AN INTERACTING GALAXY SYSTEM ALONG A FILAMENT IN A VOID

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ABSTRACT

Cosmological voids provide a unique environment for the study of galaxy formation and evolution. The galaxy population in their interiors has properties significantly different from those of average field galaxies. As part of our Void Galaxy Survey (VGS), we have found a system of three interacting galaxies (VGS_31) located in a large void. VGS_31 is a small, elongated group whose members are embedded in a common $\mathrm{H\,I}$ envelope. The $\mathrm{H\,I}$ picture suggests a filamentary structure with accretion of intergalactic cold gas from the filament onto the galaxies. We present deep optical and narrowband $\mathrm{H\alpha}$ data, optical spectroscopy, near-UV, and far-UV $\mathrm{Galaxy\ Evolution\ Explorer}$ and CO(1–0) data. We find that one of the galaxies, a Markarian object, has a ring-like structure and a tail evident both in optical and $\mathrm{H\,I}$. While all three galaxies form stars in their central parts, the tail and the ring of the Markarian object are devoid of star formation. We discuss these findings in terms of gravitational interaction and ongoing growth of galaxies out of a filament. VGS_31 is one of the first observed examples of a filamentary structure in a void. It is an important prototype for understanding the formation of substructure in a void. This system also shows that the galaxy evolution in voids can be as dynamic as in high-density environments.

Key words: galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: kinematics and dynamics – large-scale structure of universe – radio lines: galaxies

1. INTRODUCTION

Voids are vast regions occupying most of the volume in the universe with sizes in the range of 20–50 $h^{-1}$ Mpc, usually roundish in shape, and largely devoid of galaxies (see van de Weygaert & Platen 2011 for a recent review). In the large-scale structure of the universe we observe today, the most striking features along with the voids are clusters and filaments. In this picture, galaxies are distributed in a filament-dominated web-like structure. Filaments connect clusters to each other and, while tenuous, act like bridges (Zel’dovich 1970; Shandarin & Zeldovich 1989; Bond et al. 1996; Colberg et al. 2005a; Aragón-Calvo et al. 2010b). From recent redshift surveys such as the second Center for Astrophysics Redshift Survey (Davis et al. 1983), the 2dF Galaxy Redshift Survey (Colless et al. 2003), the Sloan Digital Sky Survey (SDSS; York et al. 2000), and 2MASS redshift survey (Huchra et al. 2012), we see how filaments, bridges, and sheet-like structures form substructures and surround the underdense regions.

Notwithstanding the very low density of the void regions, we do find a dilute population of galaxies in their interior. These void galaxies appear to have significantly different properties than average field galaxies. Previous studies based on redshift surveys have shown that the void galaxies are in general small, star-forming blue galaxies. They have a later morphological type and have higher specific star formation rates (SFRs) than the galaxies in average-density environments. Largely unaffected by the complexities and processes modifying galaxies in high-density environments, the galaxies living in the isolated void regions are expected to have retained vital clues to their formation and evolution. It has made the study of the relation between void galaxies and their surroundings an important aspect of the recent interest in environmental influences on galaxy formation (Szomoru et al. 1996; Kuhn et al. 1997; Popescu et al. 1997; Karachentseva et al. 1999; Grogin & Geller 1999, 2000; Peebles 2004; 2005; Tikhonov & Karachentsev 2006; Patiri et al. 2006a, 2006b; Ceccarelli et al. 2006; Wegner & Grogin 2008; Stanonik et al. 2009; Kreckel et al. 2011, 2012).

Void galaxies may be the rare probes of the faint and tenuous substructure that hierarchical structure formation theories predict to exist in voids (Dubinski et al. 1993; van de Weygaert & van Kampen 1993; Sahni et al. 1994; Sheth & van de Weygaert 2004; Furlanetto & Piran 2006; Einasto et al. 2011; Aragón-Calvo & Szalay 2013). Cosmological simulations show how voids are filled by low-density dark matter filaments, creating a network of tenuous substructures within their interior (van de Weygaert & van Kampen 1993; Gottlőber et al. 2003; Colberg et al. 2005b; Springel et al. 2006). This may indicate that the galaxies residing in voids are formed along these dark matter filaments, given that the simulations reveal that dark matter halos are forming along them. In fact, some earlier observational studies have found indications for such filamentary substructure in voids (Szomoru et al. 1996; Zitrin & Brosch 2008). For example, the latter argue that the dwarf galaxies in their local galaxy sample are located on a dark matter filament that itself is located in a low-density galaxy region and are accreting intergalactic cold gas onto the filament.

In this study, we present the most outstanding example of such a filamentary void galaxy configuration, VGS_31, which was found within the context of the Void Galaxy Survey (Kreckel et al. 2011, 2012).

