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EVOLUTION OF SYSTEMS OF GALAXIES IN COLD DARK MATTER MODELS

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ABSTRACT

We study the evolution of groups and clusters of galaxies in a $\Omega = 1$, $h = 0.5$, $\Lambda = 0$, CDM scenario using numerical simulations normalized to $\delta M/M = 1$. We construct models for galaxy formation assuming instantaneous cooling of gas and the related formation of galaxies in local high-density regions.

We compute models that inhibited galaxy formation when the corresponding galactic halo is embedded in a greater cloud for which its cooling time exceeds its crossing time. In these models we find a significant reduction of galaxy formation efficiency in large galactic systems.

Mergers of galaxies are taken into account using suitable cross sections and a binding energy criterion. We find that about $\sim 10\%$ of the galaxies have undergone mergers at the present time.

We have implemented simple models that consider the effects of energy input by supernovae winds. We find that these effects provide a successful fit to the observed Tully-Fisher relation.

We have considered gas infall in systems of galaxies and the effects of supernova winds in the intracluster medium in order to account for the observed gas-to-stars mass ratio $M_{\rm gas}/M_{\rm stars}$ as a function of temperature. Although we find a negligible amount of gas infall ($< 10\%$), the models allow significant gas mass loss due to supernova winds in small clusters which would explain their high observed galaxy formation efficiency.

We have analyzed the spatial distribution of galaxies and their peculiar velocity field in the models. Only when a moderate suppression of galaxy formation in dense environments is considered, is the galaxy-galaxy spatial correlation function consistent with observations.

We find no significant velocity bias of the galaxies with respect to the dark matter in any model. This results suggest that the observed galaxy peculiar velocity field put strong constraints to the amplitude of the primordial mass fluctuations in the cosmological models.

Subject headings: cosmology: theory — dark matter — galaxies: clustering — galaxies: formation

1. INTRODUCTION

The high complexity of the physical phenomena involved in galaxy formation has been considered in a great variety of models (see for instance, Lacey & Silk 1991; White & Frenk 1991 and references therein). The determination of the galaxy distribution in specific cosmological models is a crucial point that allows a direct comparison with observations. It is generally assumed that galactic halos originate in the high-density peaks of the mass distribution implying a distribution of galaxies more clustered than mass. In particular, the natural bias scenario in cold dark matter (CDM) models discussed by Davis et al. (1985) assumes that in all high-density peaks the gas is in a condition of cooling and forming stars, giving rise to a galaxy. In this scheme it is possible to reproduce several observational properties of galaxies, provided a high bias parameter $b \simeq 2$. However, the related amplitudes of mass fluctuations are inconsistent with cosmic radiation background fluctuations (Wright et al. 1992) which suggest a high normalization, $b \simeq 1$, for the CDM model.

The observed properties of systems of galaxies give useful information to help understand the process involved in galaxy formation. Recent X-ray observations in groups and clusters have allowed to estimate gas mass content and temperature (see, for instance, David et al. 1990). By comparison of the mass in gas and stars and the virial mass of clusters, it is possible to derive limits to the baryonic to total density parameter ratio Ω_B/Ω. For the Coma Cluster, White (1992) derives $\Omega_B/\Omega > 0.17$ for a Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1}. On the other hand, standard nucleosynthesis theory predicts $\Omega_B < 0.015h^2$ (Olive et al. 1990). Several possibilities may account for these results. An open universe with $\Omega \sim 0.3$ is a straightforward solution. If for theoretical reasons $\Omega = 1$ is adopted, the possibility of segregation between dark and baryonic matter on scales of groups and clusters should be considered. This concentration of baryonic matter in high-density regions would result from radiative dissipation once the density perturbations have entered in the nonlinear regime.

Observations also indicate that the ratio of mass in gas to mass in stars $f = M_{\rm gas}/M_{\rm stars}$ increases with the temperature T of the system. This fact may be explained assuming that galaxy formation in groups is more efficient than in clusters (Jones & Forman 1992). These results are difficult to be reproduced within a high-bias galaxy formation scenario where it is expected a more efficient galaxy formation in high density regions. Recently, David & Blumenthal (1992) have suggested a possible mechanism to explain this trend. The authors compute the correlations between linear perturbations on galactic and cluster scales assuming Gaussian fluctuations with different power spectra. For CDM they find stronger correlations in halo-group scales than in halo-cluster scales. These results would qualitatively lead to the observed f-T relation. However, as will be seen in this paper, in the absence of astrophysical mechanisms that inhibit galaxy formation in high-T systems, a nonlinear high-density peak model gives rise to more efficient galaxy formation in clusters than in groups, in

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contradiction with observations. In order to account for the observed f-T relation in systems of galaxies, it should be considered the physics of the gas concentrated in the potential wells. Efficient star formation requires both high densities and low temperatures so the gas is able to cool within a free-fall time. Silk (1977) finds an upper limit for the mass of an isolated gas cloud that can cool and fragment into smaller structures. According to his analyses when dark matter is present, gas clouds with masses greater than $M_S = \Omega_B^2 10^{12.5} M_\odot$ have $t_{\rm cool}/t_{\rm dyn} > 1$ and therefore cannot cool in a dynamical time. Thus, it is possible that this critical mass limit can provide the desired anticorrelation between galaxy formation efficiency and temperature. In effect, a halo-size perturbation in a high-density region is more likely to be part of a larger gas cloud with mass exceeding M_S. Hence, the gas in a halo in this condition will not be able to cool in a suitable time and massively form stars. We develop models that consider the effects of this critical mass limit on galaxy formation in different environments.

