SEMI-ANALYTIC GALAXY FORMATION: UNDERSTANDING THE HIGH REDSHIFT UNIVERSE

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Abstract There is now compelling evidence in favour of the hierarchical structure formation paradigm. Semi-analytic modelling is a powerful tool which allows the formation and evolution of galaxies to be followed in a hierarchical framework. We review some of the latest developments in this area before discussing how such models can help us to interpret observations of the high redshift Universe.

Hierarchical structure formation

The hierarchical structure formation paradigm is based upon the simple premise that large scale structure in the Universe results from the gravitational amplification of small, primordial density fluctuations. The origin of the fluctuations is uncertain, but one explanation is that they are quantum ripples boosted to macroscopic scales by inflation.

Many clear examples of interacting or merging galaxies, a key feature of hierarchical models, were presented during this meeting. Further convincing evidence for the paradigm can be derived by comparing the relative amplitudes of density fluctuations in Universe today with those present at some earlier epoch. The cosmic microwave background radiation is a snapshot of the distribution of photons and baryons just a few hundred thousand years after the Big Bang. Fluctuations in the temperature of the background radiation can be related to fluctuations in the distribution of baryons at the epoch of recombination, $z \sim 1000$. The inferred fluctuations are tiny, on the order of one part in a hundred thousand. However, if an additional component to the mass density of the Universe is included, weakly interacting cold dark matter, these fluc-
Fluctuations can subsequently develop into the large scale structure that we measure in the Universe today (Peacock et al. 2001).

An important challenge for theorists is to predict the formation and evolution of galaxies in a model universe in which the formation of structure in the dark matter proceeds in a hierarchical manner. Two powerful simulation techniques have been developed to address this issue: direct N-body or grid codes that follow the dynamical evolution of dark matter and gas, and semi-analytic codes that use a set of simple, physically motivated rules to model the complex physics of galaxy formation. These techniques have their advantages and disadvantages (e.g. limited resolution in case of N-body/grid based codes; the assumption of spherical symmetry for cooling gas in the semi-analytics), and so are complementary tools with which to attack the problem of galaxy formation. A preliminary study comparing the cooling of gas and merging of “galaxies” in a Smooth Particle Hydrodynamics simulation with the output of a semi-analytic code has shown that there is reassuringly good agreement between the results obtained using the two techniques (Benson et al. 2001a).

The Durham semi-analytic code

The past decade witnessed an explosion in observations of galaxies at high redshift, mainly as a result of new facilities such as the Hubble Space Telescope and the Keck telescopes in the optical, and the opening of other parts of the electromagnetic spectrum, e.g. the sub-millimetre, probed by the SCUBA instrument on UKIRT. In order to interpret these exciting new data, semi-analytic galaxy formation codes have been developed that model a wide range of physical processes. Below, I will outline the scheme developed by the Durham group and collaborators (Benson et al 2000a; Cole et al 2000; Granato et al 2000). Similar codes have also been devised by other groups (e.g. Avila-Reese & Firmani 1998; Kauffmann et al 1999; Somerville & Primack 1999).

The physical processes that play a fundamental role in hierarchical galaxy formation can be set out as follows (White & Rees 1978):

(i) The formation and merging of dark matter haloes, driven by gravitational instability. This process is completely determined by the initial power spectrum of density fluctuations and by the values of the cosmological parameters $\Omega$, $\Lambda$ and Hubble’s constant.

(ii) The shock heating and virialisation of gas within the gravitational potential wells of dark matter haloes.

(iii) The cooling of gas in haloes.
(iv) The formation of stars from cooled gas. This process is regulated by the injection of energy into the cold gas by supernovae and stellar winds.

(v) The mergers of galaxies after their host dark matter haloes have merged.

There are a number of major improvements in the Cole et al. (2000) semi-analytic code over earlier versions: a more accurate technique is used in the Monte-Carlo generation of dark matter halo merger trees, the chemical enrichment of the ISM is followed, disk and bulge scale lengths are computed using a prescription based on conservation of angular momentum and the obscuration of starlight by dust is computed in a self-consistent fashion.

