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Formation of first generation stars

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Abstract

In this note, we examine the elementary processes in star formation and discuss a strategy of developing a theory of star formation in early universe.
Key words: star formation, early universe.

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1 Introduction

Various projects, such as Hubble space telescope key project and High Red-shift Supernova project, have brought the image of early universe into focus. The cosmological parameters such as Hubble constant H and the value of Λ term are fixed. We can see the image of galaxies even at the red-shift parameter $z \sim 5$. The theory of early universe is, however, still obscure. We can not explain the genesis of galaxies. The fact that we do not yet understand the physics of star formation makes the theory unclear. This is the most tough obstacle to develop the theory of early universe. In this note, we discuss the various problems on the formation of first generation stars, which is urged to understand.

2 Environment for formation of first generation stars

In the big bang universe, when the temperature of the universe decreases to 3000K, proton and electron recombine and the neutral hydrogen is formed. Because the binding energy of hydrogen atom is 13.6eV, hydrogen atom in thermal equilibrium is neutral in low temperature.

Photon and neutral hydrogen does not interact, the interaction between matter and photon decouples, and it becomes possible for the matter to bind and form stars. As the detailed study in early 70th by Peebles[2] and Sato-Matsuda-Takeda[3] showed, the ionization rate in early universe, in fact, does not attain the value in thermal equilibrium and locked to the value around 10^{-5}. This is because the mean free path of the Lyman photon is very short ($10^{-10}c/H$), the photon emitted in recombination ionizes matter immediately. The two photon emission, decay rate of which is $8.23\,\mathrm{s}^{-1}$, or the escape of red shifted Lyman photon ceases the ionization of neutral hydrogen.

The energy density of matter varies as a^{-3} against the variation of the scale of universe a, and the energy density of radiation varies as a^{-4}. Let the temperature of present universe $T_0(= 3\,\mathrm{K})$. The universe changes from radiation dominated universe to matter dominates universe when the temperature of the universe is $T/T_0 = 10^{4.45}\Omega_{\mathrm{baryon}}$. From the theory of synthesis of light elements, we know the ratio Ω_{baryon} of the baryon density to the critical density of the universe is $0.01 < \Omega_{\mathrm{baryon}}h^2 < 0.015$, where h is the Hubble constant in units of $100\,\mathrm{km\,s^{-1}Mpc^{-1}}$. The radiation dominated universe, therefore, continues for a while after the recombination epoch.

The first generation star forms from a very small fluctuation of the density of matter in the radiation dominated universe in a small ionization environment. The fluctuation of matter density forms far before the formation of star. As the distance to the horizon is extremely short, the energy fluctuation of the scale of star can not exist, The isocurvature purterbation, which does not associate the entropy fluctuation, can exist. In this fluctuation, total fluctuation of energy density is zero. This means that, in radiation

dominated era, there can be exist comparatively large fluctuation of matter density in the environment in which fluctuation of radiation can be neglected. The first generation stars are formed from these fluctuation.

3 Growth of density fluctuation in expanding universe

The equations which describe the fluctuation are derived from equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0, \tag{1}$$

$$\frac{\partial u_i}{\partial t} + (u_j \frac{\partial}{\partial x_j})u_i = -\frac{\partial \phi}{\partial x_i} + \frac{1}{\rho}\frac{\partial p}{\partial x_i}, \tag{2}$$

$$\frac{\partial^2}{\partial x_i \partial x_i} = 4\pi\rho - \Lambda c^2, \tag{3}$$

where ρ is the mass density, u_i is the velocity of matter, Λ is the cosmological term. These are equations for Newtonian dynamics, but the equations for the fluctuation are the same derived from the general relativity because general relativity are related only to boundary conditions. Let the non-perturbative evolution to be

$$u_{0i} = H(t)x_i, \tag{4}$$

$$\rho_0 = \rho(t), \tag{5}$$

$$\phi_0 = \phi_0(r,t), \tag{6}$$

and the fluctuation to be

$$\rho = \rho_0(t) \cdot (1 + \sigma(x_i, t)), \tag{7}$$

$$u_i = u_{0i} + u'(x_i, t), \tag{8}$$

$$\phi = \phi_0 + \phi'. \tag{9}$$

When we make transformation to co-moving coordinate

$$x_i\prime = x_i e^{-t} \tag{10}$$

$$t' = t \tag{11}$$

and further transform to

$$\phi\prime = 4\pi G\rho_0 e^{2t}\phi'' \tag{12}$$

$$u_i'/H = e^t u_i'' \tag{13}$$

we finally obtain the equations:

$$\frac{\partial \sigma''}{dt} + \frac{\partial}{x_i'}\{(1+\sigma'')u_i''\} = 0, \tag{14}$$

$$(\frac{\partial}{\partial t} + 2 - q)u_i'' + (u_j''\frac{\partial}{\partial x_j'})u_i''$$

$$= -3(q + \Omega_\Lambda)\frac{\partial \phi''}{\partial x_i\prime} - \frac{e^{-2t}}{H^2\rho}\frac{\partial p}{\partial x_i}, \tag{15}$$

$$\nabla\phi'' = \sigma'', \tag{16}$$

where q is the deceleration parameter.

As the energy density of radiation is larger than that of matter, we can not neglect the drag by radiation in the equation of motion for matter. The drag is caused by the Thomson scattering with the cross section $\sigma_{\rm T}$. We can take into account of this effect by adding the term

$$-\frac{4}{3}\sigma_{\rm T}\frac{aT^4_{\rm radiation}}{m_{\rm H}c}(\frac{n_e}{n})u_i \tag{17}$$

to the right hand side of equation (15). For the energy equation for matter, the term which describe the energy exchange between radiation

$$4\sigma_{\rm T} a T^4_{\rm radiation} n_e k(T_{\rm radiation} - T_{\rm gas})/(m_e c) \tag{18}$$

is added.

We can start calculation from the time when the perturbation can be conceived to be linear, for example from the red-shift parameter $z = 10^3$, i.e., $T \sim 3 \times 10^3$ K, by imposing a periodic boundary condition for a box corresponding to a selected wave length. From the COBE observation of the spatial fluctuation for the background radiation, we can consider the strength of initial fluctuation to be of the order of $\delta\rho/\rho \sim 10^{-5}$. The initial velocity of perturbation is of the order of sound velocity.

In the first stage, the density in the simulated region starts to expand associated with the expansion of the background universe. In this expansion regime, we must take into account of the formation of H_2 molecule and the cooling by it. The cooling law by H_2 molecule has been studied in detail by Lepp and Shull[1]. The temperature in background universe is deceased proportional to $n^{1/3}$, where n is the number density of baryon. The temperature of the simulated region is decreased by adiabatic law, i.e., proportional to $n^{2/3}$. The simulated region cools faster than the background universe. The H_2 cooling accelerates this cooling. The radiation drag by Thomson scattering also play an important role.

In these density region, molecular hydrogen is formed through the processes

$$\begin{array}{lcll} H+e^- & \leftrightarrow & H^-+\gamma & (3.0\times10^{-16}\,{\rm cm^3/s^{-1}}), \\ H^-+H & \leftrightarrow & H_2+e^- & (1.5\times10^{-9}\,{\rm cm^3/s}), \end{array}$$

and

$$\begin{array}{lcll} H+H^+ & \leftrightarrow & H_2^+ + \gamma & (6.0 \times 10^{-19}\,\mathrm{cm}^3/\mathrm{s}), \\ H_2^+ + H & \leftrightarrow & H_2 + H^+ & (6.4 \times 10^{-10}\,\mathrm{cm}^3/\mathrm{s}). \end{array}$$

In this table, the reaction rates for the right direction is shown[1]. The reaction rate for inverse direction is determined by the detailed balance.

When the temperature of the gas is decreased to about $T = 10\,\mathrm{K}$, where the density of the gas cloud is about $n = 10^{-2}/\mathrm{cm}^3$, the gas cloud begins reversal collapse. The gravitational energy of the gas cloud is overwhelmingly large compared with the thermal energy. The ratio amounts to $10^4 \sim 10^6$. The collapse is complete free fall. We do not know the result of such an intense collapse, but the physics of this collapse determines the fragmentation process, which makes the first generation stars.

In these collapse, we must take into account various elementary processes such as ionization and recombination of hydrogen atom, radiation drag by Thomson scattering, free-free absorption and bremsstrahlung radiation, and the generation of Lyman photon and its escape from the gas cloud.

