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Galaxy Formation Now and Then

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Abstract.

I review the current state of our understanding of the galaxy formation and evolution process from the modeler’s perspective. With the advent of the cold dark matter model and the support of fast computers and advanced simulation techniques, there has been considerable progress in explaining the growth of structure on the largest scales and in reproducing some of the basic properties of galaxies and their evolution with redshift. However, many properties of galaxies are still only poorly understood or appear to be in conflict with the prediction of the cold dark matter model. I discuss in what direction the next generation of galaxy formation models may go and why a large space-based optical-UV telescope could be critical for the calibration and testing of these advanced models.

1. Introduction

The past couple of years have witnessed a dramatic increase in the quantity and quality of observations on the formation and evolution of galaxies. Galaxies are routinely identified at redshifts exceeding three and high resolution imaging allows us to study their internal structure. These data are complemented by high resolution spectroscopy of QSO absorption systems that provide further clues on the evolution of baryons in the universe. In fact, this increase has been so rapid that observations have outgrown their theoretical framework. Traditional approaches, which rely heavily on the morphological classification of galaxies and which intend to disentangle the star formation history of galaxies, seem outdated if compared with the much richer structure seen in galaxies at different redshifts.

Motivated by the increasing body of evidence that most of the mass of the universe consist of invisible “dark” matter, and by the particle physicist’s inference that this dark matter consists of exotic non-baryonic particles, a new and on the long run much more fruitful approach has been developed: rather than to model the formation and evolution of galaxies from properties of present day galaxies, it is attempted to prescribe a set of reasonable initial conditions. The evolution of galaxies is then modeled based on physical processes that are considered to be relevant such as gravity, hydrodynamics, radiative cooling and star formation. The outcome at different epochs is then confronted against
Figure 1. Time sequence of structure formation in a hierarchical clustering universe, here for the so-called ΛCDM model. The four snapshots correspond (from left to right) to redshifts of 9, 3.5, 1 and 0, respectively. The simulation box is 50 Mpc (comoving) on the side.

observational data. One scenario that has been extensively tested in this way is the model of hierarchical clustering, currently the most successful paradigm of structure formation.

In this contribution I review the main successes but also some of the generic problems of models in which structure forms by hierarchical clustering. I briefly compare the current state of the field with that 10-15 years ago followed by some speculations in which direction the field may develop in the next decade and how a large optical-UV telescope in space may support such developments.

2. The state of the field

Hierarchical clustering is at present the most successful model for structure formation in the universe. In this scenario, structure grows as objects of progressively larger mass merge and collapse to form newly virialized systems (Figure 1). Probably the best known representative of this class of models is the Cold Dark Matter (CDM) scenario. The initial conditions consist of the cosmological parameters (Ω, Ω_baryon, Λ, H₀) and of an initial density fluctuation spectrum such as the CDM spectrum. The remaining free parameter, the amplitude of these initial fluctuations, is calibrated by observational data, e.g., the measured anisotropies of the microwave background. Since the CDM model was introduced in the early 80s the values of these parameters have been revised and tuned to match an ever growing list of observational constraints, from the Ω₀ = 1, H₀ = 50 km s⁻¹ Mpc⁻¹, and σ₈ = 0.6 of the former “standard” Cold Dark Matter model to the currently popular “concordance” ΛCDM model. This ΛCDM model envisions an eternally expanding universe with the following properties (Bahcall et al. 1999): (i) matter makes up at present less than about a third of the critical density for closure (Ω₀ ≈ 0.3); (ii) a non-zero cosmological constant restores the flat geometry predicted by most inflationary models of the early universe (Λ₀ = 1 − Ω₀ ≈ 0.7); (iii) the present rate of universal expansion is H₀ ≈ 70 km s⁻¹ Mpc⁻¹; (iv) baryons make up a very small fraction of the mass of the universe (Ω_b ≈ 0.04 ≪ Ω₀); and (v) the present-day rms mass fluctuations on spheres of radius 8 h⁻¹ Mpc is of order unity (σ₈ ≈ 0.9). The hierarchical structure formation process in this ΛCDM scenario is illustrated in Figure 1, which depicts the growth of structure within a 50 Mpc box between
redshifts nine and zero. The ΛCDM model is consistent with an impressive array of well-established fundamental observations such as the age of the universe as measured from the oldest stars, the extragalactic distance scale as measured by distant Cepheids, the primordial abundance of the light elements, the baryonic mass fraction of galaxy clusters, the amplitude of the Cosmic Microwave Background fluctuations measured by COBE, BOOMERANG, MAXIMA and DASI, the present-day number density of massive galaxy clusters, the shape and amplitude of galaxy clustering patterns, the magnitude of large-scale coherent motions of galaxy systems, and the world geometry inferred from observations of distant type Ia supernovae, among others.

