

The K20 survey

IV. The redshift distribution of $K_s < 20$ galaxies: A test of galaxy formation models^{*}

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Abstract. We present the redshift distribution of a complete sample of 480 galaxies with $K_s < 20$ distributed over two independent fields covering a total area of 52 arcmin². The redshift completeness is 87% and 98% respectively with spectroscopic and high-quality and tested photometric redshifts. The redshift distribution of field galaxies has a median redshift $z_{\text{med}} \sim 0.80$, with $\sim 32\%$ and $\sim 9\%$ of galaxies at $z > 1$ and $z > 1.5$ respectively. A “blind” comparison is made with the predictions of a set of the most recent Λ CDM hierarchical merging and pure luminosity evolution (PLE) models. The hierarchical merging models overpredict and underpredict the number of galaxies at low- z and high- z respectively, whereas the PLE models match the median redshift and the low- z distribution, still being able to follow the high- z tail of $N(z)$. We briefly discuss the implications of this comparison and the possible origins of the observed discrepancies. We make the redshift distribution publicly available.

Key words. galaxies: evolution – galaxies: formation

1. Introduction

The mass assembly history of galaxies remains one of the critical issues in observational cosmology: did galaxies reach their present stellar mass only recently (say, at $z \lesssim 1$)? Or were most (massive) galaxies already in place by $z \sim 1$? Spectroscopic surveys of faint galaxies selected in the K -band currently offer the best opportunity to answer these questions (Broadhurst et al. 1992). The main advantages with respect to optically selected samples include: the direct sensitivity to the galaxy stellar mass rather than to the ongoing/recent star formation activity (Gavazzi et al. 1996; Madau et al. 1998), the smaller K -correction effects, and the minor influence of dust extinction.

In this framework, we have completed an optical and near-infrared spectroscopic survey down to $K_s < 20$ (dubbed “K20 survey”) using ESO VLT telescopes and instruments, with full survey details being given in Cimatti et al. (2002b, hereafter Paper III; see also

<http://www.arcetri.astro.it/~k20/>). The K20 sample includes 546 objects to $K_s \leq 20$ (Vega system) over two independent fields (52 arcmin² in total), so to be less affected by the cosmic variance. The spectroscopic redshift completeness is 94% and 87% for $K_s \leq 19$ and $K_s \leq 20$ respectively. This makes the K20 sample the largest and most complete spectroscopic sample of galaxies with $K_s < 20$ available to date (see Paper III; cf. Cowie et al. 1996; Cohen et al. 1999). Moreover, a 98% redshift completeness is reached for the $K_s \leq 20$ sample when including the photometric redshifts obtained with the available deep $UBVRIZJK_s$ imaging for those objects without a spectroscopic redshift. If stars and broad-line AGNs are excluded, the total number of galaxies with $K_s \leq 20.0$ and with redshifts is 480.

In two previous papers based on the K20 survey we showed that Extremely Red Objects (EROs, defined by $R - K_s > 5$) are nearly equally populated by old passively evolving galaxies and by dusty star-forming systems at $z \sim 1$ (Cimatti et al. 2002a, Paper I). The number of all (old+dusty) EROs is strongly underpredicted by hierarchical merging models (HMMs), whereas old EROs have a density consistent with PLE models for passive early-type galaxies (Paper I), and are

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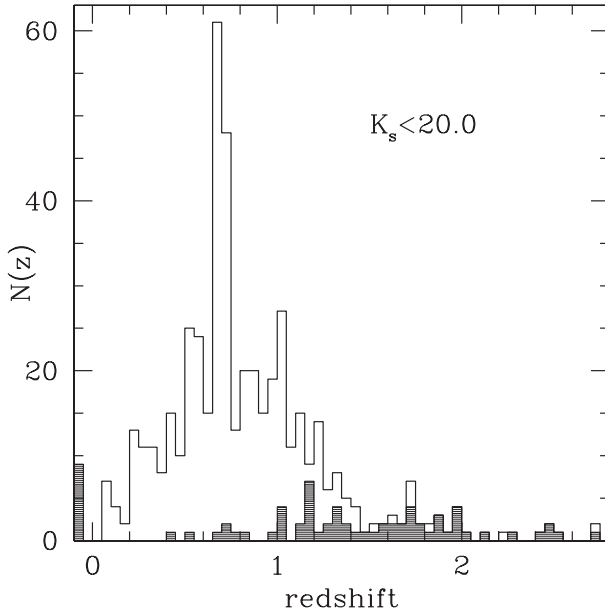


Fig. 1. The observed differential redshift distribution. The shaded histogram shows the contribution of photometric redshifts. The bin at $z < 0$ indicates the 9 objects without redshift.

strongly clustered as opposed to dusty EROs (Daddi et al. 2002, Paper II).

