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MODELING THE DENSITY-MORPHOLOGY RELATION AND THE GALAXY/AGN CONNECTION



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We present a model of hierarchical galaxy formation in the spirit of the popular semianalytical models (SAMs) developed in the last decade by various groups. The new model is particularly handy, since fully analytic. It is based on a modified version of the Press-Schechter clustering model distinguishing between gentle accretion and major mergers which allows us to accurately derive the properties of newborn halos and their baryonic content from those of their progenitors just at the time of the merger, and then monitor the evolution of these properties during the accretion phase.

1 Introduction

The way that galaxies form and evolve has been an open question since the beginning of modern cosmology. In the hierarchical scenario, a full understanding of the process of galaxy formation and evolution requires the monitoring of both the clustering of dark-matter halos and the physics of baryons taking place within them. This includes the still poorly known process of star formation, and the complex coupling between luminous objects and both the hot gas inside halos and the diffuse non-trapped intergalactic medium (IGM).

Cole (1991), Lacey & Silk (1991), and White & Frenk (1991) were the first to model the process of galaxy formation taking into account all the basic pieces of the puzzle. The simple, although physically motivated recipes they proposed were subsequently refined by the München group (Kauffmann, White, & Guiderdoni 1993), the Durham group (Cole et al. 1994), and more recently the Santa-Cruz group (Somerville & Primack 1999) who developed Semi-Analytic Models (SAMs) including Monte-Carlo simulations in order to follow the clustering of dark-matter halos. SAMs are successful in recovering the main observed features of galaxies. But there are still some points which do not fit, basically, the predicted shape of the luminosity function, the Tully-Fisher relation (one cannot predict at the same time the correct luminosity of normal galaxies and their typical rotation velocities), and the colour-magnitude relation for ellipticals.

The origin of all these troubles is likely that current models of galaxy formation and evolution are not yet realistic enough. For instance, they do not include a self-consistent description of the internal structure neither of galaxies nor of halos while this is crucial to properly estimate important aspects such as the gas cooling rate, the star formation rate, the satellite orbital decay, or the possible loss of baryons from galaxies and halos. This has been only partially solved in the most recent version of SAMs recently developed by Cole et al. (2000) which includes a fine consistent description of the internal structure of galaxies. However, the internal structure of halos and its scaling evolution is still somewhat adhoc. Likewise, to accurately deal with the environmental interactions of galaxies one should know their positions at any time while this information is not available from the Press-Schechter (1974; PS) clustering model commonly used in SAMs. Besides, current SAMs cannot properly monitor the evolution of halos between consecutive major mergers, partly due to the fact that they do not properly deal with accretion. Finally, because of memory limitations they cannot reach very high redshifts. Consequently, the initial conditions used are not fully self-consistent. Moreover, to correctly trace the formation of the first luminous objects and its feedback on the IGM, one should take into account the first generation of both stars and Active Galactic Nuclei (AGN) (e.g., Rees 1999). It is now admitted that Super Massive Black Holes (SMBHs) are very common, likely universal, at the centre of bright galaxies. These objects, with a mass as large as 10^9 $M_\odot$, should have noticeable effects not only in the surrounding IGM but also in the dynamics of their host galaxies (e.g. van der Marel 1999). Conversely, the evolution of galaxies, groups and clusters should play an important role on the growth of SMBHs and their activity (e.g., Vittorini & Cavaliere 1999). Yet, current SAMs do not include SMBHs. Only Kauffmann & Haehnelt (2000) have incorporated them in a rather rudimentary manner.

We have developed a new model of hierarchical galaxy formation and evolution with the aim to be a useful tool for the study of the origin of galaxy morphologies, the morphology-density relation, the galaxy-AGN connection, and the coupled evolution of the IGM. The skeleton of the model is a modified version of the extended PS dark-matter clustering model, over which the evolution of the baryonic component takes place. To follow this evolution, our model includes several physical processes which are shared with SAMs: radiative cooling of the shock heated gas and its deposition in a disk, continuous star formation in disks and starbursts, reheating of galactic cold gas caused by SNe explosions, chemical evolution of stars and the multiphase gas, orbital decay of satellites due to dynamical friction, and satellite capture by the central galaxy. Nonetheless, we have implemented new ones concerning satellite interactions (galaxy harassment, ram pressure stripping), and the feeding of SMBH by mergers, disk instabilities and satellite interactions. We have also taken special care in the description of the internal structure of galaxies. In this contribution we focus on the general strategy followed to build our model of galaxy formation and evolution (§ 2), and the advantages of the modified PS dark-matter clustering model (§ 3) over those used in SAMs.