The effects of supernova winds in galaxies have been the subject of several studies (Larson 1974; Dekel & Silk 1986). In particular, Dekel & Silk study the conditions for gas loss in a galaxy as the result of the first star formation bursts. The authors find a condition of instability for galactic halos of circular velocity $V_c \simeq 100$ km s^{-1}, analyzing the balance between the gas kinetic energy and the total energy input by supernovae to the galactic medium.

The models developed in our work also deal with the effects of supernovae energy input. We find a continuous function of V_c for the expected gas loss. We have applied this mechanism to our galaxy formation models providing a better agreement with the observed Tully-Fisher relation.

The effects of supernovae winds on scales of groups and clusters were analyzed together with models of gas infall through radiative cooling. These models are considered in order to explain the observed relations involving $M_{\rm gas}/M_{\rm stars}$ ratio and temperature.

The effects of galaxy merging has been the subject of several studies (see for instance, Couchman & Carlberg 1992 and references therein). Some of these papers work out in detail the effects of common dark matter halos in the merging process of galaxies. It is important to notice that a critical issue in the analysis of this problem is the galaxy identification algorithm. Couchman & Carlberg (1992) study galaxy formation in low-bias CDM scenarios with a particular scheme for the identification of galactic halos. They study the effects of mergers in the velocity and spatial distribution of halos. A high rate of mergers is found which provides good agreement between the simulated and the observed peculiar velocity field. However, these results are in contradiction with other works (see for instance Cen & Ostriker 1992) where no significant velocity bias is found. Thus it seems difficult that mergers can reconcile the observed peculiar velocities with those in CDM models. We have considered simple galaxy merging schemes to study their properties and implications.

The energy dissipated by the gas implies a dramatic reduction of the radius of the galaxy; thus, although extended galactic halos may mix efficiently in groups and clusters, the luminous central galaxy region of $\simeq$10–20 kpc might resist the merging instability through several system crossing times. This fact makes difficult to identify galactic halos inside large systems where galaxies are embedded in a common potential well. This is the central motivation for searching for different halo identification algorithms which take this issue into account. The models developed in this paper deal with the continuous formation of galaxies as the clustering grows and generates potentail wells suitable for gas cooling and star formation. We study mechanisms of galaxy formation assuming instantaneous dissipation of gas energy in density perturbations of mass $\simeq 10^{12}$ $M_\odot$ exceeding a given threshold, $\rho/\rho_b > \delta_{\rm crit}$. Thus, we can identify galaxies prior to cluster formation, and we are able to follow their orbits as well as their merging history. We have particularly centered our attention on the resulting groups and clusters of galaxies and their dynamical properties. We also investigate general statistics of the galaxy distribution as well as such properties of mergers as their spatial and velocity distribution in order to confront the models with observations. We compute the two-point correlation functions of galaxies and dark matter, the luminosity function, its evolution with redshift, z, the Tully-Fisher relation, cluster velocity dispersion, and the rate of mergers.

2. ANALYSIS

2.1. *The Numerical Simulations*

We compute the evolution of the mass distribution in CDM models with a standard 128^3 particle mesh code (PM) (Hockney & Eastwood 1988). We have used 2×10^5 particles in a comoving box of 28 Mpc, with a Hubble constant $H_0 = 100\ h$ km s^{-1} Mpc^{-1} with $h = 0.5$. We adopt the standard CDM model with $\Omega = 1$, $\Lambda = 0$; therefore, each particle has a mass $m = 7.6 \times 10^9\ M_\odot$. We have used different values for the baryonic density parameter $\Omega_B = 0.05$–0.15, consistent with nucleosynthesis theory limits (Yang et al. 1984). In Table 1 are listed the main characteristics of the models.

According to the cosmic microwave background results (Wright et al. 1992), the CDM spectrum was normalized with $\delta M/M = 1$ in 16 Mpc. This normalization of the power spectrum is performed computing the rms mass fluctuation $\delta M/M$ in spheres of radius r in the range 1–8 Mpc in the initial conditions. In order to infer the rms mass fluctuation in a 16 Mpc radius sphere, we use the analytic expression (Peebles 1980):

$$(\delta M/M)^2 = \int P(k) W(kr) d^3k\ , \tag{1}$$

where $W(kr)$ is the square of the window function in frequency space. This normalization requires expansion factors $\simeq$7.7 for the numerical simulations. We have adopted 200 equally time-spaced integration steps.

2.2. *Galaxy Formation Models*

We have implemented an algorithm for the identification of galaxy formation sites in the PM code. In each time step, we define a galactic halo if the local density contrast has achieved high values, $\rho/\rho_b > \delta_{\rm crit}$. We use a spherical region of radius R_H to measure the local density contrast. We have adopted $40 < \delta_{\rm crit} < 120$ and 150 kpc $< R_H <$ 300 kpc (see Table 1).

The baryonic density parameter Ω_B determines, in principle, an upper limit to the mass associated to a galaxy in a halo although there is also an important contribution to the galaxy mass by the infall of nonbaryonic dark matter. Dynamical models of galaxies (Freeman 1987) indicate that this infall of nonbaryonic dark matter may be as large as the baryonic infall at the Holmberg radius. We have studied the variation of galaxy properties owing to changes in Ω_B. According to standard nucleosynthesis theory calculations by Yang et al. (1984), we have used $0.01 < \Omega_B h^2 < 0.035$.

