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GALAXY ASSEMBLY FROM SELF-CONSISTENT HYDRODYNAMICAL SIMULATIONS

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RESUMEN

La enorme cantidad de información observacional que sobre los objetos que pueblan el Universo proporcionarán los numerosos proyectos observacionales, cuando estén operativos, supondrá un avance considerable en la comprensión de los mecanismos de formación y evolución de estos objetos. Sin embargo, este avance solo será posible si, paralelamente, se desarrollan los modelos teóricos de interpretación. Como contribución a este objetivo, hemos desarrollado códigos numéricos para estudiar los complejos procesos físicos que determinan la formación y evolución de objetos galácticos, en el marco de un modelo cosmológico y de forma autoconsistente. En esta charla presentamos una muestra de objetos galácticos obtenidos en nuestras simulaciones, que presentan propiedades estructurales y dinámicas consistentes con datos observacionales. Discutiremos y describiremos diferentes aspectos de su evolución y, en particular, algunas de sus propiedades a alto z.

ABSTRACT

The enormous amounts of observational data that will become available once various observational projects are operative, will imply a considerable advance in our understanding of the physical processes involved in the formation and evolution of galaxies. However, this advance will only be made possible if, at the same time, theoretical models to unify data interpretation are developed. To this end, we have developed numerical codes to study these complex processes, in connection with the global cosmological model and self-consistently. In this talk we report on a sample of galaxy-like objects formed in our numerical simulations, focusing on their structural and dynamical properties that can be constrained from observations. We describe and dicuss different aspects of their evolution and, particularly, some of their properties at high z.

Key Words: **HYDRODYNAMICS — GALAXIES — METHODS : NUMERICAL**

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1. INTRODUCTION

In the last few years most cosmological parameters have been determined to within a few percent. The comparison of measures of the cosmic microwave background (CMB) angular power spectrum, of the $m - z$ diagram from high z SN1a observations, and of light element abundance data to their theoretical predictions within different cosmological models, made it possible to constrain the values of $\Omega_{\rm tot}$, Ω_Λ, $\Omega_{\rm baryon}$, and H_0 with an unprecedented degree of accuracy (see, for example, Netterfield et al. 2001 and references therein). Observations of the large scale distribution of galaxies are consistent with the previous values of the cosmological parameters. The next challenge to cosmologists in this regard is to test the predictions of these cosmological models scales of a few hundred kpc. It turns out that these are just the relevant scales involved in galaxy formation and evolution, which are an intriguing open question. Different kinds of historical circumstances make the present moment a very favorable one for deepening our insight into the problem of galaxy formation and evolution in a cosmological framework: a) the enormous amount of observational information that presumably will be available on both local and high z galactic objects once the different observational projects, particularly the GTC, are operative; b) the very important increase in computer memory capacity and speed, and c) the development of new numerical techniques to solve equations in partial derivatives.

In this paper we report on a study (in progress) of galaxy assembly within a self-consistent numerical approach. This means that initial conditions have been set at high z as a Monte Carlo realization of the field of primordial fluctuations in a given cosmological model; the evolution of these fluctuations has then been numerically followed up to $z = 0$ by means of a computing code that solves the N$-$body plus hydrodynamical evolution equations (i.e., by means of a so-called numerical hydrodynamical simulation). This method is a very powerful one because of its

