NUMERICAL SIMULATIONS OF GALAXY FORMATION: EFFECTS OF SUPERNOVA FEEDBACKS

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Abstract

We present results of cosmological simulations of galaxy formation in which the effects of radiative and Compton cooling and feedback from supernovae explosions have been taken into account. In our 3D Hydro+N-body numerical simulations, the matter is treated as a multi phase medium having four components: dark matter, hot baryonic gas and cold gas clouds (an analog of molecular clouds) embedded in the hot gas, and stars produced from cold gas clouds. Stars with mass $> 10M_\bullet$ explode as supernova, evaporating cold clouds around and heating the hot gas. These combined effects will regulate star formation within the dark matter halos. Stellar Population Synthesis models have been used to compute luminosities and colors of the "numerical galaxies". Supernova feedbacks play an important role on the evolution of dwarf galaxies. Most of the small objects have extremely low luminosities and very red colors. However, dwarf galaxies located near bright ones tend to be significantly brighter than those in low density areas. The amount of luminous matter that is formed within the dark halos depends strongly on the modelization of the supernova feedbacks. Star formation is inhibited when a large fraction of the energy released by supernovae goes into reheating the gas rather than evaporating cold clouds. The total fraction of gas converted into stars in the whole simulation varies from 50%, when half of the supernovae energy is kinetic, to 8% when most of the energy is thermal. The distribution of gas broadly follows the dark matter distribution, except for condensations that are much less diffuse than the local dark matter. In the case of both large and small "galaxies", the distribution of luminous matter is strongly biased with respect to the dark halos. However, the biasing is not a simple function of local density but depends strongly on environment.

1 Description of the model

We have studied the formation and evolution of galaxies in the context of large-scale structure. We focus our attention on the role of supernova feedback and hydrodynamics together with gravitational and radiative processes in determining the observational properties of galaxies, including luminosities and colors, and the extent of their dependence with the environment.

In our model, matter is treated as a multi-phase fluid with different physical processes acting between them: **Collisionless Matter** (Dark + Stars) and **Collisional Matter** (baryonic gas). The gas is treated as two separate phases, depending on its temperature: *Hot Gas* ($T_h > 10^4$K) and *Cold Gas Clouds* ($T_h < 10^4$K)

There are two mechanism for gas to leave the hot phase and enter the cold phase: **Radiative and Compton cooling** and **Thermal Instability** [3]. Star formation is assumed to occur only inside cold gas clouds and leads to a decrease in the average density of the cold component. We take a constant star-formation timescale $t_* \sim 10^8$ yr. Thus most of stars with M_* larger than $(10-20)M_\odot$ will explode as supernovae (SN) during one time-step. The fraction of mass that explode as SN, β, depends on the particular form of the Initial Mass Function (IMF). For a Salpeter IMF with lower mass limit $0.1M_\odot$, $\beta = 12\%$. This value of β has been taken to be valid at all epochs.

We consider two main effects of SN explosions in the surrounding gas: **Evaporation of cold clouds** and **Reheating of hot gas.** Evaporation of cold clouds due to kinetic energy from SN explosions is an important phenomenon in the interstellar medium [5]. We incorporate this effect by supposing that the total mass of cold gas "evaporated" and transferred back to the hot gas phase is a factor A higher than that of the supernova itself. We will refer to A as the *Supernova Feedback Parameter*. Admissible values of the supernova feedback parameter A are constrained by the condition that the energy of a supernova explosion be larger than the energy required for the evaporation of cold clouds. For typical values of SN energy and hot gas temperature this condition implies the restriction $A << 250$. We take values of A ranging from 100 to 20. For $A = 100$, almost half of the SN energy goes into kinetic energy that is able to evaporate clouds.

In order to estimate observational properties of the "numerical galaxies" we have used Stellar Polulation synthesis models [2] to compute luminosities and colors from the stars created in the simulation.

1.1 Numerical Techniques

The gravitational Poisson equation is solved by means of a standard Particle-Mesh code [4]. Hydrodynamical equations are solved by applying an Eulerian code based on the Flux-Corrected-Transport technique [1]. In our code the timestep for advection of gas and motion of dark matter is the same for all cells, but cooling and star-formation processes were integrated with variable timestep for each zone. A detailed description of the code and the tests carried out can be found in ref [6].

2 Results

A number of different simulations have been carried out to study the effects of supernova feedbacks on galaxy formation. We present results for 4 different simulations of an unbiased Cold Dark Matter Model in a comoving box of size 5Mpc ($h_0 = 0.5$). The number of dark matter particles and grid points was 2097152. This gives a minimum resolution of 38kpc . In two of the simulations we took the same value $A = 100$ and two different realizations of the CDM spectrum.

