

FORMATION OF SUBGALACTIC OBJECTS WITHIN TWO-COMPONENT DARK MATTER

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ABSTRACT

We consider the Einstein–de Sitter universe dominated by two kinds of collisionless relics: neutrinos as hot dark matter, and X particles having negligible thermal velocity as cold dark matter (CDM). We assume $\Omega_c > \Omega_b \geq \Omega_b = 0.05$, which is referred to as the hybrid model. On scales larger than that of neutrino collisionless damping, neutrino fluctuations develop with time, producing large-scale neutrino overdense (NOD) and underdense (NUD) regions which evolve consequently to superclusters and huge voids, respectively. We calculate the growth of fluctuations of CDM and induced fluctuations of baryons on subgalactic scales in the NOD and NUD regions from the recombination epoch to the present. CDM fluctuations on subgalactic scales can grow faster in the NOD region than in the NUD region. It is shown that dwarf galaxies are preferably formed in NOD regions, induced by CDM potential wells; and subgalactic baryon fluctuations in NUD regions are subject to UV heating by QSOs before collapse and converted to expanding clouds unclustered in voids. These clouds are favorable candidates for Ly α absorbers with just the same neutral hydrogen column density as observed, irrespective of Ω_c . This scenario for the formation of subgalactic objects is successful if $0.15 \leq \Omega_c \leq 0.35$, and correspondingly $0.8 \geq \Omega_b \geq 0.6$, assuming the constant curvature spectrum. It is another characteristic of the hybrid model that ordinary galaxies, including QSOs, are formed early from aggregations of dwarfs; and some galaxies can also be born in voids in an environment of few dwarfs after the birth of galaxies in NOD regions.

Subject headings: cosmology — galaxies: clustering — galaxies: formation — neutrinos

1. INTRODUCTION

In recent years, some sorts of collisionless relics of the early universe have attracted special attention as mediators between the large amplitude of primeval adiabatic fluctuations required for galaxy formation and the observed isotropy of the cosmic microwave radiation (CMR). At present, the upper limit on the small-scale anisotropies of CMR (Uson and Wilkinson 1984) puts a severe constraint on the adiabatic baryon density fluctuations at the recombination epoch z_{rec} as

$$|\delta\rho_b/\rho_b| < 9 \times 10^{-5} \quad (1)$$

on comoving length scale $8(\Omega h)^{-1}$ Mpc, where Ω is the ratio of the present average density to the closure density and h is the present Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. These small-amplitude fluctuations apparently fail to form galaxies in time. In a universe dominated by neutrinos of some tens of eV (Lyubimov 1980), known as *hot* dark matter, the restriction by CMR is replaced by a softened one such that in an $\Omega = 1$ model, assuming the constant-curvature spectrum, the neutrino fluctuations on the above scale have to enter the nonlinear stage at $z_{\text{nl}} < 9$ for $h = 0.75$ or $z_{\text{nl}} < 4$ for $h = 0.5$, which enables galaxies to form at $z > 3$. In a universe dominated by *cold* dark matter (CDM) such as axions, photinos, gravitinos, and monopoles with negligibly small thermal velocities, Ω is constrained to $\Omega > 0.2h^{-4/3}$, as shown by Bond and Efstathiou (1984) and Vittorio and Silk (1984), under the usual assumption that galaxies well follow the underlying mass distribution.

However, some questions have been raised concerning the above-mentioned pictures, from observational points of view. The neutrino-dominated picture is attractive in the sense that

the maximum damping scale of primordial fluctuations by free-streaming just corresponds to the void-supercluster scale, that is, $M_{\text{vm}} = 3.2 \times 10^{15}(m_\nu/30 \text{ eV})^{-2} M_\odot$. But, as for the gravitational clustering of collisionless particles (neutrinos), without the process of dissipation and fragmentation of baryonic gas, it has been indicated by N -body simulations (White, Frenk, and Davis 1983; Dekel and Aarseth 1984) that if the caustics form at $z > 3$, the present two-point correlation function $\xi(r)$ is significantly larger than that observed for galaxies $\xi_G(r)$ (Davis and Peebles 1983). Even if the fragmentation process of a gaseous supercluster may comfortably modify $\xi_G(r)$, it is extremely difficult to explain in a neutrino-dominated universe the fact that Ly α absorption clouds found in the spectra of QSOs appear to be unclustered as $\xi_{\text{cloud}}(r) < 0.1\xi_G(r)$ (Sargent *et al.* 1980).

On the other hand, it has been tentatively suggested by Aaronson (1983) and Faber and Lin (1983) that dwarf spheroidals might have dark matter with the mass-to-light ratio of ~ 30 . If this is the case, the dark matter should be CDM at least on such a subgalactic scale (Blumenthal *et al.* 1984). Even the *warm* dark matter, such as gravitinos and photinos, of ~ 1 keV, much heavier than neutrinos, can hardly account for massive halos in dwarf galaxies. However, a universe dominated only by CDM is confronted with such difficulty that $\Omega > 0.5$ models, which safely avoid the restriction by CMR in the range $0.5 \leq h \leq 1$, conflict with $\Omega = 0.2e^{\pm 0.4}$ determined from the random velocities of galaxies in clusters (Davis and Peebles 1983; Bean *et al.* 1983). After all, aside from theories with decaying collisionless relics (Hut and White 1984; Turner, Steigman, and Krauss 1984; Fukugita and Yanagida 1984;

Suto, Kodama, and Sato 1985; Cowsik 1985), a nearly flat model of the universe dominated by dark matter, which is preferable from the viewpoint of galaxy formation and also is predicted by inflationary scenarios (Sato 1981; Guth 1981), may be acceptable only in following three cases: the neutrino-dominated universe with a significant complementary role of a baryon-dissipative process (Doroshkevich 1984), the CDM-dominated one taking into account "biased" galaxy formation (Schaeffer and Silk 1985; Davis *et al.* 1985), or the hybrid model of the universe dominated by both neutrinos and CDM with $\Omega_c = 1 - \Omega_v - \Omega_b < 0.5$, where c , v , and b represent CDM, neutrinos, and baryons respectively. The hybrid model is verified when neutrinos are massive and simultaneously there exists some CDM.

Now, we cannot ignore the fact that there are many implications for the reality of void-supercluster structure from observations of large voids (Gregory and Thompson 1978; Einasto, Joeveer, and Saar 1980; Kirshner *et al.* 1981; Davis *et al.* 1982), cluster-cluster spatial correlations (Bahcall and Soneira 1983), and alignments of clusters (Binggeli 1982) and galaxies (Djorgovski 1983), all of which are readily accounted for in the neutrino-dominated picture. However, a universe dominated only by neutrinos is so far unsuccessful in forming subgalactic objects such as unclustered Ly α clouds and dwarf galaxies with dark matter. In this paper, we consider the possibility of the hybrid model of the universe and investigate quantitatively which model is successful in ensuring the formation of subgalactic objects with the observed features. In § II, we provide some assumptions, approximations, and fundamental equations for the numerical study of the evolution of density fluctuations in the hybrid model. In § III, the numerical results of the effect of QSO UV heating and the evolution of given CDM fluctuations as well as induced baryonic ones, separately in neutrino overdense (NOD) and underdense (NUD) regions, are given. In § IV, we discuss the constraints on the hybrid model for the successful formation of subgalactic objects, and the relevant observable characteristics of subgalactic objects such as Ly α clouds and dwarf galaxies, and QSOs and galaxies as well.

