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WHAT DETERMINES THE PHYSICAL QUANTITIES OF GALAXIES? A TWO-COMPONENT GAS MODEL FOR PROTOGALAXIES WITH ENERGY INPUT FROM SUPERNOVAE

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ABSTRACT

The equilibrium structure of a protogalaxy, which is assumed to be composed of cold clouds and hot ambient gas in pressure equilibrium, is examined. The underlying characteristic time scales are the free-fall time of the system and the cooling time of the hot ambient gas. The global collapse condition used here is the well-known condition that the cooling time must be less than the free-fall time. Feedback processes are incorporated into the model via an energy balance condition between the power injected from supernovae and related processes due to the evolution of newly formed massive stars and the luminosity radiated by cooling processes. These considerations allow calculation of the characteristic mass and size of these two-component protogalaxies that can be expressed in terms of fundamental constants with some additional reasonably well constrained parameters. In addition, the pressure-equilibrium condition for protogalaxies with such a two-component interstellar medium indicates a characteristic mass for clouds, which is roughly comparable to the mass scale of globular clusters depending on the relevant cooling mechanism. The physical properties derived here for these protogalactic systems could be useful in interpreting high-redshift objects that may be possibly associated with galaxy formation.

Subject headings: galaxies: formation — galaxies: structure

1. INTRODUCTION

As is well known, the characteristic mass and radius of stars can be simply expressed by using only the fundamental constants as

$$M_* = (\hbar c/Gm_p^2)^{-3/2} m_p \sim 10^{33} \text{ g} , \quad (1)$$

$$R_* = (\hbar c/Gm_p^2)^{-1/2} \alpha^{1/2} r_c \sim 10^{10} \text{ cm} , \quad (2)$$

where $\hbar$, c, G, m_p, α, and r_c are, respectively, the Planck constant, the light velocity, the gravitational constant, the proton mass, the fine-structure constant ($= e^2/\hbar c$), and the classical electron radius ($e^2/m_e c^2$). The above expressions are obtained from two conditions: (1) that the condition that the virial equilibrium holds between the internal energy and gravitational energy of a star and (2) that the internal energy of the star mainly arises from thermal motions of electrons and protons, and the mass energy comes from protons.

A decade ago, similar considerations on the characteristic mass and radius of galaxies were presented (Ostriker 1974; Gott & Thuan 1976; Rees & Ostriker 1977; Silk 1977; Rees 1978). In these studies, a protogalactic cloud is supposed to consist of one-component homogeneous gas in a virial equilibrium state, and it was assumed that radiative cooling controls the fate of protogalactic clouds with the ratio of cooling time to the cloud collapse time being a controlling parameter. Rees & Ostriker (1977) have shown that the evolution of protogalactic clouds is essentially determined by the above parameter and is also constrained by the ratio of the cooling time to the Hubble time.

In the present paper, we investigate in detail the equilibrium state of protogalaxies composed of cool clouds and hot ambient gas which are assumed to be in a pressure equilibrium. Star formation is assumed to be triggered by cloud-cloud collisions. The energy input from winds and supernovae from the young, newly formed massive stars will heat the protogalactic gas and must be radiated. This feedback effect is incorporated in an energy balance condition. By imposing this energy balance condition, we can derive the characteristic masses and radii of galaxies and clouds, which are described in terms of fundamental constants and some additional reasonably well constrained parameters. This result is an extension of a number of important studies of galaxy formation and the structure of protogalaxies; in particular, it extends Rees & Ostriker's fundamental result for single-component protogalaxies to protogalaxies with a two-phase gaseous medium with the feedback of energy input from supernovae. Larson (1974) and Silk (1985) emphasized that the energy input from supernovae may regulate galaxy formation. Fall & Rees (1985) studied clouds in a two-component protogalaxy and showed that globular cluster masses can emerge naturally. Silk & Norman (1981) argued that such a two-component model was necessary to explain both the dissipational and the collisionless properties of observed galaxies. The issue of feedback processes is often discussed in the context of biased galaxy formation scenarios; for an excellent review of this and the current state of the simulations of galaxy formation, see White (1990).

As will be shown in this paper, it is instructive to isolate the fundamental processes which determine the essential physical quantities of such two-phase protogalaxies. In § 2, we reexamine the treatment by Rees & Ostriker (1977), and in § 3 we extend this to two-component protogalaxies. In the final section, we present implications of these results. These will be extended to the observed high-redshift galaxies associated with radio sources, quasars, and active galactic nuclei (AGNs) in a subsequent paper (Norman & Ikeuchi 1990).

