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THE K20 SURVEY: NEW LIGHT ON GALAXY EVOLUTION

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RESUMEN

Examinamos los primeros resultados del sondeo K20 y comparamos las observaciones con las predicciones de distintos modelos de formación y evolución galáctica (fusión jerárquica y evolución sólo de la luminosidad).

ABSTRACT

We review the first results of the K20 survey and compare the observations with the predictions of different models of galaxy formation and evolution (hierarchical merging and pure luminosity evolution).

Key Words: **GALAXIES: FORMATION, GALAXIES: EVOLUTION**

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 $z < 1$) ? 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 order to investigate the evolution of massive galaxies and to constrain the currently competing galaxy formation scenarios, we started in 1999 an ESO VLT Large Program that was dubbed "K20 survey" . Full details of the survey are given in Cimatti et al. (2002b) and in `http://www.arcetri.astro.it/~k20/`. The sample is made by 546 objects with $K_s < 20$ extracted from a 32.2 arcmin^2 area of the Chandra Deep Field South (CDFS; Giacconi et al. 2000) and from a 19.8 arcmin^2 field centered at 0055-269. Optical multi-object spectroscopy was made with the ESO VLT UT1 and UT2 equipped with FORS1 and FORS2. A fraction of the sample was observed with near-IR spectroscopy with VLT UT1+ISAAC. $UBVRIzJK_s$ imaging is also available for both fields, thus providing the possibility to estimate and optimize photometric redshifts for all the objects in the K20 sample. 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 (cf. Cowie et al. 1996; Cohen et al. 1999; Stern et al. 2000; Drory et al. 2001). A 98% redshift completeness is reached for the $K_s \leq 20$ sample when including the photometric redshifts 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 this paper, we review the main results obtained so far with the K20 survey. The currently favoured cosmological model is adopted, i.e., $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2. EXTREMELY RED OBJECTS (EROS)

A complete sub-sample of 78 galaxies with $R - K_s > 5$ (Extremely Red Objects; EROs) and $K_s < 20$ was extracted from the K20 full sample. For 35 of them it was possible to derive a spectroscopic redshift and a spectral classification (see Fig. 1 and Cimatti et al 2002a). Two classes of galaxies, nearly equally populated and at $0.8 < z < 1.5$, were found to contribute to the ERO population: old stellar systems with no signs of star formation, and dusty star-forming galaxies. The classification of EROs as old galaxies is based on the detection of the 4000Å break and CaII H&K absorptions with undetected [OII]λ3727 emission, while objects with [OII]λ3727 emission and no 4000Å break were assigned to the dusty-SF class.

The colors and spectral properties of old EROs are consistent with $\geq$3 Gyr old stellar populations (assuming solar metallicity and Salpeter IMF), requiring a formation redshift $z_f > 2.4$. The number density of the old ERO population is estimated to be $6.3 \pm 1.8 \times 10^{-4}$ h^{3}Mpc^{-3} for $K_s < 19.2$, consistent with the expectations of PLE models of passively evolving early-type galaxies with similar formation redshifts. Hierarchical models result in a significant deficit of such old-red galaxies at $z \sim 1$, ranging from a factor of ~ 3 (Kauffmann et al. 1999) to a factor of ~ 5 (Cole et al. 2000). The 3D clustering analysis shows that old EROs are the main source of the observed strong ERO angular clustering ($5.5 < r_0 < 16$

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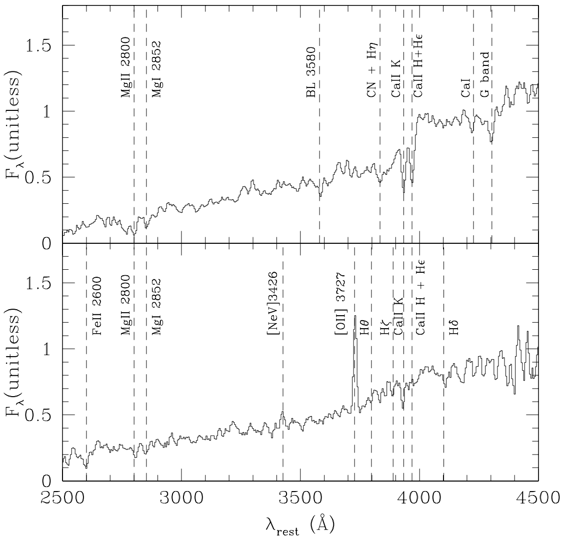

Fig. 1. The average rest-frame spectra of old (top; $z_{mean} = 1.000$) and dusty star-forming EROs (bottom; $z_{mean} = 1.096$).

