Dust Growth and Settling in Protoplanetary Disks and Evolution of Disk Spectral Energy Distributions

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Abstract

Dust growth and settling in protoplanetary disks considerably affect their spectral energy distributions (SEDs). We investigated dust growth and settling through numerical simulations to examine time evolution of the disk optical thickness and SEDs. Evolution of grains is divided into a growth stage and a subsequent settling stage. At the end of the growth stage, most of large grains settle to the mid-plane of gaseous disks to form a dust layer, while small grains remain floating above the layer. The floating small grains settle to the dust layer slowly in the settling stage. It takes typically 10^6 yr for micron-sized grains. The optical thickness is governed by the floating small grains rather than large grains in the dust layer. Rapid grain growth in the inner part of disks makes the radial distribution of the disk optical thickness is less steep than that of the disk surface density. We found that the radial distribution of the optical thickness is almost flat for all wavelengths at $t < 10^6$ yr. At $t > 10^6$ yr, the inner disk (< a few AU) becomes optically thin for the central star's light, which will be observed as an inner hole. We further examined time-evolution of disk SEDs,using our numerical results and the two-layer model. The grain growth and settling decrease the magnitude of the SEDs especially at wavelengths longer than 100 micron. Our results indicate that the decrease in the observed energy fluxes at millimeter/sub-millimeter wavelengths with the time scale of 10^6-10^7 yr can be explained by grain growth and settling without depletion of the disks.

Theoretical Model of Disk SED

* *Disk parameters can be fixed by SED observations*

$$L_\nu \propto \kappa_\nu M_{disk}$$

But we also have to fix the dust opacity to derive informations of disks from observations.

* *Two-layer Model of Disk SED*

Reproducing observational SED & Simple

(*Chiang & Goldreich 1997, Chiang et al. 2001*)

* ***This Work :***

Modeling of SED Evolution of Protoplanetary Disks due to Dust Growth and Settling

Dust opacity changes in protoplanetary disks!

Simulation of Dust Growth & Settling

* ***Disk model***

- Minimum-mass solar nebula disk around the sun
- *No* Turbulence ... WTTS

* ***Dust Growth & Settling***

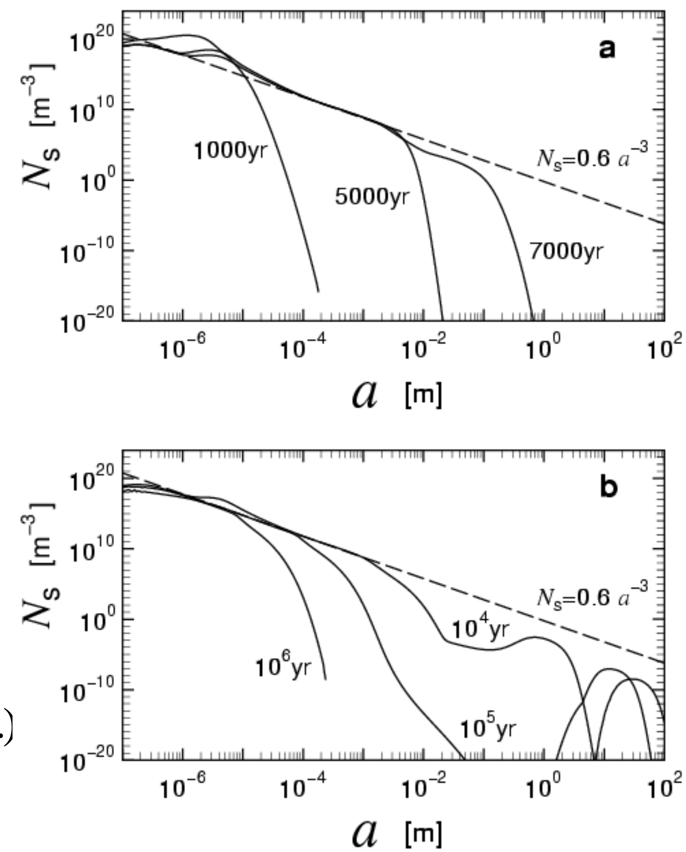
Numerical simulation of the coagulation equation
with a (vertical) advection term
(dust mass, 500 meshes × z-axis, 250 meshes)