In this Letter, we present and discuss the observed redshift distribution, $N(z)$, of all the galaxies in the K20 sample, irrespective of their color, and compare it to the expectations for the case of PLE of galaxies, as well as to the predictions of various HMM renditions. The currently favored cosmological model is adopted, i.e., $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2. Observations vs. model predictions

The observed $N(z)$ for the 480 galaxies (417 with spectroscopic and 63 with photometric redshifts respectively) with $K_s \leq 20$ is shown in Fig. 1. The redshift distribution can be retrieved from <http://www.arcetri.astro.it/k20/releases>. The spike at $z \sim 0.7$ is due to two clusters (or rich groups) of galaxies respectively at $0.665 < z < 0.672$ (23 galaxies) and $0.732 < z < 0.740$ (33 galaxies) (see Paper III). The median redshift of $N(z)$ is $z_{\text{med}} = 0.737$ and $z_{\text{med}} = 0.805$, respectively with and without the two clusters being included. Without the clusters, the fractions of galaxies at $z > 1$ and $z > 1.5$ are $138/424$ (32.5%) and $39/424$ (9.2%) respectively. The high- z tail extends beyond $z = 2$. The contribution of objects with only a photometric redshift becomes relevant only for $z > 1.5$. The fractional cumulative distributions displayed in Figs. 2, 3 (bottom panels) were obtained by removing the two clusters mentioned above in order to perform a meaningful comparison with the galaxy formation models which do not include clusters (PLE models) or are averaged over very large volumes, hence diluting the effects of redshift spikes (HMMs).

No best tuning of the models was attempted in this comparison, thus allowing an unbiased “blind” test with the K20 observational data. The model predicted $N(z)$ have been

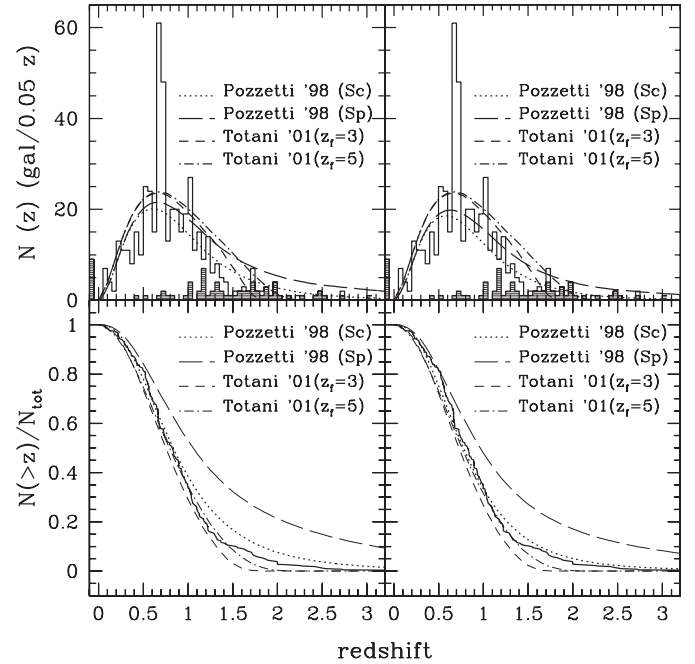


Fig. 2. *Top panels:* the observed differential $N(z)$ for $K_s < 20$ (histogram) compared with the PLE model predictions. *Bottom panels:* the observed fractional cumulative redshift distribution (continuous line) compared with the same models. The *left* and *right* panels show the models without and with the inclusion of the photometric selection effects respectively. Sc and Sp indicate Scalo and Salpeter IMFs respectively.

normalized to the K20 survey sky area. We first discuss the case of PLE expectations, as derived by Pozzetti et al. (1996, 1998, PPLE hereafter), and Totani et al. (2001) (TPLE hereafter).

