Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. (2012) doi:10.1111/j.1745-3933.2012.01311.x

Low and high surface brightness galaxies at void walls

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Accepted 2012 July 5. Received 2012 June 29; in original form 2012 May 11

ABSTRACT

We study the relative fraction of low and high surface brightness galaxies (LSBGs and HSBGs) at void walls in the Sloan Digital Sky Survey (SDSS) Data Release 7. We focus on galaxies in equal local density environments. We assume that the host dark matter halo mass (for which we use SDSS group masses) is a good indicator of local density. This analysis allows us to examine the behaviour of the abundance of LSBGs and HSBGs at a fixed local density and distinguish the large-scale environment defined by the void geometry. We compare galaxies in the field and in the void walls; the latter are defined as the volume of void shells of radius equal to that of the void. We find a significant decrement, a factor of ∼4, of the relative fraction of blue, active star-forming LSBGs in equal-mass groups at the void walls and the field. This decrement is consistent with an increase of the fraction of blue, active star-forming HSBGs. In contrast, red LSBGs and HSBGs show negligible changes. We argue that these results are consistent with a scenario where LSBGs with blue colours and strong star formation activity at the void walls are fuelled by gas from the expanding void regions. This process could lead to LSBG to HSBG transformations.

Key words: galaxies: statistics – galaxies: groups: general – large-scale structure of Universe.

1 INTRODUCTION

The large-scale environment, and in particular void walls, may have significant effects on the galaxy properties and their evolution. It is well known that galaxy properties, such as morphology, star formation rates and colours, vary strongly with the galaxy density in their local environment (Dressler 1980; Lewis et al. 2002; Kauffmann et al. 2004). These variations are related to significant differences in how the evolution of galaxies varies with the environment, mainly due to interactions, merger histories and assembly bias (e.g. Moore, Lake & Katz 1998; Bell et al. 2006).

It is expected that galaxies in voids have significantly different star formation and chemical enrichment histories in comparison to those of galaxies in denser environments (see e.g. Peebles 2001; Gottlöber et al. 2003; Hoeft et al. 2006; Hahn et al. 2007a,b, and references therein). It is well established that the highest surface brightness galaxies reside in high-density environments. However, the issue of the typical environment of low surface brightness galaxies (LSBGs) is not completely settled albeit some authors suggest LSBGs populate preferentially lower density environments (see e.g. Rosenbaum et al. 2009; Galaz et al. 2011).

LSBGs represent an important population among extragalactic objects. The central surface brightness of the disc in the B band, $\mu_0(B)$, is the photometric parameter typically used to separate the high and the low surface brightness regime of galaxies. The most common threshold values found in the literature are between 22 and 23 mag arcsec^2 (Impey, Burkholder & Sprayberry 2001).

LSBGs are characterized by many interesting observational properties such as a low density of stars, which produce the low surface brightness. They also present extended flat rotation curves (de Blok 2005; Swaters, Sanders & McGaugh 2010) having one of the highest M/L in the Universe (Sprayberry et al. 1995).

The low star formation rate as well as their rather isolated location in the cosmic web (Rosenbaum et al. 2009), as reported by several authors, gives clues for the understanding of their formation and evolution. Several results provide evidence that large-scale underdense regions, like cosmological voids, are characterized by coherent outflows of mass and galaxies moving towards the void edges (Padilla, Ceccarelli & Lambas 2005; Ceccarelli et al. 2006). Consequently, galaxies at void edges or walls have undergone evolutionary and merger histories different from their field counterparts. This could be, for instance, due to the void material accumulating around them or the fact that void galaxies most likely spent their lives inside voids.

Previous results (e.g. Ceccarelli, Padilla & Lambas 2008) have shown that galaxies at void walls present particular properties.

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Several studies have focused on the properties of galaxies in underdense regions. The luminosity function of galaxies in voids has been measured by Hoyle et al. (2005), who also study their photometric properties, finding that the population of galaxies in voids is characterized by a fainter characteristic luminosity although the relative importance of faint galaxies is similar to that found in the field. Spectroscopic properties of void galaxies have also been studied in detail (Rojas et al. 2005); these results indicate that galaxies inside voids have higher star formation rates than galaxies in denser regions and are still forming stars at the same rate as in the past.

Several authors suggest that LSBGs would be more isolated than high surface brightness galaxies (HSBGs) at small scales (less than 2 Mpc; Bothun et al. 1993) and also between 2 and 5 Mpc (Rosenbaum et al. 2009). More recently, Galaz et al. (2011) found a deficit of neighbours for LSBGs at very small scales (less than 1 Mpc). These results motivate the formulation of the following questions: Is the large-scale low-density environment, characteristic of voids, important for the set of LSBG properties? Can we find any signature in LSBGs residing in void walls?

