

The near-infrared view of galaxy evolution

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Abstract. Near-infrared surveys provide one of the best opportunities to investigate the cosmic evolution of galaxies and their mass assembly. We briefly review the main results obtained so far with the K20 and other recent near-IR surveys on the redshift distribution, the evolution of the luminosity function and luminosity density, the nature of old and dusty EROs, the evolution of the galaxy stellar mass function, the properties of the galaxies in the “redshift desert” and the nature of luminous starbursts at $z \sim 2$.

1 Introduction

Despite the detection of objects up to $z \sim 6.5$ and the impressive success of the Λ CDM scenario to account for the properties of the cosmic microwave background, one of the main and still controversial questions remains how and when galaxies assembled their mass as a function of the cosmic time. The hierarchical scenario predicts that galaxies built up their present-day mass through a progressive assembly of smaller sub-systems driven by the merging of dark matter halos.

With ground-based observations, one of the most solid approaches to address the problems of galaxy formation and evolution is to study samples of field faint galaxies selected in the near-infrared, particularly in the K -band ($2.2\mu\text{m}$) [3,23]. Firstly, since the rest-frame near-IR luminosity is a good tracer of the galaxy stellar mass [5], K -band surveys allow to select galaxies according to their mass up to $z \sim 1.5$ ($\lambda_{rest} \sim 0.9 - 1.0\mu\text{m}$). At higher redshifts, the K -band starts to sample the rest-frame optical and UV regions, and space-based observations at $\lambda_{obs} > 2\mu\text{m}$ are needed to cover the rest-frame near-infrared (e.g. SIRTf, ASTRO-F). Secondly, the similarity of the spectral shapes of different galaxy types in the rest-frame near-IR makes the K -band selection free from strong biases against or in favor of particular classes of galaxies. In contrast, the selection of high- z galaxies in the observed optical bands is more sensitive to the star formation activity than to the stellar mass because it samples the rest-frame UV light and makes optical samples biased against old passive or weakly star-forming galaxies. Last but not least, near-infrared surveys are less affected by dust extinction than optical surveys.

Motivated by the above considerations, several near-infrared surveys have been undertaken during the last decade [12,10,6,18,24,17,15,19] (Fig. 1). Spectroscopic surveys are particularly relevant thanks to their capability not only to derive the redshifts, but also to unveil the nature and the spectral properties

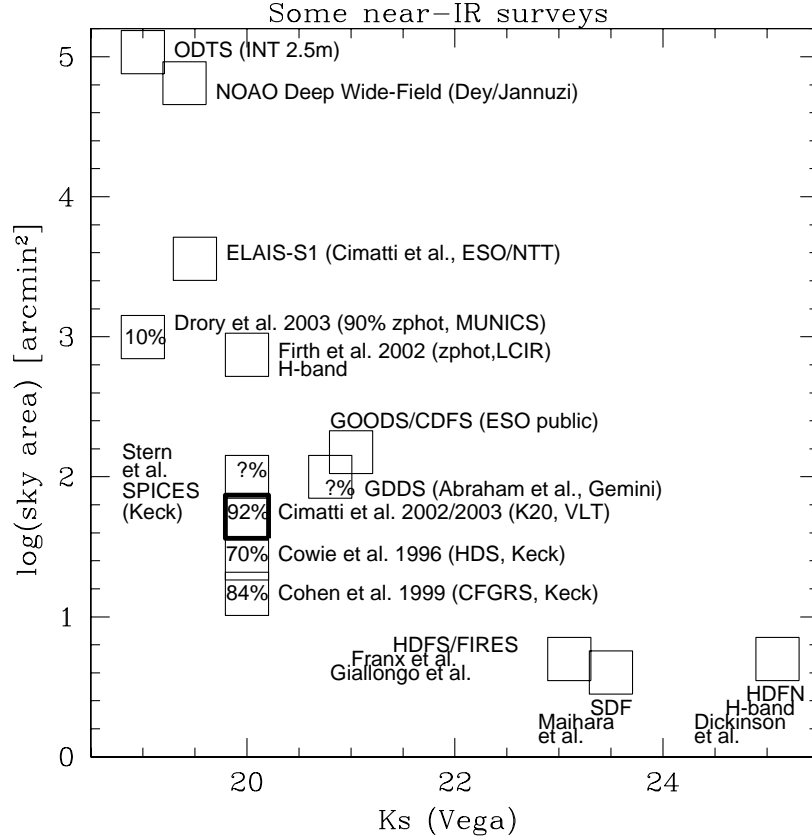


Fig. 1. Some imaging and spectroscopic near-infrared surveys. The redshift completeness is shown for spectroscopic surveys.

of the targeted galaxies. Since near-IR multi-object spectrographs are not fully available on 8-10m-class telescopes, most spectroscopy of K -selected galaxies has been done in the optical. The most crucial probes of massive galaxy evolution are galaxies with the very red colors expected in case of passive evolution at $z > 1$ (e.g. $R - K_s > 5$, usually called Extremely Red Objects, EROs). However, for the typical limiting fluxes of near-IR surveys ($K_s < 20 - 21$), they have very faint optical magnitudes ($R \sim 25 - 26$) already close to the spectroscopic limits of 8-10m-class telescopes. In addition, for $z > 1$ their main spectral features (e.g. the 4000 Å break and H&K absorptions) fall in the very red part of the observed spectra, where the strong OH sky lines and the CCD fringing and low quantum efficiency make spectroscopy even more demanding.

