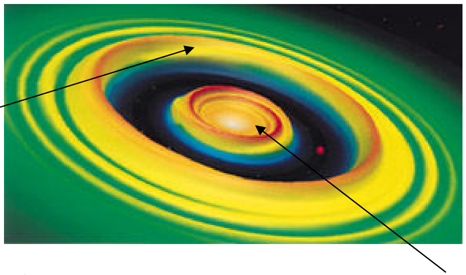
⇒Rapid phase

Accretion onto star is turned off quickly during transition phase (most objects not accreting)

Constraints for models

Inner disk clearing: planet(s)?

Giant planet forms in disk opening a gap



Wall of optically thick disk = outer edge of gap at a few AU

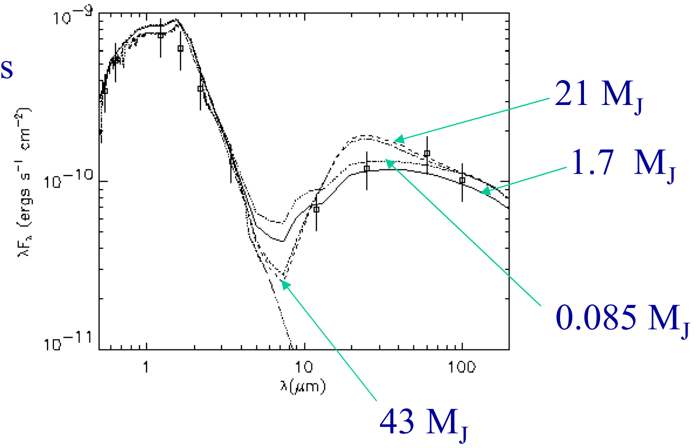
Bryden et al 1999

Inner gas disk with minute amount of small dust – silicate feature but little near IR excess, bigger bodies may be present

Inner disk clearing: planets?

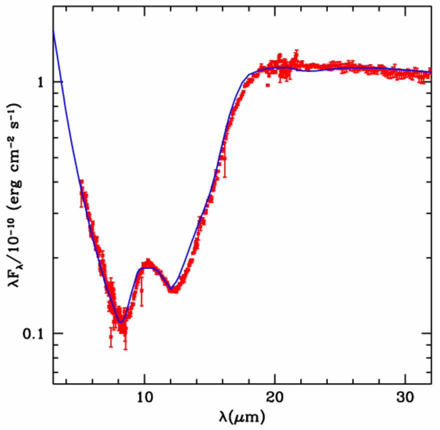
- Tidal truncation by planet
- Hydrodynamical simulations+Montecarlo transfer – SED consistent with hole created and maintained by planet – GM Aur: ~ $2M_J$ at ~ 2.5 AU – Rice et al. 2003

SED depends on mass of planet (and Reynolds number)

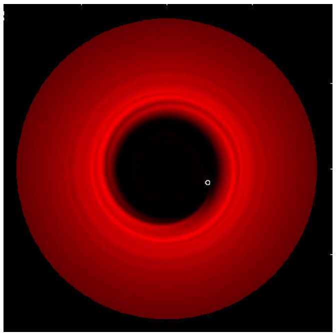


Inner disk clearing: planets

CoKu Tau 4, wall at ~ 10 AU
No inner disk



D'Alessio et al. 2005



Planet-disk system with planet mass of 0.1 M_{jup} for CoKu Tau 4
Quillen et al. 2004

Inner disk clearing: planets?

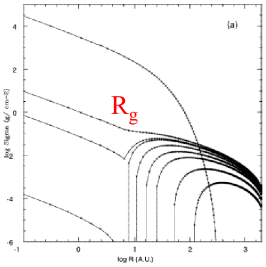
Planet formation can explain:

- SEDs of transition disks
- short timescale for transition phase ~ run-away gas accretion/gap opening
- rapid disappearance of inner disk, viscous time scale at gap, increased efficiency of MRI in low opacity inner disk

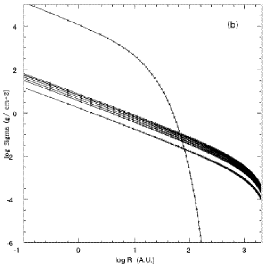
Problems: outer disk may make planet migrate inwards in viscous timescale, small α?

Inner disk clearing: photoevaporation of outer disk?

