The Predictive Power of Computational Astrophysics as a Discovery Tool
Proceedings IAU Symposium No. 362, 2023
D. Bisikalo, D. Wiebe & C. Boily, eds.
doi:10.1017/S1743921322001545

Feedback from the Vicinity of Massive Protostars in the First Star Formation

Kazutaka Kimura

Center for Gravitational Physics and Quantum Information, Yukawa Institute for
Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
email: `kazutaka.kimura@yukawa.kyoto-u.ac.jp`

Abstract. Many simulations have been performed to elucidate the formation process of first stars. In first star formation, radiative feedback is a key process in determining stellar masses. However, previous simulations which follow the feedback process don't resolve the small scale ($\lesssim 10$ AU) to realize long-term calculation, and the structure near massive protostars is still unknown. To clarify how the radiation from the protostar works, we need to resolve small scale and calculate the interaction between the radiation and the dense gas in such a region. As a first step towards understanding the phenomenon in this region, we perform the high-resolution simulation around the massive protostar without radiative transfer. We find that dense gas covers the protostar even in the polar direction and the HII region cannot expand. Solving the radiative transfer for getting accurate results is our future work. We are currently developing the new radiation hydrodynamics code for that.

Keywords. stars: formation, accretion, accretion disks, HII regions

1. Introduction

First stars, also called Pop III stars, are formed in the early universe just after the Big Bang (Greif 2015; Haemmerlé *et al.* 2020). Their radiation heats and ionizes the interstellar medium and their supernova explosions spread heavy elements into the surrounding gas. First stars are thus critical to subsequent structure formation. Especially, the initial mass function (IMF) determines their roles and much research has been devoted to the study of the IMF.

In first star formation, radiative feedback is a key process which determines stellar masses (McKee & Tan 2008), as well as turbulence and magnetic fields (e.g. Sharda *et al.* 2021). In multi-dimensional simulations (Hosokawa *et al.* 2011; Sugimura *et al.* 2020), stellar radiation ionizes surrounding gas and creates HII region in polar direction. That region expands, and finally blows off the surrounding gas, which would otherwise accrete onto the central star. As a result, the final stellar masses are larger than present-day stellar ones and range from $10 - 1000\ M_\odot$ (Hirano *et al.* 2014).

However, to reduce the computational cost for long-term calculations, previous simulations which follow the above feedback process don't resolve the structure within ~ 10 AU of the central protostar. Radiation from the protostar interacts with the dense gas near the protostar. Hence, to clarify how much the radiation can escape to a larger scale and whether the HII region can expand, we need to perform a high-resolution calculation near the massive protostar.

Here, we perform the simulation around the massive protostar with the resolution of 0.015 AU without radiative transfer. To solve radiative transfer is future work. We are currently developing the new radiation hydrodynamics code based on SFUMATO-RT

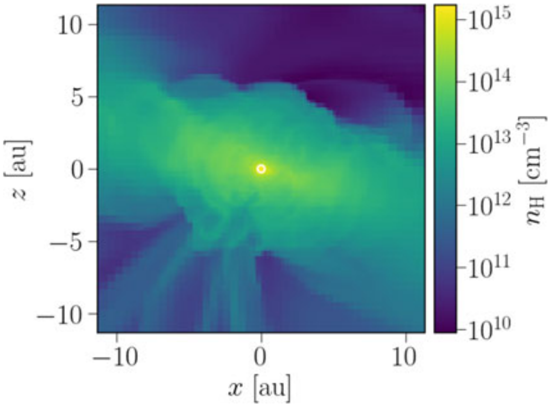

Figure 1. Simulation snapshots of the gas number density seen from the edge-on view. The central white circle represents the sink particle corresponding to the protostar. The sink radius is 0.25 AU, the stellar mass is 24 $M_\odot$, and the accretion rate is $\sim 10^{-4} - 10^{-3}\ M_\odot$/yr.

which can follow the radiative transfer accurately in the very optically thick region near the massive protostar. SFUMATO-RT is the radiation hydrodynamics code developed by Sugimura *et al.* (2020) and includes adaptive mesh refinement, sink particle method, primordial gas chemistry network and cooling processes. Sink particle method is often used in star formation simulations to save the computational cost by simplifying the small scale structure (c.f. Federrath *et al.* 2010) and we also use it in this work.

