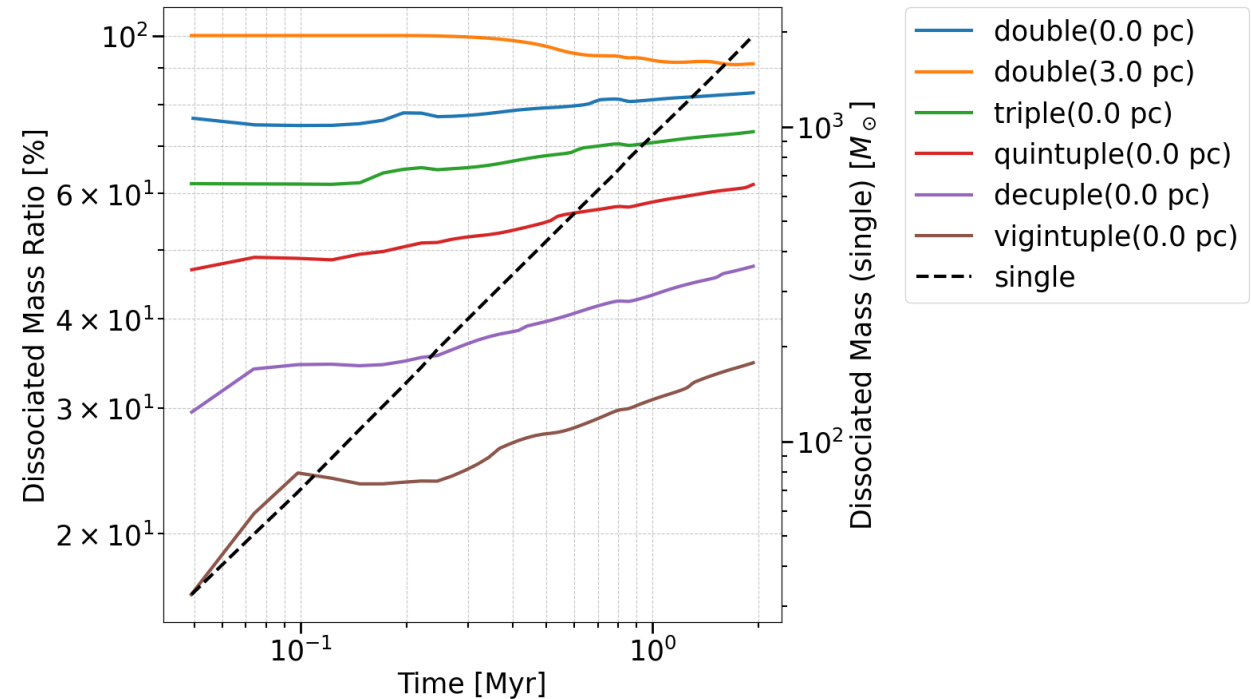
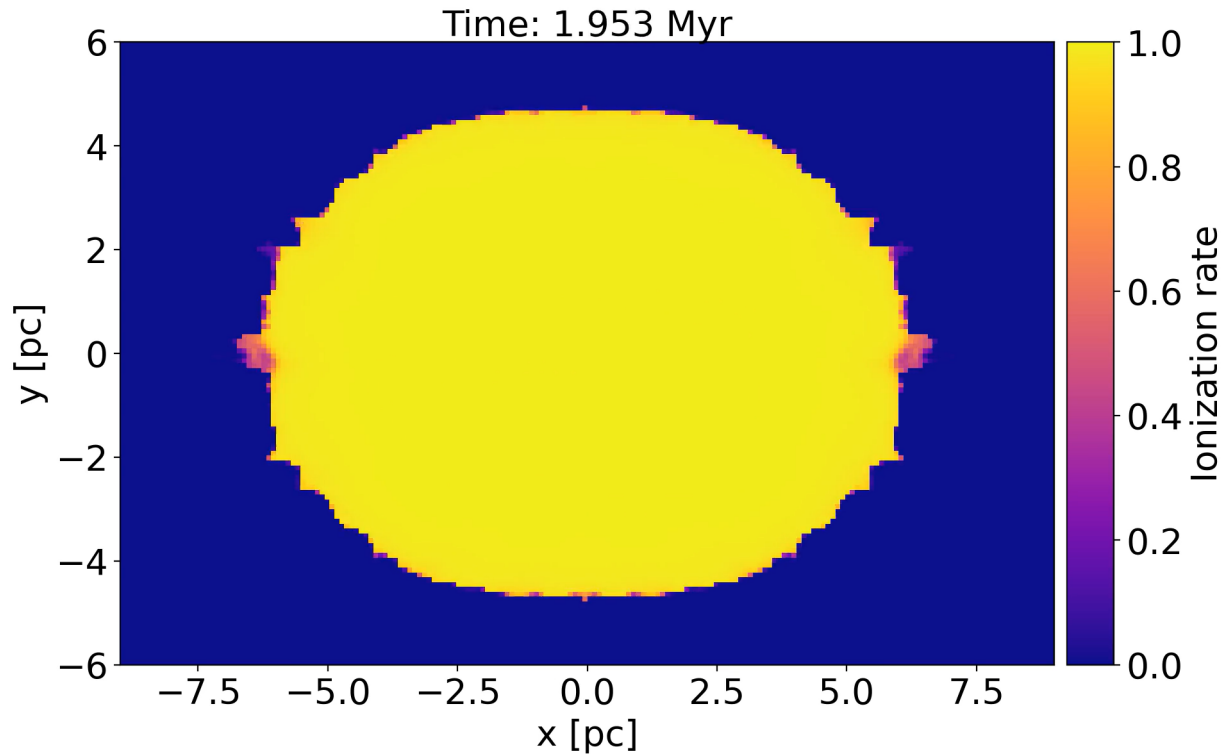


The Destruction of Molecular Clouds by Expanding HII Regions and Resulting Star Formation Efficiencies

