Photoevaporation of Externally Irradiated Protoplanetary Disks in a Young Star Cluster

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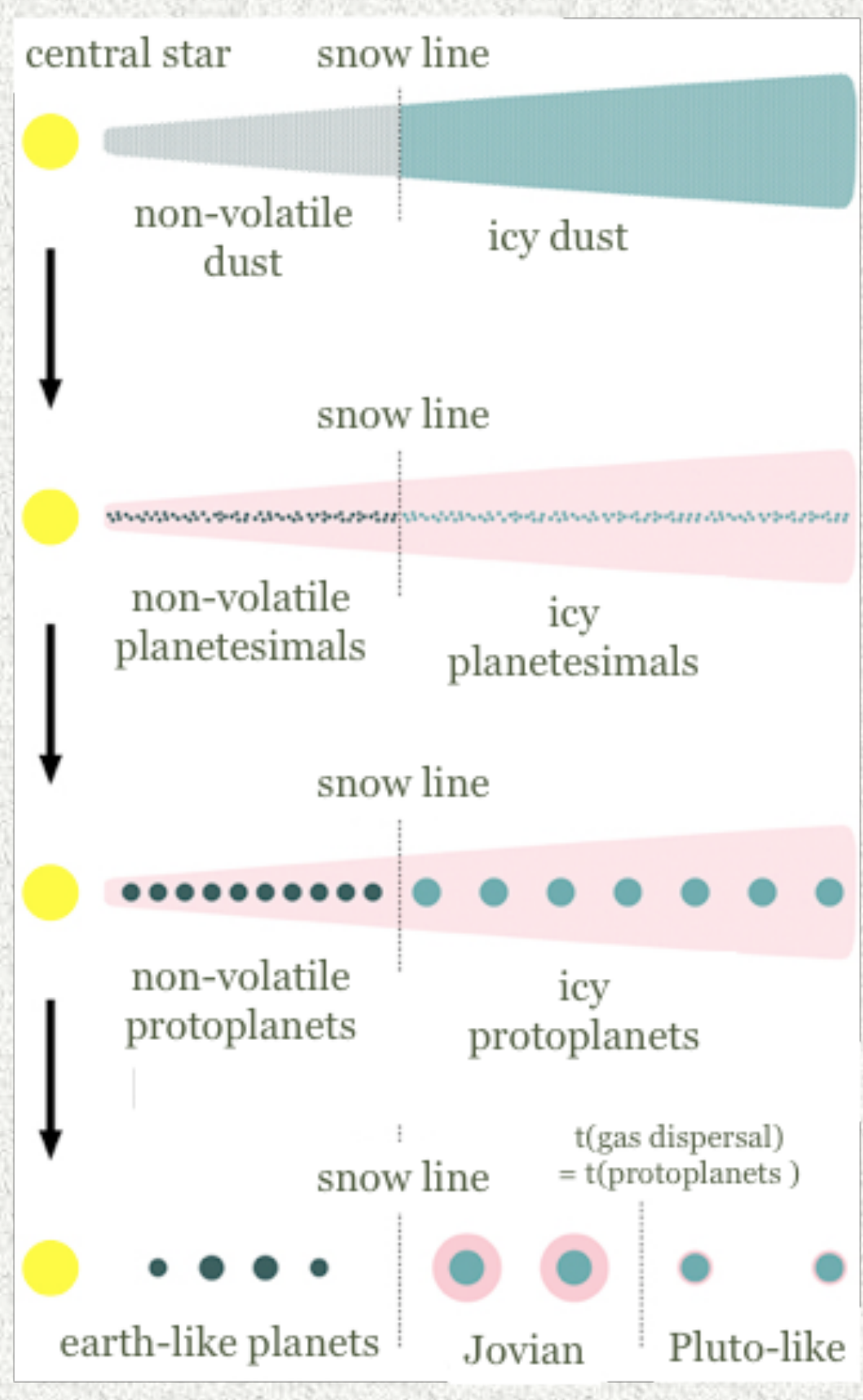
Abstract

The gas dispersal of protoplanetary disks has great influence on the formation of planetesimals and giant planets. The dominant mechanisms of the dispersal are accretion onto the central star and photoevaporation. In particular, protoplanetary disks are considered to photoevaporate rapidly when they are in star clusters. In this work, (1) we calculated the surface density evolution of the disks with considering photoevaporation due to the nearby massive star and accretion onto the central star and (2) performed hydrodynamical simulations of the photoevaporating flow from the disks, and obtained the radii of the ionization fronts around the proplyds by calculating the flux of the ionizing photons from the nearby massive star.
As a result, the outer disk rapidly evaporates and the disks shrink to several tens AU in 10^6 yr. The correlations between the ionization front radii/disk radii and the distances from the massive star observed in the Trapezium cluster are well reproduced by our model calculation.