We are conducting a multiwavelength survey of 60 void galaxies, called “the Void Galaxy Survey” (VGS; Kreckel et al. 2011). Galaxies in VGS have been selected from the Sloan Digital Sky Survey Data Release 7 (SDSS DR7) using purely geometric and topological techniques. The sample was selected on the basis of galaxy density maps produced by the Delaunay Tessellation Field Estimator (DTFE; Schaap & van de Weygaert 2000; van de Weygaert & Schaap 2009) and the subsequent application of the Watershed Void Finder (WVF; Platen et al. 2007); for a more general application of the watershed transform
to the structural analysis of the cosmic web, see Aragón-Calvo et al. (2010a). The combination of DTFE maps with WVF-detected voids allows us to identify the void galaxies from the deepest interior regions of identified voids in the SDSS redshift survey. The goal of this survey is to study the galaxy properties in the most underdense and most pristine environments in the universe where the evolution of galaxies is expected to progress more slowly and relatively undisturbed.

Our geometrically selected sample consists of small galaxies, with stellar mass less than $3 \times 10^{10} M_\odot$. Most of these are small, blue star-forming disk galaxies and many of them have companions and extended H\textsc{i} disks, which are often morphologically and kinematically disturbed (Kreckel et al. 2011, 2012).

We have found a system of three linearly aligned galaxies, VGS\textsubscript{31}, in a void as part of VGS (Figures 1 and 2). A remarkable feature of VGS\textsubscript{31} is that the whole system is embedded in a common H\textsc{i} envelope (Figure 3) and the three galaxies are at almost the same velocity (Figure 4). The fact that there is a small velocity gradient throughout the whole H\textsc{i} envelope, from the far east of VGS\textsubscript{31b} to far west to VGS\textsubscript{31c}, suggests that this is a filament in which the three galaxies are embedded.

The system exhibits strong signs of interactions (Figure 1) and star-forming activity with signs of starbursts (Figures 5 and 6). VGS\textsubscript{31} consists of a central galaxy VGS\textsubscript{31a} and two companions: VGS\textsubscript{31b} and VGS\textsubscript{31c}. VGS\textsubscript{31a} is optically slightly disturbed. It has a bar-like structure and all the star formation activity is concentrated there. VGS\textsubscript{31b} is a Markarian galaxy (Mrk 1477). Markarian galaxies are known to have UV continuum excess in their spectra. They are relatively high SFRs and many of them contain active galactic nuclei and starburst nuclei. They span a wide luminosity range between $-23$ and $-13$ mag and have a broad range of morphologies. One interesting statistic is that an unusual number of Markarian galaxies occur in tight pairs or interacting systems. In this context, VGS\textsubscript{31b} is a typical example of Markarian galaxy. VGS\textsubscript{31b} is a starburst galaxy and has enhanced star formation at center of the disk mostly concentrated in the bar. It has a tail, visible both in optical and in H\textsc{i}, and a ring-like structure around the disk. There is no sign for ongoing star formation activity either in the tail or in the ring (Figure 5). VGS\textsubscript{31c} is significantly smaller than the other two galaxies and forms stars in its central part as well.

At first glance VGS\textsubscript{31} looks like a normal interacting system. However, the observed properties described above indicate a more complex picture as we may be witnessing the growth of structure along a filament within a large cosmological void. In fact, in an accompanying paper by Rieder et al. (2013) we have explored the dynamical evolution of the growth of systems resembling VGS\textsubscript{31} in voids, within the context of the ΛCDM cosmology. In this study we analyzed the high-resolution ΛCDM simulation Cosmo-Grid (Portegies Zwart et al. 2010) to see how dark matter halo systems similar in mass, size, and environment to VGS\textsubscript{31} came to be. We found eight systems as suitable candidates for harboring a VGS\textsubscript{31}-like system and then investigated their merger histories. We found that while VGS\textsubscript{31}like systems have a large variation in formation time, the environment in which they are embedded evolved very similarly. It seems to suggest that we may be witnessing the assembly of a filament in a void by bringing together several smaller filamentary structures, each populated by individual halos. It conjures up the interesting question whether the galaxies in the VGS\textsubscript{31} configuration were formed at the same location or whether they each originate from a different location.

In order to study the current properties and assembly history of the VGS\textsubscript{31} system in detail, we have obtained a multi-wavelength data set. To investigate the low surface brightness features, we performed deep B- and R-band imaging, and to

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**Figure 1.** R-band negative image of VGS\textsubscript{31}. From left to right: VGS\textsubscript{31b}—the most remarkable member of the system, a Markarian galaxy, has a tail and a ring. Close-up images show the inner structures such as the bar. VGS\textsubscript{31a}—a disk galaxy with a bar structure. VGS\textsubscript{31c}—smallest member of the system is optically undisturbed. The black bar on the top right corner represents 10 kpc ($\sim 23\arcsec$).
derive star formation properties and star formation history we have used deep Hα and UV imaging. Gas morphology, kinematics, and molecular hydrogen content have been investigated using 21 cm H I and CO observations.

This paper is organized as follows. Section 2 describes the observations, data analysis, and the derivation of star formation properties for VGS_31. Section 3 gives the main observational results such as SFR properties, gas content, and the morphology. In Section 4, we discuss the results. Finally, in Section 5 we speculate on the nature and the importance of VGS_31.

