SEMI-ANALYTICAL GALAXY FORMATION MODELS AND THE HIGH REDSHIFT UNIVERSE

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ABSTRACT. Semi-analytical models of galaxy formation based on hierarchical clustering now make a wide range of predictions for observable properties of galaxies at low and high redshift. This article concentrates on 2 aspects: (1) Self-consistent modelling of dust absorption predicts a mean UV extinction $A_{UV} \sim 1$ mag, depending only weakly on redshift, and similar to observational estimates. (2) The models predict that the Lyman-break galaxies found at $z \sim 3$ should be strongly clustered with a comoving correlation length $r_0 = 4 - 7$ Mpc/h (depending on the cosmology), in good agreement with subsequent observational determinations.

1 Introduction

The technique of semi-analytical modelling is a powerful tool for making predictions about the observable properties of galaxies at low and high redshift, based on hierarchical clustering models of structure formation, and thus for testing ideas about galaxy formation. The models we describe here are a greatly improved version of those of Cole et al. (1994), and are fully described in Cole et al. (1998). The models include the following processes: (a) formation of dark halos through merging; (b) shock-heating and radiative cooling of gas within halos; (c) collapse of cool gas to rotationally-supported disks; (d) star formation from cold gas; (e) feedback from supernovae; (f) chemical evolution; (g) galaxy mergers producing elliptical galaxies and bulges; (h) luminosity evolution of stellar populations; and (i) absorption by dust. The treatment of dust absorption is new, and is described in Section 2. Predictions for galaxy clustering at high redshift are described in Section 3.

The outputs from the models are masses, luminosities, colours, sizes, morphologies, circular velocities and chemical compositions for the whole galaxy population at any redshift. The models depend on several parameters relating to star formation and feedback, which are chosen to match observations of present-day galaxies, as described in Cole et al. (1998). Once normalized in this way, the models match most observations of present-day galaxies well, and can be used to make predictions for the evolution of galaxy properties with redshift.

2 Dust absorption

Absorption of starlight by dust has a significant effect on optical luminosities and colours of galaxies, and a large effect on the far-UV luminosities which are used as the main tracer of star formation rates at high redshift. We calculate dust absorption in a self-consistent way for each galaxy, using the 3D radiative transfer models of Ferrara et al. (1998). The latter models include stars in a bulge and exponential disk, and dust in an exponential disk, and give the net attenuation of galaxy light as a function of wavelength, inclination, and the galaxy parameters. These models are a major improvement over previous treatments, which assume a 1D screen or slab geometry for the stars and dust. The most important parameter in the dust models is $\tau_0$, the central face-on optical depth in dust (e.g. in the V-band). This is calculated directly from the semi-analytical model, as:

$$\tau_0 \propto \frac{M_{dust}}{\pi r_{disk}} \times \frac{M_{gas} Z_{gas}}{r_{disk}} \quad (1)$$
Figure 1. The cosmic star formation history. The curves show the model predictions, for a CDM model with $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$ and a Kennicutt (1983) IMF. The 1500Å luminosity density from the model has been converted to a star formation density using a constant conversion factor, as for the observations. The dashed curve shows the model without dust, and the solid curve the model prediction including dust. The symbols show observational estimates of the star formation rate per comoving volume, derived from H$\alpha$ or UV luminosity densities assuming a Kennicutt IMF and solar metallicity. The triangles are from H$\alpha$ luminosities, and have been corrected observationally for dust (and so should be compared to the dashed curve), while the other points are from rest-frame UV (1500$\pm$3000Å) luminosities, and do not include any dust correction (and should be compared to the solid curve). The references for the observational data are: open triangle: Gallego et al. (1995); filled triangle: Tresse & Maddox (1998); filled square: Treyer et al. (1998); open circles: Lilly et al. (1996); stars: Sawicki et al. (1997); filled hexagons: Conolly et al. (1997); open squares: Madau et al. (1998). Filled pentagons show preliminary results from a new survey by Steidel et al. (1998), and may be revised when the survey is completed.

The dust is assumed to have a solar neighbourhood extinction law, with the dust/gas ratio scaling as the gas metallicity $Z_{gas}$. $Z_{gas}$ is obtained from our chemical evolution calculation, and the disk radius $r_{disk}$ is calculated based on angular momentum conservation. We assume a ratio of vertical scaleheights $h_z(dust)/h_z(stars) = 1$, but the results are only weakly dependent on this value. Thus, our calculation of dust absorption has essentially no free parameters.

