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The ALHAMBRA survey: Accurate photometric merger fractions from PDF analysis

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Abstract

The estimation of the merger fraction in photometric surveys is limited by the large uncertainty in the photometric redshift compared with the velocity difference in kinematical close pairs (less than $500\,\mathrm{km\,s^{-1}}$). Several efforts have conducted to deal with this limitation and we present the latest improvements. Our new method (i) provides a robust estimation of the merger fraction by using full probability distribution functions (PDFs) instead of Gaussian distributions, as in previous work; (ii) takes into account the dependence of the luminosity on redshift in both the selection of the samples and the definition of major/minor mergers; and (iii) deals with partial PDFs to define "red" (E/S0 templates) and "blue" (spiral/starburst templates) samples without apply any colour selection. We highlight our new method with the estimation of the merger fraction at $z < 1$ in the ALHAMBRA photometric survey. We find that our merger fractions and rates nicely agree with those from previous spectroscopic work. This new method will be capital for current and future large photometric surveys such as DES, SHARDS, J-PAS, or LSST.

1 Introduction

The merger history of a given population is estimated measuring its merger fraction $f_{\rm m}$, i.e., the fraction of galaxies in a sample suffering a merging process, both by morphological criteria (highly distorted galaxies are merger remnants, e.g., [4, 5, 12, 13, 18]), or by close pair statistics (two galaxies close in the sky plane, $r_{\rm p} \leq r_{\rm p}^{\rm max}$, and in redshift space, $\Delta v \leq 500\,\mathrm{km\,s^{-1}}$, that will lead to a merger, e.g., [9, 21, 22, 10, 11, 15, 24]).

Several efforts have been conducted in the literature to study close companions in photometric surveys. Photometric surveys are limited by the Δv condition: The $500\,\mathrm{km\,s^{-1}}$ difference translates to a redshift difference of $|z_1 - z_2| \leq 0.0017(1+z)$, with the best photometric redshifts ($z_{\rm p}$) from current broad+medium-band surveys reaching a precision $\sim 0.01(1+z)$ (e.g., [6, 23, 20]). Next-generation large photometric redshift surveys will cover huge sky areas ($> 5000\,\deg^2$) with broad-band filters, such as the LSST (Large Synoptic Survey Telescope, $ugrizY$, [7]), and with narrow-band filters, such as the J-PAS (Javalambre-Physics of the accelerated universe Astrophysical Survey, 56 optical filters of ~ 145 Å, [3]), providing photometric redshifts for hundreds of million sources. Thus, a suitable and robust methodology to estimate the merger fraction from photometric close pairs is fundamental to exploit the current and the ambitious next photometric surveys.

In this talk we present a new method to compute the merger fraction from photometric data that (i) uses the full probability distribution functions (PDF) of the sources in redshift space, (ii) includes the variation in the luminosity of the sources with z in both the selection of the samples and the luminosity ratio constrain, and (iii) splits individual PDFs into red and blue spectral templates to deal robustly with colour selections. We take advantage of the unique design, depth, and photometric redshift accuracy of the ALHAMBRA (Advanced, Large, Homogeneous Area, Medium-Band Redshift Astronomical) photometric survey [19] to develop and test our new methodology.

2 The ALHAMBRA survey

The ALHAMBRA survey provides a photometric data set over 20 contiguous, equal-width ($\sim$300 Å), non-overlapping, medium-band optical filters (3500 Å−−9700 Å) plus 3 standard broad-band near-infrared (NIR) filters (J, H, and $K_{\rm s}$) over 8 different regions of the northern sky [19]. The survey has collected its data for the 20+3 optical-NIR filters with the 3.5 m telescope at the Calar Alto observatory, using the wide-field camera LAICA (Large Area Imager for Calar Alto) in the optical and the OMEGA2000 camera in the NIR. The ALHAMBRA survey has observed eight well-separated regions of the northern sky and the data we used comprise 48 sub-fields of $\sim 180\,\mathrm{arcmin}^2$ each, which can be assumed as independent for merger fraction studies as demonstrated by [16].

