The evolution of galaxy mass in hierarchical models

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Abstract. Advances in extragalactic astronomy have prompted the development of increasingly realistic models which aim to describe the formation and evolution of galaxies. We review the philosophy behind one such technique, called semi-analytic modelling, and explain the relation between this approach and direct simulations of gas dynamics. Finally, we present model predictions for the evolution of the stellar mass of galaxies in a universe in which structure formation is hierarchical.

1 Modelling the formation and evolution of galaxies

An incredibly wide range of physical processes are believed to be influential in the formation of galaxies. Some of these processes are well understood, for example, the build up of dark matter haloes through mergers or the accretion of smaller units; the formation of haloes has been studied extensively using N-body simulations and can be described analytically with a reasonable degree of success (e.g. Lacey & Cole 1993, 1994). On the other hand, we are still some distance away from being able to simulate the formation of stars. An impressive initial step in this direction has been taken by Abel *et al.* (2002) with a simulation that leads up to the formation of the first star in the universe. However, the conditions in this calculation are much simpler than would be typical for the formation of the bulk of the stars in the universe and the simulation is stopped once additional physics not currently included in the calculation, such as radiative transfer, become important.

The absence of a complete theory of star formation need not be an obstacle to the development of a theory of galaxy formation. One can take a phenomenological approach in which a physically motivated recipe is adopted to describe star formation within a galaxy. The recipe will inevitably contain one or more uncertain parameters but these can be fixed by comparing model predictions with observational data.

Adopting this pragmatic approach, two techniques have been developed to model the formation and evolution of galaxies. The first of these is the direct simulation of gravitational instability and gas dynamics. The second class of technique is semi-analytic modelling (Kauffmann *et al.* 1993; Cole *et al.* 1994). In such models, the merger trees of dark matter haloes can either be grown using a Monte-Carlo algorithm or they can be extracted from an N-body simulation. The gas physics, namely shock heating, radiative cooling, star formation

and supernova feedback (along with galaxy mergers), is followed using approximations and simple rules.

The two techniques have complementary pros and cons. Direct simulations do not require the specialised assumptions that are necessary in the semi-analytic models, e.g. the imposition of spherical symmetry in the calculation of the gas cooling time. On the other hand, semi-analytic models are fast and flexible, allowing a wide range of parameter space to be explored. The modular structure of the semi-analytic models means that new prescriptions for processes such as star formation can be readily evaluated.

In certain respects, the two techniques are actually very similar. The direct simulation approach necessarily breaks down at some level because of the finite resolution that is attainable. It is not possible to achieve the sub-parsec resolution needed to simulate star formation in a cosmologically representative volume. Coupled with the lack of knowledge of the relevant micro-physics, this means that recipes like those used in the semi-analytic models have to be deployed in order to produce a fully specified model.

The first comparisons of the two techniques have recently been carried out (Benson *et al.* 2001a; Helly *et al.* 2002 ; Yoshida *et al.* 2002). These studies considered the rate at which gas cools in SPH simulations and in "stripped-down" semi-analytic models in which star formation and feedback have been switched off. The two approaches are in remarkably good agreement, which inspires confidence in the cooling model adopted in the semi-analytic schemes.

2   Constructing a model

In the phenomenological approach to galaxy formation, the values of the parameters in the recipes that describe processes such as star formation and feedback have to be specified to produce model predictions. This task is performed by comparing the model predictions to a subset of the available observational data. Different groups of modellers have different priorities when attempting to reproduce the data. The Munich group, for example, has attached most importance to matching the slope and zero point of Tully & Fisher's (1977) correlation between the luminosity and rotation speed of disk dominated galaxies. The Durham group instead try hardest to match the form of the present day galaxy luminosity function. The luminosity function is the most basic description of the galaxy population and is now known to a high level of accuracy in the optical from the 2dFGRS (Norberg *et al.* 2002) and SDSS (Blanton *et al.* 2000) and in the near-infrared from 2MASS photometry (Cole *et al.* 2001; Kochanek *et al.* 2001). The predictions of the fiducial model of Cole *et al.* (2000) are compared with these recent estimates of the local luminosity function in Fig. 1.