Evolution with photoevaporation

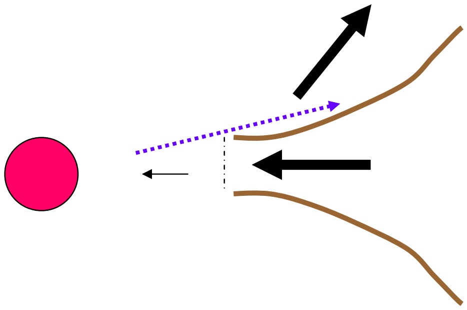


Evolution without photoevaporation

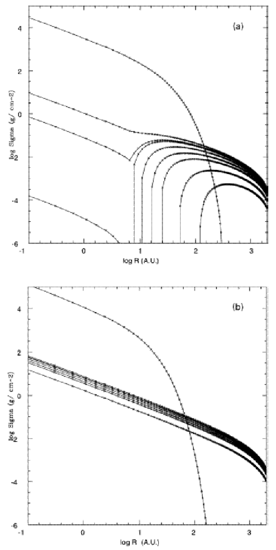


Clarke et al 2001

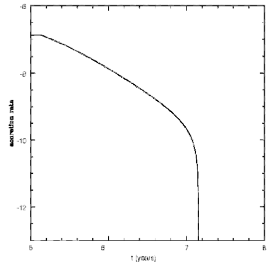
UV radiation photoevaporates outer disk
When mass accretion rate (decreasing by viscous evolution) ~ mass loss rate, no mass reaches inner disk
$R_g \sim G M_* / c_s^2(10000K) \sim 10$ AU (M_*/M_{sol})



Inner disk clearing: photoevaporation of outer disk?



Prediction: rapid decrease of mass accretion rate
= > most transitional disks not accreting

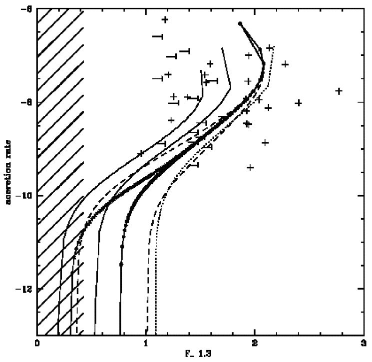


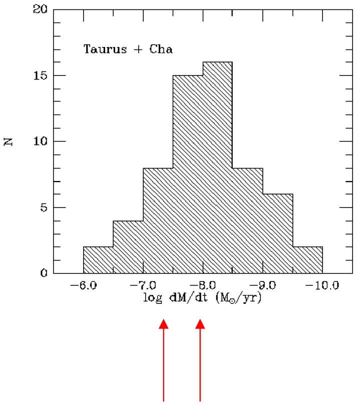
Clarke et al 2001

Inner disk clearing:photoevaporation of outer disk?

Prediction: low mass accretion rate and mm flux in transitional disks

But average mass accretion rates and high mm fluxes in GM Aur and DM Tau





Clarke et al 2001

Summary

- Protoplanetary disks are irradiated emission disks
- For typical accretion rates, stellar (and accretion shock irradiation controls the heating)
- Accretion rates onto the star constrain the surface density
- Although a minor component of the material, dust controls absorption and emission, ie, heating of the disk
- Dust properties can be inferred from the SEDs
- As a given population ages, the fraction of remaining disks tend to have lower accretion rates and their dust more settled towards the midplane
- Fraction of remaining disks decreases with age
- Can transition disks help understand how disks dissipate?

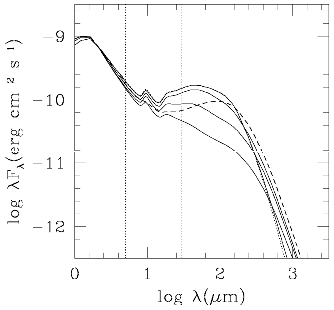
Summary

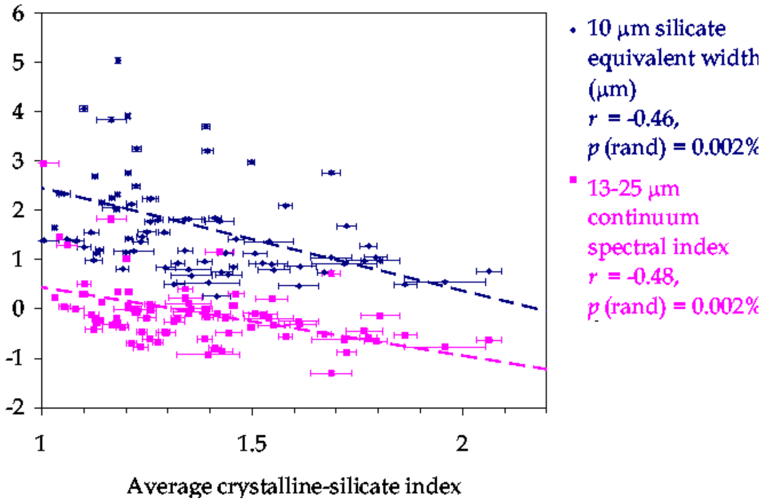
- Great progress in understanding disk evolution
- Spitzer data crucial

