

Ab Initio Galaxy Formation

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Abstract. The formation and evolution of galaxies can be followed in the context of cosmological structure formation using the technique of semi-analytic modeling. We give a brief outline of the features incorporated into the semi-analytic model of Cole *et al.* (1999). We present two examples of model predictions that can be tested using photometric redshift techniques. The first prediction, of the star formation history of the universe, has already been shown to be in broad agreement with the observational estimates. The second prediction, of the evolution of galaxy clustering with redshift, will be addressed with some of the forthcoming deep, multi-filter imaging surveys discussed at this meeting.

1. Introduction

The main ideas of hierarchical galaxy formation were set out more than twenty years ago by White & Rees (1978). These authors proposed that galaxy formation is a two stage process. In the first stage, dark matter haloes form by the dissipationless accretion of smaller units and through mergers. The second stage consists of the dissipative condensation of baryons to the center of dark matter haloes. After the first stars form from this gas, feedback effects can play an important role, regulating star formation and thus controlling the efficiency of galaxy formation in dark matter haloes of different mass.

The past decade has seen the development of semi-analytic models to study the *ab initio* formation and evolution of galaxies, within the framework of the growth of structure in the dark matter (e.g. Kauffmann *et al.* 1993, Cole *et al.* 1994, Somerville & Primack 1998). The dissipationless physics in these models is well understood and has been explored extensively using N-body simulations of gravitational instability (for recent illustrative examples see Jenkins *et al.* 1998 and Ghigna *et al.* 1999). The dissipative processes are, however, not at all well understood. The idea that hot gas would cool radiatively to make galaxies was also proposed in the late 1970s, but numerical simulations of this process with sufficient resolution to identify “galaxies” within cosmological volumes are only now becoming possible (Pearce *et al.* 1999). In the semi-analytic models, the processes of gas cooling, star formation, the attendant feedback and galaxy mergers are described by a set of simple, physically motivated rules. The values of the required parameters are set by comparing the model results with properties of the local galaxy population, such as the field galaxy luminosity function or the Tully-Fisher relation (see Somerville & Primack for a discussion

of the various models), to produce a fully specified model with strong predictive capabilities.

2. *Ab Initio* Galaxy Formation

The semi-analytic model described by Cole *et al.* (1999) is a development of the one described in earlier papers by the Durham group (e.g. Cole *et al.* 1994, Baugh, Cole & Frenk 1996). In addition to the use of improved algorithms, for example in the Monte-Carlo generation of dark matter halo merger histories, a broader range of physical processes is now modeled, greatly expanding the number of galaxy properties that we can predict.

The size of a galactic disk is determined by the conservation of the angular momentum of cooling gas. The gas is assumed to have the same specific angular momentum profile as the dark matter halo, whose spin originates from tidal torques that act during its formation. The size of a bulge is computed by conserving energy when two fragments merge to form the bulge and applying the virial theorem. The condensation of baryonic material at the center of a dark matter halo alters the structure of the halo, causing a contraction. The resulting size of the disk and bulge components depends upon the self-gravity of the baryons and the gravity of the modified dark matter halo.

The chemical enrichment of the baryons is also followed in the new model. Episodes of star formation result in the production of metals that can be transferred to the reservoirs of hot and cold gas within each dark matter halo. Feedback from star formation can reheat some of the cold gas, thus providing a further channel through which to transfer metals to the hot gas component. The calculation of the scale length of the galactic disk and of the metallicity of the cold gas allows us to obtain an optical depth for the disk, and hence to calculate the extinction of starlight by dust.

