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Formation of massive primordial stars controlled by the protostellar evolution

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Abstract. We present our recent studies following the formation of massive primordial stars under UV radiative feedback, i.e., photoevaporation of circumstellar disks. We stress that the protostellar evolution controls the strength of the UV feedback and thus determines how massive primordial stars finally appear. We propose that large streaming motion of the gas with respect to the dark matter will open a pathway of forming extremely massive ($\gtrsim 10^4 \ M_\odot$) primordial stars. With very rapid mass accretion provided, the protostellar UV feedback is dramatically weakened as the star inflates to have very low effective temperature ($T_{\rm eff} \simeq 5000$ K) and small UV emissivity.

Key words. Cosmology: theory – Early universe – Stars: Population III – Stars: formation – Accretion

1. Introduction

The evolution of an accreting protostar is critical for understanding the massive star formation, because it provides the luminosity and effective temperature as functions of the stellar mass and accretion history. If the protostar emits radiation strong enough to disturb the accretion flow, the stellar mass growth is limited by resulting feedback effects. Hence, how massive star finally appears really depends on its evolution during the accretion stage.

In the context of the primordial star formation, Francesco and his collaborators developed the stellar evolution calculations including effects of the mass accretion (e.g., Stahler, Palla, Salpeter 1986; Omukai & Palla 2003). From the viewpoint of the UV feedback (e.g., Hosokawa et al. 2011; Susa 2013), it is critical when the protostar contracts losing its energy by radiating away (i.e., the so-called Kelvin-Helmholtz (KH) contraction). The stellar effective temperature and thus UV emissivity rapidly rises when the star contracts to approach the zero-age main-sequence stage. The epoch of the KH contraction differs with different accretion histories, and the resulting UV feedback modifies the accretion histories. The protostellar evolution and interplay between the accretion flow and UV feedback are thus tightly coupled. We have to consistently solve both of them to derive the resulting final stellar mass.

2. Formation of massive primordial stars

The formation of extremely massive primordial stars has been investigated to explain the quick formation of supermassive black holes (SMBHs) in ~ 1 billion years after the big bang. It is necessary to circumvent the UV

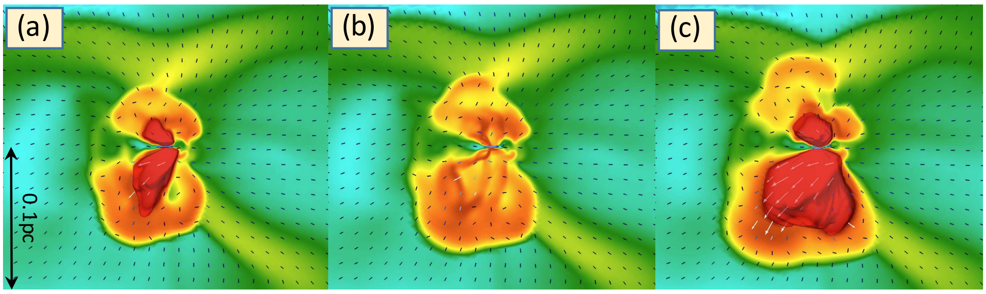

Fig. 1. The intermittent UV feedback observed in our 3D radiation hydrodynamic simulation (case C-HR2-m0 in Hosokawa et al. 2016). The panels (a)-(c) show a time sequence. In each panel, the color scale represents the gas temperature distribution. Note that an HII region (red) temporarily disappears in panel (b).

feedback to get such massive stars via mass accretion onto primordial protostars.

2.1. Intermittent UV feedback with episodic accretion

Recent stellar evolution calculations show that the protostellar evolution qualitatively changes with very high accretion rates exceeding $\dot{M}_{*,\rm cr} \sim 10^{-2}$ yr^{-1} (e.g., Hosokawa et al. 2013). In such a case, the KH contraction stage actually disappears. The protostar continues to expand as its total mass increases via accretion, approximately following $R_* \propto M_*^{0.5}$. The star has a small effective temperature of $T_{\rm eff} \simeq$ 5000 K owing to very large radius. Such "supergiant protostar" stage is a pathway to circumvent the UV feedback because only a small amount of UV photons are emitted by the inflated star.

