Tracing the formation of massive spheroids from high-z galaxy clustering

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Abstract. The high-z progenitors of local massive early-type galaxies should be characterized by a strong level of clustering, larger than that measured for \( z = 3 \) Lyman Break Galaxies and comparable to that of \( z \sim 1 \) EROs. First possible evidences for such strongly clustered objects at \( z \gtrsim 2 \) were found by the FIRES and K20 surveys, that have identified new classes of faint high-z K-selected galaxies. Some details are given here for the new population of massive star-forming galaxies at \( z \sim 2 \), found by the K20 survey in the GOODS-South area. Because of their much redder UV continuum, most of these galaxies would not be selected by the Lyman Break criterion. Such objects are good candidates for the precursors of local ellipticals caught in their formation phase. We have calibrated a two color criterion to allow the identification of these highest redshift galaxies in bright K-limited samples.

1 Introduction

Understanding the evolution, star-formation and assembly histories of early type galaxies up to their highest redshifts of formation is a crucial observational question that remains unsolved. Passively evolving, massive spheroidal galaxies appear to be common up to \( z \approx 1 \) with little evolution, if any, from present days \([6,22,2]\). It is not well constrained yet if and how many passive spheroids exist at higher redshifts, \( z > 1.5-2 \). Moreover, it is unclear up to what redshift most precursors of spheroids maintain the low-redshift signatures of morphological and stellar population properties. Approaching their formation epoch, spheroid progenitors will appear as star-forming and possibly morphologically irregular galaxies. Therefore, identifying the precursors of todays ellipticals close to their most interesting formation or assembly phases requires to rely on independent and alternative signatures than their morphologies or old stellar population properties.

2 Expected clustering of spheroid precursors

Spheroids inhabit preferentially the densest environment in the local universe. They have the largest correlation lengths among galaxies in the present day universe and up to \( z \sim 1 \) \([19,7]\). Searching for the most clustered population at any redshift is therefore a natural way to locate such progenitors and to investigate their properties.
Fig. 1. Predicted evolution for the correlation length of halos that will evolve into local massive ellipticals (dotted lines, from [17]) and of optically selected galaxies (solid line, from [1]). Together with the new constraints coming from K-selected populations at $z \gtrsim 2$ (heavy symbols), we show relevant measurements taken from the literature: ellipticals at $z \sim 0$ from [19], optically selected galaxies at $z \sim 0.8$ from [5], EROs and radio galaxies at $z \sim 1$ from [7,21], $z = 3$ LBGs from [13] and $z = 4$–$5$ LBGs from [20].

This view is supported by model predictions for the redshift evolution of the correlation length of halos hosting today massive ellipticals (Fig. 1, based on [17]). Halos clustered with $r_0 \sim 8$–$10$ in the local universe, are predicted to have $r_0 \sim 5$–$8$ $h^{-1}$ Mpc even at $2 < z < 4$. Being referred to halos, these predictions could represent only lower limits for galaxies that, at the relatively small scales probed by high-z measurements, can have enhanced correlations due to large halo occupation numbers (e.g. [18]).

In practice, it is impossible to observationally preselect a population by its clustering properties and one has to look at the clustering properties of the available classes of high-z galaxies to find putative progenitors.

Extremely red objects (EROs) and giant $z \sim 1$ radio galaxies, as well known, have an high clustering and therefore are good candidate progenitors of local ellipticals [6,16,7,21], in agreement with some significant fraction of these objects being passive spheroids (e.g. [4]).

Measurements for the highest redshifts ($z \sim 4$–$5$) star-forming galaxies [20] of $r_0 \sim 5$–$6$ may be consistent with the predictions for forming spheroids. This is also in qualitative agreement with the observation that the oldest stars (thus the ones formed at the highest redshifts) are nowadays in spheroids.

Typical $z = 3$ Lyman Break Galaxies (LBGs) appear instead to start falling short of the expected clustering level of ellipticals progenitors, with the best current estimates of $r_0 \lesssim 4$ $h^{-1}$ Mpc [24] and with fainter LBGs having even
much weaker clustering [13]. In fact the clustering of observed LBGs at $z = 3$ is much lower than that of $z \sim 1$ EROs, suggesting that possibly a large fraction of them do not evolve into EROs and ellipticals. Overall, the observed clustering of optically selected (i.e. actively star forming) galaxies from $z = 5$ to $z = 1$ is in very good agreement with the model predictions of [1]. The comparison of the two set of predictions of Fig. 1 diverging below $z \sim 4$, also confirm that by $z < 3$ ordinary star formation has began producing stars that have mainly ended in today later type or less massive galaxies.

Should it be possible to isolate the progenitors of local spheroids as a class of galaxies at $1.5 < z < 3.5$, their clustering would be expected to be fairly strong, in the cited range $r_0 \sim 5-8 \, h^{-1} \text{Mpc}$ or even more. New populations of K-selected, $z \sim 2-3$ galaxies possibly satisfying those clustering requirements were recently reported by the FIRES and K20 surveys [9,10]. Along with SCUBA sources, these galaxy populations represent the best candidates so far identified for the precursors of massive spheroids.

