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Photometric properties of void galaxies in the Sloan Digital Sky Survey Data Release 7

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ABSTRACT

Using the sample presented by Pan et al., we analyse the photometric properties of 88 794 void galaxies and compare them to galaxies that reside in higher density environments with the same absolute magnitude distribution as the void galaxies. We analysed the Sloan Digital Sky Survey Data Release 7 and found a total of 1054 dynamically distinct voids with radius larger than $10\,h^{-1}$ Mpc. The voids are not empty, but are underdense, with $\delta\rho/\rho < -0.9$ in their centres. In this paper, we study the photometric properties of these void galaxies. We look at the $u-r$ colours as an indication of star formation activity and the inverse concentration index as an indication of galaxy type. We find that void galaxies are statistically bluer than galaxies found in higher density environments with the same magnitude distribution. We examine the colours of the galaxies as a function of magnitude, dividing the galaxies into bright, medium, faint and dwarf groups, and we fit each colour distribution with a double-Gaussian model for the red and blue subpopulations. As we move from bright to dwarf galaxies, the population of red galaxies steadily decreases and the fraction of blue galaxies increases in both voids and walls; however, the fraction of blue galaxies in the voids is always higher and bluer than in the walls. We also split the void and wall galaxies into samples depending on galaxy type, as measured by the inverse concentration index. We find that late-type void galaxies are bluer than late-type wall galaxies and the same holds for early galaxies. We also find that early-type and dwarf void galaxies are blue in colour. We also study the properties of void galaxies as a function of their distance from the centre of the void. We find very little variation in the properties, such as magnitude, colour and type, of void galaxies as a function of their location in the void. The only exception is that the dwarf void galaxies may live closer to the centres of voids. As shown by Pan et al., the centres of voids have very similar density contrast and hence all void galaxies live in very similar density environments, which may explain the lack of variation of galaxy properties with location within voids.

Key words: galaxies: dwarf – galaxies: fundamental parameters – galaxies: photometry.

1 INTRODUCTION

The completion of the Sloan Digital Sky Survey (SDSS) allows the identification of $\sim 10^3$ large voids and a sample of $\sim 10^5$ galaxies that lie within the centres of the voids. With this sample we can study the photometric properties of void galaxies within specific ranges of magnitude, colour, surface brightness profiles and distance from the centre of the void.

The prominence of voids in the large-scale distribution of galaxies was brought to the attention of most astronomers by the discovery of a void with diameter of $50\,h^{-1}$ Mpc in the direction of Böotes (Kirshner, Oemler & Schechter 1981). Subsequent surveys that were larger in both areal coverage and number density of galaxies showed that voids are an important part of the cosmic web and fill more than half the volume of the Universe (da Costa et al. 1988; Geller & Huchra 1989; Pellegrini, da Costa & de Carvalho 1989; Shectman et al. 1996). Until recently, finding large voids was challenging: voids have diameters up to $60\,h^{-1}$ Mpc, which is similar to the minimum dimension of early galaxy redshift surveys. The advent of the 2 degree field (2df) Galaxy Redshift Survey and the SDSS has allowed samples of $\sim 10^3$ large voids to be identified (El-Ad, Piran & Da Costa 1997; Müller, Arbabi-Bidgoli & Einasto 2000; Plionis & Basilakos 2002; Hoyle & Vogeley 2002, 2004; Ceccarelli et al. 2006; Tikhonov 2006, 2007; Foster & Nelson 2009; Pan et al. 2012;

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Patiri, Betancort-Rijo & Prada 2012; Sutter et al. 2012; Varela et al. 2012).

The properties of objects within voids may provide strong tests of models for cosmology and galaxy formation. Peebles (2001) pointed out the apparent discrepancy between cold dark matter (CDM) models and observations. Initially, it was thought that CDM models would predict a large population of low-mass haloes inside the voids (Dekel & Silk 1986; Hoffman, Silk & Wyse 1992). However, an improved understanding of the CDM models, especially the ΛCDM model, indicates that there should be fewer low-mass haloes in the voids than originally thought as there is a shift in the mass function within the void (Goldberg et al. 2005, and references therein). Tinker & Conroy (2009) note that the sharp contrast between voids and denser structures may be caused by this shift of the halo mass function.

Pointed observations towards void regions failed to detect a significant population of faint galaxies (Kuhn, Hopp & Elsaesser 1997; Popescu, Hopp & Elsaesser 1997; McLin et al. 2002). Surveys of dwarf galaxies indicate that they trace the same overall structures as larger galaxies (Bingelli 1989). Thuan, Gott & Schneider (1987), Babul & Postman (1990) and Mo, McGaugh & Bothun (1994) showed that galaxies have common voids regardless of Hubble type. There is also no evidence for such a population of failed galaxies in voids from blind H I (21 cm) surveys. The most sensitive of such surveys to date, the The Arecibo Legacy Fast ALFA Survey (ALFALFA) survey (Giovanelli et al. 2005), has not unveiled a population of gas-rich but optically dark galaxies.

Grogin & Geller (1999, 2000) identified a sample of 149 galaxies that lie in voids traced by the Center for Astrophysics Survey. They showed that the void galaxies tended to be bluer and of later type. Their sample of 149 void galaxies covered a narrow range of absolute magnitudes ($-20 \leq B \leq -17$). 49 of their galaxies resided in a low-density contrast region with $\delta\rho/\rho \leq 0.5$.

Rojas et al. (2004) defined a sample of underdense galaxies from the SDSS Data Release 4. They used a nearest neighbour technique to identify galaxies that had fewer than three neighbours in a sphere of 7 h^{-1} Mpc. This corresponds to an underdensity of $\delta\rho/\rho \leq -0.6$ around each void galaxy, which is consistent with the local density in the interiors of voids if void galaxies are clustered with $\xi(r) = 1$ on this scale. Their sample contained ∼200 galaxies in their nearby sample (galaxies with r-band magnitudes between −13.5 and −19.5) and ∼1000 galaxies in their distant sample (galaxies with r-band magnitude between −17.5 and −21.5). They found that galaxies in underdense environments were bluer than galaxies in higher density environments. They found that this blueness was not explained by the morphology–density relation (Dressler 1980; Postman & Geller 1984) as the nearby sample of both void and wall galaxies had similar surface brightness profiles and yet the void galaxies were still bluer, although with low significance. When the distant samples were split by galaxy type, the late-type and early-type void galaxies were bluer than their counterparts at higher density.