TABLE 1
NUMERICAL SIMULATIONS

Model	Ω_b	$\delta_{\rm crit}$	$\delta_{\rm cloud}$	Model	Ω_b	$\delta_{\rm crit}$	$\delta_{\rm cloud}$
a	0.10	64	6	n	0.25	64	6
b	0.10	64	6	o	0.15	64	6
c..........	0.05	64	6	p	0.15	64	...
d	0.15	64	6	q	0.15	64	18
e..........	0.15	64	6	r..........	0.10	64	64
f..........	0.25	64	6	s..........	0.10	64	32
g	0.15	64	15	t..........	0.05	6	32
h	0.15	64	...	u	0.05	120	...
i..........	0.15	64	6	v	0.05	64	64
j..........	0.15	128	6	w.........	0.05	64	44
k	0.15	64	6	x	0.05	64	64
l..........	0.15	64	6	y	0.05	64	64
m.........	0.25	64	6	z..........	0.05	64	32

We assume that as result of the effective gas cooling a constant fraction of the halo mass condenses into a small sphere of radius $\simeq$10–20 kpc. It is also expected that a fraction of dark matter will follow the baryon infall. Accordingly, we put in the halo baricenter a clump of mass αM_H, where the parameter $\alpha = (1\text{–}3)\Omega_B$ and remove the same mass from the halo. Hereafter the galaxies (i.e., baryonic + dark matter clumps) are presented by a single massive particle. This is the only point in the model where dark matter and baryons are handled separately.

Undesirable two-body effects should be of no worry due to the large softening of the simulations.

Following Silk (1977), we check whether the halo forms part of a larger cloud with density contrast $\delta = \delta M/M > \delta_{\rm cloud}$ and mass $M > M_S = \Omega_B^2\, 10^{12.5}\, M_\odot$. For a given $\delta_{\rm cloud}$ we obtain for the critical cloud radius $R_S = 2.21\, \delta_{\rm cloud}^{-1/3} \Omega_B^{1/3}$ Mpc. If these conditions are satisfied namely $\delta > \delta_{\rm cloud}$ and mass within R_S greater than M_S, the cloud cooling time is larger than its free-fall time and galaxy formation is inhibited in these regions. If galaxy formation is allowed, the gas cools and settles in the halo center. The cooling time of galaxies is defined as $t_{\rm cool} = 3.6\ 10^{12} R_H^2({\rm Mpc})/\sigma({\rm km\ s^{-1}})$ yr, where σ is the velocity dispersion of the halo. The integration time step adopted is of the order of 10^8 yr comparable to the cooling time of halos. Therefore, it is reasonable to assume that the available gas transforms instantaneously into stars with a high efficiency.

2.3. *Galaxy Formation Rate*

We have analyzed the time evolution of the galaxy formation rate in the numerical models. The number of galaxies selected per unit volume in the simulations depends critically on the value of $\delta_{\rm crit}$ and the radius R_H chosen to determine the mass of the galaxy. Depending on the value of $\delta_{\rm cloud}$, a strong suppression of galaxy formation in clusters may be present due to the fact that in high density environments M_S criterion is more frequently satisfied. This may cause the formation of galaxies to be more efficient in relatively low density environments.

We have used different cloud definition criteria in applying M_S limit. We notice however that the density contrast criteria for halo and cloud should not be too different. Figure 1 shows the time evolution of the galaxy formation rate for a simulation where M_S criterion has been applied (*dotted line*), and where this criteria has not been considered (*solid line*). We see from this figure the presence of a well-defined maximum at $z \simeq 2$ for both models, and a more pronounced decay in the model with strong suppression of galaxy formation in high-density regions.

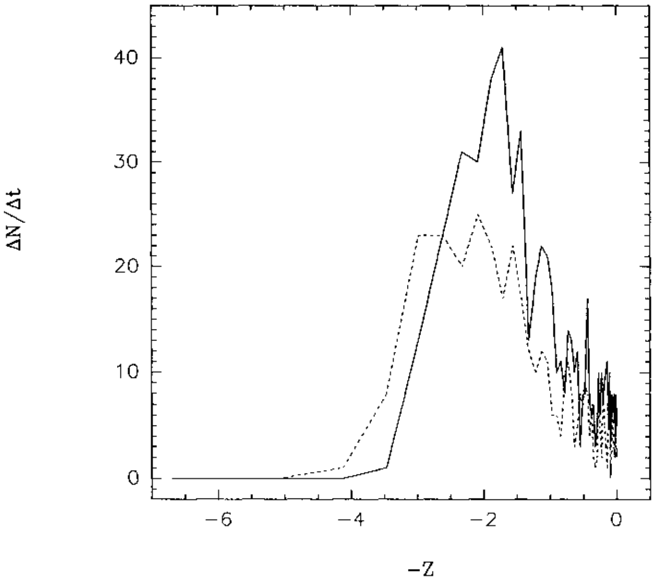

FIG. 1.—Evolution of the galaxy formation rate vs. redshift. The dotted line corresponds to a model where galaxy formation is inhibited in high-density environments through Silk's criterion. The solid line corresponds to a model where this criterion is not considered. The vertical axis correspond to the variation in the total number of galaxies in the box per 2×10^8 yr.