Motivated by these facts, in this Letter we perform a statistical study of galaxies in void wall and in the field in the Sloan Digital Sky Survey (SDSS), ensuring that their local environments traced by the mass of their host groups are the same, and analysing the fraction of blue, star-forming galaxies in equal local environments given the well-known dependence on luminosity/stellar mass and local density (Balogh et al. 2004; Kannappan 2004; Baldry et al. 2006; Dekel & Birnboim 2006; Lagos, Cora & Padilla 2008).

2 DATA SAMPLES

2.1 LSBGs and HSBGs

The galaxies studied in this work were extracted from the main galaxy sample (Strauss et al. 2002) of the SDSS Data Release 7 (DR7). The SDSS is the largest survey carried out so far covering 10^4 deg^2 and containing CCD imaging data in five photometric bands (*ugriz*; Fukugita et al. 1996). The SDSS DR7 spectroscopic catalogue (Abazajian et al. 2009) comprises 929 555 galaxies with a limiting magnitude of $r \leq 17.77$ mag. Within this magnitude limit, Strauss et al. (2002) find that 99 per cent of the galaxies have half-light surface brightness brighter than 23 mag arcsec^{-2} in r and only ∼0.01 per cent of galaxies are fainter than 24.5 mag arcsec^{-2} in r.

For a detailed description of how we select our sample, we refer the reader to Galaz et al. (2011). Essentially, we select late-type (fracDevr ≤ 0.9), nearly face-on ($b/a < 0.4$) galaxies in the redshift range $0.01 \leq z \leq 0.1$ (we choose the lower cut to prevent peculiar velocity problems). For each galaxy, we calculate the surface brightness in the B band using the band conversion from Smith et al. (2002). We correct the surface brightness for cosmological dimming. Finally, we use $\mu_0(B) = 22.5$ mag arcsec^{-2} as the surface brightness cut to distinguish between LSBGs and HSBGs.

Since the SDSS is a magnitude-limited survey, the observed populations of galaxies are not the same at different redshifts. This prevents us to compare in a statistical way properties of nearby galaxies with those situated at further distances. In fact, the faintest galaxies are only registered at small redshifts, while the brightest galaxies cover the whole catalogue. This magnitude-limited selection introduces a luminosity bias which can be removed by constructing a volume-limited catalogue, defining redshift and luminosity ranges where the absolute magnitude distributions are the same for all the galaxy populations. A volume-limited catalogue allows us to compare two populations of LSBGs and HSBGs having the same absolute magnitude range, which for $z \leq 0.1$ is $M_r \geq -19.7$.

2.2 Environmental information from SDSS galaxy group membership

We use the galaxy group catalogue of Zapata et al. (2009) in order to characterize the local environment of the galaxies in our samples. As was shown by González & Padilla (2009), Pasquali et al. (2009) and Padilla, Lambas & González (2010), the mass of the host dark matter halo is one of the best tracers of variation of galaxy properties with the environment. Therefore, we choose this parameter to this end, and use the luminosity of the four brightest members of the host group as a tracer of its mass (see e.g. Eke et al. 2004).

The groups in the Zapata et al. catalogue are identified using a friends-of-friends algorithm with varying projected linking length σ, with $\sigma_0 = 0.239\,h^{-1}$ Mpc, and a fixed radial linking length $\Delta v = 450\,\mathrm{km\,s^{-1}}$, which provide a 95 per cent complete sample with <8 per cent contamination. The minimum number of members per group is 10, with virial masses calculated using the gapper estimator for the virial radius.

The dark matter mass of the host halo of a galaxy is that of a galaxy group that lies within a projected distance of $2\,h^{-1}$ Mpc and a velocity difference of $800\,\mathrm{km\,s^{-1}}$. If no group satisfies this condition, the host halo mass is assumed to fall below the completeness limit of the group catalogue.

2.3 Identification of voids in the galaxy distribution

We define a void as the largest spherical volume within which the density is below a critical value, and we follow the procedure described in Ceccarelli et al. (2006) to identify them in galaxy catalogues. The algorithm used to find voids can be briefly described as follows. First, we set a large number of random positions (for void centre candidates) distributed throughout the catalogue. For each random position, we consider the larger sphere satisfying the condition $\delta_{gx} < \delta_{\max}$, where $\delta_{\max}$ is the maximum density contrast allowed, and all the spheres considered are selected as void candidates. Finally, if there are superimposed void candidates, all of them are removed and the only one considered as a void is the largest underdense sphere, which should contain the others.

