Chapter IX:
Massive star formation near and far

Massive Stars Near and Far
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Formation of Very Low-metallicity Stars

Kazuyuki Omukai

Astronomical Institute, Graduate School of Science, Tohoku University
Aoba, Sendai 980-8578, Japan
email: omukai@astr.tohoku.ac.jp

Abstract. I describe (i) our recent updates on first star formation, with particular emphasis on their binaries, (ii) formation of low-metallicity stars and the transition of their initial mass functions with metal enrichment, and finally (iii) formation of supermassive stars from slightly metal-enriched gas by the newly found super-competitive accretion channel.

Keywords. stars: formation, stars: Population II

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1. Some Updates on Formation of the First Stars

First stars in the universe are formed from the primordial pristine gas composed only of hydrogen, helium and a trace amount of lithium. They are thought to be very massive with a few tens to even a few hundred $M_\odot$ (see contribution by Ralf Klessen, this volume). This theoretical expectation is based on the following reasoning: i) the host dense core, inside of which a protostar is eventually formed, is massive $\sim 1000 M_\odot$ reflecting the high temperature and thus the Jeans mass. ii) after its formation, the protostar grows in mass by accretion, but the accretion is hard to stop by stellar feedback because the accretion rate is high and the opacity is low. We can naturally expect that the continued accretion from the large mass reservoir results in the formation of massive stars. How massive they are quantitatively is the question to be addressed below.

Some years ago, Hosokawa et al. (2011) studied the accretion growth of a first protostar starting from the cosmological initial condition of a minihalo taken from Yoshida et al. (2008) by way of 2D radiation hydrodynamics simulation assuming the axisymmetry and found that UV feedback from the protostar finally shuts off the accretion by photoevaporating the protostellar disk and sets the final mass of the star. By repeating similar simulations for hundreds of first-star forming sites identified in a larger cosmological simulation box, Hirano et al. (2014; 2015) statistically derived mass distribution of forming first stars, which has a wide mass range form a few tens to hundreds of the Sun. Those calculations were, however, idealistic 2D simulation and did not allow the formation of multiple stars by construction. In fact, in 3D simulations of first star formation with its radiative feedback included, stellar masses are predicted to be smaller by a factor of a few as the mass reservoir is shared among multiple forming stars (Susa et al. 2014). So far, 3D simulations of this sort only treat the central star as a UV source (e.g., Hosokawa et al. 2016). To predict the final mass of stars, however, in particular in case that a binary/multiple stellar system forms, we need to consider radiation from each forming protostar.

Recently, we carried out such 3D simulations considering multiple radiation sources by using AMR hydrodynamics code SFUMATO (Matsumoto 2007), which is combined with a newly developed radiative transfer module using ART method (Abel & Wandelt

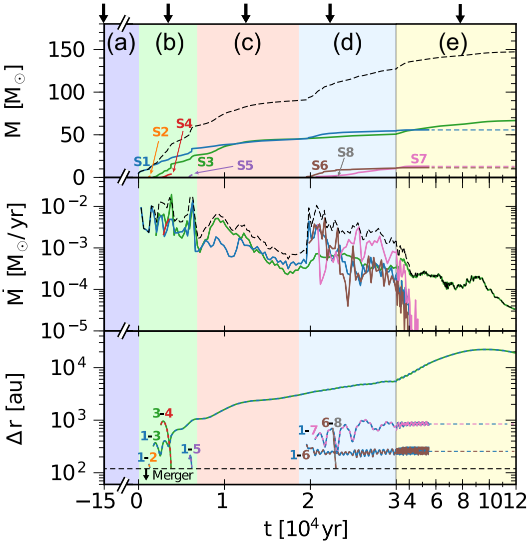

Figure 1. The time evolution of a forming first-star system; the masses of protostars, their accretion rates, and separations among them. Reproduced from Sugimura et al. (2020).

2002). Radiative transfer is solved for ionizing and dissociating photons, and a usual set of the primordial-gas microphysics is included.

