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NUMERICAL SIMULATIONS OF GALAXY FORMATION IN A Λ COLD DARK MATTER UNIVERSE

M. G. Abadi[1]

RESUMEN

El éxito del modelo de Materia Oscura Fría con constante cosmológica, al reproducir resultados observacionales de la estructura en gran escala del Universo, lo ha convertido en el nuevo escenario paradigmático para la formación y evolución de galaxias. Las simulaciones numéricas cosmológicas que incluyen efectos gravitacionales e hidrodinámicos son una herramienta muy valiosa para seguir el origen y evolución de las diferentes componentes galácticas en este marco cosmológico. Se repasan las ideas más aceptadas en la actualidad acerca de la formación de galaxias y se remarca la importancia de los diferentes efectos astrofísicos complejos usualmente involucrados. Se hace énfasis en el rol fundamental que los eventos de acreción juegan en la formación de los sistemas galácticos.

ABSTRACT

The success of the Λ Cold Dark Matter model in reproducing observational results from the large scale structure of the Universe has established it as the new paradigm for galaxy formation and evolution. Cosmological gravitational/hydrodynamical numerical simulations are an invaluable tool to study the origin and evolution of different galactic components in this cosmological framework. In the following we review the main ideas presently accepted regarding galaxy formation, and stress the importance of different complex astrophysical effects usually invoked during this process. We emphasise, as well, the fundamental role that satellite accretion events play in shaping the formation of galactic systems.

Key Words: galaxies: formation — galaxies: structure — methods: n-body simulations — hydrodynamics

1. INTRODUCCION

Galaxies are complex systems. They are formed by the superposition of different stellar components like bulge, thin disk, thick disk, bar, spiral arms, stellar halo, spheroid, etc., plus a gaseous and a dark matter component.

Any successful galaxy formation model, and in particular one of the Milky Way, should be able to explain the formation mechanism behind each one of these different components. Besides these stellar components, that combine and interact with each other to form the main galaxy itself, the globular cluster and satellite populations orbiting around it are also key components that should be explained by a successful model.

From the observational point of view, the discovery of a rich new population of faint satellites orbiting around the Milky Way galaxy by the large photometric sky survey Sloan (York et al. 2000; Strauss et al. 2002) have substantially contributed to extend our knowledge of the satellite system of the Milky Way. Some of these satellites show clear evidence of disruption, or at least of been severely disturbed, by the strong tidal gravitational field of the Milky Way. The Sagitarious stream (Ibata et al. 2001), a stream of stars that wrap around the entire Milky Way nearly perpendicular to the galactic disk, and whose progenitor is the Sagittarius dwarf galaxy, the Monoceros ring (Yanny et al. 2003; Ibata et al. 2003), a proposed ring of stars coplanar to the galactic plane whose progenitor is attributed to the Canis Major dwarf, and the Orphan stream (Belokurov et al. 2007), a tidal stream that extends over 50° in the north galactic cap, whose progenitor is unknown, are all typical examples of such disrupting satellites. Beyond the Milky Way are also some examples: the giant stream of stars uncovered in the halo of M31 (Ibata et al. 2001) or a plume of stars of a dwarf satellite galaxy in the process of being torn apart by gravitational tidal forces (Forbes et al. 2003). The detection of such structures using photometric techniques is usually a difficult task due to the low surface brightness contrast with the surrounding background. An alternative to this problem is to use phase space information (basically positions and velocities) where such structures are more easily de-

[1]Instituto de Astronomía Teórica y Experimental, Consejo de Investigaciones Científicas y Técnicas y Observatorio Astronómico de la Universidad Nacional de Córdoba, Laprida 854, X5000BGR, Córdoba, Argentina (mario@oac.uncor.edu).

tected since they preserve coherence even after being disrupted. Helmi et al. (1999) report the detection of substructure in the galactic halo and also in the galactic disk (Helmi et al. 2005). Eggen (1971), and lately Navarro et al. (2004), report the existence of the Arcturus stream, a metal-poor group of stars associated kinematically, which share similar angular momentum and apocentric distance; Meza et al. (2005) claim the detection, in the solar neighbourhood, of a group of stars with kinematics and chemical abundance, similar to the globular cluster Omega Centaurus and conjectured it to be the core of a disrupted dwarf satellite galaxy. All these observational evidence points out towards a galaxy formation scenario where mergers of satellite galaxies are a key ingredient to be taken into account.

