Modelling galaxy clustering at high redshift

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Abstract. Most phenomenological galaxy formation models show a discrepancy between the predicted Tully-Fisher relation and the luminosity function. We show that this is mainly due to overmerging of galaxy haloes, which is inherent in both the Press-Schechter formalism and dissipationless N-body simulations. This overmerging problem be circumvented by including a specific galaxy halo formation recipe into an otherwise standard N-body code. Resolving the overmerging also allows us to include models for chemical evolution and starbursts, which improves the match to observational data and renders the modelling more realistic. We use high-redshift clustering data to try and distinguish models which predict similar results at low redshifts for different sets of parameters.

1. Introduction

There has been significant recent progress in the study of galaxy formation within a cosmological context, mainly due to a phenomenological approach to this problem. The idea is to start with a structure formation model that describes where and when galactic dark haloes form. A simple description of gas dynamics and star formation provides a means to calculate the amount of stars forming in these haloes. Stellar population synthesis models then provide the spectral evolution, i.e. luminosities and colours, of these galaxies.

Many physical processes are modelled as simple functions of the circular velocity of the galaxy halo. Therefore, the Tully-Fisher relation is the most obvious observational relation to try and predict, as it relates the total luminosity of a galaxy to its halo circular velocity. However, most phenomenological galaxy formation models do not simultaneously fit the I-band Tully-Fisher relation and the B or K band luminosity function. When one sets the model parameters such that the Tully-Fisher relation has the right normalization, the luminosity functions generally overshoot (e.g. Kauffmann, White & Guiderdoni 1993; Kauffmann, Colberg, Diaferio & White 1999), certainly for the \( \Omega = 1, H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) standard CDM cosmology (in the form given by Davis et al. 1985) that we consider in this paper. Alternatively, when making sure that the luminosity functions matches by changing some of the model parameters, the Tully-Fisher relation ends up significantly shifted with respect to the observed relation (e.g. Cole et al. 1994; Heyl et al. 1995).

In order to keep the modelling as analytical as possible, an extension to the Press & Schechter (1974) prescription for the evolution of galaxy haloes...
has been a popular ingredient for implementations of a phenomenological theory of galaxy formation. However, the EPS formalism is designed to identify collapsed systems, irrespective of whether these contain surviving subsystems. This ‘overmerging’ of subhaloes into larger embedding haloes is relevant to the problem of matching both the galaxy luminosity function and the Tully-Fisher relation, as the central galaxy in an overmerged halo is the focus of a much larger cooling gas reservoir than the reservoir that galaxy is to focus on in case its parent subhalo survives. Traditional N-body simulations suffer from a similar overmerging problem (e.g. White 1976), which is of a purely numerical nature, caused by two-body heating in dense environments when the mass resolution is too low (Carlberg 1994; van Kampen 1995).

In order to circumvent these problems, we use an N-body simulation technique that includes a built-in recipe for galaxy halo formation, designed to prevent overmerging (van Kampen 1995, 1997), to generate the halo population and its formation and merger history. This resolves most of the discrepancy sketched above, and allows us to make the modelling more realistic by adding chemical evolution and a merger-driven bursting mode of star formation to the modelling. Once stars are formed, we apply the stellar population synthesis models of Jimenez et al. (1998) to follow their evolution. We have enhanced these models with a model for the evolution of the average metallicity of the population, which depends on the starting metallicity. Feedback to the surrounding material means that cooling properties of that material will change with time, affecting the star formation rate, and thus various other properties of the parent galaxy.

2. Overview of the phenomenological model

The key ingredients of the model are described below. We refer to van Kampen et al. (1999) for a much more detailed description and discussion of the model, and a list of the choices for the various parameters involved.

The merging history of dark-matter haloes. This is often treated by Monte-Carlo realizations of the analytic ‘extended Press-Schechter’ formalism, which ignores substructure. We use a special N-body technique to prevent galaxy-scale haloes undergoing ‘overmerging’ owing to inadequate numerical resolution.

The merging of galaxies within dark-matter haloes. Each halo contains a single galaxy at formation. When haloes merge, a criterion based on dynamical friction is used to decide how many galaxies exist in the newly merged halo. The most massive of those galaxies becomes the single central galaxy to which gas can cool, while the others become its satellites.

