Chapter 4
Galaxy Evolution in the Era of Digital Surveys: A Theoretical Overview

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Abstract In this review I will summarize the status of modern theories of galaxy formation and evolution. I will briefly introduce the main techniques employed and highlight recent successes and open problems.

4.1 Introduction

The explosion of digital surveys in the last decade has ushered in a new era of data richness and complexity. About 3 years ago, it was estimated that more than 1 PB (petabyte) of public data were electronically accessible, and that the data volume was growing at a rate of about 0.5 PB per year. Projections indicated that by 2020, more than 60 PB of archived data should be accessible to astronomers [1]. The growth of data in size is going to accelerate dramatically in the next years as new projects move into operation (e.g. LSST, ALMA, Euclid, SKA, just to name a few) so that it will likely turn out that the numbers given above are under-estimated. The datasets at our disposal are not just large (and will be huge in the next future!), but also multi-dimensional (i.e. for each astrophysical system, we have estimates for a number of different physical properties). Therefore, the big challenge for the future is not that of data storage, rather that of data mining (i.e. clever and efficient algorithms need to be developed in order to search within available databases, match data, and actually use them for scientific analyses).

On the theory side, we have witnessed a similar evolution: very large cosmological simulations have been completed over the last decades, by taking advantage of the rapidly growing computer performance and, at the same time, of the development of more sophisticated numerical algorithms. Theoretical models of galaxy formation are providing more and more accurate observables, and several predictions are nowadays available for completely independent models. Much of these data have been made publicly available through the development of dedicated databases [14]. This experience demonstrates that there is considerable interest from

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the astronomical community, and that this way of publishing results of theoretical research provides significant stimulus for additional scientific investigations.

4.2 Theoretical Models of Galaxy Formation

That of galaxy formation and evolution is a subject of great complexity. The very simple reason for that is that it is the result of a complex network of physical processes, most of which are quite poorly understood. Difficulties grow dramatically when one realizes that the different physical processes at play are entangled in a complex network of actions, back-reactions and self-regulations, operating on vastly different physical (from the scale of a black-hole to that of the Universe) and time scales (from the life-time of the most massive stars to the age of the Universe).

Despite this complexity, in the past years different methods have been developed to model galaxy formation and evolution in a cosmological context.

In semi-analytic models of galaxy formation, the evolution of the baryonic components of galaxies is modelled using *simple* yet *physically and/or observationally motivated prescriptions*. Modern semi-analytic models take advantage of high-resolution N-body simulations to specify the location and evolution of dark matter haloes, which are assumed to be the birth-places of luminous galaxies. Since pure N-body simulations can handle very large number of particles, this approach can access very large dynamic ranges in mass and spatial resolution. In addition, the computational costs are limited so that the method allows a fast exploration of the parameter space, and an efficient investigation of different specific physical assumptions. The main drawback of semi-analytic models is that they do not treat explicitly the gas-dynamics. This is instead done in direct hydrodynamical simulations. As a tool for studying galaxy formation, however, it is worth reminding that these methods are still limited by relatively low mass and spatial resolution, and by computational costs that are still prohibitive for simulations of galaxies throughout cosmological volumes. In addition, and more importantly, physical processes such as star formation, feedback, etc. still need to be modelled as *sub-grid*[1] *physics*, either because the resolution of the simulation becomes inadequate to treat a specific physical process or because (and this is, unfortunately, almost always true) we simply do not have a complete theory for the particular physical process under consideration.

In the following, I will discuss separately of 'central' and 'satellite' galaxies. The distinction is obvious (and convenient) from the theoretical point of view: here, central galaxies constitute a 'special' class of objects by construction, as they are the (in semi-analytic models often also the only) objects on which gas is allowed to cool. For observational data, the distinction is 'easy' (but now always, e.g. in

[1]The term is somewhat misleading as it gives the impression that the limits can be removed by increasing the resolution.

the Coma cluster there are two very bright members located in the proximity of the peak of the X-ray emission) for massive clusters, but typically very difficult, and perhaps inappropriate, for lower mass systems. With the aid of numerical simulations, however, this distinction is now routinely applied to observational data (for a discussion, see e.g. [6]).

