Abstract

The first stars are predicted to be massive, typically a few 10 $M_\odot$. On the other hand, the typical mass of the present-day stars is small ($\sim 0.4\ M_\odot$) and the distribution of massive star decreases as a power law function. Thus, the transition in the characteristic mass from high to low mass stars occurs in the low-metallicity environments.

In the massive star formation, the protostar luminosity becomes enormous and the radiative feedback effects, such as the radiation pressure on dust grains and UV feedback, potentially impact the accretion flow. In the primordial star formation, the gas does not contain dust grains, thus UV feedback only becomes effective. In this case, the stars larger than $10^3\ M_\odot$ are expected to be formed. At the solar metallicity, the radiation pressure limits mass accretion rather than UV feedback. In reality, there is no star larger than 150 $M_\odot$ in the Galaxy. Thus, the stellar mass at the massive end depends on the metallicity.

First, we investigate radiative feedback effects in the massive star formation. Assuming a spherical symmetric and steady flow, we numerically solve structure of both a protostar and an accretion envelope. As a result, the dominant radiative feedback effect changes with varying the metallicity. With a fixed mass accretion rate of $10^{-3}\ M_\odot \mathrm{yr}^{-1}$, the radiation pressure caused by the dust thermal emission terminates the accretion flow at $Z > 10^{-1}\ Z_\odot$. At $Z < 10^{-1}\ Z_\odot$, the direct light emitted from the protostar limits the mass accretion. At $Z < 10^{-3}\ Z_\odot$, the HII region formation plays an important role for terminating the accretion flow. The upper mass limits increase with the decrease of the metallicity, from $\sim 20\ M_\odot$ to $\sim 10^3\ M_\odot$ over $Z = 1 - 10^{-4}\ Z_\odot$.

Then, we perform 2D simulations for the low-metallicity massive star formation. We developed the 2D radiation hydrodynamics simulation code. This is the first code that allows us to systematically treat the radiative feedback effects considering a variation of the metallicity. We fix a cloud mass to $M_{\mathrm{cloud}} = 250\ M_\odot$ at first. At 1 $Z_\odot$, the accretion flow is terminated by the radiation pressure when the stellar mass reaches $M_* \simeq 30\ M_\odot$ in the 1D simulation. In the 2D simulation, however, the radiation pressure is weakened owing to the multidimensional effect and the final stellar mass increases to $\sim 150\ M_\odot$. At $10^{-2}\ Z_\odot$, the radiation pressure becomes ineffective. In the 1D simulation, the HII region also does not terminate the accretion flow. In the 2D simulation, on the other hand, UV feedback becomes more effective because the HII region rapidly expands to the polar direction of the accretion disk. The final stellar mass becomes $\sim 160\ M_\odot$ in this case. Thus, there is no significant difference of the final stellar mass between the cases with 1 $Z_\odot$ and $10^{-2}\ Z_\odot$. Next, we consider the cases with the higher cloud masses. The star formation efficiency is almost constant ~ 0.5 at 1 $Z_\odot$ because the radiation pressure is effective in all cases of the high metallicity. On the other hand, the star formation efficiency becomes larger with the increase of the cloud mass at $10^{-2}\ Z_\odot$. When the accretion rate is higher than $4 \times 10^{-3}\ M_\odot \mathrm{yr}^{-1}$, the stellar radius expands after the KH contraction phase. In this case, the stellar effective temperature decreases and UV

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feedback becomes ineffective. Thus, the radiation feedback cannot impact the accretion flow in the low-metallicity cases. In the case of spherical symmetric accretion or the high mass accretion, the stellar mass becomes more massive at the low-metallicity. Therefore, we expect that the transition of the upper mass limit occurs at $\sim 10^{-2}\ Z_{\odot}$.

For low-mass stars, it is considered that their formation occurs owing to fragmentation of star-forming clumps induced by the cooling of the dust thermal emission. Fragmentation of clumps is predicted to occur with $Z \gtrsim 10^{-5} - 10^{-6}\ Z_{\odot}$. Here, this metallicity is called the critical metallicity. On the other hand, the metallicity distribution of the observed metal-poor stars indicates that the critical metallicity should be $Z \sim 10^{-4}\ Z_{\odot}$ and this value does not coincide with the theoretical prediction.

We consider here dust evacuation from star-forming clouds due to the radiation pressure force from massive stars in order to explain this discrepancy. If dust evacuation occurs, the gas loses the coolant that induces fragmentation of clumps to the solar mass scale, and thus the low-mass star formation is suppressed. We analytically calculate the timescales for dust evacuation and cloud destruction. Dust evacuation occurs in compact star-forming clouds whose column density is $N_{\rm H} \simeq 10^{24} - 10^{26}\ {\rm cm}^{-2}$. Then, we consider the condition of dust evacuation for the galactic disks. The critical halo mass is lower for higher formation redshift, e.g., $\sim 10^{9}\ M_{\odot}$ ($\sim 10^{7}\ M_{\odot}$) at $z \sim 3$ (at $z \sim 9$, respectively). In addition, the radiation force on dust grains is reduced significantly if the star-forming cloud is optically thick for stellar radiation. Thus, the metallicity should be less than $\sim 10^{-2}\ Z_{\odot}$ for dust evacuation.

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