The main property of the local galaxy population that we use to constrain our models is the field galaxy luminosity function. Figure 1 shows two recent determinations of the luminosity function in the b_J -band. These surveys are taken from the same parent photometric catalogue, but extend to different apparent magnitude limits. The solid line shows the luminosity function of the fiducial model of Cole *et al.* (1999), which is in very good agreement with the measurement by Zucca *et al.* (1997) over a dynamic range of $\sim 10^4$ in luminosity and $\sim 10^5$ in space density. The dotted line shows a model in which the feedback arising from star formation is assumed to be a much stronger function of circular velocity, as in the model of Cole *et al.* (1994). Star formation in low circular velocity objects is extremely inefficient in this case, and a reasonable match is obtained to the flat faint end slope of the luminosity function found by Ratcliffe *et al.* (1998). The dashed line shows the slope of the dark matter halo mass function; this slope, $\alpha \sim -1.8$, would be obtained for the luminosity function in the absence of feedback and if galaxies merged on the same timescale as their parent dark matter haloes.

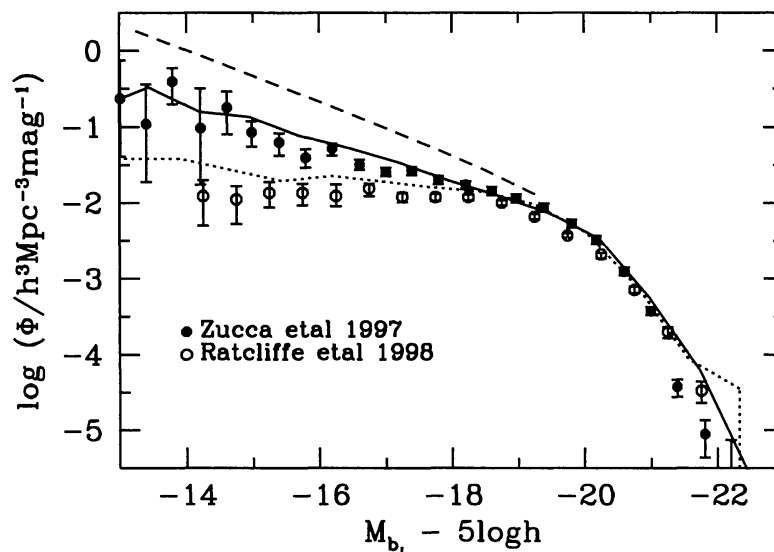


Figure 1. The points show two recent determinations of the local field galaxy luminosity function. The solid line shows the luminosity function in the fiducial model of Cole *et al.* (1999); the dotted line shows the luminosity function obtained when feedback is parameterized as a much stronger function of circular velocity, as used by Cole *et al.* (1994). The dashed line indicates the slope of the dark matter halo mass function.

3. The Star Formation History of the Universe

The use of the redshifted Lyman-break spectral feature to isolate candidate high redshift galaxies has proven to be a remarkably successful and efficient way of constructing large samples of galaxies at significant lookback times (Steidel *et al.* 1996 and references therein). The application of this photometric technique to deep images obtained from the ground and to the *Hubble Deep Fields* has allowed the star formation history of the universe to be constructed (e.g. Madau *et al.* 1996, Steidel *et al.* 1999).

Figure 2 shows a subset of the currently available observational estimates of the star formation rate per unit volume, as inferred from the flux density at various wavelengths, indicated by the key in the Figure. The dotted line shows the star formation history predicted by the model of Cole *et al.* (1994), which predates the oldest data points on the Figure by two years (see Figure 16 of Baugh *et al.* 1998).

The dashed line shows the star formation history in the fiducial model of Cole *et al.* (1999), estimated from the rest-frame luminosity density at 1500\AA . The solid line shows how this estimate is changed when obscuration by dust is taken into account; this line is the one that should be compared to the data points, which have not been corrected for the effects of dust. The star formation rate per unit volume in the model is reduced by a factor of ≈ 2.5 at $z = 4$ as a result of dust extinction of the 1500\AA light.