2 The Strategy of the Model

2.1 Philosophy

In the present model, the statistics of luminous objects are directly calculated from the distribution functions of the quantities involved in the different stochastic processes entering in their formation and evolution. These stochastic processes can be classified into two categories: those in which only the cumulative action of a large number of events is appreciable and those in which every single event has a noticeable effect. The former kind can be safely followed in a deterministic manner through the expected secular evolution they yield. The latter must instead be followed by taking into account the probability of each individual random event. In current SAMs dark-matter clustering is the only process dealt with in an individual probabilistic manner. One takes a set of random realisations of halo merger trees and computes the evolution of baryons along them in a deterministic way. In contrast, in our model we account for the full probabilistic character of any process requiring that treatment.

In the dark-matter clustering process we distinguish between minor and major mergers. Major mergers produce a big rearrangement of the structure marking *the formation of new halos* from old ones which are destroyed in the event. Therefore, these are clearly noticeable events which must be followed individually in a probabilistic manner. The random initial configuration of a halo is determined by its formation time and the configurations of its progenitors (characterized by the corresponding median mass) at that time, both quantities given by the modified PS model. Once the halo is formed it evolves through minor mergers contributing to *accretion* until its destruction in a new major merger. Since single minor mergers have a negligible effect we can simply follow their expected average action.

The evolution of the central galaxy during such an accretion phase depends on the halo properties such as the hot gas content, density, metallicity, and angular momentum as well as on the properties of the satellites it captures. Halo properties are fixed by the configurations of progenitors at formation, while the capture by the central galaxy of satellites depends on the orbits of such satellites. For a given halo potential well, these depend on the orbit initial conditions, namely the satellite radial location, the velocity modulus, and pitch angle. For those satellites much less massive than the main central galaxy, the capture produces a small effect so that the process can be dealt with, once again, in a deterministic manner through their average action. However, in the case of less numerous, massive satellites, the capture yields the destruction of the disk of the central galaxy and the formation of a new spheroid. For this reason, the possibility of any such a crucial event must be treated individually from the probability functions of the satellite radial location, velocity modulus, and pitch angle, all of them known in the present model. On the other hand, satellites experience random interactions with dark-matter particles (dynamical friction) and with other satellites (galactic harassment) with little effect each. These two processes can therefore be dealt with in a deterministic manner. More dramatic events, such as their capture by the central galaxy or the stripping of their interstellar gas, can also occur. But, since satellites are usually numerous and we do not care about their individual fate, we can assume any such dramatic events effectively realized, in a deterministic manner, in a fraction of them equal to the probability that this occurs. On the other hand, the fate of SMBHs is tightly related to that of their hosting galaxies so that this does not introduce any extra freedom in the evolution of the system.

2.2 Practical Implementation

For a discrete set of halo masses and redshifts we build a grid of halo configurations (corresponding to each halo mass and redshift but covering different halo formation times at each point of the grid) and their associated probability ready for interpolation (see Fig. 1). The grid is progressively filled from some high enough redshift down to that of the observing epoch and, at each redshift, for increasing halo masses $M_{\rm h}$ spanning the full relevant range. To obtain a new point in the grid we first calculate, for the halo located at that point, all possible formation times in equally probable intervals. For each formation time we calculate the typical progenitor masses and, for each of these progenitors, we extract a representative sample of possible configurations and the corresponding probabilities by simple interpolation inside the piece of grid previously built. Each combination of progenitor configurations fixes one possible initial configuration of the newborn halo with known probability. Finally, for each of these initial configurations we follow the random evolution of the halo and its baryonic content during the accretion phase from the merging time until the epoch of the new point in the grid.

The properties defining one specific configuration are: the halo formation time and initial mass, the mass and metallicity of the hot gas, and the properties of the member galaxies. The main central galaxy is characterized by: the total baryonic mass, the stellar and gaseous masses