Introduction



Gas dispersal of protoplanetary disk

Gas dispersal has significant impacts on planet formation proesses in protoplanetary disks - for example, planetesimal formation, gaseous planets formation, planet migration, and so on.

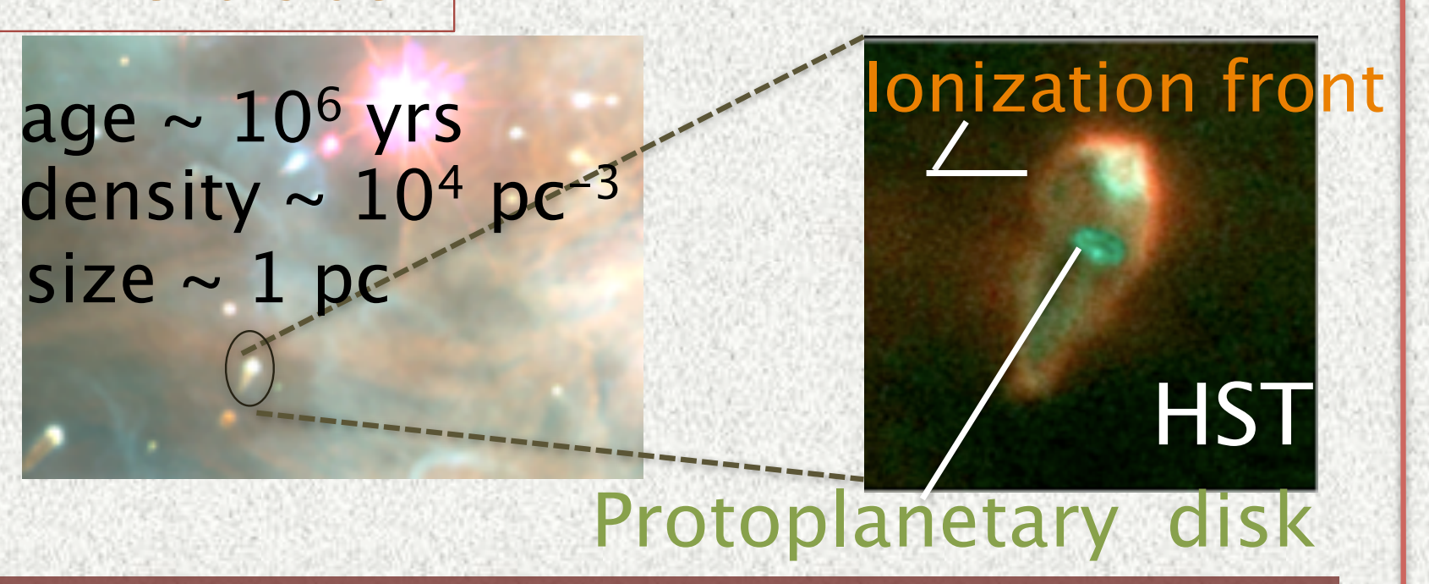
Disk evolution in a star cluster

Since many stars are born in young star clusters, studying environmental effects in clusters is essential for general under standing of planet formation process.

We studied the gas dispersal of the disks taking into account photoevaporation due to a nearby massive star.

Protoplanetary disks in the Trapezium cluster

Protoplanetary disks in the Trapezium cluster are photoevaporating due to UV irradiation from the nearby massive star θ^{I} Ori C. The disks are surrounded by tear-drop-shaped ionization fronts.



Surface Density Evolution of Protoplanetary Disks

The surface density evolution due to photoevaporation and accretion.

$$\frac{\partial \Sigma}{\partial t} = \dot{\Sigma}_{ac}(r,t) - \Sigma_{pe}(r,t)$$

Accretion

The gas in the disks accretes to the central star due to the turbulent viscosity. $\dot{\Sigma}_{\rm ac} = \frac{3}{r}\frac{\partial}{\partial r}\sqrt{r}\frac{\partial}{\partial r}\left(\sqrt{r}\nu\Sigma\right)$ e.g., Lynden-Bell & Pringle (1974)

Photoevaporation

The gas escapesfrom the disks due to the heating by UV irradiation.

