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Simulating the formation and evolution of galaxies with EvoL, the Padova N-body Tree-SPH Code

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Summary. — The importance of numerical simulations in astrophysics is constantly growing, because of the complexity, the multi-scaling properties and the non-linearity of many physical phenomena. In particular, cosmological and galaxy-sized simulations of structure formation have cast light on different aspects, giving answers to many questions, but raising a number of new issues to be investigated. Over the last decade, great effort has been devoted in Padova to develop a tool explicitly designed to study the problem of galaxy formation and evolution, with particular attention to the early-type ones. To this aim, many simulations have been run on CINECA supercomputers (see publications list below). The next step is the new release of EvoL, a Fortran N-body code capable to follow in great detail many different aspects of stellar, interstellar and cosmological physics. In particular, special care has been paid to the properties of stars and their interplay with the surrounding interstellar medium (ISM), as well as to the multiphase nature of the ISM, to the setting of the initial and boundary conditions, and to the correct description of gas physics via modern formulations of the classical Smoothed Particle Hydrodynamics algorithms. Moreover, a powerful tool to compare numerical predictions with observables has been developed, self-consistently closing the whole package. A library of new simulations, run with EvoL on CINECA supercomputers, is to be built in the next years, while new physics, including magnetic properties of matter and more exotic energy feedback effects, is to be added.

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PACS 95.75.Pq – Mathematical procedures and computer techniques.

1. – Introduction

A major challenge in modern astrophysics is to understand how galaxies formed and evolved. Historically, two scenarios have been competing: the monolithic [1], in which galaxies form in single bursts of star formation in cosmological epochs and evolve almost passively thereafter, and the hierarchical [2], in which galaxies form via mergers along the entire Hubble time. While large-scale simulations of Dark Matter evolution in cosmological epochs seem to favour the latter, reality is indeed much more intriguing, because of the complexity of baryonic physics which ultimately leads the galactic formation process. It is thus necessary to develop powerful and flexible tools, able to model such complicated systems as rigorously as possible, including small-scale physics within larger scale environments.

2. – EvoL

EvoL is a Fortran 95 code, entirely written and developed in Padova. Its first version was written ten years ago [3]; it was then revised and integrated over the years [4-6] and is still being improved [7]. A massively parallel version of the code is currently undergoing final stability tests, and should be used in all future applications. The fully Lagrangian N-body code EvoL is particularly suited to study the formation and evolution of galaxies in cosmological context, but it is flexible enough to be used in studies of dynamical properties of interacting objects (*e.g.* [8]) as well as in large-scale cosmological simulations. Gravitational interaction is described by the classic Tree-Code [9] with quadrupole corrections. In its new version, to be released this year, EvoL includes the possibility to use individual, time-and-space variable gravitational softening lengths. Basic gas hydrodynamics is described via Smoothed Particles Hydrodynamics (SPH, [10, 11]), although revisited and improved in a number of aspects in order to correctly model the properties of astrophysical media.

3. – ISM and star formation

Great attention has been paid to the problem of the multi-phase nature of the Interstellar Medium (ISM). It is substantially accepted that at least three different phases coexist in approximate pressure equilibrium: a cold, clumpy, dense, neutral and molecular phase, a warm, partially ionized phase, and a hot, diffuse, completely ionized phase, the latter being generated by supersonic shocks and stellar feedback [12]. Classic formulations of SPH fail in reproducing the properties of a multi-phase medium.

A first effort to include such complex structure in the architecture of the code was made by Merlin and Chiosi [6], who included a "sticky particles" algorithm (see, *e.g.*, Levinson and Roberts [13]) to model the cold, clumpy phase, and obtained encouraging results (fig. 1 schematically sketches the interactions between gaseous phases and stars in the code). In the new version of EvoL, a more rigorous approach will be followed, and the multi-phase properties of the medium will be self-consistently described by a revised formulation of SPH [14]. Moreover, the ionized and molecular fractions of interstellar Hydrogen will be traced using a fast and accurate algorithm [15], almost ruling out undesired free parameters. EvoL also includes detailed radiative cooling functions, which strongly depend on temperature (ranging from millions to few K) and chemical composition (from primordial to super-solar) of ISM. Another point of strength of EvoL is its detailed description of the stellar evolution, and of the energy and chemical releases of stars [4]. Because of resolution limitations, individual N-body particles cannot model single stars; rather, each particle (which is treated as collisionless) represents a Single Stellar Population (SSP) of given age, mass and metallicity. Its properties can be followed once evolutionary tracks for different SSPs are known; EvoL adopts mass-loss, Supernovae rates and chemical yields by Greggio and Renzini [16].

