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Galaxy evolution in the K-band

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Abstract. We discuss how the problem of the formation and evolution of massive galaxies can be investigated with the study of galaxies selected in the K-band. The motivations and the characteristics of the K20 survey are reviewed, and its main results on the evolution of field galaxies from $z \sim 0$ to $z \sim 2$ are discussed.

Key words. galaxy formation – galaxy evolution –

1. Introduction

Despite the recent developments in observational cosmology (Spergel et al. 2003), one of the main unsolved issues remains how and when the present-day massive galaxies built up and what type of evolution characterized their growth across the cosmic time.

There are two main scenarios proposed to explain the formation of massive galaxies. In the first, such systems formed at high redshifts (e.g. $z > 2 \div 3$) through a "monolithic" collapse accompanied by a violent burst of star formation followed by a passive and pure luminosity evolution (PLE) of the stellar population to nowadays, (Eggen, Lynden-Bell & Sandage 1962; Tinsley 1972; Larson 1975; van Albada 1982). Such a scenario makes some rigid predictions that can be tested with the observations: "old" passively evolving massive spheroidal galaxies should exist up to $z \sim 1 \div 1.5$ with a number density identical to that observed in the local universe because their number does not change through cosmic times and the only evolution is the aging of the stellar population. In another scenario, massive galaxies formed at later times through a slower process of hierarchical merging of smaller galaxies (e.g. White & Rees 1978; Kauffman, White, & Guiderdoni 1993) characterized by moderate star formation rates, thus reaching the final masses in more recent epochs (e.g. $z < 1 \div 1.5$) (e.g. Baugh et al. 1996; Cole et al. 2000; Baugh et al. 2002). As a consequence, the hierarchical merging models (HMMs) predict that massive systems should be very rare at $z \sim 1$, with a comoving density of $\mathcal{M}_{\rm stars} > 10^{11}$ M$_\odot$ galaxies decreasing by almost an order of magnitude from $z \sim 0$ to $z \sim 1$ (Baugh et al. 2002).

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2. The K20 survey: motivations and characteristics

A solid approach to investigate the evolution of massive galaxies is to study samples of field galaxies selected in the K-band (i.e. at 2.2μm; Broadhurst et al. 1992; Kauffmann & Charlot 1998). This has two main advantages. Firstly, since the rest-frame optical and near-IR light is a good tracer of the galaxy *stellar* mass (Gavazzi et al. 1996), K-band surveys select galaxies according to their mass up to $z \sim 2$. Secondly, the similarity of the spectral shapes of different galaxy types in the rest-frame optical/near-IR makes the K-band selection free from strong biases against or in favour of particular classes of galaxies. In contrast, the selection of high-z galaxies in the observed optical bands is sensitive to the star formation activity rather than to the stellar mass because it samples the rest-frame UV light and makes optical samples biased against old passive galaxies.

Motivated by the above open questions and by the availability of the ESO VLT telescopes, we started an ESO VLT Large Program (dubbed "K20 survey") based on 17 nights distributed over two years (1999-2000) (see *http://www.arcetri.astro.it/~k20/* and Cimatti et al. 2002c). The prime aim of such a survey was to derive the spectroscopic redshift distribution and the spectral properties of 546 K_s-selected objects with the *only* selection criterion of $K_s < 20$ (Vega scale). Such a threshold is critical because it selects galaxies over a broad range of masses, i.e. $\mathcal{M}_{\rm stars} > 10^{10}$ $M_\odot$ and $\mathcal{M}_{\rm stars} > 4 \times 10^{10}$ $M_\odot$ for $z = 0.5$ and $z = 1$ respectively. The targets were selected from K_s-band images (ESO NTT+SOFI) of *two independent fields* covering a total area of 52 arcmin^2: a 32.2 arcmin^2 sub-area of the Chandra Deep Field South (CDFS; Giacconi et al. 2001), and a 19.8 arcmin^2 field centered around the QSO 0055-269 at z=3.6. Deep optical and near-IR VLT spectroscopy was done in 1999-2000 with FORS1-2 and ISAAC respectively, with additional FORS2 spectroscopy performed in November 2002. The current spectroscopic redshift completeness is 92% with an overall redshift range of $0< z <2.5$. In addition to spectroscopy, $UBVRIzJK_s$ imaging from NTT and VLT observations was also available for both fields, thus providing the possibility to estimate photometric redshifts for all the objects in the K20 sample, to optimize them through a comparison with the spectroscopic redshifts and to assign a reliable photometric redshift to the 8% of objects without a spectroscopic z. The K20 survey represents a significant improvement with respect to previous surveys for faint K-selected galaxies (e.g. Cowie et al. 1996; Cohen et al. 1999) thanks to its high spectroscopic redshift completeness, the larger sample, the coverage of two fields (thus reducing the cosmic variance effects), the availability of optimized photometric redshifts. $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\rm m} = 0.3$ and $\Omega_\Lambda = 0.7$ are adopted throughout the paper.