The semi-analytic model requires a number of physical parameters to be set. Some of these describe the background cosmology and are gradually being pinned down, for example, by measurements of supernovae brightnesses at high redshift or through the production of high resolution maps of the microwave background radiation. Other parameters refer to the prescriptions we adopt to model the physics of galaxy formation. Their values are set by reference to a subset of data on the local galaxy population, as explained by Cole et al.

The observational constraint to which we attach the most weight is the field galaxy luminosity function. Somewhat disappointingly, and in spite of much effort, this fundamental characterisation of the local galaxy distribution was not well known until this year. Fig 5. of Cole et al. (2000) shows that any semblance of a consensus between the various determinations of this quantity prior to 2000 is lost even after moving just one magnitude faintwards of $L_*$. However, this situation is now changing beyond recognition. The 2dF Galaxy Redshift Survey (2dFGRS) and Sloan Digital Sky Survey are pinning down the field galaxy luminosity function to a high level of accuracy. The degree of improvement that is now possible with the 2dFGRS is readily apparent in Fig. 1. In this figure, we compare measurements obtained from the 2dFGRS with a representative determination of the luminosity function made from a redshift survey completed in the last millenium. For the first time, random errors in the luminosity function estimate are unimportant over a wide range of magnitudes.

The solid lines in Fig. 1 show the luminosity function of the Cole etal model. The faint end is influenced by the strength of feedback in low mass haloes. The break at high luminosities is due to long cooling times in more massive dark matter haloes, which have higher virial temperatures and form more recently in hierarchical models. Assuming
Figure 1. The field luminosity function in the $b_J$ and $K_s$ bands. The error bars without points show the luminosity functions estimated from the 2dF Galaxy redshift survey (the measurement in the right hand panel uses photometry from the near-infrared 2mass survey). The points with errorbars show a representative determination of the luminosity function from an earlier redshift survey. The lines show the luminosity function of the semi-analytic model of Cole et al (2000).

Figure 2. The 60$\mu$m luminosity function. The lines show the model predictions: the dashed line is the contribution of galaxies that are quiescently forming stars, the dotted lines correspond to galaxies that recently experienced or are undergoing a burst. The solid line is the total luminosity function.
a higher galaxy merger rate would depress the luminosity function at the faint end and weaken the break at the bright end. From a naive point of view, the model in Fig. 1 would be incorrectly dismissed as an abject failure due to an unacceptably large $\chi^2$ value with reference to the 2dFGRS estimate of the luminosity function. However, it is important to appreciate that the parameters in the semi-analytic model are physical parameters. As such, they have a completely different meaning to the parameters that specify a Schechter function fit to these data, which is merely a convenient mathematical shorthand to describe the data points. We are not at liberty to chose any ad hoc combination of the parameters in the semi-analytic model. For example, changing the strength of feedback in order to reduce the slope of the faint end of the luminosity function also has an impact on the shape of the Tully-Fisher relation and upon the size of galactic disks.

In collaboration with Alessandro Bressan, Gian-Luigi Granato and Laura Silva, we have combined the semi-analytic model of Cole et al. with the spectro-photometric code of Silva et al. (1998), which treats the reprocessing of radiation by dust. The range of wavelengths spanned by the spectral energy distribution of model galaxies now extends from the extreme ultra-violet through the optical to the far-infrared, sub-millimetre and on to the radio (Granato et al. 2000). One highlight of this work is the reproduction of the observed smooth attenuation law for starbursts, starting from a dust mixture that reproduces the Milky Way extinction law which has a strong bump at 2000 Å; this implies that the observed attenuation is strongly dependent on the geometry of stars and dust. In Fig. 2, we show the model predictions for the 60µm luminosity function. Above $\nu L_\nu \sim 10^{11} h^{-2} L_\odot$, the model luminosity function is dominated by galaxies undergoing bursts driven by mergers. This agrees with observations of ultra-luminous IRAS galaxies, which are all identified as being at some stage of the interaction/merger process (see Sanders’ contribution).

