Numerical and Analytical Modelling of Galaxy Formation and Evolution

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Abstract. We review recent developments in theoretical studies of galaxy formation and evolution. In combination with new data from HST, Keck and other large telescopes, numerical and semi-analytic modelling is beginning to build up a coherent picture of galaxy formation. We summarize the current status of modelling of various galactic properties such as the structure of dark matter halos, the galaxy luminosity function, the Tully-Fisher relation, the colour-magnitude relation for ellipticals, the gross morphological properties of galaxies and the counts of faint galaxies as a function of magnitude, redshift and morphology. Many of these properties can be explained, at least at some level, within a broad class of CDM cosmologies, but a number of fundamental issues remain unresolved. We use our semi-analytic model of galaxy formation to interpret the evolutionary status of the Lyman-break galaxies at $z \approx 3 - 3.5$ recently discovered by Steidel et al. The abundance and global properties of these objects are compatible with model predictions in a variety of CDM cosmologies, including the standard version. All these models predict mild evolution in the distribution of star formation rates which peaks at around $z \approx 1$, but is never much larger than it is at present. The Steidel et al. Lyman-break galaxies are among the very first objects in which appreciable star formation is taking place; they thus signal the onset of galaxy formation. We present three example evolutionary histories of Lyman-break galaxies which illustrate that these objects are the precursors of present day, normal, bright ellipticals and spirals.

1. Introduction

The spectacular new data obtained in the past year or two with HST, Keck and other large telescopes are finally giving substance to the adjective “few” in Y.B. Zel’dovich’s famous 1977 statement: “It will only be a few years before the origin and evolution of galaxies is understood.” A full understanding of the origin and evolution of galaxies, however, will require a great deal of detailed theoretical modelling to uncover the physical processes manifested in the data. At present such modelling is lagging behind observational advances partly because of the breathtaking pace of these advances and partly because some of the physical
processes at work, particularly those involving gas dynamics and star formation, are intrinsically very complex.

Two interrelated techniques are available for theoretical modelling of galaxy formation and evolution: numerical simulations and semi-analytic modelling. The overall strategy is the same in both cases: to calculate how density perturbations emerging from the Big Bang turn into visible galaxies. This requires following a number of processes: (i) the growth of dark matter halos by accretion and mergers, (ii) the dynamics of cooling gas, (iii) the transformation of cold gas into stars, (iv) the spectrophotometric evolution of the resulting stellar populations, (v) the feedback from star formation and evolution on the properties of prestellar gas and (vi) the build-up of large galaxies by mergers. Numerical simulations so far have focussed on a small subset of these processes which are treated in as realistic a way as is allowed by current algorithms and computing power. The semi-analytic approach, on the other hand, considers the combined effect of all these processes which are simplified into parametric rules distilled from simulations or analytic considerations.

The numerical and semi-analytic approaches are clearly complementary and have different strengths and weaknesses. The simulations generally attempt to model the relevant physics from first principles, but still require various approximations and free parameters. For example, when dealing with gas dynamics one needs to chose between Lagrangian methods like “Smooth Particle Hydrodynamics (SPH)” (Katz & Gunn 1991, Navarro & White 1993, Steinmetz & Muller 1995, Evrard et al. 1994) or Eulerian methods (Cen & Ostriker 1993). There are also choices to be made regarding the cooling processes to be included, the mechanism to lay down initial conditions, the resolution of the calculation, etc. For more realistic modelling of galaxies, it is also necessary to include ad hoc algorithms for turning cold gas into stars and for coupling the energy liberated by stellar winds and supernovae to the gas.

In the semi-analytic approach (Cole 1991, White & Frenk 1991, Kauffmann et al. 1993, Lacey et al. 1993, Cole et al. 1994), the required approximations and free parameters are more readily apparent. The backbone of this technique is a Monte-Carlo implementation of the “extended Press-Schechter theory” (Bower 1991, Bond et al. 1991) used to describe the formation of dark matter halos by hierarchical clustering and merging (Kauffmann & White 1993, Lacey & Cole 1993). An attractive feature of this approach is that within a fairly general framework, a full model of galaxy formation is specified by a surprisingly small number of free parameters. This a common feature of the two main semi-analytic models in existence today, that of G. Kauffmann and collaborators (Kauffmann et al. 1993, 1994, Kauffmann 1996, 1996) and that of the present authors (Cole et al. 1994, Heyl et al. 1995, Baugh, Cole & Frenk 1996a, 1996b).