2.1. Comparison with PLE models

In the PPLE model the present-day galaxy luminosity function is divided into 5 Hubble types (E, S0, Sab-Sbc, Scd-Sdm, Im). The spectral evolution for each type is described by the Bruzual & Charlot (1993) model (GISSEL version 2000) which reproduces the rest-frame colors and K -corrections of local galaxies. Exponentially declining star formation rate histories and solar metallicity are adopted. The age of each galaxy is set to 12.5 Gyr ($z_f = 5.7$) with the exception of Im galaxies ($age = 0.1$ Gyr). The e -folding times are set to 0.3, 2, 10 Gyr, and ∞ for E, S0, Sab-Sbc, and Scd-Sdm-Im galaxies respectively. Dust extinction is not taken into account. Besides the adopted cosmology, the only difference between the PPLE model used here and Pozzetti et al. (1996, 1998) is the use of the K_s -band local luminosity function from the 2MASS for different morphological types (Kochanek et al. 2001), which is in agreement with the overall local luminosity function of Cole et al. (2001). Figure 2 shows the predictions of the PPLE models for two types of initial mass function (IMF), Salpeter (1955) and Scalo (1986). With the flatter (i.e. Salpeter) IMF the intrinsic luminosity of both passively evolving and star forming galaxies increases more rapidly with redshift than in the case of the steeper (Scalo) IMF. As already discussed by

Pozzetti et al. (1996) (see also McCracken et al. 2000), the mild evolution allowed by the Scalo IMF is more consistent with the observations of the rest-frame ultraviolet luminosity density up to $z \sim 1$ (e.g. Cowie et al. 1999), and reproduces most observables (galaxy counts, color and redshift distribution from the U to the K band) without invoking the strong number density evolution or dust extinction required by the Salpeter IMF (cf. Fig. 2).

In the TPLE model galaxies are also divided into 5 types (E/S0, Sab, Sbc, Scd, Sdm) and their spectral evolution is described using the Arimoto & Yoshii (1987) models. The B -band local luminosity function is used, and the Salpeter IMF and a top-heavy IMF with exponent 0.95 are adopted for spirals and ellipticals respectively, with two options for formation redshifts: $z_f = 3$ and $z_f = 5$. Contrary to the PPLE model, the evolution of metallicity and dust extinction in galaxies is treated in this model.

Figure 2 shows fairly good agreement between the observed $N(z)$ distribution and the PLE models (with the exception of PPLE with Salpeter IMF). The predicted and the observed total number of galaxies with $K_s < 20$ agree within 10% for the PPLE and the TPLE ($z_f = 3$), 28% for the TPLE ($z_f = 5$), and 34% for PPLE with a Salpeter IMF. The predicted median redshifts are just slightly higher than observed: $z_{\text{med}} = 0.83, 0.75$ and 0.79 for the PPLE, TPLE ($z_f = 3, 5$) models respectively, but inconsistent with the PPLE with Salpeter IMF ($z_{\text{med}} = 1.05$). This is due to these PLE models somewhat overpredicting the number of galaxies at $z \gtrsim 1.2$. However, as extensively discussed in Paper III, because of the photometric selection effects present in the K20 sample (partly due to the cosmological surface brightness dimming), the total fluxes of spirals and ellipticals with $L \lesssim L^*$ (i.e. the bulk of the K20 sample) are, on average, underestimated by about 0.1 and 0.25 mag, respectively. In order to assess the influence of such effects, we compared the observed redshift distribution (down to our nominal $K_s < 20.0$) with the PPLE and TPLE models with $K_s < 19.9$ for “disk” and $K_s < 19.75$ for “early-type” galaxies. Figure 2 (right panels) shows that when such selection effects are taken into account the PLE models become much closer to the observed $N(z)$ thanks to the decrease of the predicted high- z tail. According to the Kolmogorov-Smirnov test, the PLE models are acceptable at 95% confidence level, with the exception of the PPLE model with Salpeter IMF (rejected at >99% level). We conclude that PLE models offer a satisfactory fit to the observed $N(z)$ distribution, all the way to the highest redshifts in our sample.