2.4. *Luminosity Function and Tully-Fisher Relation*

In our models a single scale and density contrast parameters determine the formation of galaxy resulting in a relatively narrow distribution in galaxy masses. Assuming a constant mass-to-luminosity ratio M/L for all galaxies we also expect a narrow distribution in luminosities where the mean absolute magnitude is fixed by the present value of M/L. If we fix M/L = 5–10 solar units, the resulting mean absolute magnitude $\langle M \rangle$ is similar to the parameter M^* of the Schechter luminosity function $M^* \simeq -21.3$.

We assume that the small fraction of mergers ($\simeq$10%) blends the luminous parts of galaxies but does not induce new star formation. We find no significant changes in the luminosity function.

The observed Tully-Fisher relation $L \propto V_c^{4.5}$ is steeper than that imposed in the models $L_i \propto V_c^2$, and we notice that this dependence cannot be modified in the models assuming different M/L ratios. Thus, consistency between models and observations might be achieved only through the effects of astrophysical processes.

It might be argued (Dekel & Silk 1986; Efstathiou 1992) that galaxies embedded in shallow potential wells have not been able to retain a considerable fraction of gas once supernovae start injecting energy to the interstellar medium. A critical value of $\simeq$100 km s^{-1} is suggested by Dekel & Silk as a lower limit of the halo circular velocity that can retain a substantial amount of the initial gas. In order to address this issue we have developed a simple model that takes into account the basic astrophysics involved. We assume a mass of baryons M_B initially with no stars ($M_{{\rm gas},i} = M_B$ and $M_{{\rm stars},i} = 0$) in a galactic halo. Once the gas has undergone a rapid cooling, it is expected that a fraction is transformed into stars $M_{\rm stars} = M_B - M_{\rm gas}$. In our model we assume that the total mass of stars of a galaxy is the maximum allowed by the balance between the gas binding energy and the total energy input by supernovae.

We assume that a star more massive than 8 $M_\odot$ is formed out of an initial gas mass $200\varsigma^{-1}$ $M_\odot$, where ς is a parameter of order unity. The rapid evolution into supernova implies one supernova per (200 $M_\odot$)/ς of gas transformed into stars. Taking into account supernovae calculations (Larson 1974) we assume each supernova input an energy of $E_{SN} = \kappa\ 10^{51}$ ergs where κ is a dimensionless parameter $\simeq 0.1$. Thus the total supernova energy input is $E_{SN} = 10^{51}\kappa\varsigma(M_{stars}/200\ M_\odot)$ ergs where M_{stars} is the total mass transformed into stars. The binding energy of this gas is $E_{bin} = 1/2 V_c^2 M_{gas}$. We assume that once E_{SN} is comparable to E_{bin}, the supernova-driven winds halt the star formation process in the system due to the ejection of the remanent gas. Therefore, the ratio of mass in stars to the total available baryonic matter ϵ results in

$$\epsilon = \frac{M_{stars}}{M_{gas} + M_{stars}} = \left[\frac{510^5\kappa\varsigma}{V_c^2(\mathrm{km\ s^{-1}})} + 1\right]^{-1} . \tag{2}$$

We therefore obtain a continuous function of V_c for the gas mass loss (White & Frenk 1991). The total luminosity of a galaxy is therefore given by $L = \epsilon L_i$.

For suitable values of $\varsigma = 2$, and $\kappa = 0.015$, galaxies with $V_c \simeq 50$ km s^{-1} retain only $\epsilon \simeq 14\%$ of the remaining gas, while halos with $V_c \simeq 200$ km s^{-1} retain $\epsilon \simeq 73\%$ of the gas. For the above values of ς and κ we find that the original luminosity function is modified in the faint end.

In Figure 2 we show the luminosity function for the identified galaxies in model w (*triangles*), and for the same model with supernova wind effects (*circles*). Also shown for comparison is the observed luminosity function (*solid line*). As seen from this figure, these typical models provides a reasonably flat distribution. We notice, however, that there is an excess of bright galaxies compared to observations. This may be related to the high normalization of the spectrum and to the galaxy identification algorithm. More detailed models would be required to clarify this issue.

Significant changes are found in the relation between luminosity and circular velocity when the effects of supernova winds are taken into account. We find that the Tully-Fisher relation derived from the initially imposed $L_i \propto V_c^2$ is modified to $L \propto V_c^{4.4\pm0.1}$ which is in remarkable agreement with observations. This fact is shown in Figure 3 where absolute magnitude versus V_c is displayed for spirals (*squares*), ellipticals (*triangles*), simulated galaxies for $\kappa = 0$ without supernova effects (*dotted line*), and for $\kappa = 0.015$, $\varsigma = 2$ (*solid line*). As seen in this figure the supernova wind effects may provide a suitable fit to observations.

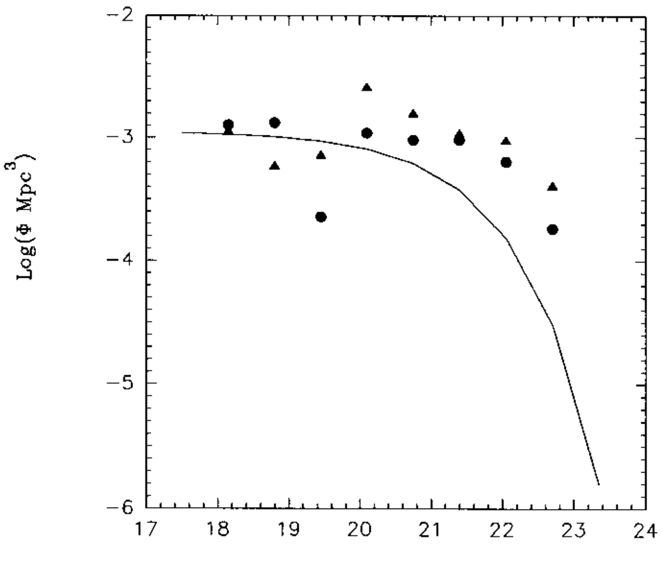

FIG. 2.—Luminosity function for model w: energy input due to supernova winds is considered (*circles*); the triangles correspond to the same models without supernova winds. For comparison the solid line shows the observed luminosity function; $H_0 = 50$ km s^{-1} Mpc^{-1} is assumed.