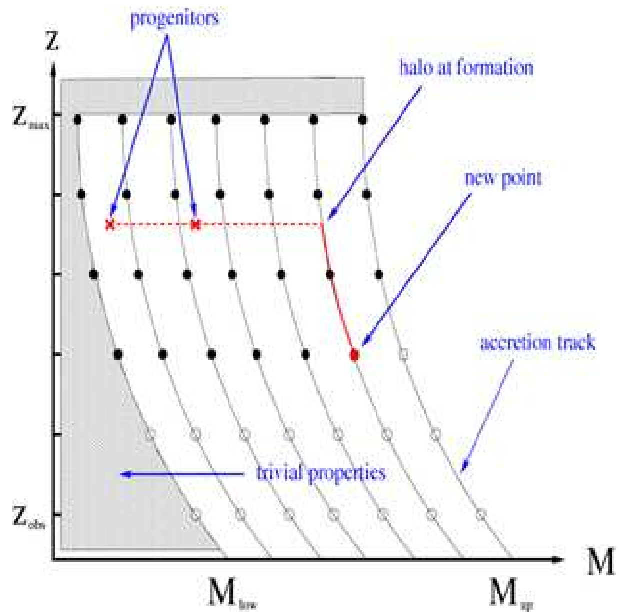

Figure 1: Scheme representing how the grid of halo properties used in the present model is build. For simplicity we only consider here one single formation time for the halo located at the new point of the grid which is being calculated. The hatched region represents the region where halos only contain just the amount of hot gas that thay have been able to trap since their formation.

and corresponding metallicities of both the bulge and the disk, the stellar formation history of each of these two components, the disk central surface density, and the mass of its central SMBH. While the information concerning satellites is stored in the form of occupation numbers in a binned multidimensional space having for axes: the radial location of the satellite, its formation time (defined as the time at which it become a satellite and could no longer grow at the centre of a halo), the total mass, the total baryonic mass, the stellar and gaseous masses and corresponding metallicities of both the bulge and the disk, the star formation history of each of these two components, and the central surface density of the disk. For each different type of satellites we also store the typical mass of their SMBH.

This strategy allows us to accurately compute, at each redshift, not only the possible properties of halos and their baryonic content in the whole range of relevant masses and associated probabilities, but also the properties of the IGM affected by feedback processes. This is very important because the evolution of the IGM strongly influences the subsequent development of galaxies. Such a coupling cannot be properly accounted for in current SAMs because there is no information about halos in the whole range of relevant masses at any redshift, but just about a few of them: those found at the corresponding level of the specific realisation of the halo merger tree which is being followed.

3 The Skeleton of the Model

Merger trees in SAMs are constructed using the popular, analytical, PS model for the clustering of dark-matter halos. This traces the growth of dark-matter halos (e.g., Governato al. 1999). However, it does not fix the internal structure of halos and its scaling evolution nor it is well suited for following the evolution of baryons within them. The use of the modified PS model avoids these shortcomings.

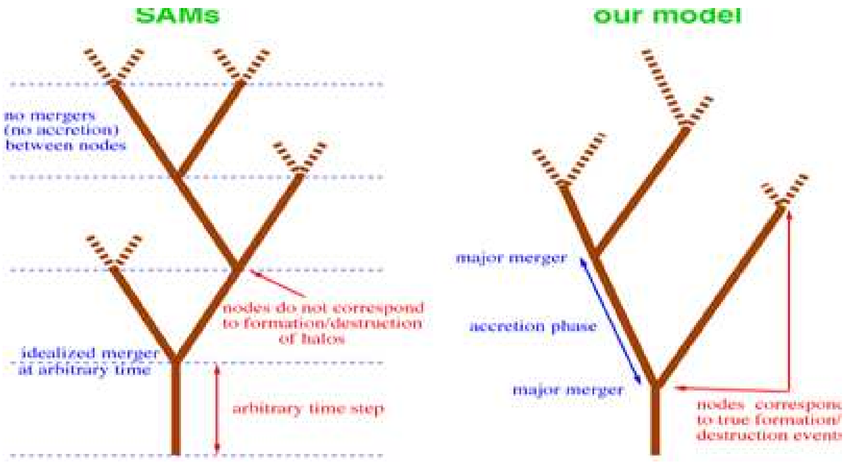

Figure 2: Schematic comparison between the idealized halo merger trees (with some adhoc finite resolution in both mass and time) that are implemented in SAMs and the more realistic ones that would result from the new version of the extended PS model used in our model.

3.1 Halo Growth

In the usual extended PS model real merger trees are infinitely ramified. For this reason one must use finite resolutions in both mass and time when implementing merger trees in practice which is at the origin of some drawbacks. The use of a finite resolution in mass prevents from properly dealing with the capture of small mass elements, what is usually interpreted as accretion. Recently, Cole et al. (2000) have introduced important improvements in this concern although all the matter estimated to be accreted during some interval of time is effectively applied at the end of it. On the other hand, to minimize the effects of a finite time step (and to ensure the binary merger approximation often used) a small time step between nodes must be adopted, restricting the initial redshift that can be reached. Even worse, the initial properties of a halo at a given node are determined from those of its progenitors at that node evolved until the next one. But, the time step is arbitrary and nodes do not trace the formation and destruction of halos. In the latest model by Cole et al. (2000) the evolution of halos is followed during what is supposed to be their lifetime, that is the interval of time between the moment at which some progenitor has reached half the mass of the halo and the time at which it doubles its mass. However, this is not fully satisfactory either since this estimated lifetime is still arbitrary (see Salvador-Solé, Solanes, & Manrique 1998 for a detailed discussion on this topic).