**Galaxy clustering at z=0**

One of the key science goals of the 2dF and SDSS redshift surveys is to produce definitive measurements of galaxy clustering over a wide range of scales for samples selected by various galaxy properties. In order to interpret the information encoded in the measured clustering, it is necessary to understand how galaxies illuminate the underlying distribution of dark matter. Progress has been made towards this end by marrying the semi-analytic galaxy formation technique with high
Figure 3. The power spectrum of galaxies at \( z = 0 \) in real space (left-hand panel) and redshift space (i.e. including the effects of peculiar motions - right-hand panel). The solid lines show the predictions for galaxies in the semi-analytic models, the dashed lines show power spectrum of the underlying dark matter, which is a CDM universe with \( \Omega_0 = 0.3 \) and \( \Lambda_0 = 0.7 \). The points with errorbars show observational determinations of the power spectrum.

Resolution N-body simulations of representative volumes of the universe (Kauffmann et al. 1999; Benson et al. 2000a,b, 2001b).

In the approach of Benson et al., the masses and positions of dark matter haloes are extracted from an N-body simulation using a standard group finding algorithm. The semi-analytic machinery is then employed to populate the dark haloes with galaxies. The central galaxy is placed at the centre of mass of the dark matter halo and satellite galaxies are placed on random dark matter particles within the halo, resulting in a map of the spatial distribution of galaxies within the simulation volume. Fig. 3 compares the power spectrum of bright, optically selected galaxies predicted by the semi-analytic model, with observational determinations and with the power spectrum of the dark matter. The left hand panel shows power spectra in real space. For \( k \gtrsim 0.1 \text{hMpc}^{-1}, \) the measured galaxy power spectrum has a lower amplitude than that of the dark matter in the popular ΛCDM model; the galaxies are said to be ‘anti-biased’ with respect to the mass (Gaztañaga 1995). The semi-analytic model provides an excellent match to the data. This is particularly noteworthy as no additional tuning of parameters was carried out to make this prediction once certain properties of the local galaxy population, such as the field galaxy luminosity function, had been reproduced (see Cole et al. 2000 for a full explanation of how the model parameters are set). Furthermore, this level of agreement is not found for the galaxy
clustering predicted in CDM models with \( \Omega = 1 \). The most important factor in shaping the predicted galaxy clustering amplitude is the way in which the efficiency of galaxy formation depends upon dark matter halo mass. This is illustrated by the variation in the mass to light ratio with halo mass shown by Fig 8 of Benson et al (2000a): for low mass haloes, galaxy formation is suppressed by feedback, whilst for the most massive haloes, gas cooling times are sufficiently long to suppress cooling.

The power of the approach of combining semi-analytic models with N-body simulations is demonstrated on comparing the left hand panel (real space) of Fig. 3 with the right hand panel, which shows power spectra in redshift space. Again, the same model gives a very good match to the observed power spectrum when the effects of peculiar motions are included to infer galaxy positions. However, the impression that one would gain about the bias between dark matter and galaxy fluctuations is qualitatively different; in redshift space galaxies appear to be unbiased tracers of the dark matter. The apparent contradiction between the implications for bias given by the panels of Fig. 3 can be resolved by turning back once more to the models. The pairwise velocity dispersion of model galaxies is lower than that of the dark matter, and as a result is in much better agreement with the observational determination of pairwise motions. Again, this difference is driven by a reduction in the efficiency of galaxy formation with increasing dark matter halo mass (Benson et al. 2000b).

