the Void Galaxy Survey

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Abstract The Void Galaxy Survey (VGS) is a multi-wavelength program to study ∼60 void galaxies. Each has been selected from the deepest interior regions of identified voids in the SDSS redshift survey on the basis of a unique geometric technique, with no a prior selection of intrinsic properties of the void galaxies. The project intends to study in detail the gas content, star formation history and stellar content, as well as kinematics and dynamics of void galaxies and their companions in a broad sample of void environments. It involves the HI imaging of the gas distribution in each of the VGS galaxies. Amongst its most tantalizing findings is the possible evidence for cold gas accretion in some of the most interesting objects, amongst which are a polar ring galaxy and a filamentary configuration of void galaxies. Here we shortly describe the scope of the VGS and the results of the full analysis of the pilot sample of 15 void galaxies.

1 Introduction: Voids and Void Galaxies

Voids have been known as a feature of the Megaparsec universe since the first galaxy redshift surveys were compiled [9, 18, 8]. *Voids* are enormous regions with sizes in the range of $20-50h^{-1}$ Mpc that are practically devoid of any galaxy, usually roundish in shape and occupying the major share of space in the Universe [37]. Forming an essential ingredient of the *Cosmic Web* [4], they are surrounded by elongated filaments, sheetlike walls and dense compact clusters.

A major point of interest is that of the galaxies populating the voids. The pristine environment of voids represents an ideal and pure setting for the study of galaxy formation. Largely unaffected by the complexities and processes modifying galaxies in high-density environments, the isolated void regions must hold important clues to the formation and evolution of galaxies. This makes the relation between *void galaxies* and their surroundings an important aspect of the interest in environmental influences on galaxy formation [33, 13, 16, 24, 26].

Amongst the issues relevant for our understanding of galaxy and structure formation, void galaxies have posed several interesting riddles and questions. Of cosmological importance is the finding from optical and HI surveys that the density of faint galaxies in voids is only $1/100$th that of the mean. As has been strongly

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emphasized by Peebles [25], this dearth of dwarf void galaxies cannot be straightforwardly understood in our standard ΛCDM based view of galaxy formation: voids are expected to be teeming with dwarfs and low surface brightness galaxies. Various astrophysical processes, ranging from gas and radiation feedback processes to environmental properties of dark matter halos, have been suggested [25, 22, 15, 11, 34]. The issue is, however, far from solved and progress will depend largely on new observations that characterize void galaxies and their immediate environment. An additional issue of cosmological interest is whether we can observe the intricate filigree of substructure in voids, expected as the remaining debris of the merging voids and filaments in the hierarchical formation process [7, 35, 12, 31].

Of particular interest in the present context is the manifest environmental influence on the nature of void galaxies. They are found to reside in a more youthful state of star formation. As a population, void galaxies are statistically bluer, have a later morphological type, and have higher specific star formation rates than galaxies in average density environments [13, 29, 24]. Whether void galaxies are intrinsically different or whether their characteristics are simply due to the low mass bias of the galaxy luminosity function in low density regions is still an issue of discussion.

An important aspect towards understanding the nature of void galaxies is that of their gas content, about which far less is known than their stellar content. The early survey of 24 IRAS selected IRAS galaxies within the Boötes void by [33] revealed that most of them were gas rich and disk-like, with many gas rich companions. Fresh gas accretion is necessary for galaxies to maintain star formation rates seen today without depleting their observed gas mass in less than a Hubble time [20]. Histori-