The void galaxies used by Rojas et al. (2004) were really underdense galaxies as, due to the geometry of the SDSS at that time, it was not possible to construct void catalogues. Using galaxies that reside in 3D voids, Patiri et al. (2006) found that there was a higher fraction of blue galaxies in the voids, but that the colours of the galaxies in the voids and walls were similar. However, von Benda-Beckman & Müller (2008) found that in their sample of 2000 galaxies taken from the 2df Galaxy Redshift Survey, as well as there being more blue galaxies in the voids than in the walls, the void galaxies were also bluer than wall galaxies.

The aim of this paper is to analyse the properties of a large sample of galaxies that reside in dynamically distinct voids (the radial profiles of the voids match the predictions of void growth by gravitational instability (see Pan et al. 2012) as opposed to smaller scale underdense environments. This sample of 88 794 galaxies is much larger than any other sample. For example there are as many voids in the current sample as there were void galaxies in the sample of Rojas et al. (2004). This allows us to compare the properties of void galaxies with galaxies in higher density environments for well-defined ranges of magnitude, colour, surface brightness profile and distance from void centre. We also have 4500 galaxies with M_r less than −17 so we can analyse the properties of dwarf galaxies in the voids as a separate sample. The larger sample of galaxies presented in this paper should address whether blue void galaxies are simply more populous than those in the walls, or whether there is a shift in the colour of the galaxies moving from void to wall region.

We organize the paper is as follows. In Section 2 we define data samples we will use. In Section 3 we describe the properties we consider, and in Sections 4 and 5 we describe the results and conclude our findings.

2 DATA

2.1 The Sloan Digital Sky Survey

The SDSS is a wide-field photometric and spectroscopic survey that covers 10^4 square degrees, including CCD imaging of 10^8 galaxies in five colours and follow-up spectroscopy of 10^6 galaxies with $r < 17.77$. York et al. (2000) provide an overview of the SDSS and Stoughton et al. (2002) describe the early data release and details about the photometric and spectroscopic measurements made from the data. Abazajian et al. (2003) describe the first Data Release of the SDSS. Technical papers providing details of the SDSS include descriptions of the photometric camera (Gunn et al. 1998), photometric analysis (Lupton et al. 2001), the photometric system (Fukugita et al. 1996; Smith et al. 2002), the photometric monitor (Hogg et al. 2001), astrometric calibration (Pier et al. 2003), selection of the galaxy spectroscopic samples (Eisenstein et al. 2001; Strauss et al. 2002) and spectroscopic tiling (Blanton et al. 2001).

In this study, we use the Korea Institute for Advanced Study Value-Added Galaxy Catalog (KIAS-VAGC; Choi, Han & Kim 2010) which is based on the SDSS Data Release 7 (DR7) sample of galaxies (Abazajian et al. 2009). The main source of galaxies is the New York University Value-Added Galaxy Catalog (NYU-VAGC) Large-Scale Structure Sample (brvoid0) (Blanton et al. 2005) which includes 583 946 galaxies with $10 < m_r \leq 17.6$ taken from DR7. 929 objects are removed from the sample as they are mostly de-blended outlying parts of large galaxies. In the KIAS-VAGC, 10 497 bright galaxies are added *into* the sample because they were too bright to be observed in the SDSS spectroscopic sample. These extra galaxies have redshifts observed earlier by the UZC, PSCz, RC3 or 2dF surveys. In the KIAS-VAGC, an additional 114 303 galaxies with $17.6 < m_r < 17.77$ are included from the NYU-VAGC (full0). This yields a total of 707 817 galaxies in the parent sample that we examine. This catalogue offers an extended magnitude range with high completeness over apparent magnitude range $10 < m_r < 17.6$.

2.2 Construction of the void galaxy sample

We use a sample of voids found within a volume limited sample constructed from the parent catalogue described above. The redshift limit we chose for finding voids was $z_{\rm max} = 0.107$, which corresponds to an absolute magnitude limit of $M_r < -20.09$. This sample contains 120 606 galaxies, which is the maximum number of galaxies possible in a volume limited sample. See Pan et al. (2012) for full details of this choice of volume limit. The resulting sample of voids found by Pan et al. (2012) includes a total of 1054 voids with radius as large as $25\,h^{-1}$ Mpc. For full details see Pan et al. (2012) and Hoyle & Vogeley (2002); here, we give a brief description of the most important aspects of VOIDFINDER.

The VOIDFINDER algorithm uses the coordinates of the galaxies in a volume limited sample to find statistically significant cosmic voids. It effectively finds large voids of density contrast $\delta\rho/\rho < 0.9$ in the centre and radius $R > 10\,h^{-1}$ Mpc. VOIDFINDER is based on the El-Ad & Piran (1997) method for finding voids and was used to find voids in galaxy redshift surveys by Hoyle & Vogeley (2002), Hoyle & Vogeley (2004) and Pan et al. (2012). VOIDFINDER has been applied to many surveys, including the *IRAS* PSCz, CfA2+SSRS2, 2dF, SDSS and 6dF. In cases where there is overlap between the different surveys, we have consistently found similar voids. Our tests on cosmological simulations demonstrated that this method works in identifying voids in the distributions of both simulated galaxies and dark matter (Benson et al. 2003).

The first step of the algorithm is to identify galaxies in the volume-limited sample that lie in low-density environments using a nearest-neighbour analysis in 3D. If a galaxy has less than three neighbours in a sphere of $6.3\,h^{-1}$ Mpc, then it is classified as a field galaxy. This threshold is chosen because in this sample it corresponds to local galaxy density $\delta\rho/\rho < -0.6$, which is consistent with voids of density ($\delta\rho/\rho < -0.8$) if void galaxies are clustered with $\xi(r) = 1$ on this scale (i.e. clustering of galaxies raises the density measured around a galaxy above the mean). These field galaxies are temporarily removed from the galaxy sample. The rest of the galaxies are then placed on a grid and void finder searches for empty grid cells. The grid cell size we use is 4.9 h^{-1} in length which guarantees that all spheres larger than 8.5 h^{-1} Mpc in radius are detected by the algorithm. A maximal sphere is grown from each empty cell, but the centre of the maximal sphere is not confined to the initial cell. Eventually, the sphere will be bound by four wall galaxies. There is redundancy in the detection of maximal spheres, but this is useful to define non-spherical voids. The largest empty sphere is the basis of the first void region. If there is an overlap of >10 per cent between an empty sphere and an already defined void then the empty sphere is considered to be a subregion of the void, otherwise the sphere becomes the basis of a new void. There is a cutoff of $10\,h^{-1}$ Mpc for the minimum radius of a void region as we seek to find large-scale structure voids that are dynamically distinct and not small pockets of empty space created by a sparse sample of galaxies. For further details of this implementation of the VOIDFINDER algorithm see Hoyle & Vogeley (2002).