* ***Disk Temperature & SED***

Calculation with Two-layer model
(Chiang et al. 2001)

Result 1: Dust Growth and Settling

Dust Size Distribution (8AU)



Dust radius

1. Growth Stage

The dust size distribution becomes power law:

$$N_s(a) = 0.6\, p_s^{-1}\, a^{-3}$$

p_s : sticking probability

2. Settling Stage

Settling onto the dust layer

Smaller dusts settle later.

(Micron-sized dusts remain floating until ~10^6yr.)

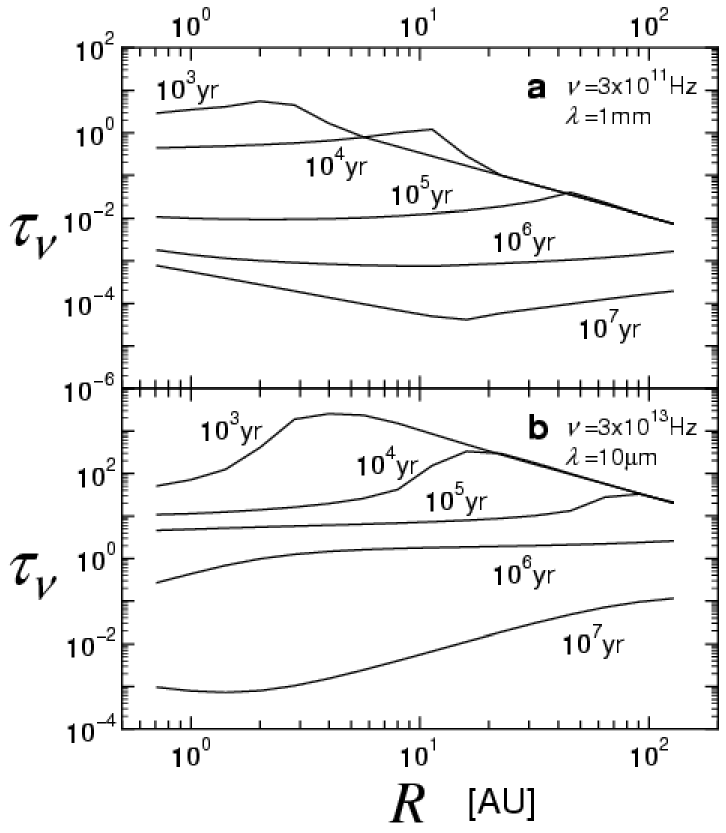
Result 2: Disk Optical Thickness

* Dust growth decreases opacity and the disk optical thickness.

* The decrease in the optical thickness starts from inside of the disk.

The radial distribution of the optical thickness becomes flat.

Radial distributions of disk optical thickness



Two-Layer Model (Chiang et al. 2001)

