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VIMOS-VLT Deep Survey: Evolution of the Large Scale Structure of the Universe from z 2 until now

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We discuss the evolution of clustering of galaxies back to z 2. For that purpose we use the VIMOS-VLT Deep Survey (VVDS) data. We analyze the evolution of the projected two-point correlation function for the global galaxy population and for particular galaxy classes, with different intrinsic luminosities, spectral types, colors and other properties. For the brightest galaxies (with L>L*), for instance, the shape of the correlation function deviated from the power-law much more strongly at z 1 than it is observed now. This finding can be interpreted e.g. in the framework of Halo Occupation Distribution models (HODs) and implies a significant change in the way luminous galaxies traced dark-matter halos at z 1 with respect to now. Our observations represent an important constraint for models trying to reproduce the evolution of galaxy clustering.

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1. VIMOS-VLT Deep Survey as a probe of the evolution of the large scale structure

According to the paradigm of the gravitational instability theory, galaxies formed and evolved inside dark matter halos. These haloes originated from the small fluctuations in the primordial, almost homogeneous distribution of matter. Then they were growing and merging under the effect of gravity, to form the skeleton of large scale structures we observe today. Processes of formation and evolution of galaxies are most clearly related to their location in the underlying dark matter distribution. However, it is still a matter of debate how different types of galaxies evolved, how big were the roles of the initial conditions and local environment in their evolution (so called "nature vs nature" problem). Answering this question is of an extreme importance now: if we can understand how evolution of galaxies was related to their position in the dark matter structures, we can use galaxies as tracers of the underlying dark matter field much more securely. Thus, understanding the evolution of galaxy clustering may be the key to understand the evolution of the Universe itself.

A unique opportunity to study the evolution of the galaxy clustering has opened with the advent of deep spectroscopic galaxy surveys. Here we present the selected results from the VIMOS-VLT Deep Survey (VVDS), [Le Fèvre et al., 2005a]. VVDS started observations in 2002. In the present moment, the data consist of three catalogues; results presented here are mainly based on the VVDS-Deep, which contains 11 564 spectra of celestial objects, strictly selected in magnitude in the range $17.5 \leq I_{AB} \leq 24$, from a complete deep photometric survey, without any color selection [Le Fèvre et al., 2005a]. The other two data sets are: a larger (32 734 spectra) and less deep ($17.5 \leq I_{AB} \leq 22$) VVDS-Wide [Garilli et al., 2008] and now on-going much deeper ($I_{AB} \leq 22.75$) VVDS-Ultra Deep. The data from VVDS-Deep and VVDS-Wide are now all open to public ([http://cencos.oamp.fr/]).

VVDS-Deep data contain 10 518 spectra of galaxies with measured spectroscopic redshifts up to $z \sim 5$ with a confidence level above 80%. Even now, when the next projects aiming to measure a large amount of galaxy spectra in the same redshift range, are being developed, VVDS-Deep remains one of the best data sets available to investigate the galaxy clustering in a broad range of time. Here we describe our results on the evolution of the clustering properties of galaxies and, in particular, its dependence on galaxy luminosities and stellar masses.

2. Galaxies: clustering of mass and light

The simplest measure of galaxy clustering is given by the 2-point spatial correlation function $\xi(r_p, \pi)$ (where the separation vector of a pair of galaxies is split into two components: π and r_p, respectively parallel and perpendicular to the line of sight). To recover the real-space correlation function and get rid of distortions due to peculiar motions of galaxies, we compute the projection of $\xi(r_p, \pi)$ along the line of sight: $w_p(r_p)$. The best power-law fit to $w_p(r_p)$ gives us it slope, γ, and the correlation length r_0 [Pollo et al., 2005].

Trying to compare similar galaxies at different epochs, we made an attempt to select them according to intrinsic properties: absolute luminosities and stellar masses.

The luminosity dependence of galaxy clustering at $z \sim 1$ is very different from what is observed in the local universe [Pollo et al., 2006]. Fainter galaxies are much less clustered than their local counterparts while the most luminous ones are practically as strongly clustered as today. However, the scale dependence of their clustering is different: we observe a change in the shape of $w_p(r_p)$, which increasingly deviates from a power-law for the most luminous samples, demonstrating a strong upturn on small ($\leq 1-2\ h^{-1}$ Mpc) scales (see the left panel of Figure 1).