2. OBSERVATIONS AND DATA REDUCTION

VGS_31 has been observed in several wavelengths with various telescopes between 2009 and 2012. B- and R-band imaging has been gathered with the Isaac Newton Telescope (INT) at La Palma using the Wide Field Camera (WFC). Long-slit spectra were obtained at the William Herschel Telescope (WHT) using the Intermediate dispersion Spectrograph and Imaging System (ISIS). Narrowband Hα imaging has been done using the Hiltner Telescope at the Michigan–Dartmouth–MIT Observatory (MDM). Near-UV (NUV) and far-UV (FUV) images have been taken from the Nearby Galaxy Atlas (NGA) of Galaxy Evolution Explorer (GALEX). Radio observations in the 21 cm H I line were performed with the Westerbork Synthesis Radio Telescope (WSRT) and CO(1–0) emission spectra have been obtained with IRAM. A summary of the observational studies is given in Table 1. Parameters, quantitative results such as SFRs, H I, and molecular hydrogen, and stellar masses are presented in Table 2, Table 3, Table 4, and Table 5, respectively.
Figure 3. H\textsubscript{i} intensity map of VGS_31. H\textsubscript{i} column density intensity contours start at $1.6 \times 10^{19}$ cm$^{-2}$ and increase with $4 \times 10^{19}$ cm$^{-2}$ increments. Note that members of VGS_31 are aligned along an H\textsubscript{i} filament and appear to be embedded in a common H\textsubscript{i} envelope.

Figure 4. Position–velocity (PV) diagram of VGS_31. Left: slice position. The black line on the total H\textsubscript{i} map indicates the position of the slice used to create the position–velocity (PV) diagram. The black cross is the the zero point (R.A.: 13:16:10). Right: PV diagram. The PV diagram is created by taking a slice along the whole H\textsubscript{i} structure, from the beginning of the tail to the end of VGS_31c, connecting each of the points. Zero corresponds to the red dot in the H\textsubscript{i} image on the left. This plot shows the velocity structure of the tail and its connection to gas around VGS_31b. Also, it shows the gas between VGS_31b and VGS_31a and VGS_31a and VGS_31c, respectively. Note the change in velocity width between VGS_31b and VGS_31a.

Figure 5. VGS_31 in four wavelength regimes. From top left to bottom right: (a) INT $B$-band image. (b) MDM H\textalpha{} continuum-subtracted image (c) GALEX FUV image, (d) GALEX NUV image. All the images are shown at the same physical scale. The white contours on each image indicate the corresponding H\textalpha{} emission regions. Note that there is no H\textalpha{} emission in the ring or in the tail of VGS_31b. Also note that the H\textalpha{} emission is confined to the central parts of the galaxies, mostly in the bar structures of VGS_31a and VGS_31b.
Figure 6. BPT diagram. The BPT diagram shows the ratio of emission line fluxes of [O iii]/Hβ to [N ii]/Hα. The comparison sample of emission-line galaxies has been constructed from the emission-line galaxy sample of Terlevich et al. (1991), galaxies defined as starbursts in SIMBAD and Markarian galaxies defined as starbursts in Coziol (2003). This diagram is adapted from Raimann et al. (2000).

2.1. \textit{H} i Imaging

We have imaged the \textit{H} i in VGS_31 as part of the VGS project, the details of which are described in Kreckel et al. (2012). Observations were done with the WSRT in the maxishort configuration providing an angular resolution of 19′ × 32′. The 36′ FWHM of the WSRT primary beam is sufficient to cover the entire VGS_31 system in a single pointing. We observed 512 channels within a total bandwidth of 10 MHz, giving a Hanning smoothed velocity resolution of 8.6 km s\(^{-1}\). Images for this paper were made with natural weighting to maximize sensitivity and CLEANed down to 0.5 mJy beam\(^{-1}\) (~1σ), reaching column density sensitivities of 2 × 10\(^{19}\) cm\(^{-2}\).

2.2. Broadband Imaging and Photometric Calibration

We used WFC at the 2.1 m INT for imaging in both \textit{B} and \textit{R} bands with Harris \textit{B} and \textit{R} filters. Total exposure times were 2400 s for the \textit{B} band and 1800 s for the \textit{R} band, spread over four exposures for the purpose of dithering and facilitating cosmic-ray detection. Standard star fields were observed each night for the photometric calibration. Flat-field exposures were taken at twilight at the beginning and/or end of each night. The data have been reduced using the standard IRAF\(^5\) and Photom Data Reduction Package (STARLINK)\(^5\) procedures for CCD imaging. All the optical images were trimmed and overscanned followed by bias subtraction and flat fielding. After that all images from each filter were aligned and median combined. The same procedures have been followed for the standard star observations.

2.3. \textit{H} α Imaging and Photometric Calibration

\textit{H} α imaging has been done with the echelle CCD in direct mode at the 2.4 m Hiltner Telescope. A redshifted \textit{H} α filter centered at 6693 Å has been used. To provide a measure of the continuum, \textit{R}-band imaging has been performed for each object. The total integration times for \textit{H} α and for the continuum have been spread over three exposures for the purpose of dithering and for facilitating cosmic-ray detection. Spectrophotometric calibration stars have been chosen either from Massey et al. (1988) or Öke (1990).