- Disks evolve accreting mass onto star and dust growing and settling to midplane
- At some point, disk enters into transitional phase, rapidly turning off accretion and clearing up inner disk

- Alternative models for clearing are planet formation and photoevaporation of outer disks. Present evidence may favor planet formation.
- Characterization of properties of transitional disks in large samples of different ages may settle the issue

Crystallinity increases as SEDs become steeper





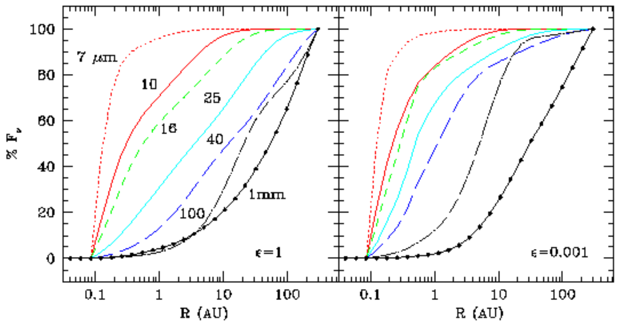
Watson et al 2006

Crystallinity increases with evolutionary stage

- Measure of evolutionary stage at a given age
- Crystallization: annealing of amorphous silicates: exposure to high T ~ 1200K followed by cooling
- More dust processing as dust in disk evolves
- Where is processing taking place?
  - exposure to high stellar high energy radiation?
  - shocks?
  - processing inside planetesimals (Bouwman et al 2003)?

Processing in inner disk

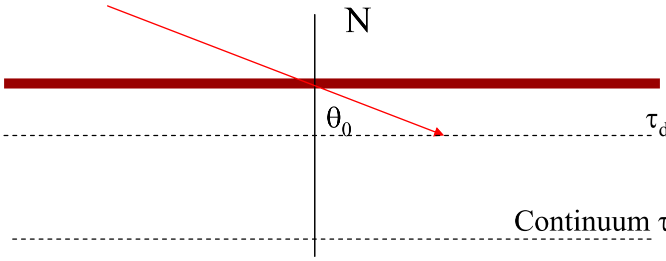
- Silicate feature formed in innermost disk – also flux $\lambda < 10\ \mu\mathrm{m}$
- As degree of settling increases, disk flux comes from a smaller region of the disk



Upper layers are hotter than regions where the continuum form

Radiation enters at angle to local normal: deposits at $\tau_* / \mu_o \sim 1$, $\mu_o = \cos\theta_{o,,}$, , $\tau_* \sim \mu_{o,}$, $\mu_0 << 1$

- Stellar energy is deposited in upper levels

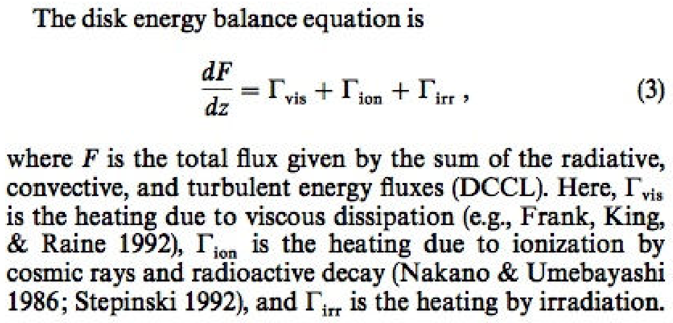


$\tau_{disk} = \mu_0/q << 1$

Continuum $\tau_{disk} \sim 1$

$q = \kappa^*/\kappa_d$

Disk vertical structure equations

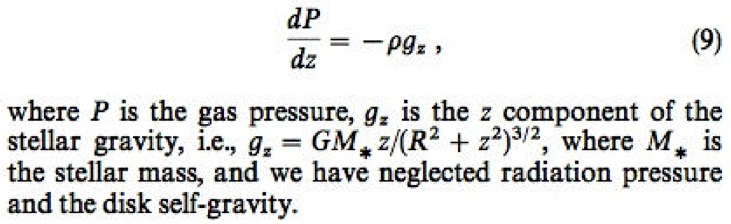


The disk energy balance equation is

$$\frac{dF}{dz} = \Gamma_{\rm vis} + \Gamma_{\rm ion} + \Gamma_{\rm irr} , \qquad (3)$$

where F is the total flux given by the sum of the radiative, convective, and turbulent energy fluxes (DCCL). Here, $\Gamma_{\rm vis}$ is the heating due to viscous dissipation (e.g., Frank, King, & Raine 1992), $\Gamma_{\rm ion}$ is the heating due to ionization by cosmic rays and radioactive decay (Nakano & Umebayashi 1986; Stepinski 1992), and $\Gamma_{\rm irr}$ is the heating by irradiation.

