Stellar Evolution at low Metallicity: Mass Loss, Eplosions, Cosmology
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Formation of the First- and Second-generation Stars

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Abstract. I describe the formation process of first and second-generation stars and speculate their mass scales. The first-generation stars are expected to be very massive, but the second-generation stars can be low-mass objects even if they are formed from metal-free gas.

1. Formation of the First Stars in the Universe

Recent studies demonstrated that the first stars in the universe are very massive (e.g., Bromm et al. 2002). However, it should be noted that the first stars in this context are not always equal to metal-free stars. Bona fide first stars are not only composed of primordial pristine gas, but also are formed from the cosmological initial condition without any feedback from stars/AGNs. In this section, we consider such true first stars and leave problems of metal-free stars forming after the first-generation to the next section.

Why the first stars are considered to be very massive and how massive are they ? Recall that star formation process is basically an accretion process by an initially small protostar. If the accretion (at a rate $\dot{M}_{\rm acc}$) continues during entire stellar lifetime (for massive stars $t_{\rm OB} \sim 10^6$yr), the stellar mass finally reaches $\dot{M} t_{\rm OB}$. However, before the stellar mass reaches this maximum value, the accretion may be halted by some stellar feedback, e.g., radiation feedback or protostellar jet/outflow, at the stellar mass of $M_{\rm feedback}$. Even if the feedback is weak, the mass reservoir for accretion, which is set by the fragmentation mass scale $M_{\rm frag}$, might not be sufficient. In summary, the stellar mass is limited by the three factors above and can be written as

$$M_* = \min(M_{\rm frag}, \dot{M}_{\rm acc} t_{\rm OB}, M_{\rm feedback}). \qquad (1)$$

For the first stars, the fragmentation mass scale of zero-metal clouds is rather massive, $M_{\rm frag} \sim 1000 M_\odot$, which comes from the nature of H_2 cooling (Bromm et al. 2002). So there is plenty of mass reservoir for accretion. The mass accretion rate onto the first protostars is very high $\dot{M} \sim 10^{-3} M_\odot$ owing to the high pre-stellar temperature of the star-forming core (Omukai & Nishi 1998). So the star becomes very massive ($\sim 10^3 M_\odot$) during its lifetime unless the accretion is halted by feedback. The mass scale of stellar feedback $M_{\rm feedback}$ is so far totally unknown.

To study the stellar feedback effects, we need to know the accretion evolution of the first protostars. Figure 1 shows the evolution of radii of the accreting protostars for different accretion rate covering the range $1.1 - 8.8 \times 10^{-3}\ M_\odot\ {\rm yr}^{-1}$

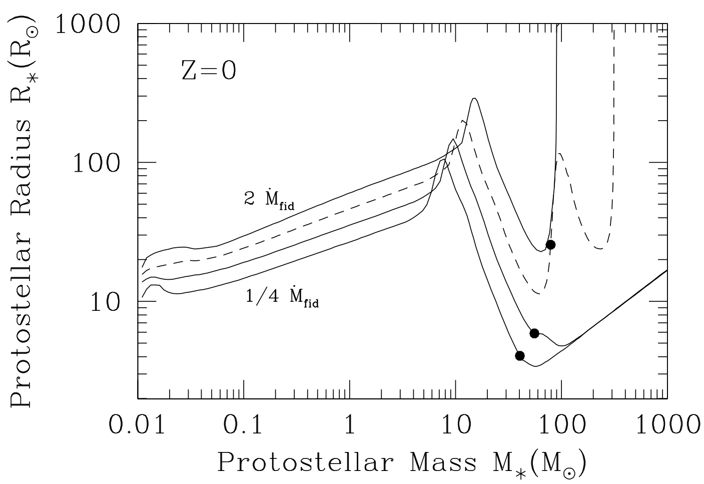

Figure 1. Mass-radius relations for metal-free protostars evolving with an accretion rate $\dot{M}_{\rm acc} = 1/4, 1/2, 1, 2\dot{M}_{\rm fid}$ (from top to bottom). The dashed line is for $\dot{M}_{\rm acc} = \dot{M}_{\rm fid}$, where the fiducial value is $\dot{M}_{\rm fid} = 4.4 \times 10^{-3} M_\odot$ yr^{-1}. The filled circles indicate the onset of H-burning via the CN-cycle.