The final steps are to identify the void galaxies and form a luminosity-matched wall galaxy sample. We use the full apparent magnitude limited sample and simply check if the coordinates of every galaxy lie within a void or not. This creates the void sample. A void galaxy does not have to lie in the central maximal sphere; it may lie in one of the outer spheres that make up the total void volume. We find a total of 88 794 void galaxies that lie in void regions with density contrast $\delta\rho/\rho < -0.9$, which yields the largest and most underdense sample of void galaxies to date. The radial and magnitude distributions of the void galaxies are shown in Figs 1 and 2 (black line in both cases). Note that void galaxies are not found at the minimum or maximum distance of the volume limited sample because the void galaxies are required to live within a void and the voids are required to be within the survey; thus, the void galaxies have a flatter radial distribution, $n(r)$, than all galaxies in the magnitude limited sample. Fig. 2 shows the wide range of absolute magnitudes of void galaxies, $-23 < M_r < -12$.

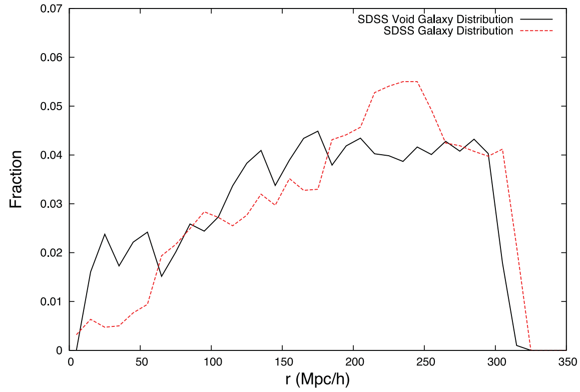

Figure 1. Radial distribution of all SDSS galaxies with $z < 0.107$ (red, dashed line) and void galaxies (black, solid line). The two distributions follow a similar trend but are not exactly the same because voids are constrained to lie completely within the survey boundaries.

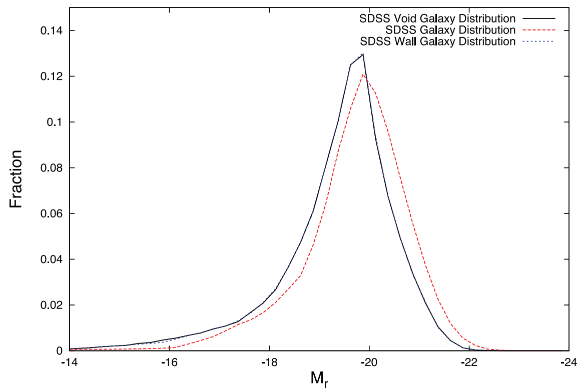

Figure 2. Fraction of galaxies as a function of their r-band absolute magnitude for all galaxies (red, dashed), void galaxies (black, solid) and the sparse-sampled set of wall galaxies (blue, dotted). By construction, this sample of wall galaxies has the same r-band absolute magnitude distribution as the void galaxies.

In our previous analysis (Rojas et al. 2004), the SDSS was incomplete, and there were only ∼200 galaxies in the nearby faint sample (with r-band magnitudes in the range −13.5 to −19.5) and ∼1000 galaxies in the distant sample (r-band magnitudes −17.5 to −21.5). Also, the manner in which galaxies were classified as void galaxies was different. In that earlier study, due to the limited volume of the SDSS at that point, galaxies were classified as void galaxies solely using a nearest neighbour analysis. Now that the SDSS is complete we have 88 794 void galaxies, all of which lie in bona fide voids. The tremendous increase in void galaxy sample size allows us to study the properties of void galaxies with greater precision and/or allows us to carefully define the range of parameters for comparison between void and wall galaxies.

2.3 Construction of the wall galaxy sample

Fig. 2 shows that the distribution of absolute magnitudes presents a clear shift towards fainter magnitudes in voids, consistent with our previous work (Hoyle et al. 2005). In Goldberg et al. (2005) we

Table 1. The name, magnitude range and number of galaxies in each sample.

Name	Magnitude range	N (galaxies)
Void	All	88 794
Void bright	$M_r < -19.9$	29 275
Void medium	$-19.9 < M_r \leq -19.2$	28 743
Void faint	$-19.2 < M_r \leq -17.0$	26 199
Void dwarf	$M_r > -17.0$	4577
Wall	All	88 356
Wall bright	$M_r < -19.9$	29 440
Wall medium	$-19.9 < M_r \leq -19.2$	28 560
Wall faint	$-19.2 < M_r \leq -17.0$	26 005
Wall dwarf	$M_r > -17.0$	4351

showed that the mass function shifts to lower masses in voids. In this paper, we want to compare the properties of void galaxies and wall galaxies with the sample absolute magnitude.

In all comparisons between void and wall galaxies that are presented below, we examine a sample of wall (non-void) galaxies that have been sparse sampled in such a way as to match the absolute magnitude distribution of the void galaxies. The r-band absolute magnitude distribution of the sparse-sampled wall galaxy sample is shown in Fig. 2. It can be seen that the void galaxies (black, solid) and the wall galaxies (blue, dotted) now have the same distributions; thus, comparisons between them will reveal differences that cannot be attributed to differences in luminosity alone.

2.4 Samples

In order to check for dependence on the luminosity of any of the results, we split both the wall galaxies and void galaxies into samples of absolute magnitude. These are defined in Table 1. 'Bright' galaxies have $M_r < -19.9$, the 'Medium' samples have $-19.9 < M_r \leq -19.2$, the 'Faint' samples have $-19.2 < M_r \leq -17.0$ and the 'Dwarf' sample has $M_r > -17.0$. The limits between bright, medium and faint are chosen such that approximately 28 000 galaxies are in each sample. The dwarf sample is defined as galaxies with magnitude less than -17 so that we look at only the faintest galaxies. There are roughly 4500 galaxies in this sample. The exact number of void and wall galaxies in each sample is given in Table 1.

3 PHOTOMETRIC PROPERTIES

It is well known that red galaxies tend to populate regions of higher density, such as clusters, and tend to be elliptical. Blue galaxies tend to be found in lower density environments, tend to be spiral and are also known to be less clustered than red galaxies (Dressler 1980; Postman & Geller 1984; Strateva et al. 2001; Hogg et al. 2002; Blanton et al. 2003; Baldry et al. 2004). This behaviour is shown in the SDSS galaxy photometry by Blanton et al. (2003); see their figs 7 and 8, in which they find that the distribution of $g - r$ colours at redshift $z = 0.1$ is bimodal.

