Simultaneous Growth of a Protostar and a Young Circumstellar Disk in the Early Phase of Disk Formation

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Abstract

- The growing process of the young protostar and the circumstellar disk is investigated.
- We focus on the viscous evolution of the non-isolated disk subject to mass loading from the envelope in the early phase of main accretion.
- We study the origin of surface density distribution of the disk and the origin of the disk to star mass ratio by numerically solving unsteady evolution of one-dimensional axisymmetric model for viscous accretion disk.
- Finally, the P-V diagram of the disk in our model is shown in order to compare with the observations of the star-forming region.

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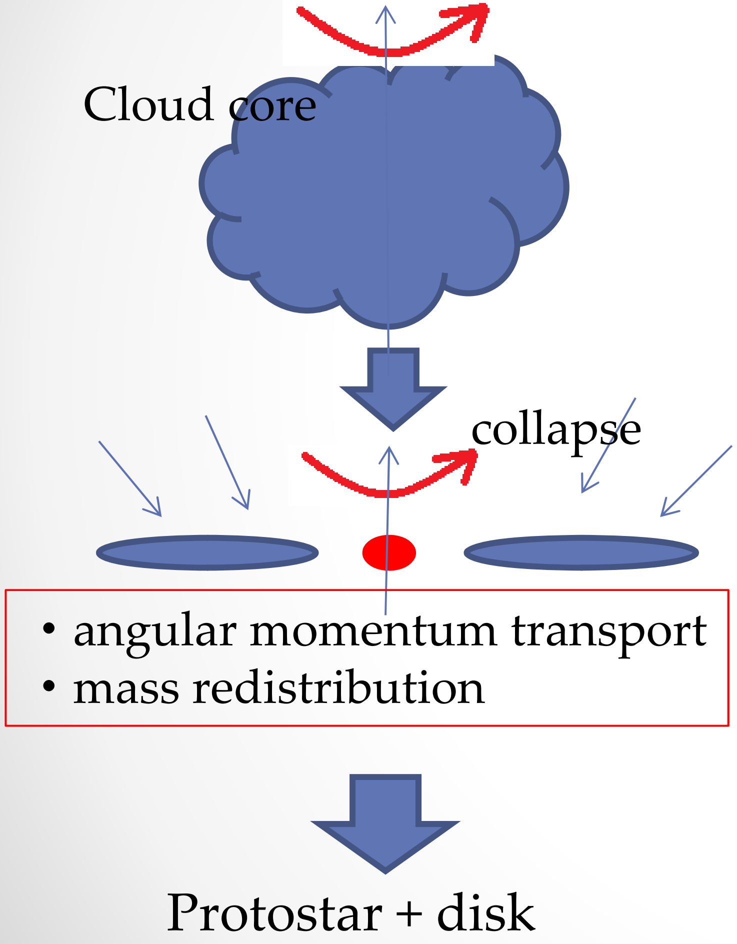
1.Introduction



Cloud core

collapse

- angular momentum transport
- mass redistribution

Protostar + disk

- Protoplanetary disks are the birthplace of planets. It is important to know the forming mechanism of young disks.
- As a result of gravitational collapse of a rigidly rotating cloud core, a small central star and a massive disk is expected as an equilibrium state if one assumes the conservation of angular momentum with a typical amount.

1. Introduction

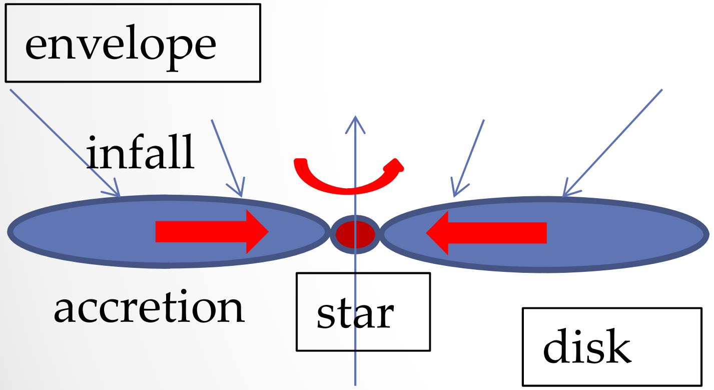
- However, observation indicates the lower mass disk than predicted above equilibrium state.
- An efficient transport of angular momentum is expected. It will drive the mass accretion flow onto the central star to decrease the disk mass.

This accretion flow is important to determine the disk to star mass ratio.