We apply the void-finding algorithm to our volume-limited sample of SDSS DR7 galaxies. We set $\delta_{\max} = -0.9$; this value is in agreement with the mean density contrast of voids identified in the literature (Hoyle & Vogeley 2004; Patiri et al. 2006). However, small variations on $\delta_{\max}$ do no affect the void statistics (Padilla et al. 2005). We have adopted $z = 0.10$ as the limiting redshift of our sample. This choice of maximum redshift is a compromise between well-resolved voids which require faint galaxies and a sufficiently large volume in order to have enough void statistics. The adopted absolute magnitude limits imply that the galaxy number density is high enough to lower the effects of shot noise in the identification of small voids. Our resulting sample, containing 184 voids, is restricted to radii within the range 8–20 h^{-1} Mpc, which comprises the best resolved systems suitable for our study. We use the normalized void-centric distance (d/r_{void}) and define the void walls by the range $0.9 < d/r_{\mathrm{void}} < 1.2$.

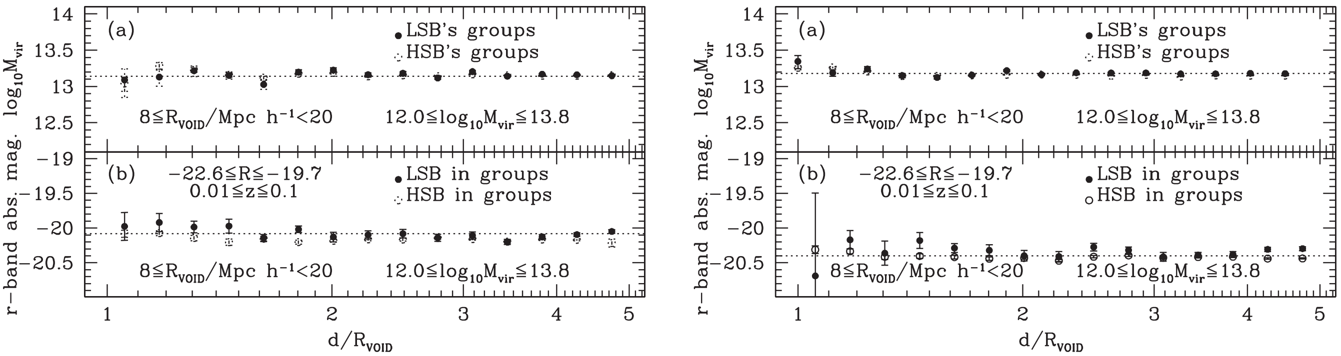

Figure 1. Upper left-hand panel: median virial masses for selected groups hosting at least one blue, $u - r \leq 2.2$, LSBG (filled circles) and HSBG (open circles) as a function of normalized void-centric distance, for void radii in the range $8\,h^{-1} \leq R_{\rm V} < 20\,h^{-1}$ Mpc and group virial masses between $10^{12.0}$ and $10^{13.8}$ $M/{\rm M}_{\odot}$. Lower left-hand panel: median absolute magnitude of blue LSBGs (filled circles) and HSBGs (open circles) in groups as a function of normalized void-centric distance, for void radii and group virial masses in the same ranges. Upper right-hand panel: median virial masses for selected groups hosting at least one star-forming, eclass ≤ -0.1, LSBG (filled circles) and HSBG (open circles) as a function of normalized void-centric distance. Lower right-hand panel: median absolute magnitude of star-forming LSBGs (filled circles) and HSBGs (open circles) in groups as a function of normalized void-centric distance.

3 LSBGS IN GROUPS AT VOID WALLS

3.1 Properties of group LSBGs and HSBGs as a function of void-centric distance

Given the well-documented dependence of galaxy properties on local density, we study galaxies in equal-mass groups, as this ensures an equal local environment (Pasquali et al. 2009; Padilla, Lambas & González 2010). We select group samples with equal distributions of virial masses at different void-centric distances. These samples allow an analysis of the properties of LSBGs in groups at void walls and a proper comparison to LSBGs in similar environments beyond the void walls. This procedure should help us to disentangle the relative weights of large-scale (void walls) and local effects (group) on LSBG properties. We use k-corrected $u - r$ colours (to $z = 0.1$) and the parameter eclass to classify the galaxies. eclass represents the projection of the first three principal components of the galaxy spectrum, and ranges from -0.35 to 0.5 corresponding to the sequence of passive to strongly star-forming galaxies. The top left-hand panel in Fig. 1 shows the mean virial mass of SDSS DR7 selected groups containing at least one blue $(u - r \leq 2.2)$[1] LSBG (HSBG) in filled (open) circles, as a function of normalized distance to the void centre. The mean virial mass of SDSS DR7 selected groups containing at least one star-forming LSBG or HSBG (*eclass* ≤ -0.1) is shown in the top right-hand panel. As can be seen, the mean virial mass of the samples shows similar values over the full range of void-centric distances. This assures that, on average, the local environments of our sample of LSBGs remain similar across the void walls.

