Effects of external radiation on protoplanetary disks

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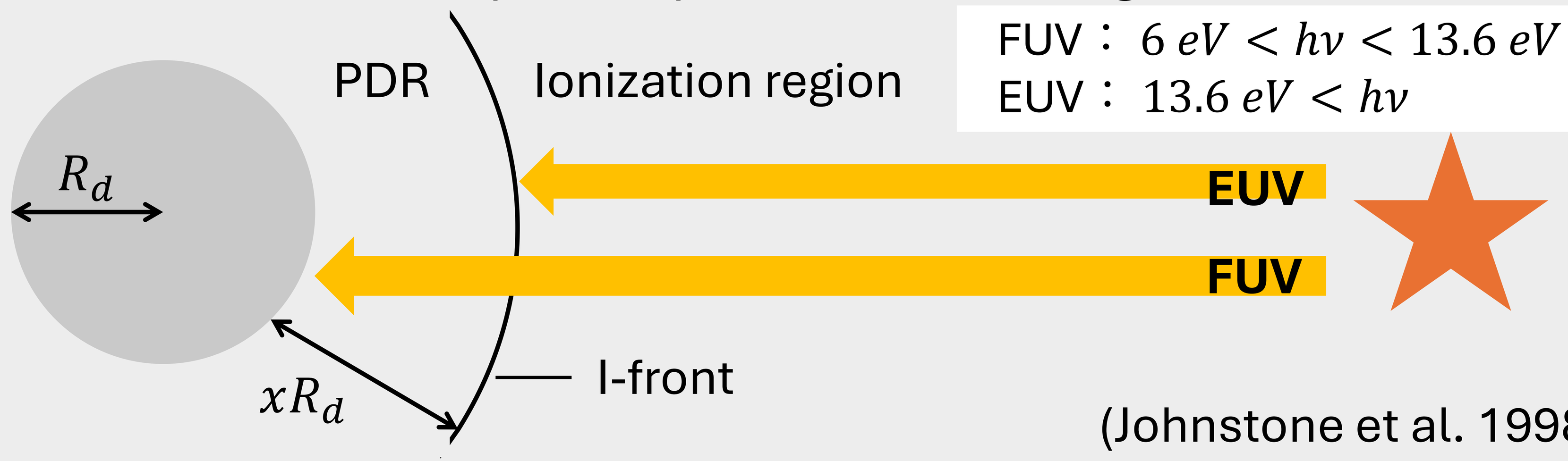
2024.11.25-26 CfCA Users Meeting for FY2024 @NAOJ Mitaka Campus

Introduction

◎ Photovaporation of protoplanetary disks

The protoplanetary disk, which is the site of planet formation, is exposed to the ultraviolet (FUV and EUV) radiation of massive stars from outside the disk, which causes photovaporation of the disk gas.

FUV : $6\ eV < h\nu < 13.6\ eV$
EUV : $13.6\ eV < h\nu$



(Johnstone et al. 1998)

R_d : Radius of protoplanetary disk
PDR(PhotoDissociation Region) : heated to $10^2 \sim 10^3\ K$ by FUV
Ionization region : heated to $10^4\ K$ by EUV and ionized gas

Evaporation rate at I-front : $\dot{M} = 4\pi \frac{(1+x)^2}{x} R_d^2 n_0 m_I \left(\frac{a_I^2}{2a_{II}}\right)$

$R_d = 100\ [au]$

$$\dot{M} = \begin{cases} 7.5 \times 10^{-8}\ M_\odot \mathrm{yr}^{-1} & \left(r_{d14} = r_d/10^{14} cm\ , x = 1.5 \ \ \text{EUV dominant}\right) \\ 1.1 \times 10^{-7}\ M_\odot \mathrm{yr}^{-1} & \left(r_{d14} = r_d/10^{14} cm\ , x = 3.0 \ \ \text{FUV dominant}\right) \end{cases}$$

◎ Previous work

①Simulations of 2D external radiation to the disk have been done.
② Observation of proplyd (photoevaporating protoplanetary disk)
③ The solar system may have been born while receiving external radiation.