We rely on the ALHAMBRA photometric redshifts to compute the merger fraction. The photometric redshifts used all over the present work are fully presented and tested in [20]. The photometric redshifts of ALHAMBRA were estimated with `BPZ2.0`, a new version of `BPZ` (Bayesian Photometric Redshift, [2]). `BPZ` is a SED-fitting method based in a Bayesian inference, where a maximum likelihood is weighted by a prior probability. The photometric redshift accuracy is $\sigma_{\rm NMAD} = 0.011$ for $I \leq 22.5$ galaxies with a fraction of catastrophic outliers of $\eta = 2.1\,\%$. The areas of the images affected by bright stars, as well as those with lower exposure times (e.g., the edges of the images), were masked following [1]. The total area covered by the current ALHAMBRA data after masking is $2.38\,\deg^2$. We refer to [20] for a more detailed discussion.

The probability of a galaxy i being located at redshift z and having a spectral type T is $\mathrm{PDF}_i\,(z,T)$. This probability distribution function is the posterior provided by `BPZ2.0`. The probability of the galaxy i of being located at redshift z is then $\mathrm{PDF}_i\,(z) = \int \mathrm{PDF}_i\,(z,T)\,\mathrm{d}T$. In the present work, the definition of red and blue galaxies takes advantage of the profuse information encoded in the PDFs. Instead of selecting galaxies according to their observed color or their best spectral template, we split each PDF into "red" templates (T = E/S0) and "blue" templates (T = S/SB). This is, a given galaxy can be both red and blue.

Throughout this work, we focus our analysis on the galaxies in the ALHAMBRA first data release. This catalogue comprises ~ 500 k sources and is complete ($5\,\sigma$, 3" aperture) for $I \leq 24.5$ galaxies [20].

3 Measuring the merger fraction in photometric samples

To compute the merger fraction, one defines a primary and a secondary sample. The primary sample comprises the population of interest and one looks for those galaxies in the secondary sample that fulfil the close pair criterion for each galaxy of the primary sample. With the previous definition the merger fraction is

$$f_{\rm m} = \frac{N_{\rm p}}{N_1}, \tag{1}$$

where N_1 is the number of sources in the primary sample and $N_{\rm p}$ the number of close pairs. This definition applies to spectroscopic volume–limited samples, but we rely on photometric redshifts to compute $f_{\rm m}$.

For each projected photometric close pair in the ALHAMBRA survey, we define the redshift probability function $\mathcal{Z}$ as

$$\mathcal{Z}(z) = \frac{2 \times {\rm PDF}_1(z) \times {\rm PDF}_2(z)}{{\rm PDF}_1(z) + {\rm PDF}_2(z)}. \tag{2}$$

We multiply the PDFs of the central galaxy (PDF$_1$) and its satellite (PDF$_2$) to obtain the shape of the function $\mathcal{Z}$, and we normalise by the number of potential pairs (2 galaxies per pair) at each redshift. $\mathcal{Z}(z)$ is the *number of close pairs in the system at redshift* z.

The merger fraction in the redshift range $z_{\rm r} = [z_{\rm min}, z_{\rm max}]$ is

$$f_{\rm m} = \frac{\sum_k \int_{z_{\rm min}}^{z_{\rm max}} \mathcal{Z}_k\,(z)\,{\rm d}z}{\sum_i \int_{z_{\rm min}}^{z_{\rm max}} {\rm PDF}_i\,(z)\,{\rm d}z} = \frac{\sum_k N_{\rm pair}^k}{\sum_i N_1^i}, \tag{3}$$

where k indexes the close pair systems and i indexes the galaxies in the primary sample. Equation (3) is the photometric analogous of Eq. (1), with $\sum_k N_{\rm pair}^k$ being the number of close pairs and $\sum_i N_1^i$ the number of primary galaxies.