4.3 Central Galaxies

One crucial ingredient to model the formation of massive central galaxies is the feedback from Active Galactic Nuclei (AGN). It has long been suspected that this powerful source of energy might play a crucial role in the so called 'cooling flow' problem, i.e. the observation that gas at the centre of massive galaxy clusters is apparently not condensing and turning into stars (at least not at a significant rate), although the observed X-ray emission implies a cooling time that is much shorter than the age of the system. Early galaxy formation models accounted for this form of feedback by simply assuming that cooling would be suppressed above some critical halo mass or circular velocity [e.g. 5, 13]. In the last decade, more sophisticated AGN feedback models have been included and these have confirmed that the 'radio-mode' feedback indeed represents a crucial ingredient to suppress the otherwise excessive number density of massive galaxies, and to keep their stellar populations old.

The efficiency of this feedback mechanism in suppressing the cooling flow at the centre of massive galaxy clusters has been extensively investigated using detailed hydrodynamical simulations. This work has shown that results strongly depend on a number of unknown parameters e.g. the duty cycle of the AGN, gas viscosity, and the geometry of the energy injection [see e.g. 2, 19]. Simulations have also clarified that the influence of this form of feedback, as resulting from current implementations, is not limited to the very central regions of galaxy clusters. Indeed, it results in an efficient extraction of enriched gas from star forming regions at high redshift. This affects for example the metallicity pattern of the intra-cluster medium leading to flatter metallicity gradients [7].

While current model implementations successfully reproduce the old stellar populations observed for massive galaxies, however, they all fail to reproduce their observed chemical abundances. Figure 4.1 shows the stellar mass-metallicity relation as predicted by the semi-analytic model presented in [3]. The model predicts a relatively tight metallicity-mass relation with a steep slope and a pronounced turn-over at the most massive end. The latter is in marked contrast with observational measurements. Similar results are found for completely independent semi-analytic models, as well as in hydrodynamical simulations [15, 17].

The middle and right panels of Fig. 4.1 show how the mass-weighted ages and metallicities of the central galaxies of massive haloes are affected when switching off the radio mode feedback (red histograms), and when adopting a different scheme for stellar (supernovae) feedback. As expected, when suppressing AGN feedback,

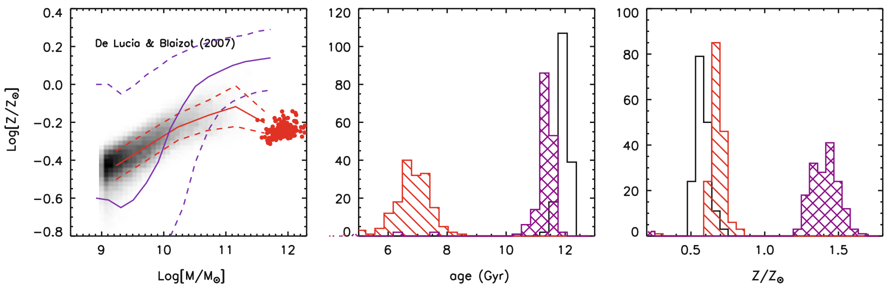

Fig. 4.1 From [4]. The *left panel* shows the metallicity-stellar mass relation predicted by the semi-analytic model presented in [3]. The *grey map* shows the distribution of model galaxies. The *red solid line* shows the median, and *dashed red lines* the 16th and 84th percentiles of the distribution. *Filled circles* show the location of the central galaxies of haloes with $M_{200} > 5 \times 10^{14}\,\mathrm{M}_\odot$. *Purple lines* show the observational measurements by [10]. The *middle* and *right panels* show the distributions of mass-weighted ages and stellar metallicities for these massive central galaxies. *Black histograms* correspond to the fiducial model described in [3], while *red* ones correspond to the same model but with AGN feedback switched off. *Purple histograms* correspond to a model with AGN feedback but using a different scheme for stellar feedback

late time gas cooling allows recent star formation episodes that make the galaxies more massive and significantly younger. The stellar metallicity is however not significantly altered because the metallicity of the cooling gas is relatively low ($\sim 0.2\,Z_\odot$, in agreement with observational data). Modifying the scheme adopted for stellar feedback can have more drastic effects on the metallicity distributions, as shown by the purple cross hatched histograms. In this case, the model adopted results in less efficient outflows, and therefore longer star formation histories and higher stellar metallicities. Unfortunately, this model also over-predicts the number density of massive galaxies. These findings suggest that the difficulty of current models in simultaneously reproducing the observed ages and metallicities of the most massive galaxies highlights a fundamental problem with the schemes currently adopted to model star formation, feedback, and recycling of gas and metals.