Extending the calculation to three dimensions provides degrees of freedom in the direction of photon radiation.
→ More realistic calculations that consider the effect on the gas disk.

Method

◎ Calculation code

SFUMATO (Self-gravitational Fluid-dynamics Utilizing Mesh Adaptive Technique with Oct-tree)

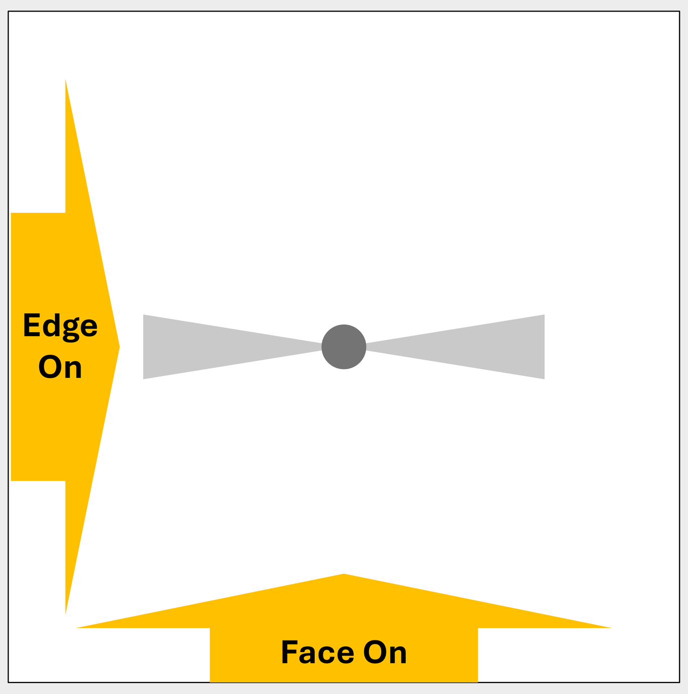
{Basic Fluid Equations
{Radiative transfer(M1 − closure)

(Matsumoto 2007)

\+
- Radiation calculations for EUV/FUV using the M1 closure method
- thermal process
  (photoionization heating, line cooling, photoelectric heating)
- thermochemical evolution

(Fukushima & Yajima 2021, Sugimura et al. 2020)

◎ Initialization



Central Star Mass : $0.5 M_\odot$,Radius : 30 au

disk ↓Density distribution of disks (Nakatani et.al 2018)

$$n_H = n_0 \left(\frac{R}{1au}\right)^{-9/4} \exp\left[-\frac{z^2}{2h^2}\right]$$

$$\left(\because h(\text{disk height}) = \frac{C_s(\text{sound speed})}{\Omega_k(\text{Keplerian speed})}\right)$$

Radius : 100 au (1/10 of calculation area)
Density outside disk : 1/100 of the disk edge

