# Thermal Structures of Low Metallicity Disks

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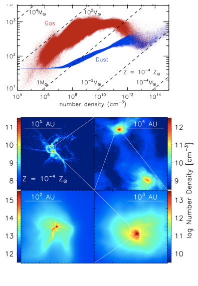
## Abstract

Disk fragments would affect the final mass of low metal stars. We analytically study the disk stability in low metallicity star formation. We evaluate the typical infall rate and the angular momentum of infalling gas for various metallicities. The accretion rates decreases with Z, and the angular momentum increases with Z. With this derived infalling model, we calculate the disk stability. For the low metal disks with Z>10$^{-5}$Zsun, disks are unstable by the dust cooling. Although this study applied the analytic steady state model for simplicity, our results would be a good guide for more realistic dynamical future studies.

## 1. Introduction

Dopcke+12



The first stars are thought to be massive ~100Msun. On the other hand, the stars in solar neighborhood are typically much lower masses of ~1Msun. How about the stars in low metallicity environment?

The dust cooling is expected to fragment the accretion gas into clamps in the low metallicity star formation.

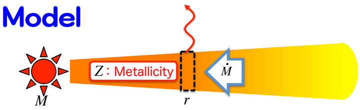
Due to the conservation of the angular momentum, the disks are the naturally formed in star formation process and most material is thought to accretes though a disk. So, in this work, we investigate followings.

How dust cooling affect the disk temperature?
How the star formation process would change by metallicity?

## 2. Temperature of Low Metallicity Disk

Here we demonstrate how the dust cooling affects on the disk temperature and stability for various metallicities.

### 2.1. Model



**Basic Equations**

Eq. for Disk Structure

$$H=\frac{c_s}{\Omega_K},\quad c_s^2=\frac{k_BT}{\mu m_H},\quad \nu\Sigma=\frac{\dot{M}}{3\pi},\quad \nu=\alpha c_e H$$

Local Thermal Equilibrium @each radius: $Q^+=Q^-$

Heating $Q^+=\frac{9}{8}\nu\Sigma\Omega^2$ : Viscous heating

Cooling $Q^-=H\left(\Lambda_{\rm line}+\Lambda_{\rm g,cont}+\Lambda_{\rm d,cont}\right)$

$$\Lambda_{\rm line}=\Sigma\Lambda_{ij}\beta_{ij},\Lambda_{\rm cont}=\frac{4\pi\rho}{1+x}\left(\kappa_{\rm g,p}T^4+\kappa_{\rm d,p}T_{\rm d}^4\right),x=\tau_{\rm p}\left(1+3\tau_{\rm R}^2/\tau_{\rm p}\right)$$

: H$_2$ line + Gas continuum + Dust continuum ( Omukai00 etc. )

Parameters

Stellar mass : $M_*=1-100M_{\rm sun}$
Disk radius : $r=1-100{\rm AU}$
Accretion rate: $\dot{M}=10^{-7}-10^{-1}M_{\rm sun}{\rm yr}^{-1}$
Metallicity : $Z=0-Z{\rm sun}$

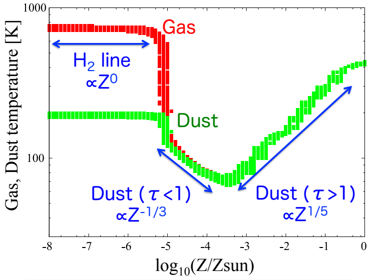
※We ignore the gas-phase metal line cooling, which is important for low density envelope. We assume the gas-to-dust ratio is simply proportional to the metallicity.

### 2.2. Results

Fig.1 shows the temperature dependence on the metallicity.

1. For Z<10$^{-5}$Zsun
   H2 line cooling dominates → Tg is independent on Z.
   Dust collision with dust is insufficient, thus Td<Tg.
2. For 10$^{-5}$Zsun<Z<10$^{-3}$Zsun
   Optically *thin* dust cooling dominates → Tg decreases with Z.
   Dust collision with dust is sufficient for Td = Tg.
3. For 10$^{-3}$Zsun<Z
   Optically *thick* dust cooling dominates → Tg increases with Z.

Fig.1: Temperature dependence on Metallicity
With 1Msun, 10$^{-3}$Msun/yr, 100AU



Dust cooling dominates when

$$Z>Z_{\rm cr}\approx4.5\times10^{-6}\beta^{-1/4}\left(\frac{\dot{M}}{10^{-3}M_{\rm sun}{\rm yr}^{-1}}\right)^{-1}\left(\frac{\Omega}{300{\rm year}}\right)^{-3/4}\left(\frac{\alpha}{0.6}\right)^{9/4}Z_{\rm sun}$$

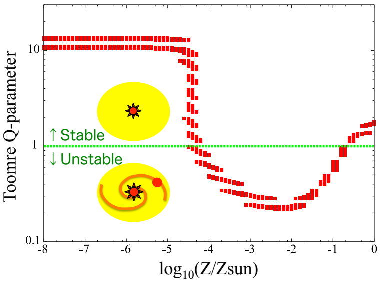
Fig.2 shows the gravitational stability dependence on the metallicity. Since the low metal disk with Z>10$^{-5}$Zsun is cooler than the zero-metal disk, the low metal disks are more unstable.