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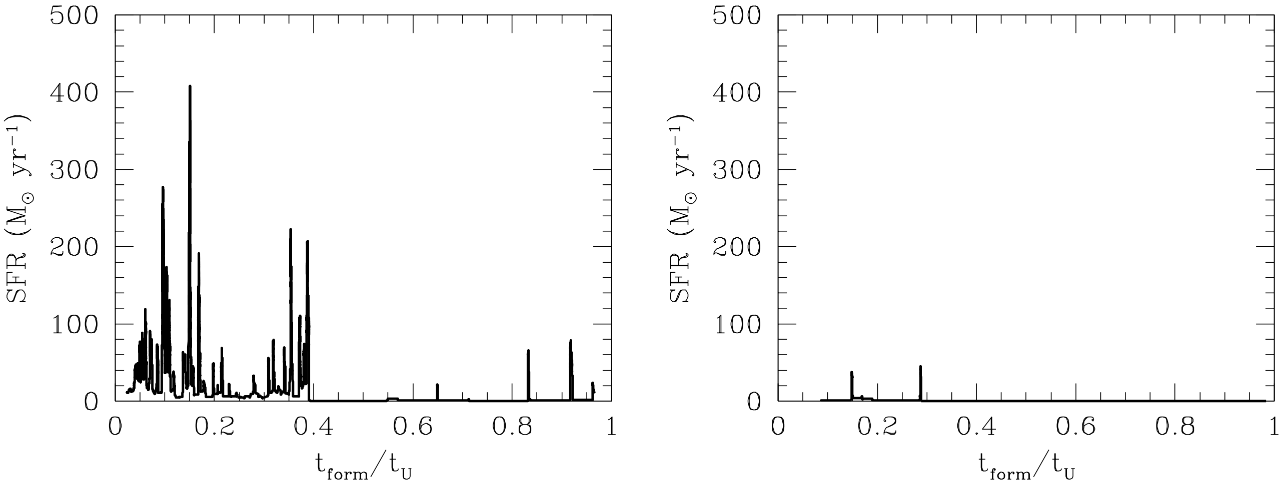

Fig. 1. Star formation rate histories of a typical spheroid-like object (left) and of a typical disk-like object (right) from the ΛCDM simulation.

accuracy: it allows us to follow the evolution of the dynamical and thermohydrodynamical properties of matter in the Universe; galaxy-like objects (GLOs) appear as a consequence of this evolution; hence, the building up of objects (cellular structure formation at high z, collapse, interactions, mergers, accretions), as well as their thermohydrodynamical consequences (instabilities, gas inflows, shocks, cooling, star formation), can be accurately followed. We get not only the *properties* of objects at any z but also an *insight* into the *physical processes* responsible for their formation and evolution. Moreover, numerical hydrodynamical simulations using particles permit very convenient comparisons of GLOs that form in simulations with observational data. Simulations *directly* provide us, at each z, with the structural and dynamical properties of each individual GLO (position and velocity of each of its constituent particles, gas density and temperature of each of its baryonic constituents) and with their individual star formation rate histories (SFRHs). It is then possible to combine hydrodynamical codes with chemical evolution codes and get the chemodynamical evolution of each GLO, to be compared with chemical abundance as well as spectrophotometrical data. These kinds of data are the current standard for comparing models of galaxy formation. It is expected that the next generation of astronomical facilities will bring about a new science: mass measurements for distant galaxies (see, for example, Bershady 2002, this volume, p. 208). GLOs formed in numerical simulations are particularly suited to comparison with these new kinds of data.

2. THE SIMULATIONS

We have run simulations in different cosmological contexts. Here we report on one run in the framework of a flat ΛCDM cosmological model, with $\Omega_\Lambda = 0.65$, $\Omega_{\rm baryon} = 0.07$, $\sigma_8 = 1.18$ and $h = 0.65$ (consistent with Netterfield et al. 2001). This study is an extension of previous work on SCDM models (Sáiz et al. 2001), using a new Lagrangian code (DEVA, Serna, Domínguez-Tenreiro & Sáiz 2002, in preparation), based on a different numerical approach and allowing an improvement in the time and mass resolution by factors of $\simeq 30$ in the denser areas and $\simeq 10$ in the number of baryon particles sampling an object of a given mass. Gravity is computed through an AP3M-like method, based on Thomas & Couchman (1992). Hydrodynamics is computed through an SPH technique where particular attention has been paid to angular momentum conservation. Time-steps are individual for particles (to save CPU time, allowing a good time resolution), as well as masses (making it possible to resolve small objects and so to study objects at high z), and time integration uses a PEC scheme. We have used 64^3 DM particles and 64^3 gas particles, with masses of $1.29 \times 10^8\ M_\odot$ and $2.67 \times 10^7\ M_\odot$, respectively, in a periodic box of 10 Mpc comoving side. The gravitational softening is $\epsilon_{\rm g} = 2.3$ kpc.