4 The merger fraction and rate in ALHAMBRA

We test the reliability of our new methodology by comparing the merger fractions in the ALHAMBRA photometric survey with those from previous spectroscopic work. We used the homogenised compilation from [14] to test the performance of the ALHAMBRA merger fractions. We defined three samples selected in $B-$band luminosity. These samples are

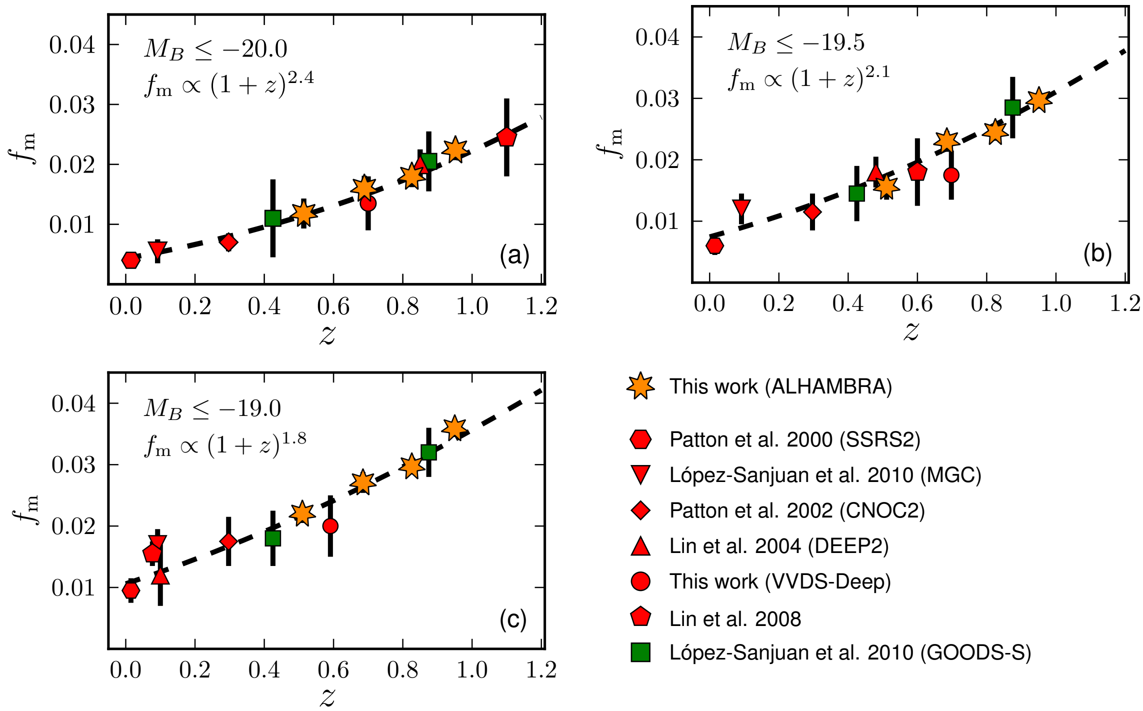

Figure 1: Merger fraction $f_{\rm m}$ as a function of redshift and the selection in B-band luminosity, *panel (a)* for $M_B \leq -20$ galaxies, *panel (b)* for $M_B \leq -19.5$ galaxies, and *panel (c)* for $M_B \leq -19$ galaxies. The orange stars are from the ALHAMBRA photometric survey (this work), the green squares from spectro-photometric pairs in GOODS-S [14], and the red symbols are from spectroscopic surveys: Hexagons from the SSRS2 [21], inverted triangles form the MGC [14], diamonds from the CNOC2 [22], dots from the VVDS-Deep (this work), triangles from the DEEP2 [10], and pentagons from [11]. The dashed lines are the best fitting of a power-law to the data.

defined with $M_{\rm B} \leq -20, -19.5$, and -19. We used these three samples as primary and secondary samples, and did not apply any luminosity condition between the galaxies in the pairs. We searched close pairs with $6\,h^{-1}\,{\rm kpc} \leq r_{\rm p} \leq 21\,h^{-1}\,{\rm kpc}$. We performed the study at $0.4 \leq z < 1$ to ensure large enough volumes at the lower redshifts and volume-limited samples at the higher ones. We show the ALHAMBRA merger fractions in Fig. 1. We find that the ALHAMBRA merger fractions are in excellent agreement with the spectroscopic values.

We parametrise the redshift evolution of the merger fraction with a power-law [9], $f_{\rm m}\,(z) = f_{\rm m,0} \times (1+z)^m$. We find that the power-law index m increases with the luminosity selection, with the merger fraction at $z = 0$ decreasing (Fig. 1). The observed trends were already find by [10] and [14], and they point out the importance of the selection when different merger fraction studies are compared.