From the theoretical point of view, the success of the so-called Λ Cold Dark Matter scenario in the large scale of the Universe points also to a hierarchical model where larger structures are build up by accretion of smaller substructures. Several authors have performed gravitational/hydrodynamical simulations of galaxy formation in this cosmological model showing its advantages and drawbacks on galactic scales (Thacker & Couchmann 2001; Steinmetz & Navarro 2002; Sommer-Larsen, Gotz, & Portinari 2003; Abadi et al. 2003a,b; Brook et al. 2004; Governato et al. 2004; Robertson et al. 2004; Okamoto et al. 2005; Kaufmann et al. 2007; Zavala, Okamoto, & Frenk 2008). The general consensus is that a variety of morphologies mimicking observed galaxies could be achieved by the regulation of complex astrophysical effects, such as cooling, feedback, supernovae explosions, metal enrichment, etc. However, the main problem (known as the angular momentum problem) is that although photometric properties are in reasonable agreement with observations, it is very difficult to produce realistic disk galaxies with angular momentum and rotational properties similar to observed late type spirals (see Figure 1). This problem, usually ascribed to an excessive gas cooling at early epochs, could be alleviated invoking some sort of astrophysical feedback from supernovae or active galactic nuclei. Feedback effects also help to fit the halo mass function of the ΛCDM model to the galaxy luminosity function (Baugh 2006) and the cosmic star formation history, which is usually over-predicted by the models (Springel 2007).

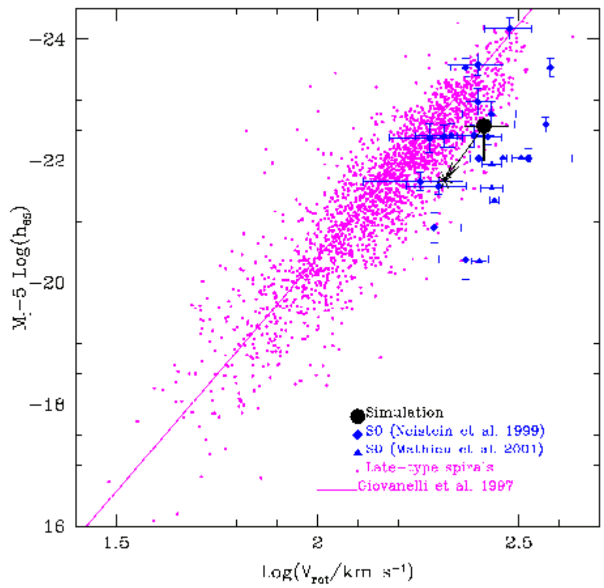

Fig. 1. Angular momentum problem: Simulated disk galaxies only marginally agree with the observed Tully-Fisher relation for late-type spirals. They fit rather well in the relation appropriated for S0 due to the net angular momentum transfer from the gas to the dark matter halo during the galaxy formation process. Solutions: involve some sort of feedback processes that regulate the gas supply to the galaxy. But see Governato et al. (2004) and Governato et al. (2007) which ascribed the problem to poor numerical resolution.

2. GALAXY FORMATION

2.1. *Spheroid, thin and thick disk*

Using cosmological numerical simulations in a Λ Cold Dark Matter cosmogony, Abadi et al. (2003a,b) present a detailed analysis of the formation of a disk-like galaxy including gas, stars and dark matter particles. At redshift $z = 0$ two different stellar components are easily identified: an old centrally concentrated massive spheroid supported by velocity dispersion with no net rotation and a young less massive disk largely supported by rotation. Based on the orbital circularity c of the star particles, they further refine these components labeling each star particle as belonging to the spheroid ($c \approx 0$ no net rotation), thick disk ($c \approx 0.5$ slow rotation) or thin disk ($c \approx 1.0$ fast rotation) (See Figure 2).

