Semianalytic modelling of the formation and evolution of galaxies

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Abstract

The high redshift observations of galaxies now becoming available from the Hubble Space Telescope and from large ground based telescopes are opening fresh windows on galaxy formation. Semianalytic models of galaxy formation provide us with a powerful tool to interpret and understand these exciting new data. In this review, we explain the philosophy behind this class of model and outline some of their remarkable successes, focussing our attention on the formation of elliptical galaxies and on the properties of galaxies at high redshift. Now that the recent discovery of star forming galaxies at $z \sim 4$ has made possible the construction of the cosmic star formation history, which is in good agreement with our model predictions, it appears that a coherent picture of galaxy formation is beginning to emerge.

1   Introduction

The fundamental questions of 'How and when do galaxies form?' and 'What are the major influences that determine their appearance?' are still unresolved. However, with the development of powerful theoretical techniques and the increasing availability of high redshift observations, impressive progress is being made towards changing this situation.

In the traditional approach to modelling galaxy evolution, pioneered by Tinsley (1980), a set of local galaxy templates are combined with the locally observed number densities to make predictions of the faint galaxy counts and redshift distributions. Simple *ad hoc* parameterisations can be made to describe the evolution of the luminosity and number density of galaxies in order to improve the fit

to the deepest observed counts. In this retrospective approach, the formation epoch of galaxies is placed at some arbitrary high redshift.

Since the start of the 1980's however, our understanding of the growth of structure in the universe has increased enormously. In the currently favoured cosmologies, the universe is gravitational dominated by some form of dark matter. Dark matter halos grow hierarchically through mergers and accretion. The formation of structure through the gravitational amplification of small, primordial density fluctuations is now well understood, mainly as a result of large numerical N-body simulations of this process (*e.g.* for a recent example see Jenkins et al 1997). The growth of dark matter halos can be equally well described analytically, at least in a statistical sense, via the theory developed by Press & Schechter (1974) and its extensions (Bond et al 1991, Bower 1991), as demonstrated by comparison with N-body simulations by Lacey & Cole (1994).

The analytical description of hierarchical clustering can be used to construct Monte-Carlo realisations of the complete merger history of dark matter halos. The merger history of a halo is then combined with a set of simple rules that encapsulate our present understanding of the processes involved in galaxy formation:

- The cooling and condensation of gas within dark matter halos (Rees & Ostriker 1977, Silk 1977, Binney 1977; White & Rees 1978).

- Star formation from the reservoir of gas that cools during the halo lifetime.

- Feedback process, such as supernovae and stellar winds, that regulate the star formation. This is necessary in hierarchical models to prevent all the gas from cooling and forming stars in small, dense objects at high redshift in which cooling is very efficient (White & Rees 1978, Cole 1991, White & Frenk 1991).

- Mergers of galaxies – galaxies can coalesce on a much longer timescale than their host dark matter halos.

- The conversion of star formation histories into spectra and broad band luminosities using stellar population models (*e.g.* Bruzual & Charlot 1993).

The result is a physically motivated, semianalytic model that is driven by structure formation in the universe. The inputs of the traditional models, the luminosity function and morphological mix of galaxies, are actually *predicted* by semianalytic models. Contrary to first expectations, surprisingly few parameters are needed to specify the model, once a cosmology has been adopted. These

parameters are set by reference to a subset of local observations (*e.g.* matching to L_* of the B-band luminosity function in the model of Cole et al 1994, or putting a galaxy in a Milky Way sized dark matter halo on the Tully-Fisher relation in the models of Kauffman, White & Guiderdoni 1993). The remaining output, number counts, colours, redshifts distributions etc., is then predictive.

It is important to realise that the models do not set out to make a 'fit' to an observable such as the local luminosity function in the usual sense – rather we attempt to choose the physical parameters to achieve the best *match* or *comparison* to observed datasets. The task of the model is to predict the entire star formation history of every type of galaxy, in all environments, starting from a set of primordial density fluctuations. We also predict the size and metallicity of the galaxy disk and bulge, the rotation speed of the disk, the amount of cold gas, the amount of hot gas in the halo and the morphology. Once we have normalised our model to the local luminosity function or Tully-Fisher relation there is no *a priori* reason to expect to obtain the reasonable level of agreement we find with observables, such as for example, the observed star formation history of the universe or the abundance and clustering of Lyman break galaxies. The semianalytic approach is complementary to fully numerical simulations with gas; several of the rule parameterisations used are calibrated against numerical results whilst the semianalytic models can explore a much wider parameter space than is feasible with numerical simulations.

The models have successfully reproduced and predicted a wide range of galaxy observables: global properties including the shape of the luminosity function, colours, faint counts, redshift distributions (Lacey et al 1993, Kauffmann et al 1993, 1994, Cole et al 1994, Heyl et al 1995) and more specific effects such as the growth of brightest cluster galaxies (Aragón-Salamanca, Baugh & Kauffmann 1997). In this review we restrict our attention to two areas that have a direct bearing on the subject of this meeting - the formation of elliptical galaxies and the properties of galaxies at high redshift.