2. ONE-COMPONENT VIRIALIZED PROTOGALAXIES

We begin by reexamining the physical state of a protogalaxy composed of a one-component gas in order to see the key assumptions which determined the characteristic mass and size of a galaxy.

Supposing that a spherical, homogeneous, protogalactic cloud with mass M, density ρ, temperature T, and radius R is in virial equilibrium satisfying

$$\sigma^2 = \frac{GM}{R} = GR^2\rho = \frac{kT}{m_p}, \quad (3)$$

where σ is the velocity dispersion, G is the gravitational constant, and k is the Boltzmann constant. Here, we simply assume the gas is composed only of hydrogen. We do not explicitly include the gravity of the dark matter in this paper. For those readers who wish to do so, a zeroth order incorporation of the effect of dark matter can be achieved by changing the gravitational constant, G, to $G[1 + M_d(r)/M_b(r)]$, and $M_d(r)$ and $M_b(r)$ are the masses of the dark and baryonic matter respectively within galactocentric radius r.

2.1. *Cooling Time to Free-Fall Time*

The condition for a protogalactic cloud to fragment into stars is that the cooling time must be smaller than the free-fall time; otherwise, it continues to contract adiabatically and will not form a galaxy. We call this the global collapse condition. The cooling rate for pure hydrogen gas can be expressed in the relevant regime as

$$\Lambda = \Lambda_{ff} + \Lambda_{bf} = (\Lambda_f T^{1/2} + \Lambda_b T^{-1/2})n^2 = (\Lambda_0 \sigma + \Lambda_{b0}\sigma^{-1})n^2, \quad (4)$$

where the coefficients for free-free and bound-free cooling are given by

$$\Lambda_0 = \Lambda_f\left(\frac{m_p}{k}\right)^{1/2} = \beta\frac{e^6}{\hbar c^3 m_e}\left(\frac{m_p}{m_e}\right)^{1/2}, \quad (5)$$

$$\Lambda_{b,0} = \Lambda_0\alpha^2\left(\frac{m_e c^2}{m_p}\right) = \beta\frac{e^{10}}{\hbar^3 c^3 m_p}\left(\frac{m_p}{m_e}\right)^{1/2}. \quad (6)$$

Here, β is a numerical factor, $\beta = 2^{9/2}\pi^{1/2}/3^{3/2} = 7.72$. The cooling time is

$$t_{cool} = nkT/\Lambda. \quad (7)$$

Recalling that the free-fall time for a cloud is

$$t_{ff} = (R^3/GM)^{1/2} = (G\rho)^{-1/2}, \quad (8)$$

then, the ratio of the cooling time to the free-fall time is expressed as

$$t_{cool}/t_{ff} = m_p R^2(Gm_p)^{3/2}/(\Lambda_0\sigma + \Lambda_{b0}\sigma^{-1})n^{1/2}. \quad (9)$$

2.1.1. *Free-Fall Cooling and the Characteristic Radius*

If free-free cooling predominates over bound-free cooling, which is satisfied when

$$\sigma > (\Lambda_{b0}/\Lambda_0)^{1/2} = \alpha(m_e/m_p)^{1/2}c = 52 \text{ km s}^{-1}, \quad (10)$$

then the condition $t_{cool}/t_{ff} \le 1$ reduces to

$$R \le R_g = \frac{\Lambda_0}{Gm_p^2} = \beta\alpha^2\alpha_G^{-1}\left(\frac{m_p}{m_e}\right)^{1/2} r_c = 73 \text{ kpc}, \quad (11)$$

where $\alpha_G = Gm_p^2/\hbar c = (m_p/m_{\rm Planck})^2$, the gravitational fine-structure constant, $m_{\rm Planck}$ being the Planck mass. In this way, we can get a characteristic radius R_g in terms of fundamental constants (Ostriker 1974; Gott & Thuan 1976; Silk 1977). For this characteristic radius, the virial mass is expressed by

$$M_g = R_g\frac{kT}{Gm_p} = \beta\alpha^3\alpha_G^{-2}\left(\frac{m_p}{m_e}\right)^{1/2}\left(\frac{kT}{m_e c^2}\right)m_p, \quad (12)$$

which is a function of gas temperature.