The critical rate for inflating the star is much higher than the typical rate in the normal primordial star formation, $\sim 10^{-3}\ M_\odot$ yr^{-1}. This is why the normal KH contraction is thought to occur, so that the mass accretion is halted by the UV feedback. However, 3D simulations show that this is not necessarily the case. The mass accretion occurs through a self-gravitating circumstellar disk, and the resulting accretion history is not steady but very variable in time (e.g., Greif et al. 2012). It is normal that the accretion rate is greatly enhanced for a short duration. Such an accretion burst is followed by a relatively long quiescent phase, where the accretion rate is reduced by orders of magnitude.

Hosokawa et al. (2016) study the interplay between such episodic accretion and resulting UV feedback, performing 3D radiation hydrodynamic simulations coupled with stellar evolution calculations. Consider the epoch when an HII region is growing in the KH contraction stage (Fig. 1-a). Once the accretion rate exceeds the critical value with an accretion burst, a protostar rapidly inflates and its UV emissivity accordingly drops. The HII region disappears (b), and it is after a while in the quiescent phase that another HII region appears as the star contracts again (c). The cycle recurrently occurs as far as the mass supply from the envelope to the disk continues. As a result, the UV feedback only operates intermittently, and it is hard to limit the mass accretion. The mass accretion continues even after the stellar mass exceeds 300 $M_\odot$ in some cases. This effect supports the stellar mass growth, and suggest that the formation of even more massive stars will be possible with the more rapid accretion.

2.2. Seeding SMBHs with supersonic gas streams

The so-called direct collapse (DC) model postulates the formation of supermassive ($\gtrsim 10^5\ M_\odot$) stars in an atomic-cooling halo (e.g., Bromm & Loeb 2003). Since a gas cloud collapses almost isothermally at high temperature $T \simeq 8000$ K, the resulting accretion rates are enhanced owing to the well-known relation $\dot{M}_* \propto T^{1.5}$. However, the DC requires a number of stringent conditions such as intense FUV radiation field to destroy hydrogen molecules via photodissociation. Even if the FUV field is provided, the cloud collapse does not actually occur in many cases. The tidal force of FUV-illuminating galaxies prevents the cloud collapse (Chon et al. 2016).

Hirano et al. (2017) show that the formation of $M_* > 10^4\ M_\odot$ primordial stars possibly occurs even without the FUV fields. They only investigate a cosmological effect, a large streaming motion of the gas with respect to the dark matter (Tseliakhovich & Hirata 2010). With a rarely large gas streaming velocity, the normal primordial star formation is completely suppressed until a dark halo becomes massive enough to trap the streaming gas (Tanaka & Li 2014). Hirano et al. (2017) follow the evolution until the massive primordial stars appear for such cases, performing a suite of 3D simulations in a full cosmological context.

In a representative case examined, the star formation first occurs in an atomic-cooling halo. Although the gas temperature drops to < 1000 K via H_2 line-cooling without the FUV fields, the rapid accretion with $\gtrsim 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$ does occur after the birth of a protostar. This is partly because the cloud effectively has a large Jeans mass owing to the additional dynamical support provided by the streaming motion. Moreover, the rapidly inflowing gas into a massive halo makes the collapsing cloud highly unstable. The resulting accretion rate is thus substantially enhanced in comparison to the naive estimate with $\dot{M}_* \propto T^{1.5}$. The intermittent UV feedback also occurs in this case, but its strength is further reduced with the enhanced mean accretion rate. As a result, the mass accretion is hardly affected by the UV feedback throughout the simulation. The stellar mass reaches 34000 $M_\odot$ for 6×10^5 years. An equally massive BH will be provided after the death of the star.

3. Conclusions

The protostellar evolution changes with different accretion histories, and controls how massive star finally appears with resulting UV feedback effects. Recent theoretical studies predict that extremely massive ($\gtrsim$ 1000 $M_\odot$) primordial stars will form with the more rapid accretion than in the normal cases, where the typical stellar mass is $\sim$ 100 $M_\odot$ (e.g., Hirano et al. 2015). It is worth noting that this is in analogy with the present-day high-mass ($\gtrsim$ 10 $M_\odot$) star formation, which occurs with the higher accretion rates than in the standard low-mass ($\sim$ 1 $M_\odot$) cases.

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