3  $J – K$ red FIRES galaxies at $2 < z < 4$

The FIRES survey of the HDF-South [15] has produced the first large sample of about 120 K-selected galaxies in the (photometric) redshift range $2 < z < 4$. From the analysis of their correlation properties [9], these $z = 3$ K-selected galaxies appear more strongly clustered than LBGs (at a fixed number density), although the comparison suffers from the small area of HDFS. A significant result was the detection in the FIRES sample of a strong color dependence of clustering, in the usual way that redder galaxies appear more clustered (but a previously unobserved effect at any $z > 1$). The clustering depends primarily on the $J – K$ color, which brackets the Balmer (or 4000 Å) break at $z \approx 3$, suggesting the effect could be due to age. Intriguingly, the existence of populations older and more clustered than LBGs could solve the paradox that $z = 3$ LBGs are too young to be direct progeny of $z > 4–6$ star forming galaxies [12].

The galaxies with the reddest ($J – K > 1.7$) colors at $z \approx 3$ have an angular two-point correlation function consistent with $r_0 \sim 8 \, h^{-1} \text{Mpc}$ (using a typical slope $\delta = 0.8$), although a weaker $r_0 \sim 5 \, h^{-1} \text{Mpc}$ could be made consistent with the data assuming enhanced small scale correlations in the ”halo occupation distribution” framework [26,14]. Overall, these clustering strengths of $5–8 \, h^{-1} \text{Mpc}$ are at the level expected for the progenitors of ellipticals seen at $z \sim 3$ (see Fig. 1). The first handful spectroscopic redshifts for this class of $J – K$ red galaxies [25] are grouped in a single redshift spike, a feature that support the presence of strong clustering.

4  Near-IR bright galaxies at $z \sim 2$ from the K20 survey

The K20 survey resulted in the observation of a significant high redshift tail of $1.7 < z < 2.3$ galaxies with bright near-IR magnitudes ($K_{\text{ Vega}} < 20$, [8]).
The coadded spectrum of the $z = 2$ K-selected galaxies (top, from [10]) is compared to the reddest and bluest composite spectrum of LBGs (center and bottom, from [23]). The strong Ly$\alpha$ emission is from the bluest LBG spectrum.

The vast majority of such galaxies appear to be actively star-forming, reddened, morphologically irregular and massive objects [10].

Remarkably, 6 out of the 9 galaxies with measured spectroscopic redshift belong to spikes with $\sim 1500$ km/s of redshift separation. Assuming a random redshift selection function within the $1.7 < z < 2.3$ range such a level of pairing has a probability of about $10^{-5}$, a clear evidence of clustering. It is intriguing that even for EROs a similarly strong level of redshift pairing is not observed. We performed Monte Carlo simulations building samples of clustered populations (using the method presented in [8]) in order to see what correlation length is necessary to produce a similar redshift pairing in our small sample. It is found that in order to have a 5% or more probability to find as many pairs as in the observed sample, $r_0 \gtrsim 7$ $h^{-1}$ Mpc is required. The fraction of close pairs in a survey is directly related to the integral of the real space two-point correlation function, and has little dependence on the correlation slope $\delta$. The pairing evidence thus suggest that these near-IR bright $z \sim 2$ galaxies are consistent with having a high-level of clustering, like the one expected for the progenitors of local ellipticals seen at $z \sim 2$. It would be extremely interesting to spectroscopically
Fig. 3. Two color diagrams showing galaxies from the K20 survey in the CDFS field with the 9 near-IR bright galaxies at $z \sim 2$ shown as asterisks, including also a few redder objects with reliable photometric redshift $z > 2$. The straight line has \((z - K)_{AB} = (B - z)_{AB}\).

confirm a much larger samples, in order to obtain improved estimates for the clustering of this galaxy population.

Galaxies at $z \sim 2$ with bright K-band magnitudes were unknown before [10] and [25], and actually most theoretical models had predicted that they should not exist at all (see e.g. [3] for relative references). As they appear to be actively star-forming, just like LBGs, it is interesting to assess whether these K-selected galaxies are just a special subsample (the brightest tip of the iceberg) of LBGs, or a different population. This is especially important as now large samples of $\sim 1000$ LBGs have been assembled down to $1.5 < z < 2.5$ [24]. Fig. 2 shows that the coadded spectrum of $z = 2$ K-selected galaxies is remarkably redder than typical LBGs at $z = 3$, even for the reddest among them. For a more direct comparison to LBGs, we used the available multicolor photometry in the CDFS/GOODS area to determine the synthetic $G$ and $R$ magnitudes of our 9 $z = 2$ objects, matching the $z = 2$ selection criterion of [24] (the available U-band data closely match the system of [24]). Although the procedure is a bit uncertain, the $G-R$ colors of near-IR bright $z \sim 2$ objects appear again generally much
redder than what required by the LBG selection criterion in the same redshift range $^{11}$. These near-IR bright $z = 2$ galaxies are thus a new population of high-$z$ galaxies, that cannot be selected with the usual LBG criterion. As they are only $\approx 5\%$ of the population in a K-limited sample at $K < 20$, it would be very useful to have an alternative method to distinguish them from lower redshift field galaxies. Using the highly complete spectroscopic sample of the K20 survey we have calibrated a very efficient two color criterion: galaxies with $(z - K)_{AB} \gtrsim (B - z)_{AB}$ have an high probability to be star-forming objects at $z \sim 1.5-2.5$ (Fig. 3). We are currently using this $BzK$ criterion to build up a much larger sample of spectroscopically identified near-IR bright $z = 2$ galaxies. This will be crucial in order to understand their properties and the role played in the formation history of galaxies and to confirm their nature of possible star forming progenitors of local spheroids.

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