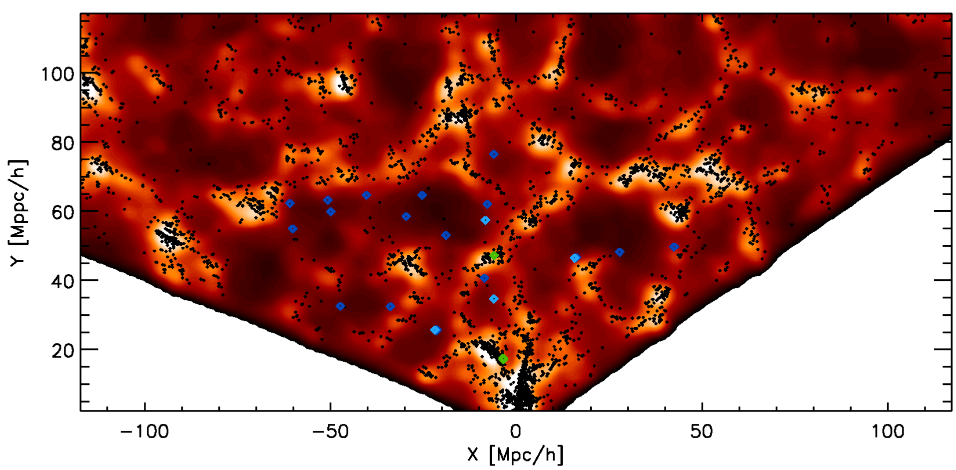

Fig. 1 SDSS density map and identification of voids in the SDSS galaxy redshift survey region from which we selected the galaxies in the Void Galaxy Survey, in a slice of thickness $4h^{-1}$Mpc. The DTFE computed galaxy density map, Gaussian smoothed on a scale of $R_f = 1h^{-1}$Mpc, is represented by the colorscale map. The SDSS galaxies are superimposed as dark dots. Blue diamonds: VGS pilot sample galaxies. Dark blue diamonds: VGS void galaxies from the full sample. Green diamonds: control sample galaxies. From Kreckel et al. 2011.

cally, this gas was assumed to condense out of reservoirs of hot gas existing in halos around galaxies [28, 38], with some amount of gas recycling via galactic fountains [10]. However, recent simulations have renewed interest in the slow accretion of cold gas along filaments [3, 17, 6].

The unique nature of void galaxies provides an ideal chance to distinguish the role of environment in gas accretion and galaxy evolution on an individual basis. Amongst others, their inherent isolation may allow us to distinguish the effects of close encounters and galaxy mergers from other mechanisms of gas accretion.

2 the Void Galaxy Survey

The Void Galaxy Survey (VGS) is a multi-wavelength study of ∼60 void galaxies, geometrically selected from the SDSS galaxy redshift DR7 survey database. The project has the intention to study in detail the gas content, star formation history and stellar content, as well as kinematics and dynamics of void galaxies and their companions in a broad sample of void environments. Each of the 60 galaxies has obtained a VGS number, VGS1 until VGS60. Ultimately, we aim to compile a sample of 50-100 void galaxies.

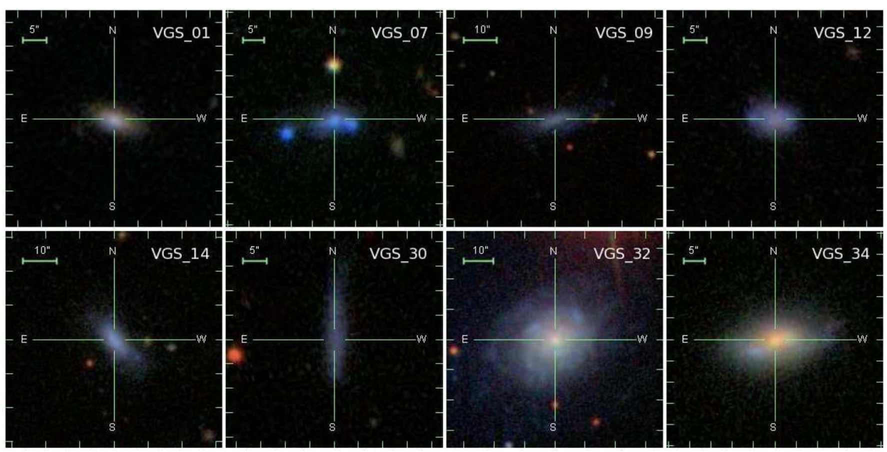

Fig. 2 A selection of 8 VGS void galaxies from the SDSS DR7 galaxy redshift survey. These galaxies are part of the VGS pilot survey. The images, composite color images from the SDSS Finding Chart tool, are scaled to the same scale. From Kreckel et al. 2011.