II. HYBRID MODEL

a) Model of the Universe

We examine the Einstein-de Sitter universe with $\Omega_v > \Omega_c \geq \Omega_b$, which retains several favorable features in the neutrino-dominated picture, because the linear evolution of primordial neutrino density fluctuations δ_v is governed by

$$2\ddot{\delta}_v + 4\frac{\dot{a}}{a}\dot{\delta}_v = 3\left(\frac{\dot{a}}{a}\right)^2(\Omega_v\delta_v + \Omega_c\delta_c), \quad (2)$$

with the cosmic expansion factor $a(t)$, and $\delta_v \approx \delta_c$ is reasonably assumed on a comoving scale beyond the length scale of neutrino collisionless damping $\lambda_{vm} = 41(m_v/30 \text{ eV})^{-1} \text{ Mpc}$. The baryon mean density $\Omega_b = 0.05$ (Yang *et al.* 1984) and $h = 1$ are assumed. Here we note that at the epoch when adiabatic cooling/heating or Compton cooling is dominant, the dynamics of systems can be scaled according to $r \propto h^{-1}$ and $\rho \propto h^2$, v and T being independent of h , and, when QSO UV heating is a main heating source, the thermal evolution is almost independent of the baryon density (Umemura and Ikeuchi 1984, hereafter UI).

b) Initial Density Fluctuations

Primordial density fluctuations are assumed to be random Gaussian processes, with rms mass fluctuations $\sigma \equiv \langle |\delta M/M| \rangle \propto M^{-(n+3)/6}$ corresponding to a Fourier power spectrum $\langle |\delta_k|^2 \rangle \propto k^n$. Here we make a familiar choice of $n = 1$, referred to as the constant curvature or Zeldovich spectrum, which is also predicted in inflationary scenarios. In a radiation-dominated era, fluctuations within the horizon grow minimally, while those beyond the horizon increase. Thus, by the epoch z_{eq} , when matter and radiation energy density become equal, the index n bends to $n = 4$ (Lifshitz 1946; Guyot and Zeldovich 1970; Mészáros 1974), so that σ becomes independent of M , if initially $n = 1$. Such an effect was indeed shown numerically in a CDM-dominated universe, first by Peebles (1984), and the resultant mass fluctuation is asymptotically scale-invariant on sufficiently smaller scales than the horizon mass at z_{eq} , $M_{eq} = 2 \times 10^{15}(\Omega h^2)^{-2} M_\odot$. By the use of this numerical result, we can obtain the fluctuation spectra in the hybrid model as follows. If CDM is dominant in the universe, the mass fluctuation $\delta_c \equiv (\delta M/M)_c$ of CDM can grow as $\delta_c \propto 1/(1+z)$ after z_{eq} . But in our model, since the mass density of neutrinos always exceeds that of CDM between z_{eq} and the recombination epoch z_{rec} , the growth of CDM fluctuations on smaller scales than λ_{vm} is significantly suppressed by an unbound neutrino background even in a matter-dominated era. In such a situation, δ_c can grow slowly according to

$$\delta_c \propto (1+z)^{-\beta} \quad \text{with} \quad \beta = \frac{1}{4}[(1+24\Omega_c)^{1/2} - 1] \quad (3)$$

(Hoffman and Bludman 1984). Thus, on subcluster scales the CDM fluctuations δ_c are at z_{rec}

$$\delta_c(z_{rec}) = \left(\frac{1+z_{eq}}{1+z_{rec}} \right)^\beta \delta_c(z_{eq}). \quad (4)$$

On the other hand, the fluctuation $\epsilon(z)$ of neutrinos and CDM on a scale of M_{vm} grows in proportion to $1/(1+z)$ (Bond and Szalay 1983; Bonometto *et al.* 1984), that is,

$$\epsilon(z_{rec}) = \left(\frac{1+z_{eq}}{1+z_{rec}} \right) \epsilon(z_{eq}). \quad (5)$$

Since we assume that fluctuations are random Gaussian processes, the distribution function of δ_c satisfies $P(\delta_c) = \exp(-\delta_c^2/2\sigma^2)/(2\pi)^{1/2}\sigma$. If δ_c is at the level of rms value σ , we obtain a relation as

$$\frac{\sigma}{\epsilon}(z_{rec}) = \left(\frac{1+z_{eq}}{1+z_{rec}} \right)^{\beta-1} \frac{\sigma}{\epsilon}(z_{eq}). \quad (6)$$

The resultant rms fluctuation spectra depending on Ω_c are shown in Figure 1, at $z_{eq} = 2.5 \times 10^4$ and $z_{rec} = 10^3$, tentatively for $\Omega_c = 0.45$ or 0.25 . We consider $\delta_c \leq 2\sigma$ as a permitted range later on. By means of these spectra, if we specify the value of $\epsilon(z_{rec})$, we can get information on the baryon mass accompanied by CDM fluctuations $\delta_{c,i} \equiv (\delta M/M)_c(z_{rec})$ given initially at z_{rec} . Especially on subgalactic scales of $10^7 \leq M_b \leq 10^9 M_\odot$, the spectra are best fitted in terms of a relation as

$$\delta_{c,i} \propto M_b^{-1/12}. \quad (7)$$

At the initial epoch z_{rec} , we set a spherically symmetric "top hat" mass fluctuation of CDM, with unperturbed baryonic matter, i.e., $\delta_b(z_{rec}) = 0$.

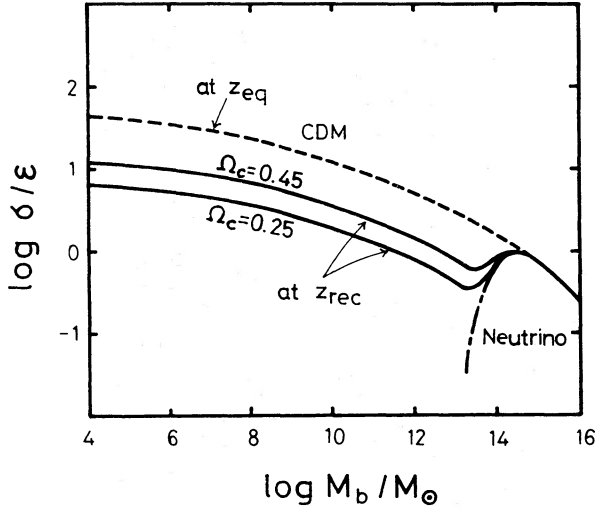


FIG. 1.—The rms mass fluctuation $\sigma \equiv \langle |\delta M/M| \rangle$ of CDM as a function of baryon mass M_b contained in the sphere of the fluctuation, at $z_{eq} = 2.5 \times 10^4$ and $z_{rec} = 10^3$. The constant curvature spectrum is assumed, and fluctuations are normalized by the peak value for neutrinos, which is postulated to be $\epsilon_v = 0.03$ at z_{rec} in this paper.

c) Neutrino Background Density

The neutrino density is reasonably approximated to be homogeneous on subgalactic scales of interest because of their large velocity dispersion. However, the density on the scale of clusters changes with time according to the growth of neutrino fluctuations, producing neutrino overdense (NOD) and underdense (NUD) regions, which evolve to superclusters and large voids respectively. Thus the development of subgalactic CDM fluctuations should be investigated separately in NOD and NUD regions. Ikeuchi and Umemura (1984, hereafter IU) have calculated the nonlinear evolution of density perturbations in a neutrino-dominated universe, including the dissipative process of baryons. Here, as the neutrino background density in NOD and NUD regions we employ the above results for the epoch of supercluster collapse, $z_{sc} = 4$, which corresponds to the case of $\epsilon(z_{rec}) = 0.03$. In an NOD region, half the maximum density is taken as the mean value of neutrino density $\bar{\rho}_v^{NOD}$. In an NUD region, taking into account that the matter in an NUD region falls into an NOD region, $\bar{\rho}_v^{NOD}$ is set to be the value at the point of the radius $R = R_v^{NOD}/3$ initially, where the matter remains in an NUD region until $z = 0$ and will be absorbed into an NOD region after $z = 0$. At $z \leq 4$, $\bar{\rho}_v^{NOD}$ is nearly equal to that at the center of an NUD region (IU).

