FORMATION AND EVOLUTION OF GALAXIES: N-BODY TREE SPH SIMULATIONS

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Understanding the formation and evolution of galaxies is one of the challenges of modern astrophysics. In this contest the origin of the elliptical galaxies is particularly demanding because there seem to some sort of contradiction between the chemical and spectro-photometric properties of their stellar contents and the paradigm of structure formation a cold dark matter dominated universe. The problem can be reduced to two paradigmatic scenarios (i) the monolithic one in which very early on, elliptical galaxies are in place with the total dark matter and baryonic matter, form the bulk stars and passively evolve ever since; and (ii) the hierarchical scheme by which big elliptical galaxies are the result of merger with sporadic stellar activity that continued up a recent past.

To contribute to this debate, over the years we have developed a research line centered on galaxy formation and evolution as described by the NBody-TreeSPH technique both in the monolithic and hierarchical schemes. To this aim an original code has been developed both in serial and parallel mode, in which Dark Matter and Baryons are considered. The gas is converted into stars and it is chemically enriched by supernova explosions and stellar winds. The models take into account energy feed back and radiative cooling. With this code we have modelled disc and spheroidal galaxies starting from suitable initial condition (e.g. Lia et al. 1998; Lia et al. 2001, Chiosi & Carraro 2002 and references) or from cosmological conditions (Merlin & Chiosi 2005). We have also simulated mergers of galaxies (Buonomo et al 2002). Pasetto et al. (2003) have simulated the tidal interactions between the MW and one of its satellite galaxies (Sculptor) to check the possibility that an irregular dwarf galaxy can be reshaped into a dwarf spheroidal. Finally, Merlin & Chiosi (2005) have derived the initial conditions for the galaxy models from cosmological simulations. The ultimate goal of this project is to put together expertises from different areas to generate realistic galaxy models with cosmological initial condions and with acuurate descriptions of star formation and chemical enrichment as input to theoretical spectral energy distributions of their stellar content.

In this area we have developed six project which are still carried out intensively. For each of these we report on recent achievements and when appropriate we shortly summarize the scientific rationale and outline the future plans.

Project 1: FORMATION AND EVOLUTION OF GALAXIES: N-BODY TREE-SPH SIMULATIONS

(1) Buonomo F., Carraro G., Chiosi C., Lia C. *Galaxy formation and evolution - II. Energy balance, star formation and feedback.* (2000). MNRAS, Volume 312, pp. 371-379

In this paper we present a critical discussion of the algorithms commonly used in N-body simulations of galaxy formation to deal with the energy equation governing heating and cooling, to model star formation and the star formation rate, and to account for the energy feedback from stars. First, we propose our technique for solving the energy equation in the presence of heating and cooling, which includes some differences with respect to the standard semi-implicit techniques. Secondly, we examine the current criteria for the onset of the star formation activity. We suggest a new approach, in which star formation is allowed to depend on the total mass density - baryonic (gas and stars) and dark matter - of the system and on the metal-dependent cooling efficiency. Thirdly, we check and discuss the separate effects of energy (and mass) feedback from several sources - namely supernovae, stellar winds from massive stars and ultraviolet flux from the same objects. All the simulations are performed in the framework of the formation and evolution of a disc galaxy. We show that the inclusion of these physical phenomena has a significant impact on the evolution of the galaxy models.

(2) Chiosi C., & Carraro G. ***Formation and Evolution of Elliptical Galaxies.*** **(2002). MNRAS, vol. 335 , pp. 335-357**