Disk vertical structure equations



$$\frac{dP}{dz} = -\rho g_z , \qquad (9)$$

where P is the gas pressure, g_z is the z component of the stellar gravity, i.e., $g_z = GM_* z/(R^2 + z^2)^{3/2}$, where M_* is the stellar mass, and we have neglected radiation pressure and the disk self-gravity.

Particle motions

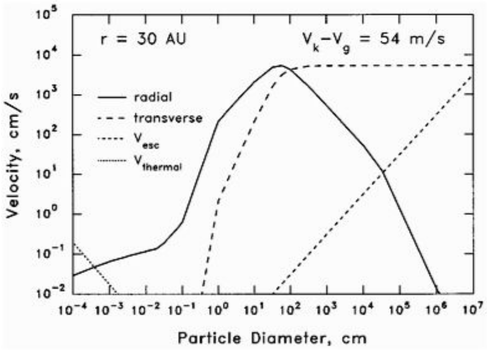


FIG. 1. Particle velocities as functions of size in the model nebula at 30 AU. Particles are assumed to have a fractal structure at sizes 10^{-2} cm, and constant density 0.7 g cm^{-3} at $d > 1$ cm. Dotted line: thermal velocity at $T = 50°\mathrm{K}$. Solid line: radial velocity, with peak value equal to $\Delta V = 54\ \mathrm{m\ sec}^{-1}$ at $d \simeq 10^2$ cm. Changes in slope are due to variation of particle density ($d \lesssim 1$ cm) and transition from Epstein to Stokes drag law ($d \sim 10^5$ cm). Dashed line: transverse velocity relative to pressure-supported gas. Short dashes: escape velocity from the particle's surface.

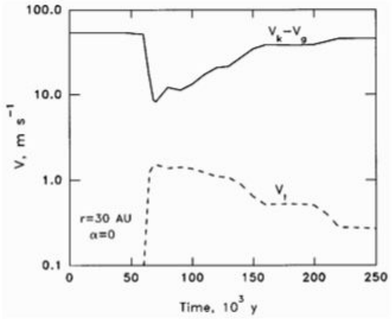
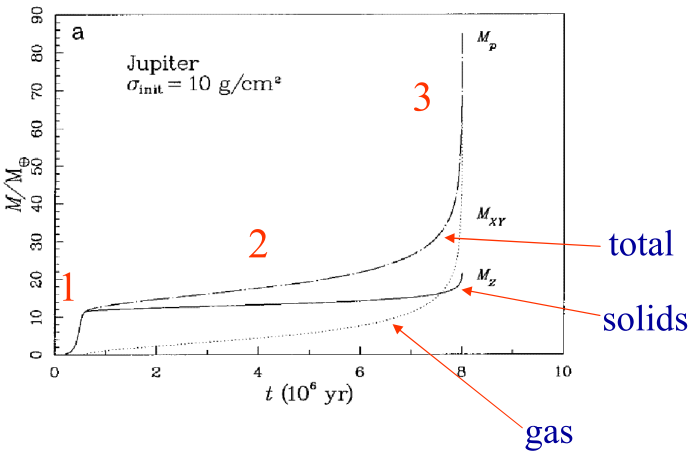


FIG. 4. Deviation of the gas velocity from the Kepler velocity in the central plane of the nebula. At $t = 0$, ΔV has the "free-stream" value of 54 m sec^{-1}. Formation of the dense particle layer drags the gas with it, decreasing ΔV to ≈ 10 m sec^{-1}. As their mean size increases with time, the particles decouple from the gas, allowing ΔV to increase. Dashed line: turbulent velocity induced by shear between the particle layer and surrounding gas.

Giant planet formation theories

Pollack et al. 1996

- Phase 1: Runaway accretion of solids (crossing of planetesimal orbits)
- stops when feeding zone depleted
- Phase 2:Accretion of gas
- Phase 3: Runaway accretion of gas
- Several timescales



- Much shorter if migration included – feeding zone not depleted (Alibert et al 2004)
- Many parameters involved – general idea of physical processes