d) Fundamental Equations

We postulate spherically symmetric perturbations. In this geometry, the equations of motion are expressed as

$$\frac{dv_b}{dt} = -\frac{1}{\rho_b} \frac{\partial P_b}{\partial r} - \frac{G(M_{br} + M_{cr})}{r^2} - \frac{4\pi}{3} G\bar{\rho}_v r \quad \text{for baryons,} \quad (8)$$

$$\frac{dv_c}{dt} = -\frac{G(M_{br} + M_{cr})}{r^2} - \frac{4\pi}{3} G\bar{\rho}_v r \quad \text{for CDM,} \quad (9)$$

where $M_{jr} = \int_0^r 4\pi r'^2 \rho_j dr'$, with $j = b$ and c for baryons and CDM respectively. Other equations coupled with (8) and (9) are those of continuity for baryons and CDM, equation of state for baryons, and (10) below.

e) Thermal Process of Baryons

The thermal history of baryons is governed by

$$\frac{d}{dt} \ln \left[\frac{T_b^{1/(\gamma-1)}}{\rho_b} \right] = \frac{H-L}{P_b}, \quad (10)$$

where H is the heating rate per unit volume by UV light from QSOs, which is assumed to act at $z \leq z_{UV} = z_{sc} = 4$, and L is the radiative and Compton cooling rate for primordial hydrogen-helium gas with the ratio of 9:1 in number. All expressions of H and L are described in detail in UI. The adiabatic exponent γ is usually 5/3, but since at $z > 100$ the residual ionization is significant (Peebles 1968), γ is approximately taken to be 4/3 in this era, though having little influence on the results. Ionization degrees are determined in terms of equilibria between radiative recombination and collisional ionization, also including photoionization at $z \leq z_{UV}$.

All the coupled equations are numerically integrated by using the spherically symmetric two-fluid Lagrange scheme (IU) with 200 meshes respectively for baryons and CDM.

III. RESULTS OF NUMERICAL CALCULATIONS

a) Effect of QSO UV Heating

UV light from QSOs plays an important role in the evolution of fluctuations on subgalactic scales at $z \leq z_{UV} = 4$. That is, it gives rise to the difference in evolution that more massive fluctuations with $M_b > M_{UV} \approx 10^9 M_\odot$ can continue to contract and finally collapse, whereas less massive ones with $M_b < M_{UV}$ bounce at $z < 4$ due to UV heating by QSOs and are driven to expand. Moreover, M_{UV} is almost independent of Ω_c . Such evolution is in a good agreement with the results without dark matter of UI. This fact leads us to the important conclusion that the formation of subgalactic collapsed objects with $M_b < 10^9 M_\odot$ should have occurred before QSOs formed, namely $z > 4$. M_{UV} is also a significant quantity in the discussion in § IV of the formation of galaxies in voids.

b) Growth of Fluctuations in the NOD Region

Since the NOD region is a locally closed universe, the fluctuations develop faster in the NOD region than in the NUD region, which is a locally open universe. Thus the formation of subgalactic objects at $z > 4$ is easier in the NOD region. The typical result of a collapsing fluctuation in the NOD region is illustrated in Figure 2, for $\delta_{c,i} = 0.13$ and $\Omega_c = 0.25$. Time variations in the central density of the spherical fluctuation, which seems to characterize well the evolution of the system, are plotted versus $1+z$ from the recombination epoch $z_{rec} = 10^3$ to the epoch of supercluster collapse $z_{sc} = 4$. The time variation of neutrino fluctuation in the NOD region, which is estimated from the result of IU, is also plotted. The CDM fluctuation forms a CDM-dominated isolated system at $z \approx 6$ before the nonlinear phase of neutrino fluctuation, so that baryons fall into the potential well of CDM with a negligible contribution of neutrino density. Such a formation process of subgalactic objects embedded in a massive dark halo of CDM is exactly analogous to the two-step theory of galaxy formation by White and Rees (1978). The suppressing effect of homogeneity on neutrino density distribution is made clear through the fact that in the above calculation the collapse epoch z_{coll} of the CDM fluctuation is ~ 6 , while the collapse of a fluctuation with the same amplitude $\delta_{c,i} = 0.13$ set in a CDM-dominated universe ($\Omega_c = 1 - \Omega_b$) occurs at the epoch $z_{coll} \approx 70$.

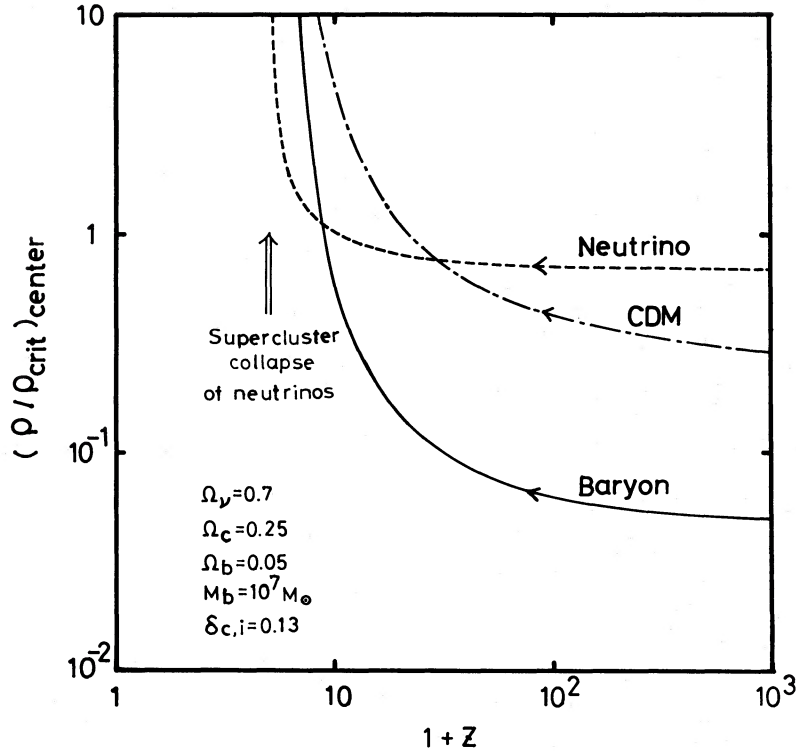


FIG. 2.—The evolution of a typical collapsing fluctuation of CDM and an induced baryonic one in the NOD region. Time variations of the central density of the spherical fluctuation are plotted, in units of the closure density ρ_{crit} , vs. $1+z$ from $z_{\text{rec}} = 10^3$ to the epoch of supercluster collapse $z_{\text{sc}} = 4$, for $\Omega_c = 0.25$ ($\Omega_v = 0.7$), $M_b = 10^7 M_\odot$, and $\delta_{c,i} = 0.13$, which satisfies 1σ at z_{rec} shown in Fig. 1.