2 The formation of elliptical galaxies

The traditional picture of elliptical galaxy formation as a monolithic collapse involving a single burst of star formation at high redshift (Eggen, Lynden-Bell & Sandage 1962) has been challenged by two recent observations. Kauffmann, Charlot & White (1996) have shown, using data from the CFRS (Lilly et al 1995) and from the Hawaii Deep Survey (Cowie et al 1996) that only one third the number of nearby bright elliptical galaxies seen today were already in place

at $z \sim 1$ or had the colours of old, passively evolving stellar populations. In an analysis of deep optical and infrared images, Zepf (1997) has demonstrated that too few galaxies with very red colours are seen when compared with the number expected if ellipticals formed exclusively at high redshift.

Semianalytic models propose a scheme whereby galactic bulges result from galaxy mergers (Kauffmann et al 1993; Kauffmann 1995, 1996; Baugh, Cole & Frenk 1996a), as originally suggested by Toomre (1977). In the models, quiescent star formation builds a disk, whilst material accreted during mergers is added to a bulge component. A major merger, in which the primary galaxy accretes more than some specified fraction of its own mass, (typically 30% or more), results in the destruction of the stellar disk and a burst of star formation, with all stars being placed in the bulge. Hence in a merger picture, the morphology of a galaxy changes with time. After a major merger, a galaxy will initially be a pure bulge system and then quiescent star formation can start to form a new disk.

Such models have been able to reproduce a range of observations that distinguish between galaxies according to their morphologies. Baugh, Cole & Frenk (1996b) demonstrated that semianalytic models could explain the form of the faint counts of galaxies from HST images separated by morphological type (full references are given in Baugh et al. 1996b) – Plate 5. Kauffmann (1995) and Baugh, Cole & Frenk (1996a) have shown that the population of galaxies found in model clusters at different redshifts exhibit evolution of the form detected by Butcher & Oemler (1984).

A key observation in pinning down the star formation history of spheroidal systems is the colour-magnitude relation for cluster E and SO galaxies (Bower, Lucey & Ellis 1992). Perhaps counter-intuitively, semianalytic models naturally reproduce the small scatter observed in the colours of early type galaxies in clusters (Kauffmann 1996, Baugh et al. 1996a) and also the slope of the colour-magnitude relation when chemical enrichment is incorporated (Kauffmann & Charlot 1997).

Baugh, Cole & Frenk (1996a) found that 50% of bright ellipticals taken from all environments in their model experience a major merger between $z = 0$ and $z = 0.5$. At these redshifts, typically only around 5% of the mass of the final galaxy is formed in the burst of star formation that accompanies the major merger. The bulk of the stars have already formed in the progenitors that merge together – the major merger represents the assembly of these stars into an elliptical. This can be contrasted with the situation at high redshift; an elliptical that experiences a major merger between $z = 1.5$ and $z = 3$ can form around 30% of its final stellar mass in the accompanying burst. Kauffmann

(1996) makes the same point by showing that the mean age of stars in cluster ellipticals is more than 10 Gyr, whilst the last major merger occured on average 7 Gyr ago.

3   The star formation history of the universe

Hierarchical clustering theories naturally predict that galaxy formation occured recently, reflecting the way in which dark matter halos are assembled. Cole et al (1994) showed that typically 50% of the stellar mass at $z = 0$ has formed since $z = 1$ in certain CDM models (Figure 1) – this is due to a combination of the strong feedback employed and the normalisation of the density fluctuations to reproduce the abundance of rich clusters. At $z = 3$ a mere 5% of today's global stellar mass was in place. The observed star formation history of the universe (Madau et al 1996) is remarkably close to the predictions of the semianalytic model, plotted as the time derivative of Figure 1 (Baugh et al. 1997; Figure 2). Again, it is important to stress that the model parameters are set to produce a reasonable match to the local galaxy luminosity function; indeed none of the data points in Figure 2 existed when the paper by Cole et al was published. The cosmic star formation history is a genuine prediction of the model – none of the model parameters have been 'tuned' to give a 'good fit' to the observed star formation rate density.