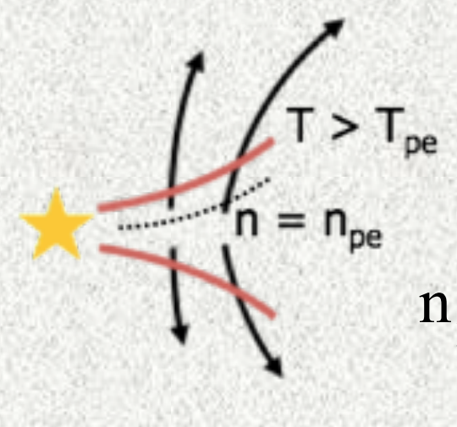
$$\dot{\Sigma}_{\rm pe} \sim \mu m_{\rm H} n_{\rm pe} c_{\rm s} = n_{\rm pe}(\mu m_{\rm H} k T_{\rm pe})^{1/2}$$

$$\frac{2\gamma}{\gamma-1}c_s^2 \sim \frac{GM_*}{r} \longrightarrow T_{\rm pe} = 3770K\left(\frac{r}{10{\rm AU}}\right)^{-1}\left(\frac{M_*}{M_{\rm sun}}\right)$$ e.g., Gorti & Hollenbach(2009)

The gas can escape from the disks when T> T_{pe}.
n_{pe} : the density at the bottom of the photoevaporating flow where T= T_{pe}.

Disk model with external irradiation

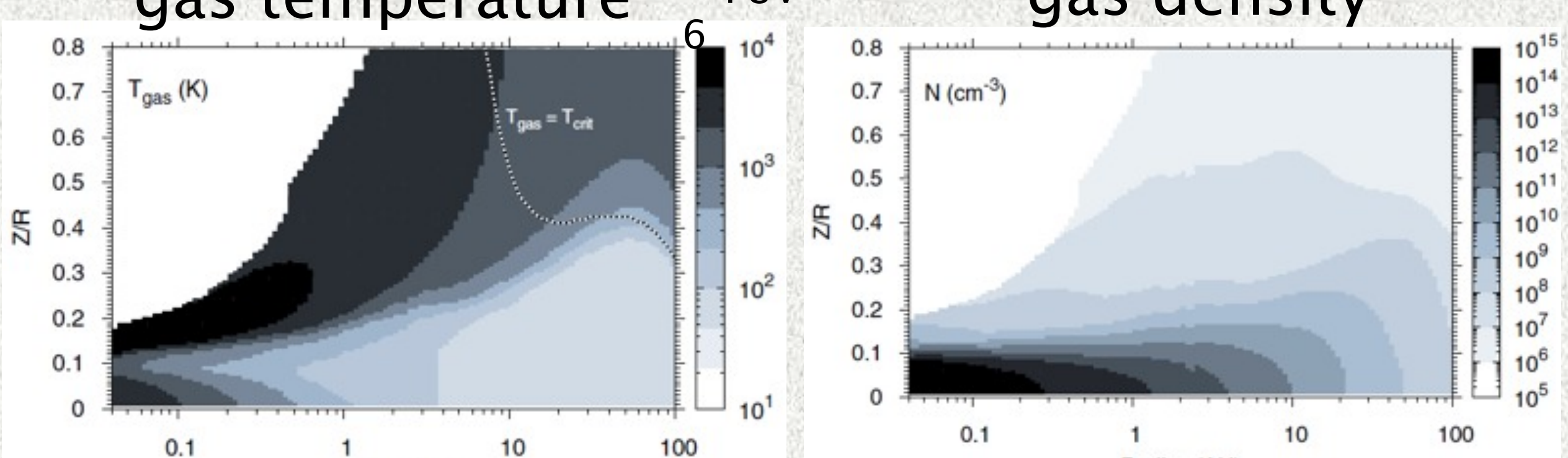
- Gas density profile: vertical hydrostatic equilibrium
- Gas temperature profile: local thermal equilibrium (G_X+ G_{pe}+L_{gr}−L_{line}=0)
- Dust temperature profile: local radiative equilibrium