We find in our models that the mean dust extinction increases strongly with galaxy luminosity, this being an effect mainly of the increase of mean surface density with galaxy mass. On the other hand, the dependence of net extinction on wavelength is much weaker than predicted by a simple foreground screen model for the dust. Figure 2 shows the effects of dust on the inferred star formation history of the universe, for a CDM model with $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$ and a Kennicutt (1983) IMF. Since most observational estimates of the star formation density are derived from far-UV luminosities, we have followed the same approach for the models, taking the predicted 1500Å luminosity density (with or without dust) and converting it to an SFR density assuming the same IMF and a constant (solar) metallicity. The mean 1500Å extinction is predicted to vary only slowly with redshift, increasing from 0.5 mag at $z = 0$ to 1.2 mag at $z = 6$, the smaller dust content of higher redshift galaxies being more than compensated by their smaller sizes, resulting in higher...
of dark matter halos of mass $M$ at redshift $z$:

$$b(M, z) = 1 + \frac{1}{\delta_c(z)} \left[ \frac{\delta^2(z)}{\sigma^2(M, z)} - 1 \right]$$

where $\delta_c(z)$ is the critical linear overdensity for an object to collapse at redshift $z$, and $\sigma(M, z)$ is the variance of linear density fluctuations of mass $M$. This formula for the halo bias is expected to be valid down to scales somewhat smaller than the co-moving radii of the halos concerned (shown by an arrow in Figure 2), at which point halo-halo exclusion effects become significant. The semi-analytical models predict that the Lyman-break galaxies found by Steidel et al. should lie in halos of masses $M \sim 10^{12} M_\odot$. This is much larger than the typical halo mass $M_* \sim 10^{10} M_\odot$ (defined by $\sigma(M_*, z) = \delta_c(z)$) at $z = 3$, and so according to equation (2) these halos and the galaxies they contain should be highly biased. Baugh et al. calculated the mean clustering bias for the $R_{AB} < 25$ Lyman-break galaxies, and found $b \approx 4$ for both $\Omega = 1$ and $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$ CDM models. The accuracy of the analytical approximations used for the halo clustering was subsequently confirmed by Governato et al. (1998), who combined the semi-analytical models with N-body simulations, and found essentially identical results for the clustering of Lyman-break galaxies. This is shown in Figure 3.

A useful measure of the clustering amplitude is the correlation length $r_0$, defined to be the separation (in co-moving coordinates) where $\xi(r_0) = 1$. The Baugh et al. prediction for the Lyman-break galaxies was $r_0 = 4$ Mpc$/h$ for $\Omega = 1$ and $r_0 = 7$ Mpc$/h$ for $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$. These predictions agree remarkably well with the values subsequently measured by Adelberger et al. (1998) from a counts-in-cells analysis of redshift surveys of these galaxies, which were $r_0 = (4 \pm 1)$ Mpc$/h$ for $\Omega = 1$ and $r_0 = (6 \pm 1)$ Mpc$/h$ for $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$. These values are also plotted in Figure 3 for comparison with the models. This successful prediction of the clustering of high-redshift galaxies is strong evidence for these galaxies be-
Figure 2. The clustering of Lyman-break galaxies brighter than $R_{AB} = 25$ at $z \approx 3$, based on an analytical halo clustering model. The solid line shows the two-point correlation function in comoving coordinates for a CDM model with $\Omega = 1$, while the dashed line shows a CDM model with $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$. The symbols with error bars show the values of $r_0$ (defined by $\xi(r_0) = 1$) found observationally by Adelberger et al. (1998) for different assumed cosmologies: filled symbol: $\Omega = 1$; open symbol: $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$.

Figure 3. The clustering of Lyman-break galaxies at $z = 3$, calculated using a combined N-body/semi-analytic method. (a) Correlation functions in comoving coordinates for the $\Omega = 1$ CDM model. Lower solid line: dark matter correlation function; dashed line: real space correlation function of Lyman-break galaxies; upper solid line: redshift space correlation function of Lyman-break galaxies; dotted line: real space correlation function of Lyman-break galaxies calculated from the analytical model, as in Figure 2. (b) Redshift space correlation functions for $\Omega = 1$ (SCDM) and $\Omega_0 = 0.3$, $\Lambda_0 = 0$ (OCDM) models.
ing in the most massive halos at this redshift, and is an important confirmation of the validity of the semi-analytical models.

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