The new dark-matter clustering model does not have any of these shortcomings. This is a modified version of the usual extended PS model including one additional ansatz: the distinction between minor and major mergers according to the fractional captured mass relative to some fixed value $\Delta_{\rm m}$. Major mergers (i.e., those with fractional capture mass above $\Delta_{\rm m}$) are the only ones which are regarded as *true* mergers; minor mergers (below $\Delta_{\rm m}$) are only considered to contribute to accretion. Under these circumstances, one can naturally define the formation and destruction of halos as the last and next (major) merger, respectively, they experience. Accordingly, a halo preserves its identity between two such dramatic events despite the continuous, gentle growth of its mass through accretion.

Making use of the original extended PS formalism one can readily compute the instantaneous merger rate, the instantaneous mass accretion rate (between mergers), and the instantaneous specific halo capture rate through accretion. The distinction between minor and major mergers does not have any influence in the predicted mass fuction of halos, so that this is simply given by the usual PS expression. One can also derive the distribution of halo formation times and of progenitor masses. Using these distribution functions one can build accurate random realisations

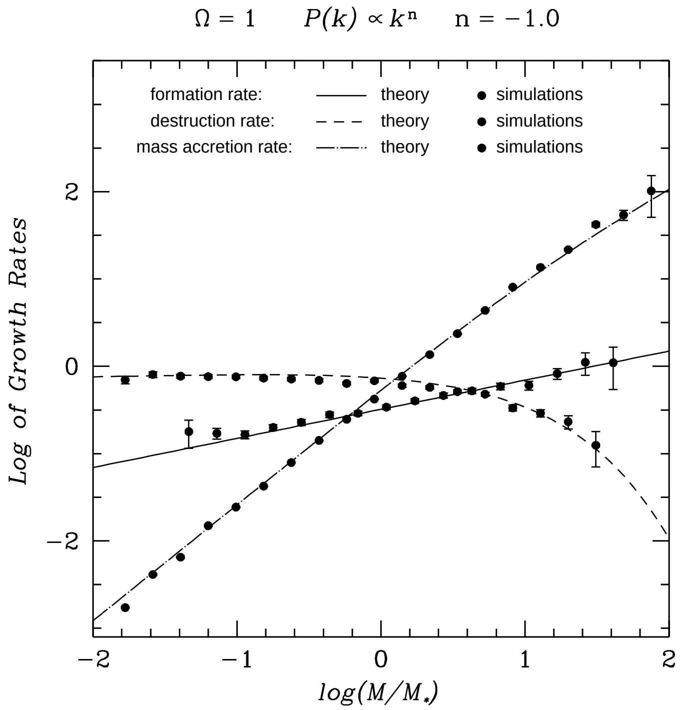

Figure 3: Formation rate (solid line), destruction rate (dashed line), and instantaneous mass accretion rate (dot-dashed line) at as a function of halo mass predicted by the modified PS clustering model with $\Delta_{\rm m} = 0.6$ for the case of the $n = -1$ scale-free cosmology.

of merger trees as required in SAMs or construct the grid of halo properties used in our analytical approach. Note that, because of the distinction between accretion and mergers, such merger trees automatically have a discrete branching without the need of imposing any finite resolution in time or mass (see Fig. 2). What is more important, the new merger trees are much more realistic: nodes in this discrete branching do trace mergers in which some halos are destroyed and others form, and their continuous evolution from node to node (separated now by non-arbitrary, uneven steps) does really trace the smooth change they experience owing to accretion during the time they preserve their identity. Similarly, the properties of halos in the grid used in our model are accurately calculated. We can even account for the detailed composition of the material which is being accreted at each moment: 1) substantial halos (with specific properties known from interpolation inside the grid), 2) tiny halos with trivial properties, (that is, just the amount of hot gas that the halo has been able to trap since its formation) and 3) diffuse gas of primordial origin mixed with the gas lost by halos at larger redshifts.

