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Multiple Feedback in Low-Metallicity Massive Star Formation

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Abstract. We theoretically investigate the impact of feedback and its metallicity dependence in massive star formation from prestellar cores at all metallicity range. We include the feedback by MHD disk winds, radiation pressure, and photoevaporation solving the evolution of protostars and accretion flows self-consistently. Interestingly, we find that the feedback does not set the upper mass limit of stellar birth mass at any metallicity. At the solar metallicity, the MHD disk wind is the dominant feedback to set the star formation efficiencies (SFEs) from the prestellar cores similar to low-mass star formation. The SFE is found to be lower at lower surface density environment. The photoevaporation becomes significant at the low metallicity of $Z < 10^{-2} Z_\odot$. Considering this efficient photoevaporation, we conclude that the IMF slope is steeper, i.e., massive stars are rarer at the extremely metal-poor environment of 10^{-5}–$10^{-3} Z_\odot$. Our study raises a question on the common assumption of the universal IMF with a truncated at $100 M_\odot$. Since the total feedback strength in the cluster/galaxy scale is sensitive to the number fraction of massive stars, the re-evaluations of IMF at various environments are necessary.

Keywords. stars: evolution – stars: formation – stars: luminosity function, mass function – stars: winds, outflows

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1. Introduction

Massive stars play a lot of important roles throughout the cosmic history. They are the main sources of UV radiation, turbulent energy, and heavy elements controlling the dynamical and chemical evolution of the interstellar interstellar medium. Massive close binaries are the progenitors of merging black holes, which have been detected by their gravitational wave emission. Theoretical studies suggest that the first stars in the universe (Population III stars) were typically as massive as $100 M_\odot$ or even higher (e.g., Hirano *et al.* 2015), which are not directly observed yet. Therefore, massive stars are the key objects to connect the observable present to the early universe. In particular, it is crucial to understand how the process of massive star formation depends on galactic environmental conditions, because this shapes the high-mass end of the initial mass function (IMF) and affects how the IMF may vary through cosmic history.

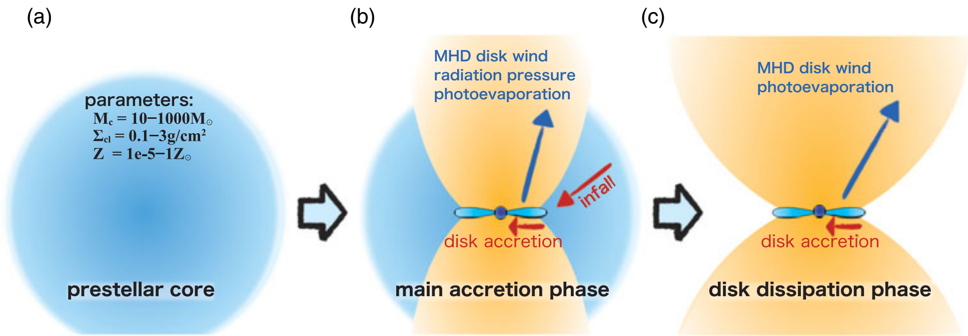

Figure 1. The schematic view of our semi-analytic model.

The feedback processes acts the main factor to determine the birth masses of stars. In the formation of low-mass stars, the magnetohydrodynamically-driven disk wind is known to be important. The MHD disk wind creates larger bipolar outflow setting the star formation efficiency (SFE) of ~ 0.4 from prestellar cores (Machida & Matsumoto 2012). In massive star formation, on the other hand, the radiation pressure acting on the dusty envelope is considered be pivotal for a long time (Wolfire & Cassinelli 1987). To overcome the radiation pressure, the disk accretion with the self-shadowing is necessary (Krumholz *et al.* 2009, Kuiper *et al.* 2010). In the very early universe, the radiation pressure is not the problem because there were not dust grains yet. Instead, the photoevaporation is the main feedback stopping the mass accretion typically at the protostellar mass of 50–100$M_\odot$ in the formation of first stars (Hosokawa *et al.* 2011).

Those feedback processes were studied separately as the previous studies focused on the formation of different type of stars, such as low-, high-mass, or first stars. However, all feedback mechanisms acts together in reality. Additionally, it is important to understand the dependence of feedback processes on the environments to connect the star formation in the present and the early universe. Therefore, we conduct a theoretical study of massive star formation with the multiple feedback processes at various metallicities (Tanaka *et al.* 2017, Tanaka *et al.* 2018).