To compare the colours of void and wall galaxies, we consider the $u - r$ colour, which is sensitive to the ultraviolet flux and the 4000 Å break. To compare morphological properties of void and wall galaxies, we examine the distribution of inverse concentration indices measured by the SDSS photometric pipeline (Lupton et al. 2001; Stoughton et al. 2002; Pier et al. 2003). The inverse concentration index (ICI) is defined by the ratio ICI $= r_{50}/r_{90}$, where r_{50} and r_{90} correspond to the radii at which the integrated fluxes are equal to 50 and 90 per cent of the Petrosian flux, respectively. A small value of ICI corresponds to a relatively diffuse galaxy and a large value of ICI to a highly concentrated galaxy. The concentration index (or the ICI) has been shown to correlate well with galaxy type (Shimasaku et al. 2001; Strateva et al. 2001).

3.1 Distance from void centre

An additional parameter we consider is the distance of the void galaxy from the centre of the void. To find the true centres of void regions, we first grid the space into cubes 0.5 h^{-1} Mpc on a side. We identify all cubes whose centres lie within the void region using the set of holes that compose the void region. Each cube is given equal weighting, and the centre of mass of the set of void cubes is found. This centre of mass is used as the centre of the void region rather than the centre of the maximal sphere but these two positions are very close together (Pan in preparation). The distance of each void galaxy from this position is then calculated. We then divide these two distances by the effective radius of the void in which the void galaxy lives.

4 RESULTS

4.1 Colour comparison

In Figs 3 and 4 we show a comparison of the $u - r$ colours of void galaxies (black, solid) and wall galaxies (black, dashed). The plots show the number of galaxies with particular $u - r$ colour divided by the total number of galaxies in the sample. In all cases there is a shift to the left for the void galaxies. This indicates that at all magnitudes, void galaxies are bluer than wall galaxies.

Fig. 3 can be compared to fig. 7, top-left, of Rojas et al. (2004). In both cases the void sample contains more blue galaxies and the wall sample more red galaxies. The differences between the void and wall samples are more significant in this work as both void and wall samples now have the same absolute magnitude distribution and the void sample contains 80 times more galaxies.

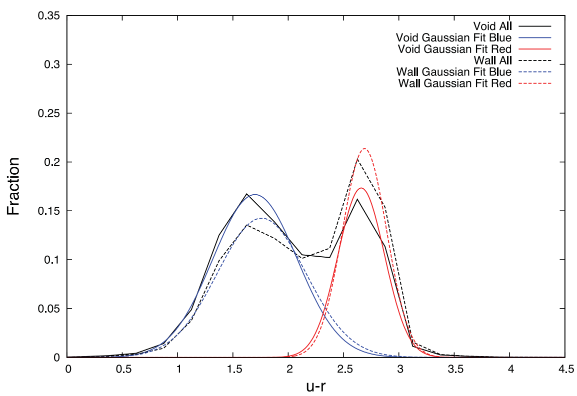

Figure 3. The fraction of galaxies as a function of their $u - r$ colour for void galaxies (black, solid) and wall galaxies (black, dashed). This diagram displays the characteristic split between blue, spiral type galaxies and red, elliptical galaxies. There are more elliptical galaxies in the walls and more spirals in the voids. To demonstrate this more clearly, we show the double-Gaussian fits to the red and blue portions of the $u - r$ distribution. The red dashed line (wall) is higher than the red solid line (void), while the blue solid line (void) is higher than the blue dashed line (wall). A K-S test indicates that it is very unlikely that the two samples are drawn from the same parent population.