The formation of the most massive galaxies is believed to be connected with the formation of the diffuse stellar component. Hydrodynamical simulations suggest that most of the stars found in the diffuse component of massive clusters come from particles that are unbound during galaxy mergers, with a minor fraction coming from tidal stripping of satellite galaxies [16]. Unfortunately, however, simulation results do not converge: increasing the resolution typically leads to increasing fractions of diffuse light. In addition, a recent work by [18] has pointed out that a significant portion of the diffuse component identified in hydrodynamical simulations forms in cold gas clouds stripped from infalling structures. Additional work is needed to clarify if (and how much of) this ‘intra-cluster star formation’ is due to spurious numerical effects (e.g. fluid instabilities, that are not well treated in smoothed particle hydrodynamical codes, might be able to destroy these clouds and reduce this contribution).

4.4 Satellite Galaxies

Figure 4.2 shows the observed (blue) stellar mass function for galaxies in clusters at low and intermediate redshifts. Observational data are compared with predictions from the galaxy formation model published in [3]. In this case, central galaxies have been excluded both for the data and for the models. The figure clearly shows that this particular model over-predicts the number densities of the satellite galaxies with mass just below the knee of the mass function. At low redshift, the model also over-predicts the number densities of the most massive galaxies, but the statistics here are lower and the large errors on the estimated stellar mass can affect significantly the shape at the massive end of the mass function. Recent theoretical work has pointed out that this excess of low-to-intermediate mass galaxies plagues all recent published semi-analytic models as well as hydrodynamical simulations [21, and references therein]. When including a strong stellar feedback, models are able to reproduce the observed galaxy stellar mass function in the local Universe, but they then consistently over-predict the number density of sub-M_* galaxies at higher redshift. Satellite model galaxies also tend to be less active than estimated observationally [22].

Early attempts to address these problems focused in particular on the assumption that the hot gas reservoir associated with infalling galaxies would be instantaneously stripped after accretion. Although improved, however, results from more sophisticated treatments were still not found to be in good agreement with observational data [8, 11]. Fontanot et al. [9] showed that the excess of low and intermediate mass galaxies in the models is mainly driven by an over-efficient formation at high redshift of central galaxies, with circular velocities $\sim 100 - 200\,\mathrm{km\,s^{-1}}$. In fact, this is the very same problem that is found in hydrodynamical simulations: gas cooling is very efficient at high redshift and in small and compact haloes. This leads to the formation of clumps that then merge via dynamical friction transferring angular momentum to the dark matter and resulting in disk galaxies that are more compact and rotate less rapidly than observed spirals. Once again, the likely solution to these problems reside in a better treatment of the feedback and recycling of gas. In a recent work, [12] showed that a model that includes an explicit dependence of the gas recycling time-scale on halo mass can successfully reproduce the observed evolution of the galaxy stellar mass function. The predicted passive fraction of low mass galaxies remains, however, significantly larger than observational measurements. The model also adopts some extreme values for other physical parameters (e.g. the chemical yield).