After performing the standard CCD reduction steps described in Section 2.1, each combined \textit{H} α image has been divided by 600 and \textit{R}-band continuum image by 120 in order to normalize them to 1 s. The mean has been calculated for an empty region in each image and the ratio of these means has been taken as the scaling factor for scaling the continuum image before subtraction from the \textit{H} α image. Photometric calibration of the final \textit{H} α images has been performed following the steps described in Gavazzi et al. (2006) and the references therein. Corrections for the atmospheric extinction and the airmass have been performed in the standard way, where each spectrophotometric calibration star observation has been fitted using airmass and instrumental magnitudes to get the atmospheric extinction coefficient.

\textit{Correction for the foreground extinction} has been derived from Balmer decrements, following the recipes in Calzetti et al. (2000) and Domínguez et al. (2013). The \textit{H} α/\textit{H} β ratios have been obtained from the MPA-JHU catalog for the SDSS DR\(^7\) measured through 3′ filters. We have calculated \(E(B – V)\) from these \textit{H} α/\textit{H} β ratios, using the reddening curve from Calzetti et al. (2000) to obtain the corresponding extinction. By using Balmer decrements we correct the foreground extinction along the entire line of sight including galactic extinction. Here an important point is that this correction assumes that the \textit{H} α/\textit{H} β ratio is the same throughout the entire \textit{H} α emission region. We checked this assumption using our WHT long-slit spectra which measure the \textit{H} α/\textit{H} β ratios along slits which covers the emission along both the minor and major optical axes. In Table 3, we give both the corrected and uncorrected \textit{H} α fluxes.

2.3.1. SFR from \textit{H} α Imaging

SFRs from the \textit{H} α emission have been calculated following the conversion from Kennicutt et al. (2009) where we used the SFR conversion factor based on a “Kroupa” initial mass function (Kroupa & Weidner 2003):

\[
SFR(H\alpha) [M_\odot \text{ yr}^{-1}] = 5.4 \times 10^{-42} \times L(H\alpha),
\]

Table 1

| Telescope | Observation Details |
|-----------|---------------------|
| INT       | \textit{B} - and \textit{R}-band imaging |
| MDM 2.4 m | \textit{H} α imaging |
| WHT       | Long-slit spectrum |
| WSRT      | 21 cm (\textit{H} i) imaging |
| IRAM      | CO(1–0) observations |
| GALEX     | NUV and PUV imaging |

\(^5\) http://iraf.noao.edu/

\(^6\) The MPA-JHU catalog is publicly available and may be downloaded at http://www.mpa-garching.mpg.de/SDSS/DR7/archive.
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Table 2
Parameters for VGS_31

| Name   | SDSS ID       | R.A. (J2000) | Decl. (J2000) | z   | m_B | M_r | g − r | m_I | M_I | δ  |
|--------|---------------|--------------|--------------|-----|-----|-----|-------|-----|-----|-----|
| VGS_31a | J131606.19+413004.2 | 13:16:06.19  | +41:30:04.25 | 0.021 | 14.75 | −20.01 | 0.32 | 14.633 | −20.194 | −0.64 |
| VGS_31b | J131614.69+412940.0 | 13:16:14.69  | +41:29:40.05 | 0.021 | 14.38 | −20.38 | 0.50 | 14.632 | −20.193 | −0.64 |
| VGS_31c | J131559.18+412955.9 | 13:15:59.18  | +41:29:55.96 | 0.021 | 16.78 | −17.98 | 0.21 | 16.735 | −18.093 | −0.64 |

Notes. Column 1: Galaxy names. Column 2: SDSS IDs of the galaxies. Columns 3 and 4: right ascensions and declinations. Column 5: spectrophotometric redshifts. Column 6: apparent model magnitudes as measured by the SDSS DR7 and corrected for galactic extinction. Column 8: g − r colors drawn from the apparent model magnitudes as measured by the SDSS DR7. Columns 9 and 10: apparent and absolute B magnitudes derived from INT B-band imaging and corrected for galactic extinction. Column 11: δ gives the filtered density contrast at $R_f = 1 h^{-1}$ Mpc as described in Kreckel et al. (2011).

Table 3
Hα Fluxes and Luminosities

| Galaxy | log$[F(\text{H}α + N\text{II})]$ | log$[F(\text{H}α)]$ | log$[I(\text{H}α)]$ | L(\text{H}α) (\text{erg s}^{-1})$ |
|--------|---------------------------------|-----------------|----------------|----------------------------------|
| VGS_31a | −12.622                         | −12.755         | −12.304 ± 0.076 | 4.7 × 10^{41}                    |
| VGS_31b | −12.345                         | −12.478         | −11.913 ± 0.104 | 1.16 × 10^{42}                   |
| VGS_31c | −13.604                         | −13.677         | −13.527 ± 0.019 | 2.8 × 10^{40}                    |

Notes. Column 1: galaxy name. Column 2: measured Hα flux including N II lines. Column 3: Hα flux corrected for N II deblending. Column 4: extinction-corrected Hα flux. Column 5: Hα luminosity derived from the extinction corrected Hα flux.

where $L(\text{H}α)$ is the luminosity, calculated as

$L(\text{H}α) (\text{erg s}^{-1}) = 4 \pi D^2 (3.086 \times 10^{24})^2 I(\text{H}α),$

where $D$ is the distance to the galaxy in Mpc and $I(\text{H}α)$ is foreground extinction corrected flux.