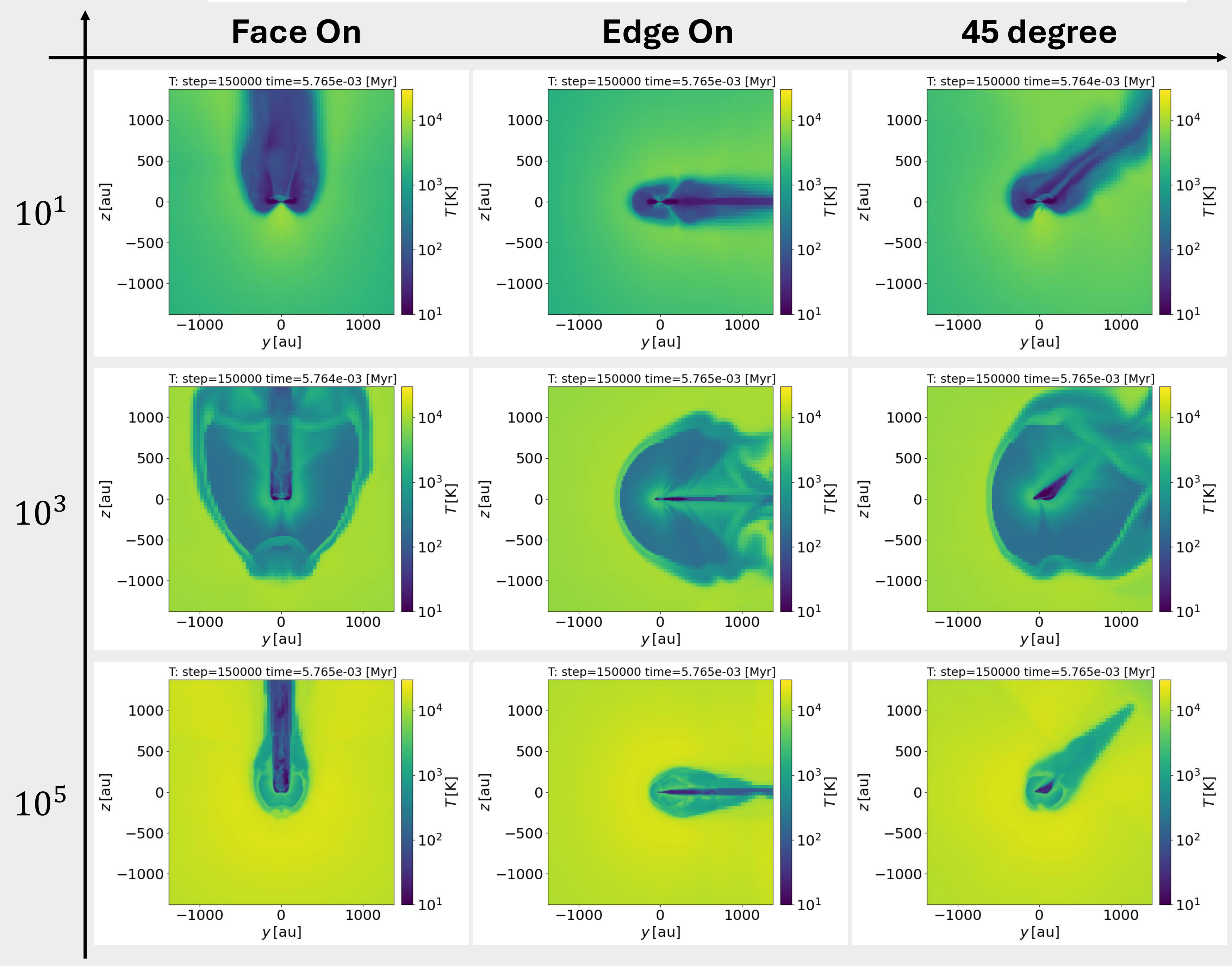
◎ External radiation

Intensity 3 patterns based on the average energy flux $\mathcal{F}_{\rm FUV}$ in interstellar space. ($\mathcal{F}_{\rm FUV} = 1.0 \times 10^1 \mathcal{F}_{\rm ISRF}$ ・ $1.0 \times 10^3 \mathcal{F}_{\rm ISRF}$ ・ $1.0 \times 10^5 \mathcal{F}_{\rm ISRF}$)

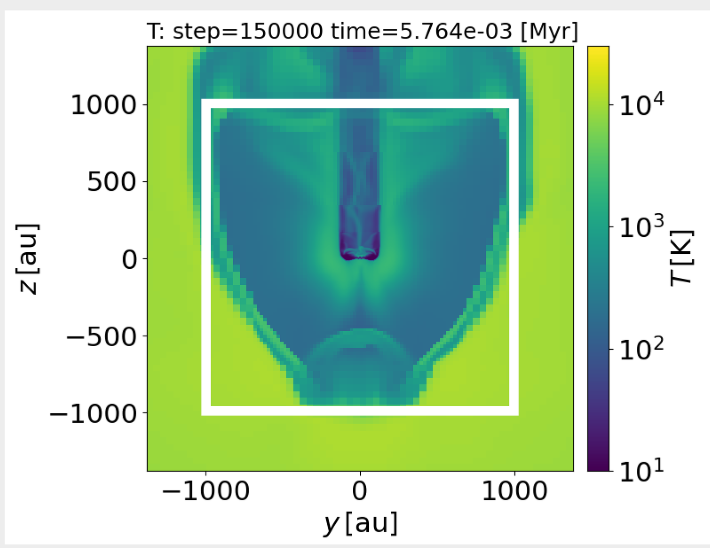
Direction 3 directions to the disk (Face On・Edge On・ oblique 45 degrees)