The hierarchical build-up is also thought to determine the morphology of a galaxy, most noticeably the difference between disk–like systems such as spiral galaxies (some of them barred) and spheroidal systems such as elliptical galaxies and bulges. This picture envisions that whenever gas is accreted in a smooth fashion, it settles in rotationally supported disk-like structures in which gas is slowly transformed into stars. Mergers, however, convert disks into spheroids. The Hubble type of a galaxy is thus determined by a continuing sequence of destruction of disks by mergers, accompanied by the formation of spheroidal systems, followed by the reassembly of disks due to smooth accretion (Figure 2). This picture of a hierarchical origin of galaxy morphology has been schematically incorporated in so-called semi-analytical galaxy formation models used to study the evolution of the galaxy population, but its validity in a cosmological setting has only just recently been directly demonstrated (Steinmetz & Navarro 2002).

Numerical simulations have been an integral part in the detailed analysis of the virtues of the CDM scenario. Only numerical techniques can account for the highly irregular structure formation process and for at least some of the complicated interaction between gravity and other relevant physical processes such as gas dynamical shocks, star formation and feedback processes. Simulations also provide the required interface to compare theoretical models with observational data and are able to link together different epochs. While simulations of structure formation on the larger scales have mainly used large massively parallel supercomputers, studies how individual structures such as galaxies or clusters of galaxies form in the ΛCDM scenario have heavily used special purpose hardware like the GRAPE (=GRAvity PipE) family of hardware N-body integrators (Sugimoto et al. 1990).

Although gas dynamical simulations were considerably successful in explaining some details of the galaxy formation process, the largest impact so far has been in the field of QSO absorption systems. Numerical simulations can reproduce the basic properties of QSO absorbers covering many orders of magnitude in column density (Cen et al. 1994; Zhang, Anninos & Norman 1995; Hernquist et al. 1996; Haehnelt, Steinmetz & Rauch 1996). Indeed, gas dynamical simulations were even responsible for a paradigm shift, as QSO absorbers are no longer considered to be caused by individual gas clouds. Absorbers of different column density (Ly-α forest, metal line systems, Lyman–limit systems and damped Ly-α absorption systems) are rather reflecting different aspects of the large-scale structure of the universe. While the lowest column density systems \((\log N \approx 12 - 14)\) arises from gas in voids and sheets of the “cosmic web”, sys-
Figure 2. Surface mass density of the gaseous and stellar components of ΛCDM halo at various epochs. Horizontal bars in each panel are 5 (physical) kpc long and indicate the scale of each figure. Rows 2, 4 and 5 show time sequences near some key evolutionary stage. Rows 1 and 3 decompose a galaxy at a particular redshift (left) into its constituents: old stars, young stars and gas (from left to right). Top row: The most massive progenitor at z=4, seen edge-on. Second row: The formation of a bulge and the rebirth of a disk. Third row: The appearance of the galaxy at z=1.8, seen edge-on. Fourth row: The tidal triggering of bar instability by a satellite resulting in the emergence of a rapidly rotating bar. Bottom row: A major merger and the formation of an elliptical galaxy.
tems of higher column density are produced by filaments ($\log N \approx 14 - 17$) or even by gas that has cooled and collapsed in virialized halos ($\log N > 17$).

Even though the above list of achievements appears quite impressive, it mainly addresses structures on scales exceeding a few hundred kpc. On smaller scales, theoretical models have at best provided some qualitative insights in the physics of the galaxy formation process, but we are still far from being able to make quantitative predictions of the properties of the galaxies now or at higher redshifts on those small scales. For example, even though we have some qualitative insight how the Hubble sequence has formed, we are still unable to account in detail for the mix of morphologies at different redshifts. To a lesser extent we still do not have the computing power in order to study the small scale properties for a cosmologically representative sample of galaxies, but the more important factor is likely our rather poor understanding of the astrophysical processes acting on such scales such as star formation, and energetic feedback from supernovae and stellar winds.

Furthermore, a list of findings has surfaced in the past few years that seem to be at odds with the model predictions: (i) Because of their negligible primordial velocity dispersion, cold dark matter particles can achieve enormous phase space densities. As a result, numerical simulations have consistently shown that near the centers of halos the density profiles of virialized CDM halos diverge as $r^{-1}$ (Navarro, Frenk & White 1996) or perhaps even as steeply as $r^{-3/2}$ (Moore et al. 1999a). These divergent profiles are at odds with the usual interpretation given to the “solid-body” HI rotation curves reported for some low surface brightness (LSB) dwarf galaxies (Flores and Primack 1994, Moore 1994). (ii) Another generic prediction of CDM models is that virialized galactic halos will typically be triaxial and have dense cores. Yet in a number of galaxies where detailed stellar and gas dynamical observations are possible, the dark matter contribution within the optical radius appears to be rather small: many disks, perhaps including the Milky Way, are “maximal” (see, e.g., Debattista & Sellwood 1999). (iii) High resolution N-body simulations indicate that, if the dark halo of our own Milky Way is made up of CDM, it should contain several hundred dark matter sub-condensations; a number that climbs to roughly one thousand if all halos within the Local Group are considered (Klypin et al. 1999, Moore et al. 1999b). On the other hand, observations of the Milky Way surroundings and of the Local Group reveal an order of magnitude fewer galaxies than expected in this picture (Mateo 1998). (iv) A difficulty indirectly related to the substructure problem concerns the angular momentum of gaseous disks assembled in hierarchical clustering scenarios. In the absence of heating, most of the mass of a galactic disk forming within a CDM halo is accreted through mergers of proto galaxies whose own gas components have previously collapsed to form centrifugally supported disks. Numerical simulations (Navarro & Benz 1991, Navarro, Frenk & White 1995, Navarro & Steinmetz 1997) show that most of the angular momentum of the gas is transferred to the surrounding halos during mergers. As a result, the spin of gaseous disks formed by hierarchical mergers is much lower than those of observed spirals.

