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High-redshift galaxies in the ALHAMBRA data

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Abstract

Population of high-redshift galaxies in the ALHAMBRA survey data is studied. We present the methodology to select and study ALHAMBRA high-redshift galaxies basing on their redshift probability distribution functions (zPDFs). It is shown how a clean galaxy sample can be selected by integrating the high-redshift part of the zPDF of each ALHAMBRA galaxy and selecting those with high probability of being at desired redshift. Also a method to derive statistical properties of the high-redshift galaxy population by summing the zPDFs of all the galaxies in the redshift bin of interest is introduced. Using this methodology we derive the galaxy restframe UV number counts in five redshift bins centred at $z = 2.5, 3.0, 3.5, 4.0$, and 4.5. With the ALHAMBRA data we especially contribute in the study of the brightest ends of these counts, sampling well the surface densities down to $m(AB) = 21 - 22$.

1 Introduction

Identifying and studying high-redshift galaxies is crucial for our understanding of the early epochs of galaxy evolution. At the beginning of nineties, the implementation of the so called Lyman-break technique opened the era for detections of copious amounts of these early galaxies (e.g. [6, 17, 18, 19, 20]). While this colour-colour technique is efficient in selecting galaxies, it is also affected by significant incompleteness and contamination. While the latter can be dealt with by obtaining spectroscopic redshifts (see e.g. [19, 20, 14]), the former remains a serious difficulty. We are not yet at the point of spectroscopic blind surveys, hence, a step forward towards less biased candidate selection is offered by multifilter surveys. They combine the efficiency and un-biased nature of photometric surveys with very low resolution spectral information, which permits to derive more information on the surveyed objects like their accurate photometric redshifts.

In this proceedings we introduce a method to study ALHAMBRA high-redshift ($z \sim 2-5$) star-forming galaxies based on their photometric redshifts. We base our study on the information in the complete redshift probability distribution functions (zPDFs). We show how a clean candidate selection can be made basing on the zPDFs and check the selected sample against some traditional colour-colour selections. We also introduce a probabilistic method and derive the galaxy restframe UV number counts in five redshift bins from $z = 2.5$ to $z = 4.5$. In theory, these counts are free from contamination and incompleteness issues, if the zPDFs used correctly reflect the uncertainties in the redshift estimations.

We base our study on the data from the Advanced Large, Homogeneous Area Medium Band Redshift Astronomical (ALHAMBRA, [11]) survey. The total area used for our study is $2.38\,\mathrm{deg}^2$, covered with 20 medium-band optical filters from 3500 Å to 9700 Å, plus J, H, and K_S in the near infra-red (NIR). In addition to the novel methodology, an advantage of our ALHAMBRA high-redshift galaxy study as compared to the previous LBG studies is the large area the survey covers, reducing biases due to the cosmic variance and allowing studying the rearest, brightest, high-redshift galaxies.

The methodology presented here could be applied to any multi-filter data set with accurate zPDFs, such as the data from the future J-PLUS (Javalambre Photometric Local Universe Survey, Cenarro et al., in prep.) and J-PAS (Javalambre-PAU Astrophysical Survey [2]).

Throughout the paper, where necessary, we assume $\Omega_\mathrm{m} = 0.3$, $\Omega_\Lambda = 0.7$, and $\mathrm{H}_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Magnitudes are given in the AB system [13].

2 The sample selection

We start our candidate selection by cleaning the ALHAMBRA catalogues of any possible spurious or false detections, duplicated detections as well as stars. For this purpose we used the masks defined in [1] describing the sky area which has been reliably observed, and an additional quality flag provided in the ALHAMBRA catalogues [12]: we set "Stellar_Flag" < 0.51 in order to remove stars. After these steps, our data consist of a total of 362788 galaxies in $2.38\,\mathrm{deg}^2$.

There is no one single correct way of applying zPDFs for candidate selection. The 'best' redshift can be derived from the zPDF and assigned to each galaxy or the zPDF can be integrated to select as candidates all the galaxies with a probability greater than a given threshold being at the desired redshift. This threshold can then be adjusted to obtain the desired balance between the completeness and contamination. To introduce this technique, we decided to opt for a clean selection and select as candidates the objects fulfilling the criterion:

$$\int_{2.2}^{5.0} PDF(z)\,\mathrm{d}z >= 0.90, \tag{1}$$

i.e. all the galaxies with a probability of 90% or higher to be at the redshift range of our interest. This leads to a sample of a total of 9203 high-redshift galaxies.