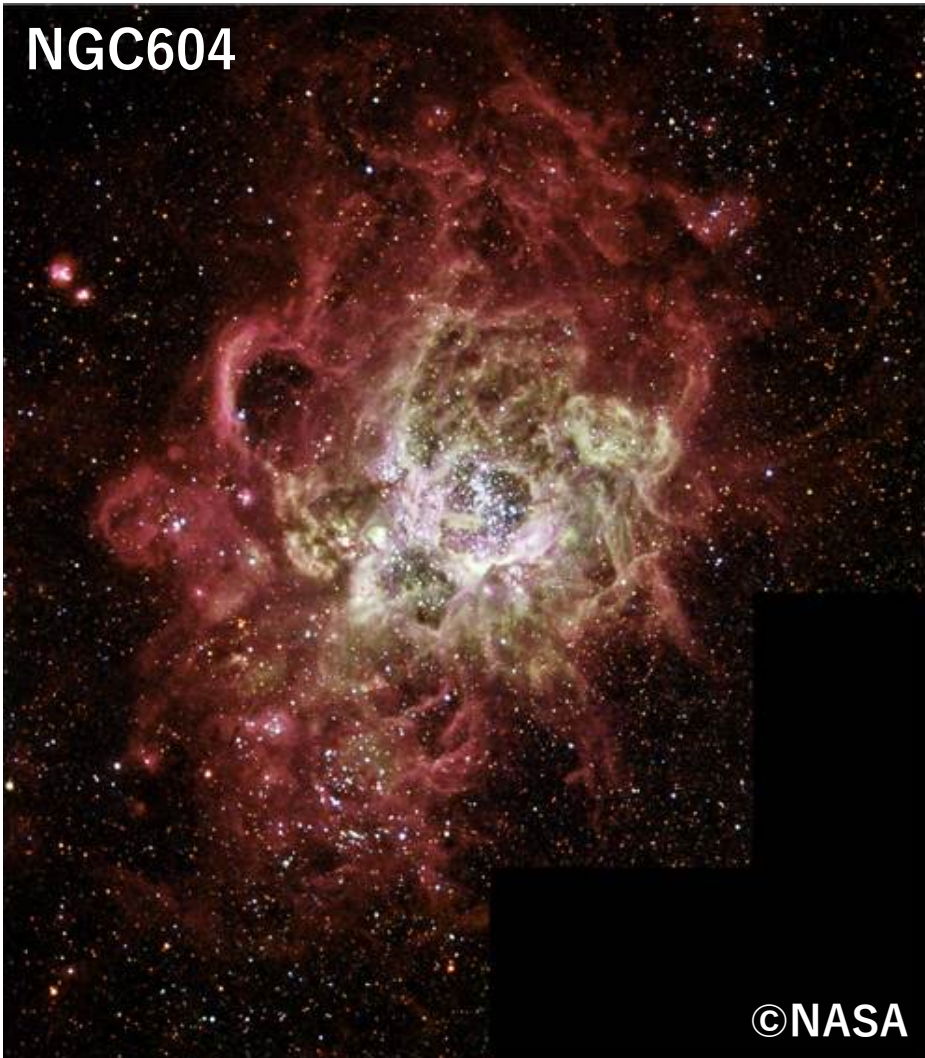


Kota Kobayashi, Shu-ichiro Inutsuka (Nagoya University)

Formation of HII regions in star formation

Appearance of HII region

NGC604



©NASA

When star formation begins, **HII region** is formed by radiation from massive stars.

■ HII region

The temperature and particle density increase within the HII region due to ionization.

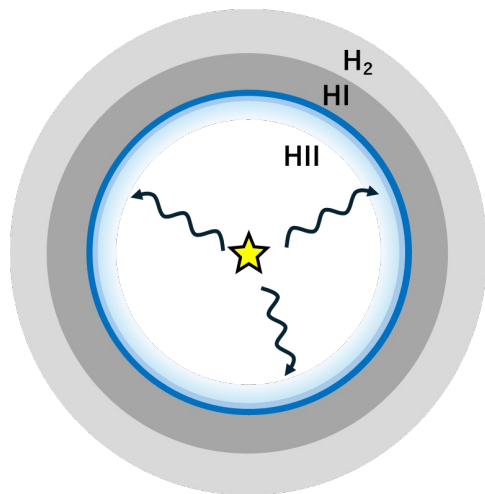
→ Increased pressure sweeps away circumstellar medium.

➔ **Decrease in mass accretion rate
+ Destruction of molecular clouds**

Destruction of molecular clouds and Star Formation Efficiency

◆ Star Formation Efficiency(SFE) [Inutsuka et al. 2015]

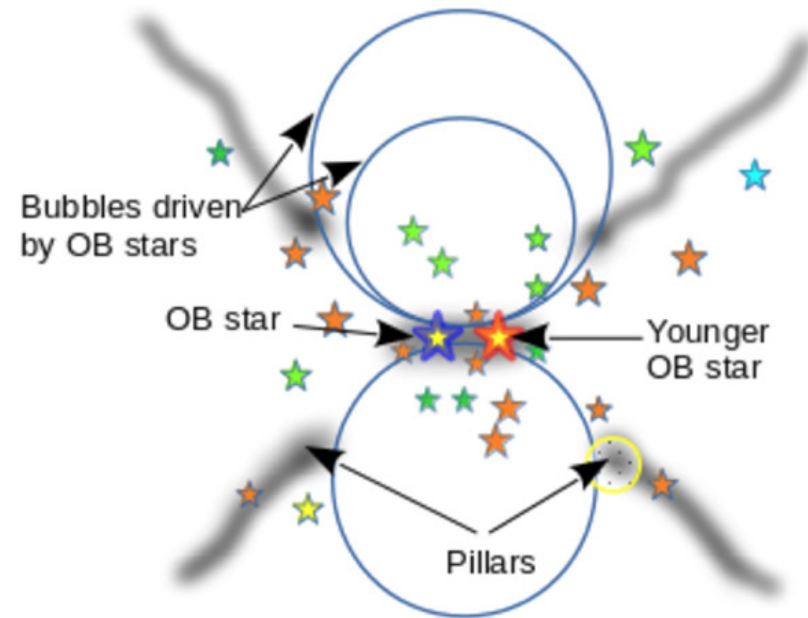
1. According to Initial Mass Function(IMF),
one massive star($\geq 20M_{\odot}$) is made from 10^3M_{\odot} new born stars.
2. Massive stars emit huge dissociation photons.
→one massive star can destroy 10^5M_{\odot} molecular cloud.