Although most weight is given to reproducing the luminosity function when setting model parameters, matching other datasets, such as the Tully-Fisher relation, the distribution of disk scale lengths, the metallicity of gas in spiral disks and of stars in ellipticals, and the gas fraction in spiral disks, is also important. This greatly restricts the viable range of parameter space of the models.
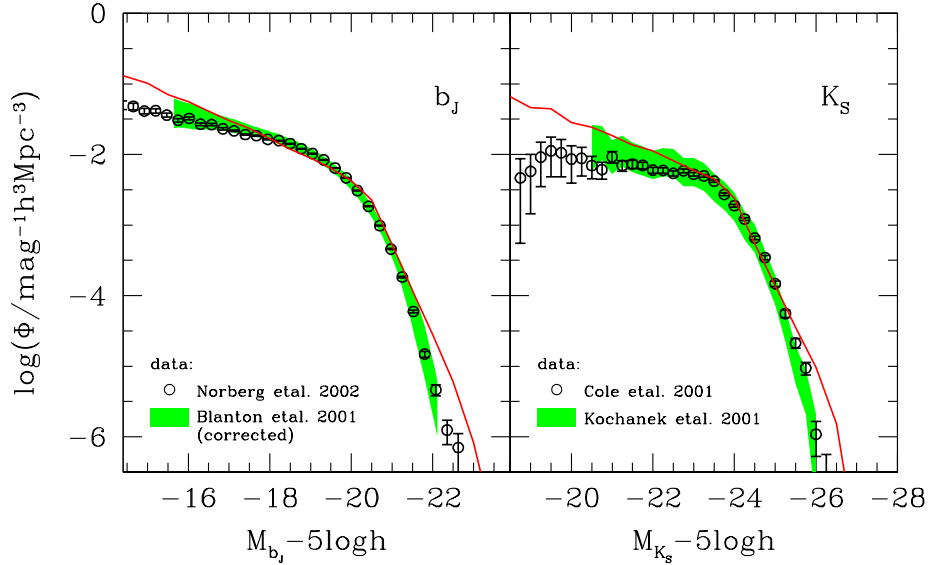
Fig. 1. The local galaxy luminosity function, in the b_J- and K_S- bands. The predictions of the fiducial model from Cole *et al.* (2000) are shown by the solid line in each panel. In the left panel, the symbols shows an estimate of the luminosity function from the 2dFGRS (Norberg *et al.* 2002). The shaded region shows an estimate based on the analysis of SDSS data in Blanton *et al.* (2000) (see Norberg *et al.* 2002 for full details). In the right panel, a combination of 2dFGRS redshifts and 2MASS photometry was used to estimate the near infrared luminosity function (Cole *et al.* 2001). The shaded region shows another observational estimate which also uses 2MASS photometry (Kochanek *et al.* 2001).