3 Comparison with traditional colour selections

To see if the candidates in our *clean sample* would have been selected by traditional methods, we tested how they would be located in some traditional colour-colour diagrams. In particular, we opted for testing the BX selection ($\langle z \rangle = 2.20 \pm 0.32$) of [22], LBG selection ($\langle z \rangle = 2.96 \pm 0.29$) of [21], and BRi' ($\langle z \rangle = 4.0 \pm 0.3$), $Vi'z'$ ($\langle z \rangle = 4.7 \pm 0.3$), and $Ri'z'$ ($\langle z \rangle = 4.9 \pm 0.2$) LBG selections of [23].

First, we carried out SED fitting on our sample galaxies in order to find a spectrum which we then could convolve with the broadband filters used in the above colour selections. To assure a good SED-fitting, we considered only the galaxies with good quality photometry in all of the filters by setting "irms_OPT_Flag" = 0 and "irms_NIR_Flag" = 0, and required them to be brighter than $m = 24$ in the first filter redwards from the Ly-α line in order to discard the objects too faint to be reliably measured in our data. These requirement reduced our sample to 8023 galaxies. For the SED fitting we used the single stellar population (SSP) models of [4] of all the available metallicities (six metallicity values in the range $Z = 0.001 - 0.05$) and of 40 ages roughly logarithmically spaced from 10 Myr to the age of the Universe. We added extinction adopting the extinction law of [7] at the wavelength range 970 Å – 1200 Å, and that of [5] for longer wavelengths. At wavelengths below 970 Å, where none of the two laws is defined, we adopted a constant extinction with a value equal to that at 970 Å. The colour excess, $E(B-V)$, was varied in a range of realistic values: from 0.0 to 0.5 [16] in steps of $\Delta E(B-V) = 0.025$. The model spectra were moved in redshift in steps of $\Delta z = 0.025$ to sample the redshift range of our interest, so that at each redshift only the SSPs up to the age of the Universe at that time were considered. The Lyman forest was modelled following the prescriptions of [8].

These template spectra were convolved with the ALHAMBRA filter passbands. Each galaxy in our sample was fitted by this template library using the χ^2-method so that only the templates with redshifts $z_{\rm template} = \langle z \rangle \pm \sigma_z$ were considered, i.e. those templates whose redshift is inside one sigma from the median redshift of the fitted galaxy as derived from its zPDF. The template spectrum whose fit produced the lowest value of χ^2 was then assigned as the best fit template for each galaxy in our sample. Finally, only the galaxies with the reduced $\chi^2_r < 2$ ($\chi^2_r = \chi^2/(1-N)$, where N is the number of filters used in the fit) were accepted for the analysis. After this step, we are left with 6631 galaxies.

The original spectra of these best fit templates were then convolved with the filter passbands of the broad band filters of interest and the objects were placed in the colour-colour diagrams (Fig. 1). In each diagram in Fig. 1 we plotted only those candidates of our sample whose (ALHAMBRA median) redshifts are within one sigma from the one targeted by the corresponding colour selection. We see that most of the galaxies in our sample would also have been selected by these traditional methods. The galaxy clearly outside the selection boxes in the bottom-right corners of the bottom diagrams is the same one in both diagrams. It is a very faint object, and even though it is brighter than $m = 24$ in the first filter redwards the Ly-α (the magnitude being $m = 23.8$), in all the other filters it is fainter than the 5σ limiting magnitude for the corresponding filter.

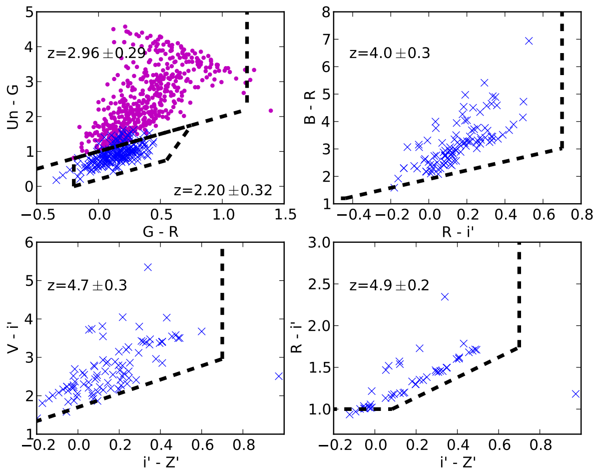

Figure 1: Locations of our *clean sample* candidates in four colour-colour diagrams used for traditional selections. The selection boxes in each diagram are shown with dashed lines and the redshift ranges their target are indicated in each panel. Plotted are only the candidates in the redshift range within one sigma the one targeted by these diagrams (blue crosses). In the *top right* diagram the blue crosses refer to the BX selection while the magenta dots to the LBG selection. See the text for more details.