Galaxy-like objects of different morphologies appear in the simulation: disk-like objects (DLOs), spheroid-like objects (SLOs), and irregular objects. DLOs contain gas in an extended disk, and most of the stars in a massive compact central concentration. In simulations with lower $\epsilon_{\rm g}$ values (not reported here), stars form also in the disks, along arms. SLOs

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are very gas poor and their stellar component have relaxed regular ellipsoidal shapes. Irregulars have not defined shapes. In this work we focus on *direct* results obtained with the simplest implementation of star formation in the code: through a phenomenological parameterization, with a low value of the efficiency parameter (see Tissera et al. 1997); stellar feedback effects have not been explicitly considered, but the *inefficient* star formation we use could have allowed us to mimic them.

3. SFRHS, STRUCTURE, AND DYNAMICS

The SFRHs of individual GLOs are a direct result of their dynamical and thermohydrodynamical activity history. They show two extreme patterns (see Figure 1), depending on their morphological type: while SLOs have high rates of SF at high z their activity then decreasing substantially, DLOs have, at any z, very low rates of SF and, except for some bursts at high and/or intermediate z, most of their SF is continuous. Intermediate patterns of SFRHs also appear in the simulations.

To compare the structural and dynamical properties of GLOs with observational data we have developed software devices to *"observe" into the simulations*. For example, the usual bulge–disk decomposition of the projected brightness profiles of spiral galaxies (Sersic 1968; Courteau et al. 1996; Graham 2001) has been applied to the projected mass density profiles of DLOs to obtain their bulge shape parameters, and bulge and disk scale lengths $R_{\rm b}$ and $R_{\rm d}$, respectively. Also, different parameters very often used by observers (Rhee & van Albada 1996; Courteau 1996) have been measured on their rotation curves, such as the rotation velocity at $R_{2.2} = 2.2R_{\rm d}$, $V_{2.2}$; parameters related to the central mass concentration as $V_{\rm cir}^{\rm peak}$ and $R_{\rm peak}$; or other properties like the logarithmic slope, LS (Casertano & van Gorkom 1991). The analysis shows us that these parameters are compatible with observations of real spirals (Sáiz et al. 2001, 2002), even if some excess of dissipation is detected in the very central regions of DLOs. Figure 2 is a plot of the *dynamical* Tully–Fisher relation (TFR), a correlation that presumably results from some kind of regularity in gas collapse at scales of some hundreds to tens of kpc (Rhee 1996). The values of the slope, zero point, and dispersion measured in this plot are consistent with observations. The average sample evolution from $z = 1.25$ up to $z = 0$ is not very important. In contrast, the fate of individual DLOs in this z range is quite diverse: while some of them do not evolve, others are involved in mergers, interactions, and halo gas infall processes, and so they change their morphological type or even disappear. This variety of behavior is largely determined by the environment.

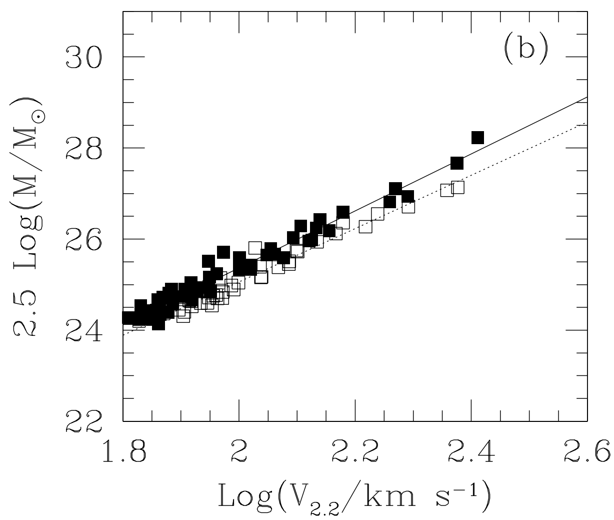

Fig. 2. Tully–Fisher relations constructed with $M_{\rm tot}$ and $V_{2.2}$ for DLOs in the simulation. Open (filled) squares: $z = 1.25$ ($z = 0$); lines are best fits at $z = 1.25$ and $z = 0$.