2.1.2. *Bound-Free Cooling and the Characteristic Mass*

If bound-free cooling dominates, the condition $t_{cool}/t_{ff} \le 1$ leads to the constraint on the mass

$$M \le M_G = \frac{\Lambda_{b0}}{G^2 m_p^2} = \beta\alpha^5\alpha_G^{-2}\left(\frac{m_p}{m_e}\right)^{1/2} m_p \simeq 10^{45.3} \text{ g}, \quad (13)$$

which is also written only in terms of fundamental constants. This mass is related to the above characteristic radius as

$$R_g = \frac{GM_G}{c^2}\alpha^{-2}\left(\frac{m_p}{m_e}\right). \quad (14)$$

The virial radius for the mass M_G becomes

$$R_G = GM_G\frac{m_p}{kT} = \beta\alpha^4\alpha_G^{-1}\left(\frac{m_p}{m_e}\right)^{1/2}\left(\frac{m_e c^2}{kT}\right)r_c. \quad (15)$$

2.1.3. *Implication*

At the critical state, $\Lambda_{ff} = \Lambda_{bf}$, we have $R_g = R_G$ and $M_g = M_G$, which come from $kT = \alpha^2 m_e c^2$.

The importance of these characteristic masses and sizes has been stressed by Rees (1978). Except for the critical state, the mass (or radius) of a protogalactic cloud is deduced, and the remaining radius (or mass) is given as a function of gas temperature. In order to determine the temperature, we must therefore introduce another condition which is related to the thermal energy balance. We call this the Energy Balance Condition.

2.2. *Energy Balance Condition*

Rees & Ostriker (1977) have proposed that in order for galaxies to form at a given epoch, the cooling time must be less than the Hubble time, i.e.,

$$t_{cool} \le t_H = t_0(1 + z)^{-3/2} \quad (\Omega = 1), \quad (16)$$

where z is the redshift at the epoch of galaxy formation. Then, the characteristic masses and sizes can be shown to be as follows:

Free-Free Cooling:

$$R \le R_g, \quad M \ge M_g = 6\pi R_g^3\rho_{crit}(1 + z)^3, \quad (17)$$

Bound-Free Cooling:

$$M \ge M_G, \quad R = R_G = (M_G/6\pi\rho_{crit})^{1/3}(1 + z)^{-1}, \quad (18)$$

where $\rho_{crit} = 3H_0^2/8\pi G$ is the critical density.

This energy balance condition is a natural constraint and obviously must be satisfied, but it may not necessarily be the unique controlling condition, and we study alternatives to this in § 3 that are related to feedback processes such as energy input into the protogalactic medium from supernovae, etc.

2.3. *Summary*

For the above one-component model we get the relations among observable quantities from only the energy balance condition for virialized protogalaxies:

Free-Free Cooling:

$$R \propto \sigma^{1/2}\,, \quad M \propto \sigma^{5/2}\,, \quad R\rho \propto \sigma^{3/2}\,, \tag{19}$$

Bound-Free Cooling:

$$R \propto \sigma^{-1/2}\,, \quad M \propto \sigma^{3/2}\,, \quad R\rho \propto \sigma^{5/2}\,. \tag{20}$$

These relations may be checked soon in high-redshift galaxies that are candidates for protogalaxies.

Here, we would like to stress that the characteristic masses and sizes for the virialized protogalaxies are determined by two conditions: one is $t_{\rm cool}/t_{\rm ff} \leq 1$, and the other is the energy condition. This means that the fundamental structures of galaxies are determined by the competition between elementary atomic (cooling) processes associated with pressure forces and macroscopic gravitational force. This situation is very similar to the case of stars, in which characteristic masses and radii are determined by the competition of the pressure force of electrons with gravitational force of macroscopic bodies as in equations (1) and (2). In the next section, we extend this consideration to a two-phase protogalactic cloud whose interstellar medium is composed of cold clouds and hot ambient gas.

3. TWO-COMPONENT VIRIALIZED PROTOGALAXIES

We investigate the two-phase model for a protogalaxy in which cold clouds and hot ambient gas are in a pressure equilibrium. The suffices c and h denote, respectively, the cold clouds and hot gas component.

The virial equilibrium condition is written as

$$\sigma_h^2 = \frac{G(M_h + N_c M_c)}{R_h} = \frac{kT_h}{m_p}\,, \tag{21}$$

where N_c and M_c are the total cloud number in a protogalaxy and the mass of a cloud.

The pressure equilibrium between clouds and hot gas indicates

$$\tilde{P} = n_c T_c = n_h T_h\,. \tag{22}$$

The unknowns in the present two-component model are (n_c, T_c, R_c, N_c) for clouds and (n_h, T_h, R_h) for hot gas. Since we have two conditions, (21) and (22), for them, we must give five additional conditions to completely determine all the above quantities.