$$\text{SFE} : \epsilon_{\text{SF}} = \frac{10^3 M_{\odot}}{10^5 M_{\odot}} = 0.01$$

Stage IV

[Kumar et al. 2020]



However, multiple massive stars have been observed in compact regions. (e.g. Hub Filament System)

Necessary to take into account the influence of multiple massive stars.

Basic equation

Hydro simulation code : Athena++ [Stone et al. 2020]

■ EoC :

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

■ EoM :

$$\frac{\partial (\rho v_i)}{\partial t} + \frac{\partial}{\partial x_j} (\rho v_i v_j + P \delta_{ij}) = 0$$

■ EoE :

$$\frac{\partial}{\partial t} \left(\frac{1}{2} \rho v^2 + \rho \epsilon \right) + \nabla \cdot \left[\rho \mathbf{v} \left(\frac{1}{2} v^2 + \epsilon + \frac{P}{\rho} \right) \right] = \Gamma - \Lambda$$

■ EoS :

$$P = (\gamma - 1) \rho \epsilon \quad \gamma = \frac{5}{3}$$

Radiation

■ Radiation transfer :

$$F(r) = \frac{Q}{4\pi r^2} \exp(-\tau)$$

(We use Adaptive Ray-Tracing)

[e.g. Abel et al. 2002]

■ Ionization :

$$\frac{\partial n_{\text{HII}}}{\partial t} + \nabla \cdot (n_{\text{HII}} \mathbf{v}) = n_{\text{HI}} \sigma_{\text{EUV}} F_{\text{EUV}} - \alpha^{(2)}(T) n_{\text{HII}} n_e$$

■ Dissociation :

$$\frac{\partial n_{\text{H}_2}}{\partial t} + \nabla \cdot (n_{\text{H}_2} \mathbf{v}) = -n_{\text{H}_2} k_{\text{H}_2}$$

Heating & Cooling

$$\blacksquare \text{ EoE : } \frac{\partial}{\partial t} \left(\frac{1}{2} \rho v^2 + \rho \epsilon \right) + \nabla \cdot \left[\rho \mathbf{v} \left(\frac{1}{2} v^2 + \epsilon + \frac{P}{\rho} \right) \right] = \Gamma - \Lambda$$

Heating function Γ

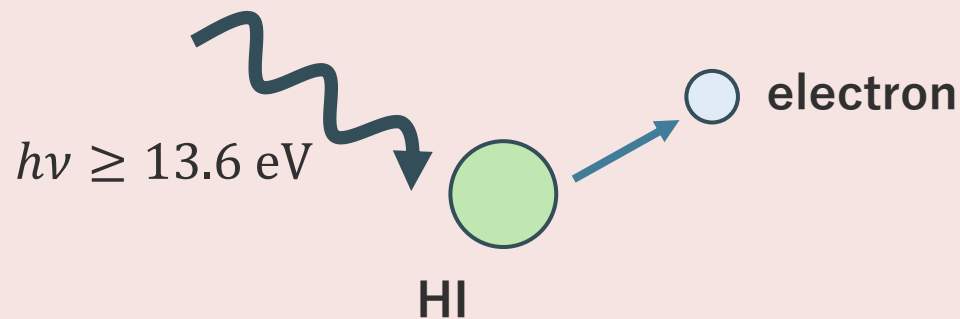
1. Photo-Electric Heating from Dusts

[Koyama & Inutsuka 2002]

2. Dissociation Heating

[Abel et al. 1997]

3. Ionization Heating

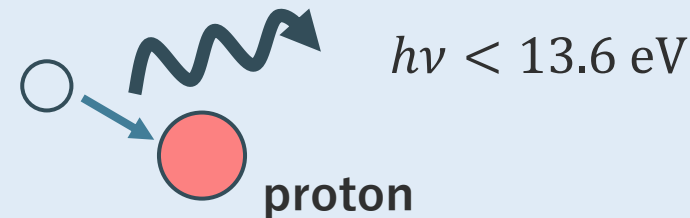


Cooling function Λ

1. Ly- α + CII Line Cooling

[Koyama & Inutsuka 2002]

2. Recombination Cooling



3. Metal Cooling

[Henney et al. 2009]

HII region

Simulation setup

◆ Properties of the Star

[Diaz et al. 1998]

Model star	Mass M_* (M_\odot)	Effective Temperature T_{eff} (K)	Ionization Photon Number S_{EUV} (s^{-1})
S19	19.0	33,000	5.62×10^{47}

