Evolution of colour-dependence of galaxy clustering up to $z \sim 1.2$ based on the data from the VVDS-Wide survey

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We discuss the dependence of galaxy clustering according to their colours up to $z \sim 1.2$. For that purpose we used one of the wide fields (F22) from the VIMOS-VLT Deep Survey (VVDS). For galaxies with absolute luminosities close to the characteristic Schechter luminosities M^* at a given redshift, we measured the projected two-point correlation function $w_{\mathrm{p}}(r_{\mathrm{p}})$ and we estimated the best-fit parameters for a single power-law model: $\xi(r) = (r/r_0)^{-\gamma}$, where r_0 is the correlation length and γ is the slope of correlation function. Our results show that red galaxies exhibit the strongest clustering in all epochs up to $z \sim 1.2$. Green valley represents the "intermediate" population and blue cloud shows the weakest clustering strength. We also compared the shape of $w_p(r_p)$ for different galaxy populations. All three populations have different clustering properties on the small scales, similarly to the behaviour observed in the local catalogues.

1 Introduction

According to the widely accepted hierarchical model of the origin and evolution of the large scale structure of the Universe, gravitational collapse around primordial overdensities in the density field of the Universe initiated the formation of dark matter haloes, in which baryonic gas collapsed and condensed. From these baryon overdensities first galaxies evolved.

Thanks to the large local surveys, like the 2dF Galaxy Redshift Survey, the Sloan Digital Sky Survey or ESO-Sculptor Survey, the local Universe is relatively well known. From these surveys we know that clustering properties of galaxies depend, for example, on their colour, luminosity or environment. Moreover, we know that spiral and irregular galaxies occupy less dense regions than elliptical galaxies. It implies that red elliptical galaxies are much more clustered than the blue spirals and irregulars. An important issue both for the theory of the structure formation and for our understanding of the galaxy evolution is to find out how these environmental dependencies evolved. We want to know how did these relations look like for higher redshifts and when they were determined: during the galaxy formation or maybe as a consequence of interactions between galaxies.

Thanks to the DEEP2 Galaxy Redshift Survey, the zCOSMOS survey and the VIMOS-VLT Deep Survey we know that the red population was more clustered than the blue one already at $z \sim 1$ and that red galaxies was already formed at this epoch in dense environments. Here we present the results of the analysis of the dependence of galaxy clustering on their colours from the VIMOS VLT Deep Survey Wide (VVDS-Wide; Le Fèvre et al. 2005; Garilli et al. 2008).

2 Data description

The VIMOS-VLT Deep Survey was designed to study the formation and evolution of galaxies and the large scale structure of the Universe. The survey is composed of two main parts: wide and deep. The deep one is magnitude limited by $17.5 \leq I_{\rm AB} \leq 22.5$, while the wide one is in range $17.5 \leq I_{\rm AB} \leq 24$. For the analysis presented here we chose one of the wide fields - the so-called F22 field, as it has the largest number of available redshifts: for 10,852 galaxies, 162 QSOs and 6,607 stars.

We excluded quasars and stars, and chose galaxies with reliable redshift measurements in the redshift range $z = [0.2 - 1.2]$, with absolute magnitudes comparable with the characteristic Schechter absolute magnitude M^* as these galaxies can be treated as the "most typical" population at a given cosmic time. Galaxies were then divided into four samples according to the redshift (i.e. $z_1 = [0.2{-}0.5]$, $z_2 = [0.5{-}0.7]$, $z_3 = [0.7{-}0.9]$ and $z_4 = [0.9{-}1.2]$), as we wanted to investigate the colour-dependence of galaxy clustering for typical galaxies at different cosmic epochs. In Table 1 we present the basic properties of these four samples.

	$z_1 = [0.2 - 0.5]$	$z_2 = [0.5 - 0.7]$	$z_3 = [0.7 - 0.9]$	$z_4 = [0.9 - 1.2]$
$z_{\rm med}$	0.37	0.59	0.79	0.98
$B_{\rm cor}$	[-1,1]	[-1,1]	[-1,0.1]	[-1,-0.4]
$(B_{\rm cor})_{\rm med}$	0.28	0.12	-0.39	-0.74
$N_{\rm gal}$	2334	1857	1081	544
$n_{\rm red}[\%]$	27	41	35	30
$n_{\rm green}[\%]$	47	31	30	27
$n_{\rm blue}[\%]$	26	28	35	43

Table 1: Properties of our four samples of VVDS-Wide galaxies. Here $z_{\rm med}$ is the median value of the redshift; $B_{\rm cor}$ denotes the range of $B - B^*$, where B^* is the characteristic value of the absolute magnitude in the B-band; $(B_{\rm cor})_{\rm med}$ means the median value of $B_{\rm cor}$; $N_{\rm gal}$ is the number of galaxies in a sample and $n_{\rm red}$, $n_{\rm green}$, $n_{\rm blue}$ are the corresponding percentages of red, blue, and green galaxies, respectively.