**The evolution of the galaxy distribution**

Once the parameters of the semi-analytic model have been set by comparing the model output with a subset of data for the local galaxy population, firm predictions can be made regarding the evolution of the galaxy distribution (Benson et al. 2001b). The properties of the distribution of galaxies and the way in which these properties evolve with redshift are intimately connected to the growth of structure in the dark matter, as illustrated by a sequence of high resolution pictures in Benson et al. (2001b) that show the evolution of galaxies and of the dark matter. An example of this is the morphology-density relation, namely the correlation of the fraction of early type galaxies with local galaxy density. The semi-analytic models reproduce the observed form of the morphology density relation at \( z = 0 \). Remarkably, essentially the same strength of effect is also predicted at \( z = 1 \). The physical explanation for this result lies in the accelerated dynamical evolution experienced by galaxies that form in overdensities destined to become rich clusters by the present day.
A generic prediction of hierarchical clustering models is that bright galaxies should be strongly clustered at high redshift compared to the underlying dark matter (Davis et al. 1985). Fig. 4 shows the evolution of the power spectrum for galaxies and for dark matter in a ΛCDM universe. The amplitude of the dark matter power spectrum increases as fluctuations grow through gravitational instability. Between $z = 3$ and $z = 0$, the amplitude of the dark matter power spectrum increases by an order of magnitude on large scales. The shape of the dark matter power spectrum is significantly modified on small scales (high $k$) through nonlinear evolution of the density fluctuations – ‘cross-talk’ between fluctuations on different spatial scales. However, the amplitude and shape of the galaxy power spectrum show little change over the same redshift interval (Pearce et al. 2000; Benson et al. 2001b). The amplitude of the galaxy power spectrum drops by around 50% from $z = 3$ to $z = 1$, and by $z = 0$ it has been overtaken in amplitude by the mass power spectrum (Baugh et al. 1999). The clustering predictions can be readily explained. At $z = 3$, bright galaxies are only found in the most massive haloes in place at this time. Such haloes are much more strongly clustered than the underlying dark matter, hence the large difference in amplitude or bias between the galaxy and dark matter spectra at $z = 3$. The environment of bright galaxies becomes less exceptional as $z = 0$ is approached.
The formation and evolution of QSOs

The similarity in the general evolution of the global star formation rate per unit volume and of the space density of luminous quasars suggests a connection between the physical processes that drive the formation and evolution of galaxies and those that power quasars (see Dunlop’s contribution). Spurred on by mounting dynamical evidence for the presence of massive black holes in galactic bulges (e.g., Magorrian et al. 1998), Guinevere Kauffmann and Martin Haehnelt have produced the first treatment to follow the properties of QSOs within a fully fledged semi-analytic model for galaxy formation (Kauffmann & Haehnelt 2000; Haehnelt & Kauffmann 2000).

The model of Kauffmann & Haehnelt assumes that black holes form during major mergers of galaxies, and that during the merger event, some fraction of the cold gas present is accreted onto the black hole to fuel a quasar. The qualitative properties of the observed quasar population are reproduced well by the model, including the rapid evolution in the space density of luminous quasars. There are three key features of the model responsible for the evolution in quasar space density between $z \sim 2$ and $z = 0$: (i) a decrease in the merger rate of objects in a fixed mass range over this interval, (ii) a reduction in the supply of cold gas from mergers, and (iii) an increase in the time-scale for gas accretion onto the black hole. The mass of cold gas available in mergers is reduced at low redshift because the star formation timescale in the model is effectively independent of redshift; at lower redshifts, gaseous disks have been in place for longer and a larger fraction of the gas has been consumed in quiescent star formation and so less gas is present in low redshift mergers (see Fig 6 of Baugh, Cole & Frenk 1996). If the star formation timescale is allowed to depend upon the dynamical time, gas is consumed more rapidly in the disk and less gas is present in mergers at all redshifts.

The Kauffmann & Haehnelt model predicts strong evolution in the properties of QSO hosts with redshift, suggesting that quasars of a given luminosity should be found in fainter hosts at high redshift. This issue is just beginning to be addressed observationally (see, for example, the contributions of Ridgway and Kukula). At present, it is hard to reach any firm conclusions, though there is apparently little evidence for a strong trend in host luminosity with redshift.

The 2dF QSO redshift survey has recently reported measurements of the clustering in a sample of QSOs that is an order of magnitude larger than any previous sample (Hoyle et al. 2001). It should be relatively
straight forward to obtain predictions for the clustering of quasars from the semi-analytic models to compare with these new data.

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