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THE REDSHIFT DISTRIBUTION OF NEAR-INFRARED–SELECTED GALAXIES IN THE GREAT OBSERVATORIES ORIGINS DEEP SURVEY AS A TEST OF GALAXY FORMATION SCENARIOS[1]

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ABSTRACT

The redshift distribution of near-IR–selected galaxies is often used to attempt to discriminate between the classical view of galaxy formation, in which present-day luminous galaxies were assembled at early times and evolve through the passive aging of their stellar populations, and that of hierarchical structure formation, in which galaxies were assembled more recently via the merging of smaller objects. We carry out such a test here by computing the distribution of photometric redshifts of $K_{AB} < 22$ galaxies in the Great Observatories Origins Deep Field Survey (GOODS) southern field, and comparing the results with predictions from a semianalytic model based on hierarchical structure formation, and a classical "passive evolution" model. We find that the redshift distributions at $z \lesssim 1.5$ of both the hierarchical and passive models are very similar to the observed one. At $z \gtrsim 1.5$ the hierarchical model shows a deficit of galaxies, while the passive model predicts an excess. We investigate the nature of the observed galaxies in the redshift range where the models diverge, and find that the majority have highly disturbed morphologies, suggesting that they may be merger-induced starbursts. While the hierarchical model used here does not produce these objects in great enough numbers, the appearance of this population is clearly in better qualitative agreement with the hierarchical picture than with the classical passive evolution scenario. We conclude that the observations support the general framework of hierarchical formation, but suggest the need for new or modified physics in the models.

Subject headings: galaxies: evolution — galaxies: formation

1. INTRODUCTION

While the stars that produce the bulk of the optical light in nearby luminous galaxies are known observationally to be quite old, it is possible that the time at which the mass was assembled into a single object is different from the formation time of the stars. In fact, in the hierarchical paradigm of galaxy formation, one expects mass assembly to be a gradual process, in contrast to the classical monolithic dissipative collapse picture (Eggen, Lynden-Bell, & Sandage 1962). A generic prediction of hierarchical (cold dark matter [CDM]) theories is that galaxies should be less massive in the past. Direct searches for galaxies at high redshift should therefore provide a crucial test of this class of theories (Kauffmann & Charlot 1998). Determining the epoch of formation and assembly of present-day luminous galaxies is central to our understanding of galaxy formation and cosmology and is a primary goal of the Great Observatories Origins Deep Survey (GOODS), as well as of many other deep surveys.

In practice, however, there are many complications involved in carrying out this test. Of course, we cannot follow an individual galaxy back in time, but can only study populations observed at different redshifts. Cosmological *k*-corrections (redshifting of light to longer wavelengths) and stellar evolution both make it difficult to relate high-redshift populations to local ones. One can attempt to account for these effects by artificially redshifting template spectra for representative galaxy types and/or by using stellar population models with assumed star formation histories. Starting from an empirical low-redshift luminosity function, one can then predict how the local galaxy population would appear at high redshift with the effects of *k*-corrections only ("no evolution") or with the additional effects of stellar evolution ("passive evolution") included. However, these corrections can be sensitive to the input assumptions.

There are several advantages to carrying out this test using a sample selected in the near-IR rather than the optical. The corrections described above are considerably smaller, and the near-IR light more closely traces the stellar mass. The observed *K*-band (2.2 μm) probes the spectral energy distribution (SED) longward of the rest-frame *I* band (~8600 Å) out to $z \sim 1.5$. However, it is also necessary to probe a large enough volume to contain a statistically significant sample of rare luminous objects. The availability of accurate photometric redshift estimates, requiring multiband *U* through *K* photometry, enables such tests to be extended into the $z \gtrsim 1.2$ "spectroscopic desert," where spectroscopic redshifts are difficult to procure. Only recently have sufficiently deep and wide near-IR–selected surveys with multiband photometry begun to become available.