A detailed description of the Hα photometry, foreground extinction correction, and star formation derivation will be given in a separate paper.

2.4. Spectroscopy

We used the ISIS at the 4.2 m WHT at La Palma to take high-resolution spectra. The R1200R grating in the red arm and the R600B grating in the blue arm have been used, giving resolutions of, respectively, 0.026 nm pixel$^{-1}$ over 620–720 nm and 0.045 nm pixel$^{-1}$ over 360–540 nm. Cu–Ne–Ar lamp exposures were taken for wavelength calibrations. All the reduction has been performed using IRAF. In addition to the basic steps explained above, the illumination function along the slit has been determined via sky and lamp flats. Flux calibration has been done using spectrophotometric standard stars.

Figure 7 shows the Hα emission along the optical major and minor axes of VGS_31a and VGS_31b. In this figure, we compare the Hα emission line profiles with the Hα images of the corresponding regions on the galaxies.

2.5. GALEX UV Observations

GALEX NUV and FUV data have been obtained from the NGA, taken in 2004 with an exposure time of 3754 s in the NUV and 3002 s in the FUV. VGS_31 falls as a background object in the GALEX pipelines.

The SFR has been calculated from the GALEX NUV and FUV luminosities and corrected for internal dust attenuation.

Table 4
Star Formation Properties

| Galaxy | SFR$_{\alpha}$ (M$_\odot$ yr$^{-1}$) | SFR$_{\text{UV}}$ (M$_\odot$ yr$^{-1}$) | S$\text{SFR}_{\alpha}$ (M$_\odot$ yr$^{-1}$) | SFR$_{\alpha}$/M$_{\text{H}1}$ (M$_\odot$ yr$^{-1}$) | SFR$_{\text{UV}}$/M$_{\text{H}1}$ (M$_\odot$ yr$^{-1}$) |
|--------|-----------------------------------|------------------------------------|---------------------------------|---------------------------------|---------------------------------|
| VGS_31a | 2.5                               | 1.4                                | 0.07                            | 0.13                            | ...                             |
| VGS_31b | 6.3                               | 2.2                                | 0.06                            | 0.43                            | 0.7                             |
| VGS_31c | 0.15                              | 0.22                               | 0.05                            | 0.09                            | ...                             |

Notes. Column 1: galaxy names. Column 2: star formation measured from Hα flux luminosities. Column 3: star formation calculated from NUV. Column 4: specific star formation rate. Column 5: star formation rate per H1 mass. All three galaxies have similar S$\text{SFR}_{\alpha}$'s while their SFR$_{\alpha}$/M$_{\text{H}1}$ are different.

Table 5
Stellar, H1, and Molecular Masses and CO(1–0) Luminosities for VGS31

| Galaxy | M$_*$ (M$_\odot$) | M$_{\text{H}1}$ (M$_\odot$) | L$_{\text{CO}}$ (10$^8$ K km s$^{-1}$ pc$^2$) | M$_{\text{H}2}$ (M$_\odot$) | M$_{\text{H}2}$/M$_*$ | M$_{\text{H}1}$/M$_*$ |
|--------|-----------------|-----------------|-----------------|-----------------|----------------|-----------------|
| VGS_31a | 35.1            | 19.89 ± 2.90    | …              | …              | …              | …              |
| VGS_31b | 105.31          | 14.63 ± 1.97    | 2.8            | 8.9            | 0.085          | 0.608          |
| VGS_31c | 2.92            | 1.66 ± 0.95     | …              | …              | …              | …              |

Notes. Stellar masses are taken from the publicly available MPA-JHU catalog for SDSS DR7 which were derived using fits to the broadband $agriz$ photometry. VGS31 galaxies are all spectroscopic targets in SDSS DR7 with 3′ fiber spectra in their central regions and these spectra have been analyzed and included in this catalog.
following the method outlined in Schiminovich et al. (2010):

$$\text{SFR} = \frac{L_{UV} f_{UV}(\text{young})}{\eta_{UV}} 10^{0.4 A_{UV}},$$

where \( L_{UV} \) is the luminosity in erg s\(^{-1}\) Hz\(^{-1}\), \( f_{UV}(\text{young}) \) is the fraction of light that originates in young stellar populations, \( \eta_{UV} \) is the conversion factor between UV luminosity and recent-past-averaged SFR, and \( A_{UV} \) is the dust attenuation.

To determine the values of \( A_{UV} \) and \( A_{IR} \) we assume \( f_{UV}(\text{young}) = 1 \) and \( \eta_{UV} = 10^{28.165} \) (Schiminovich et al. 2010).