2 The K20 survey

The K20 survey is a project aimed at investigating galaxy evolution through deep ESO VLT spectroscopy of a sample of 546 objects with $K_s < 20$ selected from two fields covering a total area of 52 arcmin². The two fields are completely independent, and one of them is a sub-area of the Chandra Deep Field South. Most spectroscopy was done in the optical with FORS1 and FORS2 and designed to reach the highest possible signal-to-noise ratio in the red. ISAAC near-IR spectroscopy was also done for a small fraction of the sample. The multi-band ($UBVRIZJK_s$) imaging available for both fields was used to derive high-quality photometric redshifts “trained” with the spectroscopic redshifts. The final sample covers a redshift range of $0 < z < 2.5$, and the current redshift completeness is 92% (spectroscopic) and 100% (spectroscopic + photometric redshifts).

The K20 survey represents a significant improvement with respect to other surveys for faint K -selected galaxies thanks to its high spectroscopic redshift completeness (the highest to date) extended to very faint red objects, the larger sample, the coverage of two fields and the availability of optimized photometric redshifts. We note here that the distribution of the sample over two independent sky fields is a significant advantage in reducing the field-to-field variation effects. For more details on the K20 survey see [6] and <http://www.arcetri.astro.it/~k20/>.

3 Established results: galaxy evolution to $z \sim 1$

Overall, the K20 and other recent near-IR surveys show that galaxies are characterized by little evolution to $z \sim 1$, so that the observed properties can be mimicked by a pure luminosity evolution (PLE)-like scenario. This is in contrast with the current Λ CDM hierarchical merging models where the assembly of galaxies occurs later than what is actually observed. In particular:

- For $K_s < 20$, $N(z)$ has a median redshift of $z_{med} \sim 0.8$ and a high- z tail extended beyond $z \sim 2$. Current hierarchical models do not match the observed redshift distribution [8,18] (Fig.2), but an improved treatment of the merging processes is providing encouraging results [29,25].
- The rest-frame K_s -band luminosity function shows a mild luminosity evolution up to $z \sim 1$, with a brightening of about 0.5 magnitudes. Significant density evolution is ruled out up to $z \sim 1$ [11,26,17]. The high-luminosity tail at $z \sim 1$ is dominated by red early-type galaxies [26]. Current hierarchical models fail in reproducing the shape and the evolution of the LF as they over-predict the number of sub- L^* galaxies, under-predict that of luminous galaxies, and predict a strong density evolution.
- The rest-frame K_s -band luminosity density evolves slowly to $z \sim 1$ with $\rho_{K_s}(z) \propto (1+z)^{0.37}$, and much slower than the UV luminosity density [26].
- The properties of “old” EROs with $K_s < 20$ at $z \sim 1$ (morphology, spectra, luminosities, ages, stellar masses, clustering) imply the existence of a substantial population of old (a few Gyr), passively evolving and fully assembled massive spheroids which requires that major episodes of massive galaxy formation occurred at least at $z_{form} \sim 2$ [7,9]. Their number density at $z \sim 1$ is consistent