3. Main results

3.1. Redshift distribution

The redshift distribution of field galaxies (Fig.1) has a median redshift $z_{med} \sim 0.80$, with $\sim 32\%$ and $\sim$9% of galaxies at $z > 1$ and $z > 1.5$ respectively (Cimatti et al. 2002b). A "blind" comparison was made with the predictions of a set of the most recent ΛCDM hierarchical merging and pure luminosity evolution (PLE) models. The hierarchical merging models (HMMs) 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 $N(z)$.

3.2. The near-IR luminosity function and its evolution

The luminosity function (LFs) has been derived in the rest-frame J and K_s bands us-

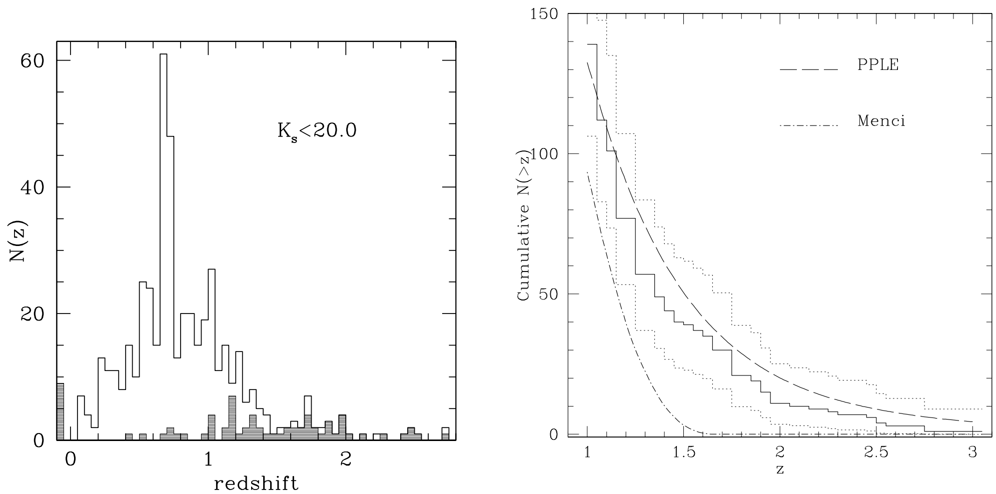

Fig. 1. Left panel: the observed differential redshift distribution. The shaded histogram shows the contribution of photometric redshifts. Right panel: the observed cumulative *number* of galaxies between $1 < z < 3$ (continuous line) and the corresponding poissonian $\pm 3\sigma$ confidence region (dotted lines). Two model predictions are shown: the PLE model of Pozzetti et al. (PPLE; 1996,1998) and the HMM of Menci et al. (2002). Both model predictions are corrected for the photometric biases.