Our simulation method is as follows. Here, we use the original SFUMATO-RT. As a initial condition, we pick up a typical primordial star-forming cloud from the cosmological simulations (Hirano *et al.* 2014, 2015). We can't simulate from this initial condition to the formation of massive protostar with high resolution all the time due to expensive computational cost. Thus, we first simulate with low resolution. At this time, the sink radius is 64 AU. Then, after the massive star is formed, we gradually shrink the sink radius to 0.25 AU.

2. Structure near the massive protostar without radiative transfer

Fig. 1 shows the gas number density in the simulation seen from the edge-on view. At this time, the protostellar mass is 24 $M_\odot$ and the accretion rate is $\sim 10^{-4} - 10^{-3}\ M_\odot$/yr. As we can see, the protostar is covered with the dense gas even in the polar direction. Moreover, Fig. 2 shows the one-dimensional profile of the gas density and temperature in the polar direction. The blue line represents the simulation result and the orange dashed line represents the analytical solution of the static equilibrium of the gas pressure and the stellar gravity. The vertical dashed line corresponds to the sink radius. We can see the bounded structure (< 6 AU) by the protostellar gravity with the high density and temperature and fit the simulation result well with the analytical solution by tuning the mass and entropy in the bounded structure. The density is high up to 10^{14} cm^{-3} near the central protostar. In this bounded structure, the gas is fully ionized. Such a hot and ionized disk has been found in many previous one-dimensional disk models (e.g. Takahashi & Omukai 2017; Matsukoba *et al.* 2019; Kimura *et al.* 2021).

Note that in our simulation, we estimate the cooling rate by using the jeans length derived from the density and temperature at each cell. This method is accurate under the condition in which the self-gravity of the gas is dominant. However, near the massive protostar, the stellar gravity is strong and the self-gravity of the gas is subdominant. Then, this method is not accurate, and we overestimate the temperature. If we solve radiative transfer with the new code we are currently developing, this bounded structure

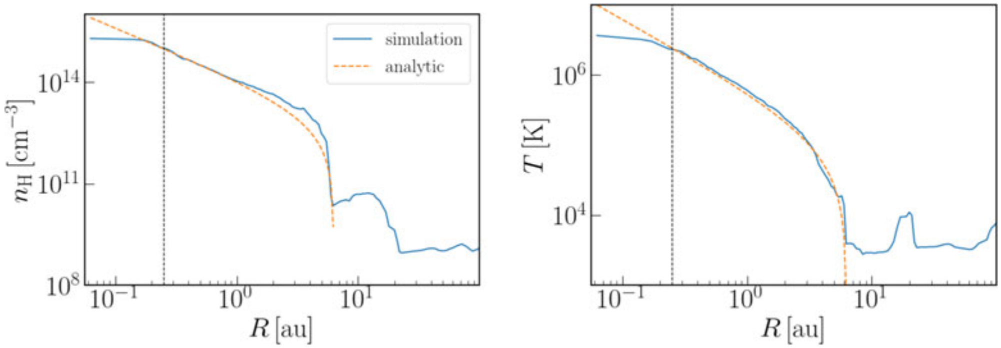

Figure 2. One-dimensional profile of gas density and temperature in the polar direction at the snapshot corresponding to Fig. 1. The blue line represents the simulation result, and the orange dashed line show the analytic solution of static equilibrium of the gas pressure and the stellar gravity.

would become cooler and smaller with lower gas pressure. Here, we estimate whether the HII region can expand or not, using this profile in the next section.

3. Can HII region expand?

Here, we estimate whether the HII region can expand when the gas structure in our simulation is realized. As shown in Fig. 2, in the bounded structure ($< 6\ AU$), the gas is very hot and fully ionized. Then, we judge whether the radiation from the surface can create the expanding HII region. The radiation from the bounded structure has an effective temperature of 10^4 K because the gas is very optically thick in the bounded structure and the photosphere lies almost at the surface. The density just outside the bounded structure is about $10^{10}\ {\rm cm}^{-3}$. At this time, the Strömgren radius is

$$r_{St} = \left(\frac{3\dot{Q}}{4\pi\alpha_{\rm B} n_H^2}\right)^{1/3} \simeq 2\ {\rm AU} \left(\frac{\dot{Q}}{10^{49}\ {\rm s}^{-1}}\right)^{1/3} \left(\frac{n_H}{10^{10}\ {\rm cm}^{-3}}\right)^{-2/3}, \qquad (3.1)$$