3.1. *Ratio of Cooling Time to Free-Fall Time*

As in the one-component model, we set the conditions $t_{\rm cool}/t_{\rm ff} \leq 1$ in order for a protogalactic cloud to collapse. The cooling time is calculated for the hot gas, and the free-fall time is calculated for both components. The condition $t_{\rm cool}/t_{\rm ff}$ leads to

Free-Free Cooling:

$$R_h = R_g\Big/\left(1 + \frac{N_c M_c}{M_h}\right), \tag{23}$$

Bound-Free Cooling:

$$M_h = M_G\Big/\left(1 + \frac{N_c M_c}{M_h}\right)^2, \tag{24}$$

where R_g and M_G are the same as equations (11) and (13), respectively. Then, if we assume the hot gas mass significantly exceeds the mass in cold clouds, $M_h \gg N_c M_c$, these relations reduce to the same ones as the one-component model.

3.2. *Energy Balance Condition*

We now wish to study the effects of the galaxy formation process on the structure of the resulting galaxy itself. We focus in this paper on how the energy released from newly formed massive stars, via supernovae, etc., during the formation phase will affect the thermal state of the protogalactic gas through a feedback process. As a simple model, we examine the case that the energy loss from the hot gas, L_r, balances the energy injection due to star formation which is here assumed to be triggered by cloud-cloud collisions, $L_{\rm cc}$. Clearly if this condition is violated, in the sense of insufficient cooling, the hot phase of the protogalaxy will be blown away or at least greatly expanded until the collision rate drops below critical. If, on the other hand, this condition is not met due to insufficient cloud collisions, the clouds will continue to form and build up until this condition is met. This energy balance condition is written as

$$L_r = \Lambda(T_h)R_h^3 = L_{\rm cc} = \eta N_c M_c c^2 (N_c R_c^2 \sigma_h)/R_h^3\,, \tag{25}$$

where we assume the efficiency of energy liberation by cloud-cloud collision–induced star formation is a fraction η of the rest mass energy of a cloud. This parameter is the product of the efficiency of star formation in a cloud-cloud collision and the energy liberated per unit mass of the freshly formed stars as they evolve and eventually explode as supernovae. From the above conditions (21), (22), and (25) as well as $t_{\rm cool} = t_{\rm ff}$, we can have a simple relation

$$N_c^2\left(\frac{R_c}{R_h}\right)^5 = \frac{kT_c}{\eta m_p c^2}\,. \tag{26}$$

Here, we define the surface covering factor f_s and the volume filling factor f_v as

$$f_s = N_c(R_c/R_h)^2\,, \tag{27}$$

$$f_v = N_c(R_c/R_h)^3\,. \tag{28}$$

Since these are not known a priori, we must assign at least one of them by an appropriate physical consideration.

3.2.1. *Free-Free Cooling*

The above two functions are rewritten by using equation (23) as

$$f_s = \eta^{-1/2}\left(\frac{M_F}{M_c}\right)^{1/2}\left(\frac{kT_c}{m_p c^2}\right)^{1/2}\left(1 + \frac{N_c M_c}{M_h}\right)^{-1/2}, \tag{29}$$

$$f_v = f_s\left(\frac{M_c}{M_F}\right)\left(1 + \frac{N_c M_c}{M_h}\right), \tag{30}$$

where M_F is a characteristic mass defined as

$$M_F = M_G \alpha^{-2}\left(\frac{kT_V}{m_e c^2}\right), \tag{31}$$

and T_V is the virial temperature of a cloud

$$kT_V = GM_c m_p / R_c \,. \tag{32}$$

The surface covering factor of clouds is the ratio of the cloud collision time to the free-fall time. This is probably in the range $f_s = 0.1$–10 for star formation to occur during collapse since in our cloud-cloud collision model the star formation occurs in cloud-cloud collisions and the timescale for such collisions is $\sim t_{ff}/f_s \sim (0.1\text{–}10)t_{ff}$ for $f_s \sim 0.1$–10. Then we can write the cloud mass in terms of

$$M_c = M_F(\eta f_s^2)^{-1}\left(\frac{kT_c}{m_p c^2}\right)\left(1 + \frac{N_c M_c}{M_h}\right)^{-1/2} . \tag{33}$$