◆ Initial Condition

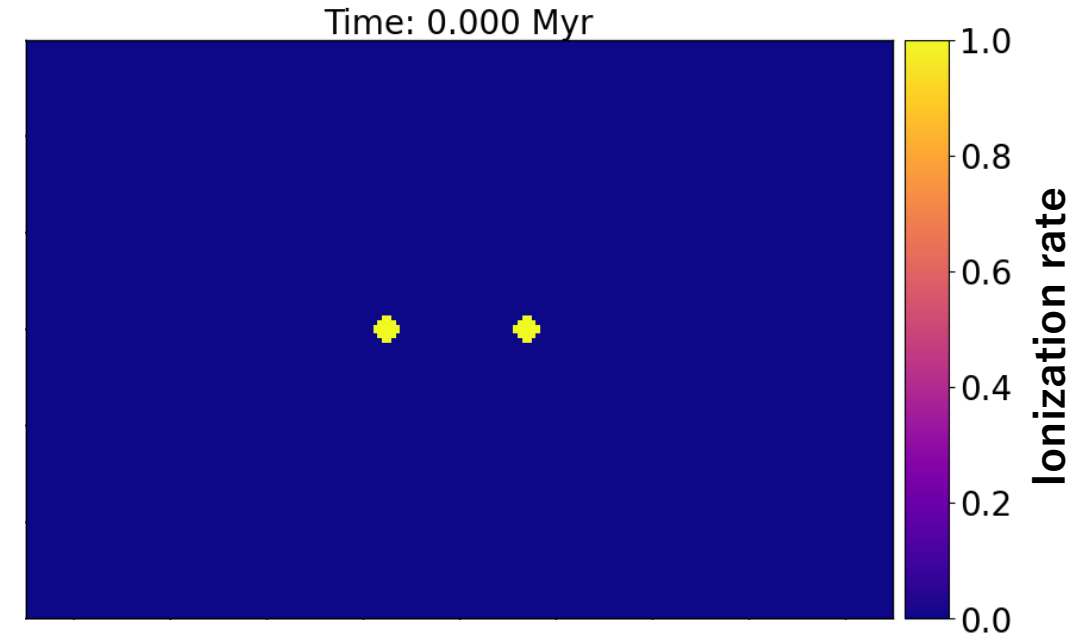
Number of stars : $N_{\text{star}} = 1, 2, 3, 5, 10, 20$ (interval: 0 pc)
 = 2 (interval: 2, 3 pc)

Uniform density : $n_{\text{H}} = 10^3 \text{ [cm}^{-3}\text{]}$

Abundance : $X_{\text{HII}} = 1.0, X_{\text{H}_2} = 0.0$ ($r \leq R_S$),
 $X_{\text{HII}} = 0.0, X_{\text{H}_2} = 1.0$ ($r \geq R_S$)

Temperature : $10,000 \text{ [K]}$ ($r \leq R_S$),
 10 [K] ($r > R_S$)

initial state



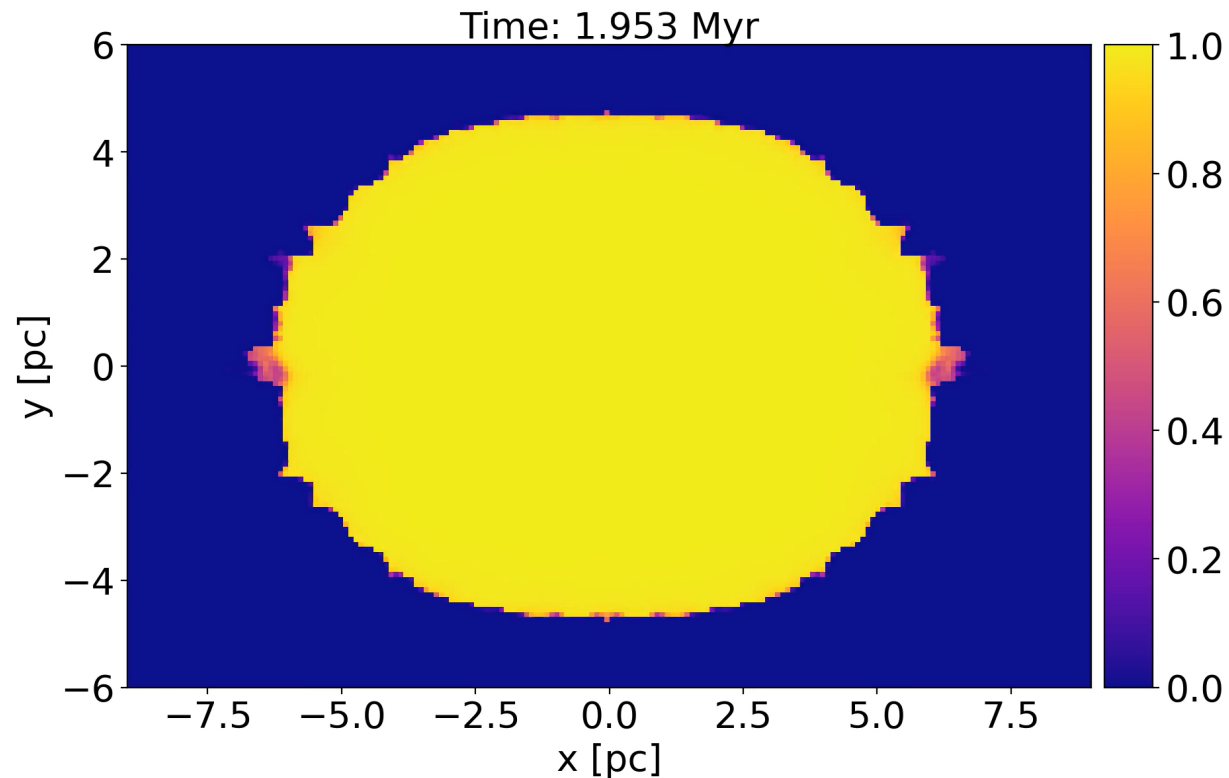
boundary condition : outflow

- All stellar radiation start at the same time.
- **Change the number and arrangement of stars.**