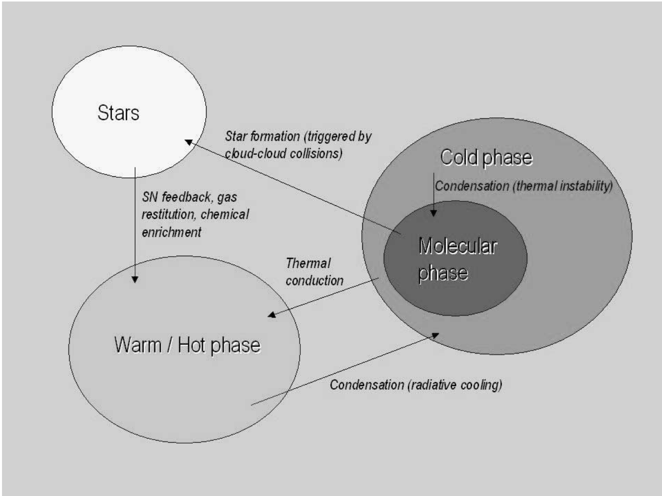

Fig. 1. – Interaction between gaseous phases and stars in EvoL.

4. – Development

Using the first version of EvoL, Chiosi and Carraro [17] investigated the problem of the formation of elliptical massive galaxies, building a library of models with different initial masses and densities, with *ad hoc* initial profiles and void boundary conditions. Despite the relative crudeness of the models, they obtained several interesting results, finding in particular that star formation histories strongly depend on the initial properties of the proto-galaxies, supporting a monolithic scenario at least for high-mass galaxies.

New models were then obtained by Merlin and Chiosi [5], who introduced "quasi-cosmological" initial conditions, *i.e.* primordial perturbations and cosmic expansion (although keeping void boundary conditions), obtaining similar results. Buonomo [18] introduced the possibility to include ambient environmental "ghost particles" to model the gravitational action of distant surrounding matter, thus mitigating the problem of void boundary conditions. In its new release, EvoL will include comoving integration of the equation of motions within an arbitrary cosmological context, as well as periodic boundary conditions, so to minimize problems deriving from inaccuracies in the description of the galactic environment.

5. – Observational data comparison

Chinellato [19] combined the Evolutionary Population Synthesis (EPS) technique to the three-dimensional numerical simulations, reproducing observational integrated properties of ETGs (in any photometric bandpass), thus allowing quantitative comparisons between the theoretical models and the observational data of modern imaging surveys, in any spectral regime and cosmological context. By matching the photometric tool with the three-dimensional geometric information of the simulated galaxies' structure and chemical properties, synthetic/artificial images of a galaxy in a bi-dimensional plane and for any given photometric system can be created.

The theoretical results obtained from Padova model galaxies have been compared with the observational data from the major surveys, *e.g.*, COSMOS and GOODS database.

Models follow the general trend of the selected ETGs up to high redshifts. The most interesting aspect of these results is that the investigation of the simulated galaxies, via the photometric analysis of the artificial images, led us to recover properties that resemble those of observed galaxies: we derive the structural and morphological parameters, such as the galaxy's effective radius and luminosity within this, which enter the scaling laws (*e.g.*, Kormendy relation), the shape indices through Fourier and Sersic analysis, color profiles, and radial profiles of most of the parameters that enter the structure of galaxies.

6. – What's next?

Work is still in progress to include new physics in the complex structure of EvoL. The very next steps should be the inclusion of Magneto-hydrodynamics (MHD) in the SPH algorithm (an extremely tricky issue given the importance of magnetism in the star formation process), and a detailed description of Active Galactic Nuclei energy feedback, as well as other sources of energy such as cosmic rays. Using the CINECA facilities, we plan to use EvoL to build a new library of cosmo-dynamical galactic models within the next few years. New models should have different initial masses, densities and environmental properties, allowing to study the link between initial conditions and final characteristics of objects. Hopefully, this will help to obtain new insights on some of the still obscure processes leading galaxy formation.

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