With a given value of Ω_c , the relation between $1+z_{\text{coll}}$ and $\delta_{c,i}$ is expressed in terms of a power law, $1+z_{\text{coll}} \propto \delta_{c,i}^{\alpha(\Omega_c)}$. The initial amplitude of CDM fluctuations which collapse in the NOD region right before $z_{\text{sc}} = z_{\text{UV}} = 4$ is denoted by $\delta_{c,\text{crit}} \equiv \delta_{c,i}(z_{\text{coll}}^{\text{NOD}} = 4)$. Then we have

$$1+z_{\text{coll}} \approx 5(\delta_{c,i}/\delta_{c,\text{crit}})^{\alpha(\Omega_c)}. \quad (11)$$

The values of α and $\delta_{c,\text{crit}}$ are tabulated in Table 1. In order to form subgalactic collapsed objects before QSO UV heating, we need CDM fluctuations at z_{rec} to be roughly

$$\delta_{c,i} > \delta_{c,\text{crit}} \approx (2-3) \times 10^{-2} \Omega_c^{-1}. \quad (12)$$

The baryon mass M_b accompanied by this CDM fluctuation depends on $\delta_{c,i}$ through the fluctuation spectrum. Since $\delta_{c,i}$ is related to z_{coll} by equation (11), M_b of a formed object depends sensitively on z_{coll} . Let the baryon mass within the fluctuation which initially had the amplitude $\delta_{c,\text{crit}}$ be $M_{b,\text{crit}} \equiv M_b(z_{\text{coll}}^{\text{NOD}} = 4)$, then M_b is expressed, in terms of equation (11) and the approximate relation (7) on subgalactic scales, as

$$M_b \approx M_{b,\text{crit}} \left(\frac{5}{1+z_{\text{coll}}} \right)^{12/\alpha(\Omega_c)}, \quad (13)$$

TABLE 1
NUMERICAL RESULTS IN THE NOD REGION

Ω_v	Ω_c	α	$\delta_{c,\text{crit}}$
0.5.....	0.45	1.2	4.3×10^{-2}
0.6.....	0.35	1.3	6.6×10^{-2}
0.7.....	0.25	1.5	0.11
0.8.....	0.15	2.0	0.20
0.9.....	0.05	3.5	0.44

and this relation is illustrated in Figure 3, together with the result for $\Omega_v = 0$ for reference. Since α is always positive, $M_b \geq M_{b,\text{crit}}$ for $4 \geq z_{\text{coll}}$. Figure 3 shows that the greater the neutrino background, the more sensitive the formation epoch becomes to the mass of the object.

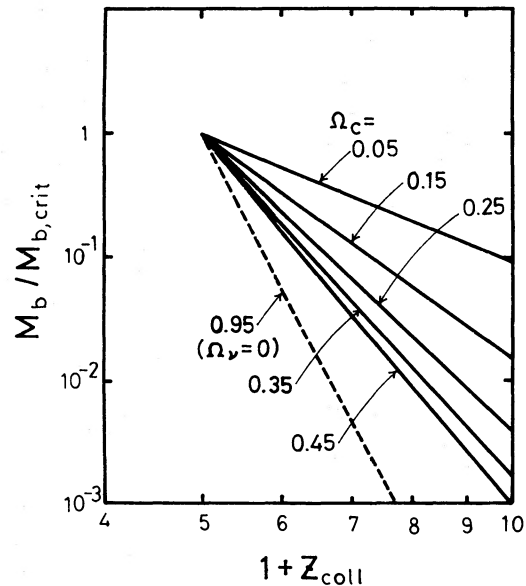


FIG. 3.—Relations between the baryon mass M_b within the fluctuation collapsing at $z > 4$ in the NOD region and the collapse epoch z_{coll} , for various hybrid models. M_b is normalized by $M_{b,\text{crit}}$, which is the baryon mass accompanied by the fluctuation to collapse just before $z = 4$.

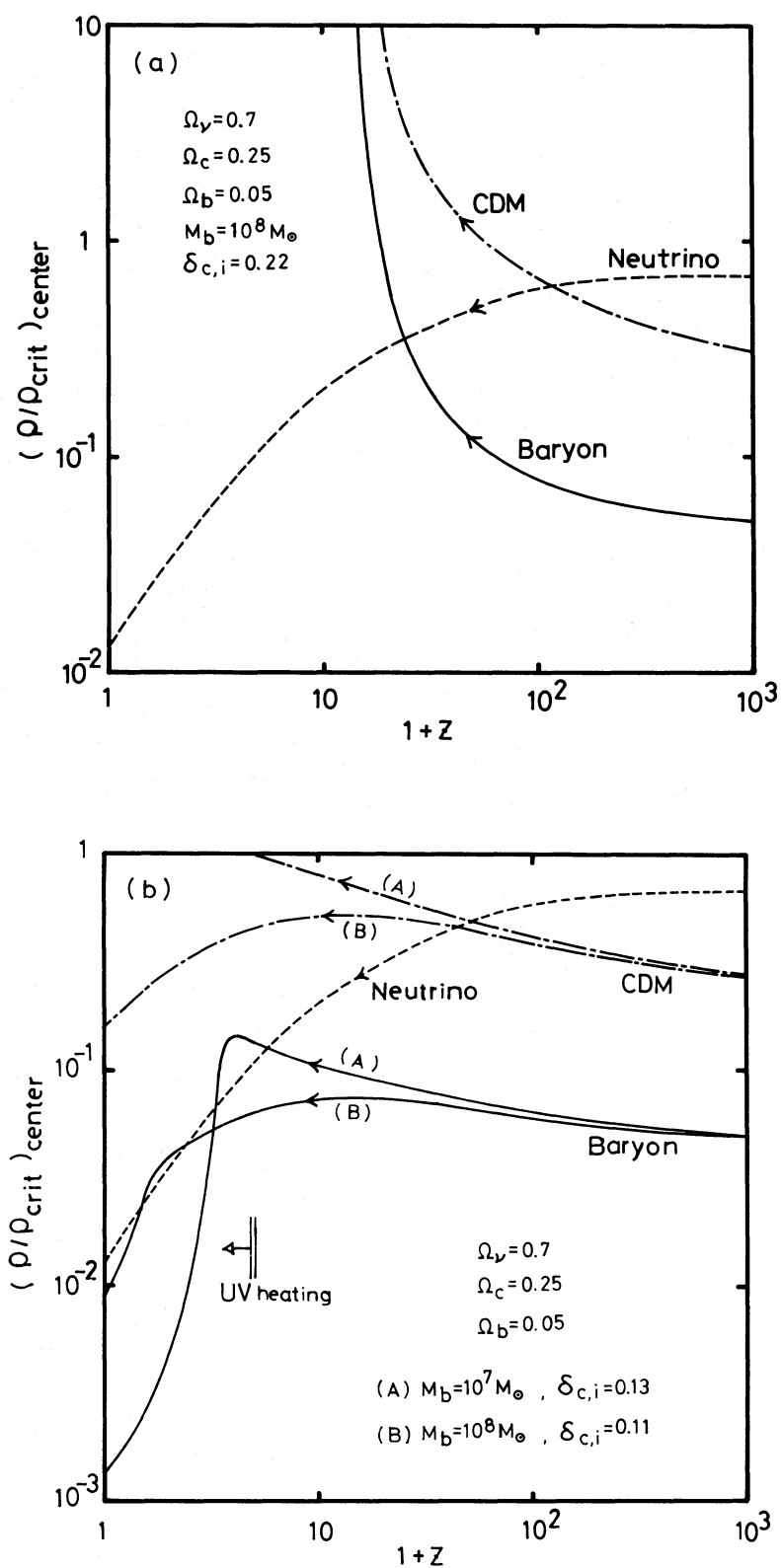


FIG. 4.—The evolutions of typical fluctuations destined for (a) collapse and (b) expansion in the NUD region. The plotted quantity is the same as in Fig. 2. Initial fluctuations for (a) and (b) satisfy 2σ and 1σ respectively.

