Galaxy Formation Simulations

Anders Pinzke

October 23, 2006

1 Introduction

The perturbations needed to form galaxies are thought to be created from quantum fluctuations and starts evolving fractions of a second after the big bang. In the hot plasma in the early Universe sound-waves transversed the matter - both ordinary matter and Dark Matter (DM) - which led to further inhomogeneities in the plasma. After the matter-radiation equality, perturbations in the DM grew on all scales while the baryonic density perturbations oscillated on the scales of the order of the jeans wavelength or smaller. When the photons “froze out”, the imprint of these perturbations froze and can be seen in the cosmic microwave background radiation. Further, after recombination, fluctuations in the radiation were quickly damped and the baryonic fluctuations started to grow. Consequently they are pulled into the already formed DM potentials and obtain the same fluctuation amplitude. After a while these fluctuations become non-linear, which lead to quite complicated gravitational dynamics and hydrodynamics, since it involves the interplay of both Dark Matter and ordinary matter. In most cases the best way to obtain a description of this phase, is to perform an numerical simulation.

The aim of this work is to try to answer three important questions regarding a Galaxy Formation Simulation (GFS): why do we need GFSs?; how does a GFS work?; and what have we learned/not learned from the GFSs?

2 The importance of simulations of galaxy formation

Galaxy clusters and the halo of galaxies are formed from initially over-dense regions in the Universe. The regions can be considered as mini-universes with a matter density $\Omega_m > 1$, that expand to a maximum radius and then re-collapse. Doing GFSs is a much messier problem than doing large-scale structures (LSS) simulations using Cold Dark Matter (CDM) - which show a similar structure of what is observed - since the physical processes for galaxy models are completely different. In addition to gravity and the evolution of DM halos, effects like shock heating of gas, star formation and its feedback via stellar winds and SN explosions, gas flows and dissipation, chemical evolution, black hole effects and much more play an important role [1]. Since there is no good way to study this analytically, perhaps the best way to study galaxy formation theoretically is in numerical simulations using hydrodynamical N-body models accounting for the relevant effects above, even though it is a messy problem. Although, the numerical simulations of structure formation and galaxy evolution have evolved a lot during the last years reaching an resolution of $10^{10}$ particles, thanks to more powerful computers and better tools, which increases the power to predict how galaxies evolve and form. Some of the questions one hope to answer with the GFSs are: what determines the current morphology of a Galaxy?; what produces a spiral vs. an elliptical?; where the angular momentum from spirals come from?; and how does the morphology evolve with time?

3 A general overview of the theory behind galaxy formation simulations

Cosmological simulations of structure formation can be divided up into four important parts: the equations and its solution; boundary conditions; initial conditions; interpretation of the result. In the simulations a basic set of equations describe the dynamics of the collisional component (DM or stars in galaxies) and an ideal gas (baryons, mostly hydrogen and helium). The two types of matter interact through gravity and an expanding background space. To describe DM, the collisionless Boltzmann equation coupled to the Poisson equation in an expanding Universe are used. These equations are best solved with the N-body method, where phase-space density is represented by a finite number of trace particles. According to the CDM scenario, galaxies and larger structures are built up by the process of hierarchical clustering [2], which has both been confirmed with more detailed analysis and with the result of N-body simulations. There exist several techniques to simulate the formation of galaxies. In the
hierarchical picture two of the models used are: the semi-analytic (SA) model\textsuperscript{1} and the other on is based on smoothed particle hydrodynamics (SPH). The two models differ in how the gas process is accounted for: analytic methods mixed with N-body simulations are used in the SA model, and direct numerical integration of the equations of hydrodynamics\textsuperscript{2} for a set of discrete particles are used in the SPH case. More specifically SPH uses a set of discrete tracer particles to describe the state of a fluid (the gas), where the coordinates, velocities and masses are best thought of as fluid elements that sample the gas using Lagrangian techniques [4]. The thermodynamical state of each fluid is usually defined in terms of thermal energy per unit mass, or in terms of entropy per unit mass. The particles have a spatial distance $\hbar$ over which their properties are “smoothed” by a kernel function $w$. The equation for any quantity of a particle $i$, represented as $A_i$ is given by the equation

$$A_i(r) = \sum_j m_j \frac{A_j}{\rho_j} w(r_i - r_j, \hbar),$$

where $m_j$ is the mass of particle $j$ and $\rho_j$ the density associated with particle $j$. What this means is that any physical quantity can be obtained by summing over the relevant properties of all particles inside two smoothing lengths. The contribution of each particle to a property (e.g. temperature) is weighted according to their distance from the particle of interest. This saves a lot of computer power compared to if ordinary Gaussians were to be used, where relatively minor effects from distant particles are included. In addition the smoothing length can be changed itself to yield a higher spatial resolution to a higher density area.