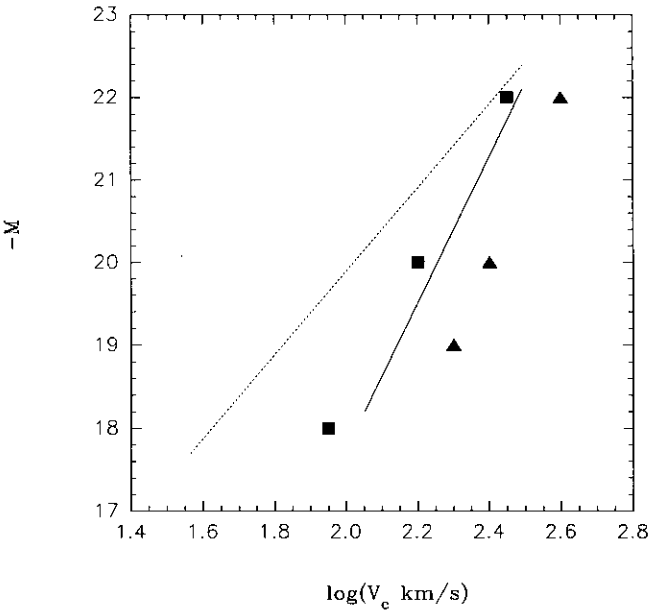

FIG. 3.—Tully-Fisher relation in the models taking into account the input energy due to supernovae winds (*solid line*) and without this effect (*dotted line*). For comparison the squares show the Tully-Fisher relation for elliptical galaxies and the triangles for spirals.

2.5. *Properties of Groups and Clusters*

In this section we analyze the ability of the different models explored to address the observational properties of groups and clusters of galaxies.

It is known that clusters obey the following relations (Oemler 1992):

$$\sigma_{cl} \propto L_{cl}^{1/3} , \quad M_{gas} \propto L_{cl}^2 , \tag{3}$$

where σ_{cl} is the cluster velocity dispersion, M_{gas} is the X-ray–emitting gas mass, and L_{cl} is the total cluster luminosity.

We analyze M/L ratios and the relation between and the total mass in stars in a system M_{stars} and its velocity dispersion σ. In the models which take into account M_S criterion, the computed M/L ratios in clusters are in excess with respect to observations unless a large value $\delta_{cloud} \simeq \delta_{crit}$ is assumed. We find that equal density contrasts $\delta_{crit} \simeq \delta_{cloud} = 64$ give correct M/L ratios in clusters for reasonable individual M/L ratios in galaxies, $M/L_{gx} = 5$–$10\ M_\odot/L_\odot$. Under these conditions we find that $M_{stars} \propto L_{cl} \propto \sigma^3$, in qualitatively agreement with observations. In Figure 4 we show M_{stars} versus σ for clusters for two models: the triangles correspond to a model where M_S criterion has been applied and the squares correspond to the same model suppressing this criterion. For comparison, a $M_{stars} \propto \sigma^3$ relation is shown (*solid line*).

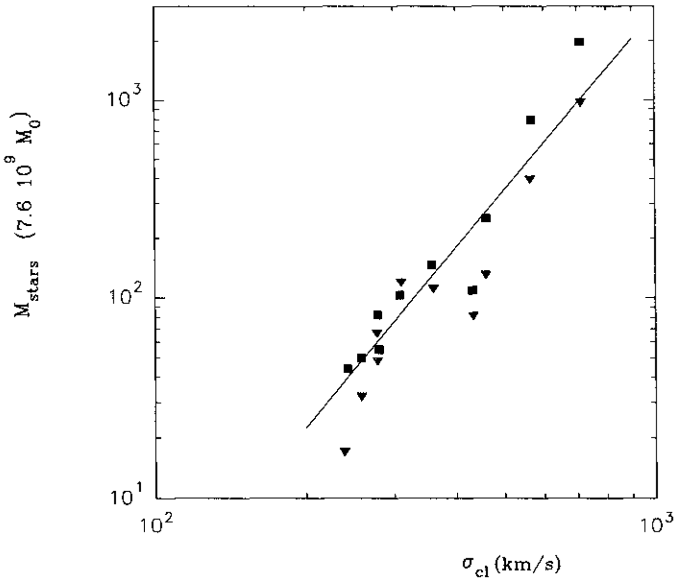

FIG. 4.—The cluster mass in stars plotted against the cluster velocity dispersion for a model with Silk's criterion (*triangles*) and for a model without this criterion (*squares*). For comparison, the solid line shows $M_{stars} \propto \sigma_{cl}^3$.

Models with very efficient galaxy suppression ($\delta_{cloud} \ll \delta_{crit}$) originates a weaker dependence, $M_{stars} \propto \sigma^2$. This fact indicates the unviability of antibias mechanisms which are too strong to reproduce the observations.