3.2.2. *Bound-Free Cooling*

Similarly, we get the relations by using equation (24) as

$$f_s = \eta^{-1/2}\left(\frac{M_B}{M_c}\right)^{1/2}\left(\frac{kT_c}{m_p c^2}\right)^{1/2}\left(1 + \frac{N_c M_c}{M_h}\right)^{-1/2}, \tag{34}$$

$$f_v = f_s\left(\frac{M_c}{M_B}\right)\left(1 + \frac{N_c M_c}{M_h}\right), \tag{35}$$

where M_B is another characteristic mass for the bound-free cooling case defined as

$$M_B = M_G\left(\frac{T_V}{T_h}\right) = M_F \alpha^2\left(\frac{m_e c^2}{kT_h}\right). \tag{36}$$

If we assume the ratio of cloud-cloud collision time to free-fall time is roughly of order unity, then the cloud mass can be written as

$$M_c = (\eta f_s^2)^{-1} M_B\left(1 + \frac{N_c M_c}{M_n}\right)^{-1}, \tag{37}$$

where for numerical estimates in this case one should take $f_s \sim 1$.

As we have seen, depending upon the relevant cooling mechanisms we find two characteristic masses M_F and M_B.

3.3. *Model of Two-Component Protogalaxies*

Summarizing the above considerations we can now assign seven conditions for determining the seven unknowns (n_h, R_h, T_h) and (n_c, R_c, T_c, N_c). The seven conditions which we adopt are as follows:

1. Virial equilibrium for protogalaxies as expressed in equation (21).
2. Pressure equilibrium between cool clouds and ambient hot gas, expressed in equation (22).
3. Equality of cooling time in equation (23) for free-free cooling and equation (24) for bound-free cooling to the free-fall time.
4. Energy balance condition as in equation (25) for the radiative losses of power supplied from the star formation triggered in cloud-cloud collisions.
5. Mass ratio of cold clouds to hot gas expressed as a parameter, $q \equiv N_c M_c / M_h (\sim 1)$.
6. Cloud temperature as a parameter, $T_c = 10^4 T_4$ K.
7. Covering factor, which represents the ratio of the crossing time to the cloud collision time, $f_s = N_c (R_c/R_h)^2 (\sim 1)$.

Although conditions (5), (6), and (7) would be the most physically sensible, they are rather arbitrary. Therefore, we choose instead to use the conditions for f_v, T_V, and M_c. Here, we keep three quantities as parameters g, T_4, and f_s in the following discussion. Another parameter is the energy liberation efficiency η associated with cloud collisions, which will be written as $\eta = 10^{-6}\eta_{-6}$.

The derived physical parameters of these two-component protogalaxies are summarized for two cooling processes.

3.3.1. *Free-Free Cooling*

The hot gas component is written as follows:

$$R_h = \frac{R_g}{1+g} = 10^{1.9}\,\frac{1}{1+g}\ \text{kpc}\,, \tag{38}$$

$$T_h = \frac{f_s g \eta}{k}\, m_p c^2 = 10^{7.0} f_s g \eta_{-6}\ \text{K}\,, \tag{39}$$

$$n_h = \frac{f_s g(1+g)\eta c^2}{G R_g^2 m_p} = 10^{0.9} f_s g(1+g)\eta_{-6}\ \text{cm}^{-3}\,, \tag{40}$$

$$M_h = \frac{f_s g}{(1+g)^2}\,\frac{R_g \eta c^2}{G} = 10^{12.2}\,\frac{f_s g}{(1+g)^2}\,\eta_{-6}\, M_\odot\,. \tag{41}$$

The cloud quantities are written as follows;

$$R_c = \frac{R_g}{f_s^2(1+g)}\,\frac{kT_c}{\eta m_p c^2} = 10^{-1.3}\,\frac{T_4}{f_s^2(1+g)\eta_{-6}}\ \text{kpc}\,, \tag{42}$$

$$T_c = 10^4 T_4\ \text{K}\,, \tag{43}$$

$$\begin{aligned} n_c &= \frac{f_s g^2(1+g)}{G R_g^2}\,\frac{(\eta c^2)^2}{kT_c} \\ &= 10^{2.3} f_s^2 g^2(1+g)\,\frac{\eta_{-6}^2}{T_4}\ \text{cm}^{-3}\,, \end{aligned} \tag{44}$$

$$\begin{aligned} M_c &= \frac{g^2}{f_s^4(1+g)^2}\left(\frac{kT_c}{\eta m_p c^2}\right)\left(\frac{kT_c R_g}{G m_p}\right) \\ &= 10^{5.9}\,\frac{g^2}{f_s^4(1+g)^2}\,\frac{T_4^2}{\eta_{-6}}\, M_\odot\,, \end{aligned} \tag{45}$$

$$N_c = f_s^5\left(\frac{\eta m_p c^2}{kT_c}\right)^2 = 10^{6.0} f_s^5\,\frac{\eta_{-6}^2}{T_4^2}\,. \tag{46}$$