The small differences between the dotted line (Cole *et al.* 1994) and the solid line are mainly due to the different parameterizations of the strength of

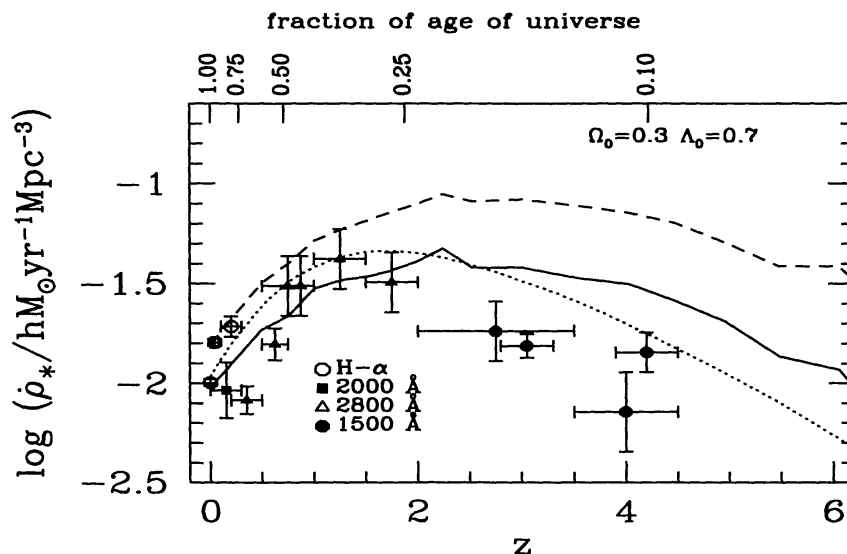


Figure 2. The star formation history of the universe. The dotted line shows the prediction of Cole *et al.* (1994). The dashed line shows the star formation rate density in the model of Cole *et al.* (1999), inferred from the 1500Å luminosity density. The solid line shows the effect on this estimate of obscuration of UV starlight by dust in the model. The points show a subset of recent observational determinations of the star formation density, using various indicators of the star formation rate as indicated by the key.

feedback as a function of circular velocity used in the two models. The particular choice of feedback model is motivated by the attempt to reproduce the faint end of the local luminosity function (see Figure 1 and the discussion in the previous Section). The weaker feedback employed by Cole *et al.* (1999) results in a somewhat broader peak in the global star formation rate around $z \approx 2 - 3$, compared with the dotted line, which peaks at $z \approx 1.5 - 2$. However, when expressed in terms of lookback time (as shown by the scale at the top of the Figure), which is the appropriate variable for computing the integrated stellar mass, this difference is in fact quite small.

4. The Evolution of Galaxy Clustering

Two approaches have been used to obtain predictions for the clustering of galaxies from semi-analytic models. In the first approach, a bias parameter is computed for dark matter halos to relate the amplitude of the correlation function of the haloes to that of the underlying dark matter distribution (Mo & White 1996). The semi-analytic model is then used to populate dark matter haloes with galaxies, and a selection criterion, such as an apparent magnitude limit, is applied to the model galaxies. The bias parameter for the galaxies is obtained by summing the bias of each halo, weighted by its abundance and the number of galaxies it contains that satisfy the selection criterion (e.g. Baugh *et al.* 1999). This approach was used by Baugh *et al.* (1998) to predict successfully that Ly-

man break galaxies have a correlation length similar to that of bright galaxies at the present day, and much larger than that of the dark matter in any viable model at $z \sim 3$.

Another method is to use the semi-analytic model to populate dark matter haloes in a N-body simulation of hierarchical clustering with galaxies (Kauffman *et al.* 1997, 1999; Governato *et al.* 1998, Benson *et al.* 1999). This approach has the advantage of being able to probe galaxy clustering down to small scales and to include the distortion of the clustering pattern that arises from the peculiar motions of galaxies. Benson *et al.* (1999) find that the clustering of galaxies in the fiducial model of Cole *et al.* (1999) is in very good agreement with the two point correlation function measured for APM galaxies. This is a remarkable result because the measured correlation function is a power law over more than a decade in separation, whereas the correlation function of the dark matter has two inflection points over the same range of scales. Furthermore, on scales around $1h^{-1}\text{Mpc}$, the amplitude of the dark matter correlation function is higher than that measured for galaxies, implying that galaxies are *anti*-biased or less clustered compared to the dark matter. The level of small scale clustering depends sensitively on how dark matter haloes are populated by galaxies, and thus upon the details of the galaxy formation process.