(Omukai & Palla 2003). The adiabatic accretion phase ($M_* \lesssim$ a few to $\sim 10 M_\odot$) is marked by a gradual expansion of the radius and lasts until the arrival of the internal luminosity wave at the surface, whose eruption causes the sudden swell of the external layers (e.g., Palla & Stahler 1991). In the Kelvin-Helmholtz contraction phase (a few-$10 M_\odot \lesssim M_* \lesssim 30 - 60 M_\odot$) the increased gravitational pull of the growing star stops the expansion and forces the star to contract toward the conditions appropriate for a main sequence object. The third phase varies markedly, depending critically on the adopted value of $\dot{M}_{\rm acc}$. If the rate is comparable to $\dot{M}_{\rm fid}$ radiation pressure causes the abrupt expansion of the surface layers seen in the two upper curves of Figure 1 computed for $\dot{M}_{\rm acc} = (1-2)\,\dot{M}_{\rm fid}$. The protostellar radius increases tremendously and the impulsive release of energy likely causes the stripping of the external layers of the protostar by a radiation-driven stellar wind. This event signals the end of the accretion phase and sets the maximum value of the protostellar mass. In the opposite case where $\dot{M}_{\rm acc} < \dot{M}_{\rm fid}$, contraction proceeds unimpeded by accretion. In the cases shown in Figure 1 and computed for $\dot{M}_{\rm acc} = 1/2$ and $1/4\dot{M}_{\rm fid}$, the protostar reaches the ZAMS at a mass of $\sim 50\ M_\odot$.

We have seen the evolution of the first protostars as a function of accretion rate. So, how much is the actual accretion rate ? We also calculated the accretion evolution of a protostar, using accretion rate derived by a 3D simulation (Abel et al. 2000). Although the accretion rate starts at very high values, well above $\sim 10^{-3}\ M_\odot$ yr^{-1} up to about 60 $M_\odot$, it falls rapidly for very massive stars. In this case, similar to the low $\dot{M}$ cases in Figure 1, accretion continues unimpeded to very high masses. With continuing accretion, the final mass of the forming star is set by how much material can be accreted during the stellar lifetime. A detailed analysis has concluded that if the accretion continues, the mass attained during the entire stellar lifetime is about $600 M_\odot$.

Recently, Tan & McKee (2003) proposed some mechanisms to stop accretion by stellar radiation. Among them, evaporation of the accretion disk by stellar UV irradiation seems to be the most promising, which becomes important at $\sim 200 M_{\odot}$. Other effects, for example, the Lyα radiation force can become significant earlier, but perhaps it works only the gas perpendicular to the disk, and doesn't stop the accretion through the disk. Even if the photoevaporation of the disk works, the stellar mass is already very massive. That is, $M_{\rm feedback} > 100 M_{\odot}$.

2. Formation of the Second-generation Stars

In comparison with the first-generation star formation, formation process of second-generation stars is already very complicated. First, the initial condition is different from the cosmological one and is not yet fully constrained. The initial ionization and molecular fractions are different from the well-known values for the homogeneous background universe. Secondary density fluctuations can be created for example by SN blast waves, expansion of HII regions, etc. Besides the cosmic background radiation, we may need to consider UV radiation field by stars and/or galactic nuclei and sometimes even cosmic rays. Of course, metal and dust enrichment of interstellar gas affects the chemical and cooling process significantly.

Among these complexities, I discuss only the effects of ionization and metal enrichment in this contribution.