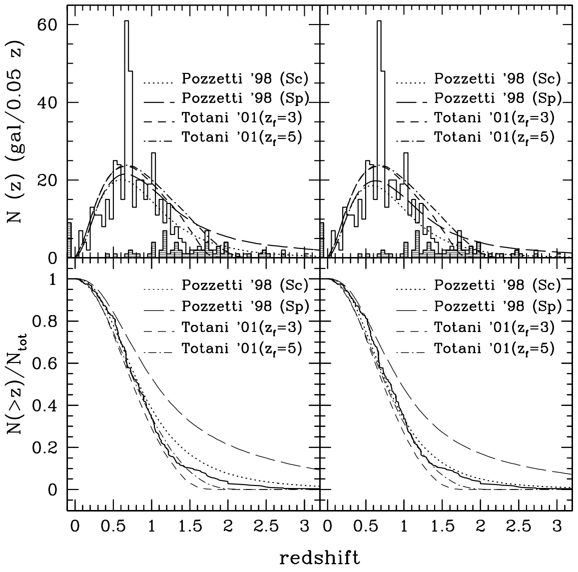

Fig. 2. *Top panels:* the observed differential $N(z)$ for $K_s < 20$ (histogram) compared with the PLE model predictions. *Bottom panels:* the observed fractional cumulative redshift distribution (continuous line) compared with the same models. The *left* and *right* panels show the models without and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

h^{-1}Mpc comoving; Daddi et al. 2002).

The spectra of star-forming EROs suggest a dust reddening of $E(B-V) \sim 0.5$–1 (adopting the Calzetti extinction law), implying typical star-formation rates of 50-150 $M_\odot$/yr, and a significant contribution ($> 20\%$) to the cosmic star-formation density at $z \sim 1$. The comoving density of dusty EROs is $\sim 6 \times 10^{-4}$ h^{3}Mpc^{-3} at $K_s < 19.2$. The GIF simulations[2] (based on Kauffmann et al. 1999 semianalytical hierarchical model) predict a comoving density of red galaxies with $SFR > 50$ $M_\odot$/yr that is a factor of 30 lower than the observed density of dusty EROs. The 3D clustering of star-forming EROs is found to be low ($r_0 < 2.5$ h^{-1} Mpc comoving; Daddi et al. 2002).

3. THE REDSHIFT DISTRIBUTION

Differential and cumulative redshift distributions for all the galaxies in the K20 sample are presented in Fig. 2 (see Cimatti et al. 2002c), together with the predictions of different scenarios of galaxy formation and evolution, including both hierarchical merging models (HMMs) from Menci et al. (2002, M02), Cole et al. (2000, C00), Somerville et al. (2001, S01), and pure luminosity evolution models (PLE) based on Pozzetti et al. (1996, PPLE) and Totani et al. (2001, TPLE). The K20 redshift distribution can be retrieved from `http://www.arcetri.astro.it/ k20/releases`.

[2]http://www.mpa-garching.mpg.de/GIF/

The spike at $z \sim 0.7$ is due to two clusters (or rich groups) of galaxies. The median redshift of $N(z)$ is $z_{med} = 0.737$ and $z_{med} = 0.805$, 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 $z > 1.5$. 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 normalized to the K20 survey sky area.