All galaxies have been selected from the deepest interior regions of identified voids in the SDSS redshift survey on the basis of a unique geometric technique, with no a priori selection on intrinsic magnitude, color or morphology of the void galaxies. The most isolated and emptiest regions in the Local Universe are obtained from the galaxy density and structure maps produced by the DTFE/spine reconstruction technique [30, 36, 27, 1]. From the spatial distribution of the SDSS galaxies, in a volume from $z = 0.003$ to $z = 0.03$, we reconstruct a density field by means of the DTFE procedure, the Delaunay Tessellation Field Estimator . In addition to the computational efficiency of the procedure, the density maps produced by DTFE have the virtue of retaining the anisotropic and hierarchical structures which are so characteristic of the Cosmic Web. The Watershed Void Finder is applied to the DTFE density field for identifying its underdense void basins.

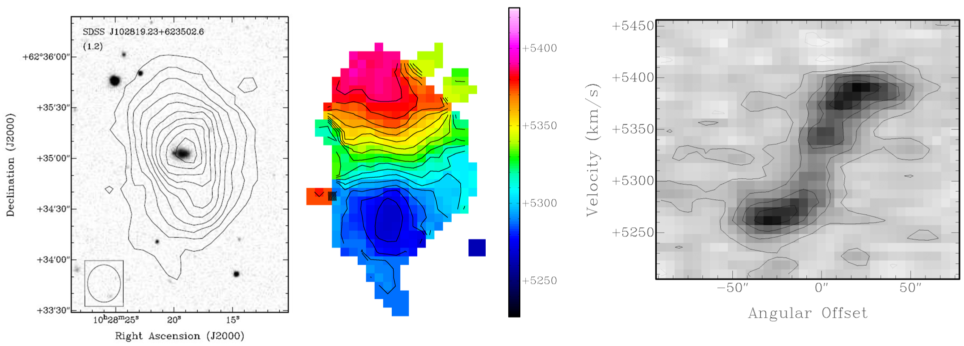

Fig. 3 Targeted void galaxy VGS12, the polar ring void galaxy. Left: HI intensity map, superimposed on optical image. Contours are at $5 \times 10^{19} cm^{-2}$, plus increments of $10^{20} cm^{-2}$. Centre: velocity field. Lines indicate increments of 8 km s^{-1}. Right: position-velocity diagram along the kinematic major axis. From Kreckel et al. 2011.

Using the WSRT we have thus far mapped the HI structure of 55 of the 60 galaxies. Of the total VGS sample of 60 void galaxies, the pilot subsample of 15 galaxies has been fully analyzed [32, 19]. A necessary sample of comparison galaxies is obtained through simultaneous coverage of regions in front and behind the targeted void galaxies, probing the higher density regions surrounding the targeted void. Note that existing blind HI surveys (alfalfa, HIPASS) are limited in not resolving the tell-tale HI structures found in the VGS.

In addition to the 5-band photometry and spectroscopy from the SDSS, we obtain deep B- and R-band imaging of all sample galaxies with the La Palma INT telescope and high resolution slit spectroscopy of a subsample of our VGS galaxies. The deep imaging allows us to detect low surface brightness features such as extended, unevolved, stellar disks, tidal streams, the stellar counterparts of several detected HI features (polar rings, tails, etc.) and of the faint HI dwarf companions. Such information is crucial for distinguishing intrinsic formation and evolution scenarios from external processes such as merging and tidal interactions. To probe the old stellar population of the VGS void galaxies, for 10 galaxies we have obtained near-IR JHK WIRC imaging at the 5-meter Palomar Hale telescope. In order to assess the distribution of star formation and associated star formation rates, we are obtaining GALEX UV data of 45 galaxies, and have obtained Hα imaging of the complete sample at the MDM telescope.

3 Results of the VGS survey: current state of affairs

The first results of the Void Galaxy Survey are tantalizing and has revealed a few surprising gas configurations. With a HI mass limit of $\sim 2 \times 10^7$ $M_\odot$ and column density limit of $\sim 10^{19}\mathrm{cm}^{-2}$, our HI survey provides a significantly improved view of HI in void galaxies compared to past studies [33]. Figure 3 shows one of the most surprising specimen in our survey, the polar ring void galaxy VGS12 (see sect. 3.3). It is one of the relatively large number of void galaxies, possibly together with e.g. KK246 and VGS31, that show evidence for cold mode accretion.