2. Methods

Figure 1 shows the schematic view of our semi-analytic model. The initial condition is the spherical prestellar cloud core, which is characterize by following parameters (the left panel of Fig. 1), i.e., the mass of cores M_c, the surface density of the surrounding clump gas $\Sigma_{\rm cl}$, and the metallicity Z. For simplicity, the formation of the single star from the individual core is assumed. The material accrete onto the protostar through the accretion disk, while some fraction of gas ejected by the multiple feedback mechanism. The MHD disk winds, the radiation pressure, the photoevaporation, and also the stellar wind are considered here as the feedback processes. The time evolution of the protostellar structure, the accretion flow structure, and feedback processes are calculated self-consistently from the beginning of the cloud-core collapse. At the end of each calculation, the all material in the initial core accretes onto the protostar at center or is ejected by feedback processes.

3. Results & Conclusions

First, let us explain the results at the solar metallicity (Tanaka *et al.* 2017). The left panel of Figure 2 shows the accretion history as the function of the protostellar mass

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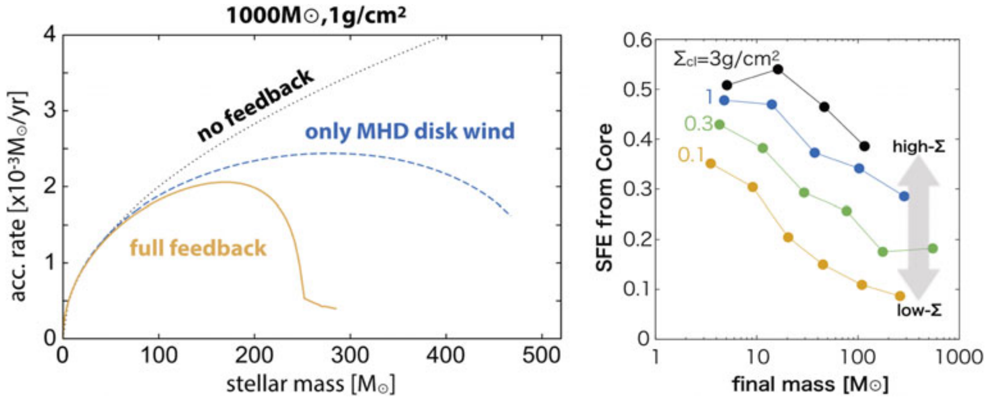

Figure 2. Results at the solar metallicity. (*left*) The accretion history as the function of the protosteller mass (no feedback in black, MHD disk wind in blue, and full feedback case in orange). (*right*) The SFE as the function of the final stellar mass. The feedback does not set the upper mass limit.

m_* in the case of the initial core with $1000M_\odot$ and $1\,\mathrm{g\,cm^{-2}}$. If the MHD disk wind is included, the accretion rate gets smaller than the no-feedback limit case and the final stellar mass is $470M_\odot$. Added the radiative feedback, the accretion rate becomes even smaller especially at $m_* > 150M_\odot$ and the final stellar mass is also smaller as $290M_\odot$. In this manner, the radiative feedback makes the SFE smaller from 0.47 to 0.29 in this particular initial condition.

The obtained SFEs as functions of the final stellar masses from the different initial core cases are shown in the right panel of of Figure 2 (the result of full feedback cases are presented). It is seen that the SFE is smaller at higher-mass star formation at all $\Sigma_{\rm cl}$. This is simply because the radiative feedback is stronger at the higher stellar masses. However, it should be emphasized that the decline of SFE is relatively gradual without the truncation at least up to $500M_\odot$. In other words, the feedback does not set the upper mass limit of the stellar birth mass. This result rises a question on the common assumption of the IMF truncation at $100M_\odot$ in population synthesis models. Our result is consistent with most recent observation in the super cluster 30 Doradus in the Large Magellanic Cloud where tens of over-$100M_\odot$ stars were found (Crowther *et al.* 2010, Schneider *et al.* 2018). The other aspect from our result is that the SFE is lower at lower surface density, indicating that the high pressure of $\gtrsim 1\,\mathrm{g\,cm^{-2}}$ is favored for the formation of observed very massive stars.