We summarize here the free parameters that appear in our semi-analytic model since this will be used in the remainder of this paper. Within a given cosmology, the model requires fixing five parameters (see Cole et al. (1994) for further details): (i) the star formation timescale, i.e. the timescale on which gas that has cooled inside a dark matter halo is turned into stars; (ii) a feedback parameter which determines the efficiency with which energy liberated from supernovae and stellar winds reheats gas cooling inside a halo; (iii) the initial mass function of the stars that form; (iv) the timescale on which a galaxy falling
onto a halo merges with the central galaxy and (v) the fraction of the stellar mass in stars above the hydrogen burning limit. To describe the broad morphology of a galaxy (i.e. its bulge-to-disk ratio) a sixth parameter is required: (vi) a threshold mass fraction for a merger to turn a disk into a spheroid. It must be emphasized that these are not fitting parameters but rather parameters that describe various astrophysical processes, mostly related to star formation, that are poorly understood. Lacking a full physical understanding of these processes, it seems sensible to adjust the parameters so as to obtain as good a match as possible to a few basic observational data, in our case, to the local galaxy luminosity functions in the B and K bands.

In this article, we summarize some of the lessons learned from numerical and semi-analytic models of galaxy formation, highlighting a number of unresolved issues (Section 2). We then deploy our semi-analytic tools to explore the implications of the recent discovery by Steidel et al. (1996) of a population of star forming galaxies at redshift \( z > 3 \) (Section 3). We conclude with a brief discussion in Section 4.

2. A summary of current theoretical issues

Most theoretical work on galaxy formation is carried out within the framework of hierarchical clustering and gravitational instability (e.g. White & Rees 1978, Peebles 1980). Within this general picture, the various relevant processes are understood at different levels. Progress in several of these areas may be summarized as follows.

- **Dark matter halos.** Processes associated with the gravitational evolution of dark matter halos are reasonably well understood. This subject has progressed significantly in the past 15 years as a result of the increased sophistication of N-body simulations allied to some degree of analytic insight. Thus, in a given cosmological model, the abundance of dark matter halos, their merging history and their internal structure can be predicted reliably (Press & Schechter 1974, Frenk et al. 1988, Lacey & Cole 1993, Navarro, Frenk & White 1996, Cole & Lacey 1996). For example, recent high resolution N-body simulations by Navarro, Frenk & White (1996) have established that independently of the cosmological model, dark matter halos of all masses develop a mass density profile that follows a simple, two-parameter form, scaling like \( r^{-1} \) in the central regions and like \( r^{-3} \) near the virial radius. The two parameters of the fit, which can be expressed as the mass and characteristic density of each halo, turn out to be strongly correlated: low-mass halos are significantly denser than more massive halos because, on average, they form earlier. Thus, in effect, the spherically averaged density profiles of dark matter halos are described by a universal one-parameter function.

- **The shape of the luminosity function.** Both numerical simulations and analytic considerations indicate that the mass function of galactic halos has a steeper slope at the low-mass end (\( \alpha \simeq 2 \)) than the observed field galaxy luminosity function (\( \alpha \simeq 1 \)) (Loveday et al. 1992, but see Marzke et al. 1994). The semi-analytic models, however, have demonstrated that the faint end of the galaxy luminosity function is determined by the combined effect of mergers and feedback
but, in general, no model so far has succeeded in producing a faint end slope much flatter than $\alpha \simeq 1.5$. At the bright end, the galaxy luminosity function cuts off exponentially, much as observed, as a result of the large cooling time of gas in massive halos.

- **The Tully-Fisher relation.** The Tully-Fisher relation predicted in semi-analytic models in a variety of cosmologies has a slope and scatter quite similar to those observed (White & Frenk 1991, Kauffmann et al. 1993, Lacey et al. 1993, Cole et al. 1994, Heyl et al. 1995). However, so far it has proved impossible to match simultaneously the zero-point of this relation and the amplitude of the galaxy luminosity function. The overall luminosity normalization of the models (parameter ($v$) above) can be chosen to match one or the other, but not both. This is another outstanding problem and results from the overabundance of galactic dark halos predicted in the models. The problem is particularly severe for standard CDM, but it is still present in low-density variants of this cosmology.