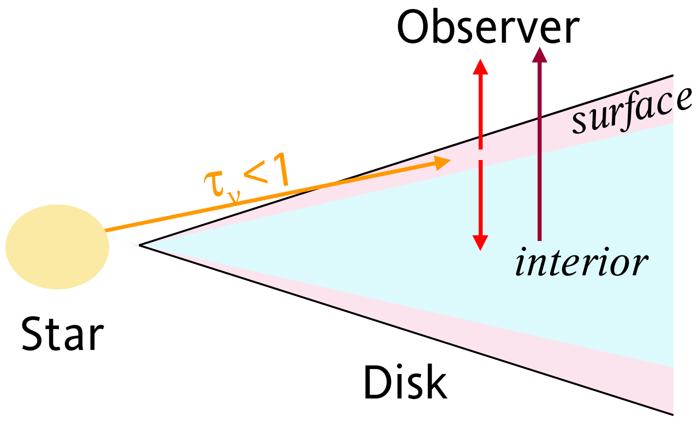
* Two-layer model

Surface layer

- Absorb the radiation from the star
- Optically thin
- High temperature

Disk interior

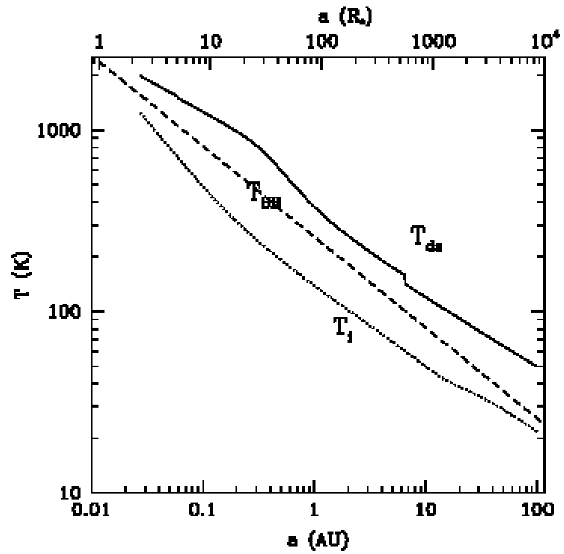
- Heated by the surface layers
- Low temperature



* SED in Two-layer model

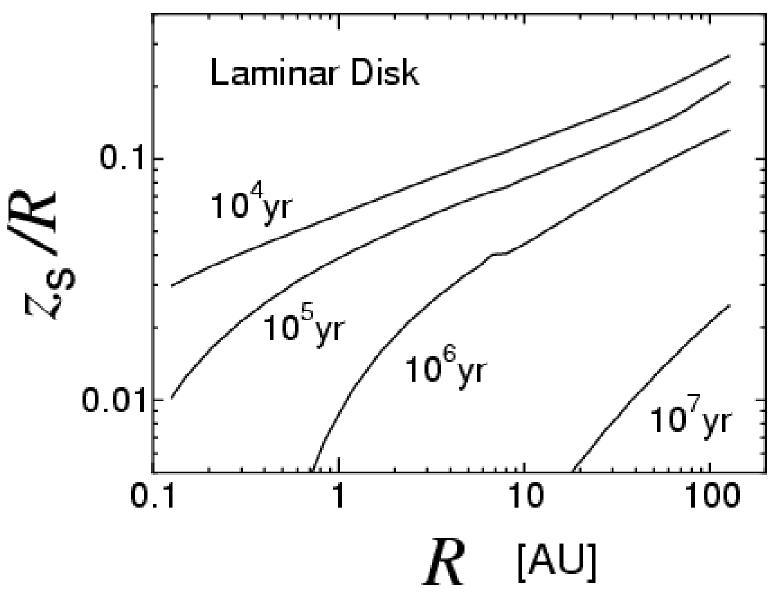
$$L_\nu = L_\nu(\text{surface}) + L_\nu(\text{interior})$$

$$L_\nu(\text{interior}) = \int 4\pi\, B_\nu(T_i)\left(1 - e^{-\tau_{\nu\, i}}\right) 2\pi r dr$$