As initial conditions, three minihalos (cases A, C, and D in Hosokawa et al. 2016) are picked up from the cosmological simulation of Hirano et al. (2015). Results of one case (case C) has been published in Sugimura et al. (2020), and is reproduced in Fig. 1. We find that a binary system composed of 70 and 60 $M_\odot$ massive stars is forming, along with a few other smaller stars. Such system is very interesting as an origin of merging binary black holes observed by gravitational waves if its separation is close enough (< 0.1au, e.g., Kinugawa et al. 2014). Unfortunately, the separation of this system becomes wider in time due to accretion of high angular momentum matter initially locating at outer part and reaches as wide as $\sim 10^4$ au. In the other two cases studied, we also find massive binary systems with similar masses ($370 + 130 M_\odot$ and $60 + 30 M_\odot$) with very wide separations of $10^3 - 10^4$ au (Sugimura et al. in prep.). Although our numerical resolution prohibits to follow systems with the separations below ~ 100 au, their binary separations are much wider. This suggests that formation of close first-star binary systems needs some other tricks, e.g., angular momentum transport by magnetic field, hierarchical system etc. The bottom line of our calculation is that *massive but wide binaries seem to be common among the first stars.*

2. Formation of Pop II Stars and Transition of IMF with Metallicity

As we have just seen, the first stars are typically massive $\sim 100 M_\odot$ according to theoretical studies. On the other hand, we know that low-mass very-metal-poor Pop II stars are present in Milky Way and other galaxies, and of course Pop I stars in the solar neighborhood are typically low-mass, $0.1 - 1 M_\odot$, following a Salpeter-like IMF. This means that there has been a transition in the characteristic stellar mass from very massive to low-mass ones in the cosmic history (*"Pop III-II transition"*).

The exact physical mechanism is still not very clear, but probably triggered by the accumulation of metals and dust grains in the ISM, which alters the thermal properties of star-forming gases (Omukai 2000, Schneider et al. 2001, Omukai et al. 2005; see Fig. 2).

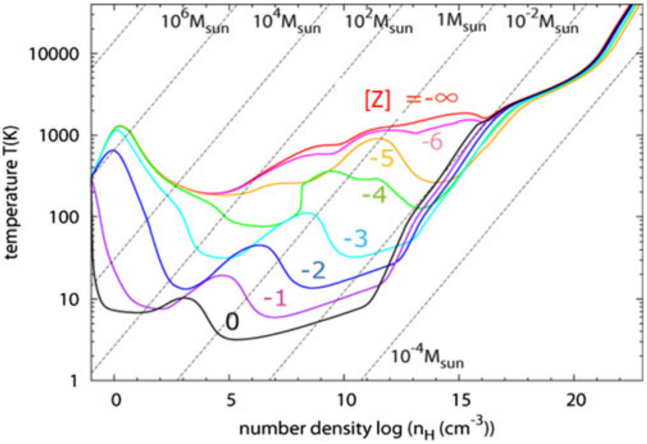

Figure 2. The temperature in star-forming clouds with different metallicities. The Jeans masses are indicated by dotted lines. Reproduced from Omukai et al. (2010).

With respect to the temperature in the primordial gas, which is controlled mostly by the H_2 cooling, with metallicity of $\log Z/Z_\odot \gtrsim -5$, a temperature dip begins to develop due to dust cooling at high densities ($\simeq 10^{12} \mathrm{cm}^{-3}$), where the Jeans mass is sub-solar. Because a rapid temperature drop likely causes fragmentation of the cloud, the dust cooling produces low-mass fragments and perhaps low-mass stars. With more metallicity, another temperature drop appears at lower densities due mainly to the metal (fine-structure) lines of C and O, but the Jeans mass at those densities is rather high $\gtrsim 100 M_\odot$ and resultant fragmentation does not produce low-mass stars.

This theoretical expectation has also been confirmed by more detailed numerical simulations (Tsuribe & Omukai 2006, Clark et al. 2008, Dopcke et al. 2013). Recently, we performed hydrodynamics simulations for star cluster formation from low-metallicity star-forming gas (Chon, Omukai & Schneider 2021) until a relatively late phase of protostellar accretion to obtain the mass distribution of forming stars. These are SPH simulations using Gadget3, with simplified chemistry and radiative processes of a low-metallicity gas. As an initial condition, we use a Bonner-Ebert sphere with transonic turbulence as is often used in studies on the present-day star formation.