Fig. 2 shows fairly good agreement between the observed $N(z)$ distribution and the PLE models (with the exception of PPLE with Salpeter IMF). As extensively discussed in Cimatti et al. 2002b, because of the photometric selection effects present in the K20 sample, the total fluxes of spirals and ellipticals with $L \sim L^*$ (i.e. the bulk of the K20 sample) are, on average, underestimated by about 0.1 and 0.25 magnitudes, respectively. In order to assess the influence of such effects, we compared the observed redshift distribution (down to our nominal

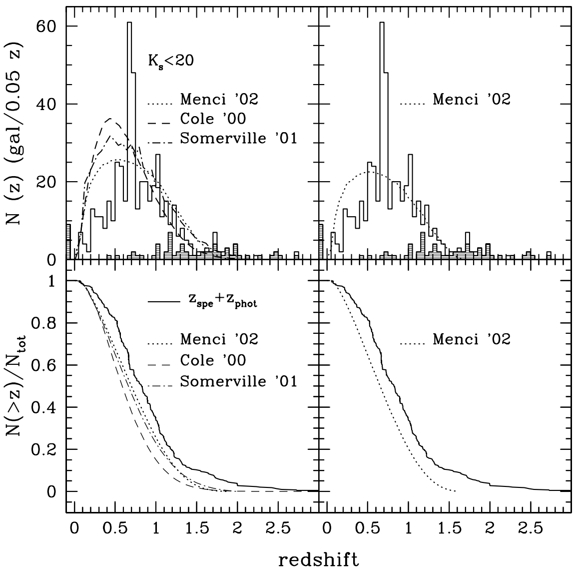

Fig. 3. *Top panels:* the observed differential redshift distribution for $K_s < 20$ (histogram) compared with the HMM predictions. *Bottom panels:* the observed fractional cumulative redshift distribution (continuous line) compared with the same models of top panels. The *right* panels show the M02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

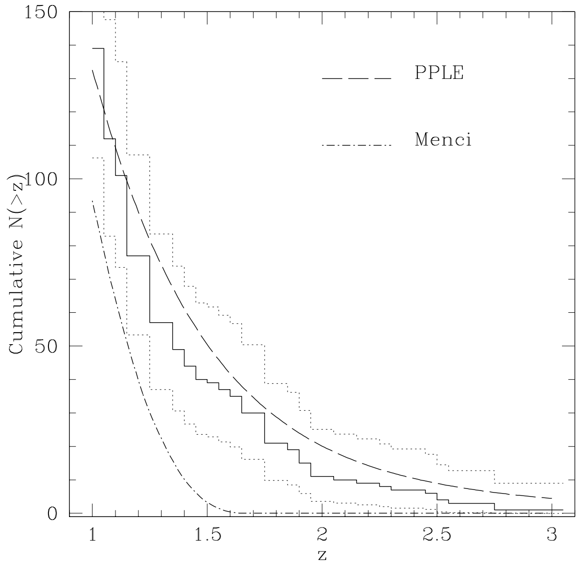

Fig. 4. The observed cumulative *number* of galaxies between $1 < z < 3$ (continuous line) and the corresponding Poissonian $\pm 3\sigma$ confidence region (dotted lines). The PPLE (Scalo IMF) and the M02 models are corrected for the photometric biases.

$K_s < 20.0$) with the PPLE and TPLE models with $K_s < 19.9$ for "disk" and $K_s < 19.75$ for "early-type" galaxies. Fig. 2 (right panels) shows that when such selection effects are taken into account the PLE models become even 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).

On the other side, the hierarchical merging models (HMMs) show an excess of predicted galaxies at $z < 0.5$. The predicted median redshifts are z_{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. 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). The excess of galaxies at $z \sim 0.5$ seen in Fig. 3 is due to HMMs predicting too many low-mass, low-luminosity galaxies. 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 $\geq 3\sigma$ level (up to $> 5\sigma$ for $1.5 < z < 2.5$).

4. THE NEAR-IR LUMINOSITY FUNCTION

The luminosity function of galaxies has been estimated in the rest-frame K_s-band and in three mean redshift bins (z = 0.5,1,1.5) (Pozzetti et al. 2002 in preparation). Fig. 5-6 show a comparison of the observed luminosity function with PLE and hierarchical merging model predictions. Such a comparison confirms the results already obtained for the redshift distribution: the K_s-band luminosity function evolves mildly in luminosity, whereas the possibility of a strong density evolution, as predicted by all the HMMs, is excluded by the observed data.