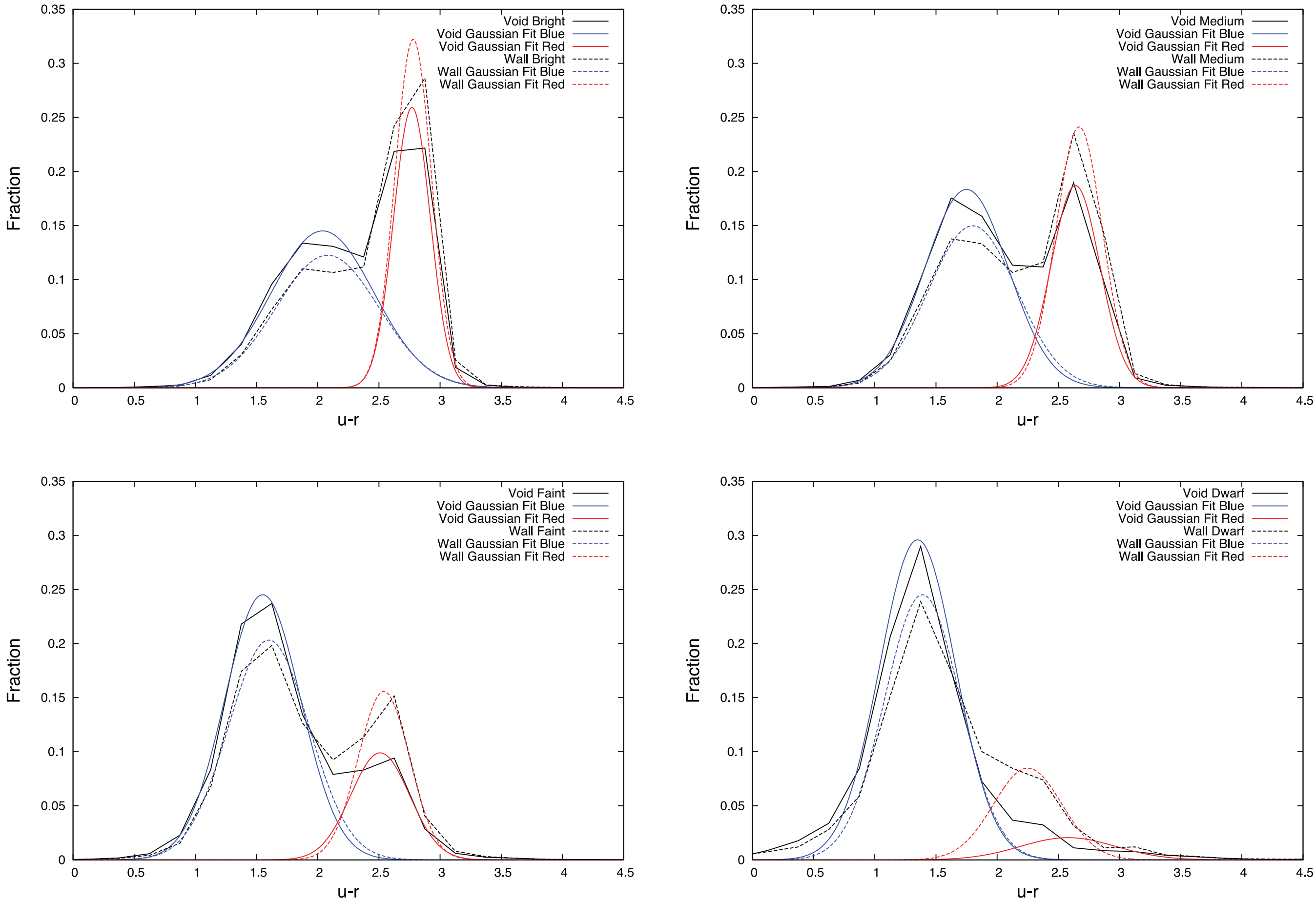

Figure 4. The fraction of galaxies as a function of their $u - r$ colour for void galaxies (black, solid) and wall galaxies (black, dashed) for the bright (top, left), medium (top, right), faint (bottom, left) and dwarf (bottom, right) samples of galaxies. As we move from bright magnitudes to fainter magnitudes the mix of galaxies changes. The proportion of red galaxies in the bright sample is higher than that in the dwarf sample and vice versa for blue galaxies. In all plots, there are more red galaxies in the walls and more blue galaxies in the voids. In all cases, the red dashed line (wall) is higher than the red solid line (void), the blue solid line (void) is higher than the blue dashed line (wall). A K-S test indicates that it is very unlikely that the two samples are drawn from the same parent population.

Table 2. Mean colours and inverse concentration indices of void and wall galaxies. The columns sd represent the sample deviation, which is the standard deviation divided by the square root of the total number of galaxies in the sample. As the galaxy sample is large, these values become small.

Sample	$u - r$ Void	sd Void	$u - r$ Wall	sd Wall	ICI Void	sd Void	ICI Wall	sd Wall
All	2.043	0.002	2.162	0.002	0.4219	0.0002	0.4143	0.0002
Bright	2.324	0.003	2.422	0.003	0.3980	0.0004	0.3889	0.0004
Medium	2.090	0.003	2.203	0.003	0.4223	0.0004	0.4121	0.0004
Faint	1.786	0.003	1.917	0.003	0.4414	0.0004	0.4083	0.0004
Dwarf	1.422	0.008	1.589	0.009	0.464	0.001	0.466	0.001

In Table 2, for each sample we list the mean $u - r$ colour and the sample deviation, which is the standard deviation divided by the square root of the total number of galaxies. The sample deviations are small due to the large number of galaxies that we have available. As can be seen, the mean colour of bright void galaxies is more than 5σ bluer than the brightest wall galaxies. As we move from brighter to fainter galaxies, both the void and wall galaxy samples become bluer. The dwarf void galaxies are also bluer than the dwarf wall galaxies, although due to the smaller sample size the difference is not as significant.

Looking at Fig. 4, it is clear that, in addition to an overall shift in colour between void and wall regions, there is also a change in population from red galaxies to blue galaxies as the magnitude of the sample becomes fainter. In the brightest sample there are more red galaxies than blue in both void and wall samples. As the luminosity decreases, the height of the red peak decreases and the blue peak grows. By the time we reach the dwarf population, there are hardly any red galaxies in the void sample and only a few red galaxies in the wall sample.

In all of the above cases, we apply a Kolmogorov–Smirnov (K-S) test to the void and wall $u - r$ distributions. The results very strongly reject the hypothesis that the two samples are drawn from the same parent population, and the dwarf samples have probabilities of less than 10^{-46} of being drawn from the same parent population. The samples which contain more galaxies have even lower probabilities. These low probabilities cannot be trusted as exact probabilities but such low numbers strongly indicate that the samples are not drawn from the same parent population.

To better understand how the proportion of red and blue galaxies changes from sample to sample, we fit a double Gaussian model to the $u - r$ distribution, as suggested by Baldry et al. (2004). One

Table 3. Gaussian fits to the various samples of void and wall galaxies. As the sample changes from bright to dwarf, the proportion of red galaxies decreases and the proportion of blue galaxies increases. The mean blue and red values of the void galaxies are always bluer than those of the wall galaxies, except for the fit of the red wing of the dwarf galaxies, where there are very few galaxies to confine the fit.

Sample	μ_{blue}	μ_{red}	σ_{blue}	σ_{red}	$norm_{blue}$	$norm_{red}$	Sample	μ_{blue}	μ_{red}	σ_{blue}	σ_{red}	$norm_{blue}$	$norm_{red}$
Void all	1.70	2.66	0.38	0.21	6.30	10.95	Wall all	1.76	2.69	0.40	0.20	7.00	9.33
Void bright	2.04	2.77	0.42	0.15	6.55	10.26	Wall bright	2.08	2.78	0.42	0.15	7.75	8.25
Void medium	1.75	2.64	0.34	0.20	6.40	10.67	Wall medium	1.80	2.67	0.36	0.19	7.40	8.71
Void faint	1.55	2.51	0.31	0.24	5.25	16.80	Wall faint	1.60	2.54	0.33	0.21	5.95	12.21
Void dwarf	1.35	2.57	0.31	0.39	4.35	49.7	Wall dwarf	1.39	2.25	0.31	0.28	5.25	16.80

Table 4. Mean colours of void and wall galaxies classified with ICI > 0.42. The columns sd represent the sample deviation, as described in Table 2.

Sample	N	$u - r$	sd	Galaxy type	N	$u - r$	sd
All late void	46 209	1.770	0.002	All late wall	41 793	1.835	0.002
Bright late void	11 354	1.993	0.004	Bright late wall	9952	2.045	0.004
Medium late void	14 816	1.824	0.003	Medium late wall	13 046	1.880	0.004
Faint late void	16 653	1.641	0.003	Faint late wall	15 523	1.722	0.003
Dwarf late void	3386	1.417	0.008	Dwarf late wall	3272	1.554	0.009

Table 5. Mean colours of void and wall galaxies classified with ICI < 0.42. The columns sd represent the sample deviation, as described in Table 2.

