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The Minimum Mass of the First Stars and the Anthropic Principle

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The lower limit of the mass of the first stars suggested recently may imply the formation of massive stars of mass greater than $8 M_{\odot}$ irrespective of the details of the initial mass function. The production of heavy metals from the first stars will provide a requisite for the existence of life without the anthropic principle.

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§1. Introduction

It was recently shown that the initial mass function (IMF) in the Galactic disk increases monotonically with decreasing mass and is reasonably well described by a power law $n(m) \propto m^{-\alpha_{disk}}$ with $\alpha_{disk} \sim 2 \pm 0.5$ from $\sim 0.6 M_{\odot}$ down to the hydrogen-burning limit¹⁾. The bimodal IMF with a turn-over around $\sim 0.2 M_{\odot}$ ²⁾ is shown to be due to unresolved binaries in the photometric luminosity function.

In the Galactic disk, grains made from heavy metals are the main coolants in the star formation process. While in the formation of the first stars after the recombination of the universe, hydrogen molecules are the only coolants for temperature below 2000K since in the Big Bang Nucleosynthesis no nuclei heavier than B^8 are formed. This implies that the star formation process of the first stars may be different from the present one. For example, the power index of the IMF of the first stars α_{first} may be completely different from α_{disk} .

The lower end of the mass of the stars in the present IMF is not known either. One might think that the lower end should be $\sim 0.08 M_{\odot}$ because this is the lower limit of the hydrogen-burning star. However in the Hayashi phase, the pre-main sequence star itself does not know if the hydrogen is ignited in the end. At present there is no reason to believe that only stars of mass larger than $\sim 0.08 M_{\odot}$ are formed. In reality the existence of brown dwarfs (=low mass stars of mass less than $\sim 0.08 M_{\odot}$) has been confirmed observationally³⁾ and microlensing events opened the possibility that the halo of our Galaxy might consist of such dim brown dwarfs⁴⁾.

§2. The minimum mass of the first stars and the anthropic principle

As for the first stars, we know neither the IMF nor the lower end of the mass. Then what guarantees the formation of the massive first stars of mass $M > 8 M_{\odot}$

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which can scatter metals into the interstellar gas ? One might wonder why this is a problem. However the following hypothetical universe will make the problem clear. Suppose that if the IMF of the first stars is a steep power law with α_{first} greater than 5 and the lower end of the mass m_l is $0.01M_\odot$, which is suggested through the analysis of the spherically symmetric collapse of the primordial gas cloud⁵⁾. Then the number of stars of mass heavier than $\sim 8M_\odot$ is given by

$$N(> 8M_\odot) = C \int_8^{m_u} m^{-\alpha_{first}} dm, \quad (2.1)$$

where m_u is the upper mass limit. The numerical constant C is determined by the total mass of a galaxy

$$M_{tot} = C \int_{m_l}^{m_u} m^{-\alpha_{first}} m dm. \quad (2.2)$$

Since we consider the index of $\alpha_{first} > 2$, the integral in Eq.(2.2) is insensitive to the upper end of the mass. If we consider a typical galaxy of mass $M_{tot} \sim 10^{11}M_\odot$, then we have

$$N(> 8M_\odot) \simeq \frac{\alpha_{first} - 2}{\alpha_{first} - 1} M_{tot} m_l^{\alpha_{first} - 2} 8^{-(\alpha_{first} - 1)} < 20 \quad (2.3)$$

for $\alpha_{first} > 5$ and $m_l \sim 0.01M_\odot$. This suggests that few supernovae occur and only a small amount of heavy elements are returned to the interstellar gas. The final destiny of this hypothetical universe is the assembly of cooled brown dwarfs, white dwarfs and the diffuse hydrogen and helium gas. No habitable planets, and therefore, no human beings exist in this universe. The anthropic principle may reject this hypothetical universe⁶⁾. In the universe with such a steep power index of the IMF, no human being would exist. Thus in the actual universe α_{first} must be sufficiently small.

Recently analyzing the fragmentation process in the primordial gas cloud, Uehara et al.⁷⁾ suggest that the minimum mass of the first stars is essentially given by the Chandrasekhar mass $\alpha_G^{-3/2} m_p \sim 1M_\odot$, where m_p is the proton mass and $\alpha_G \equiv Gm_p^2/hc$. The argument of Uehara et al. is as follows. The primordial gas cloud collapses losing its thermal energy by line emissions due to hydrogen molecules. When the collapse proceeds enough, the collapsing timescale t_{dyn} becomes equal to the cooling timescale t_{cool} . For the cylindrical cloud with line density M and scale radius R , t_{cool} is estimated by

$$t_{cool} \sim \frac{1}{\gamma-1} \frac{M}{\mu m_H} \frac{k_B T}{2\pi R \sigma T^4 \frac{\Delta\nu}{\nu} \alpha_c}, \quad (2.4)$$

where μ, σ and α_c are the mean molecular weight, the Stefan-Boltzmann constant, and the effective number of line emissions, respectively. The cloud temperature and the line profile are estimated as

$$k_B T = \frac{1}{2} \mu m_H G M, \quad \frac{\Delta\nu}{\nu} = \frac{v_{H_2}}{c} = \sqrt{\frac{k_B T}{m_H c^2}}. \quad (2.5)$$

The collapsing cloud fragments when the collapse is almost halted⁸⁾, i.e., when the condition

$$t_{dyn} \sim t_{frag} \quad (2.6)$$

is satisfied, where $t_{frag} = 2.1/\sqrt{2\pi G\rho_0}$ is the time scale of fragmentation⁹⁾. From Eqs.(2.4) to (2.6) we obtain the minimum mass of the fragment as

$$M_{frag} \sim 2\pi RM \sim \alpha_G^{-3/2} m_p. \quad (2.7)$$

The difference between the results of Uehara et al.⁷⁾ and those of Palla et al.⁵⁾ is that the former estimates the mass when the condition (2.6) is satisfied, while the latter does so when the Jeans mass becomes a minimum.

If the lower end of the mass of the first stars is $\sim 1M_\odot$ as suggested by Uehara et al.⁷⁾, even for the steep IMF with $\alpha_{first} = 5$, the number of stars of mass heavier than $\sim 8M_\odot$ is

$$N(> 8M_\odot) \simeq \frac{3}{4} 10^{11} 8^{-4} > 10^7 \quad (2.8)$$

for the typical galaxy of mass $\sim 10^{11}M_\odot$, which is large enough to make the metal abundance $Z \sim 10^{-4}$. Therefore the above hypothetical universe is rejected without the anthropic principle, that is, even if we do not know the details of the IMF of the first stars^{*)}, it is certain that the interstellar gas is polluted by the metals, which is a requisite for the existence of life.

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^{*)} Actually, α_{first} has only to satisfy $\alpha_{first} < 13 + \log\left(\frac{M_{total}}{10^{11}}\right)$ in order to ensure the existence of massive stars.