We address the problem of the formation and evolution of elliptical galaxies (from dwarf to normal/giant systems). In particular, by means of N-body-Tree-SPH simulations, incorporating cooling, star formation, energy feed-back and chemical evolution, we intend to explore whether the formation of elliptical galaxies from the monolithic collapse of baryons inside non rotating, virialized halos of dark matter leads to results compatible with the main body of observational data on these systems. We show that this scenario can indeed reproduce the basic structural properties of observed elliptical galaxies of different mass. We study the star formation history and the chemical enrichment of the models showing that the duration, strength and shape of the star formation rate as function of time strongly depend on the galaxy mass and the initial density. More precisely, massive elliptical galaxies, independently of their initial density, show a single burst of star formation, whereas the low mass ones have a varied star formation history. It is early and monolithic in the high initial density systems, and irregular and intermittent in the low density ones. The occurrence of galactic winds is also analyzed, concluding that in general all galaxies are able to eject part of their gas content into the inter-galactic medium. However, the percentage of the ejected material increases at decreasing galaxy mass. Our models are used to interpret the Fundamental Plane (mass-to-light ratio versus mass relationship), the Mass-to-Light ratio versus central velocity dispersion, the Color-Magnitude relation, and the Mass-Radius relationships of elliptical galaxies from dwarfs to giants. For each relationship in question the agreement between observations and theory is remarkable. Based on this, we endeavor to speculate on a unified scheme for the formation of stellar aggregates going from globular clusters to normal/giant elliptical galaxies in which initial density, type of star formation (single initial episode or recurrent bursts of activity) and galactic winds are the key ingredients. Finally we draw some remarks about the long standing question whether the hierarchical or the monolithic scheme for the formation of galaxies (ellipticals) ought to be preferred.

(3) Pasetto S., Chiosi C., Carraro G. ***Morphological Evolution of Dwarf Galaxies in the Local Group.*** **(2003). Astronomy & Astrophysics, vol. 405, pp. 931**

The dwarf galaxies of the Local Group can be separated in three morphological groups: irregular, elliptical and spheroidal. Like in the large galaxy clusters, there seems to be a morphology-position relationship: irregular galaxies are preferentially found in the outskirts (low density regions) of the Local Group, whereas dwarf ellipticals and spheroidals are more frequent in the central, high density regions. In the aim of casting light on the nature and origin of dwarf galaxies in the Local Group, Mayer et al. (\cite{Mayer}) have suggested that a dwarf irregular galaxy tidally interacting with a galaxy of much larger mass may be re-shaped into a dwarf spheroidal or elliptical object. In this paper by means of N-Body Tree-SPH simulations we check whether this is possible for a selected sample of galaxies of the Local Group. Using the best data available in literature to fix the dynamical and kinematical status of a few dwarf galaxies in the Local Group, we follow the evolution of an ideal satellite, which supposedly started as an irregular object, during its orbital motion around the Milky Way. We find that the tidal interactions with the Milky Way remove a large fraction of the mass of the dwarf irregular and gradually reshape it into a spherical object.

(4) Carraro G., Chiosi C., Girardi L., Lia C. ***Dwarf Elliptical Galaxies: Structure, Star Formation, and Color-Magnitude Diagrams.*** **(2001). MNRAS. vol. 327, pp. 69-79**

The aim of this paper is to cast light on the formation and evolution of elliptical galaxies by means of N-body/hydro-dynamical simulations that include star formation, feed-back and chemical evolution. Particular attention is paid to the case of dwarf spheroidals of the Local Group which, thanks to their proximity and modern ground-based and space instrumentation, can be resolved into single stars so that independent determinations of their age and star formation history can be derived. Indeed, the analysis of the color-magnitude diagram of their stellar content allows us to infer the past history of star formation and chemical enrichment thus setting important constraints on galactic models. Dwarf galaxies are known to exhibit complicated histories of star formation ranging from a single very old episode to a series of bursts over most of the Hubble time. By understanding the physical process driving star formation in these objects, we might be able to infer the mechanism governing star formation in more massive elliptical galaxies. Given these premises, we start from virialized haloes of dark matter, and follow the infall of gas into the potential wells and the formation of stars. We find that in objects of the same total mass, different star formation histories are possible, if the collapse phase started at different initial densities. We predict the final structure of dwarf spheroidal galaxies, their kinematics, their large scale distribution of gas and stars, and their detailed histories of the star formation and metal enrichment. Using a population synthesis technique, star formation and metal enrichment rates are then adopted to generate the present color-magnitude diagrams of the stellar populations hosted by dwarf spheroidal galaxies. The simulations are made assuming the red-shift of galaxy formation $z_{for}=5$ and
varying the cosmological parameters H_0 and q_0. The resulting color-magnitude diagrams are then compared with the observational ones for some dwarf spheroidals of the Local Group.