where $\dot{Q}$ is the emissivity of EUV photons and $\alpha_{\rm B}$ is the case B recombination coefficient. This radius is within the bounded structure. Moreover, the escape velocity is

$$v_{\rm esc} = \sqrt{\frac{2GM_*}{r}} \simeq 134\ {\rm km/s} \left(\frac{M_*}{20\ M_\odot}\right)^{1/2} \left(\frac{r}{2\ {\rm AU}}\right)^{1/2} \qquad (3.2)$$

where G is the gravitational constant. This value is larger than the typical sound velocity in the HII region and we conclude that HII region cannot expand.

As said in the previous section, in our simulation we overestimate the temperature by the method using the jeans length. Additionally, we don't treat the radiation pressure by diffusive photons. Near the massive protostar, the diffusion process of the radiation is effective because the gas is very dense and optically thick. If we include these effects, there is the possibility that the bounded structure would change, that the radiation pressure can push off the gas in the polar direction, and that the HII region can expand. We plan to perform such a simulation in the future with the new code we are currently developing.

4. Summary

In first star formation, the radiation from the protostar creates the expanding HII region and this determines the stellar mass. However, previous simulations don't resolve the structure in the vicinity of the massive protostar, and how the gas and radiation interact with each other in this region is still unknown. To understand the gas structure in this region, here as a test calculation we perform the high-resolution simulation around the primordial massive protostar without radiative transfer.

As a result, the hot and dense bounded structure is formed around the protostar. If this gas structure is realized, the HII region cannot expand and the radiative feedback is not effective, which leads to very massive first stars. However, if we include the effects of the diffusive process of radiation and the radiation pressure, there is the possibility that HII region would expand.

Now, we are developing the new radiation hydrodynamics code which can calculate the radiative transfer in the optically thick region based on the SFUMATO-RT. In the future, we will perform the simulation with this new code to elucidate the structure near the massive protostar.

References

Federrath, C., Banerjee, R., Clark, P. C., Klessen R. S., 2010, *ApJ*, 713, 269

Greif, T. H. 2015, *Computational Astrophysics and Cosmology*, 2, 3

Haemmerlé, Mayer, Klessen, Hosokawa, Madau, & Bromm, 2020, *SSRv*, 216, 48

Hirano, S., Hosokawa, T., Yoshida, N., et al. 2014, *ApJ*, 781, 60,

Hirano, S., Hosokawa, T., Yoshida, N., Omukai, K., & Yorke, H. W. 2015, *MNRAS*, 448, 568

Hosokawa, T., Omukai, K., Yoshida, N., & Yorke, H. W. 2011, *Science*, 334, 1250

Kimura, K., Hosokawa, T., Sugimura, K. 2021, *ApJ*, 911, 52

Matsukoba, R., Takahashi, S. Z., Sugimura, K., & Omukai, K. 2019, *MNRAS*, 484, 2605

McKee, C. F., & Tan, J. C. 2008, *ApJ*, 681, 771

Sharda, P., Federrath, C., Krumholz, M. R., Schleicher, D. R. G., 2021, *MNRAS* (Letters), 503, 2014

Sugimura, K., Matsumoto, T., Hosokawa, T., Hirano, S., & Omukai, K. 2020, *ApJ* (Letters), 892, L14

Takahashi, S. Z., & Omukai, K. 2017, *MNRAS*, 472, 532

Discussion

Audience: You increased the resolution to the protostar and you try to get a kind of asymptotic regime which does not depend on the size of the sink. You showed the profile. Where does this analytic model come from?

Kimura: This is a static equilibrium of the gas pressure and the gravity of the protostar.

Audience: Just a quick question about the initial configuration. How would you expect more angular momentum, for example, a few increased angular momentum? Do you think that it would make it easier to blow off the polar gas? Because it would be less dense, for example. Would you like to comment on that?

Kimura: I have no exact answer. But I think this bounded structure is determined from the mass and entropy.

Audience: I'm cuious about the velocity structure of the disk. Whether it's Keplerian or maybe wouldn't at some radius?

Kimura: Within 1 AU, there is a difference from the Keplerian motion.