The results can be summarized as follows: at relatively high metallicity, say $\gtrsim 10^{-3} Z_\odot$, the temperature drops soon due to efficient cooling, supersonic turbulence makes the cloud filamentary in shape, while at lower metallicities, turbulent effect is not obvious due to inefficient cooling and the cloud morphology is more centrally concentrated with a massive core at the center. The difference in the cloud morphology naturally affects the fragmentation property, and roughly speaking the fragmentation is more vigorous at higher metallicities.

What is more interesting to us might be the mass distribution of stars formed. As we can see in Fig. 3, the IMF is bimodal at low metallicities, consisting of low-mass Salpeter-like and massive log-normal components. At lowest metallicity, only the massive component is present. At $\log Z/Z_\odot \gtrsim -5$, in addition to the massive component, a low-mass component appears and grows in fraction with increasing metallicities. With metallicity as high as $\log Z/Z_\odot \sim -1$, only the low-mass component remains and the massive component disappears. *The IMF transition proceeds rather gradually with metallicity* in this way, rather than abrupt change from top-heavy Pop-III to low-mass Pop-I IMFs at some single metallicity.

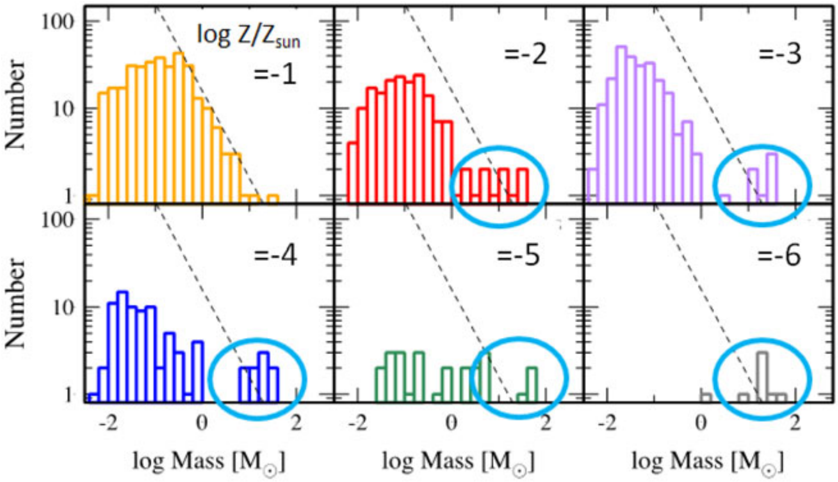

Figure 3. The mass distribution of stars, or the IMF, formed from clouds with different metallicities. The IMF consists of two components, low-mass and massive ones. The latter is indicated by circles in the panels. Plotted is at our final snapshot when the total stellar mass is $150 M_{\odot}$. Although the mass distribution changes with time, it has become almost stationary by this time. Reproduced from Chon, Omukai & Schneider (2021).

3. Formation of Super-Massive Stars

Finally, we consider super-massive stars (SMSs), with mass $\gtrsim 10^5 M_{\odot}$. Originally in 1960's, those monsters are proposed as the engine of active galactic nuclei, which are now commonly believed to be accreting super-massive BHs (SMBHs). Interestingly, fifty years later, in the last decade or so, interests on SMSs revived as an origin (i.e., seeds) of SMBHs. SMSs begin at some point in their evolution to ungergo gravitational collapse due to the general relativistic instabilily and form similar mass BHs (Umeda et al. 2016, Woods et al. 2017, Haemmerlé et al. 2018, see contribution by Tyrone Woods this volume).

But, how such massive objects are formed? A current popular scenario supposes the collapse of a massive primordial gas cloud irradiated by a strong far-UV field, which disables H_2 cooling. Without H_2, the cloud cools solely by atomic cooling and collapses isothermally at 8000K. This causes monolithic collapse without fragmentation and the rapid accretion at a rate as high as $1 M_{\odot}/\mathrm{yr}$ on to a protostar formed inside (Regan & Haehnelt 2009, Inayoshi et al. 2014, see contribution by John Regan in this volume). Also protostellar evolution becomes very different in cases with such rapid accretion: the stellar envelope inflates enormously to ~ 10 au, 10^3 times larger than the main-sequence stellar radius. As a result, the protostar looks like a red giant with the effective temperature ~ 6000K and thus emit a negligible amount of UV photons. With no radiative feedback to stop accretion, the star is expected to eventually become supermassive by continued accretion.