After all, if $M_{b,\text{crit}}$ is of subgalactic scales, i.e., $\sim 10^7\text{--}10^9 M_\odot$, we succeed in forming the dwarf galaxies dominated by dark matter. The constraint on the hybrid model by this requirement is presented in § IV.

c) Growth of Fluctuations in the NUD Region

In Figures 4a and 4b, the evolutions of density fluctuations in the NUD region are shown in terms of the central density for typical cases destined for collapse and expansion respectively. The amplitude of initial fluctuations is taken to be consistent with the spectrum of 2σ and 1σ respectively for Figures 4a and 4b. The dependence of the collapse epoch on the amplitude $\delta_{c,i}$, without UV heating, is shown in Figure 5. By this figure, we obtain $\delta_{c,i}(z_{\text{coll}}^{\text{NUD}} = 4)$, which is plotted in terms of Ω_c in Figure 6, together with $\delta_{c,\text{crit}}$. When the fluctuation destined to collapse in NOD regions just before $z = 4$ is set in NUD regions, before collapse it is subject to UV heating by QSOs and changes to expansion, irrespective of the behavior of CDM as shown in Figure 4b. Such expanding clouds are favorable candidates for Ly α absorbers found in QSO spectra, because these clouds formed in NUD regions are almost unclustered in accord with the observed distribution. We are interested in the neutral hydrogen column density N_{HI} of these expanding clouds as an observable physical quantity. In Figure 7, for several values of Ω_c , we illustrate the time variations of N_{HI} for clouds with $M_{b,\text{crit}} = 10^8 M_\odot$, together with one case of 10^7 or $10^9 M_\odot$ for comparison. They all had the initial amplitude of CDM fluctuations destined to collapse if they are in NOD regions. As is seen, N_{HI} is almost independent of Ω_c for the same $M_{b,\text{crit}}$, as far as $\Omega_c < \Omega_v$. This has been confirmed also in cases of $M_{b,\text{crit}} = 10^7$ and $10^9 M_\odot$. The impressive property is the faster decrease of N_{HI} with decreasing z . This trend is more conspicuous for the smaller M_b , in which the time for turning from contraction to expansion is shorter, as seen also in Figure 4b. In Figure 8, the variation of N_{HI} for a cloud with $10^7 M_\odot$, whose initial amplitude satisfies 1σ in Figure 1, is compared with the results shown in Figure 7. The quantity N_{HI} is exactly the same for different masses just after

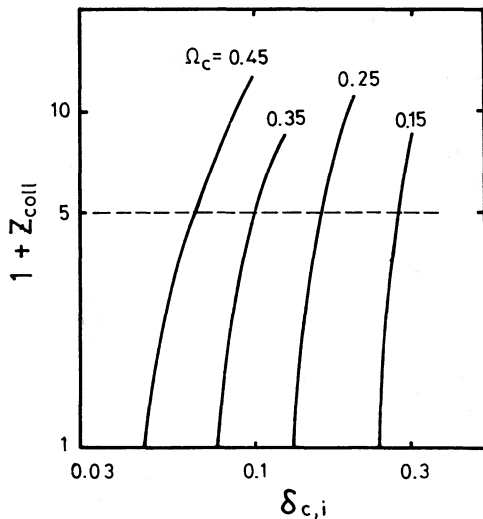


FIG. 5.—The dependence of the collapse epoch z_{coll} on the initial amplitude of fluctuations of CDM $\delta_{c,i}$ in the NUD region. UV heating by QSOs is neglected.

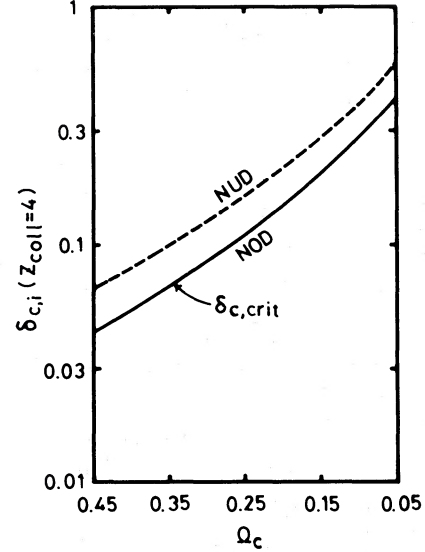


FIG. 6.—The initial amplitude of fluctuations which collapse just before $z = 4$ in both the NOD and NUD regions is plotted in terms of Ω_c ; $\delta_{c,i}(z_{\text{coll}} = 4)$ for the NOD region is $\delta_{c,\text{crit}}$ by definition in this paper.

the ionization by UV light from QSOs, and the degree of decrease of N_{HI} is analogous to that shown in Figure 7. From these results, we can conclude that the leading parameter of N_{HI} is $M_{b,\text{crit}}$, and, if $M_{b,\text{crit}}$ is of subgalactic scale, the formation of expanding clouds is ensured. That is to say, if subgalactic collapsed objects are formed from CDM fluctuations in NOD regions, then the same fluctuation spectrum yields subgalactic expanding clouds in NUD regions. The numerical results for N_{HI} are compared with the observations in § IV.

IV. DISCUSSION

a) Constraints on the Hybrid Model

The spectrum at z_{rec} for the rms fluctuations σ is determined by Figure 1, with the assumed value of $\epsilon(z_{\text{rec}}) = 0.03$ corresponding to $z_{\text{sc}} = 4$. For other values of Ω_c , the procedure for the determination of σ is the same. By these spectra, constraints are imposed on the possibility of the above scenario for the formation of subgalactic objects. Here, we adopt $\delta_{c,i} = m\sigma$, with $m \leq 2$ as a permitted range. For a given value of m , the relations between $\delta_{c,i}(z_{\text{coll}} = 4)$ and Ω_c shown in Figure 6 are converted into those between $M_b(z_{\text{coll}} = 4)$ and Ω_c . They are illustrated in Figure 9 for $m = 0.5, 1$, and 2 in both NOD and NUD regions, where $M_{b,\text{cool}}$ is the minimum mass of fluctuations which can collapse by means of sufficient hydrogen molecular cooling under an environment without UV heating as

$$M_{b,\text{cool}} \approx 5.5 \times 10^6 \left(\frac{\Omega_b}{0.05} \right)^{-0.415} \left(\frac{1+z_t}{10} \right)^{-2.75} M_\odot, \quad (14)$$

with the turnaround epoch z_t (Blumenthal *et al.* 1984). Knowing $z_t \approx 7$ in the present calculations, $M_{b,\text{cool}} \approx 10^7 M_\odot$. Therefore, if $M_{b,\text{crit}} \equiv M_b(z_{\text{coll}}^{\text{NOD}} = 4)$ is greater than $10^7 M_\odot$, subgalactic collapsed objects such as dwarf galaxies can indeed be born in NOD regions. This condition is equivalent to

$$\Omega_c \geq 0.15 \quad (15)$$

for the range of $\delta_{c,i} \leq 2\sigma$, as seen in Figure 9. Then expanding