The original study by Kauffmann & Charlot (1998, hereafter KC98) showed that the cumulative redshift distribution of

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K-selected galaxies differed greatly in a hierarchical model compared with a passive (or pure luminosity evolution [PLE]) model: they found that the fraction of galaxies at $z > 1$ with $18 < K_{\rm Vega} < 19$ was an order of magnitude higher in the PLE model. Based on the small observational samples available at the time, KC98 concluded that the hierarchical model provided a better match to the observed redshift distribution out to $z \sim 1$. Recently, several studies have carried out this test using updated hierarchical models (including, among other things, the transition to a low-Ω_m, cosmological constant–dominated cosmology) and larger, deeper observational samples (Firth et al. 2002; Cimatti et al. 2002b; Kashikawa et al. 2003). Both Cimatti et al. (2002b) and Kashikawa et al. (2003) concluded that the PLE models produced better agreement with the observed redshift distribution at $z \gtrsim 1.5$ than the hierarchical models, although the disagreement was relatively subtle compared with the expectations set out in KC98.

In this Letter, we use a K_s-band–selected sample ($K_{\rm AB} < 22$) from the GOODS southern field to repeat the KC98-type redshift distribution test, using accurate, well-calibrated photometric redshifts (Mobasher et al. 2004). The GOODS field probes a considerably larger area and volume than previous studies at a similar depth. We also have the advantage of the exquisite Advanced Camera for Surveys (ACS) imaging, which allows us to investigate the morphologies of high-redshift galaxies, gaining further insights into the nature of these objects. We confront these observations with predictions from semianalytic hierarchical galaxy formation models, and with PLE models, both normalized to the $z = 0$ *K*-band luminosity function recently determined from the Two Micron All Sky Survey (2MASS) survey (Kochanek et al. 2001; Cole et al. 2001).

2. THE DATA

The GOODS data are described in Giavalisco et al. (2004). Our study is based on the GOODS southern field (Chandra Deep Field–South [CDF-S]), which has an area of 160 arcmin^2. In addition to the four-band (*BViz*) ACS imaging, we make use of an extensive set of complementary ground-based observations from the VLT, NTT, and ESO 2.2 m telescopes, including optical WFI (*U′UBVRI*) and FORS (*RI*), and infrared SOFI (JHK_s) photometry, which covers the entire ACS GOODS CDF-S field. This work is based on a point-spread function–matched SOFI-K_s–selected catalog. Clearly unresolved sources (stars) based on the ACS z_{850} data down to $z_{\rm AB} < 26.2$ have been removed. The 50% completeness limit is $K_s = 22.8$, and the sample should be close to 100% complete at $K_s < 22$ (Moy et al. 2003; Giavalisco et al. 2004), the limit we adopt for our analysis. Photometric redshifts were estimated as described in Mobasher et al. (2004) using all the available bands (U' through K_s), and are well calibrated to $K_{\rm Vega} < 20$ using spectroscopic redshifts from the K20 survey (Cimatti et al. 2002a) and additional spectra obtained from FORS2 on the VLT as part of the GOODS program. Typical redshift errors for the $K_s < 22$ sample are $\sim\Delta z/(1 + z_{\rm spec}) = 0.1$ (Mobasher et al. 2004).

In the remainder of the paper we refer to the K_s band as *K* for brevity and give all magnitudes in the AB system, unless otherwise specified. Note that for our filter bands, $K_{\rm AB} = K_{\rm Vega} + 1.85$ and $(R-K)_{\rm AB} = (R-K)_{\rm Vega} - 1.65$.

3. MODELS

Where relevant, we assume the following values for the cosmological parameters: matter density $\Omega_m = 0.3$, baryon density $\Omega_b = 0.044$, dark energy $\Omega_\Lambda = 0.70$, Hubble parameter $H_0 = 70$ km s^{-1} Mpc^{-1}, fluctuation amplitude $\sigma_8 = 0.9$, and a scale-free primordial power spectrum $n_s = 1$. These values are consistent with the recent *Wilkinson Microwave Anisotropy Probe* (*WMAP*) data (Spergel et al. 2003).