In conventional views, it is supposed that the above SMS formation channel is operative only for a primordial pristine cloud. This is because even a slight amount of dust causes steep temperature decline in the cloud and fragmentation into smaller pieces of $< 1 M_{\odot}$ (Omukai et al. 2008, Latif et al. 2016). The actual outcome of the collapse of a slightly metal-enriched cloud irradiated by strong FUV radiation field has not been clear. Recently, we studied this problem by way of SPH simulations (Chon & Omukai 2020). The initial condition is taken from a cloud in a halo that is strongly irradiated in

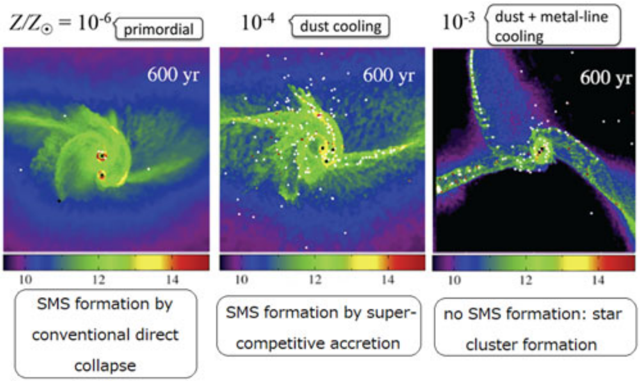

Figure 4. The outcome of the gravitational collapse of strongly irradiated clouds with different metallicities 10^{-6} (left), 10^{-4} (middle) and $10^{-3} Z_\odot$ (right). On the density distribution, protostars are overplotted by dots (black: massive ($> 10 M_\odot$), white: less massive). Reproduced from Chon & Omukai (2020).

the cosmological simulation of Chon et al. (2016) and we put different metallicity values on it.

The result is presented in Figure 4. In the lowest metallicity case of $10^{-6} Z_\odot$ (left panel) the cloud collapse proceeds as in the conventional direct collapse and (binary) SMSs form at the center with few small fragments. With some more metals ($> 10^{-5} Z_\odot$, middle panel), the cloud in fact violently fragments by the dust cooling and numerous small protostars are formed. This, however, does not immediately mean a SMS does not form in the cloud. Fragmentation induced by the dust cooling occurs at very high densities $\gtrsim 10^{12}\mathrm{cm}^{-3}$, while global flow patterns set at lower densities effectively feed the central objects the material in spite of the fragmentation during inflow. By this way, as shown for the case of $10^{-4} Z_\odot$, the central objects become super-massive in a similar but more scaled-up way as in the so-called competitive accretion in the context of present-day star formation (*super-competitive accretion*). Once the metallicity becomes as high as $10^{-3} Z_\odot$, the metal-line cooling becomes important at lower densities. As a result, the global flow pattern is significantly changed and no clear central object appears. Also the accretion rates onto the stars are largely reduced due to lower temperature. In such a case, a star cluster appears without SMS formation. In conclusion, *SMSs can be formed not only from the primordial gas but also from slightly metal-enriched gas* as long as the metal-line cooling is not effective yet. This new SMS formation pathway by the super-competitive accretion would enhance the number of formed direct collapse BHs by some factor (see Sassano et al. 2021) and might be able to explain the universal origin of SMBHs in galaxies.

References

Abel, T & Wandelt, B. D. 2002, *MNRAS*, 330, L53
Clark, P. C., Glover, S. C. O. & Klessen, R. S. 2008, *ApJ*, 672, 757
Chon, S., Hirano, S., Hosokawa, T. & Yoshida, N. 2016, *ApJ*, 832, 134
Chon, S., & Omukai, K. 2020, *MNRAS*, 494, 2851
Chon, S., Omukai, K. & Schneider, R. 2021, *MNRAS*, 508, 4175
Dopcke, G., Glover, S. C. O., Clark, P. C., & Klessen, R. S. 2013 *ApJ*, 766, 103
Haemmerlé, L., Woods, T. E., Klessen, R. S. et al. 2018, *MNRAS*, 474, 2757
Hirano, S., Hosokawa, T., Yoshida, N. et al. 2014, *ApJ*, 781, 60
Hirano, S., Hosokawa, T., Yoshida, N. et al. 2015, *MNRAS*, 448, 568