3 Classification of galaxies

It is well known that in the local Universe morphological types of galaxies are correlated with their colours. Distribution of galaxy colours is bimodal - early and late-type galaxies occupy two different regions in the colour-magnitude and colour-colour diagrams. Galaxies can be divided into two main classes: "red sequence" (early-type, spheroidal, red, without active star formation) and "blue cloud" (late-type, disk-dominated, blue, with active star formation).

These dependencies were also found in deep redshift surveys up to at least $z \sim 1.5$ (e.g. Franzetti et al. 2007). Moreover, with increasing redshift, the colour of red galaxies becomes bluer (Bell et al. 2004). Also, an additional significant population was found at $z \sim 1$ between red sequence and blue cloud. This population is known as "green valley".

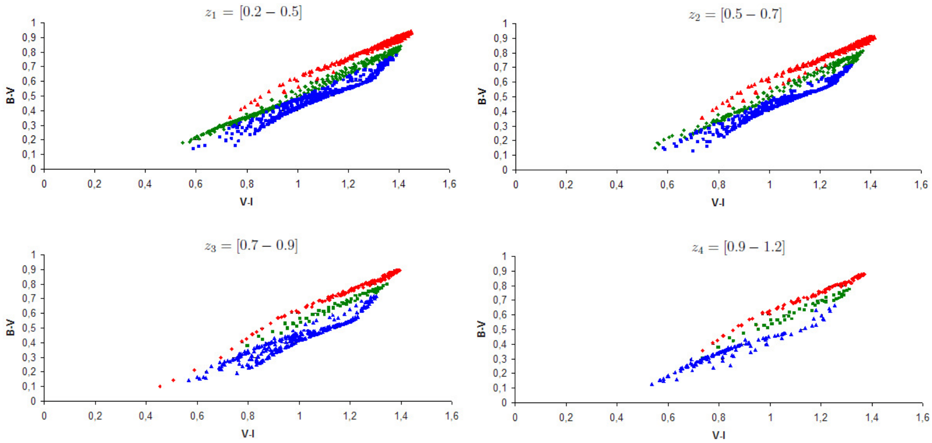

Fig. 1: Colour-colour diagrams in four redshift bins: $z_1 = [0.2 - 0.5]$, $z_2 = [0.5 - 0.7]$, $z_3 = [0.7 - 0.9]$ and $z_4 = [0.9 - 1.2]$ Red, green and blue points correspond to red sequence, green valley and blue cloud, respectively.

Colour-colour diagrams, based on absolute luminosities allow to define populations of galaxies to these three groups. According to them, we divided our samples into these three populations, as presented in Figure 1. The division may look artificial since the absolute magnitudes used as an input we computed the synthetic galaxy models (see Franzetti et al. 2007 for details; methods based on the template fitting give less discrete but similar results).

4 Methodology

To study galaxy clustering, we used the two-point correlation function $\xi(r)$, which is defined as a probability P above random that we can find a pair of galaxies within two infinitesimal volume elements dV_1 and dV_2 in the specific separation r:

$$P = n^2 dV_1 dV_2 [1 + \xi(r)], \tag{1}$$

where n is the mean number density.

In practice, different estimators are used since we need to take into account e.g. the missing data outside a sample. Here we use the Landy-Szalay estimator, which minimizes the cosmic error and bias and gives the best boundary corrections.

Next, we need to remove the effects of the proper velocities of galaxies, mainly the "Fingers of God", which lead to the elongation in the radial direction. For this purpose, we decompose the separation between a pair of galaxies into two components: perpendicular (r_p) and parallel (π) to the observer's line of sight. The Landy-Szalay estimator can be then written in the form of:

$$\xi(r_\mathrm{p}, \pi) = \frac{N_\mathrm{R}(N_\mathrm{R} - 1)}{N_\mathrm{G}(N_\mathrm{G} - 1)} \frac{GG(r_\mathrm{p}, \pi)}{RR(r_\mathrm{p}, \pi)} - 2 \frac{N_\mathrm{R} - 1}{N_\mathrm{G}} \frac{GR(r_\mathrm{p}, \pi)}{RR(r_\mathrm{p}, \pi)} + 1, \tag{2}$$

where N_R and N_G are the number of objects in the random and in the galaxy samples, correspondingly. GG(r) and RR(r) are the total numbers of the galaxy-galaxy and respectively random-random pairs in the range of $(r, r + dr)$. GR(r) corresponds to the cross-pairs (galaxy-random pairs) from both catalogues.