In particular, the PLE models describe reasonably well the shape and the evolution of the luminosity function up to the highest redshift bin, z_{mean} = 1.5, with no evidence for a strong decline of the most luminous systems (with $L > L^*$). This is in constrast, especially in the highest redshift bin, with the prediction by the HMMs of a decline in the number density of luminous (i.e. massive) systems with redshift (related to the building of galaxies via merging). Moreover, hierarchical merging models (namely M02 and C00) result in a significant over-

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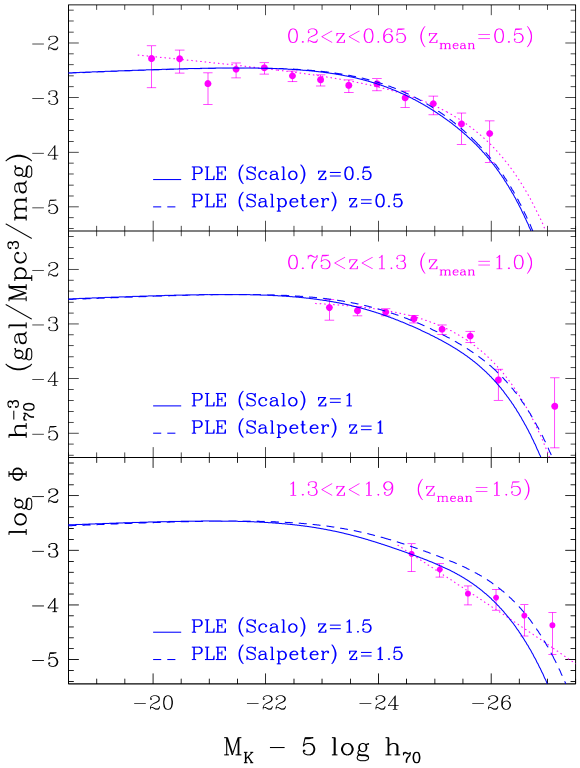

Fig. 5. The rest-frame K_s-band Luminosity Function in different redshift bins: $z_{mean} = 0.5$ (top) $z_{mean} = 1.0$ (middle) and $z_{mean} = 1.5$ (bottom) compared to PLE models. The observed data were derived from the $1/V_{max}$ analysis, while dotted curves are the LF Schechter fits derived from STY analysis (see text for more details).

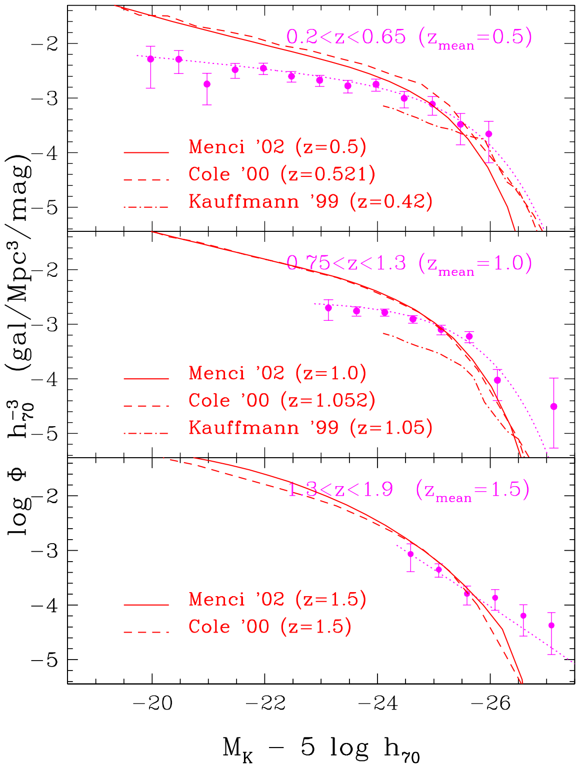

Fig. 6. The rest-frame K_s-band Luminosity Function in different redshift bins: $z_{mean} = 0.5$ (top) $z_{mean} = 1.0$ (middle) and $z_{mean} = 1.5$ (bottom) compared to HMMs. The GIF predictions (Kauffmann et al. 1999) lie below both the observed LF and the LFs predicted by the other HMMs.

prediction of faint, sub–L^* galaxies at $0 < z < 1.3$. This problem, also evident in the comparison with $N(z)$ (Fig. 3), was already known and is related to the so called HMM "satellite problem".