Hosokawa, T., Omukai, K., Yoshida, N. & Yorke, H. W. 2011, *Science*, 334, 1250
Hosokawa, T., Hirano, S., Kuiper, R. et al. 2016, *ApJ*, 824, 119
Inayoshi, K., Omukai, K., & Tasker, E. 2014, *MNRAS*, 445, L109
Kinugawa, T., Inayoshi, K., Hotokezaka, K. et al. 2014, *MNRAS*, 442, 2963
Latif, M. A., Omukai, K., & Habouzit, M. et al. 2016, *ApJ*, 823, 40
Matsumoto, T. 2007, *PASJ*, 59, 905
Omukai, K. 2000, *ApJ*, 534, 809
Omukai, K., Hosokawa, T. & Yoshida, N. 2010, *ApJ*, 722, 1793
Omukai, K., Schneider, R, & Haiman, Z. 2008, *ApJ*, 686, 801
Omukai, K., Tsuribe, T., Schneider, R, & Ferrara, A. 2005, *ApJ*, 626, 627
Regan, J. A. & Haehnelt, M. G. 2009, *MNRAS*, 393, 858
Sassano, F., Schneider, R., Valiante, R. et al. 2021, *MNRAS*, 506, 613
Schneider, R., Ferrara, A., Natarajan, P. & Omukai, K. 2001 *ApJ*, 571, 30
Sugimura, K., Matsumoto, T., Hosokawa, T. et al. 2020, *ApJ* (Letters), 892, L14
Susa, H., Hasegawa, K., & Tominaga, N. 2014, *ApJ*, 792, 32
Tsuribe, T. & Omukai, K. 2006, *ApJ*, 642, L61
Umeda, H., Hosokawa, T. Omukai, K. & Yoshida, N. 2016, *ApJ*, 830, L34
Woods, T. E., Hegar, A., Whalen, D. J., et al. 2017, *ApJ*, 842, L6
Yoshida, N., Omukai, K. & Hernquist, L. 2008, *Science*, 321, 669

Discussion

ANONYMOUS: If SMSs are so big and luminous, are they bright enough to be observed by current or future telescopes?

OMUKAI: Yes, they are above the JWST sensitivity limit. But if those sources are rare, we cannot find them without a clue to where to look for. Still, there have been some claims of candidate detection.

FROST: In the first-star binary formation simulation you showed, you highlighted a merger happening before the bipolar HII regions formed for each of the main binary stars. It seemed like there were discs surrounding these stars and one of these also fragmented after the bipolar flows were generated - can you comment on whether those companions would also merge or whether there is any possibility of them surviving and creating higher order multiple systems?

OMUKAI: In that case, fragments are formed after HII region starts developing. They survived until the end of our simulation without merger. Although an $N > 2$ system tends to be dynamically unstable and is easily subject to ejection, it is possible that a hierarchical higher-order system is formed.

QUINTANA: I was wondering: now that we can see the evolution of the mass distribution for population III to population I stats, with population III having more massive stars, have there been extrapolations/predictions to know what will be the mass distribution of future generation of stars?

OMUKAI: We can carry out similar simulation for future high-metallicity, low CMB temperature environment and predict stellar mass distribution. But the greatest uncertainty is external radiation other than CMB: Since the temperature will be very low, even its small contribution would change the result.

OEY: So intriguing that you find fragmentation in filaments at solar and core concentration below. Does this mean that SF is only hierarchical when filamentary SF occurs? This should affect the IMF.

OMUKAI: We first expected to be so, but the result indicates the power-law mass functional form of the low mass component do not change regardless of filament or disk fragmentation. The reason is not yet very clear due to stochasticity of fragmentation and ejection process.

OEY: It sounds maybe that both modes are hierarchical then? I ask because the Salpeter slope can be obtained from a simplistic hierarchical scenario.

OMUKAI: If hierarchical fragmentation predicts the Salpeter like slope, mixture of hierarchical fragmentation and growth of protostars by competitive accretion may be setting the slope. Both of them give a similar slope. The slope may remain the same for this reason although fragmentation appears more hierarchical at higher metallicities and not so at lower metalicities.