The history of gas within dark-matter haloes. When a halo first forms, it is assumed to have an isothermal-sphere density profile. A fraction $\Omega_b/\Omega$ of this is in the form of gas at the virial temperature, which can cool to form stars within a single galaxy at the centre of the halo. Application of the standard radiative cooling curve shows the rate at which this hot gas cools below $10^4$ K, and is able to form stars. Energy output from supernovae reheats some of the cooled gas
back to the hot phase. When haloes merge, all hot gas is stripped and ends up in the new halo.

**Quiescent star formation.** The star formation rate is equal the ratio of the amount of cold gas available and the star-formation timescale. The amount of cold gas available depends on the merger history of the halo, the star formation history, and the how much cold gas has been reheated by feedback processes.

**Starbursts.** We also model star bursts, i.e. the star-formation rate may suffer a sharp spike following a major merger event.

**Feedback from star-formation.** The energy released from young stars heats cold gas in proportion to the amount of star-formation, returning it to the reservoir of hot gas.

**Stellar evolution and populations.** Our work assumes the spectral models of Jimenez et al. (1998); for solar metallicity, the results are not greatly different from those of other workers. The IMF is generally taken to be Salpeter, but any choice is possible. Unlike other workers, we take it as established that the population of brown dwarfs makes a negligible contribution to the total stellar mass density, and we do not allow an adjustable $M/L$ ratio, $\Upsilon$, for the stellar population.

**Chemical evolution.** The evolution of the metals must be followed, for two reasons: (i) the cooling of the hot gas depends on metal content; (ii) for a given age, a stellar population of high metallicity will be much redder. The models of Jimenez et al. (1998) allow synthetic stellar populations of any metallicity to be constructed.

### 3. Low-redshift results

With the set-up described above we match both the B and K band luminosity function and the I-band Tully-Fisher relation, for an $\Omega = 1$ standard CDM structure formation scenario. Resolving the overmerging problem is the major contributor to this result, but the inclusion of chemical evolution and starbursts are also important ingredients.

The new ingredients we have added to the modelling of galaxy formation are needed in order to make the models more realistic, and are not introduced simply in order to give yet more free parameters. Nevertheless, our resolution to the Tully-Fisher / luminosity function discrepancy may well not be unique, and various other changes to the ingredients of the phenomenological galaxy formation recipe might produce similar results. For example, we have not studied the influence cosmological parameters have on the model galaxy populations, where $\Omega$, $\Lambda$, and $\sigma_8$ are likely to be the important parameters. Other types of ingredients are possible as well: Somerville & Primack (1998) resolve some of the discrepancy using a dust extinction model plus a halo-disk approach to feedback.
4. High-redshift clustering

One way of resolving the worries about degeneracies in the cosmological/physical parameter space will be to include data at intermediate and high redshifts, which is being gathered with increasing speed and ease, and at increasingly higher redshifts. In this contribution we show a preliminary comparison of the correlation properties of galaxies at redshift $z = 3$. Recently, Giavalisco et al. (1998) gave an estimate for the galaxy-galaxy correlation function $\xi(r) = (r_0/r)^\gamma$ for a sample of Lyman-break galaxies at this redshift. They found $r_0 = 2.1 h^{-1} \text{Mpc}$ and $\gamma = 2.0$.

We selected our model galaxies in exactly the same way as Giavalisco et al. (1998) did, and compared two of the models produced by van Kampen et al. (1999), models $n$ and $b$, to the observational data. The first model ($n$), which is as close as possible to the model by Cole et al. (1994), but with the mass-to-light parameter $\Upsilon = 1$, gives $r_0 = 3.5 h^{-1} \text{Mpc}$ and $\gamma = 1.72$. The second model ($b$), which includes starbursts and chemical evolution, gives $r_0 = 4.4 h^{-1} \text{Mpc}$ and $\gamma = 2.1$. Both models fit the correlation function at $z = 0$ very well, and cannot be distinguished from each other.

As the observed correlation data are still relatively uncertain at this moment in time, it is premature to rule out models on the basis of this data. The two models discussed above have similar predictions for low redshifts, but predict different clustering properties at high-redshift. However, the differences are not large, so one needs either really good data, or a much larger variety of observational characteristics of the high-redshift galaxy population.

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