2.2. Comparison with hierarchical merging models

For the comparison with the HMM predictions we were kindly granted access to the model databases of Cole et al. (2000, C00 hereafter), Somerville et al. (2001, S01 hereafter) and Menci et al. (2002, M02 hereafter). These models are tuned to reproduce some low- z observable, such as the local galaxy luminosity function near $L \simeq L^*$ (C00, M02) or the Tully-Fisher relation (S01). The main difference among the HMMs used here is the inclusion in S01 of the merging-promoted “starburst” mode

of star formation besides the “quiescent” mode, the only one included in C00 and M02. The starburst mode has the effect of increasing the overall star formation at high redshift, when most of the merging takes place. Moreover, merging between satellite galaxies within DM haloes is included in S01 and M02, but neglected in the C00, where satellites are allowed to merge only onto the central massive galaxy. The M02 model without merging between satellites is otherwise equivalent to the C00 rendition. The effect of merging between satellites is to deplete the number of low-mass galaxies which aggregate to form larger units, thus flattening the galaxy mass function at the faint end and slightly increasing the number of intermediate mass galaxies (see S01 and M02 for more details). All the HMMs used here adopt a Salpeter IMF.

The HMMs overpredict the total number of galaxies with $K_s < 20$ in the K20 survey area by factors of 30–45%. In particular, Fig. 3 (top panels) shows that all the HMMs show an excess of predicted galaxies at $z < 0.5$, e.g., by a factor of ~ 2.5 at $z \sim 0.4$ for the C00 model, and ~ 1.5 – 2 for the M02 and S01 models, respectively. The predicted median redshifts are $z_{\text{med}} = 0.59, 0.70$ and 0.67 for the C00, M02 and S01 models, respectively, thus being systematically lower than the observed z_{med} . Moreover, all the HMMs have a deficit of $z > 1$ galaxies, in particular with a fraction at $z > 1.5$ smaller by factors of ~ 4 for the C00 model and ~ 2 – 3 for the M02 and S01 models. Such a discrepancy increases dramatically for higher redshifts, where all the HMMs predict no galaxies with $z > 2$. Figure 3 (bottom panels) illustrates that in the fractional cumulative distributions the discrepancy with observations appears systematic at all redshifts. The Kolmogorov-Smirnov test shows that all the HMMs are discrepant with the observations at >99% level. The inclusion of the photometric biases exacerbates this discrepancy, as shown in Fig. 3 (right panels) for the M02 model calculated for $K_s < 19.8$ in order to include an average photometric bias for spirals and ellipticals (the discrepancy for the C00 and S01 models becomes even stronger).

The excess of galaxies at $z \lesssim 0.5$ seen in Fig. 3 is due to HMMs predicting too many low-mass, low-luminosity galaxies. This excess has typically afflicted HMMs, with the merging between satellites improvement being apparently insufficient to provide a better agreement with the data. But in addition, HMMs underpredict the number of high-redshift objects. This is illustrated by Fig. 4, where the PPLE model is capable to reproduce the cumulative *number* distribution of galaxies at $1 < z < 3$ within 1 – 2σ , whereas the M02 model is always discrepant at $\gtrsim 3\sigma$ level (up to $>5\sigma$ for $1.5 < z < 2.5$). All the results described in this section remain valid if shallower limiting magnitude thresholds are adopted (see Fig. 5).

3. Discussion

Early predictions of the expected fraction of galaxies at $z > 1$ in a $K < 20$ sample indicated respectively $\approx 60\%$ and $\approx 10\%$ for a PLE case and for a (then) standard $\Omega_m = 1$ CDM model (Kauffmann & Charlot 1998). This version of PLE was then ruled out by Fontana et al. (1999). The more recent PLE and HMM used in this paper consistently show that for $z > 1$ the difference between the predictions of different scenarios is