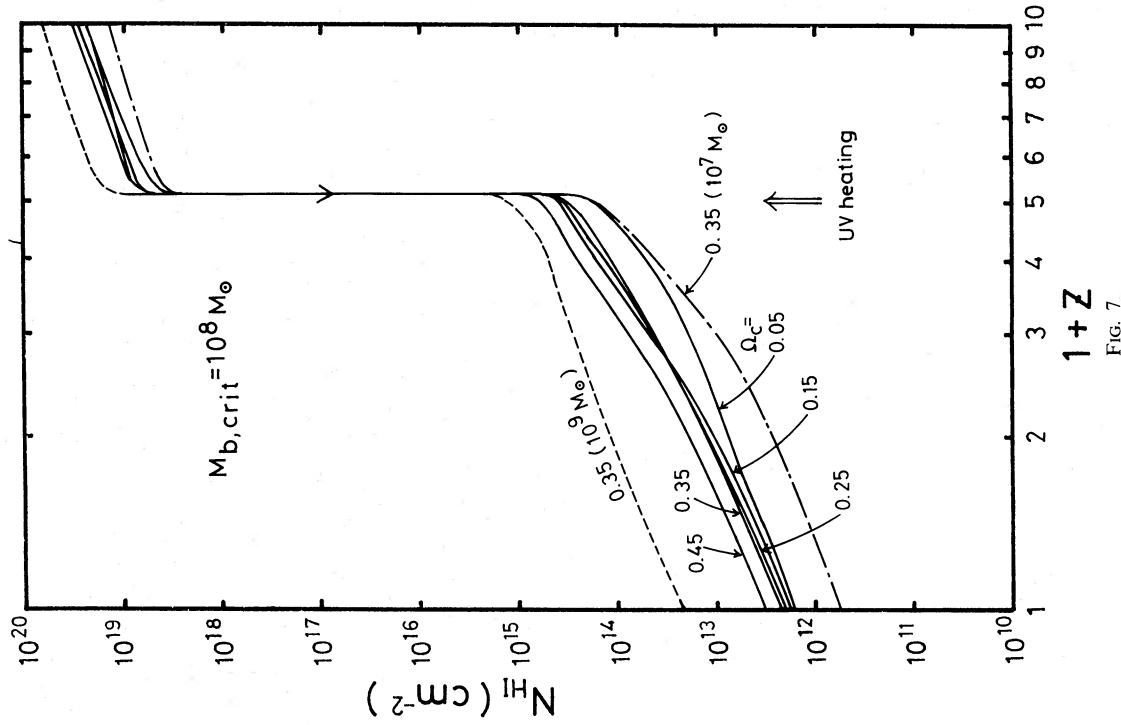


FIG. 7.—Time variations of the neutral hydrogen column density N_{HI} of expanding clouds in the NUD region, for $M_{\text{b,crit}} = 10^8 M_{\odot}$ and various Ω_c , with the typical cases of $M_{\text{b,crit}} = 10^9$ and $10^7 M_{\odot}$. N_{HI} turns out to be almost independent of the model (Ω_c) for the same $M_{\text{b,crit}}$.

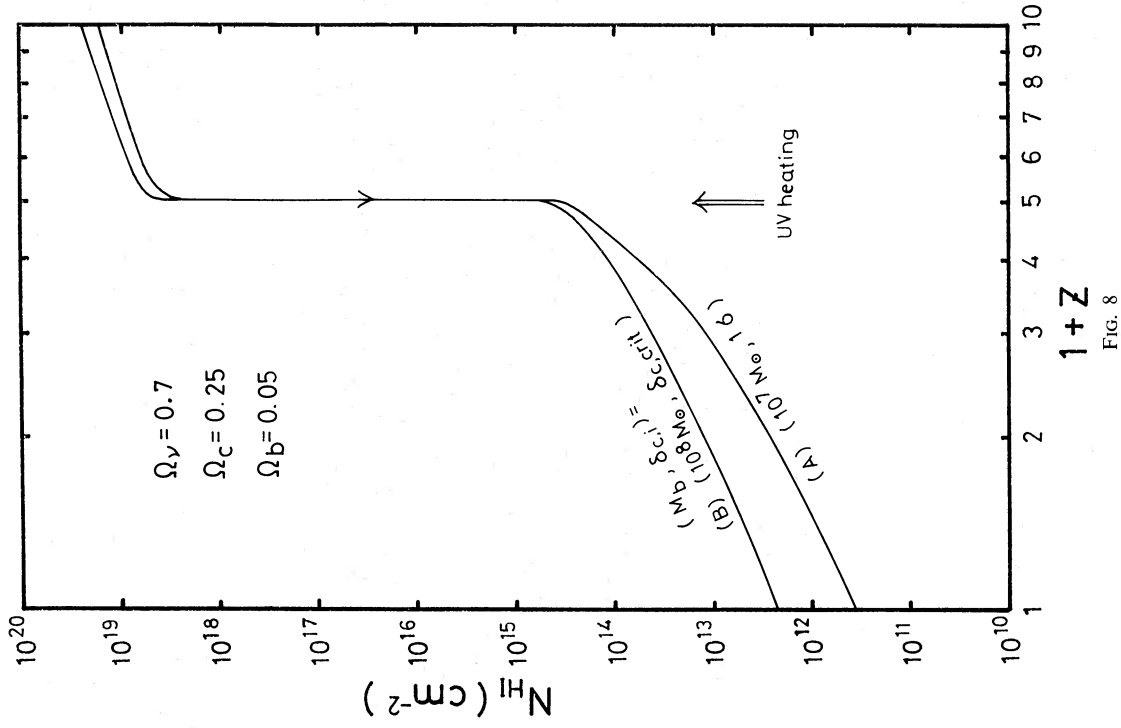


FIG. 8

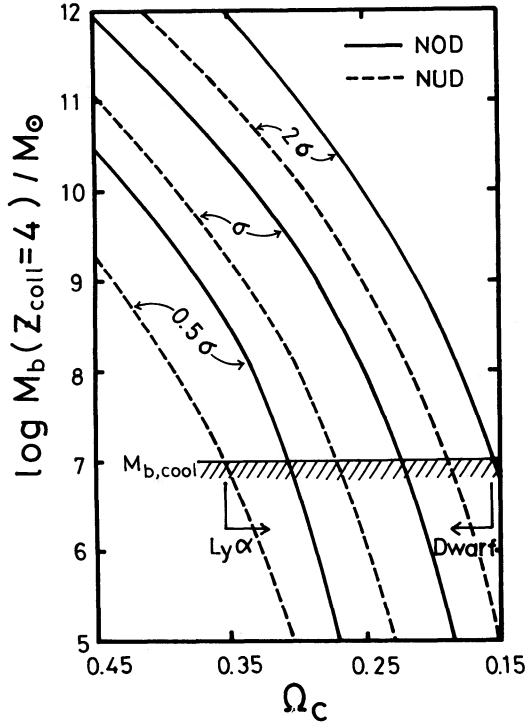


FIG. 9.—Baryon mass within fluctuations which collapse just before $z = 4$ in the NOD and NUD regions, for $\delta_{c,i} = 0.5\sigma$, 1σ , and 2σ , is plotted vs. Ω_c ; $M_{b,cool}$ is the mass scale above which fluctuations can collapse due to sufficient hydrogen molecular cooling. $M_b(z_{coll} = 4)$ for the NOD region is $M_{b,crit}$.

clouds can be born in NUD regions. However, on behalf of successful formation of expanding clouds as probable candidates for Ly α absorbers, another restriction must be imposed from a statistical point of view. If $M_b(z_{coll}^{NUD} = 4) \geq 10^7 M_\odot$ for $\delta_{c,i} \geq 0.5\sigma$, then about half the subgalactic objects will collapse by $z = 4$ even in NUD regions, and the fraction of surviving expanding clouds is $f_{cloud} \approx 0.5$. In the same way, $f_{cloud} \approx 0.8$ for $\delta_{c,i} \geq \sigma$. If we pose $f_{cloud} \geq 0.5$, this condition is equivalent to

$$\Omega_c \leq 0.35, \quad (16)$$

and the requirement of $f_{cloud} \geq 0.8$ corresponds to $\Omega_c \leq 0.27$. Although we have no information on the number ratio of clouds to dwarf galaxies in NUD regions because of the lack of observations of dwarfs in voids so far, it may not be unreasonable to take $f_{cloud} \geq 0.5$ as a condition for sure production of unclustered Ly α forest. The models with $0.15 \leq \Omega_c \leq 0.35$ are also not incompatible with $\Omega_{cluster} = 0.2e^{\pm 0.4}$ from the observations on velocity dispersion of galaxies (Davis and Peebles 1983; Bean *et al.* 1983).

b) Observable Characteristics

The hybrid model with $0.15 \leq \Omega_c \leq 0.35$ and therefore correspondingly $0.8 \geq \Omega_v \geq 0.6$ ensures the simultaneous formation of dwarf galaxies embedded in massive dark halos and unclustered Ly α clouds, in the sense that the CDM fluctuation spectra which yield dwarf galaxies in NOD regions (superclusters) produce at the same time Ly α absorbers in