4 Galaxy number counts from a probabilistic approach

The selection of the sample above is an example of the use of zPDFs when one needs a candidate selection and wants to be certain the selected galaxies really are at desired redshift. However, selecting both a clean and complete sample is challenging.

For many purposes the candidate selection is not needed but the galaxies and their properties can rather be considered like continua described by their zPDFs. Using this approach, the number N of objects in a redshift bin $z_1 < z < z_2$ and magnitude bin $m_1 < m < m_2$ of our interest can be obtained by carrying out a summation over each object i in the ALHAMBRA catalogue of the form:

$$N = \sum_{m_1 < m_i < m_2} \int_{z_1}^{z_2} PDF_i(z) dz. \tag{2}$$

For each redshift bin the apparent magnitude refers to the magnitude at the UV continuum as measured by the first filter redwards from the Ly-α (and not containing the possible Ly-α line) at the corresponding redshift. The summation was carried out in five redshift bins and the resulting *probabilistic number counts* in a total area of 8572.5 arcmin^2 are shown in Fig. 2. For comparison, we have also plotted in Fig. 2 the colour selected BX and LBG candidates of [15] (R08), and the BRi' and $Vi'z'$ colour selected LBG candidates of [23] (Y06), both corrected for incompleteness and contamination. According to R08, their samples are

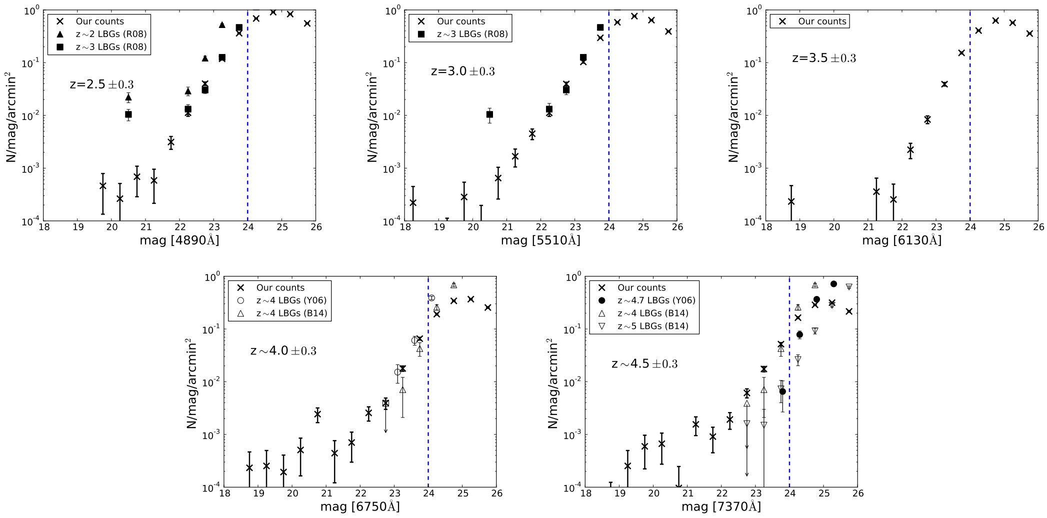

Figure 2: Observed *probabilistic number counts* for high-redshift ALHAMBRA galaxies. The directly derived counts are shown as crosses while the counts derived from an '*Odds*" selected sample are shown as black dots. The error bars reflect Poisson errors. For comparison, we show the BX ($z \sim 2.20 \pm 0.32$) and LBG ($z \sim 2.96 \pm 0.29$) number counts of Reddy et al. (2008; R08), the BRi' ($z \sim 4.0 \pm 0.3$) and $Vi'z'$ ($z \sim 4.7 \pm 0.3$) LBG number counts of Yoshida et al. (2006; Y06), and the ~ 4 and ~ 5 LBG number counts of Bouwens et al. (2014; B14). See the text for more details.

centred at redshifts $z \sim 2.20 \pm 0.32$ (BX) and $z \sim 2.96 \pm 0.29$ (LBG). The LBG samples of Y06 are centred at $z \sim 4.0 \pm 0.3$ (BRi') and $z \sim 4.7 \pm 0.3$ ($Vi'z'$). We have also overplotted in Fig. 2 the $z \sim 4$ and $z \sim 5$ colour selected LBGs of [3] (B14). In the two lowest redshift bins our counts tend to be slightly smaller than the counts derived from the literature while in the two last bins the tend is opposite. These differences could be explained by possible systematics as the methodology used to derive the counts and the correction factors in each work varies. However, the general trends of the counts from different works coincide. Thanks to the wide area of ALHAMBRA, in all the panels our counts sample the distributions down to brighter magnitudes than the counts from the literature.

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