4 What we get from the simulations of galaxy formation

There are many classes, and different types of evolutionary paths for galaxies. The N-body hydrodynamical simulations of the different scenarios have different problems. However, the numerical simulations of galaxy evolution have reached such a point where they can be linked with cosmological simulations for the large-scale structure evolution. This means that morphological evolution of galaxies can be explored in a proper cosmological context. The problem is a rather poor resolution (< 10$^6$ particles per galaxy)[6]. Although, simulations with higher resolution using pure N-body gravitational codes have been undertaken, but at the expense of neglecting important hydrodynamical effects. The simulations with best resolution is of course the one that study individual galaxies, or small systems of galaxies, in isolation. Simulations still fails to account for a number of observations. The constant core density of DM halos observed in some galaxies do not agree with the power law-like cusps density profile observed from simulations, and also the number of companions to large galaxies inferred from simulations is about an order of magnitude to large compared to observations. The most crucial problem is their failure to account for galaxy sizes. According to [6] do all cosmological codes predict much more luminous disks around $z \approx 1$ than what is observed. However, the semi-analytic models outshine the SPH models in predicting galaxy sizes as a function of redshift, as well as in modeling the morphological evolution with redshift.

4.1 Galaxies with a disk

The first GFS which included star formation provided strong evidence that hierarchical models do create rotationally supported stellar systems. However, GFSs in a full cosmological context have not been able to form realistic disk galaxies since friction from dense gaseous lumps and subsequent angular momentum loss caused typical disk scale lengths to deviate from observations [8]. Additionally, simulations of DM halos in CDM models have far more substructures than observations, which could destroy the stellar disk in spiral galaxies. Possible solutions to these problem is a strong supernovae feedback,

\textsuperscript{1}In most of these models Monte Carlo method on extended Press-Schechter models (e.g. [3]) are used - providing the mass functions of progenitor halos to describe merging histories or merger trees of DM halos. The building block of these models is the Press-Schechter model [2] on mass functions of dark halos, which are derived from the power spectrum of initial density fluctuations combined with a spherically symmetric collapse model describing the non-linear nature of the evolved perturbations.

\textsuperscript{2}The relevant equations describing the cosmic fluid (in this case only one species is considered) are: the continuity equation

$$\dot{\rho} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

the Euler equation of hydrodynamics

$$\dot{\mathbf{v}} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla \mathbf{F} + \frac{\mathbf{F}}{\rho},$$

and the Poisson equation of Newtonian gravity

$$\nabla^2 \Phi = 4\pi G \rho.$$
alternatives to the $\Lambda$CDM paradigm, an external UV background produced by quasi-stellar objects or massive stars. In rather recent (2004) simulations [7], a SPH GFS was performed in a $\Lambda$CDM model including: cooling; star formation; supernovae feedback; and redshift dependent UV background. The result was a successfully formed object with bulge-to-disk mass ratios, scale lengths, current star formation, disk age and dynamical properties corresponding to what is observed in present day massive spirals. The problem with the large angular momentum loss reported in the early works was also partly solved and showed to be dependent to some extent on insufficient mass or force resolution.