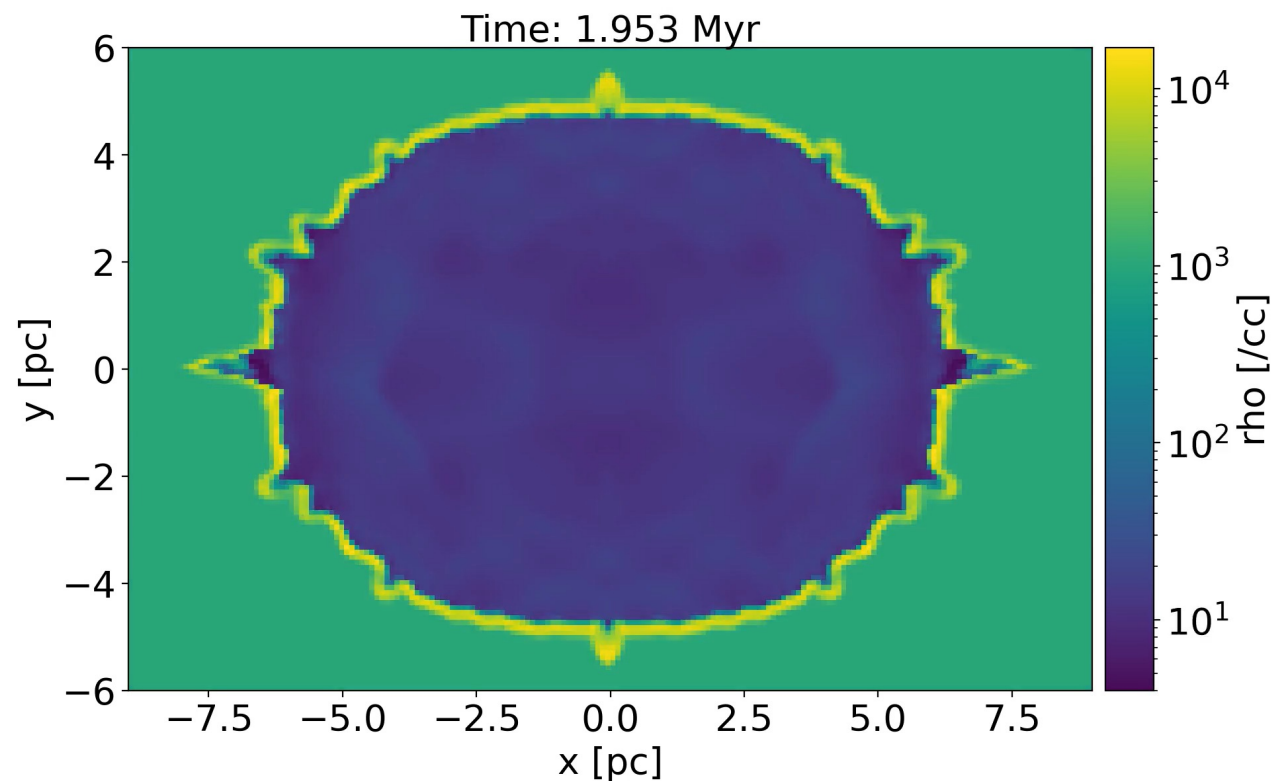
Simulation results for the case where two stars are created nearby

◆ Side view (x-y plane) $N_{\text{star}} = 2$, interval : 3.0 pc

■ Ionization rate



■ density



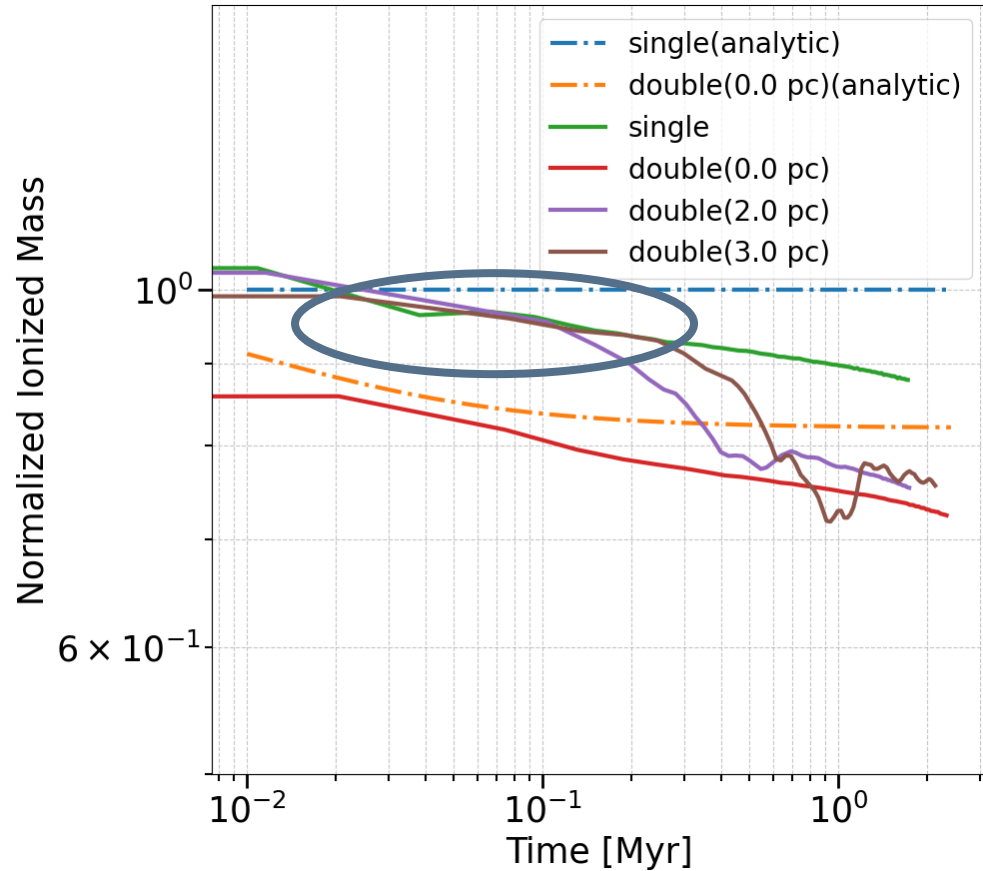
Note : characteristic structures are due to D-front instabilities.