The first fully analyzed sample of 15 void galaxies demonstrated the success of our strategy [19]. With 14 detections out of 15, the HI detection rate is very high. We discovered one previously known and five previously unknown companions, while two appear to be interacting. Of these five befriended void galaxies, two are interacting in HI. All HI-detected companions have optical counterparts within the SDSS. Of the nine isolated void galaxies, many exhibit irregularities in the kinematics of their gas disks. Based on their 150 km s^{-1} velocity width, the detected target galaxies have a range of HI masses from $0.35 - 3.8 \times 10^9$ $M_\odot$, Companion galaxies have masses ranging from $0.5 - 4.5 \times 10^8$ $M_\odot$.

While our targeted void galaxies are small, they would not be classified as dwarf galaxies [14]. All have $M_r <$ -16 and exhibit small circular velocities of 50-100 km/s. All exhibit signs of rotation, though limiting resolution and lower sensitivity at the disk outskirts means we do not always see a flattening of the rotation curve. M_{dyn} is typically 10^9-$10^{10} M_\odot$. The detected companions are more dwarfish.

The void galaxy population appears to represent the extreme blue and faint tail of an otherwise normal galaxy population. There are a few characteristics which seem to set them apart, mainly concerning their HI gas content and star formation activity.

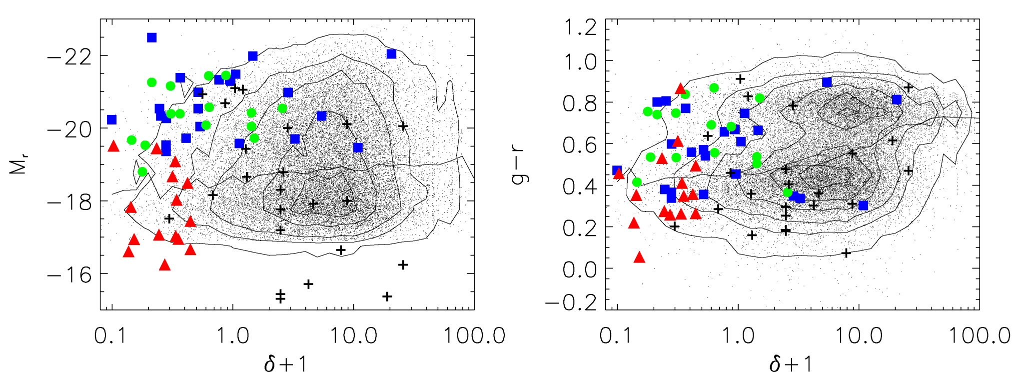

Fig. 4 Magnitudes and colour of void galaxies as a function of density excess/deficit δ. Left: distribution of r-b absolute magnitudes for our void galaxy sample (triangles), the Boötes void galaxy sample of Szomoru et al. (1996) (blue squares) and the CfA void galaxy sample of Grogin & Geller (1999) (crosses). These are compared to the general colour-magnitude diagram of a volume-limited sample of SDSS galaxies, with $z < 0.02$ and $M_r < -16.9$ (dots). From Kreckel et al. 2011.

3.1 Magnitudes and Colors

Despite their affected outer regions, our study finds that in the colour-magnitude diagram the target void galaxies nicely reside at the faint end of the blue cloud of galaxies. This can be immediately appreciated from the diagrams in figure 4, showing the magnitude and color distribution of our galaxies as a function of density excess/deficit δ. Most of our galaxies find themselves on the blue sequence of SDSS galaxies, towards the bluest edge of these galaxies. We find that our pilot sample galaxies are at the faint end of the galaxy luminosity function (see e.g. also [29]) ! Because our geometric selection procedure manages to probe the extremely underdense and desolate void interiors, our void galaxy sample is able to probe specifically those low luminosity galaxies which make up the bulk of the void galaxy population and were previously inaccessible (fig 4, left). Also apparent is the dominance of blue galaxies at the deepest underdensities (fig. 4, right).