One criticism levelled at semi-analytic models that has entered into popular folklore is the inability of the models to match the zeropoint of the Tully-Fisher relation at the same time as reproducing the break in the luminosity function at L_*. The Tully-Fisher relation of the fiducial model of Cole *et al.* is compared with the observed relation in Fig. 2. The solid line shows the model prediction when the rotation speed at the half-mass radius of the disk is plotted; the dashed line shows how the zeropoint shifts when the rotation speed of the halo at the virial radius is plotted instead, which is much closer to the observed zeropoint. The shift is around 20% - 30%, which is comparable to the accuracy one might expect in the calculation of the rotation speed at the half-mass radius. This depends upon several effects, such as the self gravity of the baryons and their gravitational influence on the halo dark matter.
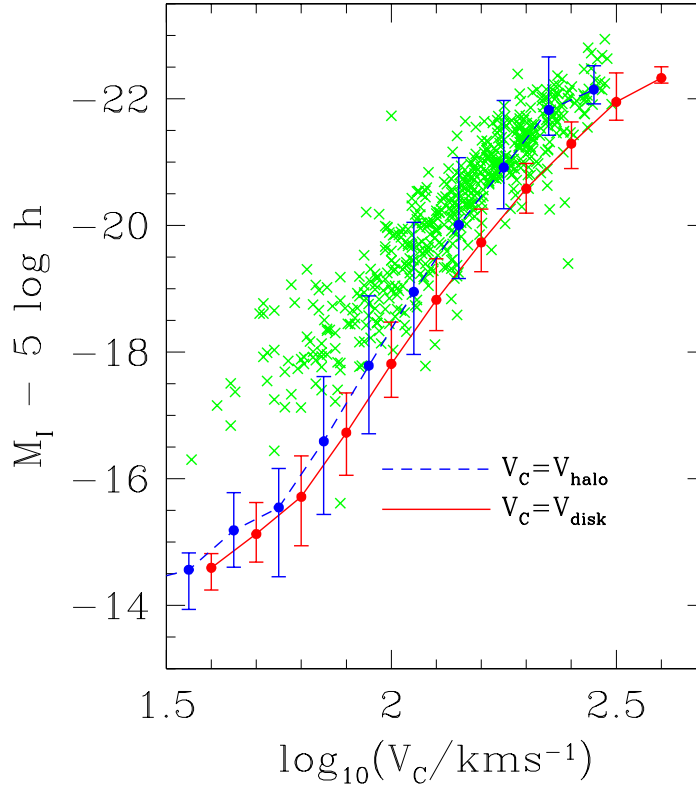
Fig. 2. The Tully-Fisher relation for star forming disk galaxies. The crosses show data from the sample of Mathewson, Ford & Buchhorn (1992). The dashed line shows the model prediction for the Tully-Fisher relation when the rotation speed of the halo at the virial radius is plotted. The solid line shows the predictions when the rotation speed at the half mass radius is plotted instead.

3   Model predictions - an example

Now that we have arrived at a fully specified model by comparing the output against a subset of the observations to fix the model parameters, we can make predictions for other quantities. Benson *et al.* (2000a,b; 2001b) populated a high resolution N-body simulation with galaxies using the semi-analytic model of Cole *et al.*. The simulation gives the spatial distribution of galaxies and allows their clustering to be measured. Remarkably, without any further adjustment to the model parameters, Benson *et al.* found that the fiducial ΛCDM model of Cole *et al.* predicts a correlation function that is in extremely good agreement with that measured for APM galaxies (Baugh 1996). This is particularly noteworthy as the galaxy correlation function is close to a power law, whereas the correlation function of the dark matter shows considerable curvature.
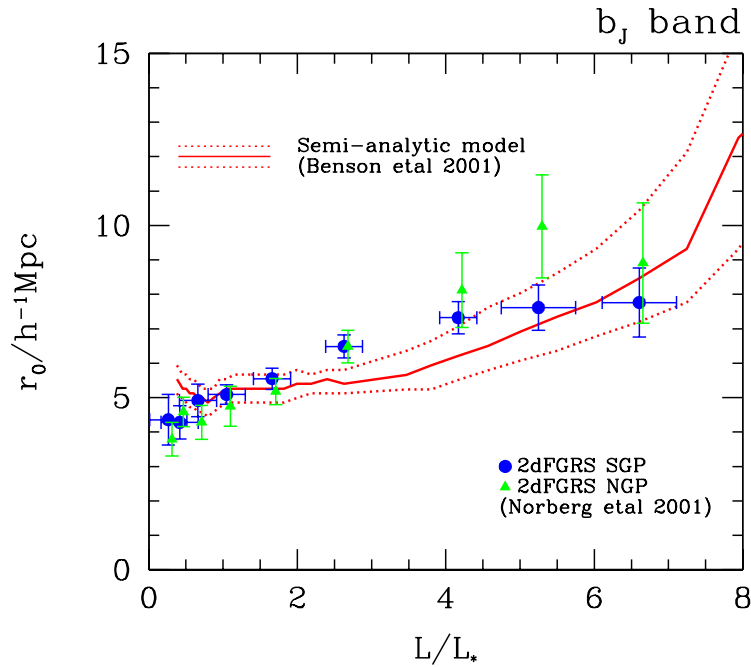
Fig. 3. The correlation length in real space, obtained by fitting a power law to the measured correlation function, $\xi(r) = (r_0/r)^\gamma$, plotted as a function of luminosity. The solid line shows the model predictions taken from Benson *et al.*(2001b). The dotted lines show the Poisson errors derived from the pair counts. The symbols show the subsequent measurements made from the 2dFGRS (Norberg *et al.*2001). In this case, the errors are estimated from mock 2dFGRS catalogues constructed from N-body simulations and include sample variance.