$$n_{pe} = 3.4(\log G_{FUV} - 3.6)\times 10^6 {\rm cm}^{-3}$$

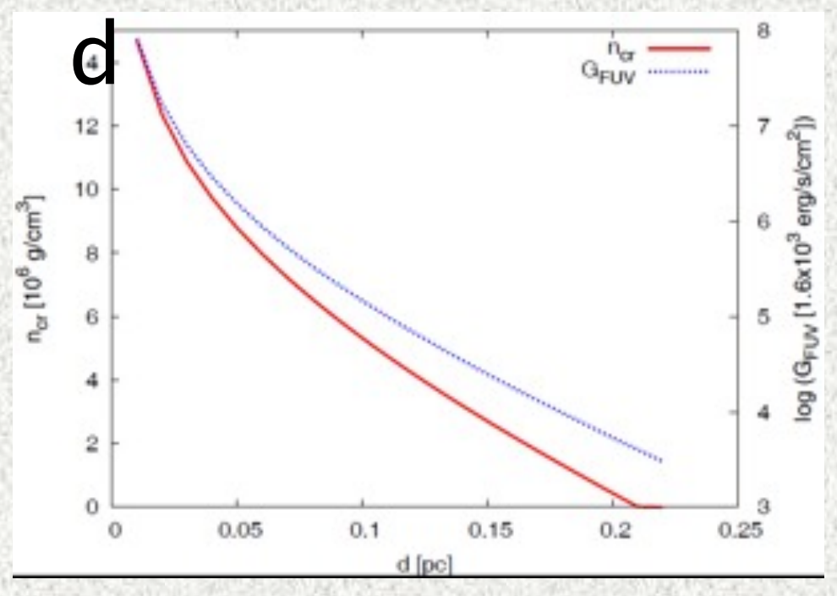
$$G_{FUV} = \frac{L_{*,FUV}}{4\pi d^2}\exp(-n_{bc}\sigma_{ext}d)$$

gas temperature $G_{FUV}=10^6$ gas density



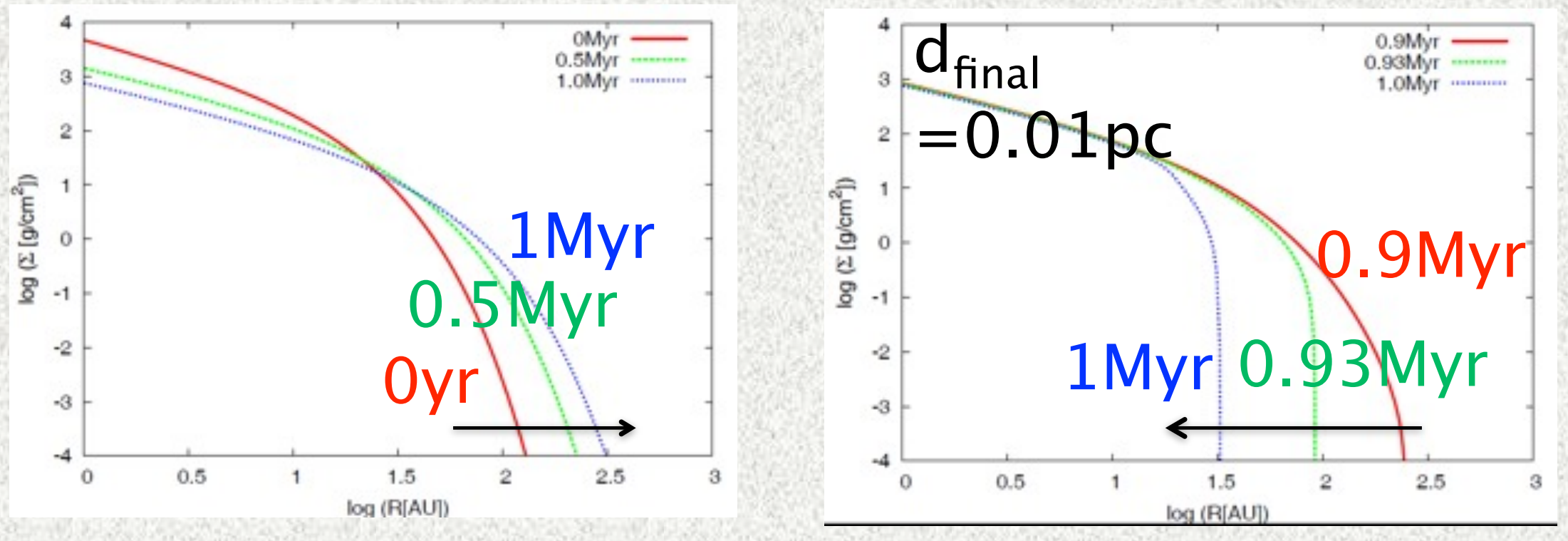
Walsh et al. (2013)