Galaxy type	N	$u - r$	sd	Galaxy type	N	$u - r$	sd
All early void	42 585	2.340	0.002	All early wall	46 563	2.455	0.002
Bright early void	17 921	2.534	0.003	Bright early wall	19 488	2.614	0.003
Medium early void	13 927	2.373	0.004	Medium early wall	15 514	2.475	0.004
Faint early void	9546	2.039	0.006	Faint early wall	10 482	2.207	0.005
Dwarf early void	1191	1.44	0.02	Dwarf early wall	1079	1.70	0.02

of the Gaussians fits the red wing of the colour distribution, and the other the blue wing. There are six parameters in the model, μ_{blue}, μ_{red}, σ_{blue}, σ_{red} and two normalization factors, $norm_{blue}$ and $norm_{red}$:

$$g(x)_{blue} = \frac{1}{\sqrt{2\pi}\sigma_{blue}} e^{\frac{-(x-\mu_{blue})^2}{2\sigma_{blue}^2}} \quad (1)$$

$$g(x)_{red} = \frac{1}{\sqrt{2\pi}\sigma_{red}} e^{\frac{-(x-\mu_{red})^2}{2\sigma_{red}^2}}. \quad (2)$$

Because the sum of the two Gaussian distributions is fixed by the total number of galaxies in each sample, there are only five free parameters. We choose the normalization of the red wing to be the fixed parameter:

$$\Sigma \left(\frac{g(x)_{blue}}{norm_{blue}} + \frac{g(x)_{red}}{norm_{red}} \right) = 1. \quad (3)$$

To find the parameters, we use a coarse grid of the five free parameters to get an estimate of the values. We then refine the search around the best-fitting parameters. The values of μ, σ and the blue normalization are refined to ± 0.01.

We define the best fit as the one with the lowest value of

$$\chi^2 = \Sigma \frac{(N_{data}(i) - (g_{blue}(i) + g_{red}(i)) \times N_{tot})^2}{((g_{blue}(i) + g_{red}(i)) \times N_{tot})}, \quad (4)$$

where N_{tot} is the total number of galaxies in the sample. The bins of $u - r$ are 0.25 in size.

Because bins with very few galaxies can cause the value of χ^2 to be excessively large, we do not include any bin that contains less than 100 galaxies. We do not apply any other smoothing to the distribution of galaxies.

The double Gaussian fits to the $u - r$ distribution are shown in Figs 3 and 4 and the values are listed in Tables 3, 4 and 5. As the galaxies change from bright to dwarf, the fraction of blue galaxies increases in both the wall and void samples. These fits also show that the proportion of blue galaxies is higher in the voids than in the walls in the full sample and in each of the samples split by magnitude (the red dashed line is higher than the red solid line and the blue solid line is higher than the blue dashed line). The void galaxies are still bluer than the wall galaxies as the values of the mean blue and red Gaussians are bluer in the voids than in the walls in each of the Gaussian fits, apart from for the red wing of the dwarf sample, where there are very few galaxies to confine the fit.

4.2 Inverse concentration index comparison

In Fig. 5 we show the normalized histogram of inverse concentration indices for the void galaxies (black, solid) and wall galaxies (blue, dashed) for all the void and wall galaxies. Fig. 6 shows results for the samples as a function of magnitude. It is clear that there is very little difference in the types of galaxies within each magnitude bin; the black solid and blue dashed lines are very similar. What can be seen is that as the magnitude of the galaxies shifts from bright to faint, the mix of galaxies changes. In the bright sample there are more early-type galaxies and in the dwarf samples there are more late-type galaxies. This is reflected in Table 2 as the mean value of the ICI shifts from 0.3980 to 0.464 in the voids and from 0.3889

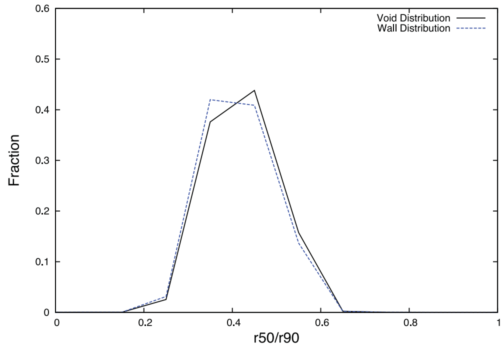

Figure 5. The fraction of galaxies as a function of their ICI. Elliptical galaxies have low values of the ICI, and spiral galaxies have higher values of the ICI. There is little visual difference between the curves for the void (black, solid) and wall (blue, dashed) samples, although the wall galaxies have statistically lower values than the void galaxies, as shown in Table 2.

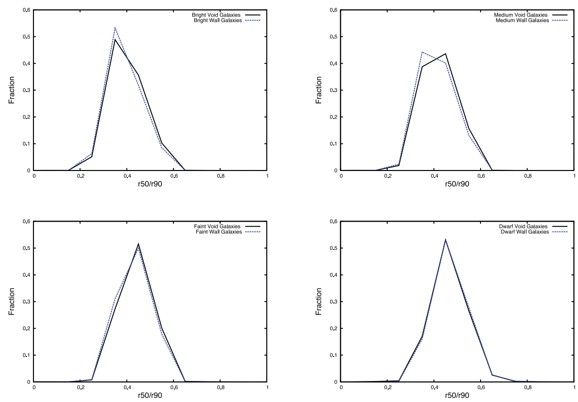

Figure 6. The fraction of galaxies as a function of their ICI for void galaxies (black, solid) and wall galaxies (blue, dashed) for the bright, medium, faint and dwarf samples as indicated in the figure. There is little visual difference between the values for the void and wall samples but the wall galaxies do have lower values of the ICI than the void galaxies as shown in Table 2. As we move to fainter magnitudes, the galaxies have higher inverse concentration indices, representing more late-type galaxies.

to 0.466 in the walls. This means that when we are comparing void and wall galaxies in the bright, medium, faint and dwarf samples, we are comparing galaxies with the *same magnitude and galaxy type.*

4.3 Colour as a function of type

To investigate further the properties of void galaxies, we split each of the samples (bright dwarf) into subsamples of early or late-type galaxies, as measured by their ICI. We split at ICI = 0.42, with galaxies with ICI less than 0.42 considered early type and values greater than 0.42 late type. In Figs 7 and 8 we show the $u - r$ colour distribution for void galaxies (black solid) and wall galaxies (blue, dashed) for galaxies with specific ICI as described in the caption. In all cases, we see that there is a slight shift to the blue for void galaxies as compared to wall galaxies. The differences in colours by galaxy type are visually more striking for the faint galaxies than the bright galaxies, although in the dwarf sample there are fewer galaxies so the differences are less statistically significant.

The late-type galaxies shown in Fig. 7 show a shift towards the blue as the brightness of the sample decreases. This is also true for the early-type galaxies in Fig. 8. It is also interesting that even

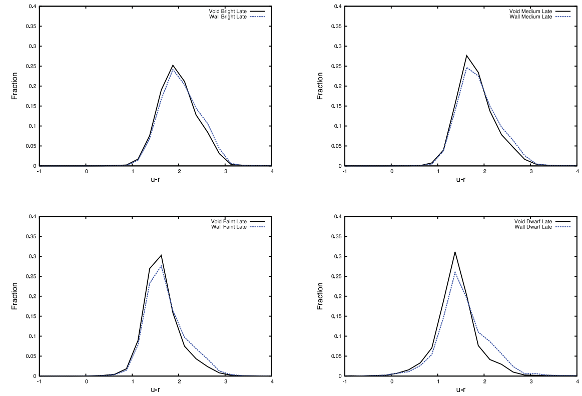

Figure 7. The fraction of galaxies as a function of their $u - r$ colour for late-type (ICI $>$ 0.42) void galaxies (black, solid) and wall galaxies (blue, dashed) as a function of magnitude, as indicated in each figure.