To get a better understanding of what is going on in a galaxy formation simulation I have included Fig.1-3, taken from [9], that show the distribution of DM, gas, and star particles in the simulation at various times. The simulation was performed (2002) in a $\Lambda$CDM model with GRAPE-SPH, a particle-based, fully three-dimensional Lagrangian hydrodynamical code that combines the SPH technique with the speed of the special-purpose hardware GRAPE for computing gravitational interactions. The algorithm includes only two free parameters: the relation between local dynamical and star formation timescales; and another parameterizing the efficiency of feedback energy on the bulk kinetic energy of gas in star forming regions. The two parameters are determined by matching empirical relations to normal star forming galaxies in the local Universe. The initial values at $z \sim 5$ in Fig.1 is rather typical in the assembly process of DM halos in the $\Lambda$CDM paradigm. As can be seen at $z \sim 5$ the regions have collapsed into a sheet-like structure mapped out by the DM halos. Gas is pulled into these non-linear structures, where it cools, condenses, and start forming stars. Gas in the filaments has short cooling times, and remains cold throughout the formation process as opposed to the gas outside the main sheet-like structure that heats up to about a million degrees. For lower redshifts the non-linear clumps slowly merge together as matter drains down the filamentary structure into the most massive progenitor. Most of the gas (seen in Fig.2) that build up the disk is cold throughout the accretion process and reaches the center either by accompanying satellites pulled to the center by gravity or along dense filament of mass. In Fig.3 most of the stars form and remain in a centrifugally supported thin disk at $z \sim 0$. Also, the central galaxy has two easily distinguishable components at this redshift: a spheroid composed mainly out of old stars formed before merging activity goes down at $z \sim 1$, and a thin stellar disk mainly populated by young stars. Even though the simulations in Fig.1-3 seem to describe roughly what is observed, especially photometrically, where it resembles the nearby galaxy UGC615, their dynamical properties still differ significantly. The rotation of the simulated galaxy rotates faster and it has a declining rotation curve which is not seen in observations.

In Fig.4, a simulation [10] of the assembly of an elliptical galaxy is shown. For high redshift mergers between progenitors of comparable mass is shown. Major mergers seem to mix stars into a spheroid, around which accreting gas may form a new disk-like component. At $z \sim 2$ the simulated galaxy resembles a bright Sa/Sb spiral. Going to lower redshift, the growing disk is tidally shaken by another disk galaxy one third as massive. During the merging, the remaining gas is efficiently funneled to the center, where it trigger star formation. This last episode of star formation is over at $z \sim 0.5$, leaving a small core of younger, metal rich stars, surrounded by a large spheroid of older stars. In terms of morphology, the last merger evolve the galaxy from a centrifugal supported disk into a spheroid. When performing discrete galaxy simulations, it have been shown that elliptical galaxies in general could form from the collision of smaller units, such as spiral galaxies. This have yet not been confirmed (2001) by observations, although merger induced ellipticals remains the favored theoretical model along with the monolythical dissipation collapse, where the galaxies form quickly in the Universe and the age to present day.

5 Summary

It is impressive to see how far the area of galaxy formation simulations has evolved during the last ten years. The simulations presented in this work show a pretty good description of what is going on. But, GFS is a messy business. The physical processes considered are many and complicated. The models describing these processes are getting more accurate with time and the computers are improving in speed, which is needed to take on some of the puzzles in the simulations today. As seen in the figures, the morphology of the galaxies varies substantially in response to changes in the initial conditions, but the dominant mode of mass accretion which is affected by the feedback also plays an important role. The problems that I have discussed in this report is just the major problems in certain scenarios, there are still a lot of other problems and other different models. Accounting for the morphologies and abundance of galaxies in the $\Lambda$CDM paradigm will likely require a better understanding of the physical processes like the way gas cooling and accretion and star-formation couple together, especially at high redshift where the roots to galaxy evolution start growing.
References

Figure 1: Dark matter particles inside a cube of 320 kpc sides, shown at various redshifts. Bottom right panel zooms into the innermost 40 kpc of the system. Red and blue correspond to $\rho_{dm} \gtrsim 10^{10} M_\odot/kpc^3$ and $\rho_{dm} \gtrsim 10^9 M_\odot/kpc^3$, respectively. For further details see [9].

Figure 2: Gas particles inside a cube of 320 kpc sides, shown at various redshifts. Bottom right panel zooms into the innermost 40 kpc of the system. The galaxy is seen edge on. Red and blue correspond to $T \gtrsim 5 \times 10^5$ K and $T \lesssim 3 \times 10^4$, respectively. For further details see [9].
Figure 3: Star particles inside a cube of 320 kpc sides, shown at various redshifts. Bottom right panel zooms into the innermost 40 kpc of the system. Each particle is colored according to its age the time show. Blue and red correspond to $\tau \lesssim 4$ Gyr and $\tau \gtrsim 10$ Gyr, respectively. For further details see [9].

Figure 4: Star particles inside a cube of 40 kpc sides, shown at various redshifts. Bottom right panel zooms into the innermost 40 kpc of the system. Each particle is colored according to its age the time show. Blue and red correspond to $\tau \lesssim 4$ Gyr and $\tau \gtrsim 10$ Gyr, respectively. For further details see [10].