2.6. CO(1–0) Emission-line Observations

CO(1–0) line observations have been carried out with the IRAM 30 m telescope at Pico Veleta, Spain in 2011. We used the Eight Mixer Receiver (EMIR) to observe simultaneously the CO(1–0) (rest frequency, 115.271 GHz) and the CO(2–1) emission line (rest frequency, 222.8118 GHz) with a resolution of 5 km s\(^{-1}\). The FWHM is, respectively, \( \sim 22'' \) and \( \sim 11'' \) at the two frequencies. The Wideband Line Multiple Autocorrelator (WILMA) and the Fast Fourier Transform Spectrometer (FTS) were used as back ends. WILMA and FTS cover a channel width of 4 GHz with 2 MHz and 195 KHz resolution, respectively. The observations were carried out in wobbler switching mode with a frequency of 1 Hz and a throw of 120'' . The data were reduced with the CLASS software.

We have detected CO(1–0) emission from VGS_31b and the profile is shown in Figure 7. VGS_31b was not detected in CO(2–1). The detection limit for CO(2–1) is \( \sim 1 \) K km s\(^{-1}\). This is consistent with a normal CO(1–0)/CO(2–1) ratio, provided that the CO(2–1) emission is distributed over the CO(1–0) beam area.

The data for VGS_31a were not usable because of an error in the focus setting. VGS_31c has not been observed.

2.6.1. CO Luminosity and Mass

IRAM spectra are expressed in terms of antenna temperature \( (T_A^*) \). In order to convert it to a flux density we adopted the expressions following Costagliola et al. (2011) and Saintonge et al. (2011):

$$S_{\text{CO}}[\text{Jy}] = T_A^*[\text{K}] \times 3.906 \times \frac{F_{\text{eff}}}{\eta_{\text{A}}},$$

where \( F_{\text{eff}} \) is the forward efficiency and \( \eta_{\text{A}} \) is the antenna efficiency. The total flux is then derived by integrating the observed CO profile over velocity.

From the total flux we have calculated the luminosity as follows:

$$L'_{\text{CO}} = 3.25 \times 10^7 S_{\text{CO}} v_{\text{obs}}^{-2} D_L^2 (1 + z)^{-3},$$

where \( L'_{\text{CO}} \) is the luminosity, \( v_{\text{obs}} \) is the observed frequency in units of GHz, \( D_L \) is the luminosity distance in Mpc, and \( z \) is redshift. Finally, molecular hydrogen mass \( M_{H_2} \) is calculated as

$$M_{H_2} = L'_{\text{CO}} / \alpha_{\text{CO}},$$

where \( \alpha_{\text{CO}} \) is the Galactic conversion factor of 3.2 \( [\text{K} \text{ km s}^{-1} \text{ pc}^2]^{-1} \) which does not include a correction for the presence of helium.

3. RESULTS

Combining the data from the diverse set of observations presented in Section 2, the following picture emerges of the nature of VGS_31.

VGS_31 consists of three galaxies located in a void, VGS_31a, b, and c (Figure 1). A careful study of the H\(_\text{i}\) properties suggests that the galaxies are embedded in an elongated H\(_\text{i}\) cloud (Figures 3 and 4). In addition, both the optical and H\(_\text{i}\) observations suggest strong interactions in the system (Figure 3). This emerging picture tells us that we may be dealing with two different processes. One is the assembly of a filamentary structure in a void, the other is an interaction between the galaxies. We will describe these two main results separately.

VGS_31 exhibits a very peculiar structure in H\(_\text{i}\). The H\(_\text{i}\) column density map and the position–velocity (PV) diagram (Figures 3 and 4) present two views elucidating the nature of the system: (1) the filamentary structure and (2) its kinematic properties.

3.1. Filamentary Structure

The PV diagram seen on the right-hand side of Figure 4 is created by taking one single slice through the H\(_\text{i}\) data cube, from the far east to the far west of the VGS_31. In the H\(_\text{i}\) column density map (Figure 3) galaxies appear to be lined up in an H\(_\text{i}\) filament. The whole H\(_\text{i}\) envelope extends over \( \sim 120 \) kpc on the sky. The PV diagram shows that the three galaxies are at about the same systemic velocity. Also the extreme ends of the filament are at the same velocities, suggesting a single, coherent filamentary structure.

![Figure 7. IRAM spectrum of VGS_31b in the 115.271 GHz. The intensity scale is in \( T_A^* \), in kelvin.](image)
3.2. Kinematic Properties

The kinematics along this perceived filamentary structure is, however, rather complex. We will examine this galaxy by galaxy, going from east to west in Figure 4.

**VGS_31b.** The optical tail has an H\textsc{i} counterpart, showing almost no velocity gradient. There is a slight offset between this H\textsc{i} tail and its optical counterpart. It is kinematically connected to the inner disk and the ring of VGS_31b. The spatial resolution is insufficient to distinguish the gas associated with the ring from the gas associated with the disk. Therefore, we cannot say whether the H\textsc{i} tail is connected to the inner disk or the ring. The galaxy disk and the ring exhibit rotation with a velocity spread of 325 km s\(^{-1}\). The H\textsc{a} spectrum (Figure 8) shows the rotation along the optical major axis. In the PV diagram, the velocity gradient is not as steep because the slice has not been exactly placed along the optical major axis but rather toward the northeast. There is a ring-like structure around the disk. The tail and the disk seem to be connected. The first zoomed image shows the inner disk. The second zoomed image displays the bar positioned asymmetrically in the disk and the bright central part. The H\textsc{a} emission of VGS_31b shows clear rotation along the optical major axis. In addition there is a very fast rotating inner structure, about 1 kpc in extent with a velocity width of \(\sim 500\) km s\(^{-1}\). The H\textsc{a} emission region within \(\sim 0.6\) kpc. Each diagram showing optical spectra has axes of relative distance from the center (in kpc) vs. heliocentric radial velocity (in km s\(^{-1}\)).