Given that the distribution of LSBGs could exhibit a dependence on luminosity and local density, we have explored the mean M_r magnitude of LSBGs for group galaxies in void walls and outside voids separately. The bottom left-hand panel in Fig. 1 shows the mean r-band absolute magnitude for blue $(u - r \leq 2.2)$ LSBG (filled circles) in groups as a function of normalized distance to the void centre; open circles correspond to blue HSBGs in groups. The corresponding mean magnitude for star-forming LSBGs and HBSGs is shown in the bottom right-hand panel. As can be seen, the mean luminosity of group LSBG and HSBG samples is nearly constant for galaxies in the void walls and in the field. Thus, differences in the properties of LSBGs and HSBGs should mainly be related to the astrophysical effects associated with the special star formation history of galaxies which today reside within void walls and the field.

3.2 Relative abundances of galaxies according to colour and spectral type

We analyse the relative fraction of LSBGs and HSBGs in groups at different distances from void centres, taking into account their k-corrected $u - r$ colours (to $z = 0.1$).

The results are shown in Fig. 2, where it can be appreciated that the sample of HSBGs (lower panels) shows the well-documented behaviour that bluer galaxies occupy preferentially the void neighbourhoods.

The left-hand panels in Fig. 2 show the relative fraction of LSBGs (upper panel) and HSBGs (lower panel) in groups, corresponding to blue objects $(u - r < 2.2)$. It can be seen that at the void walls there is a strong systematic drop in LSBG fraction (upper panel), whereas the fraction of HSBGs increases (lower left-hand panel of Fig. 2), at a fixed local density (Ceccarelli et al. 2008; González & Padilla 2009).

The right-hand panels in Fig. 2 show the relative fraction of LSBGs (upper panel) and HSBGs (lower panel) in groups, corresponding to red objects $(u - r > 2.2)$. As can be appreciated, we obtain similar fractions of red LSBGs and HSBGs over the full range of void-centric distances. From a more detailed analysis of the lower right-hand panel of Fig. 2, a slight drop on the faction of red HSBGs in groups at void walls can be noticed. However, in general, the mean fraction of group LSBG and HSBG samples is nearly constant for red galaxies in the void walls and in the field.

We have also examined the star formation activity of these LSBGs at void walls through the eclass parameter. In Fig. 3, we present the relative fraction of LSBGs and HSBGs considering high and low eclass parameter values separately. Again we have considered a division into passive and star-forming galaxies with the eclass threshold $= -0.1$. In the upper left-hand panel of Fig. 3, we show the fraction of star-forming galaxies for LSBGs in groups. As can be seen, we find a decrement in the fraction of star-forming galaxies at walls in comparison to the field. As it is expected, the fraction of star-forming HSBGs increases at the void walls (lower left-hand

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[1] The colour and eclass adopted cuts divide the samples into the red and blue (and active and passive star formation) populations.