3.2 Star Formation and Gas Content

A key aspect of the HI observations is that even in these rather desolate and underdense void regions it revealed several cases of very irregular HI morphologies, marked by *features* such as disturbed HI disks, tails, warps, and cold gas filaments. This suggests that void galaxies are activily building up. A related second key aspect is the high abundance of faint *companions*, non-interacting as well as merging.

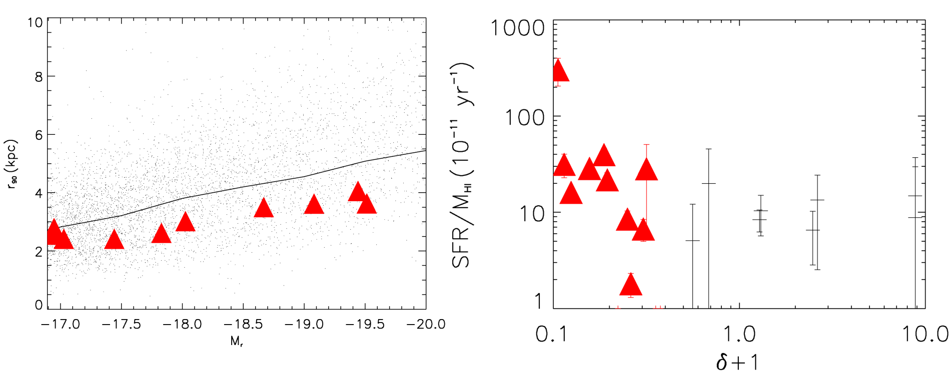

Fig. 5 Two deviant characteristics of VGS void galaxies. Left: The *r*-band r_{90} radii of the stellar disk. Our late-type void galaxies (triangles) fall systematically below the median (line) of a volume limited SDSS sample of late-type galaxies (dots). Right: star formation rate per hydrogen mass, SFR/M_{HI}, as a function of density of our void galaxies (triangles) and our control sample (crosses). The void galaxies have a higher star formation rate per hydrogen mass. From Kreckel et al. 2011.

One particular aspect in which we find a systematic deviation of our void galaxies, with respect to the norm for similar galaxies, is their size. They have stellar disks that are smaller than average, with the *r*-band r_{90} radius of our late type void galaxies systematically lower than the median for late type galaxies (fig. 5, left). However, the result is tentative and might be beset by a hidden selection effect.

Perhaps the most outstanding characteristic of void galaxies is that of their star formation properties. In general, the stellar and star formation properties of our VGS pilot sample are in agreement with the values found in other samples of void galaxies [29]. In this respect, it is relevant that the HI mass of the VGS galaxies appears to be typical in following the global trend of an increasing hydrogen mass M_{HI} as their optical (r-band) luminosity decreases: the smallest galaxies have been less efficient at turning gas into stars. However, when assessing possible trends with density, we find that the specific star formation rate (SFR per stellar mass) of the galaxies displays a suggestive systematic trend. There is a distinct trend for an increase of the star formation rate per HI mass for galaxies in lower density areas (fig. 5, right).

In all, we find that the outer regions and immediate environment of void galaxies testifies of strong recent interactions and star formation activity. This, by itself, is a surprising finding for galaxies populating the most desolate areas of our Universe.

3.3 Exuberance in the Desert

An outstanding specimen of our sample is the polar disk galaxy VGS12 [32]. Amongst the most lonely galaxies in the universe, it has a massive, star-poor HI disk that is perpendicular to the disk of the central void galaxy. No optical counterpart to the HI disk has yet been found, even though the inner optical galaxy is actively forming stars. The galaxy is located within a tenuous wall in between two large roundish voids. The undisrupted appearance of the original stellar disk renders a merger origin unlikely. It suggests slow accretion of cold gas [3, 17, 6], at the crossing point of the outflow from the two voids. Cold accretion as a formation mechanism for polar ring galaxies has been seen to occur in simulations [21, 5].