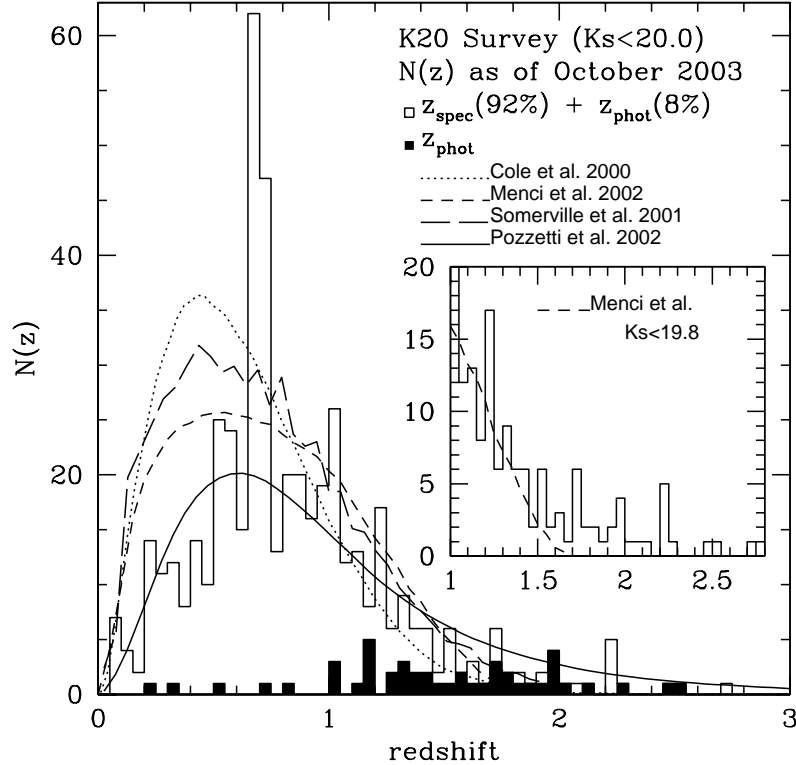


Fig. 2. The K20 survey $N(z)$ compared with the predictions of three hierarchical merging model (dotted and dashed lines) and a pure luminosity evolution (PLE) model (solid line). The models refer to *total* magnitudes $K_s < 20$ and are not corrected for the average under-estimate of 0.2 magnitudes due to the photometric selection effects evaluated in the K20 sample (see [6]). Including this bias in the models results in improving the agreement with the PLE models and increasing the discrepancy with the hierarchical models, as shown in the inserted plot where the model of Menci et al. (2002) for $K_s < 19.8$ is compared to the observed $z > 1$ tail of $N(z)$ (see [8]).

(within 2σ) with that of local luminous E/S0 galaxies. Current hierarchical models severely under-predict the number of “old” EROs [7,9].

- A numerous population of dusty star-forming EROs with disk-like and irregular morphologies emerges at $0.7 < z < 1.7$ from near-IR surveys [7,28,9]. These objects are often too faint to be detected in submm surveys due to their inferred far-IR luminosities $< 10^{12} L_{\odot}$ and represent an ensemble of galaxies important to complement other star-forming systems selected with different techniques. They are also expected to be important contributors to the cosmic

star-formation density [7,9,4,28]. Also in this case, current hierarchical models under-estimate the number of “dusty” EROs.

- “Old” EROs seem to have much stronger clustering than “dusty” EROs, with a comoving r_0 similar to that of present-day luminous ellipticals [13].
- The number density of massive galaxies and the cosmic stellar mass density Ω_* show a slow decrease from $z \sim 0$ to $z \sim 1$ qualitatively consistent with a hierarchical scenario, but much slower than what the current models predict [20,2,16,11,15,19].

4 Beyond $z \sim 1$: galaxies in the “redshift desert”

At higher redshifts, the picture becomes more controversial: at $z > 1$ the evolution of the near-IR luminosity function seems to depart from a PLE-like pattern [26], it is still not clear if the number density of old spheroids drops at $z > 1.3$ [1,27], and unexpected populations of massive star-forming galaxies are being found in the range of $1.5 < z < 3$ thanks to near-IR surveys [21,31,14].

Moreover, the galaxy stellar mass function and $\Omega_*(z)$ display a fast evolution at $z > 1$ [15,19], and the K20 survey results suggest a rapid increase of the stellar mass density from $20^{+20}_{-10}\%$ of the local value at $2 < z < 3$ to about 100% at $z \leq 1$ [20].

These results suggest that $1.5 < z < 2.5$ may be the critical cosmic epoch during which most star formation activity and galaxy mass assembly took place. However, probing the $1.5 < z < 2.5$ range is difficult due to the lack of strong spectral features and emission lines redshifted in the observed optical and to the strong OH emission sky lines severely affecting the spectra beyond ~ 8000 Å. Due to the limited number of spectroscopically identified galaxies, this redshift range has been traditionally called “redshift desert”.

Thanks to the very deep red-optimized optical spectroscopy and to near-IR spectroscopy, the K20 survey allowed us to populate the “redshift desert” and to unveil the nature of K -selected galaxies in this critical redshift range. By combining deep HST+ACS imaging with K20 spectroscopy, we found that a variety of galaxy types are present at $1.5 < z < 2.5$: spheroids at $z \sim 1.5$, disk- and spiral-like systems, and many irregular merging-like objects.

Particularly relevant is a sub-sample of luminous galaxies at $1.7 < z < 2.3$ spectroscopically identified in the K20 survey [14]. Their inferred star formation rates of $\sim 100 - 500 M_\odot \text{yr}^{-1}$, stellar masses up to $10^{11} M_\odot$ derived from the fitting of their multi-color spectral energy distributions, and their merging-like optical morphologies becoming more compact in the near-IR, suggest that these galaxies may be massive galaxies caught during their major episode of mass assembly and star-formation, possibly being the progenitors of the present-day massive spheroidal systems. Current semi-analytical models under-predict by a factor of ~ 30 the number density of such galaxies [14,29]. Other near-IR surveys are independently finding candidate massive systems at $z \sim 2 - 3$ [21,31].

In order to draw a coherent picture of galaxy evolution at $1.5 < z < 2.5$, it will be crucial to combine K -selected samples (e.g. K20, FIRES [21], GDDS

[22]) with UV- and optically-selected samples more biased toward star-forming objects with little dust extinction such as those resulting from the Lyman-break selection at $z > 1.4$ [30].

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