The first approach described above has been used to predict the evolution of the correlation length of galaxies, measured in comoving units, with redshift, as shown in Figure 3 (Baugh *et al.* 1999; similar results are found using the N-body technique, Kauffmann *et al.* 1998). The clustering evolution of galaxies is markedly different to that displayed by the dark matter, and furthermore is not well described by the ‘ ϵ -model’ commonly used to interpret such data. The correlation length of galaxies initially decreases to $z \approx 1$, and then starts to increase again at higher redshifts. The model predicts that galaxies that are bright enough to be seen at high redshift are hosted by the most massive dark matter haloes in place at these redshifts. Such haloes are biased tracers of the dark matter distribution.

Traditionally, the angular clustering of galaxies imaged in one band has been quantified in terms of the correlation amplitude measured at a fixed angular scale plotted as a function of the limiting apparent magnitude of the sample. Even at very faint magnitudes, the median redshift of the sample does *not* increase rapidly and in addition, the clustering signal is diluted by projection effects. A powerful observational technique that is now being pursued by many groups is to take deep images in many different filters and to measure the angular clustering of galaxies selected to lie within a limited baseline in photometric redshift. This method has been applied to study the evolution of galaxy clustering to redshift $z \sim 1$ (Connolly *et al.* 1998) and beyond using the Hubble Deep Field (e.g. Magliocchetti & Maddox 1998). At present, the fields studied are small and the results may be subject to sample variance. The detection of the dip in the galaxy correlation length shown in Figure 3 would provide evidence for hierarchical galaxy formation, but it may tell us more about the details of the process of galaxy formation than about the underlying cosmology. In any event, the semi-analytic models described here will have an important part to play in the interpretation of such results.

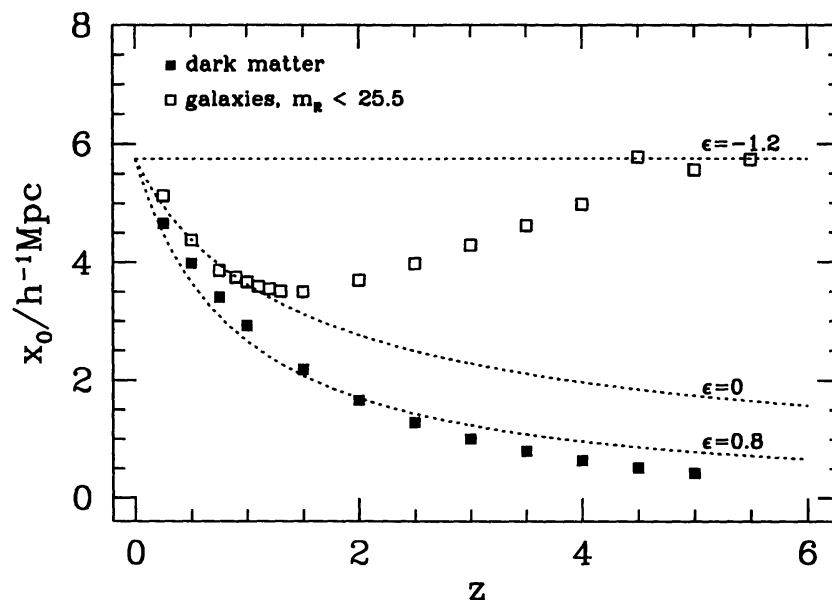


Figure 3. The evolution of the correlation length of clustering, defined as the *comoving* length scale for which the two point correlation function is unity: $\xi(x_0) = 1$ (Baugh *et al.* 1999). The filled squares show the evolution of the clustering length of dark matter in an $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$ universe, with density fluctuations normalized to reproduce the observed local abundance of hot X-ray clusters. The open squares show the evolution of the correlation length of galaxies in the model, selected to be brighter than $m_R = 25.5$. The dotted lines show the prediction of the ϵ -model, for typical values of the ϵ -parameter.

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Conference Summary