This collapse continues adiabatically to the temperature of $T = 10^4\,\mathrm{K}$, then proceeds almost isothermally. The ionization rate is from 10^{-2} at $n \sim 10^3/\mathrm{cm}^{-3}$ to 10^{-4} at $n \sim 10^{10}\mathrm{cm}^{-3}$.

We do not know how the collapse stops. The fragmentation of gas cloud occurs when the collapse stops. In order to make this process clear, we must study the dissipation process in detail. The density at bounce exceeds $10^{10}\,\mathrm{cm}^{-3}$, but in this density H_2 formation through three body reaction can not be neglected and the cooling law changes drastically.

The morphological form of the gas cloud is expected to be disk-like from the property of gravity. The temperature in the shocked region formed in this condition attains to the order of $10^6 \sim 10^7\,\mathrm{K}$. This is far higher than the binding energy of hydrogen atom. In order to make clear the shocked dissipation, we must calculates the radiative transfer exactly, taking into account the atom and molecular reactions.

In order to simulate the collapse and the fragmentation process, we must trace the density variation of the order of 15 figures. That the form of the gas cloud is disk-like means that we must trace the variation of 15 figures in length. This is impossible in practice. Therefore, the strategy is divided into three parts. First, we calculate the collapse using three dimensional code in order to make the physics of disk formation clear. Then, we calculate the shock formation in disk using one dimensional code in detail. Then, we calculate the fragmentation process in linear approximation.

4 The property of gravity

A gas body in gravitational collapse has an tendency to form a filamentary configuration. This can be understood from the property of gravity as follows: We consider the gravity at the vertices of an uniform density tri-axial ellipsoid,

$$(\frac{x}{a})^2 + (\frac{y}{b})^2 + (\frac{z}{c})^2 = 1.$$

In the filamentary limit, $a/c \to 0$, $b/c \to 0$, the asymptotic expansions of gravities are given by

$$F_x = F_y = -\frac{3}{2}\frac{GM}{c}\frac{2}{a+b} \times (1 + \text{second order term})$$

$$F_z = -\frac{3GM}{c^2}\ln\frac{4c}{a+b} \times (1 + \text{second order term}).$$

The fact that $F_x = F_y$ in this asymptotic expansion independent of the ratio of axes a/b means that the fragmentation process in a free gravitational collapse is the fragmentation process of a cylinder. If the gas body attains the cylindrical equilibrium configuration independent of the initial conditions which stems from the perturbation in early universe, and if the fragmentation occurs in this equilibrium, the problem reduces to an easy one.

Under this assumption, the line mass of the equilibrium cylinder is given by $GM_{\mathrm{line}} = q_n \frac{P_c}{\rho_c}$, and the optical depth of the cylinder is given by $\tau = w_n \kappa (P_c/\pi G)^{1/2}$, where the constant q_n (~ 1.5) and w_n (~ 1) are almost independent of the polytrope index n. The equation of state is given approximately by $P = 2nkT + \beta(a/3)T^4$, where a is the radiation density constant and the β is the dilution factor of the black body radiation. If we give the line mass from the observed mass and diameter of the galaxy ($M_{\mathrm{line}} = 1.6 \times 10^{22}\,\mathrm{g/cm}$) or the globular cluster ($M_{\mathrm{line}} = 1.6 \times 10^{19}\,\mathrm{g/cm}$), we can estimate the temperature, number density, etc., at $\tau = 1$ as a function of the dilution factor β. The fragment mass is determined by the cylinder instability, $M_{\mathrm{frag}} = (\frac{4\pi}{\rho_c})^{1/2} M_{\mathrm{line}}^{3/2}$. For the line mass of the galaxy, if the number density of the gas is $n_c = 1\,\mathrm{cm}^{-3}$, the fragment mass is $M_{\mathrm{frag}} \sim 2 \times 10^{12}\mathrm{M}_\odot$. For the line mass of the globular cluster, if the number density

of the gas is $n_c = 10^4\,\mathrm{cm}^{-3}$, the fragment mass is $M_{\mathrm{frag}} \sim 9 \times 10^5 \mathrm{M}_\odot$. So, the problem is reduced to the determination of the dilution factor β.

The correctness of this assumption is, however, open to numerical simulations.

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