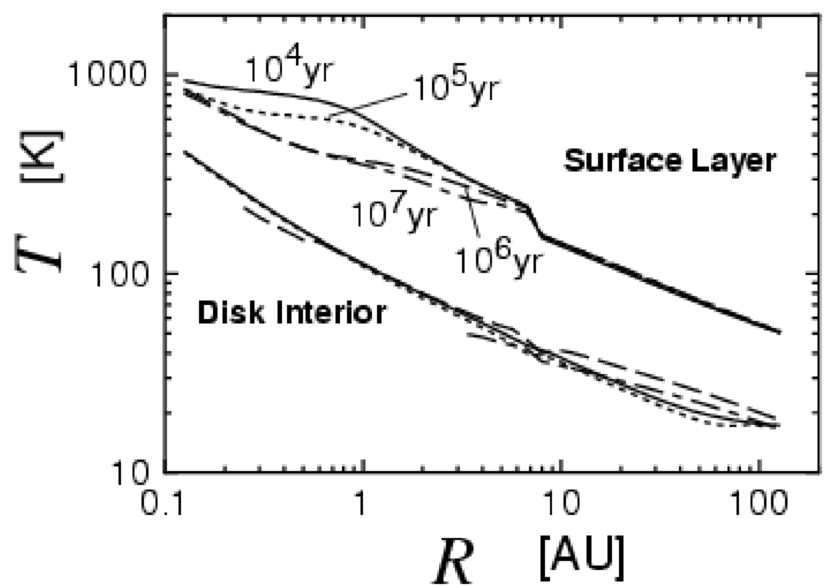


Result 3: Disk Temperature

Descent of Surface Layer



Disk Temperature



Settling of micron-sized dusts makes the surface layer descend.

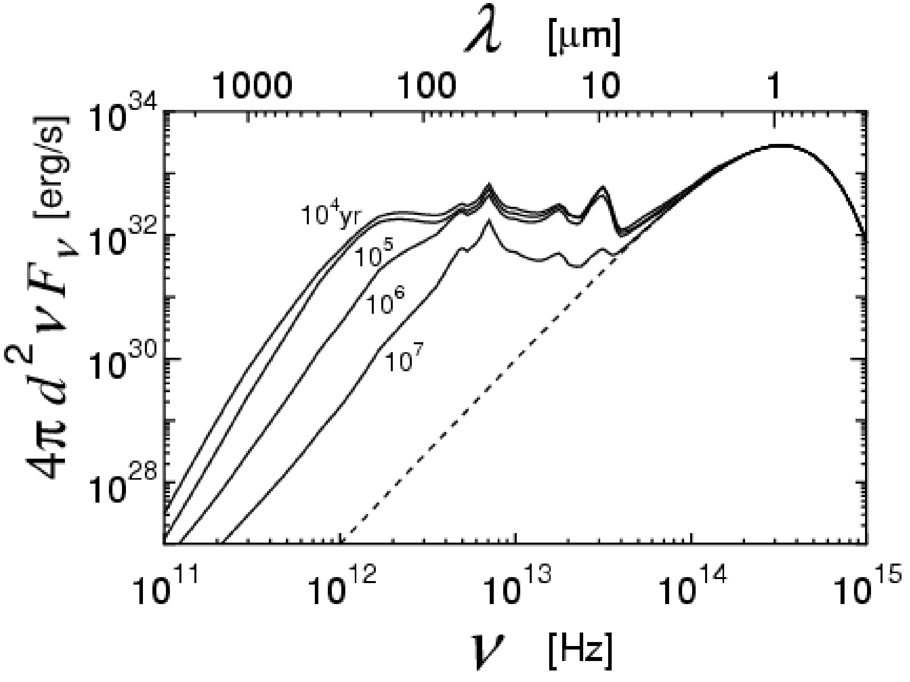
The descent of the surface layer does not changes the disk temperature much.

(In infrared observations, disks would become geometrically thinner.)

(The snow line is at ~0.5AU. Icy planetesimals are created at 1AU!)