- **The colours of galaxies.** Standard stellar population synthesis models and a standard IMF are sufficient to produce model galaxies with the spread of colours observed in the local population. This is true in most popular cosmologies except in the mixed dark matter model in which galaxies are much too young and thus much too blue compared to observations (Heyl et al. 1995).

- **The morphologies of galaxies.** N-body/gas dynamic simulations produce galaxies with spiral disks and bulges (Katz & Gunn 1991, Steinmetz & Muller 1995) and merger remnants that resemble ellipticals (Barnes & Hernquist 1996, Mihos & Hernquist 1996). However, gaseous disks in simulations with realistic initial conditions have much smaller radii than observed disks because the fragments from which they form lose angular momentum to the halo as they merge (Navarro & Benz 1991, Navarro, Frenk & White 1995). Thus, contrary to common belief, the origin of the angular momentum of spiral disks is not yet fully understood. Incorporating a simple prescription for merger-induced transformations of disks into spheroids in semi-analytic models reproduces the Dressler (1980) morphology-density relation (Kauffmann 1995, Baugh et al. 1996a). This success provides suggestive support for the view that accretion of rotating gas and mergers are the key ingredients in understanding the broad morphological characteristics of galaxies. The same environmental effects in clusters that produce the morphology-density relation today are responsible for the Butcher-Oemler effect (Kauffmann 1996, Baugh et al. 1996a).

- **The colour-magnitude relation of cluster ellipticals.** Semi-analytic models tend to produce colour-magnitude relations with an approximately flat slope and small scatter (Kauffmann 1996, Baugh et al. 1996b). This is a counterintuitive result in hierarchical clustering models in which small objects form first and might therefore be expected to be redder. It arises because star formation in subgalactic fragments generally precedes the assembly of the galaxy by mergers. Furthermore, elliptical galaxies tend to form from fragments whose mass is biased towards large values. The traditional argument that the small scatter in the colour-magnitude relation requires ellipticals to be old and mergers to be unimportant thus appears to be incorrect. However, the observed colour-magnitude relation has a small but non-negligible slope (Bower, Lucey & Ellis 1992). In the context of current models, this must arise from metallicity effects.
which are neglected at present. It remains a major challenge for the models to reproduce the observed slope while retaining a small scatter.

Figure 1. The redshift distribution of galaxies with magnitudes in the range $22.5 < B < 24.0$. The solid histogram shows the data of Glazebrook et al (1995), while the dashed histogram shows the (more complete) data of Cowie et al (1996). The lines show the predictions of the model of Cole et al (1994) for a Scalo IMF (solid line) and a Miller-Scalo IMF (dotted line).

- **Counts of faint galaxies as a function of magnitude, redshift and morphology.** A notable success of the semi-analytic models is the excellent match they provide to the counts of faint galaxies as a function of magnitude, redshift and morphology. The supporting data are presented in the papers by White & Frenk (1991), Lacey et al. (1993), Kauffmann et al. (1993), Cole et al. (1994), and Baugh et al (1996a). The agreement is particularly good in the standard CDM model but it is also acceptable in low-density CDM models. Particularly noteworthy is the match to the morphological data from the Hubble Deep Field discussed by Baugh et al. (1996a) and the prediction that faintwards of $I \simeq 25$ the galaxy counts should become increasingly dominated by irregulars. Also noteworthy is the successful prediction of the redshift distribution of $B \simeq 24$ mag galaxies. The model predictions of Cole et al. (1994), published before the observations were made, are compared with the recent data of Cowie et al. (1996) in Figure 1. This agreement is the most striking indication so far that the models contain some element of truth. A consequence of these successes is that the models of Baugh et al. (1996a) also give a reasonable match to the redshift evolution of the luminosity function recently measured from the CFRS survey by Lilly et al. (1995) and from a combination of surveys by Ellis et al (1996). It should be
noted, however, that the good match to faint data is due, in part, to the steep faint end slope in the model luminosity function for local field galaxies.

3. The Lyman break galaxies

Steidel et al. (1996) have recently discovered a population of star forming galaxies at redshift $z \simeq 3 - 3.5$. In the context of the models discussed here, these galaxies are among the first objects in which appreciable star formation has taken place. Because of their great importance in understanding galaxy formation, we discuss them here in some detail.