The basic ingredients of the semianalytic hierarchical models used here are described in Somerville & Primack (1999) and Somerville, Primack, & Faber (2001). The models are based on hierarchical merger trees within a ΛCDM model and include modeling of gas cooling, star formation, supernova feedback, chemical enrichment, stellar population synthesis, and dust. We use the multimetallicity stellar SED models of Devriendt, Guiderdoni, & Sadat (1999), assuming a Kennicutt IMF. Here we have considered a model based on the "collisional starburst" recipe described in Somerville et al. (2001) that was found to produce the best agreement with high redshift ($z \sim 3$) galaxy observations. Several parameters and model ingredients have been adjusted to give better agreement with the low-redshift optical and *K*-band luminosity functions recently determined by the Sloan Digital Sky Survey (SDSS) and 2MASS (e.g., Blanton et al. 2001; Cole et al. 2001), and with low-redshift galaxy colors (details will be given in R. S. Somerville et al. 2004, in preparation). We produced a mock catalog with the same angular extent and depth as the GOODS ACS and ground-based data, which was run "blind" before the data were analyzed.

The passive evolution models are computed as described in Gardner (1998) and are normalized to the type-dependent $z = 0$ *K*-band luminosity functions derived from the 2MASS survey by Kochanek et al. (2001). These models contain six different types of galaxies with simple parameterized star formation histories: E, S0, Sb, Sc, Irr, and starburst. All galaxies except the starburst type begin forming stars at $z = 15$. The E, S0, Sb, and Sc types have exponentially declining star formation rates with *e*-folding timescales of 1 Gyr for the E/S0, 4 Gyr for the Sb, and 7 Gyr for the Sc types. The Irr types have a constant star formation rate. The starburst population has a constant star formation rate and constant age (1 Gyr) at every redshift.

4. RESULTS

The cumulative and differential redshift distributions for the $K < 22$ selected samples are shown in Figure 1 for the GOODS data, the K20 survey, and the semianalytic and passive models. The redshift distribution of GOODS agrees very well with that obtained from the K20 spectroscopic survey, which was carried out independently in a smaller area of the same field. The agreement between the semianalytic models and the observations is quite good—well within the fluctuations expected from large-scale structure—up to about $z \sim 1.5$. This good low-redshift agreement is in contrast with previous comparisons with semianalytic models from several groups (Firth et al. 2002; Cimatti et al. 2002b). In previous models, the luminosity function was too steep on the faint end, leading to an excess of intrinsically faint galaxies at low redshift. Improved modeling of subhalo merging, and inclusion of ejection of gas by superwinds and suppression of gas infall in small halos after reionization, produce better agreement with the observed *K*-band luminosity function at $z = 0$ (Somerville 2002; Benson et al. 2002), and also better agreement with the low-redshift $N(z)$ shown here. Also of note is the similarity of the predicted $N(z)$ at $z < 1$ for the hierarchical and the PLE models—in contrast to the results of KC98.

At $z \gtrsim 1.5$ the number of $K < 22$ galaxies in the semianalytic models is significantly and systematically smaller than the ob-