This dynamical decomposition of the simulated galaxy allows to trace back the origin, formation and evolution of each stellar component. The spheroid is old and there are basically no young stars in this component. At high redshift, inefficient feedback effects lead to a high star formation rate and subsequent major and minor mergers of proto-galaxies form this massive component. The galactic thin disk forms from the inside out by accretion of new gas, being mostly young and dating from the time of the last major merger. However, there is a significant

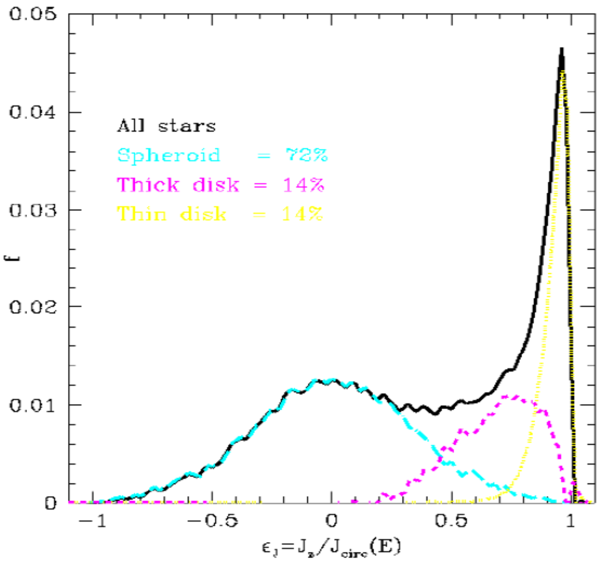

Fig. 2. Circularity parameter c distribution for a possible dynamical decomposition of the stellar component of the simulated galaxy analyzed by Abadi et al. (2003a,b): a spheroid (long dashed curve), a thin disk (dotted curve) and a thick disk (short dashed curve).

number of unexpected old stars (15% are older than 10 Gyrs) as a result of satellite accretion events in orbits coplanar to the galactic disk which are eroded by dynamical friction. The thick disk is old and it is not a former thin disk thickened by a minor merger but actually the debris from satellite accretion events.

2.2. *Dark and luminous halos and satellites*

Satellite companions of bright galaxies are exceptionally useful probes of the galaxy formation process. The properties of the satellite population found around galaxies are of crucial importance to infer the presence and properties of the non-luminous dark matter halos that surround galaxies. Numerical simulations offer an opportunity to study the spatial distribution of stellar and dark matter galactic halos in order to compare them with both the observed and simulated distribution of satellites around galaxies. Sales et al. (2007a,b) have identified and analyzed the satellite population in the same suite of N-body/gas dynamical simulations of galaxy formation of Abadi et al. (2006) and have compared their properties with dark and luminous halos.

2.2.1. *Density profiles*

Dark matter halos follow a NFW (Navarro, Frenk, & White 1997) density profile while stellar halos are found to have a much more concentrated profile with a logarithmic slope that bends from -3 in the central part of the halo to -4 in the outer parts (Abadi et al. 2006). These authors have shown that simulated stellar halos consist almost exclusively of stars formed in satellites that are accreted and disrupted due to the tidal interaction with the main galaxy. Sales et al. (2007a,b) found that the number density profile of simulated satellites trace very well the underlying dark matter density profile, being one of the best dark matter tracers in the outer parts of galaxies. When computed cumulatively, these distributions show also a very good agreement with the observed Milky Way and Andromeda spatial satellite population distribution. These simulations show that luminous satellites are resilient to disruption by tides and that they can survive as self-bound entities closer to the primary galaxy, whereas the substructure in dark-matter-only simulations is much more easily disrupted (White & Rees 1978). On the other hand, the number density profile of the globular clusters of the Milky way (as well as of Andromeda) is very similar to the simulated stellar halos profiles and much more concentrated than the simulated satellite and dark matter NFW profiles (see Figure 3).