The interpretation of the data points in Figure 2 is subject to a number of caveats. First, the conversion from Hα or UV flux to star formation rate depends upon the form of IMF adopted; for example the amount of flux at 1500Å produced by a star formation rate of one solar mass per year is three times higher with a Miller-Scalo IMF than if a Scalo IMF is used – both these IMFs are compatible with local determinations of the form of the IMF. Second, the observations generally probe a limited range of galactic star formation rates. To get the integrated rate per unit volume, some form of extrapolation is necessary and is usually done by fitting a Schechter function to the observed star formation rates. Last, and perhaps most uncertain, is the correction for the presence of dust in the primeval galaxies. Even a small amount of dust will attenuate the UV flux, leading to a potentially serious underestimate of the amount of star formation in the galaxy. Upper limits (Kashlinsky et al 1996) and tentative detections (Puget et al 1996) of the infrared background light currently provide some constraints on the amount of starlight from galaxies that can be reprocessed into the infra-red by dust (Madau, Pozzetti & Dickinson 1997). A comparison of the intrinsic colours of high redshift galaxies with the observed,
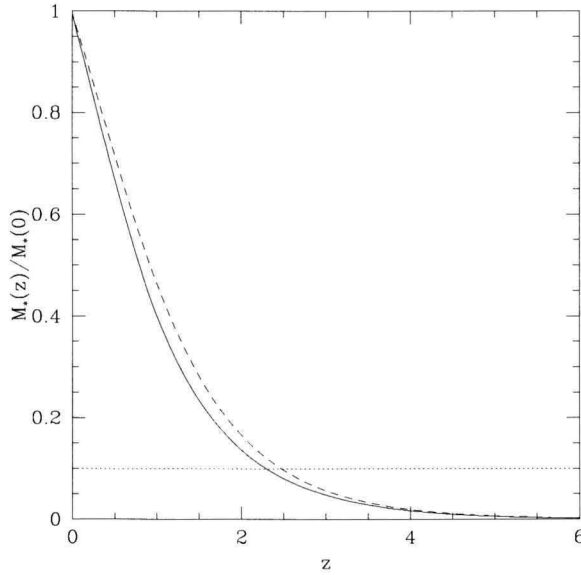
Figure 1. The global build-up of stellar mass in two hierarchical structure formation models. The curves show the fraction of the present day mass in stars that was in place by a given redshift. The solid line shows standard CDM and the dashed line shows a flat, low density CDM model. The horizontal line marks 10% of the present day stellar mass. The close agreement between the two cosmologies can be traced to the strong feedback used and the normalisation of the density fluctuations to reproduce the present day abundance of rich clusters.

dust reddened colours is possible, although this is sensitive to the choice of model galaxy and to the form of the dust extinction law adopted. For the most extreme case in which the model galaxies are young starbursts, and therefore extremely blue, and the greyest dust extinction curve is used, a correction to the inferred star formation rate by a factor of up to ten is suggested (Meurer et al 1996). For less extreme assumptions a factor in the range $1.5 - 3$ is advocated (Pettini et al 1997, Dickinson et al in preparation).
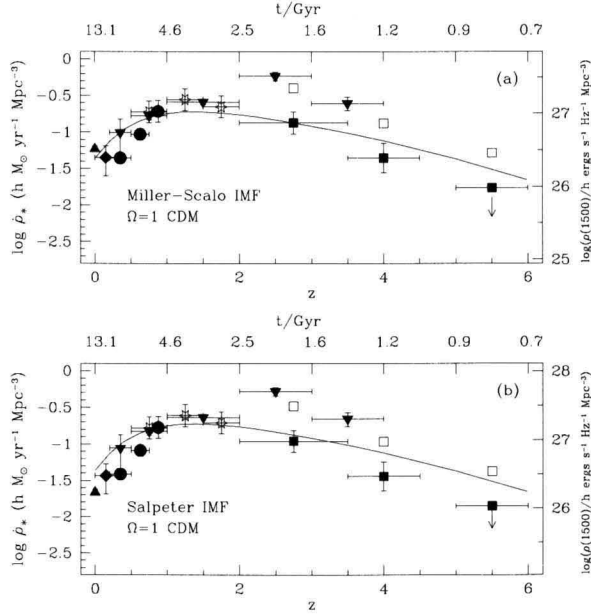
Figure 2. The cosmic star formation history. The lines show the predictions of the semianalytic models for the star formation rate per comoving volume in a CDM universe with the critical density, which is essentially the prediction made by Cole et al (1994). The right hand axis shows the corresponding flux density at 1500Å. The symbols show a number of determinations of the star formation rate at different redshifts, using the luminosities at different rest frame wavelengths. The data are taken from the following references: triangle − Gallego et al (1995); diamond − Treyer et al (1997); circles − Lilly et al (1995) ; inverted triangles − Sawicki et al (1997); stars − Connolly et al (1997); filled squares − Madau et al (1996). The conversion from UV flux to star formation rate depends upon the IMF: (a) shows a Miller-Scalo IMF and (b) shows a Salpeter IMF. The open squares show a correction of a factor of 3 (Pettini et al 1997) to the Madau et al points to account for possible obscuration by dust.