- The unsteady and viscous evolution of the disk is studied taking into account of the simultaneous growth of the disk and the central star.

2.Models

We consider the model in which it is assumed that disk mass is fueled by infalling envelope, and simultaneously loses its mass via accretion onto the central star.



The simultaneous growth of the disk and star includes two processes.

- Accretion from an infalling envelope to the disk
- Accretion from the disk onto the central star

(viscous mass accretion)

Models

2.1 Accretion from an infalling envelope to a disk

Self-Similar solution given by Saigo& Hanawa(1998)

- The disk formation following the runaway collapse of a rotating cloud core
- Axisymmetric and inviscid isothermal flow

Mass accretion rate of isothermal collapse

$$\dot{M} = \mu_d \frac{{c_s}^3}{G}$$

Saigo& Hanawa(1998) $\mu_d = 6\sim10$(accretion rate onto the disk)

depends on the speed of rotation

Models

The coefficient μ_d depends on the detail of the collapse.

Axisymmetric dynamical flow onto the disk is assumed in this model.

c.f.) Isothermal self-similar solution with spherical asymmetry

Hunter(1977) $\mu_d = 46.915$ Shu(1977) $\mu_d = 0.975$

Solution	Collapse
Hunter (pair solution for Larson(1969) and Penston(1969)), Saigo & Hanawa	Dynamical
Shu	Quasi-static

Models

2.2 Accretion from the disk onto the central star

- Basic equations

Standard accretion disk (Pringle1981)

axisymmetric thin disk

Continuity Equation

$$r\frac{\partial \Sigma}{\partial t}+\frac{\partial}{\partial r}\left(r\Sigma v_r\right)=0$$

Equation of motion

$$\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}=-\frac{c_s{}^2}{\Sigma}\frac{\partial \Sigma}{\partial r}-F_r+\frac{v_\phi{}^2}{r}$$

Equation for conservation of the angular momentum

$$r\frac{\partial}{\partial t}\left(\Sigma r v_\phi\right)+\frac{\partial}{\partial r}\left(r\Sigma v_r r v_\phi\right)=\frac{\partial}{\partial r}\left(\nu\Sigma r^3\frac{\partial \Omega}{\partial r}\right)$$

Gravitational force

$$F_r \equiv \frac{GM}{r^2}\ , M = M_* + M_{disk}\quad M_{disk} = \int_0^r 2\pi r\Sigma dr$$

Viscous coefficient

$$\nu=\alpha c_s h \qquad h\sim\frac{c_s}{\Omega}$$

The range of α: 0.01~1

Models

Approximation

- Pressure gradient force is negligible.
- Accretion speed within the disk is sufficiently slow.

The above equations can be combined to

$$\boxed{\frac{\partial \Sigma}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{1}{\frac{\partial (r v_\phi)}{\partial r}} \frac{\partial}{\partial r}\left(\nu \Sigma r^3 \frac{\partial \Omega}{\partial r} \right) \right)}$$

- Temprature (barotropic EOS)

$$c_s = \begin{cases} 0.2(\mathrm{km/s})(\rho < \rho_{\mathrm{crit}}) \\ 0.2\left(\frac{\rho}{\rho_{\mathrm{crit}}}\right)^{\frac{\gamma-1}{2}}(\mathrm{km/s})(\rho > \rho_{\mathrm{crit}}) \end{cases}$$

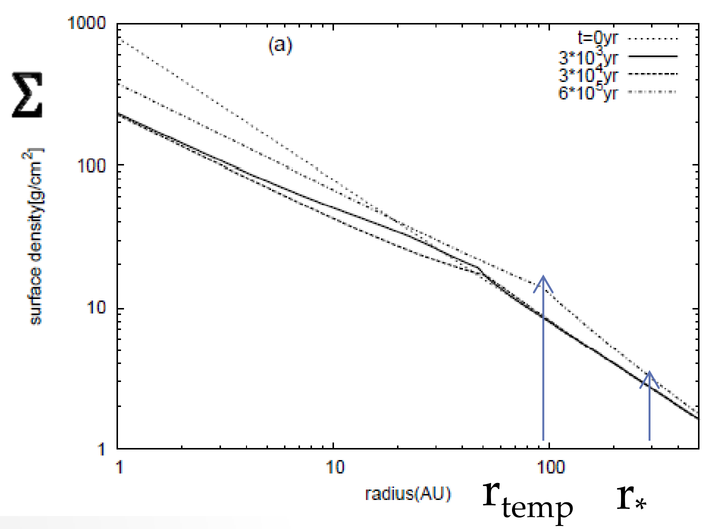
- Radial profiles of the inviscid disk Saigo&Hanawa(1998)