The model is extended to the lower metallicity regime to connect the star formation in the present and the early universe (Tanaka *et al.* 2018). The SFE at low metallicity cases are shown in the left panel of Figure 3. The SFE gradually declines with the final stellar mass without truncations at all metallicities as at the solar metallicity. Therefore, we confirm that the feedback does not the upper mass limit at all metallicity range. While the SFE is almost identical at any metallicity at lower mass of $\lesssim 10M_\odot$, the SFE is lower at lower metallicity at higher mass cases. This is because the photoevaporation feedback is more efficient at low metallicity.

As a discussion, we evaluate the IMF at different metallicities assuming the CMF is "universal" with the Salpeter slope (the right panel of 3). At 0.1–$1Z_\odot$ which is the typical value of observed dwarf galaxies, the IMF variation is not apparent because the dominant feedback mechanism is always the MHD disk wind at this metallicity range. Thus, the surface density is more significant environmental parameter to set the SFE and the IMF (see Fig.1). On the other hand, at the extremely low-metallicity case of

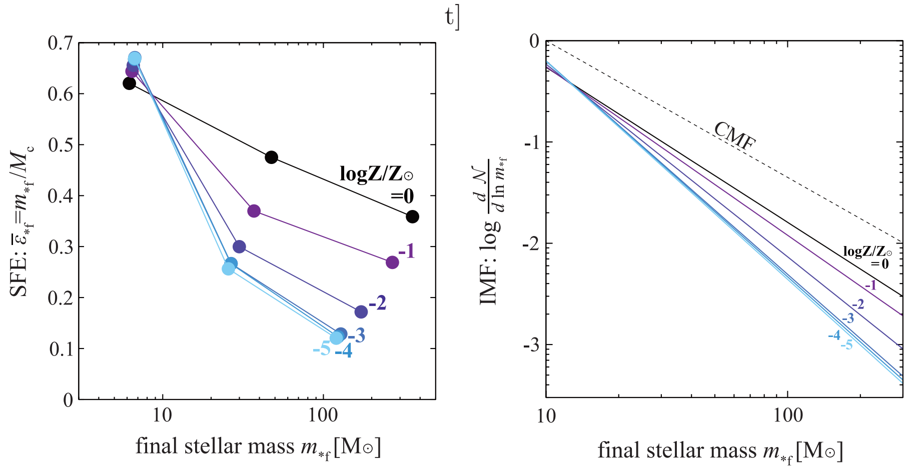

Figure 3. Results at various metallicities. (*left*) The SFE as the function of the final stellar mass at all metallicity range. (*right*) The estimated IMF from the Salpeter CMF and our SFE. Very massive stars would be rarer at extremely low metallicity.

10^{-5}–10^{-3}, the IMF gets apparently steeper than the Salpeter slope. This is because the photoevaporation becomes the dominant feedback at this low-metallicity regime. Thus, very massive stars would be rarer at such a low metallicity which is typical value for second generation stars (Chiaki *et al.* 2018).

We developed the semi-analytic model of massive star formation at various metallicity. Our results suggests request reconsideration of the common assumption of "universal" IMF with a truncation at $100 M_\odot$.

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Discussion

Q1: What is the effect of massive cores on other surrounding cores?

A1: The radiative feedback from massive collapsing core affects the surrounding core-mass-function. The dynamical interaction between cores would have some importance.

Q2: How's the accretion rate implemented? Is it a formula or are there physics behind? $10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$ is a high value.

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A2: The order of accretion rates is basically set by initial core properties (which is based on theories and observations). Our model does consider the competition between accretion and feedback. Accretion can continue in the shadow of the bipolar outflow.

Q3: You mentioned that stellar winds are not important as a feedback process during star formation. Which description did you use for the winds and would you say from your experience that different descriptions could lead to a different outcome?

A3: I use the model from Vink *et al.* 2011 and have not tried other wind models. However, comparing the accretion rate and other feedback mass-loss rates of $> 10^{-3}\,M_{\odot}\,\mathrm{yr}^{-1}$, the wind rate (which is $< 10^{-4}\,M_{\odot}\,\mathrm{yr}^{-1}$) is too small to become the dominant one. Please note that, in the evolutionary stage at 10^6 years, the wind is very important.

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