2.1. Effect of Initial Ionization: Star Formation in Fossil HII Regions

Zero-metal stars in the ranges 10-40$M_{\odot}$ and 140-260$M_{\odot}$ end their lives as type II SNe or pair-instability SNe, respectively. Considering that the first stars are very massive $\gtrsim 100 M_{\odot}$ and the narrow mass range for pair-instability SNe, the majority of the first stars becomes black holes directly without SN explosion. Here I show what will happen for the gas ionized by the first star after its death. Suppose that an exciting star of HII region dies without SN. After that, hydrogen recombines and molecular clumps will form inside the fossil HII region. Star formation can occur there again. In Figure 2, we plot the chemical evolution of initially ionized gas since the death of the central star (Nagakura & Omukai 2005). Molecular hydrogen is immediately formed in a large amount (Figure 2) through the H^- channel

$$\mathrm{H} + \mathrm{e}^- \rightarrow \mathrm{H}^- + \gamma, \tag{2}$$

$$\mathrm{H} + \mathrm{H}^- \rightarrow \mathrm{H}_2 + \mathrm{e}^-, \tag{3}$$

because the electron, which is the catalyst of this reaction, is abundant in our initial state. On the other hand, the electron fraction declines dramatically through recombination with increasing density. Because of the reduced number of electrons, the abundance of molecular hydrogen becomes saturated. Around the center, the H_2 fraction finally reaches about 5×10^{-3}, which is well above that in the case of a halo without initial ionization (about 10^{-4} for $n_{\rm H} \lesssim 10^4$ cm^{-3}). In our case, the temperature drops enough to trigger HD formation. Owing to the higher binding energy by $\Delta E/k_{\rm B} = 464$K, HD is a state preferable

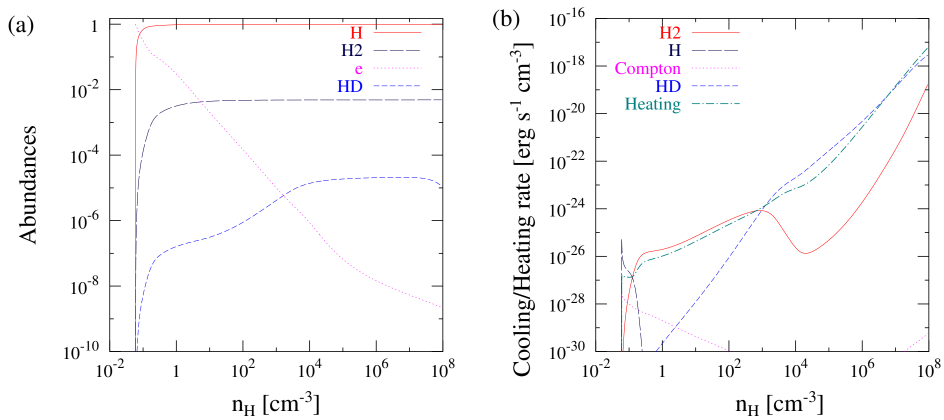

Figure 2. The evolution of (a) the chemical species and (b) the coolants at the center as a function of its number density. We plot for a halo of z_{vir}=15, M_{halo}=10^7 $M_\odot$.

to H_2 at the lower temperature. Resultant HD cooling reduces the temperature below 100 K (see Figure 3). The HD cooled region, which is finally cooled below 100 K, is about 30 $M_\odot$. Even in a small halo, the cloud can contract without evaporation owing to the instant effect of H_2 cooling. Under such a low temperature environment, with further contraction the gas is expected to fragment into low-mass (~ 1 $M_\odot$) gas clumps (Uehara & Inutsuka 2000). If those low-mass stars accrete metal-polluted interstellar medium after the formation, they might resemble ultra metal-deficient stars (e.g., Yoshii 1981). This may explain the origin of the ultra metal-deficient low-mass stars discovered recently (Christlieb et al. 2002; Frebel et al. 2005).

2.2. Effect of Metal Enrichment

Temperature evolution of prestellar clouds with different metallicities is shown in Figure 4 (Omukai et al. 2005). The presence of metals as low as $[Z/H] \lesssim -6$ does not significantly alter the thermal evolution in any density range. Among metallicity effects on thermal evolution, the cooling due to dust thermal emission is the most important in clouds with slightest amount of metals. For the cloud with $[Z/H] = -5$ this effect can be observed as a temperature dip around $10^{13} - 10^{14}\mathrm{cm}^{-3}$. For clouds with $[Z/H] > -4$, the H_2 formation on grain surface supercedes the gas-phase H^- channel. The enhanced H_2 cooling results in HD formation by a similar mechanism to the HD formation in fossil HII regions. The temperature deviation in the cases $[Z/H] \sim -4$ from the metal-free one around $10^5\mathrm{cm}^{-3}$ is caused by this effect. For clouds with $[Z/H] \gtrsim -3$, the carbon and oxygen lines dominate the cooling in the low density regime $< 10^5\mathrm{cm}^{-3}$.