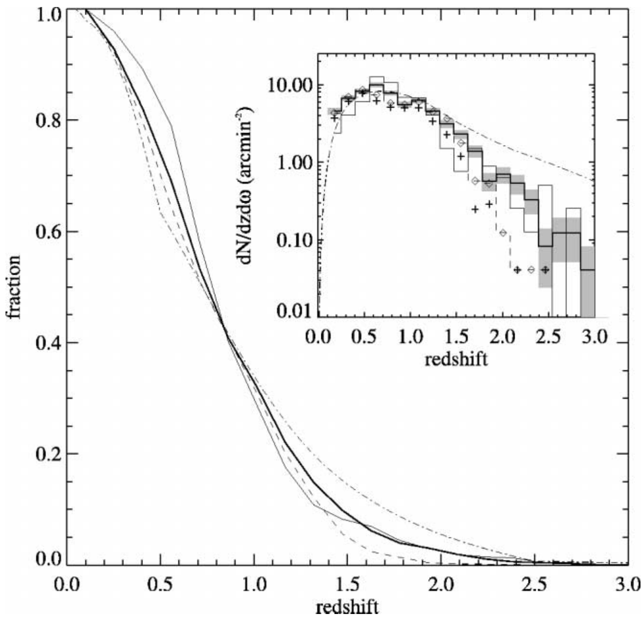

FIG. 1.—Cumulative redshift distribution of $K < 22$ galaxies. *Heavy solid line*, GOODS CDF-S; *light solid line*, K20 sample; *dashed line*, semianalytic model; *dot-dashed line*, passive model. The inset shows the differential redshift distribution ($K < 22$), with Poisson errors shown on the GOODS data (*bold histogram*). Line types are as in the main plot. The hierarchical model is highlighted by diamond symbols. The crosses show the hierarchical model with a crude correction of 0.2 mag applied to account for the isophotal magnitudes used in the GOODS observations (see text).

served value, while the PLE model systematically *overpredicts* the number of objects in this range by a similar factor. The isophotal magnitudes used in our GOODS catalog are probably fainter than the true total magnitudes by about 0.2–0.3 mag (Cimatti et al. 2002a). Correcting the semianalytic models for this effect further exacerbates the discrepancy, as shown in Figure 1. We note that the redshift range in which the models suffer from the most significant discrepancy ($z \gtrsim 1.5$) is precisely where the photometric redshifts are the least secure, as very few spectroscopic redshifts are available to test them—although progress is being made in this area (Daddi et al. 2004). In addition, at these redshifts, the observed K band has shifted into the rest optical and is therefore more sensitive to recent star formation activity.

It is interesting to investigate the nature of the galaxies that appear in the high-redshift tail of the observed distribution but are underrepresented in the hierarchical models. Figure 2 shows the (observed frame) $R-K$ colors as a function of redshift for the observed and semianalytic model galaxies. The colors of solar metallicity, single-age populations are also shown. The semianalytic model reproduces the locus of observed colors fairly well up to $z \sim 0.8$. At $z \sim 0.8$–1.2 the semianalytic model produces enough $K < 22$ galaxies overall but does not produce enough galaxies with very red colors. This problem has been noted before (Daddi, Cimatti, & Renzini 2000; Firth et al. 2002; Cimatti et al. 2002b). The number densities and morphologies of these $R-K \gtrsim 3.35$ extremely red objects (EROs) in GOODS are discussed in more detail in Moustakas et al. (2004).

At higher redshift ($z \gtrsim 1.5$), the observed distribution of $R-K$ colors is bimodal, with the "dip" around $R-K \sim 3$ (see Fig. 2). Focusing on galaxies in the redshift interval $1.7 < z < 2.5$ and with $K < 22$, we find that about 60% (44 out of 75) of the GOODS galaxies have colors bluer than $R-K = 3$, while in the semianalytic mock catalog, 52% (11 out of 21) of the objects have $R-K < 3$. Considering the small number statistics, this implies that the semianalytic model produces approximately the correct *relative fraction* of red and blue galaxies.

We have visually inspected all of the objects in this subsample and find that the great majority of both red and blue galaxies have highly irregular morphologies, many with multiple components and the appearance of ongoing mergers.