Toomre Q-parameter (Toomre64)

$$Q_{\rm T}=\frac{c_s\Omega}{\pi G\Sigma}=\frac{3\alpha c_s^3}{G\dot{M}}=3\left(\frac{T}{1000{\rm K}}\right)^{3/2}\left(\frac{\dot{M}}{10^{-3}M_{\rm sun}{\rm yr}^{-1}}\right)^{-1}\left(\frac{\alpha}{0.6}\right)\left(\frac{\mu}{2.3}\right)^{-3/2}$$

1<Q$_T$: stable, Q$_T$<1: unstable

Fig.2: Stability dependence on Metallicity
With 1Msun, 10$^{-4}$Msun/yr, 100AUの場合



The unstable disks would form fragments or companion, relay on the strength of its instability. Hydrodynamic simulations by Kratter+10 shows that disks with $\xi\sim10\alpha/Q_T>5$ forms the binary systems.

## 3. Disk Stability in Low Metallicity Star Formation

The infall rate and angular momentum reflect its pre-stellar core properties (i.e. infall rate, radius, and angular velocity), which depend on the metallicity. We evaluate the typical infall rate and typical pre-stellar radius for each metallicity, and investigate the stability for those pre-stellar cores.

### 3.1. Model

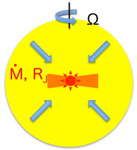
We evaluate typical pre-stellar core properties from the one-zone model (Omukai+10). From (ρ,T) in one-zone model is converted to the pre-stellar core infall rate M$_{\rm infall}$ and its radius R$_J$ as fûnction of the instantaneous stellar mass. Using this derived infalling gas mode, we calculate the disk stabilities as shown above.

**Conversion Relations**

Enclosed mass: $M_{\rm J}=\rho R_{\rm J}^3$

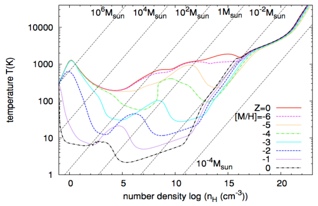
Accretion rate : $\dot{M}_{\rm infall}=\frac{c_s^3}{G}$

Radius: $R_{\rm J}=c_s\sqrt{\frac{\pi}{G\rho}}$



※Rotational velocity cannot be determine by one-zone model

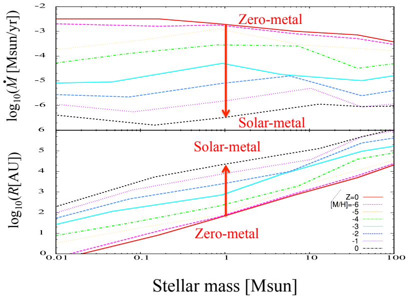
One-Zone model by Omukai+10



### 3.2. Results

Fig.3 shows the typical infall rate and core radius for various metallicities. The pre-stellar core temperature decreases with Z. Therefore, the infall rate decreases with Z (Mdot∝T$^{3/2}$). For a fixed Jeans mass, the Jeans length decreases with T as R∝T$^{-1}$. Then, the typical core radius for same enclosed mass increases with Z.

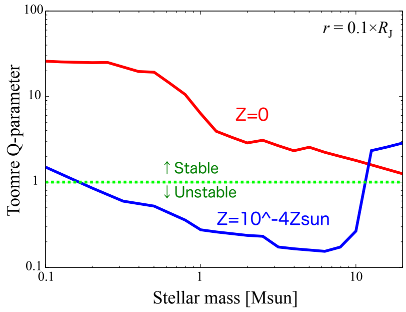
Fig.3: Accretion rate & core radius as functions of stellar mass for various metallicities



Z↑ leads core-Mdot↓ and core-R↑(Fig.3).
Mdot↓ stabilize the disk, but R↑ destabilize the disk .
Z↑ also leads the disk temperature lower (Fig.1),which destabilize the disk.
So then, Z↑ makes the disk stable? or unstable?... Unstable!!

Fig.4 shows the disk stability as functions of the stellar mass for Z=0,10$^{-4}$Zsun, using the infall rate and core radius obtained from one-zone model. The low metallicity disk is unstable. Such an unstable disk would be fragment, or forms the binary system.

Fig.4: Disk stability for various metallicities



## 4. Conclusion

We analytically evaluated the disk thermal structure and its stability. We found that
1) The dust cooling dominates Z>10$^{-5}$Zsun.
2) In the formation of the low metallicity stars, the disk would be unstable by dust cooling.

From these results, We conclude that the low metallicity stars tend to be formed as binary systems. However, our model is still limited and we need to include the accretion luminosity heating which could stabilize the low metal disks. Of course, It is also necessary to the dynamical effect by simulations.