ing 3 redshift bins (z_{mean}= 0.5, 1, 1.5) and compared to the local near-IR LF (Pozzetti et al. 2003). The faint-end of the LFs is consistent with the local estimates, with no evidence for a change either in the slope or normalization up to $z < 1.3$. Viceversa, the density of luminous galaxies ($M_{Ks} - 5logh_{70} < -25.5$) is higher than locally at all redshifts and relatively constant or mildly increasing with z within our sample. The data are consistent with a mild luminosity evolution both in the J and K_s-band up to $z = 1.5$ ($\Delta M_J = -0.69 \pm 0.12$ and $\Delta M_K = -0.54 \pm 0.12$ at $z = 1$). Moreover, we find that red and early-type galaxies dominate the bright-end of the LF, and that their number density shows at most a small decrease (<30%) up to $z = 1$, thus suggesting that massive elliptical galaxies were already in place at $z = 1$ and they should have formed their stars and assembled their mass at higher z. There appears to be a correlation of the optical/near-IR colors with near-IR luminosities, the most luminous/massive galaxies being red/old. We find a slow evolution with z of the near-IR comoving luminosity density to $z = 1.5$. Hierarchical models overpredict significantly the density of low luminosity galaxies at $z \leq 1$ and underpredict the density of luminous galaxies at $z \geq 1$, whereas PLE models are more consistent with the data up to $z = 1.5$. The GIF model (Kauffmann et al. 1999) shows a clear deficiency of red luminous galaxies at $z = 1$ compared to our observations and predicts a decrease of luminous galaxies with z not observed in our sample.

3.3. Extremely Red Objects

Extremely Red Objects (EROs, i.e. galaxies with $R - K > 5$) are very important because allow to select old passively evolving galaxies at $z > 1$. Thanks to our deep red-optimized VLT optical spectroscopy, for a fraction of EROs (80% to $K_s < 19$, 62% to $K_s < 20$,) it was possible to derive a spectroscopic redshift and a spectral classification (Cimatti et al 2002a, 2003). The VLT optical spectra unveiled that two classes of galaxies at $z \sim 1$ contribute to the ERO population: the expected old stellar systems (∼40%), but also a substantial fraction of dusty star-forming galaxies (∼60%). Deep HST+ACS public imaging (GOODS project) shows that "old" EROs have morphologies consistent with being dynamically relaxed spheroids (E/S0), whereas the class of dusty star-forming EROs is made by disk-like systems and irregular/merging-like objects.

The colors and spectral properties of old EROs are consistent with ≥3 Gyr old passively evolving stellar populations (assuming solar metallicity and Salpeter IMF), requiring a formation redshift $z_f > 2.4$. The observed $R - K_s$ color distribution suggests a significant spread in the formation redshifts of the identified E/S0 galaxies ($2 < z < 3$). The number density is $6.3 \pm 1.8 \times 10^{-4}$ h^{3}Mpc^{-3} for $K_s < 19.2$, consistent with the expectations of PLE models for passively evolving early-type galaxies with similar formation redshifts (Cimatti et al. 2002a). HMMs underpredict such old red galaxies at $z \sim 1$ by factors of ~ 3 (Kauffmann et al. 1999) and ~ 5 (Cole et al. 2000). The morphology, spectral properties, inferred ages, formation redshifts and stellar masses imply the existence of a substantial population of old, passively evolving and fully assembled massive spheroids at $z \sim 1 - 1.5$. Such galaxies require that major episodes of massive galaxy formation occured at $z \geq 2$.

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^{-1}, and a significant contribution ($> 20 - 30\%$) to the cosmic star-formation density at $z \sim 1$ (see also Smail et al. 2002). A recent analysis based on their X-ray emission provided a similar estimate of the SFRs (Brusa et al. 2002). Such dusty star-forming systems are also underpredicted by HMMs. For instance, the GIF simulations predict a comoving density of red galaxies with $SFR > 50$ M$_\odot$yr^{-1} that is ∼30 times lower than the observed density of dusty EROs.

Taking advantage of the spectroscopic redshift information for the two ERO classes, we compared the relative 3D clustering in real space (Daddi et al. 2002). The comoving correlation lengths of dusty and old EROs are constrained to be $r_0 < 2.5$ and $5.5 < r_0 < 16$ h^{-1} Mpc comoving respectively, implying that old EROs are the main source of the ERO strong angular clustering. It is important to notice that the strong clustering measured for the old EROs is in agreement with the predictions of hierarchical merging (Kauffmann et al. 1999).