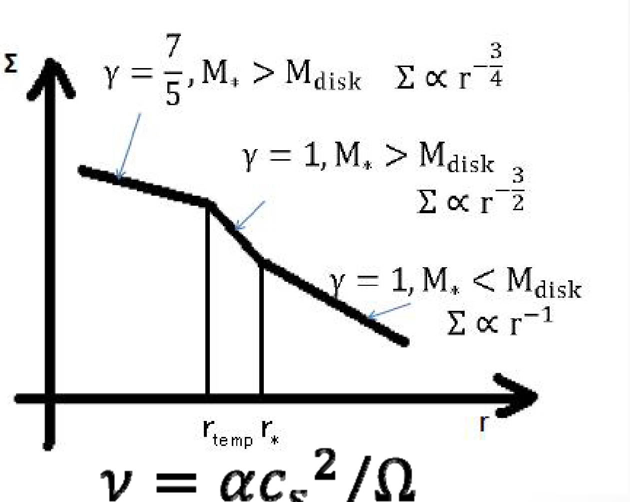
(Initial condition of the disk for viscous mass accretion)

$$\Sigma = \Sigma_1 r^{-1}, M_{disk}(r) \propto r \qquad j = \omega \frac{GM(r)}{c_s}$$

3.Results

3.1 Surface density profile





$$\nu = \alpha {c_s}^2/\Omega$$

- The radial profile of surface density is determined mainly by the process of angular momentum transport rather than the original distribution of angular momentum in the cloud core.
- The profile of surface density is derived from the equation $\dot{M}$ =constant with radius.

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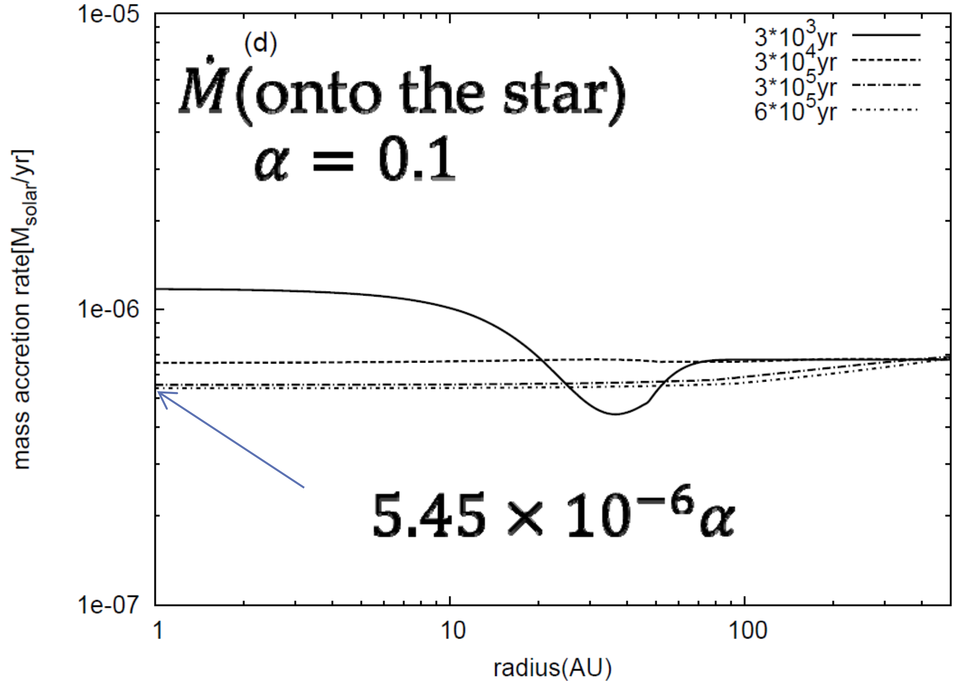
3.2 Masses