4 The clustering of Lyman-break galaxies

The extraction of high redshift galaxies from deep images of the sky using exposures taken in several filters has made the detection of large numbers of primeval galaxies possible (Steidel & Hamilton 1992). High redshift star forming galaxies are identified by their Lyman break moving through one of the filters, giving a

red colour, whilst the other filters indicate a blue colour. This technique has been applied from the ground (Steidel et al 1996) and with the HST (Madau et al 1996) to identify galaxies in the redshift range $z = 2 - 4.5$ (Steidel et al 1997; Lowenthal et al 1997).

Using the full colour selection employed by Steidel et al (1996) and including attenuation of the light due to intervening cold gas (Madau 1995), semianalytic models have demonstrated that a range of CDM models can reproduce the observed abundance of Lyman break galaxies, in spite of the fact that typically only 5% of the stars that will have formed by today are already in place at this time (Baugh et al 1997). The models give the mass of the dark matter halo that hosts the Lyman break galaxy, allowing a bias parameter for these objects to be computed using the formalism developed by Mo & White (1996). Baugh et al find a bias between fluctuations in Lyman break galaxies and the fluctuations in the underlying density distribution of $b = 4$ at $z = 3$. Since the Lyman break galaxies are found to form in the most massive halos that have collapsed at high redshift, it is natural for these objects to be highly biased tracers of the mass distribution.

The observation of large numbers of Lyman break galaxies, followed up by spectroscopic confirmation of their redshifts, will soon make it possible to measure the angular and spatial correlation functions of these objects. Baugh et al (1997) use their computation of the bias parameter of the Lyman break galaxies to make an estimate of these correlation functions. The approximations used in this calculation break down on small scales where the clustering signal is strongest.

In order to improve the accuracy of these predictions, in collaboration with Fabio Governato, Tom Quinn and Joachim Stadel, we have combined semianalytic modelling with high resolution N-body simulations. We identify dark matter halos in the simulation at $z = 3$ and run the semianalytic galaxy formation model for each halo mass. Halos that the semianalytic model predicts should contain a Lyman break galaxy are labelled and the correlation function of these objects is measured (Figure 3). Some of the more massive dark matter halos contain more than one Lyman break galaxy. The bias parameters measured in the simulation are in good agreement with those predicted analytically. Steidel et al (1997) have discovered a large concentration of Lyman break galaxies in one of their fields (see also the contribution of John Peacock to this volume). Using our simulations we have found that such structures are not unexpected, even in a standard Cold Dark Matter simulation. The semianalytic model allows us to reach this conclusion without having to resort to making uncertain assumptions about the masses of halos that contain Lyman break galaxies or
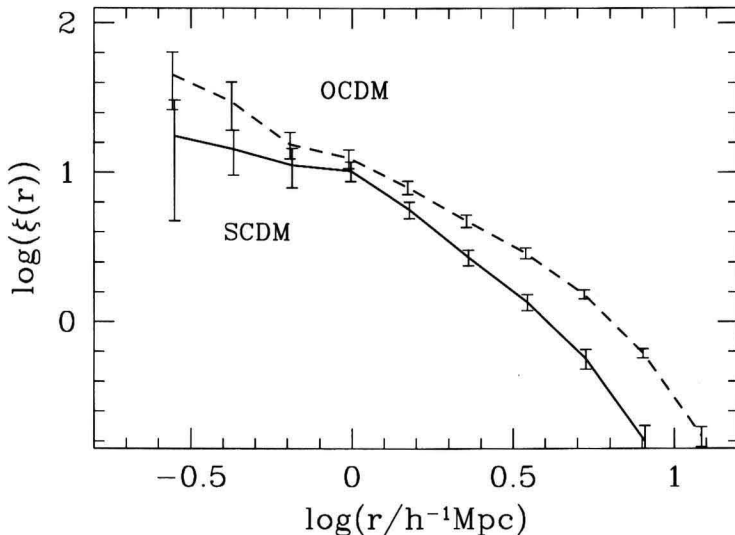
Figure 3. The correlation function of Lyman break galaxies, computed by taking the halos identified in a high resolution N-body simulation at $z = 3$ and using the semianalytic model of galaxy formation to predict which halos should contain Lyman break galaxies. Two cosmologies are shown: standard CDM (SCDM) and a low density open model (OCDM). The error bars are bootstrap estimates.

about the number of these objects per halo – indeed the result that a dark matter halo can contain more than one Lyman break galaxy has an important bearing on the assessment of the significance of the observed concentration of Lyman break galaxies.

5 Conclusions

This is an exciting period for the study of galaxy formation which promises to continue with the construction of more large telescopes and observations being carried out of galaxies at many different redshifts. Many of the details of the galaxy formation process remain unknown and are currently inaccessible to numerical investigation. However, in view of the remarkable successes enjoyed by semianalytic models, especially when one considers the magnitude of the task

attempted, it would appear that any future, more complete theory of galaxy formation will share many features in common with the models discussed here.

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