Another fascinating object is VGS31. It defines a system of three galaxies, stretching out over 57 kpc and possibly connected by a HI bridge. The easternmost object is a Markarian galaxy, marked by prominent stellar streams wrapping around the central galaxy and a separate tidal tail or stream (see fig. 6). These might be the remnants of the recent infall of one or two satellite galaxies [2]. The westernmost object is considerably fainter than the other two galaxies. The tails and streams are also visible in the recent deep INT B imaging as well as on the NIR J and K maps, possibly with a slight and unique misalignment. The fact that the gas and all objects involved appear to be stretched along a preferred direction may be suggestive of a system situated within a tenuous filament within the large encompassing void.

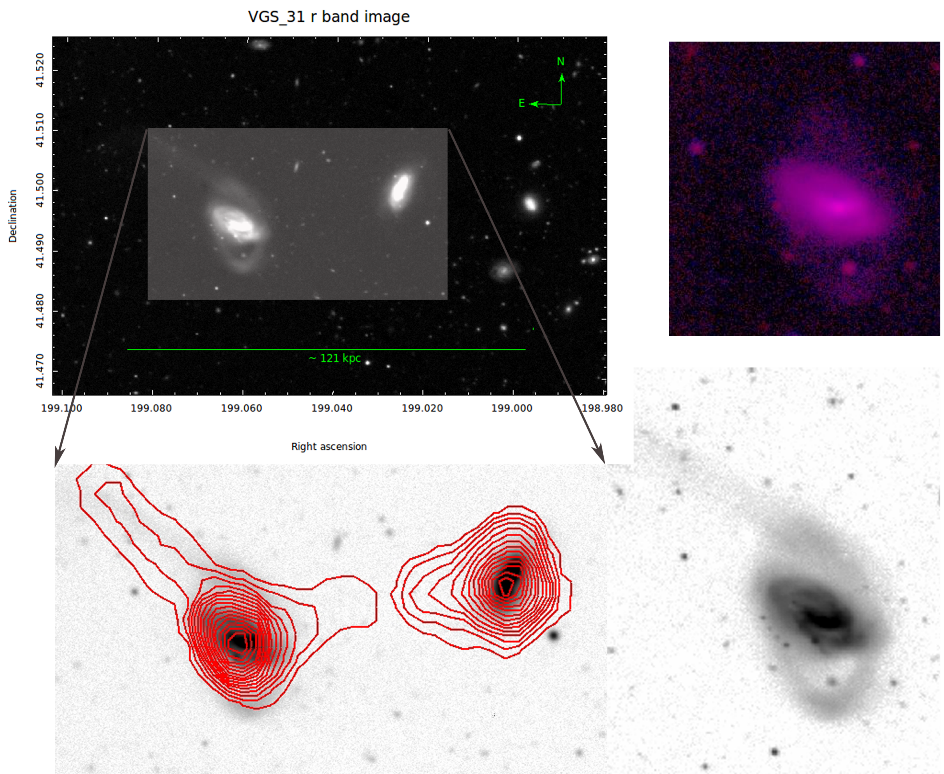

Fig. 6 The elongated void galaxy complex VGS31. Top left: INT r-band image of the complex. It consists of Markarian galaxy VGS31b (left), the VGS target galaxy VGS31a (centre) and the faint galaxy VGS31c (right). Zooming in on the central region with VGS31a and VGS31b, the bottom panel displays the HI intensity contour map superimposed on the r-band image. The intricate tails and/or streams around VGS31a, as well as the rather distorted interior of VGS31b are clearly visible in the r-band image zoom-in (lower rigthand corner). The old stellar population surfaces in th J+K image in the top righthand panel. From Beygu et al. 2011.

4 Conclusions

With the analysis of the first 15 galaxies completed, and the analysis of 45 additional ones in progress, we find that the VGS void galaxies have small optical stellar disks and typical HI masses for their luminosity. Consistent with previous surveys, they are bluer and have increased rates of star formation, with the suggestion of a trend towards increased star formation at lowest density. While this pilot sample is too small for any statistical findings, we did discover many of our targets to be individually interesting dynamically and kinematically in their HI properties. In particular, a few show direct evidence of ongoing cold mode accretion. Ultimately, we aim to compile a sample of 50-100 void galaxies.

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