COSMOLOGICAL GALAXY FORMATION

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Abstract

We discuss the first results from two successful simulations of galaxy formation within a cosmological volume. With over 2000 large objects forming in each we have sufficient numbers to reliably produce both galaxy correlation and luminosity functions. We find that the observed galaxy counts are well fitted by these models and that the galaxies display an almost un-evolving correlation function back to a redshift of 3 which closely resembles the featureless observed form and amplitude.

1 Introduction

The quest for a detailed understanding of galaxy formation has become one of the central goals of modern astrophysics. On the observational side data from the Keck and Hubble Space telescopes have revolutionised our view of the high redshift Universe and there are claims that the epoch of galaxy formation has already been observed [1]. From the theoretical point of view the problem is fundamental because its resolution involves the synthesis of work from a wide range of specialities. A full treatment requires consideration of the early Universe processes that create primordial density fluctuations, the microphysics and chemistry that precipitate star formation within giant molecular clouds, the energy exchange present in supernova feedback [13], the dissipational processes of cooling gas, the dynamics of galaxies moving within a dense environment [12, 5] and the large scale tidal torques which determine the angular momentum profiles of the resultant objects.

Analytic approaches to the problem founder partly because of the lack of symmetry. As high redshift observations show, real galaxies do not form in a smooth, spherically symmetric fashion but rather form as complicated collections of bright knots which merge and evolve into normal galaxies [15]. Because of its complexity this problem is often approached using numerical simulation. In one of the first attempts [4] demonstrated the a wide variety of observed galaxy properties could be fitted by even the most basic of simulations. Unfortunately their computational volume (like that of [11]) was too small to produce a reliable correlation function and they had to stop the simulation at $z = 1$ but this work clearly demonstrated the potential for simulations of this kind. Both these groups used smoothed particle hydrodynamics (SPH) to model the gas. In a complimentary investigation [3] used a grid based code, providing a useful cross-check of the results. More recently several groups have attempted to tackle the problem by coupling a semi-analytic approach to a collisionless simulation and have again produced interesting results [7, 10].

In this paper we simulate the process of galaxy formation within a representative volume of the Universe in two contrasting cosmologies. The volume is large enough – 100 Mpc on a side – that several thousand galaxies form and we can reliably measure the galaxy correlation function and study the effects of bias. Previous work by the Virgo Consortium [8] predicted the magnitude of the bias that would be required to reconcile state-of-the-art collisionless simulations to the observed galaxy correlation function. Here we examine whether the inclusion of a gaseous component and basic physics can indeed produce this bias.

2 The simulation

The simulations we have carried out are state-of-the-art SPH calculations of 2 million gas plus 2 million dark matter particles in a box of side 100 Mpc using a parallel adaptive particle-particle particle-mesh plus SPH code [14] We have completed both a standard Cold Dark Matter (SCDM) run and a run with a positive cosmological constant (ΛCDM). Both have the same parameters as detailed by [8]. The baryon fraction was set from nucleosynthesis constraints, $\Omega_b h^2 = 0.015$ and we assume an unevolving gas metallicity of 0.5 times the solar value. This leads to a gas mass per particle of $2 \times 10^9\,\mathrm{M}_\odot$ for both runs. As we typically smooth over 32 SPH particles this gives us an effective minimum gas mass resolution of $6.3 \times 10^{10}\,\mathrm{M}_\odot$. We employ a comoving Plummer gravitational softening of $10h^{-1}$ kpc and the minimum SPH resolution was set to match this.

3 Underlying assumptions

This simulation is based upon two fundamental assumptions. These are that the feedback of energy due to supernovae explosions can be approximated by assuming that this process effectively imposes a mass resolution threshold. Objects below this mass cannot form whereas objects above this mass are unaffected. Comparing the simulated star formation rate to the observed one shows that such an approximation does not lead to a ridiculous star formation history. The second assumption is that once gas has cooled into tight, dense blobs it is effectively decoupled from the surrounding hot gas. This is equivalent to assuming that this gas has been converted into stars or is isolated by additional physics such as magnetic fields. The main further approximation we are forced to employ for computational reasons is a spatial resolution of $10h^{-1}$ kpc. This is over twice the value we would have liked to have used and leads to enhanced tidal disruption, drag and merging within the larger clusters of objects.