Results

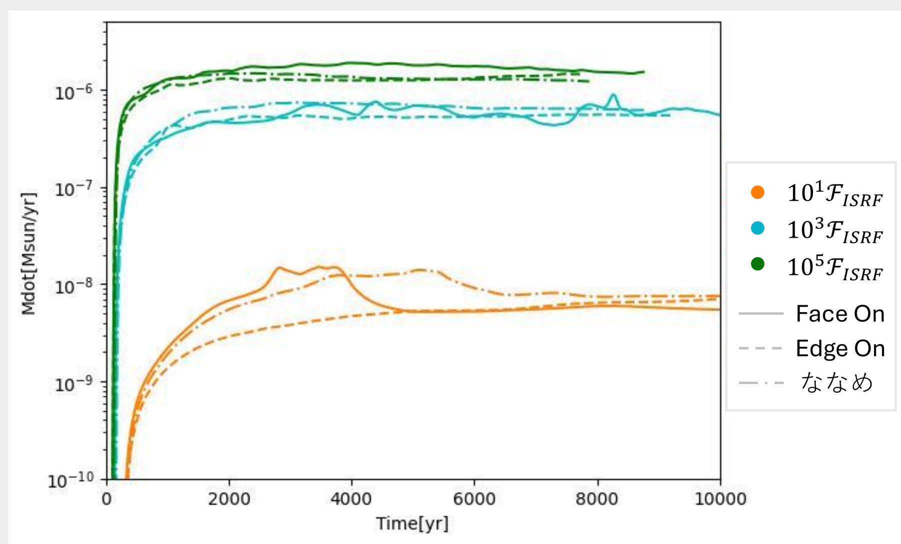
Temperature distribution in the yz plane for each model



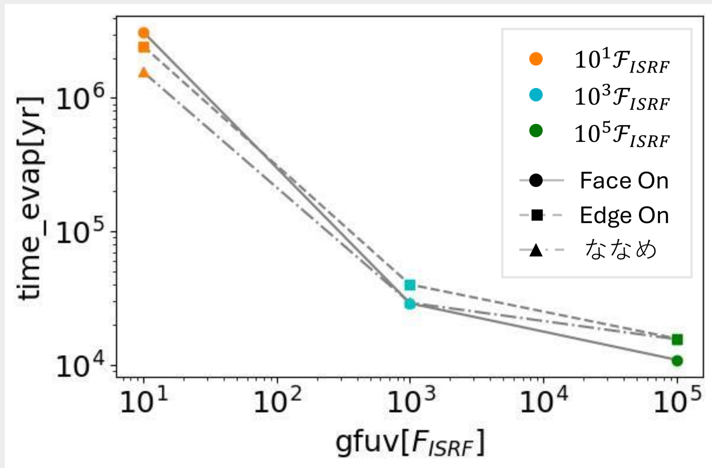
- $\mathcal{F}_{\rm FUV} = 1.0 \times 10^1 \mathcal{F}_{\rm ISRF}$ ・ $1.0 \times 10^5 \mathcal{F}_{\rm ISRF}$
  ▶ **The I-front is approaching the disk** due to external radiation.
- $\mathcal{F}_{\rm FUV} = 1.0 \times 10^3 \mathcal{F}_{\rm ISRF}$
  ▶ **The I-front is far from the disk** and the PDR is wide.