SLOs have masses and sizes consistent with data for elliptical galaxies (see Figure 3); their projected mass density profiles are well fitted by an $R^{1/4}$ law; their sizes, mass surface densities, and velocity dispersions are such that they lie on a dynamical fundamental plane (Burstein et al. 1987); they present diffuse hot X-ray emission from haloes, with X-ray luminosities and temperatures consistent with observations (Xu et al. 2001 and references therein). Their evolution is only moderate (see Figure 3), as either individual objects or samples. These results suggest that the values of parameters describing global structural and dynamical properties of DLOs and SLOs are largely determined by DM halo masses and dynamics, irrespective of physical processes on smaller scales and largely irrespective of the cosmological model.

4. BACK TO THE EARLY UNIVERSE

The SFRHs of individual GLOs are strongly dependent on the global cosmological model. In our ΛCDM case, SF activity is very important around $z \simeq 1$; it then decreases substantially at lower z. No such notable decrease occurs in SCDM models. In any case, dynamical evolution and SF activity appear to be tightly coupled. They are particularly important in some regions of our 10 Mpc^3 box, where SLOs form.

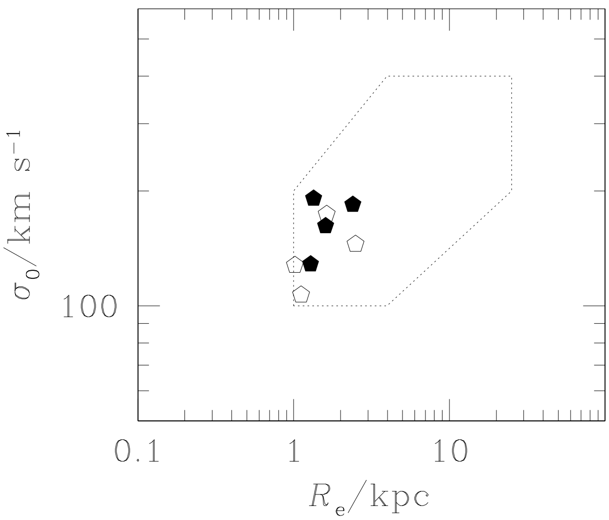

Fig. 3. Central velocity dispersions and effective radii of a sample of spheroid-like objects formed in the simulations. Open (filled) symbols: values at $z = 1$ ($z = 0.1$). The box encloses the region occupied by Djorgovski & Davis (1987) data.

To elucidate the origins of such strong environmental effects, we have kept track of the particles forming each individual SLO and each individual DLO at low z, and we have discovered how the environment of their progenitors looks like at higher z. We have taken high enough z values such that the cellular structure of the early Universe, caused by flow dynamics (Gurvatov et al. 1989; Shandarin & Zel'dovich 1989; Frisch & Bec 2001), is still very apparent. Proto-SLOs have been found to lie at the center of flow convergence, where different filaments meet. The high rates of mass inflow towards these flow convergence areas at high z translate into a high merger and SF activity. The environments of proto-DLOs are completely different: proto-DLOs live within filaments, where the mass inflow rate is only moderate or low, and the dynamical and SF activity are also low. These results strongly suggest that initial conditions at very high z in a given point within the box (in terms of the initial velocity field, see Shandarin & Zel'dovich 1989) play a fundamental role at determining the Hubble type of the galactic objects forming later in the corresponding point.

5. SUMMARY AND PROSPECTS

We report on results of an analysis of the properties of GLOs formed in a fully self-consistent (i.e., non multimass) cosmological simulation, run with a new code allowing to broaden their mass range. The analysis shows that GLOs have observational counterparts at intermediate and low z. To illustrate the possibilities of our (Lagrangian) code, we have analyzed the environments of proto-GLOs at high z and obtained very interesting clues on the origins of the Hubble sequence. We may conclude that hydrodynamical simulations are a promising method for learning about galaxy formation and evolution in connection with the global cosmological model. By coupling our code with chemical evolution models, we will be able to gain a deep insight into the links among dynamical, thermohydrodynamical, SF, and chemical evolutionary processes. By exploring the parameter space of cosmological models and comparing with galaxy observational data, it will be possible to test models on scales of some hundreds of kpc. These issues are interesting not only for physicists and cosmologists but for observers too. A tight connection between observations and theoretical modeling (and simulations) has been in the past, and is likely to be in the future, a necessary condition for the advancement of astronomical science.

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