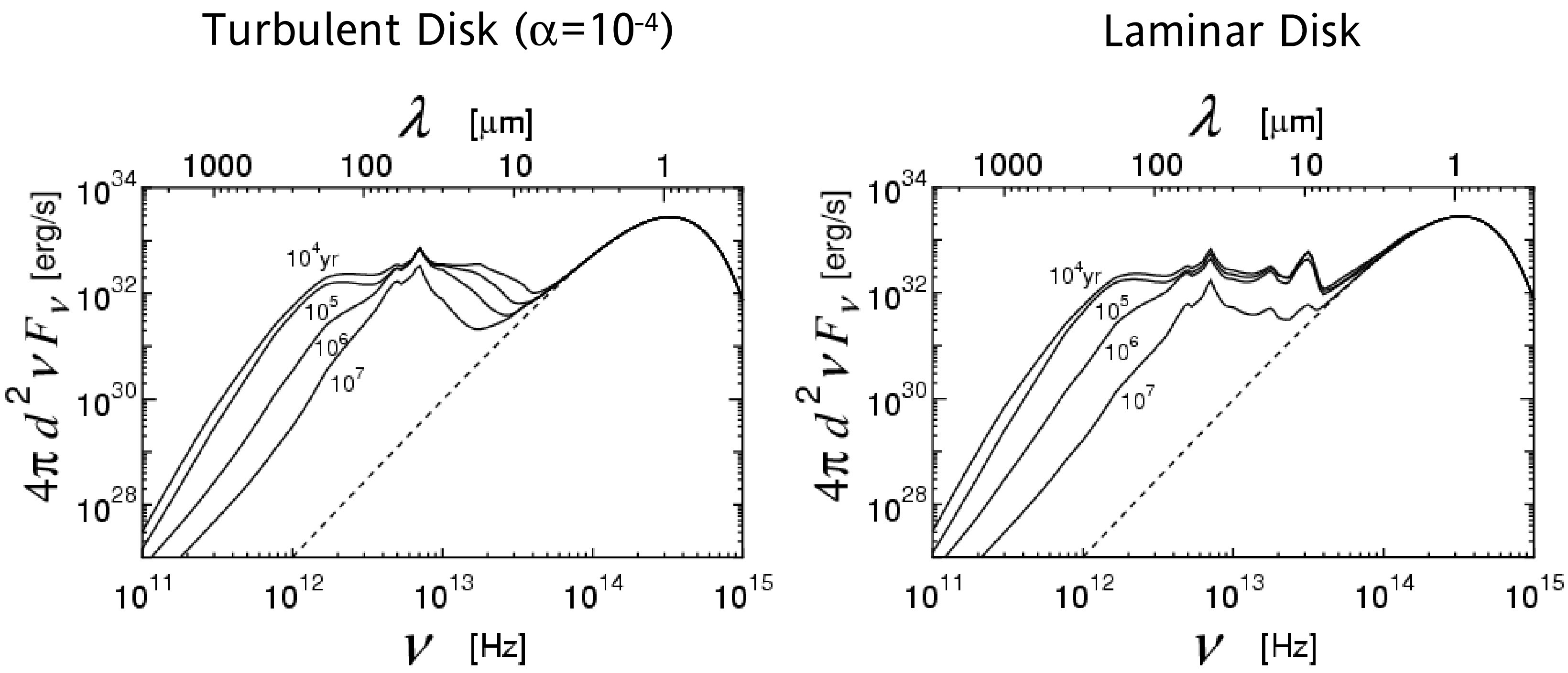
Result 4: Evolution of Disk SED

SED Evolution due to Dust Growth & Settling



Depletion of infrared excess at t >10⁷yr can be explained by dust growth and settling!

Result 5: Effect of Turbulence



Even weak turbulence enhances grain growth much, especially in the inner part of the disk.

SUMMARY

1. Dust growth & settling makes the disk thinner optically & geometrically.
2. Dust size distribution becomes power-law:

   $N_s(a) = 0.6\ p_s^{-1}\ a^{-3}$ (It is independent of disk properties.)

3. Dust growth makes the radial distribution of the disk optical thickness flat.
4. Disk temperature does not change much due to growth & settling. In the minimum-mass disk around a one-solar-mass star, the snow line is at ~ 0.5AU.
5. Depletion of the infrared excess at $t>10^7$yr can be explained by dust growth & settling. Disk life time may be longer than 10^7yr.