4.5 Final Remarks

As discussed above, recent theoretical work has identified a number of persistent problems that are common to independently developed models, and to different methods to model the formation of galaxies in a hierarchical context. In particular,

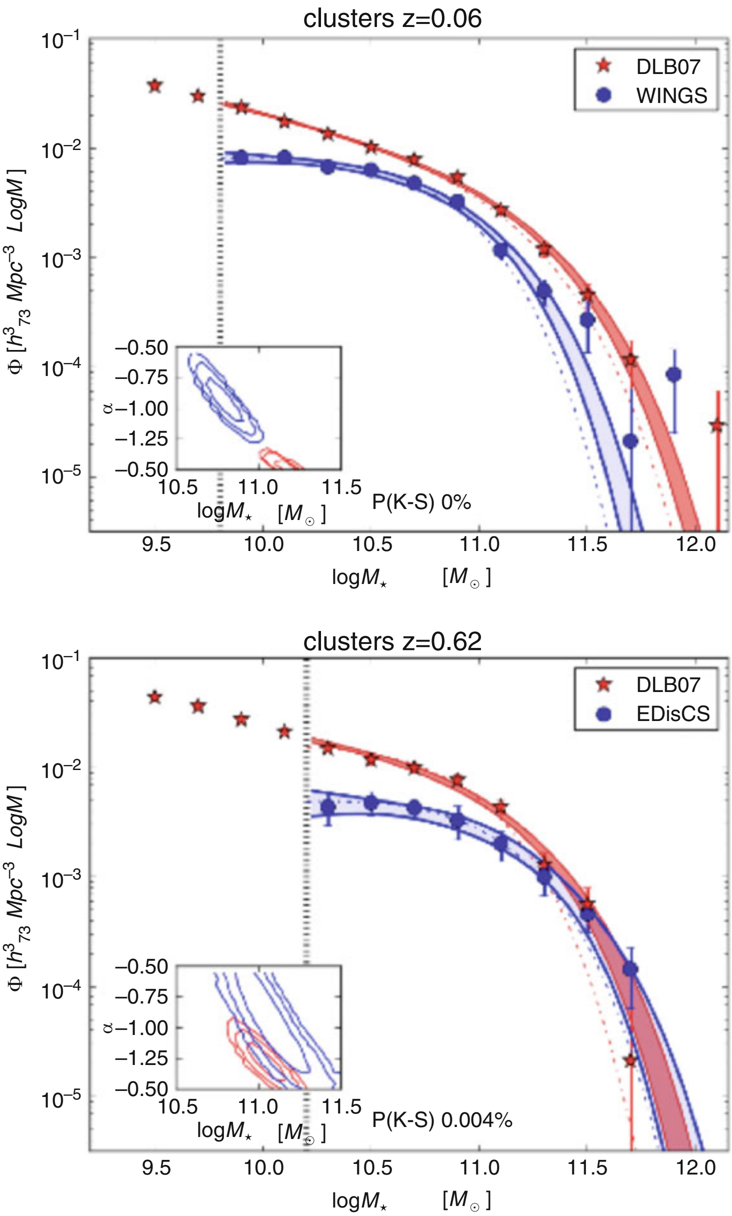

Fig. 4.2 From [20]. Observed (*blue*) and projected model (*red*) mass functions, for galaxies in clusters at low (*top*) and intermediate (*bottom*) redshift. Error bars on the y-axis are computed combining the Poissonian errors and the uncertainties due to cosmic variance or cluster-to-cluster variations. *Solid lines* and *shaded areas* represent Schechter fits with 1σ errors, *dashed lines* represent the mass function obtained from the deconvolution with the uncertainties on masses. See original paper for details

the number densities of low-to-intermediate mass galaxies are over-predicted; galaxies in this mass range are typically older than observed; the metal content of massive central galaxies is under-estimated with respect to observational determinations. I argue that these are probably different manifestations of the same problem, that likely relies in our (simplified) treatment of the self-regulation between star formation and feedback.

The era of 'data tsunami' has just started. In order to be prepared to interpret in a theoretical framework the new wave of data coming, it is necessary, on the one hand, to clarify the origin of the above mentioned problems and identify plausible and physically motivated solutions. On the other hand, further developments of the available models are required so as to extend the range of predicted observables. E.g. an explicit modelling of the transition between atomic and molecular gas and a detailed treatment of the chemical compositions of different galactic phases are necessary to take advantage of ongoing and planned programmes. Only through keeping this very close link between theoretical predictions and observable data, will it be possible to shed light on the physical processes governing galaxy formation and evolution as a function of cosmic time.

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