We have also analyzed the efficiency of star formation in systems of galaxies computing $f = M_{gas}/M_{stars}$ for the different models. The results indicate that only a severe suppression of galaxy formation in high-density regions can provide a small decreasing efficiency (increasing f) with cluster virial temperature $T_{virial} = \mu m_p \sigma^2/k$, where k is Boltzmann's constant, μ is the mean molecular weight (75% hydrogen and 25% helium is assumed), and m_p is the proton mass. Even in these extreme cases the increase in f is not as strong as in the observations (Jones & Forman 1992). In addition, as explained above, M/L ratios which are too large are obtained in clusters of galaxies for these models, a factor 2–5 in excess with observations.

In models where M_S criteria have not been applied, f shows a systematic decrease with T opposed to observations. Thus, our analyses suggest that moderate suppression of galaxy formation in high-density environments may provide a useful frame to understand the observed f-T relation.

In order to explore the effects of supernova winds on the gas content of groups and clusters, we have also included in our analyses simple models to take into account their basic physics. Significant gas loss can occur in groups of galaxies by supernova winds. The amount of gas lost by a cluster of velocity dispersion σ and total mass in stars M_{stars} can be calculated using similar arguments to those of the previous section resulting in

$$M_{\text{lost gas}} = 10^{51} \kappa \varsigma \frac{M_{stars}}{200\ M_\odot} \sigma^{-2} \text{ ergs} . \quad (4)$$

We computed the remaining gas mass in groups of galaxies according to this equation for our models. We find that supernova energy input is effective in removing substantial amounts of gas from galaxy systems with $\sigma < 400$ km s^{-1} if large values of $\kappa > 0.1$ are used. We argue that the observed high galaxy formation efficiency in groups with respect to rich clusters may be strongly conditioned by supernovae.

We have also explored the possibility that an important fraction of gas may be accreted by galactic systems. We compute models for the infall of gas in clusters through radiative cooling assuming that once a large-scale inhomogeneity has reached a high density contrast $\delta > 6$, the mass of gas $M_{gas,i}$ is in suitable conditions for nearly isothermal radiative dissipation. Thus, the system undergoes gas infall from the surrounding environment at constant temperature $T = T_{virial}$. The amount of gas ΔM_{gas} that can be accreted by a system may be estimated equating the dissipated energy by gas cooling to the increase in dynamical energy assuming virial equilibrium:

$$\Delta M_{gas} = \frac{3\Lambda_{ff}\sigma^3 \Delta t}{4\pi m_p^2 R G^2} , \quad (5)$$

where R is the radius of the cloud, G is the gravitational constant, and Λ_{ff} is the free-free cooling constant defined as

$$\Lambda_{ff} = \beta \frac{2\pi e^6 m_p^{1/2}}{h_p c^3 m_e^{3/2}} \quad (6)$$

with $\beta = 7.72$; e and m_e as the electron charge and mass, respectively; h_p as Planck's constant; and Δt as the time interval of effective gas cooling.

Since $M_{gas,i} \propto \sigma^2$, it follows that $\Delta M_{gas} \propto \sigma^3 \Delta t$ at constant volume V.

So if the amount of gas accreted is significant with respect to the initial amount, $M_{gas} \simeq \Delta M_{gas} \propto \sigma^3 \Delta t$. Since $M_{stars} \propto \sigma^3$, it follows $M_g/M_{stars} \propto \Delta t$. In hierarchical clustering $\Delta t_{groups} < \Delta t_{clusters}$ and the observed trend of the f-T relation may be accounted for. Nevertheless, in our models we find only a small amount of gas infall in clusters $\Delta M_{gas} < 10\%$ providing no significant contribution to the actual clusters gas content.

In Figure 5 we show the resulting M_{gas}/M_{stars} ratio as a function of cluster virial temperature for model w, where the

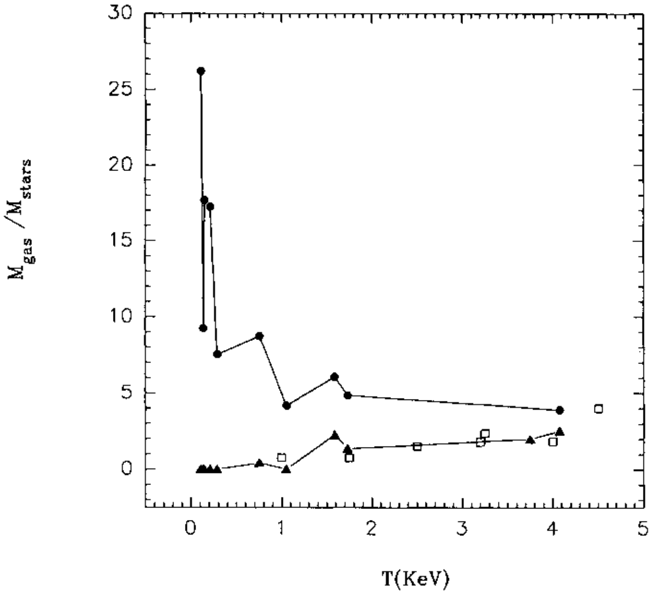

FIG. 5.—Gas-to-star mass ratio in systems of galaxies in model w as a function of virial temperature T. The circles correspond to the results without supernova effects and gas infall. The triangles correspond to the results taking into account these effects. For comparison, the squares correspond to observational data taken from Jones & Forman (1992).