The final goal of merger studies is the estimation of the merger rate $R_{\rm m}$, defined as the number of mergers per galaxy and ${\rm Gyr}^{-1}$. The merger rate is computed from the merger

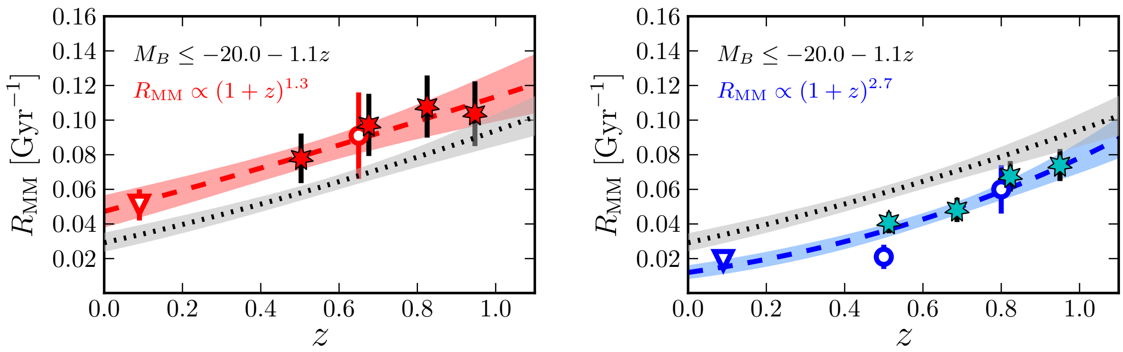

Figure 2: Major merger rate $R_{\rm MM}$ of red (*left panel*) and blue (*right panel*) $M_B \leq -20 - 1.1\,z$ galaxies as a function of redshift. The stars are from the ALHAMBRA photometric survey, the circles from the VVDS-Deep spectroscopic survey, and the inverted triangles from the MGC spectroscopic survey. The dashed line in both panels is the best fitting of a power-law to the data. The dotted lines mark the best fitting to the global population.

fraction by close pairs as $R_{\rm m} = C_{\rm m} \times T_{\rm m}^{-1} \times f_{\rm m}$, where $C_{\rm m}$ is the fraction of the observed close pairs that finally merge after a merger time scale $T_{\rm m}$. In this work the merger time scales from [8] were used to translate our merger fractions and the merger fractions from the literature to a common scale. The $T_{\rm m}$ from [8] already includes the merger probability, so we assume $C_{\rm m} = 1$ in the following.

We estimate the major merger rate $R_{\rm MM}$ of red (E/S0 templates) and blue (S/SB templates) galaxies in the ALHAMBRA survey. We define primary galaxies with $M_{B,1} \leq -20 - 1.1\,z$. This selects galaxies brighter than L_B^* up to $z = 1$. We searched major companions with $\Delta M_B \leq 1.5$ magnitudes. The companion sample therefore comprises galaxies with $M_{B,2} \leq -18.5 - 1.1\,z$. We estimated the major merger rate from the merger fraction of $10\,h^{-1}\,{\rm kpc} \leq r_{\rm p} \leq 50\,h^{-1}\,{\rm kpc}$ close pairs, and following [15] we used $T_{\rm m}^{\rm red} = 2.1 \pm 0.3\,{\rm Gyr}$ for red galaxies and $T_{\rm m}^{\rm blue} = 2.6 \pm 0.3\,{\rm Gyr}$ for blue galaxies.

We summarise our results in Fig. 2. We find that the major merger rate of red galaxies is larger than the major merger rate of blue galaxies at any redshift. We compare the ALHAMBRA results with those from the VVDS-Deep and the MGC. The ALHAMBRA major merger rates are in agreement with the spectroscopic values. We fit a power-law to the data and we find that (i) the evolution of the red merger rate is $R_{\rm MM}^{\rm red} = (0.047 \pm 0.008) \times (1+z)^{1.3\pm0.4}\,{\rm Gyr}^{-1}$. And (ii) the evolution of the blue merger rate is $R_{\rm MM}^{\rm blue} = (0.012 \pm 0.003) \times (1+z)^{2.7\pm0.5}\,{\rm Gyr}^{-1}$.

These results demonstrate that our new methodology deals naturally with color segregations and that accurate merger rates of red and blue galaxies can be estimated with only photometric data. More details can be found in [17]

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