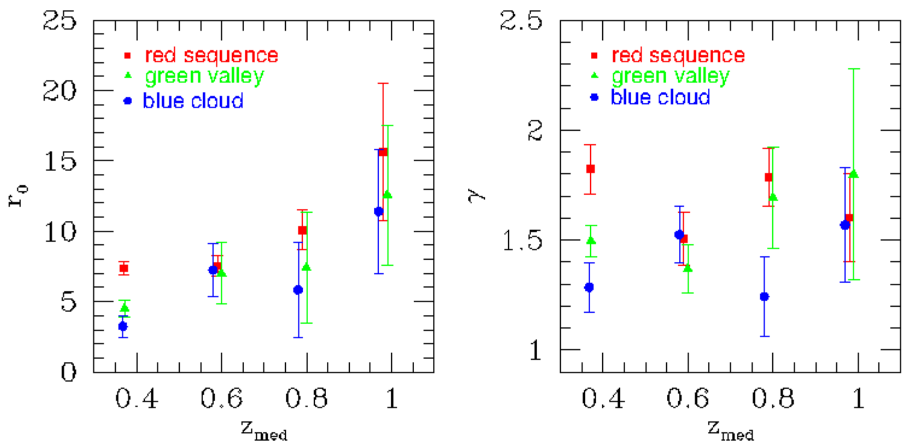

Fig. 2: Correlation length r_0 (left panel) and the slope γ of correlation function (right panel) as a function of median redshift z_{med} for red sequence, green valley and blue cloud galaxies. Symbols: red squares, green triangles and blue circles correspond to the red, green and blue populations, respectively.

After projecting $\xi(r_\mathrm{p}, \pi)$ along the line of sight (on r_p axis), we obtain $w_\mathrm{p}(r_\mathrm{p})$, which is the recovered real-space correlation function, free of the redshift-space distortions. In practice, $\xi(r)$, and, consequently, $w_\mathrm{p}(r_\mathrm{p})$, can be often well described by a single power-law model:

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}, \tag{3}$$

where r_0 is the correlation length and γ is the slope of correlation function. However, as we show below, this simple approximation is not equally good for all galaxy populations.

5 Results

5.1 *Evolution of correlation function*

To study evolution of galaxy clustering, we compared the best-fit parameters of correlation function for red sequence, green valley and blue cloud at different cosmic time. Figure 2 presents the dependence of the correlation length r_0 and the slope of correlation function γ on median redshifts z_med of our samples.

It can be seen that in all the epochs red galaxies show a higher correlation length than the other populations. It implies that red galaxies are more clustered than other types, which is similar to the trends found for today's galaxies. The weak evolution of the correlation length for the red sequence in the epoch $z = [0.2 - 0.7]$ indicates that a large amount of these galaxies was already in their today's place in the large scale structure at the earlier epochs. Higher values of r_0 for epochs with $z = [0.7 - 1.2]$ are related rather to the selection effects, as we observe systematically more luminous populations there.

At all epochs we observe a very similar difference between the slopes of the projected correlation function measured for the red population and for the remaining galaxies, and the slope for the red population is always higher. It implies that clustering at small scales was the strongest for the red population all the time from $z \sim 1.2$ and the colour segregation of the M^* galaxies with respect to the cosmic structures was well established at $z \sim 1$ and did not evolve significantly since then.