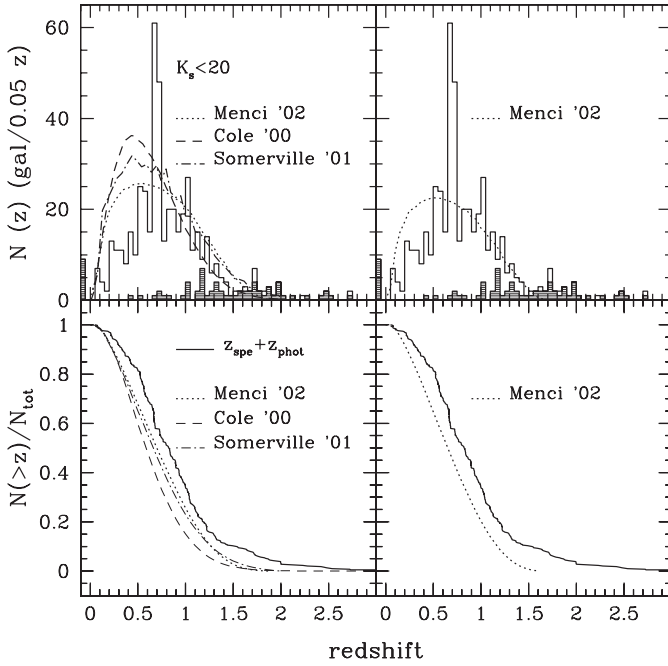


Fig. 3. *Top panels:* the observed differential redshift distribution for $K_s < 20$ (histogram) compared with the HMM predictions. *Bottom panels:* the observed fractional cumulative redshift distribution (continuous line) compared with the same models of top panels. The *right panels* show the M02 model with the inclusion of the photometric selection effects.

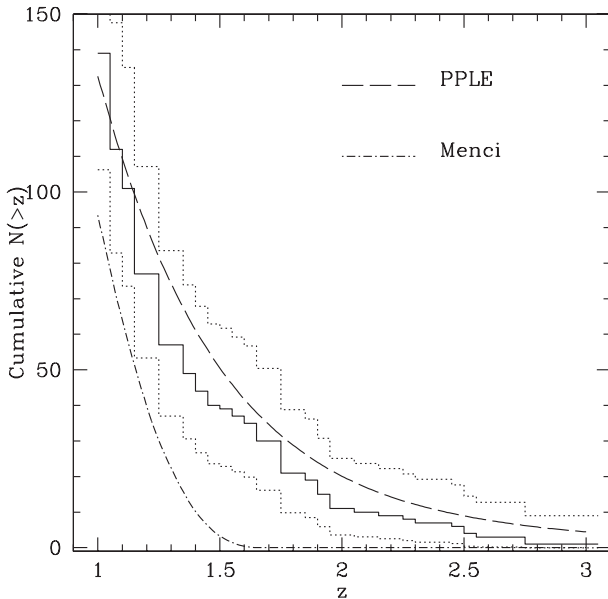


Fig. 4. The observed cumulative number of galaxies between $1 < z < 3$ (continuous line) and the corresponding poissonian $\pm 3\sigma$ confidence region (dotted lines). The PPLE (Salo IMF) and the M02 models are corrected for the photometric biases.

much less extreme. These results partly from the now favored Λ CDM cosmology which pushes most of the merging activity in hierarchical models at earlier times compared to τ CDM and SCDM models with $\Omega_m = 1$, and partly to different recipes for the star formation modes, which tend to narrow the gap between HMMs and the PLE case (e.g. Somerville et al. 2001;