Evaporation rate calculation box

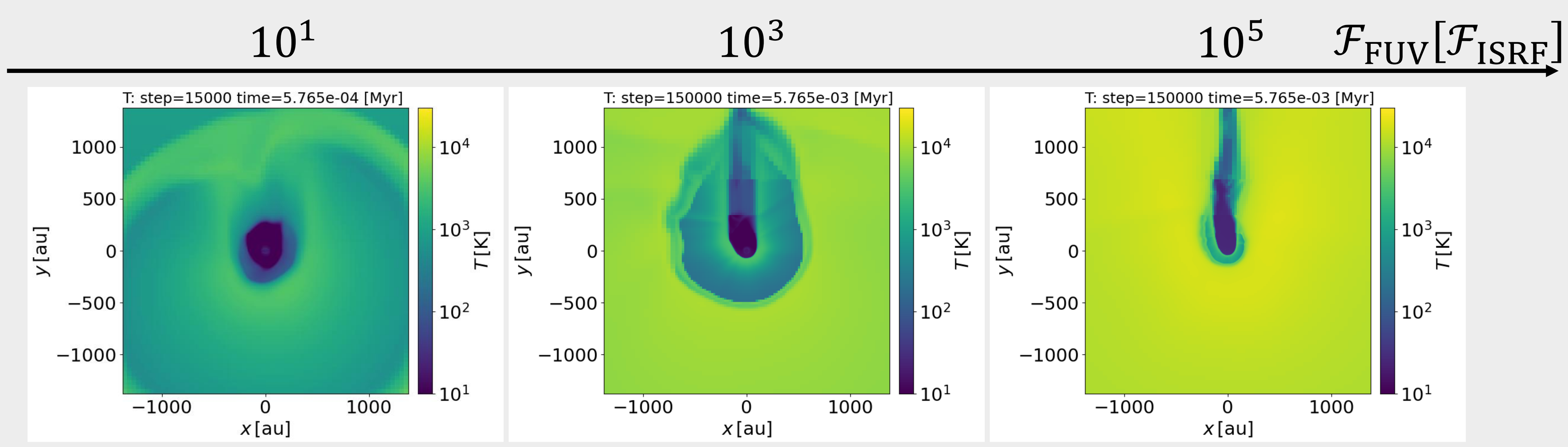


Time variation of evaporation rate of disks



Time for all gas to evaporate dependence on UV intensity

- Evaporation rate becomes steady after about $6 \sim 8 \times 10^3$ years.
- The dependence of **the evaporation rate** on the direction of the external radiation is small, while **the dependence on the radiation intensity is large**.
- $\mathcal{F}_{\rm FUV} = 1.0 \times 10^3$ ・ $10^5 \mathcal{F}_{\rm ISRF}$ because all the gas will evaporate **within 10^5 (< 100 million) years**, planet formation may be deterred.



Temperature distribution in the xy plane (external radiation is given by Edge On)

The structure of **the evaporative flow is distorted** compared to the direction of the external radiation.
▶ This may be due to the fact that the disk is rotating counterclockwise when viewed from the positive direction of the z-axis.

Conclusion

- The simulation of the previous work was extended to three dimensions, and a total of 9 models (3 directions and 3 radiation intensity patterns) were calculated by varying the parameters of the external radiation to the disk.
- When external radiation $\mathcal{F}_{\rm FUV} = 1.0 \times 10^1 \mathcal{F}_{\rm ISRF}$ ・ $1.0 \times 10^5 \mathcal{F}_{\rm ISRF}$ is given, the I-front approaches to the vicinity of the disk due to external radiation, but when external radiation $\mathcal{F}_{\rm FUV} = 1.0 \times 10^3 \mathcal{F}_{\rm ISRF}$ is given, the distance between the I-front and the disk increases.
- Regardless of the intensity and direction of the external radiation, the evaporation rate of the disk reaches a steady state after about $6 - 8 \times 10^3$ years. There is no directional dependence in the value of its evaporation rate, but **a large intensity dependence**.
- $\mathcal{F}_{\rm FUV} = 1.0 \times 10^3$ ・ $10^5 \mathcal{F}_{\rm ISRF}$ because all the gas will evaporate **within 10^5 (< 100 million) years, planet formation may be deterred**.
- When external radiation is given at **Edge On**, the evaporative flow structure is **distorted in the direction of disk rotation**. When analyzing the direction of external radiation in proplyd observations, the effect of the direction of rotation of the disk may have to be considered.