5.2 *Colour dependence of the shape of the galaxy correlation function*

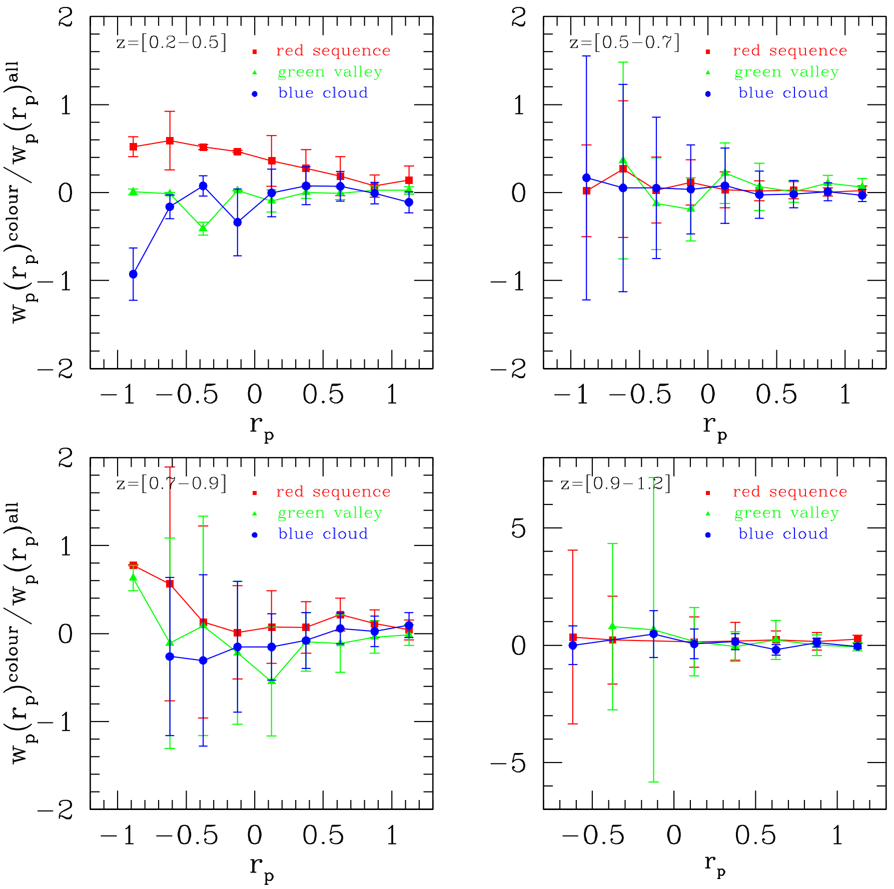

Fig. 3: The projected correlation function for each population divided by a value obtained for all galaxies without division into populations. Red squares, green triangles and blue circles show, respectively, $w_\mathrm{p}(r_\mathrm{p})^\mathrm{colour}$ for red, green, and blue galaxies, divided by a value of $w_\mathrm{p}(r_\mathrm{p})^\mathrm{all}$ measured for all galaxies.

We divided measured values of $w_\mathrm{p}(r_\mathrm{p})^\mathrm{colour}$ for each population by a corresponding value of $w_\mathrm{p}(r_\mathrm{p})^\mathrm{all}$ obtained for all galaxies in an appropriate redshift bin. Results, shown in Figure 3, demonstrate that the power-law model does not reflect precisely the observed shape of correlation function. Up to $z \sim 0.7$ red galaxies are more strongly clustered at the smallest scales, while blue galaxies show a clear deficit of pairs. The green population is located in between. In the last bins $z > 0.7$ the error bars are, unfortunately, too large to draw any strong conclusions. The observed effect can be explained in the framework of the Halo Occupation Distribution (HOD) model.

The differences in the shape of correlation function between small and large scales depend on the density distribution of galaxies belonging, respectively, to the same dark matter halo and to different haloes. Red galaxies are often located in the same dark matter haloes, while blue galaxies avoid dense areas. This behaviour is similar to the one observed in the local Universe (Zehavi et al. 2005).

Green galaxies on small scales reveal similar properties as the blue population, while on large scales they behave similarly to the red sequence. This also can be interpreted in terms of the HOD model. Having the same two-halo term as the red population indicates that green valley occupies peripheries of haloes, remaining closely related to red galaxies. In the same time, one-halo term similar to the blue population reflects a lower radial concentration of green population within their haloes.

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References

Bell, E. F., et al., *Nearly 5000 Distant Early-Type Galaxies in COMBO-17: A Red Sequence and Its Evolution since* $z \sim 1$, *ApJ* **608**, 752 (2004)

Franzetti, P., et al., *The VIMOS-VLT deep survey. Color bimodality and the mix of galaxy populations up to* $z \sim 2$, *A&A* **465**, 711 (2007)

Garilli, B., et al., *The Vimos VLT deep survey. Global properties of 20,000 galaxies in the* $I_{AB} < 22.5$ *WIDE survey*, *A&A* **486**, 683 (2008)

Le Fèvre, O., et al., *The VIMOS VLT deep survey. First epoch VVDS-deep survey: 11 564 spectra with* $17.5 \leq IAB \leq 24$*, and the redshift distribution over* $0 \leq z \leq 5$, *A&A* **439**, 845 (2005)

Zehavi, I., et al., *The Luminosity and Color Dependence of the Galaxy Correlation Function*, *ApJ* **630**, 1 (2005)