Benson *et al.*(2000b; 2001) presented predictions for the dependence of clustering strength on luminosity in the same model and found an approximately linear dependence of correlation length on luminosity; galaxies six times more luminous than L_* have a correlation length 50% longer than that predicted for L_* galaxies. At the time, the picture emerging from the data was unclear. This has now been resolved by measurements from the 2dFGRS (Norberg *et al.*2001) and SDSS (Zehavi *et al.*2002), which are in reasonable agreement with the trend predicted by the semi-analytic models.

4   The evolution of the stellar mass of galaxies

Advances in detectors that operate in the near infrared have led to a huge increase in the size of K selected samples over the past decade. The first direct estimate of the K-band luminosity function from a K-selected sample used ~ 500 galaxies (Gardner *et al.*1997); the estimate of the K_S-band luminosity function
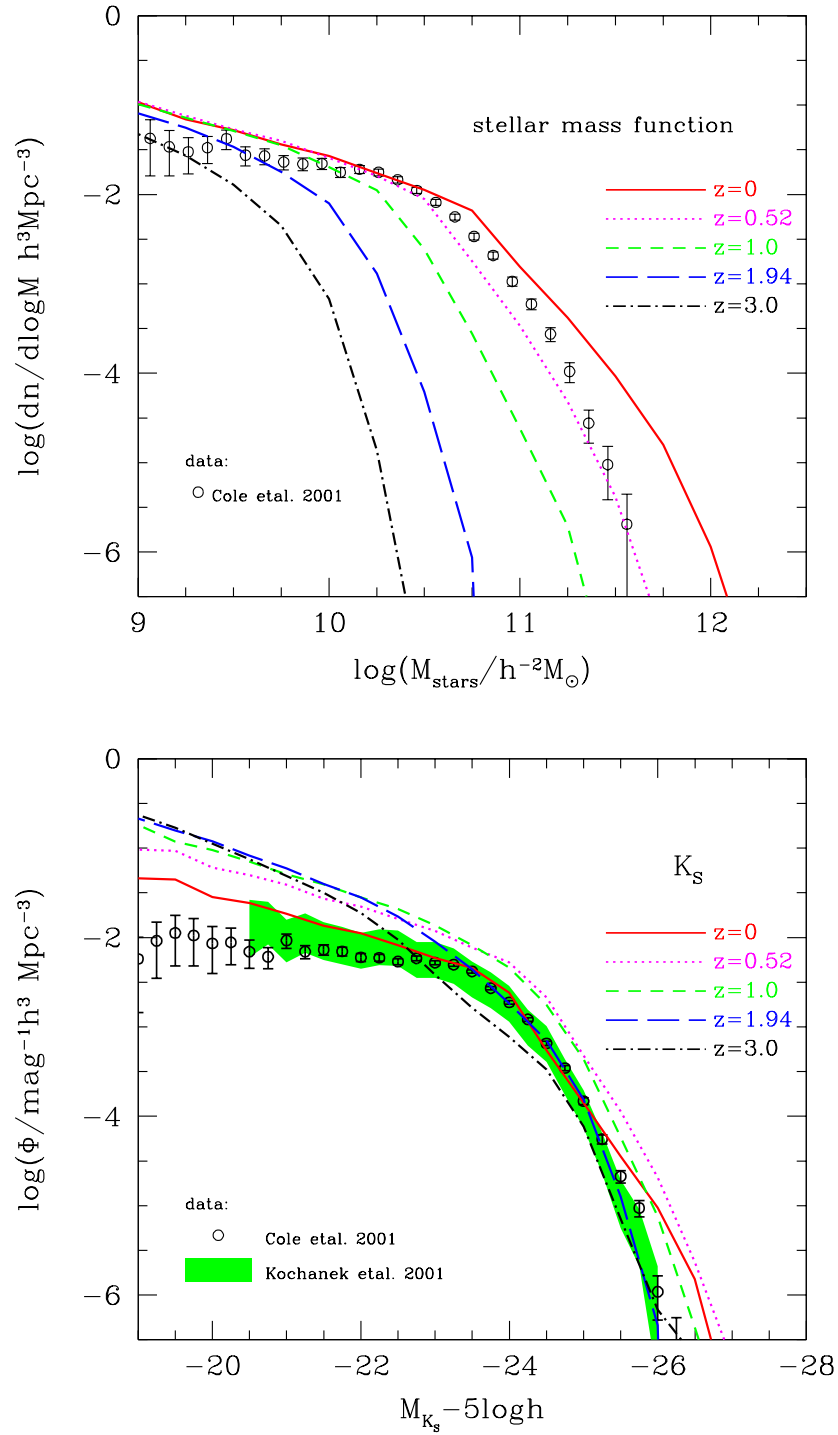
Fig. 4. *Top:* The evolution of the stellar mass function with redshift. The lines show the model predictions at different redshifts, as indicated by the key. The datapoints show the present day stellar mass function inferred from the K_S-band luminosity function by Cole *et al.* (2001). *Bottom:* The evolution with redshift of the *observer* frame K_S-band luminosity function. The symbols and shaded region show the present day K_S-band luminosity function estimated with 2MASS photometry.