However, it is interesting to note that at $z \sim 1$ the HMMs seem not to be in strong disagreement with the observations relative to the bright end of the galaxy luminosity function. Thus, the key issue is to verify whether the bright $L > L^*$ galaxies in the K20 survey have the same nature of the luminous galaxies predicted by the HMMs, in particular for their mass to light ratios (M/L). Fig. 7 compares the $R - K_s$ colors and luminosity distributions of galaxies with $0.75 < z < 1.3$ (a bin dominated by spectroscopic redshifts) as observed in our survey to the predictions of the GIF simulations (Kauffmann et al. 1999). Fig. 7 highlights that a serious discrepancy is present between the two distributions: galaxies with $M_K - 5\log h_{70} > 25$ have a median color of $R - K_s \sim 5$ vs $R - K_s \sim 4$ in the K20 and GIF samples respectively, and the two distributions have a very small overlap. Given that red galaxies have old stellar populations and higher mass to light ratios, we suggest that the apparent agreement with HMM predictions of the $z \sim 1$ bright end of the luminosity function (Fig. 6) is fortuitous and is a result of an underestimate of the M/L present in the same models. This is equivalent to saying that the number density of massive galaxies at $z \sim 1$ is underpredicted by HMMs, and the predicted galaxies have incorrect colors, i.e. ages and star formation rates.

The analysis of the Galaxy Stellar Mass Function (GSMF) will be presented in a forthcoming paper (Fontana et al., in preparation). Here we note that the observed mild luminosity evolution of the rest-frame near-IR luminosity function up to $z \sim 1.5$ is an indication of a little and slow evolution of the GSMF in the same redshift range. The little evolution of the luminosity function and the absence of a strong density evolution provide an additional indication that massive and old stellar systems were already in place at $z \sim 1$. Both these results are in contrast with the current renditions of the hierarchical merging scenario, where the GSMF is expected

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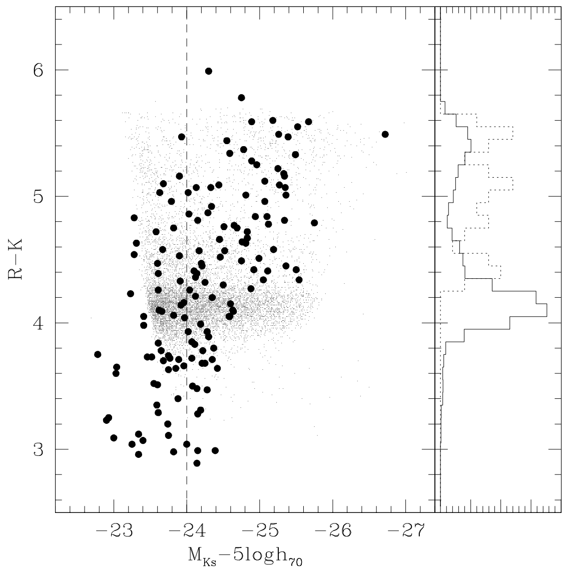

Fig. 7. *Left* The color and the absolute K magnitude diagram for the K20 galaxies with $0.75 < z < 1.3$ (only those with spectroscopic redshift) and for the galaxies simulated by the GIF team at $z = 1.05$ (small dots). Both samples are expected to be complete for galaxies with $M_{K_s} - 5\log h_{70} < -24$ (dashed line). *Right* The distribution of colors in the two samples for $M_{K_s} - 5\log h_{70} < -25$ (normalized to the same total number).

to evolve rapidly at $z < 2$ (e.g. Baugh et al. 2002).

5. CONCLUSIONS

The results of the K20 survey indicate that the observed redshift distribution and the luminosity function of $K_s < 20$ galaxies are in broad agreement with the expectations of PLE models, while disagreeing 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 (Cimatti et al. 2002a).

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; Firth et al. 2002). Thus, adopting the hierarchical merging ΛCDM 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 enhancing merging and star formation in massive haloes at high redshift (say, $z \sim 3$), while in the meantime suppressing star formation in low-mass haloes.

In summary, the redshift distribution presented of $K_s < 20$ galaxies (Cimatti et al. 2002c), together with the space density, nature, and clustering properties of the ERO population (Cimatti et al. 2002a, Daddi et al. 2002) and the redshift evolution of the luminosity and stellar mass functions derived for the K20 sample 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 $z \sim$ 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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