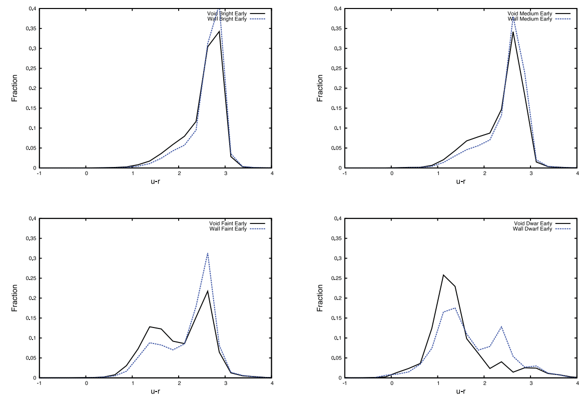

Figure 8. The fraction of galaxies as a function of their $u - r$ colour for early-type (ICI $<$ 0.42) void galaxies (black, solid) and wall galaxies (blue, dashed) as a function of magnitude, as indicated in each figure.

though we cut by ICI, the bimodality of the $u - r$ distribution is apparent again in the last two panels of Fig. 8. It is not the case that all early-type galaxies are red. There exists a population of early-type galaxies, as identified by the ICI, that are faint and blue in colour.

4.4 Void galaxy properties as a function of distance from void centre

One possible factor that could change the photometric properties of the void galaxies is their location in the voids. We found above that void galaxies are bluer than wall galaxies. Continuing this trend, perhaps the voids closest to the centre are bluer than those at the edge? In order to investigate this possibility, we look at the histograms of distance from the void centre as a function of magnitude, colour and type.

In Fig. 9, we show the histograms of the distance from the void centre for void galaxies with different magnitudes. We determine the centre of the void in two ways. In the upper figure we use the centre of the maximal sphere as the centre of the void. In the lower figure we use the centre of mass to define the void centre, as described earlier in Section 3.1.

The peak of the distribution of void galaxy distances from their centre divided by the radius of the void is at 87 per cent. About 20 per cent of void galaxies have normalized distances (void centre/void radius) larger than 1 which might appear to indicate that the galaxies

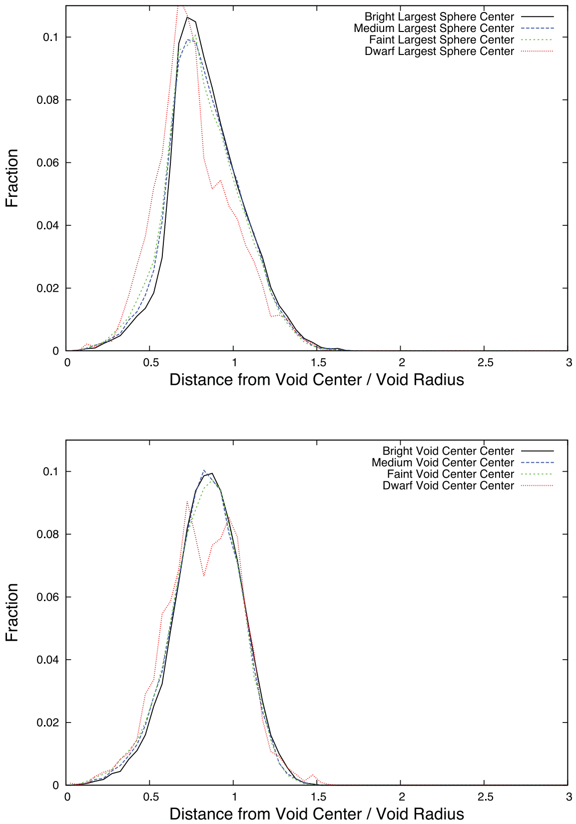

Figure 9. Histogram of the distance of a void galaxy from the centre of its void, divided by the radius of that void. In the upper plot, the centre of the void is defined as the centre of the maximal sphere of the void. In the lower plot, the centre of the sphere is defined as the centre of mass as described in Section 3.1. The different lines show the distribution for the different magnitude samples. There is very little difference between the distributions, except for the dwarf sample.

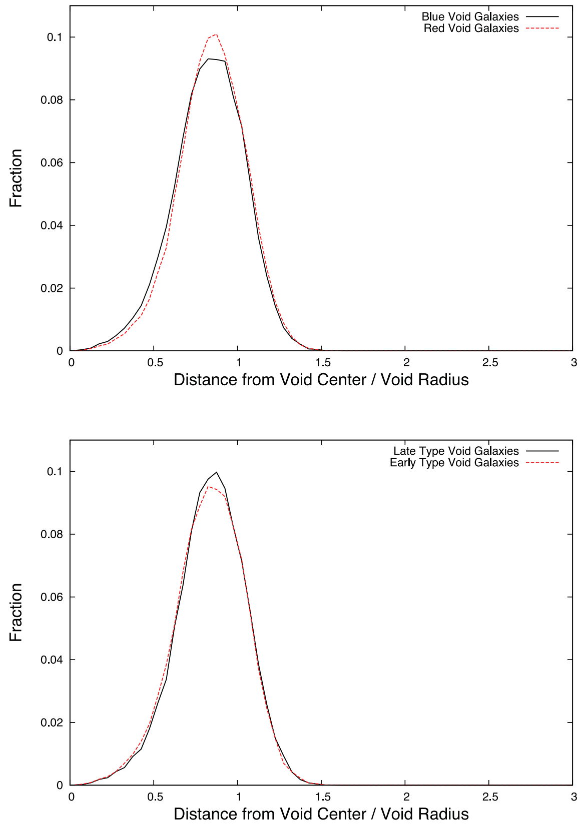

Figure 10. The upper plot shows the histogram of the distance of a void galaxy from the centre of its void, divided by the radius of that void. There is little difference between the distribution of blue ($u - r < 2$) and red ($u - r \geq 2$) void galaxies. The lower plot shows the histogram of the distance of a void galaxy from the centre of its void, divided by the radius of that void. Again there is little difference between the distribution of late (ICI > 0.42) and early (ICI ≤ 0.42) void galaxies.

live outside of the voids. This is not the case, because voids are not constrained to be spherical although the effective radius of the void is calculated assuming that the void is a sphere.