(5) Buonomo F., Carraro G., Chiosi C., Lia C. ***High redshift mergers of disc galaxies: can they form spheroidal galaxies?*** **(2005). MNRAS, submitted**

In this study we investigate the possibility that present day elliptical galaxies are formed by high redshift mergers of disc (spiral) galaxies. All galaxy models are calculated with the N-body Tree Smoothed Particle Hydrodynamics (NB-TSPH) technique. They include baryonic and dark matter, star formation, cooling, stellar feed-back, and chemical evolution. First we consider the case of an isolated disc galaxy, which is followed from the initial formation stage inside a rotating halo of dark matter to past the stage in which the bulk of star formation has taken place. Under the action of cooling and driven by the velocity field, the gas settles onto a rotating disc in which star formation occurs, gradually turning the gas into stars. Subsequently we consider the case of two disc proto-galaxies in suitable orbits so that a close encounter and a merger can occur at a certain age, forming a composed system, and follow the evolution of this latter for a long period of time. The results show that a bound object resembling a spheroidal (elliptical) galaxy is indeed formed. By changing the orbital parameters and time of the encounter, the disc galaxies are let merge at different stages of their evolution, i.e. when their gas content is either low (most of star formation has already occurred) or high (the bulk of stars are not yet formed). These simulations are according to the classical hierarchical scheme. Finally, we calculate a galaxy model whose initial total mass is twice the mass of a disc galaxy and follow its evolution in isolation. This model is the prototype of the so-called monolithic scheme. We then compare the three models of spheroidal galaxies we have obtained looking for signatures of the underlying formation mechanism. In particular, we consider the past history of star formation, the degree of metal enrichment, the internal gradient in mass density and velocity dispersion, and the dimensions and shapes. We find that mergers of two gas-rich disc galaxies generate elliptical galaxies denser and cooler than those formed by the encounter of two gas-poor disc galaxies but in any case an order of magnitude less dense than the case of an elliptical galaxy resulting from the monolithic collapse. Furthermore, metallicity, mass gradients, velocity dispersions, total dimensions and shapes are significantly different passing from the hierarchical to the monolithic scenario. Therefore hints on the formation mechanism could be inferred from the present-day properties of real elliptical galaxies.

(6) Merlin E., Chiosi C. ***Formation and evolution of early-type galaxies. II. Models with quasi-cosmological initial conditions.*** **(2005). MNRAS, submitted**

Galaxies are the building blocks on which our understanding of the large scale structure of the Universe is grounded. They show a large variety of shapes and dimensions, so that, despite the taxonomical classifications chief among which is the Hubble sequence, it is possible to say that each galaxy stands on its own, with detailed properties that likely mirror its individual history of formation and evolution. The major challenge of modern astrophysics is to understand the origin and evolution of galaxies, the bright elliptical ones in particular, on which we focus our study. In a Universe dominated by Cold Dark Matter (CDM) and containing a suitable mix of baryons and photons, cosmic structures are formed by the gravitational dissipation-less collapse of dark matter. They are organized in a hierarchy of complexes (halos) inside which baryons dissipate their energy and collapse to form luminous galaxies. In this context, modelling the formation of early-type galaxies with simulations taking into account the dynamics of dark matter halos and gas, radiative cooling of baryons, star formation, and gas loss by galactic winds can be reduced to two schemes: the monolithic and the hierarchical scenarios. The monolithic scenario of galaxy formation suppose and predict that all early-type galaxies form at high red-shift by rapid collapse and undergo a single star formation episode (Eggen, Lynden-Bell, Sandage 1962; Larson, 1975; Arimoto, Yoshii 1987; Bressan, Chiosi, Fagotto 1994; Gibson 1996) ever since followed by quiescence. The hierarchical scenario according to which the massive galaxies are the end product of subsequent mergers over time scales almost equal to the Hubble time in a certain cosmological model. As the look back time increases, the space density of bright (massive) elliptical galaxies should decrease by a factor 2 to 3 (White, Rees 1978; Katz 1992; Kauffmann, White, Guiderdoni 1993). There is a third hybrid scenario named revised monolithic, proposed by Shade et al (1999), who suggest that a great deal of the stars in massive galaxies are formed very early-on at high z and the remaining ones at lower z. In favour of the classical monolithic view, are the observational data (see below) that convincingly hint for old and homogeneous stellar populations. It is worth mentioning, however, that Kaufmann, White, Guiderdoni (1993) and Barger et al (1999) argue for the presence of recent evolution in the stellar populations of elliptical galaxies. In favour of the hierarchical scenario are some observational evidence that the merger rate likely increases with $(1+z)^3$ (Patton et al 1997) together with some hint for a color-structure relationship for E & S0 galaxies: the colour becomes bluer at increasing complexity of a galaxy' structure. This could indicate some star formation associated to the merger event. Finally, the many successful numerical simulations of galaxy encounters, mergers and interactions (e.g. Barnes & Hut 1996) Nevertheless, contrary to the expectation from this model, the number density of elliptical does not seem to decrease with the red-shift, at least up to $z = 1$ (Im et al 1996). Schade et al. (1999) argue that the revised monolithic, ought to be preferred to the classical monolithic as some evidences of star formation at $0.2 < z < 2$ can be inferred from the presence of the emission line [OII]) and also the nearly constant number frequency early-type galaxies up to $z = 1$. However, a sharp distinction among the three scenarios could not exist in reality. As pointed out by Longhetti et al (2000) early-type galaxies in isolation and in interaction (such as pair-and shell galaxies) share the same distribution in diagnostic planes such as H□ vs [MgFe] the classical tool to infer age differences. This means that secondary episodes of star formation may not only occur in merging (dynamically interacting) galaxies, but also in the isolated ones because of internal processes. Captures (mergers) of small satellites by a galaxy born in isolation according to the monolithic scheme are reasonably possible (e.g. the Milky Way which is currently capturing the Sagittarius dwarf galaxy). In any case, as thoroughly discussed by Chiosi (2000), Chiosi & Carraro (2002) and Tantalo & Chiosi (2004), the age and intensity of the last episode of star formation (measured by the fractionary mass engaged in newly formed stars) cannot exceed some stringent limits, a few per cent and about one third of the Hubble time even in a massive elliptical, otherwise the typical broad band colours cannot be matched. They would be to blue compared to observations.