NUD regions (voids). This scenario provides several suggestive observable characteristics.

i) Ly α Clouds

In Figure 10, we compare N_{H1} of expanding clouds for $\Omega_c = 0.35$ and 0.25 models with the observation on Ly α absorption lines by Sargent *et al.* (1980). Here, we adopt the value integrated along the line of sight passing half the cloud radius on average. In both models, N_{H1} for $M_{b,crit} = 10^{7-9} M_\odot$ is in remarkable agreement with the observed values. A cloud expands with nearly the same velocity throughout the evolution, and the expansion velocity is dependent on $M_{b,crit}$ in such a way that the cloud originating in the smaller $M_{b,crit}$ expands with the lower velocity. The cloud expansion produces two significant characteristics (UI; Ostriker and Ikeuchi 1983). One is the Doppler width of the absorption line, and the difference of velocity along the line of sight is $\langle \Delta V_r \rangle \approx 50 \text{ km s}^{-1}$ on the average for $M_{b,crit} = 10^{7-9} M_\odot$ and $\Delta V_c \approx 30 \text{ km s}^{-1}$ especially for $M_{b,crit} = 10^7 M_\odot$. These values are comparable to $\sim 33 \text{ km s}^{-1}$ estimated by Oke and Korycansky (1982). The other characteristic is, as seen in Figure 10, the rapid decrease of column density with decreasing z . This trend is well connected (UI) with the observations pointed out by Peterson (1978), who has indicated that the number density of absorption lines decreases with decreasing z . As for the spatial distribution of Ly α clouds, it is probable that f_{cloud} is larger in regions less dense in neutrinos near the center of voids, where CDM fluctuations scarcely collapse at $z > 4$.

ii) Dwarf Galaxies

Dwarf galaxies are born with massive halos of CDM (Aaronson 1983; Faber and Lin 1983) preferentially in NOD regions rather than in NUD regions. Therefore they show the more distinct contrast in distribution on supercluster scales than in a CDM-dominated universe, where the formation of dwarf galaxies occurs nearly uniformly, and then they cluster gravitationally. In the present model, dwarf galaxies are the first objects made from primordial hydrogen-helium gas, and globular star clusters may be formed secondly through gravitational instability in dwarf galaxies (Fall and Rees 1985).

iii) QSOs and Galaxies

IU have shown that the most gravitationally unstable fragments of a flattened gaseous protosupercluster in a neutrino-dominated universe are exactly of galactic scale, $M_b \approx 10^{11} M_\odot$, irrespective of the epoch of fragmentation after z_{sc} . This scale, moreover, does not depend on the thermal property but only on the dynamics of the protosupercluster (Tomisaka and Ikeuchi 1985). Hence, also in the hybrid model, we expect objects of galactic scale from the fragmentation of a supercluster composed of gas and numerous dwarf galaxies, resulting in QSOs and galaxies as aggregations of dwarf galaxies. If globular clusters have already been born in dwarfs, a galaxy may have globular clusters which are distinctive in kinematics and metallicity, as reported by Rodgers and Paltoglou (1984). Galaxies in NOD regions possibly tend to show a stronger spatial correlation with dwarf galaxies than galaxies in NUD regions do.

iv) Galaxies in Voids

In Figure 11, we show the mass scales of fluctuations which collapse at the present epoch ($z = 0$) in the NUD region. The hatched line represents the mass M_{UV} as the Jeans mass at

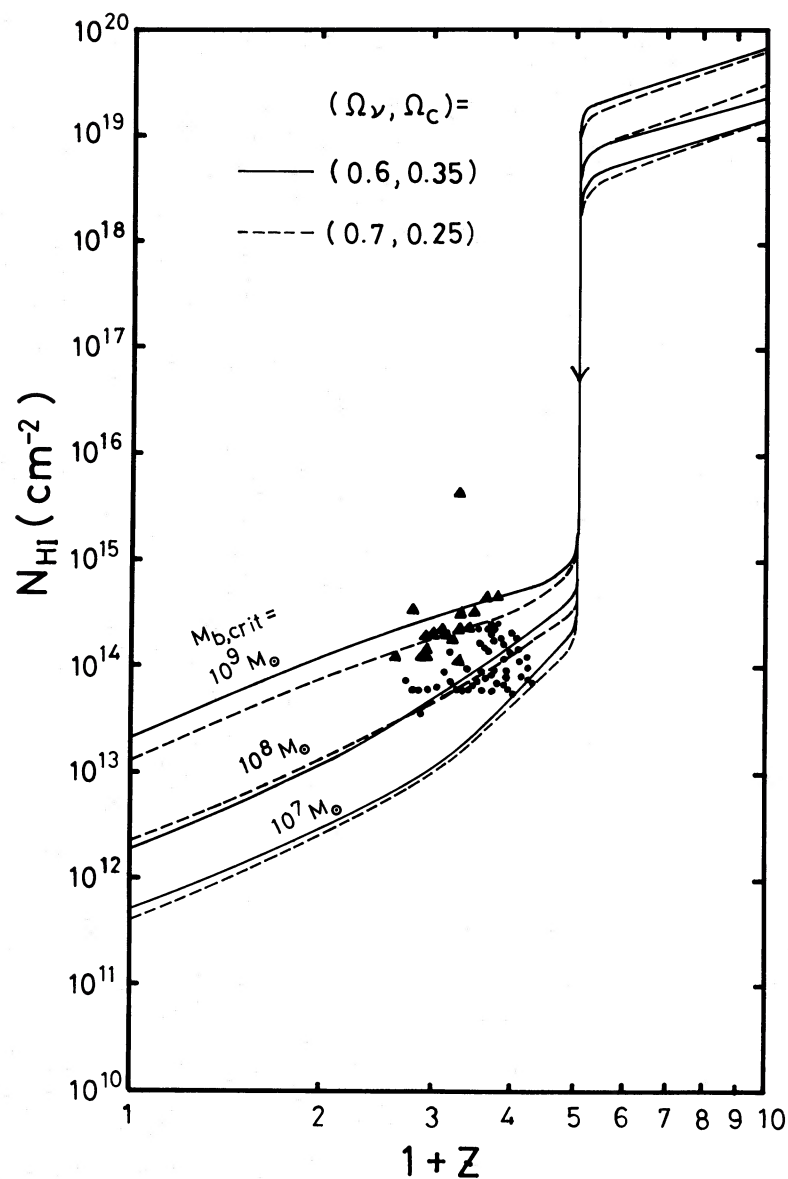


FIG. 10.—The comparison of N_{HI} of expanding clouds with the observational data by Sargent *et al.* (1980). Triangles represent all identified Ly α absorption lines, and dots are random samples which are believed to be Ly α absorption.

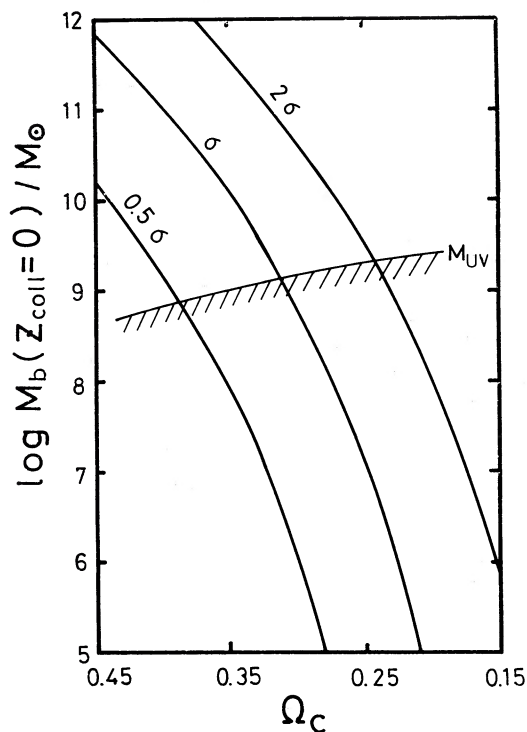


FIG. 11.—The mass scale of fluctuations which collapse at $z \approx 0$ in the NUD region is plotted in terms of Ω_c for $\delta_{c,i} = 0.5\sigma$, 1σ , and 2σ . M_{UV} is the mass below which fluctuations cannot collapse but expand due to the pressure force enhanced by UV heating by QSOs.