It should be clear from this list that a considerable concerted effort is required by the community in order to promote our cosmological concordance model to a concordance model of galaxy formation. Considering the complexity
of the processes involved, progress is likely to continue to be drive by observations.

3. Where did we come from?

Before speculating what the state of the field may be like in 10–15 years, it may be illustrative to reconsider how the current state described above compares to the state of the field 10–15 years ago, i.e. before the advent of the Hubble Space Telescope and ground-based 8m class telescopes. Cosmological parameters were only very poorly constrained, the Hubble constant was known to only within a factor of 2, $\Omega$ at best to within a factor of ten. Hierarchical clustering in the form of a $\Omega = 1$ CDM model was already favored by most theorists, but it was certainly not accepted within the larger community as it is today. Similar statements can be made concerning the more basic concept that the morphological type of a galaxy may primarily reflect its merging history. From the observational side, barring some episodic evidence of very high redshift objects (radio galaxies, QSOs) and some indirect evidence for evolution (e.g. Butcher-Oemler effect), whose relationship to regular galaxies was quite unclear, galaxy properties were mainly determined only at very low redshift. In fact, most galaxy models did not, or if so only very schematically, include a cosmological context. Similarly, galaxy populations were mainly discussed in terms of non-evolution vs passive evolution models. It should be clear from this listing how rapidly the field of galaxy formation has changed in the past decade.

4. Prospects

Considering this rapid progress it seems (and probably is) impossible to make sound predictions how the field may change over the next ten or even fifteen years. Nevertheless, the exercise may be entertaining especially if one comes back for an evaluation after ten years. Assuming that the field continues to progress at the same pace and that basic concepts (like $\Lambda$CDM as a cosmological concordance model) remain unchanged, the following list appears to be “fair bets”:

- Microwave background experiments, in particular satellite missions like MAP and PLANCK, will accurately determine the cosmological parameters. Extragalactic astronomy will therefore be dominated by the quest to understand the formation and evolution of galaxies and the astrophysics behind it, and will no longer be just a tool to measure cosmological parameters.

- The Next Generation Space Telescope (NGST) will provide us with a look at the so-called dark ages of the universe, i.e. the universe at redshift larger than six. Furthermore, NGST will allow us to study the evolution of the stellar component between redshift 3 and 1, the epoch in which galaxies appear to have developed from some irregular bright clumps into the Hubble sequence.
• Astrometric missions like GAIA will provide a detailed dynamical and chemical record of how the Milky Way has been built up and how it transformed its gas into stars.

• In ground-based astronomy, the second generation of instrumentation on 8m-class telescopes will be routinely used, and (from an optimist’s point of view) first data may already come in from 30m optical telescopes.

• Galaxy formation models will largely benefit from the increase in computing power. According to Moore’s law, the speed of computers doubles every 18 month. If this trend continues to hold, then standard PCs in 15 years will have a speed comparable to the largest supercomputers today. By then numerical simulation should be capable of simulating cosmologically representative volumes (a few hundred Mpc) of the universe at a resolution better than a kpc. The understanding of astrophysics rather than the availability of sufficient CPU power will limit our insight into the details of the galaxy formation process.

What will be the role of a 8m optical/UV space telescope in this framework? Two potential applications that depend critically on the availability of large UV-sensitive instruments are:

• Observe the development of the Hubble sequence. Deep high-resolution imaging of UV dropout galaxies between redshift 3 and 1 will unravel the building blocks of typical L* galaxies at the present day epoch. Furthermore the transition from clumps at $z \approx 3$ to Hubble-type galaxies at $z \approx 1$ can be observed. By low-resolution spectroscopy, the kinematics and thus the development of scaling relations like the fundamental plane or the Tully-Fisher relation can be investigated.

• Create a 3D-map of the baryons in the universe between $z=3$ and $z=0$. Using fainter QSOs (as obtained, e.g., by the Sloan Survey) as background sources, several patches of the night sky can be probed by many lines-of-sight. High-resolution spectroscopy of these background sources will map out the distribution of baryons in the IGM and eventually provide detailed 3D maps of the gas density, temperature, metallicity and ionization state. The current paradigm that galaxies preferentially form at the intersections of filaments in the cosmic web can be directly probed. Studies of the transverse proximity effect measure in detail the evolution of the cosmic UV background and thus on the reionization history of the universe. Furthermore they can constrain the amount of beaming in the UV flux of QSOs.

Should these developments be accompanied by a corresponding increase in our understanding of how stars form, how they release energy to the ISM and thus how star formation interacts with the evolution of galaxies, we may indeed make a major step toward a standard model of galaxy formation by 2020.

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