by Cole *et al.* (2001), using 2MASS photometry and 2dFGRS redshifts was made from over 17,000 galaxies. The K-band luminosity of a galaxy gives a reasonable indication of its stellar mass. The output from the semi-analytic model suggests that the scatter in the stellar mass$--K$-band magnitude relation is a factor of ~ 2, showing the relative insensitivity to star formation history.

It is important to make a fair comparison between observational estimates and theoretical predictions for stellar mass. The stellar mass inferred from the K-band light is sensitive to the choice of IMF. Also, one needs to be clear whether recycling of gas is included i.e. whether the quantity under consideration is the mass locked up in stars or the total mass that had been turned into stars (some of which is subsequently expelled in stellar winds and supernovae). Cole *et al.* (2001) estimated the stellar mass function from the K_S-band luminosity function (shown by the symbols in Fig. 4), and found that only a small fraction of the baryons in the universe, perhaps as little as 5%, is actually locked up in stars. (Similar results were obtained by Kochanek *et al.* 2001.)

We plot the evolution of the stellar mass function in Fig. 4. There is a steady increase in the typical stellar mass with time; the value of M_* increases by a factor of ~ 2 between $z = 1$ and the present. The observable counterpart to the stellar mass function, the *observer* frame $K-$band luminosity function shows more complex evolution (Fig. 5). This is due to band shifting.

Summary We have given an outline of the semi-analytic approach to modelling galaxy formation. This technique is complementary to direct simulation of the relevant gas dynamic processes. In fact, both methods rely upon physically motivated recipes to deal with star formation and feedback. The model predicts strong evolution in the mass of stellar systems, with more than an order of magnitude increase in the abundance of $10^{11}h^{-2}M_\odot$ systems between $z = 1$ and the present day. Constraints on these predictions are now beginning to emerge, with the advent of the first results from deep, near-infrared photometry (see, for example, Drory *et al.* 2001, and the contributions by Drory and by Papovich *et al.* to this volume).

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