$z < 4$, below which fluctuations cannot collapse due to the pressure force enhanced by UV heating by QSOs. If $0.25 \leq \Omega_c \leq 0.35$, in the range $\delta_{c,i} \leq 2\sigma$, fluctuations with $M_b \approx 10^9$ – $10^{11} M_\odot$ can collapse at $0 \leq z_{\text{coll}} < 4$ even in the NUD region. Consequently, some galaxies may have recently been born in voids (Brosch 1983) and fallen toward superclusters, forming nonvirialized isolated systems with large peculiar velocities. If fluctuations with considerably larger mass than the Jeans mass, $\sim 10^{10}$ – $10^{11} M_\odot$, form flattened systems in a process analogous to the Zeldovich theory (1970), then the systems may gain angular momentum through the tidal field of superclusters (Shaya and Tully 1984) and be liable to evolve to spiral galaxies. Such young galaxies can hardly be expected to be in alignment with clusters of galaxies. Moreover, they, with dwarf galaxies, chemically pollute the gas in voids (Brosch and Gondhalekar 1984), in contrast to a neutrino-dominated universe.

The hybrid model not only successfully removes the difficulty regarding subgalactic objects in a neutrino-dominated universe but also presents characteristic features on galactic and supercluster scales. This model can be tested in further detail when more information on faint galaxies is accumulated.

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REFERENCES

- Aaronson, M. 1983, *Ap. J. (Letters)*, **266**, L11.
 Bahcall, N. A., and Soneira, R. M. 1983, *Ap. J.*, **270**, 20.
 Bean, A. J., Efstathiou, G., Ellis, R. S., Peterson, B. A., and Shanks, T. 1983, *M.N.R.A.S.*, **205**, 605.
 Binggeli, B. 1982, *Astr. Ap.*, **107**, 338.
 Blumenthal, G. R., Faber, S. M., Primack, J. R., and Rees, M. J. 1984, *Nature*, **311**, 517.
 Bond, J. R., and Efstathiou, G. 1984, *Ap. J. (Letters)*, **285**, L45.
 Bond, J. R., and Szalay, A. S. 1983, *Ap. J.*, **274**, 443.
 Bonometto, S. A., Lucchin, F., Occhionero, F., and Vittorio, N. 1984, *Astr. Ap.*, **138**, 477.
 Brosch, N. 1983, in *IAU Symposium 104, Early Evolution of the Universe and its Present Structure*, ed. G. O. Abell and G. Chincarini (Dordrecht: Reidel), p. 207.
 Brosch, N., and Gondhalekar, P. M. 1984, *Astr. Ap. Letters*, **140**, 43.
 Cowsik, R. 1985, preprint.
 Davis, M., Efstathiou, G., Frenk, C. S., and White, S. D. M. 1985, *Ap. J.*, **292**, 371.
 Davis, M., Huchra, J., Latham, D. W., and Tonry, J. 1982, *Ap. J.*, **253**, 423.
 Davis, M., and Peebles, P. J. E. 1983, *Ap. J.*, **267**, 465.
 Dekel, A., and Aarseth, S. J. 1984, *Ap. J.*, **283**, 1.
 Djorgovski, S. 1983, *Ap. J. (Letters)*, **274**, L7.
 Doroshkevich, A. G. 1984, *Soviet Astr.*, **28**, 378.
 Einasto, J., Joeveer, M., and Saar, E. 1980, *Nature*, **283**, 47.
 Faber, S. M., and Lin, D. N. C. 1983, *Ap. J. (Letters)*, **266**, L17.
 Fall, S. M., and Rees, M. J. 1985, *Ap. J.*, **298**, 18.
 Fukugita, M., and Yanagida, T. 1984, *Phys. Letters*, **144B**, 386.
 Gregory, S. A., and Thompson, L. A. 1978, *Ap. J.*, **222**, 784.
 Guth, A. H. 1981, *Phys. Rev.*, **D23**, 347.
 Guyot, J. E., and Zeldovich, Ya. B. 1970, *Astr. Ap.*, **9**, 227.
 Hoffman, Y., and Bludman, S. A. 1984, *Phys. Rev. Letters*, **52**, 2087.
 Hut, P., and White, S. D. M. 1984, *Nature*, **310**, 637.
 Ikeuchi, S., and Umemura, M. 1984, *Progr. Theor. Phys.*, **72**, 216 (IU).
 Kirshner, R. P., Oemler, A., Schechter, P. L., and Shectman, S. A. 1981, *Ap. J. (Letters)*, **248**, L57.
 Lifshitz, E. M. 1946, *JETP Letters*, **16**, 587.
 Lyubimov, V. A., Novikov, E. G., Nozik, V. Z., Tret'yakov, E. F., and Kozik, V. S. 1980, *Phys. Letters*, **94B**, 266.
 Mészáros, P. 1974, *Astr. Ap.*, **37**, 225.
 Oke, J. B., and Korycansky, D. G. 1982, *Ap. J.*, **255**, 11.
 Ostriker, J. P., and Ikeuchi, S. 1983, *Ap. J. (Letters)*, **268**, L63.
 Peebles, P. J. E. 1968, *Ap. J.*, **153**, 1.
 ———. 1984, *Ap. J.*, **277**, 470.
 Peterson, B. A. 1978, in *IAU Symposium 79, The Large Scale Structure of the Universe*, ed. M. S. Longair and J. Einasto (Dordrecht: Reidel), p. 389.
 Rodgers, A. W., and Paltoglou, G. 1984, *Ap. J. (Letters)*, **283**, L5.
 Sargent, W. L. W., Young, P. J., Boksenberg, A., and Tytler, D. 1980, *Ap. J. Suppl.*, **42**, 41.
 Sato, K. 1981, *M.N.R.A.S.*, **195**, 467.
 Schaeffer, R., and Silk, J. 1985, *Ap. J.*, **292**, 319.
 Shaya, E. J., and Tully, R. B. 1984, *Ap. J.*, **281**, 56.
 Suto, Y., Kodama, H., and Sato, K. 1985, preprint.
 Tomisaka, K., and Ikeuchi, S. 1985, *Pub. Astr. Soc. Japan*, Vol. **37**, No. 3.
 Turner, M., Steigman, G., and Krauss, L. M. 1984, *Phys. Rev. Letters*, **52**, 2090.
 Umemura, M., and Ikeuchi, S. 1984, *Progr. Theor. Phys.*, **72**, 47 (UI).
 Uson, J. M., and Wilkinson, D. T. 1984, *Ap. J. (Letters)*, **277**, L1.
 Vittorio, N., and Silk, J. 1984, *Ap. J. (Letters)*, **285**, L39.
 White, S. D. M., Frenk, C. S., and Davis, M. 1983, *Ap. J. (Letters)*, **274**, L1.
 White, S. D. M., and Rees, M. J. 1978, *M.N.R.A.S.*, **183**, 341.
 Yang, J., Turner, M. S., Steigman, G., Schramm, D. N., and Olive, K. A. 1984, *Ap. J.*, **281**, 493.
 Zeldovich, Ya. B. 1970, *Astr. Ap.*, **5**, 84.

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