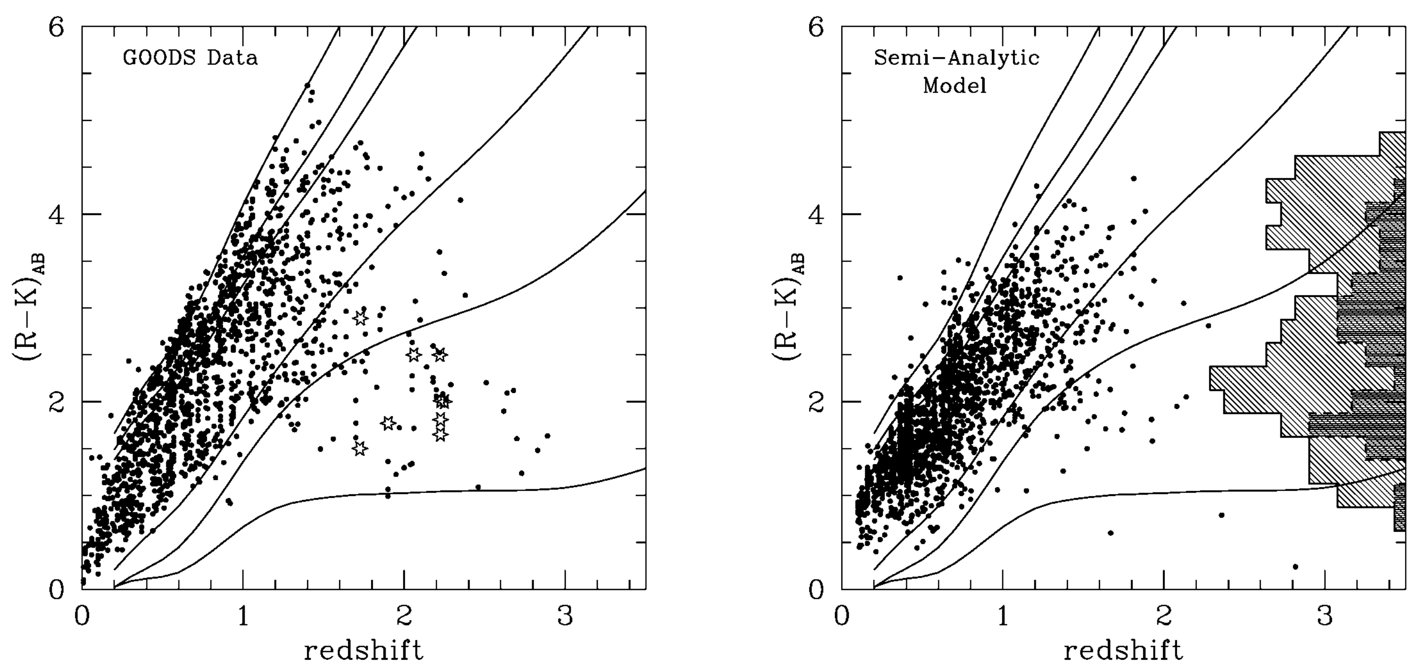

FIG. 2.—Observed frame color $(R-K)_{AB}$ vs. redshift for the GOODS CDF-S (*left*) and the semianalytic mock catalog (*right*). Tracks are shown for single-age, stellar metallicity populations with ages of 13.5, 5.8, 3.2, 1, 0.5, and 0.1 Gyr (unreddened), from top to bottom. Open stars show the colors of spectroscopically confirmed objects from Daddi et al. (2004). The color distribution of galaxies with $K < 22$ in the redshift range $1.7 < z < 2.5$ is shown in the right panel as histograms (*diagonal hatched*, GOODS; *horizontal fill*, mock catalog).

From comparison with the single-burst model tracks, we can deduce that the high-redshift, blue galaxies ($R-K \lesssim 3$) must be dominated by extremely young ($\lesssim$500 Myr), nearly unreddened stars. Intriguingly, Daddi et al. (2004) have recently obtained spectra for a sample of galaxies with $K_{\rm Vega} < 20$ and $z_{\rm phot} > 1.7$ in the GOODS CDF-S/K20 field and have successfully obtained redshifts for nine such objects, confirming that they lie in the range $1.7 \lesssim z \lesssim 2.3$. On the basis of these spectra and the ACS images, Daddi et al. (2004) argue that these objects are strongly clustered, massive, merger-driven starbursts. We show the location of these objects on our color-redshift diagram and see that they lie precisely in the regime of the "missing blue galaxies."