[e.g., Frieman 1954, Spitzer 1954 , Williams 2002]

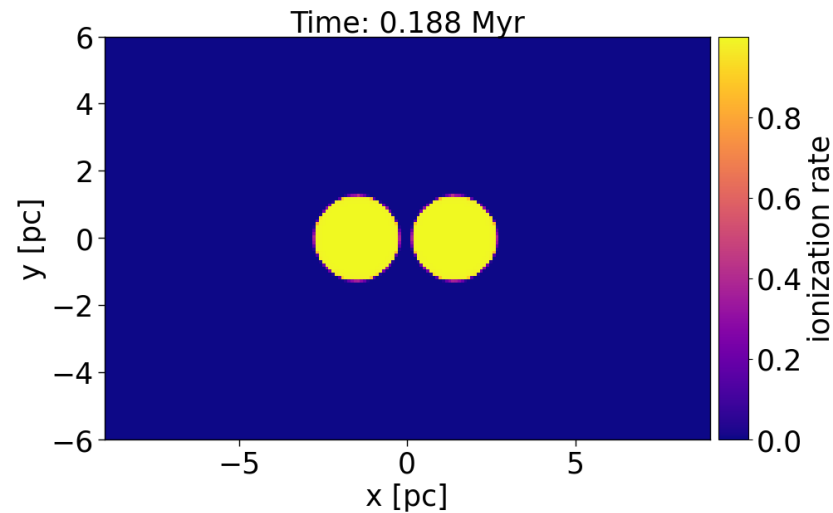
Variation in ionization efficiency

◆ Variation in ionization efficiency per massive star Solid line : simulation Dashed line : analytical

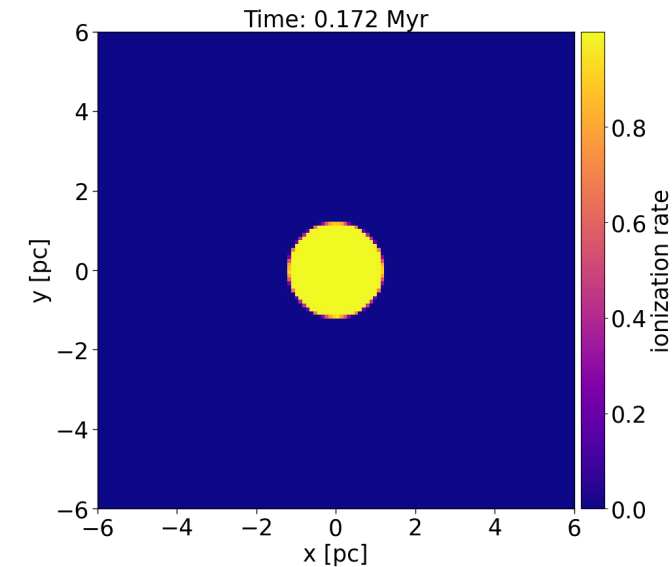
■ Normalized Ionized mass (Normalized by single star analytical solution) [Hosokawa & Inutsuka 2006]



Before collision :
double (2.0, 3.0 pc)



single

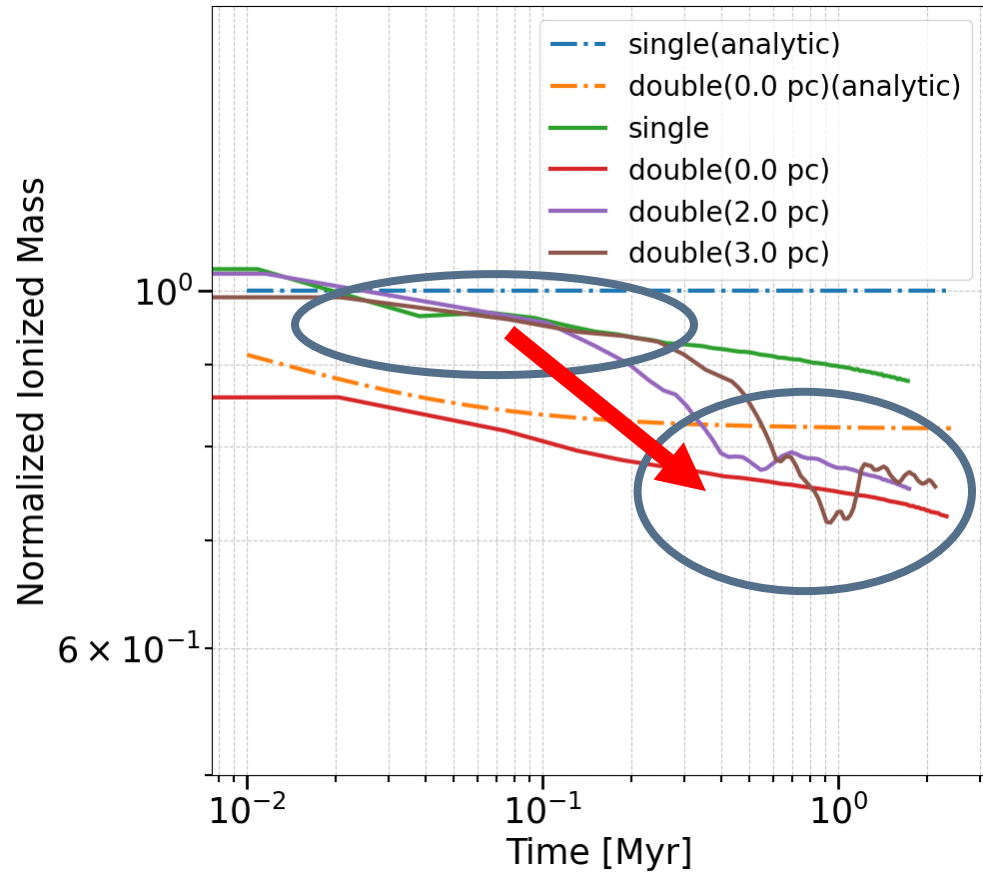


The ionization efficiency of double (2.0, 3.0 pc) is the same as that of single.