How much is the fragmentation mass scale in slightly metal-enriched gas? According to numerical simulations for metal-free clouds, fragmentation occurs when the rapid (H_2) cooling phase terminates ($10^4\mathrm{cm}^{-3}$; Bromm et al. 2002). Assuming that this rule also holds in other metallicity cases, we expect that another fragmentation episode takes place following the rapid cooling by dust grains. In this case, the fragmentation mass scale drops almost suddenly from $1000 M_\odot$ to $1 M_\odot$ at the critical metallicity $[Z/H] = -(4-5)$.

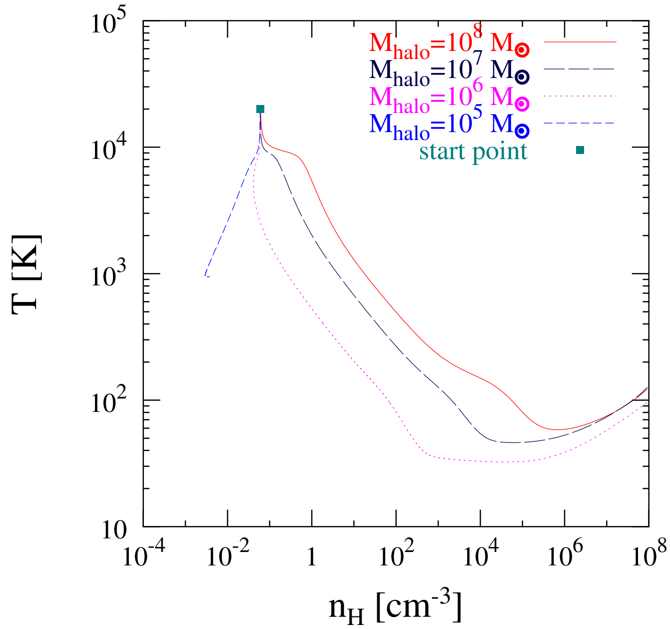

Figure 3. The evolution of the central temperature as a function of the central number density for halos virializing at $z_{\rm vir} = 15$. We plot the cases of $M_{\rm halo} = 10^5$, 10^6, 10^7, and 10^8 $M_\odot$. The square represents the initial state.

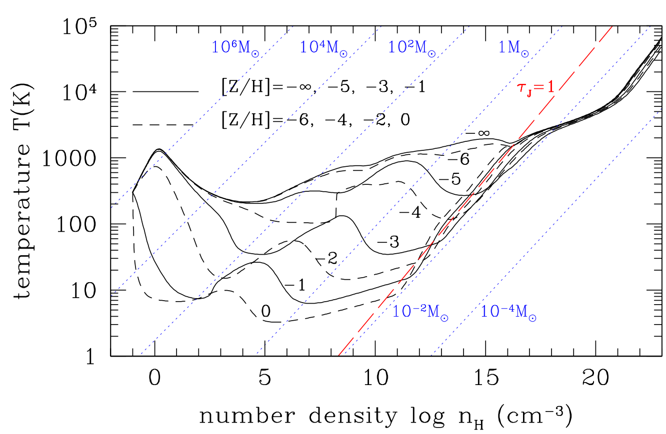

Figure 4. Temperature evolution of prestellar clouds with different metallicities. Those with metallicities [Z/H]=-∞ (Z=0), -5, -3, and -1 (-6, -4, -2, and 0) are shown by solid (dashed) lines. The lines for constant Jeans mass are indicated by thin dotted lines. The positions where the central part of the clouds becomes optically thick to continuum self-absorption is indicated by the thin solid line. The intersection of the thin solid line with each evolutionary trajectory corresponds to the epoch when the cloud becomes optically thick to the continuum. To the right of this line, the clouds are optically thick and there is little radiative cooling.