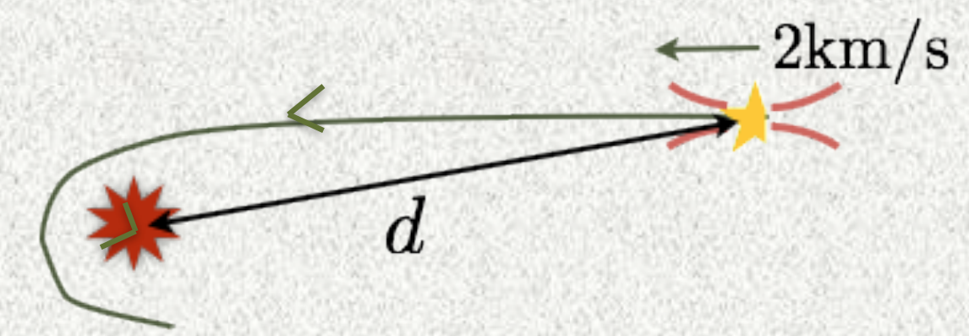
G_{FUV} vs. d, n_{pe} vs. d



Results

without irradiation with irradiation



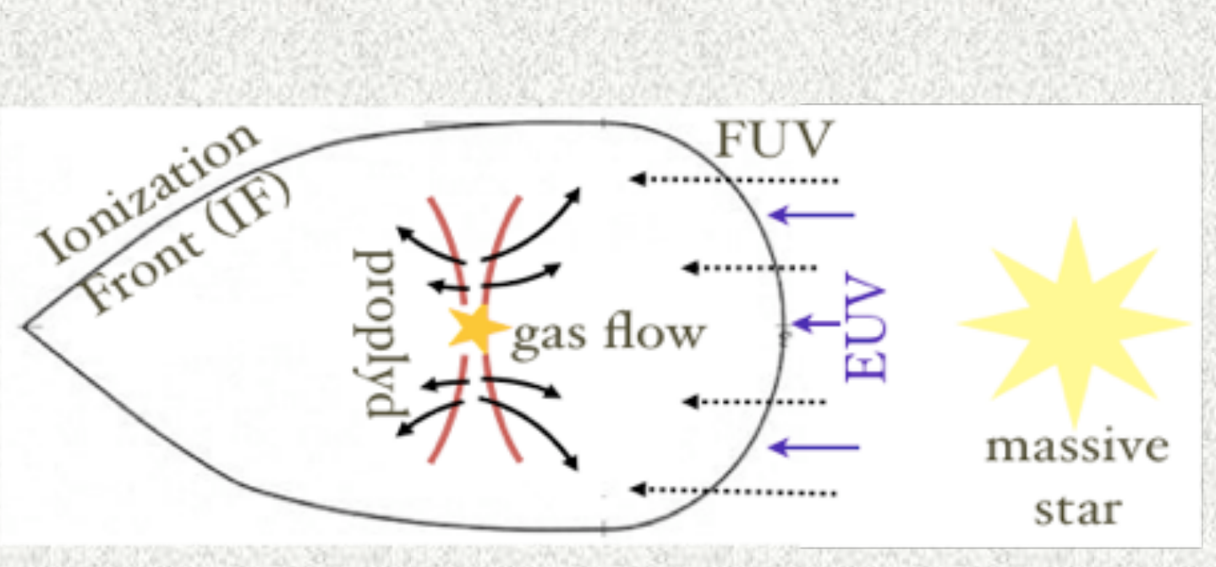


Disks are assumed to move toward the massive star.

Disk shrinks rapidly when it is close enough to the massive star.

Photoevaporating Flow and Ionization Front

The ionization front is formed in the photoevaporating flow.