Figure 2. The properties of Lyman-break or “UV drop-out” galaxies identified in our models using identical selection criteria to those applied to the observations of Steidel et al (1996). Results are given for the standard CDM model (solid lines) and the ΛCDM model (dashed lines). The top panel shows the distribution of stellar mass and halo mass; the middle panel shows the distribution of halo circular velocities; and the bottom panel shows the distribution of star formation rates. The arrows in the middle panel indicate the range inferred from the observations.
Candidate high-z galaxies were identified spectroscopically, using $U_n$, $G$ and $R$ filters (Steidel, Pettini & Hamilton 1995). At $z \simeq 3$ the 912 Å break produced by the Lyman limit shifts into the $U_n$ filter passband while, for the roughly flat spectrum characteristic of a star-forming object, the fluxes in the two other filters are comparable. Follow-up spectroscopy at Keck revealed that the objects so identified are indeed star-forming galaxies at $3.0 \leq z \leq 3.5$. Steidel et al. find that these galaxies represent 1.3% of the faint counts brighter than $R = 25$, corresponding to a comoving number density comparable to that of present day $L_*$ galaxies. The spectra of these galaxies are similar to those of nearby star-forming regions; their circular velocities are $250 \leq V_c/(\text{km s}^{-1}) \leq 450$ (if the line widths of saturated interstellar lines are assumed to reflect the circular velocity of the galaxy); and their typical star formation rates are inferred to be $\sim 2h^{-2}\text{M}_\odot \text{yr}^{-1}$ for $q_0 = 0.5$ and $\sim 6h^{-2}\text{M}_\odot \text{yr}^{-1}$ for $q_0 = 0.05$ (where $h$ is Hubble’s constant in units of 100 km s$^{-1}$ Mpc$^{-1}$.)

At first sight, the existence of a sizeable population of massive star-forming galaxies at such high redshifts may appear surprising, particularly in the context of the standard $\Omega = 1$, $h = 0.5$ CDM cosmology in which, as has been emphasized for a number of years, galaxy formation is a relatively recent phenomenon (Frenk et al. 1995). Our semi-analytic machinery allows us to investigate in detail whether galaxies with the required properties occur in a given cosmological model. Here we present results for our standard CDM model (normalised to $\sigma_8 = 0.67$ so as to give the observed local abundance of rich galaxy clusters) and for a flat COBE-normalized “$\Lambda$CDM” model ($\Omega = 0.3$, $\Lambda = 0.7$, $h = 0.6$, $\sigma_8 = 0.97$). Further details of this analysis and results for other cosmologies will be presented in a forthcoming paper.

Following our general philosophy, we apply our fully specified model, i.e. the model in which all free parameters have been previously fixed by reference to local galaxy data, in essence the model published by Cole et al (1994). The only change we have made is to assume a Miller-Scalo rather than a Scalo IMF. As Cole et al. discuss, the choice of IMF has little effect on the properties of the local galaxy population but it does affect the properties of galaxies at high redshift. We first selected galaxies using exactly the same filters and colour criteria as Steidel et al., taking into account the effects of absorption by intervening cold gas (Madau 1995). These criteria did indeed pick out galaxies at $2.8 \leq z \leq 3.5$. The standard CDM model produced 2400 galaxies per square degree brighter than $R = 25$ satisfying the colour criteria, of which 1200 lie in the redshift interval $z = 3 - 3.5$. The corresponding numbers in the $\Lambda$CDM model are 3700 and 1700. From their 31 robust candidates, Steidel et al. estimated $1400 \pm 300$ galaxies per square degree in this redshift interval.

The properties of our model “Lyman-break” galaxies are displayed in Figure 2. In the standard CDM model their typical stellar masses are a few times $10^9h^{-1}\text{M}_\odot$ ($\sim 10^{10}h^{-1}\text{M}_\odot$ in the $\Lambda$CDM model) and these galaxies inhabit dark matter halos with typical mass $10^{12}h^{-1}\text{M}_\odot$. The velocity dispersions of the standard model galaxies are remarkably similar to those measured by Steidel et al. Finally, the model star formation rates also agree well with the rates inferred by Steidel et al. (Star formation rates are not directly measured in the data but inferred from the $R$ magnitude assuming an IMF and a stellar popula-
tion synthesis model which are similar, but not identical, to those in our galaxy formation model.)