Figs 9 and 10 show that magnitude, colour or type hardly alter the shapes of the histograms. The histograms are very similar for red/blue void galaxies and for late-/early-type void galaxies. The bright, medium and faint samples also have similar distributions.

At first, it may seem surprising that the location of the void galaxy *within* the void does not seem to impact its properties while the properties of void galaxies as a group are different than those at higher density: void galaxies are bluer and of slightly later type. However, as shown by Pan et al. (2012), and repeated in Fig. 11, voids are very empty, $\delta\rho/\rho < -0.9$, and the density profile is essentially flat within the void. This means that *within the void, galaxies reside in very similar density environments.*

The only histogram that does appear to differ is that of the dwarf galaxies. When we calculate the centre of the void using the centre of the maximal sphere, it appears that the dwarf galaxies possibly live closer to the centres of the voids than the brighter galaxies. However, there are fewer galaxies in this sample and when we use the centre of mass as the centre of the void there is little difference between the distributions. This possible finding is, however, in agreement with high-resolution simulations by Kreckle, Joung & Cen (2011b), who find an excess of very faint, $M_r < -14$, galaxies in the centres of voids.

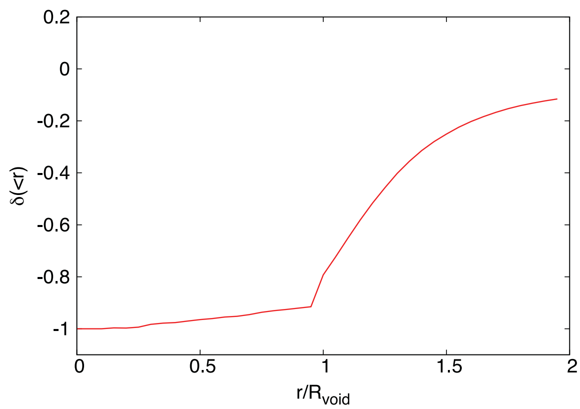

Figure 11. The radial density profile of voids taken from Pan et al. (2012). The centres of voids are very empty, with $\delta\rho/\rho$ close to -1, the lowest possible value, until close to the radius. At the radius, the density of the void rises significantly.

Pan (2011) found that Lyman α (Lyα) systems also prefer to reside at the centre of cosmic voids, although this is disputed by Tejos et al. (2012). Of a sample of 119 absorbers from Danforth & Shull (2008) that overlap with the SDSS main sample, 87 lie in void regions. Most of these absorbers are in close proximity to a nearby void galaxy. Fig. 6.3 of Pan (2011) shows that the absorbers are not randomly distributed in the nearby Universe, but rather they have a preference to reside towards the centres of the most underdense structures in the Universe. The centres of voids are clearly an area that require more investigation.

5 CONCLUSIONS

We examine a sample of 88 794 void galaxies that reside in void environments with density contrast $\delta\rho/\rho < -0.9$. This is the largest sample of void galaxies available at the moment and, with no redshift survey of comparable sampling density in the pipeline, this sample will be the largest for a while. The properties of void galaxies are compared to a sample of galaxies at higher density that have the same magnitude distribution as the void galaxies. This allows us to control for differences due to luminosity alone.

As we found in previous work, but with greater significance here, void galaxies are statistically bluer than galaxies found in higher density environments. This holds true for the whole sample of galaxies as well as for samples of galaxies restricted to a narrower range of magnitude. By fitting a double Gaussian to the $u - r$ distribution of galaxy colours in the voids and walls, we find that there are more blue galaxies in the voids than in the walls in all magnitude bins. As the galaxies decrease in magnitude, the blue population grows in both void and wall environments. A K-S test shows that it is very unlikely that the void and wall galaxies are drawn from the same parent population for all the various samples we show in this work.

Void galaxies are also of slightly later type than wall galaxies, as measured by the ICI. We split the void and wall galaxy samples into late and early subsamples and find that both late- and early-type void galaxies are bluer than the comparison group of late- and early-type wall galaxies. We find that faint, dwarf galaxies, classified as early by the ICI, are blue in colour.

In agreement with this work, Patiri et al. (2006) found that the fraction of blue galaxies in the voids was higher than the fraction of blue galaxies in the wall. However, they also found that the mean values of the colours of the two populations were very similar. Tinker & Conroy (2009) suggest that the properties of a galaxy are determined only by the mass of the halo in which the galaxy resides, independent of large-scale environment, and that the process of galaxy formation removes any dependence on location. Kreckel et al. (2012) also find little difference in the star formation rates, H I mass-to-light ratios and small scales clustering in a sample of 60 void galaxies. With 88 000 void galaxies, we find that there are small but statistically significant differences in the mean colour values of void and wall galaxies; the void galaxies are slightly bluer than the wall galaxies, in agreement with the results of von Benda-Beckman & Müller (2008). One possible explanation for the different colours between the void and wall galaxies is the role of gas. Rojas et al. (2004) suggested the presence of fresh gas to explain the differences between the properties of galaxies in voids and walls. Kreckel et al. (2012) find evidence of ongoing gas accretion on to at least one void galaxy and, as stated by Tinker et al. (2008), it only takes a small amount of star formation to turn a red galaxy blue, so even if just a small percentage of void galaxies have enhanced star formation from ongoing gas accretion, there could be a slight difference in their mean values. Another possibility is the role of active galactic nucleus (AGN) activity in voids. As discussed by Croton & Farrar (2008), AGN quench star formation. They conclude that galaxies living in vastly different large-scale environments should have similar properties. Here, we find that the colours are similar but if the fraction of AGN was slightly different in voids versus wall environments, as found by Constantin Hoyle & Vogeley (2008), small differences in the colours could be detected, consistent with our results.

We have shown that the void environment affects both the colours and types of the galaxies. However, within the void there is little variation in the properties of the galaxies as a function of distance from the centre of the void. Bright, medium and faint galaxies have a very similar distribution of distances from the void centre. Late- and early-type galaxies within the voids have similar distance distributions, as do galaxies splitted by colour. The lack of difference is probably because the density profile of a void is very flat in the centre. Most of the galaxies within the voids live in regions with the same density contrast. The only exception is for the faintest void galaxies, where there is a slight indication that they are found closer to the centres of the voids. This is potentially very interesting as Tinker & Conroy (2009) show that in simulations, the maximum halo mass is strongly dependent on location within the void and in the inner regions ($R < 5\,h^{-1}$ Mpc) there are only haloes with $M_{\rm h} < 10^{10}\,{\rm M}_{\odot}$. Kreckel, Joung & cen (2011) also find an excess of faint galaxies in the centres of voids in simulations and Pan et al. (2012) find an excess of Lyα clouds in the centres of voids.

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