Basing on the pioner studies by Kawata (1999), the scenario we have in mind and we intend to prove with the present simulations is the following one. At a certain (high) red-shift a massive perturbation made of Dark Matter and Baryons detaches from the Hubble flow and collapses on its own. It becomes a massive proto-galaxy, rich of substructures, which moving inside the common gravitational potential well merge, form stars and eventually give rise to a single entity (the galaxy). The process is complete at high redshift (say before 2) and from now on the galaxy evolves in "isolation". Subsequent captures of small satellites are possible without significantly altering the overall structure and evolution. In the case of a low-mass perturbation the stellar activity is prolonged over long time scales. Mergers between two galaxies may occur but they are a sort of rare, spectacular event and not the basic mechanism for assembling massive ellipticals.

In this study, with aid N-body-TSPH simulations based on quasi-cosmological initial conditions we have followed the formation and evolution of two early-type galaxies from the stage when they separate from global expansion of the Universe to their collapse to virialised structures, the formation of stars and subsequent nearly passive evolution up to the age of 7 Gyr. Two typical cosmological backgrounds have been considered, namely the standard CDM (model A) and □□CMD (model B). For both models we have highlighted the structural, dynamical and chemical properties to be compared with observational data. Although the models contain several parameters, among which we recall the softening parameter for Dark Matter, gas and stars, the specific efficiency driving the star formation rate and the fraction of energy released by a supernova explosion which goes into the gas as kinetic and thermal energy, the results we have obtained are satisfactory and in agreement with other studies of the same subject. The final systems morphologically resemble real elliptical galaxies of intermediate dimensions. This is proved by their density profiles matching the theoretical ones by de Vaucouleurs (1948) that are expected for galaxies of the same mass and scale lengths. Hjorth & Madsen (1991) have indeed showed that violent relaxation in a deep potential well leads to systems obeying the de Vaucouleurs law. Kawata (1999) outlines that dissipative processes bear very much on the final results. Our simulations strongly support the revised monolithic scenario of galaxy formation: a single episode of star formation occurred in the far past, during the virialization of the proto-galaxy, perhaps followed by minimal stellar activity in the central regions and almost negligible morphological and structural evolution. Star formation lasts longer in the central regions than in the outskirts thus producing gradients in metallicity that closely agree with the observational data for elliptical galaxies (Davies et al 1993).

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117 refereed articles
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