The success of our CDM models of galaxy formation in accounting for the observed abundance and overall properties of the Steidel et al. galaxies is both striking and surprising. However, several caveats are in order. Firstly, the predicted abundance of star-forming galaxies at high redshift depends sensitively on at least two model assumptions: the IMF and the normalisation of the linear density fluctuation spectrum, $\sigma_8$. Adopting a Scalo rather than a Miller-Scalo IMF reduces the total number of faint R-band counts by only 20% but it reduces the number of Lyman-break galaxies in the redshift interval of interest by about a factor of 10. Similarly, reducing $\sigma_8$ from our adopted value of 0.67 in the standard CDM model to 0.5 reduces the number of high redshift galaxies also by a factor of approximately 10. These uncertainties dwarf the changes produced by varying the other cosmological parameters of the model.

![Figure 3](image)

Figure 3. The mass in stars formed by redshift $z$ as a fraction of the final mass in stars at redshift zero. The solid line shows results for the standard CDM model, while the dotted lines show results for flat COBE-normalised cosmological models with $\Omega_0 = 0.3$, $\Lambda = 0.7$ and $h = 0.6$. The lower dotted curve has a spectral shape parameter $\Gamma = 0.18$ and the upper dotted curve has $\Gamma = 0.3$. In all cases, less than 10% of the total mass of stars has formed by $z = 3.5$.

Regardless of the uncertainties just discussed, the Lyman-break galaxies of Steidel et al. correspond to the first objects in our models in which significant star formation is taking place. Figure 3 shows how the overall stellar population builds up in our two models (and in a variant of the $\Lambda$CDM model in which the initial power spectrum has more power on galactic scales.) In all cases, only a small fraction of the final stellar component of the Universe has formed by $z = 3.5$. The standard CDM and $\Lambda$CDM models have almost identical star formation histories and both have formed less than 5% of the total stellar population by $z = 3.5$. In the low-density model with more small scale power this
fraction is still less than 10%. Thus, in the class of models we are considering, the redshift \( z \simeq 3.5 \) at which the Steidel et al. Lyman break galaxies are found is close to the onset of galaxy formation. Very few bright objects should exist beyond this redshift.

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\text{Figure 4. The distribution of star formation rates at four redshifts: } \ z = 3 \text{ (dot-dashed curves), } z = 2.35 \text{ (dashed curve), } z = 1 \text{ (dotted curves) and } z = 0 \text{ (solid curves). The upper panel shows results for our standard CDM model and the lower panel for our } \Lambda \text{CDM model. The distribution of star formation rates evolves slowly between the epochs shown and is highest at } z = 1.}
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Our predicted (differential) star formation rates at four different redshifts are shown in Figure 4. The upper panel gives results for the standard CDM model and the lower panel for the \( \Lambda \)CDM model. The lower abscissa is labelled by the actual star formation rate while the corresponding 1500 Å luminosities are given in the upper abscissa. In both cosmological models, the distribution of star formation rates has a similar shape at all times, but the rates are higher at \( z = 1 \) than at \( z = 3 \) or \( z = 0 \). The evolution in the star formation rate is relatively mild: over most of the range, the comoving abundance of galaxies varies by less than an order of magnitude between the peak at \( z \simeq 1 \) and the present.
We can interrogate our galaxy formation model to find out what sort of objects the Lyman-break galaxies eventually turn into. Two examples taken from our standard CDM model are shown in the “tree diagrams” of Figure 5. Redshift decreases downward in these plots and the width of the shaded region is proportional to the mass in stars at each epoch. Stars generally form in subgalactic fragments at high redshift which grow larger as gas cools onto a disk and turns into stars. Fragments can merge together and, if the merger is massive enough, the disks turn into a spheroid; a new disk may grow by subsequent accretion of gas (Kauffmann et al. 1993, Baugh et al. 1996b). The galaxy on the left of Figure 5 experienced only two very small mergers at $z \simeq 3$ and grew almost entirely by accretion. This object ends up as a late type spiral galaxy with a very small bulge. The galaxy on the right formed by the merger of several fragments, including a major merger at $z \simeq 0.3$. This galaxy ends up as an elliptical. The asterisks at high $z$ represent Lyman-break objects that satisfy the Steidel et al. selection criteria. The spiral galaxy is the descendant of a single fairly massive Lyman-break object; the elliptical harbours the descendants of two less massive Lyman-break objects which merged at relatively recent epochs.