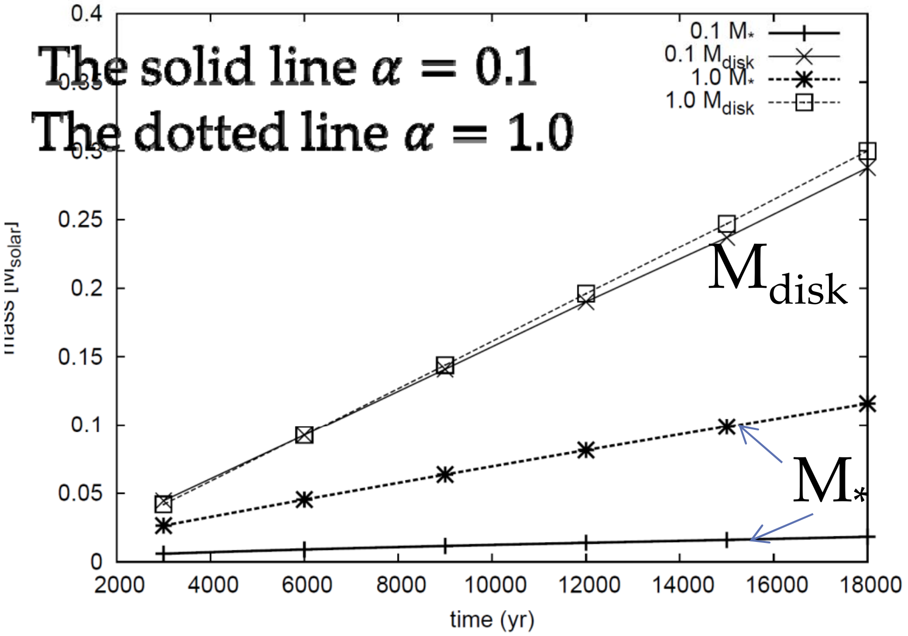
$$\dot{M}_{infall}(\text{onto the disk}) = 1.6 \times 10^{-5}(M_{solar}/yr)$$



$\dot{M}$(onto the star)

$\alpha = 0.1$

$5.45 \times 10^{-6}\alpha$



The solid line $\alpha = 0.1$

The dotted line $\alpha = 1.0$

M_{disk}

M_*

- It is seen that both M_* and M_{disk} grow with time.
- It is found that the disk to star mass ratio M_{disk}/M_* is larger than unity in the case with α< 1 in the long time limit, as long as the constant dynamical flow onto the disk is assumed.

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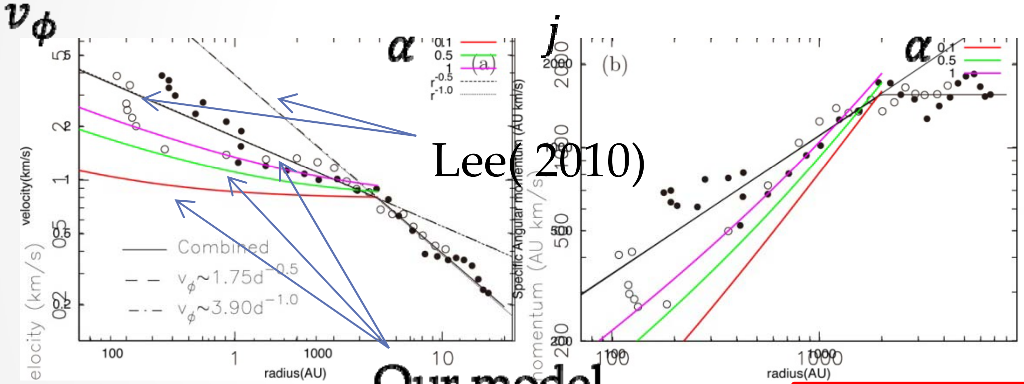
3.3 Comparison with the observation

Lee(2010) The HH111 protostellar system (Class I) is observed.
The rotational velocity is observed using line emission around VLA 1 source.
The inner part of envelope(~2000AU) is thought to rotate with Kepler velocity $v_\phi \propto r^{-0.5}$ perpendicular to the jet axis.

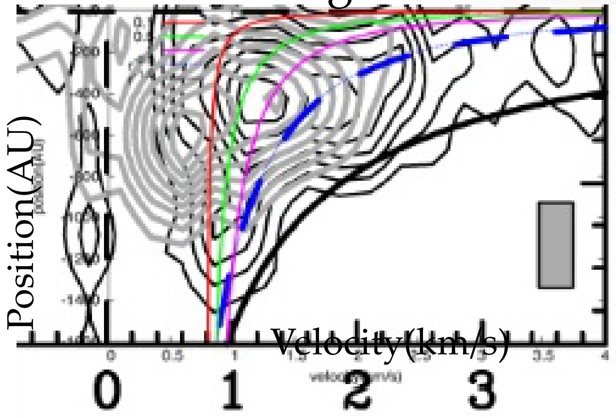
Lee,C., F.,2010 ApJ,725,712



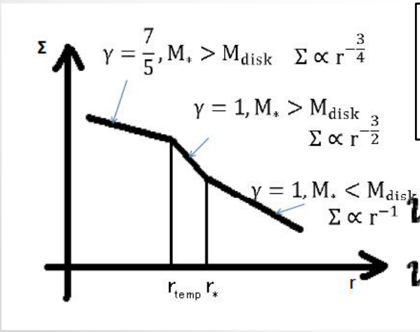
Lee(2010)