2.2.2. *Velocity profile*

Beside density profiles, it is also interesting to compare the velocity dispersion profiles of simulated satellites. Simulated galactic stellar halos are made of disrupted satellites and are supported by preferentially radial velocity dispersion while the population of surviving satellites (and also the dark matter halos) are supported by a more isotropic velocity dispersion. The existing differences between density and also velocity dispersion profiles for the disrupted and surviving satellite population points to an intrinsic difference between these two components. Analyzing the statistical properties of the surviving and merged satellite population in N-Body/SPH numerical simulations, Sales et al. (2007a,b) show that there are systematical differences between them. The main result is that large mass satellites are very likely to merge with the host; more explicitly, any satellite more massive than 10% of the host mass is unable to survive since it will be merged with the central galaxy. Merged satellites are more massive and have been accreted earlier than surviving ones; on the contrary, surviving satellites are predominantly low-mass systems that have been accreted more recently. The building blocks of the stellar halo were on average more massive and were accreted (and disrupted) earlier than the population of satellites that have survived until the present. Also,

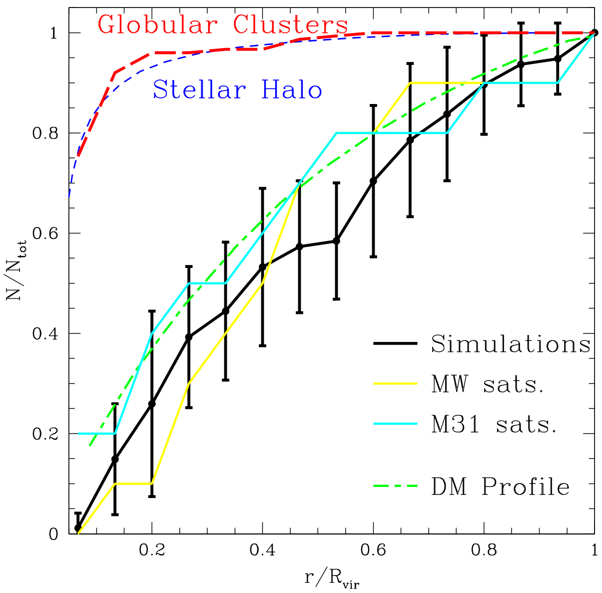

Fig. 3. Normalized cumulative number fraction as a function of distance r for different galactic components out to the virial radius $R_{\rm vir}$ for a set of 8 simulated galactic systems analyzed by Abadi et al. (2006) and Sales et al. (2007a,b). Label "Simulations" corresponds to simulated satellites using a stacking technique, "DM profile" corresponds to the simulated dark matter halos and "Stellar halo" to the simulated stellar halos. "MW sats." and "M31 sats." correspond to observed Milky Way and Andromeda satellite system, respectively and "Globular Cluster" to the observed distribution of the Milky Way globular cluster system.

merged satellite are accreted on more eccentric orbits than the surviving ones, hinting to a stellar halo supported preferentially by radial velocity dispersion. These results may help to explain the difference between the abundance metallicity patterns of halo star in the solar neighborhood and in galactic dwarfs.

3. CONCLUSIONS

(1) N-body/gasdynamical numerical simulations in the ΛCDM model produce galaxies with photometric properties like surface brightness and colors that agree with observed galaxies.

(2) Simulated galaxies marginally agree with Tully-Fisher relation. Strong feedback effects could alleviate this problem. Feedback is also needed in order to match both the galaxy luminosity function and the cosmic star formation rate.

(3) Simulated galaxies show two different stellar components: an spheroid plus a disk. The spheroidal component is formed earlier by mergers of protogalaxies, while the disk component is formed by later gas accretion.

(4) Density profile of the simulated satellite population similar to dark matter halo following an NFW density profile. However, the stellar halo density profiles much more steep with a logarithmic slope that bends from -3 in the central part of the halo to -4 at the virial radius.

(5) The simulated satellite population and the dark matter halo are supported by rather isotropic velocity dispersion with a anisotropy parameter $\beta \approx 0.4$ in the outer parts of the halo. The stellar halo is more biased to radial direction with $\beta \approx 0.8$.

(6) More massive simulated satellites are accreted earlier and merge with the main galaxy, while less massive satellite are accreted later and survive.

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