The present-day luminosity function of galaxies which had a Lyman-break progenitor at $3 < z < 3.5$ is shown in Figure 6 for our two cosmological models and compared with estimates of the local field luminosity function. In both models the descendants populate the bright end of the luminosity function and, in the standard CDM model, most galaxies with $M_B - 5 \log h \simeq -21$ once harboured a Lyman-break object.

Figure 5. Star formation histories of two present day galaxies that contained a Lyman-break progenitor (marked by an asterisk) satisfying the selection criteria of Steidel et al (1996). Redshift decreases downward and the width of the shaded region is proportional to the mass in stars at each epoch. The galaxy on the left ends up as a late-type spiral; the galaxy on the right ends up as an elliptical.
Figure 6. Present-day luminosity functions. The squares show estimates of the field galaxy luminosity function in the local universe by Loveday et al. (1992; open symbols) and Marzke et al. (1994; solid symbols). The curves show predicted galaxy luminosity functions in the standard CDM (solid curves) and ΛCDM (dotted curves) models. The curves that extend over the entire range of magnitudes are the predicted local field galaxy luminosity functions. The curves near the bottom left of the diagram are the predicted present-day luminosity functions of galaxies which had a Lyman-break progenitor at $3 < z < 3.5$. Many of the brightest galaxies seen today harboured a Lyman-break object at high redshift.

4. Conclusions

Theoretical studies of galaxy formation, based on numerical simulations and semi-analytic techniques are an essential complement to observational studies of the high redshift universe. Such modelling is required in order to establish the connection between different types of data and their relation to the physics of galaxy formation in a cosmological setting. Although some of the physical processes involved, particularly those associated with star formation, are very complex and poorly understood, progress can be made by complementing a physically based description with heuristic rules to describe star formation.

Semi-analytic models now exist in which the detailed properties of the galaxy population at all epochs can be predicted \textit{ab initio}, starting from a cosmological spectrum of density fluctuations. The various physical processes can be characterised by a minimum of free parameters, all of which are fixed by reference to a small subset of the data for local galaxies. We have illustrated the predictive power of these semi-analytic models by comparing our published predictions for the redshift distribution of galaxies of $B \simeq 24$ mag with recent data from Cowie et al. (1996) (Figure 1). The excellent agreement between them is the most striking demonstration so far of the virtues of this approach.
In general, the best understood aspects of galaxy formation are those related to their dark matter component. The abundance, merging history and internal structure of galactic halos are all reasonably well established in a variety of cosmological models of hierarchical clustering. Some understanding also exists of the physical basis of observable properties such as the general shape of the galaxy luminosity function, the slope and scatter of the Tully-Fisher relation, the general features of the colour-magnitude diagram, the gross morphological properties of galaxies in different environments, and the counts of faint galaxies as a function of magnitude, redshift and morphology. All of these properties can be explained, at least at some level, within a broad class of CDM cosmologies.

Several fundamental properties of the galaxy population remain poorly understood. Examples include the faint end slope of the field luminosity function which is predicted to be significantly steeper than the standard estimate (Loveday et al. 1992). None of the existing models can simultaneously match the zero-point of the Tully-Fisher relation and the overall amplitude of the galaxy luminosity function, a problem which can be traced back to an overabundance of dark matter halos predicted in all CDM cosmologies. While the small scatter in the observed colour-magnitude relation for cluster ellipticals does not seem incompatible with hierarchical clustering, none of the models published to date can account for the measured slope in this relation.

In spite of the unsolved problems just mentioned, semi-analytic modelling remains a powerful tool to interpret the recent exciting new data on the high redshift universe. As an example, we presented in this article results from new calculations which attempt to identify the evolutionary status of the Lyman-break galaxies at \( z \approx 3-3.5 \) recently discovered by Steidel et al. (1996). Perhaps surprisingly, we found that the abundance and global properties of these objects is almost exactly what is predicted by our fiducial model of galaxy formation based on the standard CDM cosmology. Although the predicted abundance is, in fact, quite sensitive to certain model assumptions such as the IMF and the amplitude of mass fluctuations, in general, these galaxies are among the first objects in which appreciable star formation is taking place. Within a broad class of CDM models, it appears that the Steidel et al. objects signal the onset of significant galaxy formation. These objects evolve into the population of bright normal galaxies seen today. Our models seem to imply that the long awaited discovery of the early phases of normal galaxy evolution has now taken place.

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