3.4. Luminous starbursts at $z \sim 2$

Spectroscopic redshifts have been measured for 9 K-band luminous galaxies at $1.7 < z < 2.3$, selected with $Ks < 20$ in the K20 survey region of the CDFS/GOODS area. Star formation rates (SFRs) of $\sim 100 - 500$ M$_\odot$ yr^{-1} are derived when dust extinction is taken into account. The fitting of their multi-color spectral energy distributions indicates stellar masses M∼ 10^{11} M$_\odot$ for most of the galaxies. HST+ACS optical imaging shows that their rest-frame UV morphology is highly irregular, suggesting that merging-driven starbursts are going on in these galaxies. The morphologies tend to be more compact in the near-IR, a hint for the possible presence of older stellar populations. Such galaxies are strongly clustered, with 7 out of 9 belonging to redshift spikes, which indicates a correlation length $r_0 \sim 9$–17 Mpc (1 σ range). Current semianalytical models of galaxy formation appear to underpredict by a large factor (~ 30) the number density of such a population of massive and powerful starburst galaxies at $z \sim 2$. The high masses and SFRs together with the strong clustering suggest that at $z \sim 2$ we may have started to explore the major formation epoch of massive early-type galaxies.

3.5. Galaxy stellar mass function evolution

The stellar mass of each galaxy was estimated with two independent methods (Fontana et al. 2003): (1) fitting the multicolor SED with a wide range of synthetic stellar population spectra and leaving the mass as a free parameter, (2) adopting exponentially declining star formation histories with high formation redshifts and assigning a mass-to-light ratio according to the color of each galaxy. The results show that the masses estimated with the first method are typically a factor of two lower than the maximal masses derived with the second method. Preliminary results indicate that the galaxy stellar mass function (GSMF) shows a mild decrease of a factor of 2-3 from $z \sim 0$ to $z \sim 1$. This is qualitatively in agreement with a hierarchical merging scenario, but inconsistent with the more rapid drop predicted by the current HMMs (e.g. Baugh et al. 2002).

4. Discussion and summary

Overall, the results of the K20 survey show that galaxies selected in the K_s-band are characterized by little evolution up to $z \sim 1 - 1.5$, and that the observed properties can be successfully described by a PLE scenario. In contrast, HMMs fail in reproducing the observations because they predict a sort of "delayed" scenario where the assembly of massive galaxies occurs later than what is actually observed. However, it is important to stress here that the above results do not necessarily mean that the whole framework of hierarchical merging of CDM halos is under discussion. For instance, the strong clustering of old EROs and the clustering evolution of the K20 galaxies (irrespective of colors) seem to be fully consistent with the predictions of CDM models of large scale structure evolution (Daddi et al. 2001; Firth et al. 2002; Daddi et al. 2003 in preparation).

The observed discrepancies highlighted by the K20 survey may be ascribed to how the baryon assembly, the star formation processes their feedback, and the dust content and evolution are treated by HMMs 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.

In summary, the redshift distribution of $K_s < 20$ galaxies, together with the space density, nature, and clustering properties of the ERO population, and the redshift evolution of the rest-frame near-IR luminosity function and luminosity density provide a new invaluable 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 $z \geq 2$–3. This set of observables poses a new challenge for theoretical models to properly reproduce.

The K20 survey is triggering several studies where our team is actively involved. Ultradeep spectroscopy was obtained in November 2002 with FORS2 (MXU mode and with the new red-optimized MIT CCD mosaic) in order to study (with higher resolution spectroscopy) the kinematics of $z > 1$ galaxies in order to estimate their dynamical masses (Vernet et al. 2003, in preparation). Preliminary results seem to confirm the existence of substantial population of $z \sim 1$ early- and late-type galaxies with dynamical masses $\geq 10^{11}$ $M_{\odot}$.

Since the sub-area of the CDFS observed in the K20 survey is also a target of the HST+ACS GOODS Treasury Program (PI M. Giavalisco), and of the SIRTF GOODS (PI M. Dickinson) and SWIRE (PI C. Lonsdale) Legacy Programs, the K20 database, complemented by such additional observations, will allow to derive new constraints on the formation and evolution of galaxies out to higher redshifts.

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