5. DISCUSSION

In this paper we address a central question in galaxy formation theory: were most of the luminous galaxies that we see today already in place at high redshift, or were they assembled gradually over time? To answer this question, we confronted observations from the GOODS CDF-S field with predictions from two models representing what are traditionally considered opposing points of view: a semianalytic hierarchical model based on CDM theory, and a "passive evolution" model in which galaxy properties evolve only due to the aging of their stellar populations. Our main conclusions are as follows:

1. Up to $z \sim 1$, redshift distributions of $K < 22$ galaxies in the hierarchical model, the passive model, and the data are all consistent with one another. However, the hierarchical model underproduces the number of EROs at $z \sim 1$.
2. The hierarchical model underproduces near-IR–selected objects ($K < 22$) by about a factor of 3 at $z \gtrsim 1.7$ and by an order of magnitude at $z \gtrsim 2$. The PLE model overproduces these galaxies by about a factor of 2 at $z \sim 2$.
3. At $z \gtrsim 1.5$, the objects underproduced in the hierarchical model are nearly equally divided between red ($R-K > 3$) and blue galaxies. Based on ACS imaging, many of these objects appear to be highly morphologically disturbed, and a large fraction may be merger-driven starbursts.

Not surprisingly, the predicted colors of model galaxies in the hierarchical models are quite sensitive to the details of the star formation recipes, as well as the stellar IMF and dust modeling. For example, if we assume that starbursts occur in major mergers only, we can produce more extremely red galaxies at $z \sim 1$, but we then produce even fewer luminous blue galaxies at $z \sim 1.5$–2. Alternatively, if we brighten all model galaxies by 0.5 mag (40%), we find that the semianalytic model then produces sufficient numbers of $K < 22$ objects at $z \gtrsim 1.5$, but this naturally causes an excess at lower redshift. Cosmic variance is also expected to be significant for these luminous, rare objects—assuming that these objects are strongly clustered, like EROs at $z \sim 1$ (e.g., Daddi et al. 2001), we estimate an uncertainty due to cosmic variance of about 60% in the number density of objects at $1.5 \lesssim z \lesssim 2$ (see Somerville et al. 2004). This implies that the semianalytic model is discrepant at less than 2 σ. Results from additional fields will determine whether there is an overdensity of objects at $z \gtrsim 1.5$–2 in the CDF-S.

A significant conclusion from this work is that the test proposed by KC98, when carried out with recent models, is not as strong a discriminator between the traditionally opposing points of view of hierarchical versus PLE models as was found in that work. Adoption of the flat, low-Ω_m cosmology now favored by observation, and the refinement of the star formation and feedback recipes, has resulted in more early star formation in the modern semianalytic models. At the same time, the use of the observed K-band $z = 0$ luminosity function to normalize the PLE models has reduced the uncertainty due to dust and k-corrections in those models. The net effect is that the two scenarios diverge significantly only at a higher redshift ($z \gtrsim 1.5$) than predicted by KC98. Several other recent studies (Cimatti et al. 2002a; Firth et al. 2002; Kashikawa et al. 2003) have reached a similar conclusion.

However, the morphologies of the observed objects in this redshift interval are inconsistent with the passive evolution hypothesis—the majority seem to be highly disturbed morphologically, and many are clearly interacting or merging (see also Daddi et al. 2004). Qualitatively, this is clearly more consistent with the hierarchical scenario. However, the *quantitative* disagreement between the number of predicted and observed objects indicates that some ingredients in the models need to be modified, or else that some physics is missing. Further study of the nature of this population at $1.5 \lesssim z \lesssim 2.2$, which forms a "bridge" between the better studied populations of "normal" galaxies at $z \lesssim 1$ and Lyman break galaxies at $z \gtrsim 2.2$, will certainly provide important new insights into some of the remaining mysteries of galaxy formation.

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