Gas temperature :
Inner region of the ionization front : ~ 10^3 K (FUV heating)

Outer, perfectly ionized region : ~ 10^4 K (EUV heating)

1D Hydrodynamical simulations are performed to reproduce photoevaporating gas flow from proplyds, using the CANS stellar wind module.

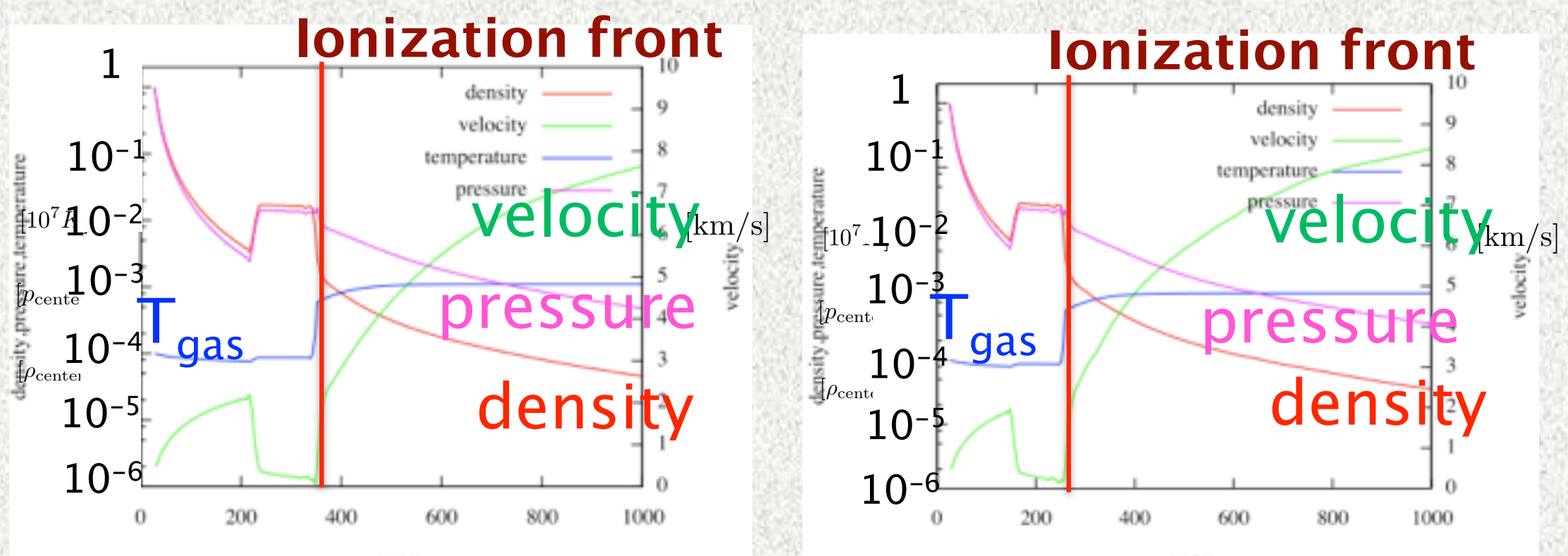
Ionization front

$$\frac{e^{-\tau_{\rm d}}}{4\pi d^2}\Phi_{\rm i} = \int_{r_{\rm IF}}^{\infty} n_{\rm II}^2 \alpha dr$$

Φ_i: UV flux from the massive star
d: distance from the massive star
α: recombination const.

n_{II}: electron density
τd: optical depth
r_{IF}: radius of the IF

Results



$\dot{M} = 1.6\times 10^{-6} M_{\rm sun}/yr$
$d = 0.22{\rm pc}$

$\dot{M} = 8\times 10^{-7} M_{\rm sun}/yr$
$d = 0.37{\rm pc}$

normarization:
velocity : sound speed (3km/s)
density
: density at the flow-launching point