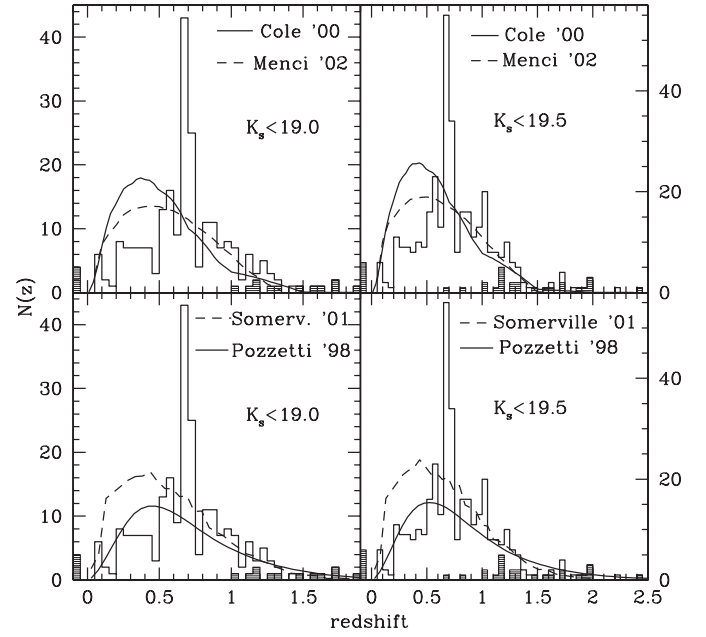


Fig. 5. The observed differential redshift distribution for $K_s < 19$ and $K_s < 19.5$ (histograms) compared with the model predictions (not corrected for photometric selection effects).

Firth et al. 2002). The disagreement between the observed $N(z)$ and the predictions of the most updated HMMs based on a Λ CDM cosmology would then become even stronger in the case of old-fashioned CDM models with $\Omega_m = 1$ because structures form later in a matter-dominated universe, and thus they would predict an even lower fraction of galaxies at high- z . In this respect, our results can be seen as additional evidence that the universe is not matter-dominated ($\Omega_m < 1$), and suggest that the HMMs may perform better if Ω_m is even lower than the currently favored $\Omega_m = 0.3$.

Nevertheless, the results of the K20 survey indicate that the shape and the median of the observed redshift distribution of $K_s < 20$ galaxies are in broad agreement with the expectations of PLE models, while disagree with the predictions of current hierarchical merging models of galaxy formation. This discrepancy refers to all galaxies, irrespective of color or morphology selection, and therefore is more general than the already noted discrepancies with EROs (Daddi et al. 2000, Paper I; Cimatti 2002). The poor performance of HMMs in accounting for the properties of even $z = 0 \rightarrow \sim 1$ early-type galaxies has been emphasized in the past (e.g., Renzini 1999; Renzini & Cimatti 1999). Moreover, among low-redshift galaxies there appears to be a clear anti-correlation of the specific star formation rate with galactic mass (Gavazzi et al. 1996; Boselli et al. 2001), the most massive galaxies being “old”, the low-mass galaxies being instead dominated by young stellar populations. This is just the opposite than expected in the traditional hierarchical merging scenario, where the most massive galaxies are the last to form.

On the other hand, the strong clustering of EROs seems to be rather consistent with the predictions of CDM models of large scale structure evolution (Daddi et al. 2001, Paper II; Firth et al. 2002). Thus, adopting the hierarchical merging Λ CDM

scenario as the basic framework for structure and galaxy formation, the observed discrepancies may be ascribed to the heuristic algorithms adopted for the star formation processes and their feedback, both within individual galaxies and in their environment. Our results suggest that HMMs should have galaxy formation in a CDM dominated universe to closely mimic the old-fashioned *monolithic collapse* scenario. This requires to enhance merging and star formation in massive haloes at high redshift (say, $z \gtrsim 3$), while in the meantime suppressing star formation in low-mass haloes. For instance, Granato et al. (2001) suggested the strong UV radiation feedback from the AGN activity during the era of supermassive black hole formation to be responsible for the suppression of star formation in low-mass haloes, hence imprinting a “anti-hierarchical” behavior in the baryonic component. The same effect may well result from the feedback by the starburst activity itself (see also Ferguson & Babul 1998).

In summary, the redshift distribution presented in this paper, together with the space density, nature, and clustering properties of the ERO population (Paper I, Paper II) and the redshift evolution of the luminosity and stellar mass functions derived for the K20 sample (Pozzetti et al. 2002; Fontana et al. 2002) provide a new set of observables on the galaxy population in the $z \sim 1$ – 2 universe, thus bridging the properties of $z \sim 0$ galaxies with those of Lyman-break and submm/mm-selected galaxies at $z \gtrsim 2$ – 3 . While making a step towards the fully empirical mapping of galaxy formation and evolution, this set of observables poses a new challenge for theoretical models to properly reproduce.

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