Variation in ionization efficiency

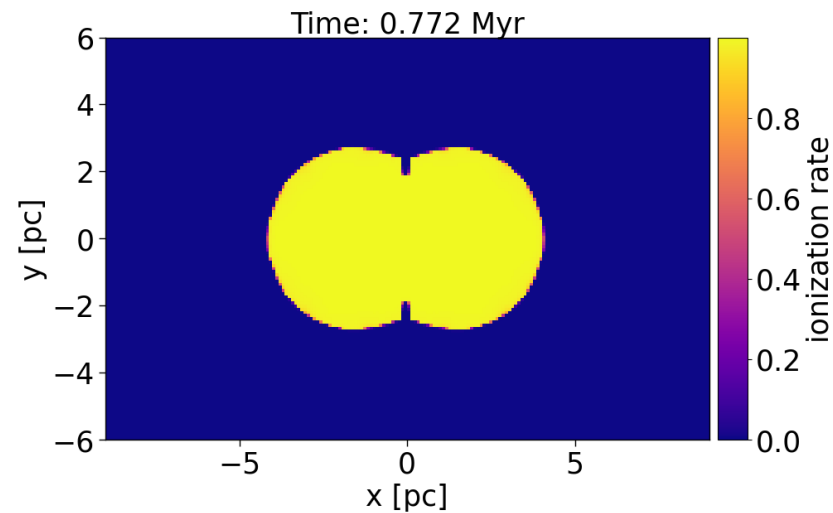
◆ Variation in ionization efficiency per massive star Solid line : simulation Dashed line : analytical

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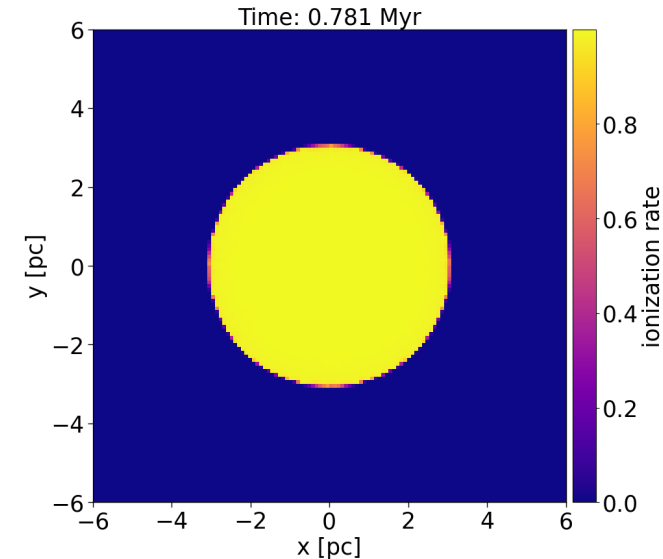


After collision :

double (2.0, 3.0 pc)



double (0.0 pc)



Same ionization efficiency
regardless of the distance between stars.

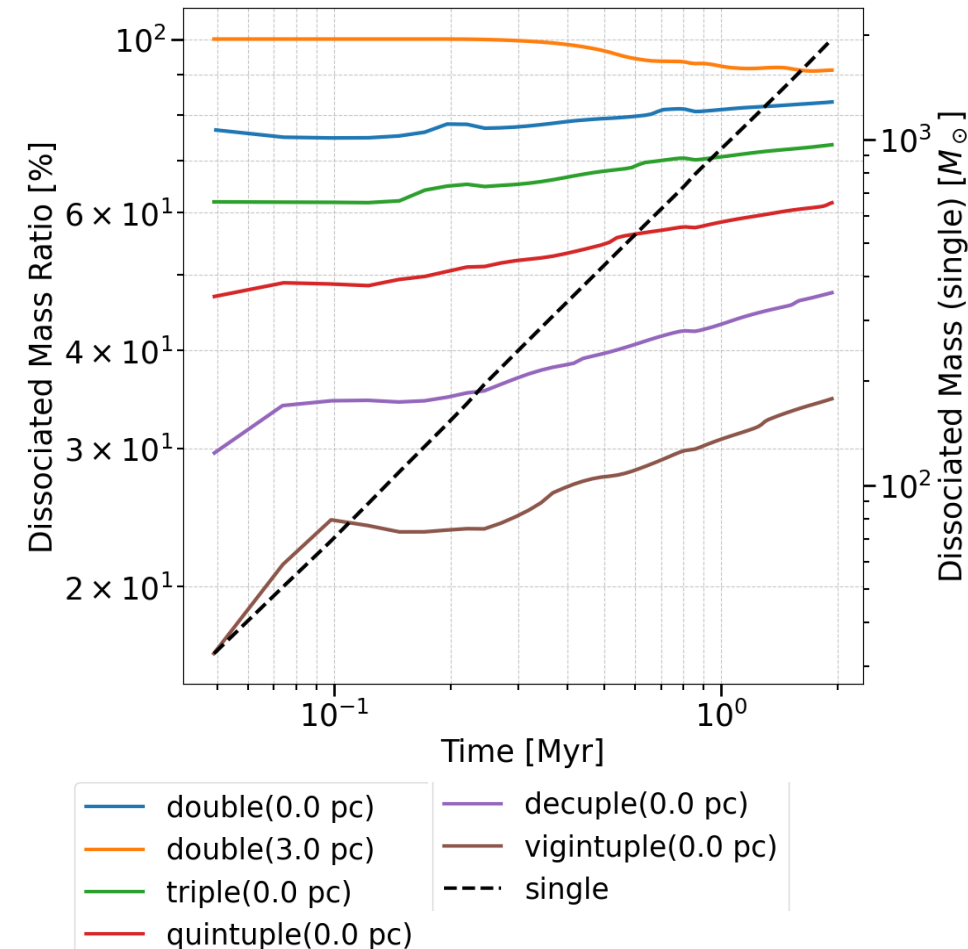
Molecular cloud destruction by multiple massive stars

◆ Variation in dissociation efficiency per massive star

Solid line : Normalized simulation

Dashed line : Non-normalized simulation

■ Normalized Dissociated mass



➤ Reduction Factor of Destruction Efficiency

A factor represents how much the destruction efficiency decreases compared to the case with only 1 massive star.