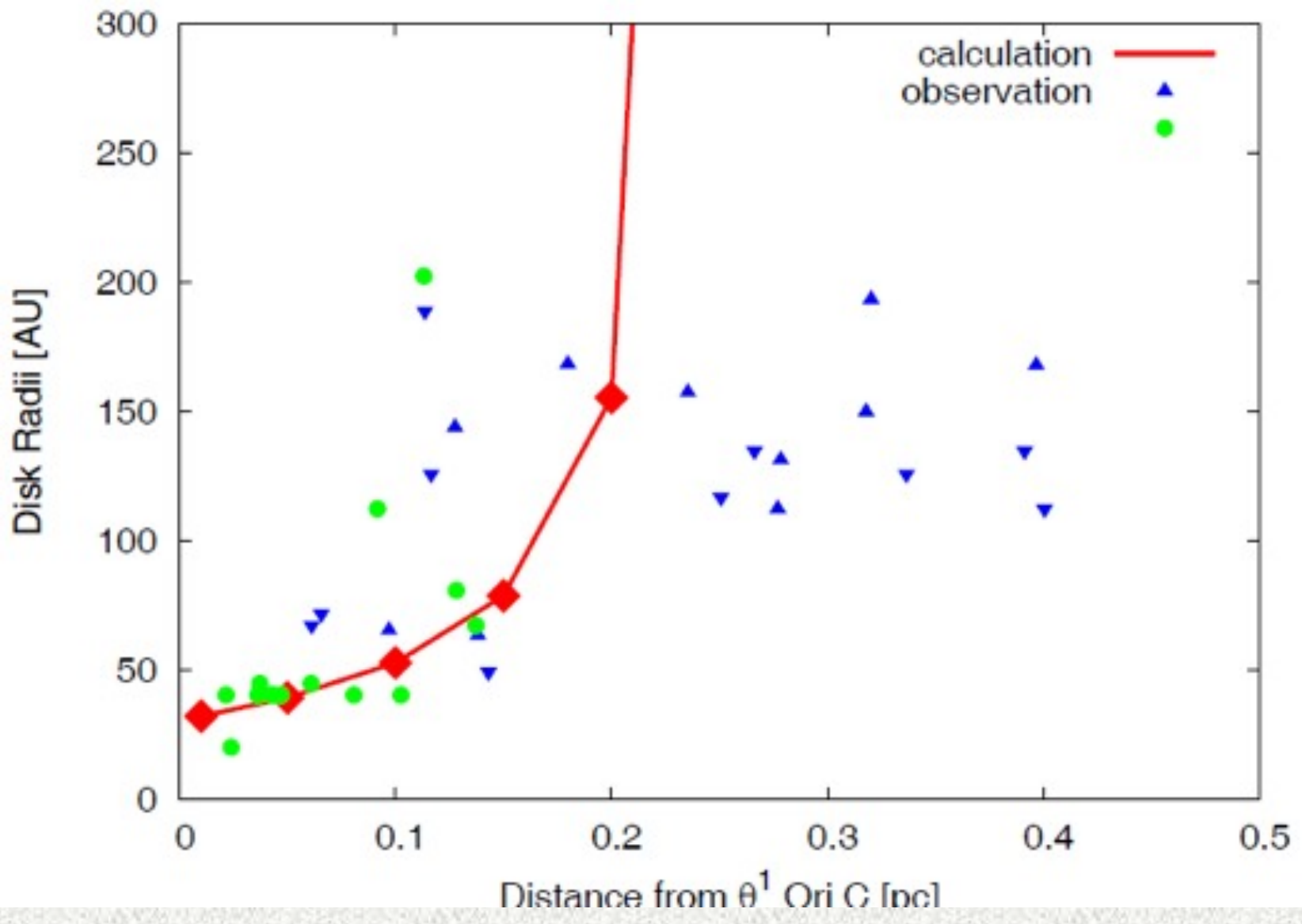
mass loss rate: $\dot{M} = 4\pi r^2 \rho c_{\rm s}$

The location of ionization front depends on the EUV photon flux (that is, the distance from the massive star) and the mass loss rate of the flow from the disk.(e.g., Jonstone et al. 1998)