**VGS_31a.** However, halfway to VGS_31a the velocity dispersion becomes significantly larger, \(\sim 125\) km s\(^{-1}\). This behavior is repeated at the other side of VGS_31a as well. The H\textsc{i} bridge has not been detected in the optical or UV. The gas associated with VGS_31a shows broad velocity range. However, we do not have the spatial resolution to map the H\textsc{i} kinematics in detail. As we move away from the galaxy toward the west, we continue to see H\textsc{i} with a broad velocity dispersion. The H\textsc{a} spectrum (Figure 8) has much higher resolution and shows a large kinematic asymmetry.

**VGS_31c.** Very little H\textsc{i} is detected between VGS_31a and VGS_31c. A clear H\textsc{i} connection is however visible in Figure 4. The velocity dispersion of the H\textsc{i} bridge becomes again narrower as we approach VGS_31c. As for the bridge between VGS_31b and VGS_31a, there is no stellar counterpart for this H\textsc{i} bridge either. The H\textsc{i} resolution is not enough to determine the detailed gas kinematics of VGS_31c.

3.3. Structure of the Galaxies

In addition to H\textsc{i}, optical data complement the picture of VGS_31's complex dynamics. We will continue to describe the peculiar features of the system going from east to west.

**VGS_31b.** As seen from Figure 1, VGS_31b is, optically, the most disturbed galaxy. It has a one sided tail, curved toward the northeast. There is a ring-like structure around the disk. The tail and the disk seem to be connected. The first zoomed image shows the inner disk. The second zoomed image displays the bar positioned asymmetrically in the disk and the bright central part. The H\textsc{a} emission of VGS_31b shows clear rotation along the optical major axis. In addition there is a very fast rotating inner structure, about 1 kpc in extent with a velocity width of \(\sim 500\) km s\(^{-1}\). Along the minor axis a minor velocity difference is seen, indicative of non-circular motions along the bar (Figure 8). Also, all star formation is concentrated in this central region where the bar is present. VGS_31b has been detected in CO(1–0). The velocity of the CO(1–0) peak is at \(\sim 6200\) km s\(^{-1}\), which is similar to the velocity of the H\textsc{i}.

**VGS_31a.** The zoom-in image (Figure 1) of VGS_31a shows that it is slightly disturbed and the bar-like structure in the center overlaps with the H\textsc{a} emission region (Figure 5). Like VGS_31b, rotation is along the optical major axis. However, the H\textsc{a} emission line profile along the major axis is quite irregular.

**VGS_31c.** This is the smallest of the three galaxies without any significant morphological irregularities (Table 5). As in the other two galaxies, the star formation is confined to the central part of the disk.

3.4. Star Formation Properties

The H\textsc{a} and UV results show that all three galaxies exhibit recent star formation activity concentrated in their central parts.
(Figure 5 and Table 4). The tail and the ring of VGS_31b are not detected in Hα or UV. The same is true for the H1 bridges between VGS_31b, VGS_31a, and VGS_31c. Among the three galaxies, VGS_31b has significantly higher SFR$_\alpha$ (Table 4). We also emphasize that the small D$_v$(4000) break values are indications for young stellar populations in the central part of the galaxies.

From the SDSS spectra we may determine the location of the VGS_31 members in a Baldwin, Phillips, & Terlevich (BPT) diagram (Baldwin et al. 1981) shown in Figure 6. For this diagram, emission lines of all galaxies, including VGS_31, have been extracted from the SDSS DR7 spectral database of 3\(^2\) fiber apertures. In this diagram, both VGS_31a and VGS_31b are located in the H\alpha/ starburst region in the BPT diagram, while VGS_31c is placed inside the normal star-forming zone.

Stellar masses of the three galaxies range from $3 \times 10^8$ $M_\odot$ to 1.06 $\times 10^{10}$ $M_\odot$ (Table 5). In contrast to the difference in their stellar masses, they have similar $S_{\text{SFR}}$. It is worth nothing that their $S_{\text{SFR}}$ and SFR$_\alpha$/M$_{HI}$ are significantly above the median of those of the ALFALFA average density sample (Kreckel et al. 2012), indicating enhanced star formation in comparison with galaxies of similar mass and gas content.

4. DISCUSSION

VGS_31 is a peculiar system through which we may be witnessing the ongoing growth of three galaxies along a filament inside a void. Here we discuss possible scenarios for the evolution of the VGS_31 galaxies in the void including gas accretion from an intra-void filament, interactions, and merging. These processes are difficult to disentangle from one another on the basis of the observational material presented. Yet we will discuss the observed phenomena in the context of all of these processes and indicate which we consider most important in each of the individual galaxies.