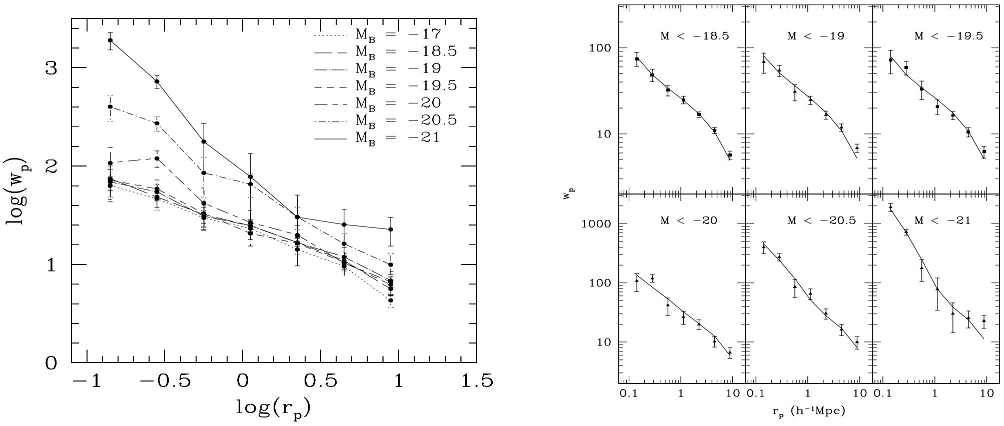

Figure 1: Left panel: projected correlation function $w_p(r_p)$ for the most luminous galaxies at $z \sim 1$ shows a clear deviation from a power-law, with a strong upturn on the smallest scales. Right panel: This behaviour can be interpreted using the HOD models of $w_p(r_p)$.

This behaviour can be interpreted in terms of the halo occupation distribution (HOD) model which fully describes the bias in the galaxy distribution with respect to the underlying dark matter. In the right panel of Figure 1 we present a fit of the HOD model to our data, using a model originally proposed in [Tinker et al., 2005]. The model not only fits well the data but also provides us with interesting information regarding the dark matter halos hosting VVDS galaxies. An average mass of the dark matter halo seems to rise consistently with the average brightness of the sample. In case of fainter samples we tend to observe typically just one, central galaxy per halo, while for the brightest galaxies this number jumps suddenly to almost two. This means that in the latter case we typically start seeing a second bright satellite per halo.

This excess of close luminous galaxy pairs at small scales might reflect a difference in the clustering of mass between $z \sim 1$ and now. However, it may be also related to some evolutionary phenomena, e.g. to an enhanced galaxy formation in close pairs at this epoch. The clustering of galaxies selected according to their stellar mass shows that galaxies containing the most stellar mass are also more strongly clustered, with a particular enhancement at small ($\leq 1-2\ h^{-1}$ Mpc) scales [Meneux et al., 2007]. The observed effect, however, is less strongly pronounced than for the case of the most luminous galaxies.

The answer may lay in the fact that although the most luminous galaxies generally have larger stellar masses, a significant number also have relatively low stellar masses (see the left panel of Figure 2). As can be seen in the right panel of Figure 2, the projected correlation function of these luminous galaxies with low stellar mass displays a complete lack of close pairs. All the strong signal in the correlation function of luminous galaxies on the small scales comes from pairs of two massive and of one massive and one low-mass galaxy. A likely explanation of this phenomenon is that these low-mass bright galaxies are mostly satellite galaxies of more massive central galaxies

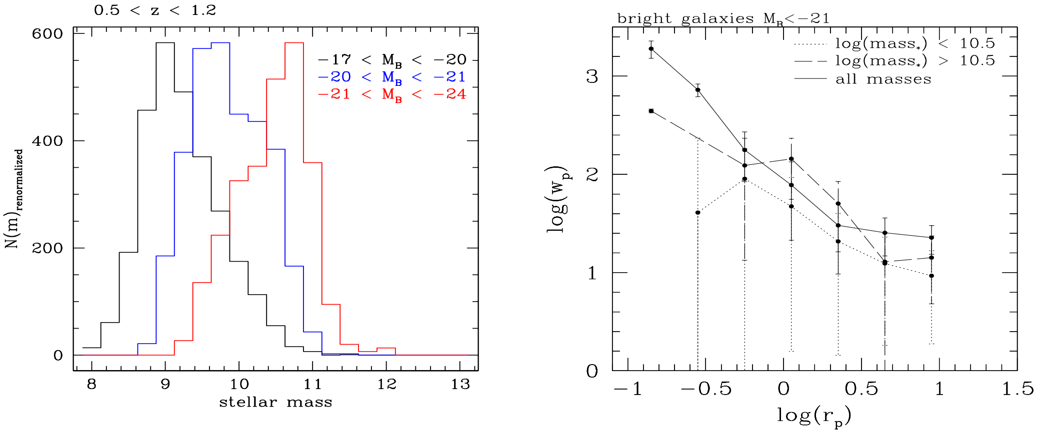

Figure 2: Left panel: distribution of the values of galaxy stellar masses in different ranges of absolute luminosities for VVDS galaxies at $z \sim 1$ (increasing masses from left to right). Right panel: projected correlation function $w_p(r_p)$ for luminous ($M_B \geq 21$) galaxies with low and high stellar mass. Note a complete lack of close pairs for low-mass luminous galaxies.

of the dark matter halos and that their high luminosity is related to some intergalactic interactions inside the halo. This finding may be interpreted then as an evidence for the existence of a population of low-mass bright satellite galaxies at $z \sim 1$ present in the most massive galaxy halos, which is not observed today. This is in a perfect agreement with the results given by the HOD model presented here and suggests a significant environmental dependence of the evolution of the galaxy luminosity.

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