Our model
$(6 \times 10^4 (\mathrm{yr}))$

P-V diagram



Our results



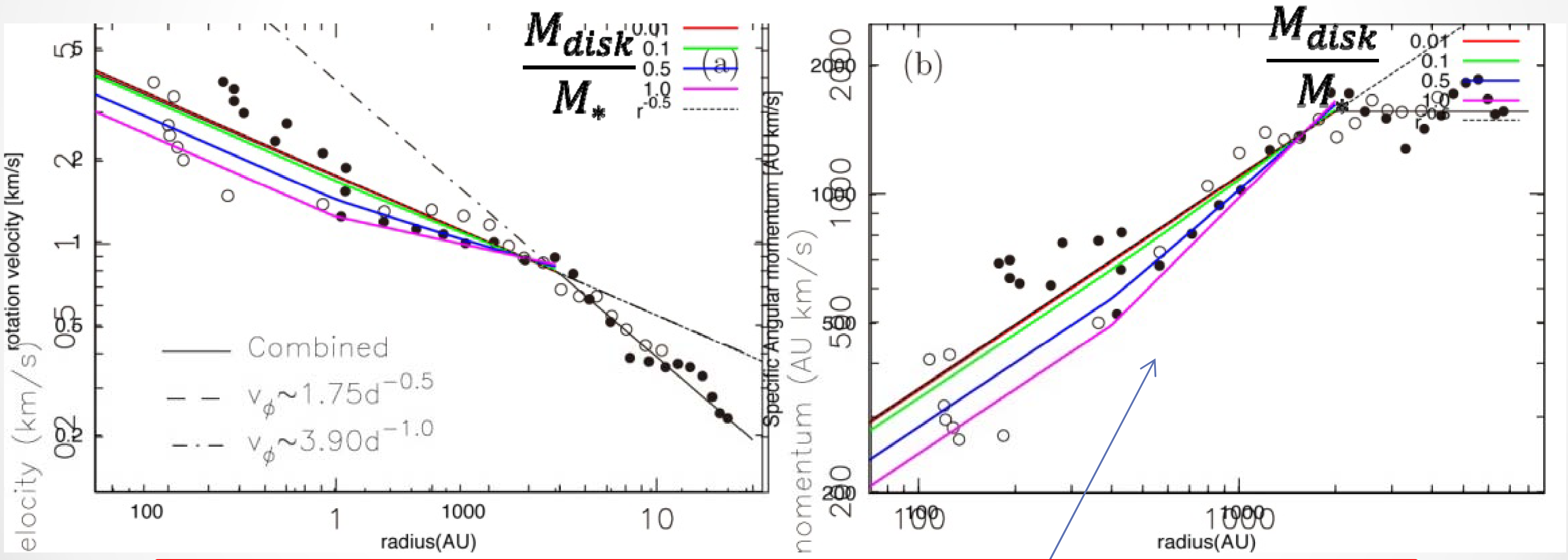
The existence of the heavy disk

$v_\phi \propto r^{-0.5}$ in $r < r_*$
$v_\phi \propto r^{-1}$ in $r > r_*$

- The azimuthal velocity in our model consists with the that of observation in 300-2000AU for the cases with $\alpha > 0.5$. Mass ratios (M_{disk}/M_*) are 5.4/1 $(\alpha = 0.5)$ and 3/1$(\alpha = 1.0)$.
- The effect of flat rotation can be seen in the self-gravitating region.

- Dependence on $\frac{M_{disk}}{M_*}$

The disk is assumed to exists in 400-1600(AU).
The power index of the radial profile of $\Sigma(r)$ satisfies the result in 3.1.



$\frac{M_{disk}}{M_*} > 0.5$ is required in order to explain the observation.

Conclusion

- The disk evolution is determined mainly by the process of angular momentum transport rather than initial profile of angular momentum distribution in the molecular cloud core.
- The disk to star mass ratio M_{disk}/M_{*} is larger than unity in the case with $\alpha < 1$ in the long time limit, as long as the constant dynamical flow onto the disk is assumed.
- The effect of flat rotation can be seen in the observation of star-forming region.