The microphysics of star formation and supernovae explosions typically have parsec length-scales and so happen far below our resolution limit. The combination of poor man's feedback and decoupling the cold, dense gas effectively negates these effects (over which we have no control anyway) for all objects above our resolution threshold. All objects must cross this threshold at some time (as a large object cannot simply *pop* into existence, presumably via the merger

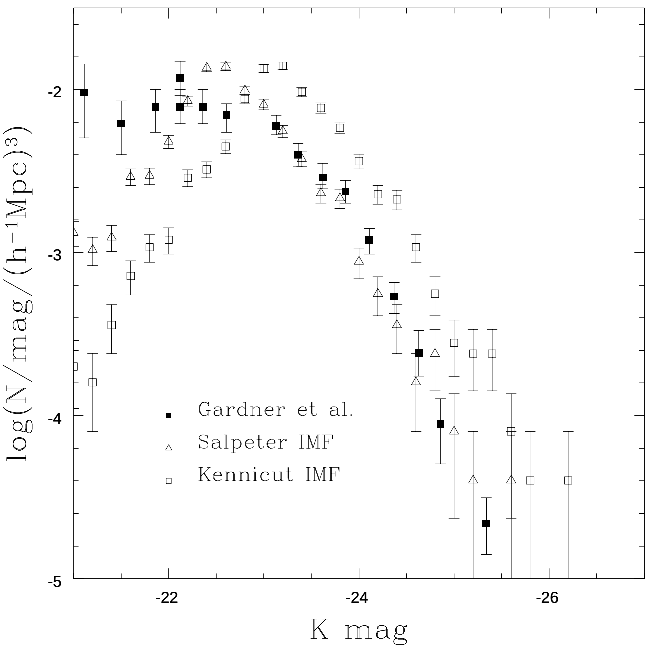

Figure 1: A comparison between the observed K-band luminosity function and that obtained by the SCDM simulation with two different assumptions for the stellar IMF.

of smaller, sub-resolution (and so unresolved) fragments. Our assumptions are equivalent to presuming that the absence of previous levels of the hierarchy has no effect on the subsequent evolution or properties of our objects and that these objects are large enough to resist the destructive effects of supernovae explosions.

It should be stressed that because of our relatively poor physical resolution we can only predict accurate masses and positions for our objects. We do not have sufficient resolution to resolve internal structure and so cannot directly ascertain a morphological type for our galaxies as each object typical only contains between 100 and 1000 particles.

4 Analysis

The presence of gas makes the identification of a set of objects which we would like to equate to galaxies very straightforward. Cooling leads to large collapse factors and small knots of cold gas residing within a much hotter halo. For the purposes of this paper we use a standard friends-of-friends group finder with a small linking length to reliably extract a group catalog from each simulation output time. At the end of the simulation there are over 2000 significant objects within each simulation volume, roughly the observed number density.

The luminosity of any object is then extracted by tracking each of the particles that finally reside inside each object backwards in time and extracting the time at which each of them first became cold and dense. Standard population synthesis techniques (*e.g.* [2]) can then be applied to produce the luminosity of each object in any desired pass band.

In Fig. 1 we show a comparison between the observed K-band luminosity function [6] and the SCDM simulation. The observations are neatly bracketed by the simulation within the uncertainties imposed by the choice of initial mass function. Clearly the *shape* of the observations are well reproduced with no excess at the bright end. The faint end slope is not well reproduced because of the relatively high resolution imposed mass cut-off which was deliberately chosen to be close to L_*. For the LCDM simulation the shape of the luminosity function is also well modelled but the objects tend to be too bright. This is because the parameters chosen for this simulation lead to a higher global fraction of cold, dense gas making all objects more luminous.

5 Conclusions

For the first time we have been able to model galaxy formation within a large enough volume of the Universe that reliable calculations can be made of the galaxy correlation and luminosity functions. As has been shown elsewhere in these proceedings ([9]) the observed correlation function is well fitted by these models which also simultaneously fit the observed luminosity functions. The galaxies in our models are not only reasonably distributed, they also have a sensible range of masses and formation times.

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