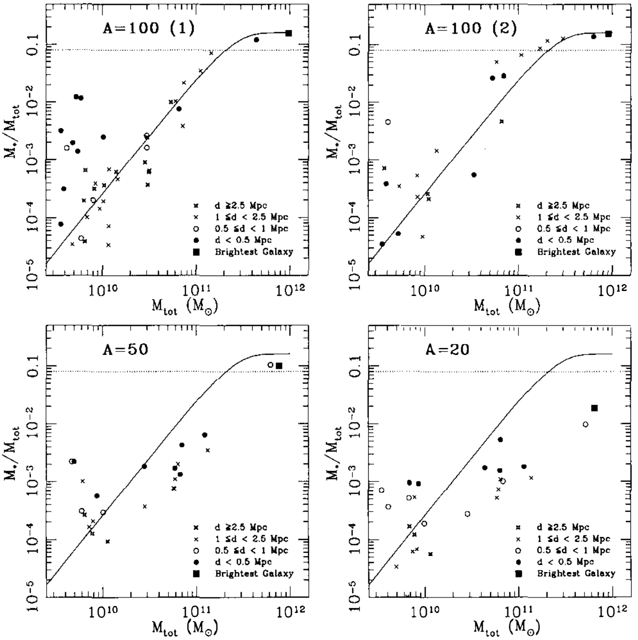

Figure 1 Fraction of Luminous to total mass as a function of total mass for the galaxies in the 4 simulations described in the text. The solid line represents a fit to the large objects in the first simulation.

In the other two, we started with the same initial conditions for dark matter, but varied the value of A. We took $A = 50$ and $A = 20$. In this sense we can check both the effects of the supernovae and environment at the same time. Initial conditions were generated at $z \sim 65$ and evolved until $z = 0$. Numerical "galaxies" are found in the simulation by identifying the Center-of-Mass of dark halos within spheres of 2 cell radius (80 kpc) and 1 cell radius (40 kpc). See ref [6] for further details of this method.

In Figure 1 we show the fraction of luminous mass to total mass in the galaxies identified in the 4 simulations as a function of the total mass of the halos and in terms of their distance to the brightest galaxy in each simulation. The amount of luminous (star) matter depends very strongly on the value of A. For low values of A the energy from supernovae mostly goes to reheat the gas and not to evaporate the cold clouds around. Then, the gas needs more time to cool down to produce cold gas cloud from which stars can be formed. As a result of this, a smaller fraction of gas is converted into stars. For $A = 20$, only 8% of the total gas in the simulation was transformed into stars, while for $A = 100$ almost 50% was converted. Another important feature is that the large mass objects are not very affected by environment. Looking at the two top panels of Figure 1 we see that the amount of stars in the more massive galaxies is almost the same, as well as their colors (Figure 2) and luminosities, although they correspond to 2 different realizations of the spectrum. On the contrary, the low mass objects are very much affected, not only by the environment (dwarfs located near bright galaxies tend to be brighter) but also by the modelization of the supernova feedbacks (value of A).

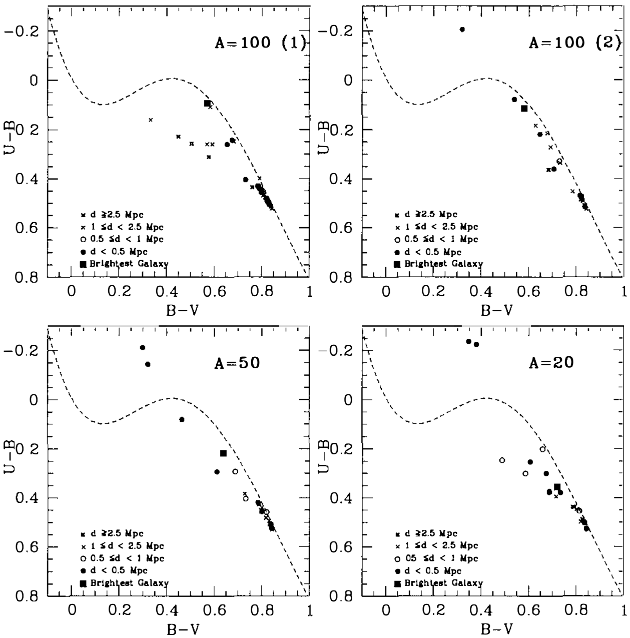

Figure 2 UBV Color indices for the galaxies in the simulations. The dotted line represents the position in the diagram of the main sequence stars of luminosity class V

In Figure 2 we show the color indices of the objects in the UBV diagram. As we can see, most of the dwarf galaxies found in the simulations have very red colors corresponding to old K stars. As A decreases the colors of all objects tend to be redder. In CDM the small objects form first. Star formation begins very early ($z \sim 4 - 9$) for most of the objects. When the first stars form, the supernovae associated with them are able to blow the gas away from the shallow potential wells of dark matter, stopping subsequent star formation. As a result, the colors of the objects are dominated by the older stars. This effect is enhanced for low values of A, when most of the SN energy is assumed to be thermal.

The above results underline the rather complicated interaction of gas dynamics, SN feedback and gravitation in the formation and evolution of observable properties of galaxies in cosmological scenarios.

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