Comparison with Observations

Disk Radii

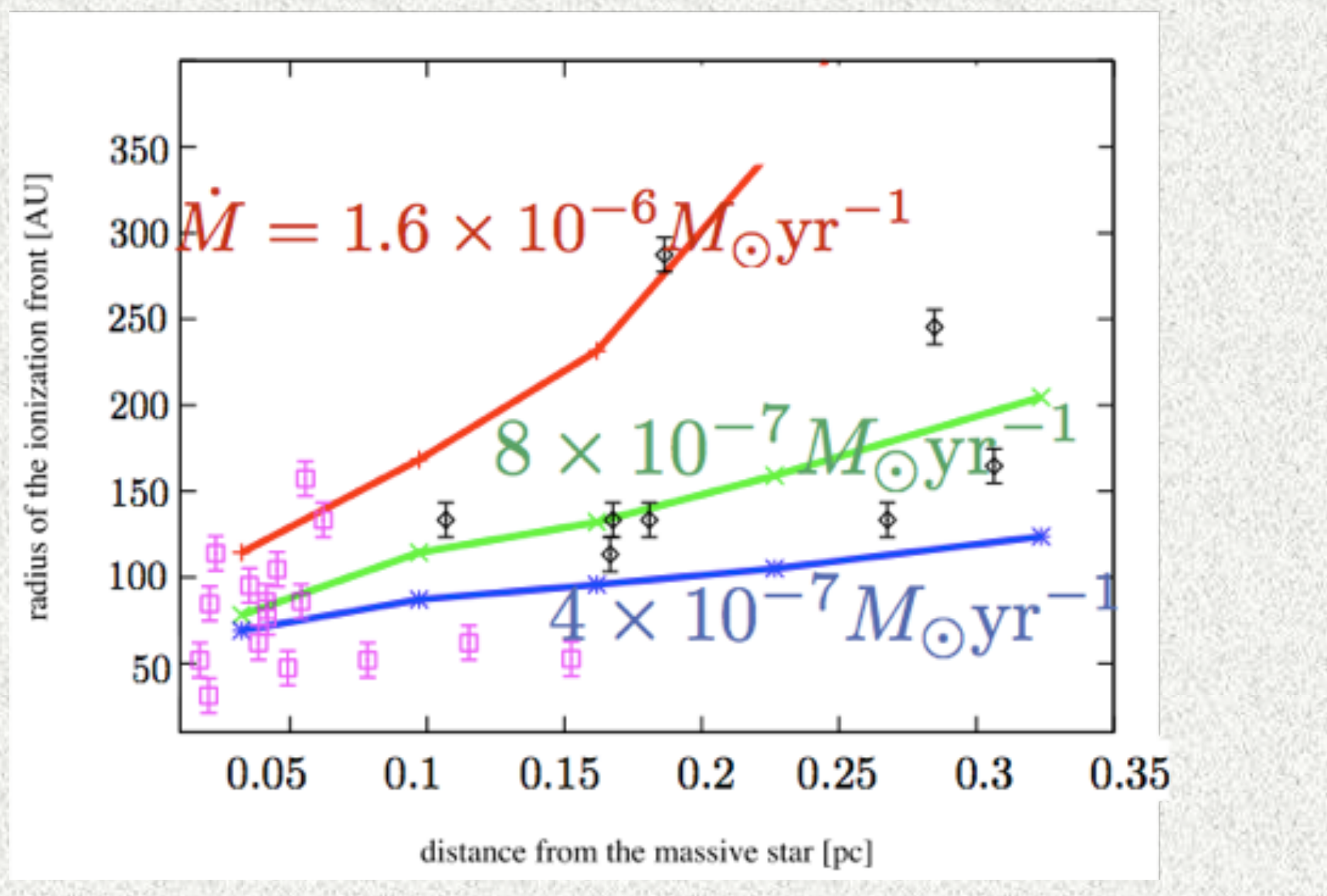
Calculated by solving the equation for the surface density evolution for 10^6yrs.



Observation data from
Bally et al.(1998), Vicent et al. (2005)

Ionization fronts

Calculated by performing the HD simulation for the photoevaporating flow irradiated by ionizing photons.



Observation data from
Johnstone et al.(1998)

- The observed correlations between the distance from the massive star and the radii of the disks as well as the radii of ionization fronts are reproduced by our calculation.
- The mass loss rate obtained from the calculations of surface density evolution (~ 5 x 10^{-7} Ms yr^{-1}) is consistent with the rate which reproduces the observations of radii of ionization fronts.

Summary

We calculated the surface density evolution of photoevaporating protoplanetary disks and performed the hydrodynamical simulations of the photoevaporating flow and the ionization fronts, which are caused by irradiation from a nearby massive star.
The observed correlations between the ionization fronts/disk radii and the distances from a massive star are well reproduced by our model with the mass loss rate of ~5x10^{-7} M_{sun}/yr.

Our results show that the photoevaporation and accretion control the gas dispersal of protoplanetary disks in the cluster.