3. Conclusion

Metal-free stars consist of two populations, i.e., the first-generation stars and the metal-free second-generation stars. The former is stars formed from the cosmological initial condition in an environment without any astrophysical feedback. Their protostellar collapse is induced by the H_2 cooling and the mass scale is typically very massive, $10^2 - 10^3 M_\odot$. On the other hand, even in metal-free environment, second-generation stars can be less massive. We demonstrated that low-mass star formation is possible in fossil HII regions. Also slight amount of metals ($\sim 10^{-5} Z_\odot$) causes the transition from massive to low-mass star formation mode.

References

Abel, T., Bryan, G. L., & Norman, M. L., 2002, Science, 295, 93
Bromm, V., Coppi, P. S., & Larson, R. B., 2002, ApJ, 564, 23
Christlieb, N. et al., 2002, Nature, 419, 904
Frebel, A. et al., 2005, Nature, 434, 871
Nagakura, T., & Omukai, K., 2005, MNRAS, in press
Omukai, K., 2000, ApJ, 534, 809
Omukai, K. & Nishi, R., 1998, ApJ, 508, 141
Omukai, K. & Palla, F., 2003, ApJ, 589, 677
Omukai, K., Tsuribe, T., Schneider, R., & Ferrara, A., 2005, ApJ, 626, 627
Tan, J. C., & McKee, C. F., 2003, in Proc. 13th Annual Astrophysics Conference in Maryland: The Emergence of Cosmic Structure, ed. S. Holt & C. Reynolds (New York: AIP), 666, 93
Uehara, H., & Inutsuka, S., 2000, ApJ, 531, L91
Yoshii, Y., 1981, A&A, 97, 280

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Discussion

Oey: Do you think the formation of binary or multiple stars is more difficult in primordial conditions?

Omukai: In primordial gas, fragmentation is more difficult than in present-day ISM. But with angular momentum a disk is formed during the collapse. This disk may fragment and evolve into a binary or multiple.

Zinnecker: You found a critical metallicity for dust formation of $Z \sim 10^{-5}$. Which kind of dust did you put into your calculations? Much fewer dust grains but with the present-day dust size and composition or the same number density of dust grains as today but very different composition and size?

Omukai: I assumed the same size distribution and composition as the dust in local star forming regions, and just decreased them linearly to Z. Recently, we carried out another calculation where dust from the first stars are adopted, whose average size is smaller than the present-day one. In this case total area of dust per limit dust mass is increased. Then with the same mass fraction, effect of dust becomes more important.

Maeder: Why is H_2 and HD formation favored by previous ionization?

Omukai: In the primordial gas, H_2 formation occurs via the reaction, which uses electron as a catalyst: $H + e \rightarrow H^- + \gamma$ & $H^- + H \rightarrow H_2 + e$. Then a large amount of H_2 is formed from gas with initial ionization. The cooling by this abundant H_2 makes the temperature lower than the ordinary. This low temperature ($\lesssim 150$K) environment favors the HD formation, which proceeds by the exchange reaction: $H_2 + D^+ \rightarrow HD + H^+$.

Lamers: Can you explain why dust cooling becomes important at $Z \gtrsim 10^{-5}$, whereas line cooling becomes important at higher $Z \gtrsim 10^{-3}$. I would expect that line cooling is important before dust cooling is important.

Omukai: In the low-density regime line cooling is more important, while in high-density regime, dust cooling dominates in low metallicity environments. The reason is as follows: both gas (i.e. line) and dust cooling rate per unit mass depend on (density)^2, before the LTE (for gas) or the gas–dust coupling (for dust) is reached. For higher density, both depend linearly on density. In low metallicity gas, the gas–dust coupling occurs at higher density than the LTE. Therefore at some density, the dust cooling rate exceeds the line cooling rate.

Harris: You find that HD can provide an efficient cooling mechanism which can facilitate the formation of second generation low mass stars. Have you considered the possible effects of other molecular species such as LiH?

Omukai: I included LiH as a coolant in another calculation, but I found it is not important. If all Li became LiH, LiH would be an important coolant in a high-density regime (say 10^{10} cm^{-3}). However, unlike HD, LiH is less stable than H_2. As a result; LiH is destructed by the reaction $LiH + H \rightarrow Li + H_2$ and sufficient LiH is never produced in the primordial gas.