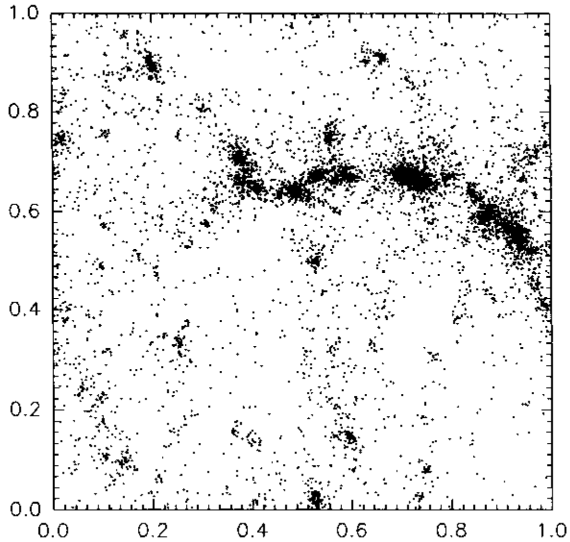

FIG. 6a

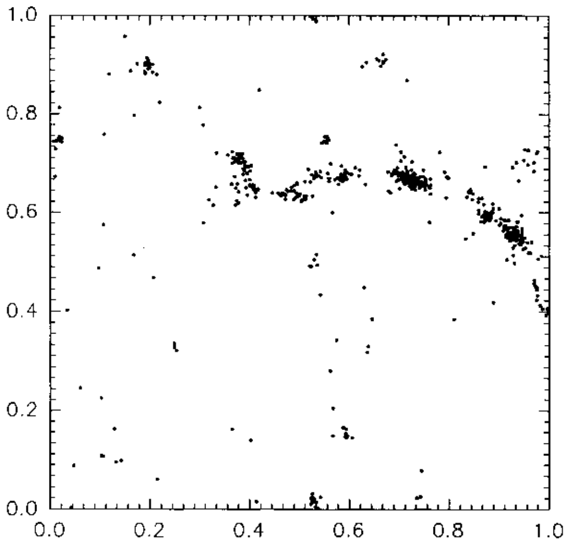

FIG. 6b

FIG. 6.—(a) Projected xy mass distribution for model v. Only 35% of the particles are plotted. (b) Projected xy distribution of galaxies corresponding to the mass distribution shown in Fig. 6a. In both Figs. 6a and 6b the box size corresponds to a comoving length of 28 Mpc.

circles indicate the original ratio and the triangles show the effects of supernova winds after a small gas infall calculated with the models described above. For comparison, the squares correspond to observational data taken from Jones & Forman (1992). As can be seen in this figure a large amount of energy input into the intracluster medium by supernova winds ($\kappa = 0.5$) can provide the observed increase in the $M_{\rm gas}/M_{\rm stars}$ versus temperature relation.

2.6. *Spatial and Velocity Distributions*

We have analyzed the spatial distribution of galaxies and dark matter in our models. In Figures 6a and 6b are shown xy projections of the identified galaxies and the dark matter (only 35% of the particles are shown), respectively, for model v at redshift $z = 0$. As can be seen in these figures, galaxies trace the large-scale structures of dark matter. We stress that our continuous galaxy formation algorithms permit the identification of galaxies in clusters even though they have at the present a smooth mass distribution.

We have computed the two-point spatial correlation function for galaxies $\xi_{\rm gx}(r)$ and dark matter $\xi_{\rm dm}(r)$ in the simulations. We find that for both components the spatial correlation functions are well represented by power laws $\xi(r) = (r/r_0)^{-\gamma}$. We find that if M_S criterion is not considered $\xi_{\rm gx}(r)$ is steeper than $\xi_{\rm dm}(r)$. For these models we obtain large slopes $2 < \gamma < 3$ for both the dark matter and the galaxies compared to the observed $\gamma \simeq 1.7$. For models where M_S criterion is applied, much flatter $\xi_{\rm gx}$ are obtained with slopes $\gamma \simeq 1.7$–2., consistent with observations, while the dark matter has larger values $\gamma > 2$.

In Figures 7a and 7b we show the two-point correlation function for galaxies (*circles*) and dark matter (*triangles*). Figure 7a displays the results of a model without galaxy suppression through M_S criterion. Figure 7b corresponds to a model where M_S criterion is applied. For the model shown in Figure 7a we notice the larger amplitude of $\xi_{\rm gx}(r)$ compared to $\xi_{\rm dm}(r)$. The opposite behavior can be appreciated in the model shown in Figure 7b.

Taking into account the model developed by Lambas et al. (1993) we compute the probability $P(\rho)$ of identifying a galaxy in a region of mass density ρ measured in a sphere of radius 2 Mpc. Power-law fits to our models with M_S criterion give $P(\rho) \propto \rho^{-\beta}$ with $\beta \simeq 0.2$–0.4. According to their analyses for $\beta \simeq 0.3$, the angular galaxy correlation function in $\delta M/M = 1$ CDM models is consistent with APM angular correlation function (Maddox et al. 1990). Thus, we conclude that the antibiased galaxy distribution obtained in these models is consistent with the observed galaxy clustering on large scales. If M_S is not applied, the galaxy distribution in the models has an excess of clustering on small scales, inconsistent with observations.