3.3.2. *Bound-Free Cooling*

The hot gas component is written as follows:

$$R_h = \frac{1}{f_s g(1+g)}\,\frac{GM_G}{\eta c^2} = 10^{1.7}\,\frac{1}{f_s g(1+g)\eta_{-6}}\ \text{kpc}\,, \tag{47}$$

$$T_h = \frac{f_s g \eta}{k}\, m_p c^2 = 10^{7.0} f_s g \eta_{-6}\ \text{K}\,, \tag{48}$$

$$\begin{aligned} n_h &= f_s^3(1+g)g^3\left(\frac{\eta c^2}{GM_G}\right)^3 \frac{M_G}{m_p} \\ &= 10^{-0.5} f_s^3 g^3(1+g)\eta_{-6}^3\ \text{cm}^{-3}\,, \end{aligned} \tag{49}$$

$$M_h = \frac{M_G}{(1+g)^2} = 10^{12}\,\frac{1}{(1+g)^2}\, M_\odot\,. \tag{50}$$

The cloud quantities are written as follows:

$$R_c = \frac{1}{f_s^3(1+g)}\left(\frac{kT_c}{\eta m_p c^2}\right)\left(\frac{GM_G}{\eta c^2}\right)$$

$$= 10^{-1.4}\frac{T_4}{f_s^3 g(1+g)\eta_{-6}^2}\ \mathrm{kpc}\ , \qquad (51)$$

$$T_c = 10^4 T_4\ \mathrm{K}\ , \qquad (52)$$

$$n_c = f_s^4 g^4(1+g)\left(\frac{\eta c^2}{GM_G}\right)^3 \frac{\eta M_G c^2}{kT_c}$$

$$= 10^{2.6} f_s^4 g^4 (1+g)\frac{\eta_{-6}^4}{T_4}\ \mathrm{cm}^{-3}\ , \qquad (53)$$

$$M_c = \frac{g}{f_s^5(1+g)^2}\left(\frac{kT_c}{\eta m_p c^2}\right)^2 M_G$$

$$= 10^{5.7}\frac{gT_4^2}{f_s^5(1+g)^2\eta_{-6}^2} M_\odot\ , \qquad (54)$$

$$N_c = f_s^5\left(\frac{\eta m_p c^2}{kT_c}\right)^2 = 10^{6.0} f_s^5 \frac{\eta_{-6}^2}{T_4^2}\ . \qquad (55)$$

3.3.3. *Implications*

Regardless of the specific cooling mechanisms, the hot gas component is independent of the cloud temperature, whereas all the cloud quantities depend on T_c. The numerical values have uncertainties of an order of magnitude because we have dropped the geometrical factors of a cloud and of a protogalaxy and the parameters for η, f_s, g, and T_c, etc., are not precisely specified. (A recent discussion of the likely values of T_c is given in Kang et al. 1990). However, it is interesting that the values obtained correspond well to those of galaxies, if we take $f_s \sim \eta_{-6} \sim T_4 \sim 1$ and $g \sim (1$–$10)$.

4. SUMMARY

The results in the previous section show the critical physical properties of a protogalaxy whose interstellar medium is composed of cool clouds and hot ambient gas in pressure equilibrium which are determined by the conditions $t_{\mathrm{cool}} = t_{\mathrm{ff}}$ (global collapse condition) and $L_r = L_{\mathrm{cc}}$ (energy balance condition), if it is in the virial equilibrium state. The key physical processes are the microscopic atomic process, which underlies the cooling function and the star formation process and its associated energy injection which is parameterized here by the efficiency factor, η. Feedback processes are incorporated by allowing the energy injection from star formation triggered by cloud-cloud collisions to heat the protogalactic gas. The global condition gives the mass or size of a global system (M_h, R_h), and the energy balance condition relates this to the cloud mass or size (M_c, R_c). The parameters f_s, g, T_c, and η represent the diversity of protogalaxies. Choosing appropriately for these parameters, we can set an initial model for protogalaxies with relatively normal star formation. We continue this work to study the evolution of protogalaxies with a wide range of masses, and we also analyze the properties of protogalaxies associated with powerful central energy sources such as radio sources, quasars, and AGNs (Norman & Ikeuchi 1990).

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