3.2 The Internal Structure of Halos

In Figure 3 we show the halo growth rates predicted by our modified PS model compared with the output of N-body simulations for a scale-free cosmology with power spectrum index n equal to -1 and a value of the parameter $\Delta_{\rm m}$ equal to 0.6. Similarly good agreement is found for any other cosmogony analyzed and *any reasonable value of* $\Delta_{\rm m}$ *used.* This means that the frontier between minor and major mergers is a mere convention as far as the mass growth of halos is only concerned. However, their internal structure depends crucially on $\Delta_{\rm m}$.

Dark-matter halos in high-resolution N-body cosmological simulations show a universal spherically averaged density profile of the form

$$\frac{\rho(s)}{\rho_{crit}} = \frac{\delta_{\rm c}}{s^{\rm n1}(1+s^{\rm n2})^{\frac{\rm n3-n1}{\rm n2}}}\,, \tag{1}$$

where s is the radial distance to the halo centre in units of the scale radius $r_{\rm s}$, and $\delta_{\rm c}$ is the characteristic halo density $\rho_{\rm c}$ in units of the critical density ρ_{crit}. The parameters $r_{\rm s}$ and $\rho_{\rm c}$ are linked by the condition that the mean density within the virial radius $R_{\rm h}$ of a halo of a given mass is 200 times the cosmic critical density. Therefore, the density profiles of halos at a given epoch depend on their mass $M_{\rm h}$ through one single scaling parameter, $\delta_{\rm c}$ or $x_{\rm s} = r_{\rm s}/R_{\rm h}$. Navarro, Frenk, & White (1997, NFW) found n1 = 1, n2 = 1, and n3 = 3, while Moore et al. (1998) using a higher resolution obtained n1 = 1.4, n2 = 1.4, and n3 = 2.8. In any event, it is found that the more massive, the less dense halos are, reflecting the fact that, in hierarchical clustering, less massive objects form earlier when the mean density of the universe is higher.

Salvador-Solé et al. (1998) showed, indeed, that the empirical mass-density relation is recovered in any hierarchical cosmogony assuming spherical halos with NFW density profiles with characteristic density proportional to the cosmic density at formation *provided only that* $\Delta_{\rm m}$ *is* ≈ 0.6. These authors also showed that such a proportionality is what one would expect if halos form (in mergers) with universal *dimensionless* density profiles, i.e., with a fixed value of $x_{\rm s}$ dependent only on the cosmology, and grow (during the accretion phase) by keeping the *dimensional* form of the density profile unaltered, i.e., $r_{\rm s}$ fixed, and simply expanding the virial radius according to the mass increase and the diminution of the cosmic density. This evolutionary scheme is supported by simulations (see, e.g. Tormen, Bouchet, & White 1997). On the other hand, as shown by Raig, González-Casado & Salvador-Solé (1998; RGS) it satisfies energy conservation provided only that the universal length scale $x_{\rm s}$ at halo formation takes the value drawn from the empirical mass-density relation. Therefore, it is clear that the ability of the modified PS model to recover the empirical mass-density relation in any cosmogony for $\Delta_{\rm m} \approx 0.6$ is not a coincidence but reflects the fact that the internal structure of halos is essentially set in major mergers in a universal adimensional form smoothly extending inside-out during the accretion phase.

In contrast, the original PS model used in SAMs puts no constraint on the internal structure of halos which must be rather arbitrarily chosen. (Note that the singular-isothermal profile commonly used in SAMs is scale-free and does not require any assumption concerning its scaling evolution.) Apart from the uncertainty introduced by that choice, there is the more serious problem that the adopted density profile will not conserve, in general, the total energy in the merging process (RGS). Hence, adopting the physically motivated evolution mentioned above, consistently fixed (for a given shape of the universal density profile) by the results of high resolution N-body experiments and the distinction between merger and accretion, represents a notable improvement with respect to the usual procedure. In addition, that evolution of the internal structure of halos harbours important information on the spatial location of the material collected by halos as they grow.

4 Conclusions

We have built a new model of galaxy formation and evolution in the spirit of SAMs. However, we have used a different approach concerning the strategy and the skeleton of the model. The main differences with respect to current SAMs are: 1) it is fully analytical, that is, it does not use neither Monte-Carlo, nor N-body simulations, dealing nonetheless with the full statistics of luminous objects, and 2) it makes use of a modified version of the extended PS model for the dark-matter clustering which allows us to accurately monitor the evolution of halos during the accretion phase between major mergers. The above features allow the tracking of the parallel evolution of the diffuse IGM since the dark age, and the radial location of galaxies inside groups and clusters. In addition, we incorporate a fine, consistent description of the dynamics of galaxies, including central SMBHs, and follow in detail their main environmental interactions, i.e., galaxy harassment and ram-pressure stripping.

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