1. When multiple stars (2–20) were placed, **the dissociated mass decreased by about 20–65%.**
2. Reduction factor of double(0.0 pc) > Reduction factor of double(3.0 pc)

Clustered massive star formation results in less-efficient destruction of GMC.

Molecular cloud destruction by multiple massive stars

◆ Variation in dissociation efficiency per massive star

Number of Stars(interval)	Reduction Factor of Destruction Efficiency per massive star
2 (0.0 pc)	18%
2 (3.0 pc)	9%
3 (0.0 pc)	27%
5 (0.0 pc)	38%
10 (0.0 pc)	52%
20 (0.0 pc)	65%

➤ Reduction Factor of Destruction Efficiency

A factor represents how much the destruction efficiency decreases compared to the case with only 1 massive star.

1. When multiple stars (2–20) were placed, **the dissociated mass decreased by about 20–65%.**
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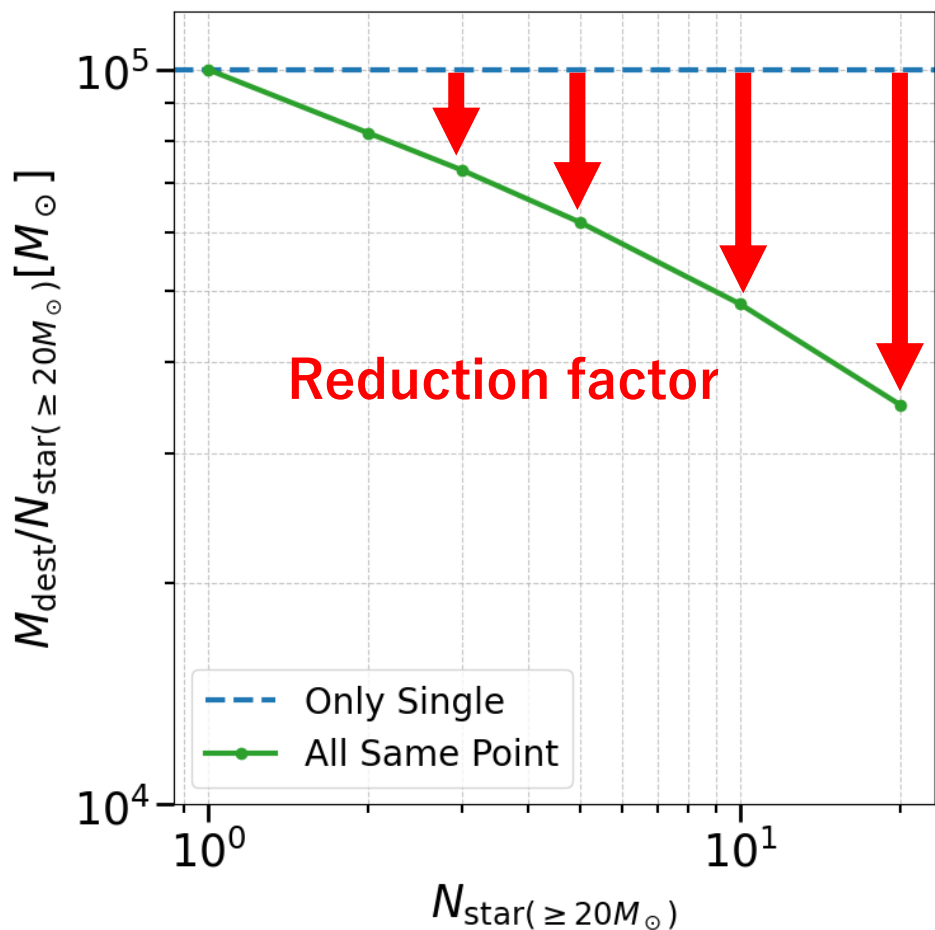
Clustered massive star formation results in less-efficient destruction of GMC.

Star formation efficiency accounting for the influence of multiple stars

◆ Star Formation Efficiency

The green line connects the estimation from dissociation efficiencies in the simulation results (interval: 0.0 pc).

■ Destruction of molecular gas per star



1. For $N_{\text{star}(\geq 20M_{\odot})} = 20$, the dissociated mass decreases by about 65%.
2. When the interval is small, the dissociation efficiency decreases.

Dissociation efficiency is reduced only by 50% at maximum!

Previous Work

[Inutsuka et al. 2015]

$$\epsilon_{\text{SF}} = \frac{10^3 M_{\odot}}{10^5 M_{\odot}} = 0.01$$

Our Research

$$\epsilon_{\text{SF}} \approx \frac{20 \times 10^3 M_{\odot}}{20 \times 0.5 \times 10^5 M_{\odot}} = 0.02$$

It increases **only slightly** compared to the SFE derived by Inutsuka et al. (2015)!

Summary

In massive star-forming regions, multiple massive stars create multiple H II regions.

It is necessary to take into account the influence of overlapping HII regions.

◆ Summary

- We performed **three-dimensional radiation hydrodynamics simulations** with multiple massive stars.
- Quantitatively measured **a decrease in ionization and dissociation efficiency** in the cases of overlapping HII regions.
- However, **SFE is only slightly increased by interacting multiple HII regions.**

◆ Future Works

- Simulations with realistic internal filamentary structures in a GMC.
- Theoretical explanation of overall star formation law such as Kennicutt-Schmidt Law.