Couchman & Carlberg (1992) and Cen & Ostriker (1992) compute the peculiar velocity field of galaxies and dark matter in CDM numerical simulations and analyze the possibility that galaxy velocities are biased with respect to dark matter. The results obtained by Couchman & Carlberg indicate that galaxy velocities are systematically lower than those corresponding to dark matter. However, Cen & Ostriker find no significant differences between the velocities of galaxies and dark matter. In order to analyze this point we have computed the velocity dispersion of groups and clusters in our models for both galaxies and dark matter. We have also considered the velocity dispersion of galaxies that have undergone mergers. The analyses performed in the different models strongly argue against the existence of galaxy velocity bias, although we find that mergers have a slightly lower velocity dispersion (only a factor 0.8–0.9 with respect to galaxies). Thus, we conclude that there is not a significant galaxy velocity bias in agreement with Cen & Ostriker. The particular algorithm for galaxy identification adopted by Couchman & Carlberg may be the origin of their strong galaxy velocity bias reported.

3. CONCLUSIONS

We have developed and analyzed a model for galaxy formation through the hierarchical clustering in the CDM cosmology. The model takes into account the basic astrophysics of the

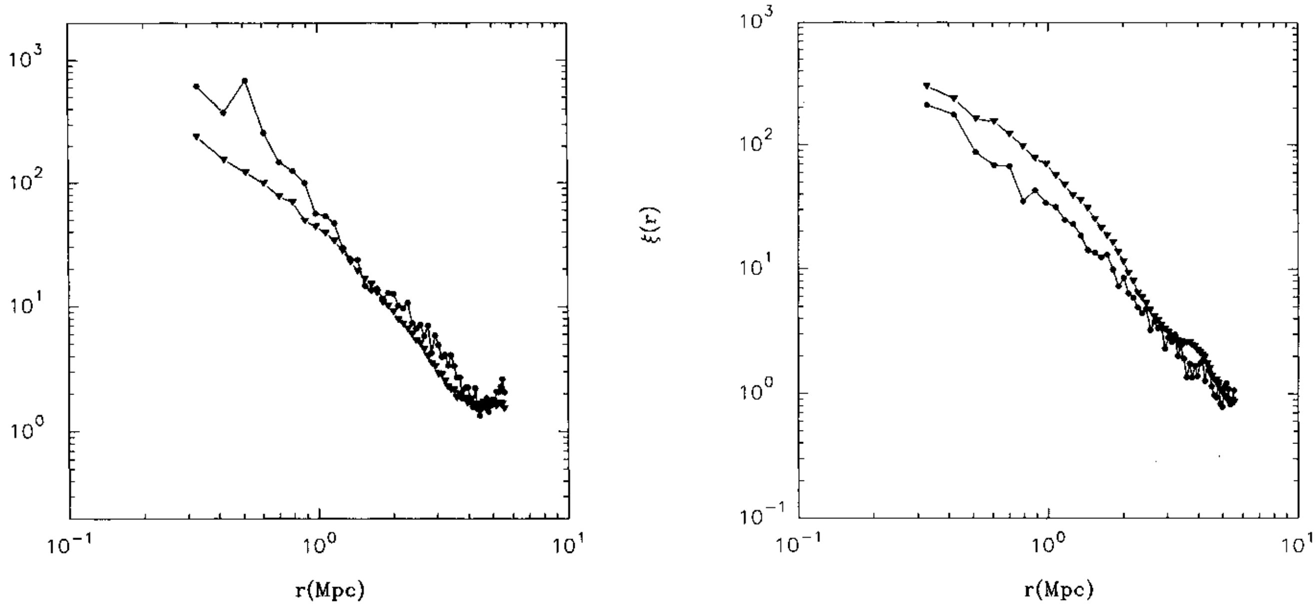

FIG. 7a FIG. 7b

FIG. 7.—(*a*) Spatial correlation function for galaxies (*circles*) and mass (*triangles*) for model p (biased). (*b*) Spatial correlation function for galaxies (*circles*) and mass (*triangles*) for model v (antibiased).

gaseous component, supernovae effects, and galaxy mergers. In particular, we have analyzed the statistical properties of groups and clusters of galaxies. The main conclusions may be summarized as follows:

We find that the galaxy formation rate increases rapidly up to a well-defined maximum at $z \simeq 2$–3.

In models where galaxy suppression in high-density environments is considered, we find that the galaxy correlation function is substantially flatter than the mass correlation function. This fact may allow for a reasonable fit of a CDM model with $\delta M/M = 1$ to the observed angular correlation function.

We find no significant velocity bias of the galaxies with respect to dark matter. The galaxy peculiar velocity dispersions in systems of galaxies in the models are too high when compared to observations. This fact is a difficult point to address successfully in the CDM model with $\delta M/M = 1$.

In the models, the mass in stars in groups and clusters of galaxies is related to the system velocity dispersion through $M_{\rm stars} \propto \sigma^3$, in agreement with observations.

Supernova wind effects in the interstellar medium provide a suitable fit to the observed Tully-Fisher relation. The models considered give $L \propto V_c^{4.5}$ in contrast with the initial $L_i \propto V_c^2$.

The observed higher galaxy formation efficiency in rich clusters can be reproduced in the models if supernova winds are effective in removing a substantial amount of gas from the intracluster medium in low-velocity dispersion systems. This can be accomplished assuming a large amount of energy input by supernova winds.

We estimate a small amount of gas infall into rich clusters (<10%). Thus, the large ratio $\Omega_B/\Omega \simeq 0.2$ derived from X-ray observations argues against a large density parameter, $\Omega = 1$, taking into account current limits in Ω_B from standard nucleosynthesis theory.

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