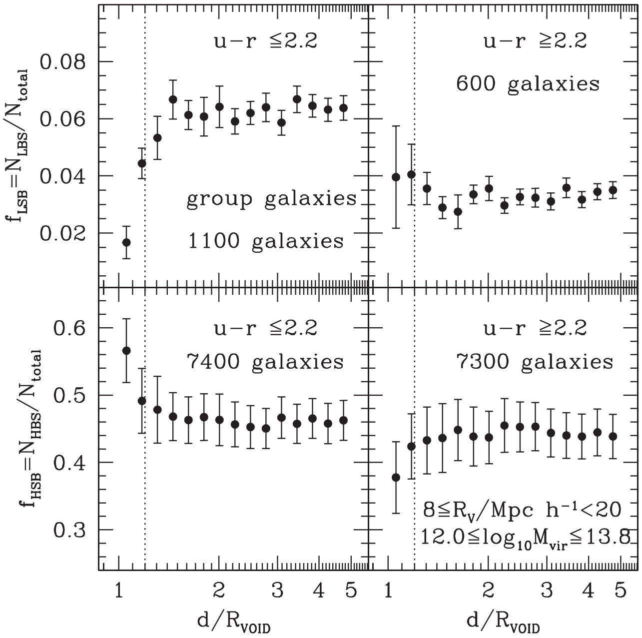

Figure 2. Left: relative fraction of blue, $u-r\leq 2.2$, LSBGs (upper panel) and HSBGs (lower panel) in groups as a function of normalized void-centric distance. Right: relative fraction of red, $u-r\geq 2.2$, LSBGs (upper panel) and HSBGs (lower panel) in groups as a function of normalized void-centric distance. Void radii are in the range $8\,h^{-1}\leq R_{\rm V}<20\,h^{-1}$ Mpc and group virial masses between $10^{12.0}$ and $10^{13.8}\,M/{\rm M}_{\odot}$. The dotted lines indicate the outer boundary of the void wall.

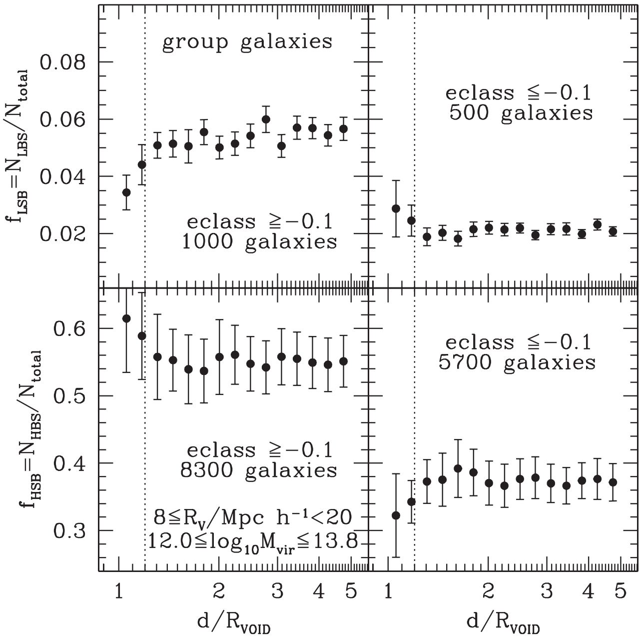

Figure 3. Left: relative fraction of star-forming, eclass ≥ -0.1, LSBGs (upper panel) and HSBGs (lower panel) in groups as a function of normalized void-centric distance. Right: relative fraction of non-star-forming, eclass ≤ -0.1, LSBGs (upper panel) and HSBGs (lower panel) in groups as a function of normalized void-centric distance. Void radii are in the range $8\,h^{-1}\leq R_{\rm V}<20\,h^{-1}$ Mpc and group virial masses between $10^{12.0}$ and $10^{13.8}\,M/{\rm M}_{\odot}$. The dotted lines indicate the outer boundary of the void wall.

panel of Fig. 3), in agreement with the results from Fig. 2. This is consistent with the relative changes in the fractions of blue and red galaxies of Fig. 2.

Given our careful selection procedure and tests of uniformity of the local environment of the galaxies in our samples, we conclude that the behaviour of low fraction of blue, star-forming LSBGs is an intrinsic property of void walls. We argue that this can be associated with the transformation of void-wall LSBGs into star-forming HSBGs, possibly due to the gas arriving from the void interior as a consequence of void expansion [we refer the reader to Padilla et al. (2005) and Ceccarelli et al. (2006) for evidence suggesting that material from voids reaches walls]. We will explore this and others scenarios in numerical simulations in a forthcoming paper.

4 CONCLUSIONS

We have performed a statistical study of the population of galaxies at void walls in comparison to the field. We studied their colours and spectral classes. Since these properties have been shown to depend on environment and galaxy luminosity, we made sure that the immediately local environment of void wall and field galaxies is the same, via a selection of host group masses and luminosities, so that their average values are matched. This selection allowed us to focus only on the effects of the global environment associated with the void walls. Our findings can be summarized as follows: (i) there is a remarkable systematic decrease of blue, active star-forming LSBG fractions in groups at void walls, even when their luminosities and environment are the same; (ii) under the same conditions, we find an increase in the fraction of blue, active star-forming HSBGs at void walls; (iii) there is also a mild decrease of the fraction of red, passive star-forming HSBGs at void walls; (iv) we find no significant trend in the fraction of red, passive star-forming LSBGs at void walls for galaxies with equal environment and luminosity.

ACKNOWLEDGMENTS

This work has been partially supported by the Consejo de Investigaciones Científicas y Técnicas de la República Argentina (CONICET) and the Secretaría de Ciencia y Técnica de la Universidad Nacional de Córdoba (SeCyT). GG is supported by Fondecyt regular 1120195 and NDP by Fondecyt regular 1110328.

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