First we will discuss different interaction scenarios for VGS_31a and VGS_31b using the observational results presented above. VGS_31b is the most eye-catching member in the system. A one-sided tidal tail and a ring-like structure are clearly visible in the optical (Figure 1). This morphology suggests a minor merging incident with a low-mass galaxy. A satellite galaxy could have left the tail and formed the ring by wrapping the disk of VGS_31b (Mihos & Hernquist 1994, 1996; Duc & Renaud 2013). It is less likely that the tail has been caused by tidal interaction between VGS_31b and VGS_31a. As the mass ratio of these systems is three to one, one would expect greater damage to the disks and more prominent tails and counter-tail features as usually seen in tidal interactions and major mergers (Hibbard & van Gorkom 1996). The disks of VGS_31b and VGS_31a are not destroyed as expected in minor mergers (Schweizer 2000; Martínez-Delgado et al. 2010; Duc & Renaud 2013).

VGS_31b has a bar, visible in close-up images in Figure 1. The bar is pronounced in Hα as well (Figure 5). The kinematics of the Hα (Figure 8) indicates a fast rotating inner structure and evidence for streaming motions characteristic for a bar. In addition, VGS_31b is a starburst Markarian galaxy having enhanced star formation in its central part overlapping with the bar (Figures 5 and 8, Table 4). The detection of CO and location of VGS_31b in the BPT diagram support the starburst picture, presumably the consequence of gas accretion into its central part as seen in many galaxy mergers and interactions (Mihos & Hernquist 1994, 1996; Duc & Renaud 2013). There is an offset between the stellar and the gas component of the tail (Figure 3). This is also observed in some tidally interacting systems (Mihos 2001) and may be due to different initial distributions of both components or additional processes that act on one component and not on the other (see Duc & Renaud 2013 for a recent review). On the other hand, in most of the tidal tails in mergers, ongoing star formation is observed (Hibbard & van Gorkom 1996; Neff et al. 2004); in the case of VGS_31b, however, no ongoing star formation has been detected neither in the tail nor in the ring (Figure 5).

VGS_31a, however, shows different characteristics. It has no visible tails, but the internal kinematics is disturbed (see the Hα kinematics in Figure 7) and the H1 shows that gas east and west of the galaxy exhibits a large spread in velocity as if there is a corotating halo filled with H1 rather than tidal features with simple kinematics (Figure 4). Like VGS_31b, VGS_31a is a starburst galaxy with enhanced star formation in its central part (Figures 5 and 6, Table 4). There are two possibilities for the mechanism which could cause the enhanced star formation and the morphological disturbance: (1) VGS_31a could be in interaction with VGS_31b and this may cause the disturbance in its morphology and results in the irregular Hα emission line profile. (2) Instead of accreting gas from VGS_31b, VGS_31a may experience steady gas infall from the intergalactic medium, presumably from the structure outlined by the location of the galaxies and the H1 “connecting” them (Figure 4). This could cause the enhanced star formation as in the first scenario and better explains the broad velocity range of the H1 surrounding VGS_31a. One could argue that if VGS_31a exhibits such accretion from a large-scale structure (LSS) filament, then one would also expect VGS_31b to show the same characteristics. On the other hand, it is conceivable that a minor merger as suggested by the tail and ring could have disrupted the accretion process. Detailed simulations of such scenarios are required to test the validity of these scenarios.

VGS_31c, the smallest of the three galaxies, has enhanced star formation and its H1 shows the characteristics of interactions, albeit at very low signal to noise. It is difficult in this case to determine conclusively the process(es) responsible for the H1 structure and enhanced star formation.

The most exciting result is that we may be witnessing the assembly of structure within a void, and the birth process of galaxies in such a desolate area. It does fit into the theoretically expected buildup of voids and galaxies therein. Voids evolve in a hierarchical fashion, leaving planar and filamentary substructure within the emerging voids (Dubinski et al. 1993; van de Weygaert & van Kampen 1993; Sahni et al. 1994; Sheth & van de Weygaert 2004; Aragón-Calvo & Szalay 2013; Rieder et al. 2013). The question is whether we see here the manifestation of this process. VGS_31 could be a density enhancement within an underlying dark matter filament. The complication is that in addition to accretion of material from an LSS filament the galaxies also suffer from tidal interactions and minor merging. As for the cold flow accretion scenarios we can only make a very rough estimate because we do not know exactly the orientation of the system. If we take the size of the H1 filament and the velocity gradient from east to west, then we can estimate a rough accretion timescale of at least a gigayear. An important next step will be to use advanced simulations with gas and star formation to see
whether the scenario proposed here does indeed take place in voids.

Finally, it is of interest to note that VGS\textsubscript{31} is not the only case for a filamentary structure and cold flow accretion in our VGS. We have discovered at least two other cases which seem to exhibit this hierarchical structure formation. In addition to another filamentary galaxy configuration, VGS\textsubscript{38} (Kreckel et al. 2011), we also found a polar disk galaxy, VGS\textsubscript{12} (Stanonik et al. 2009). VGS\textsubscript{38} is a system of chain galaxies which share the same H\textsubscript{i}. VGS\textsubscript{12} is located right at the center of a tenuous wall between two large voids. It has a polar H\textsubscript{i} disk much more extended than its stellar disk. The polar disk has no stellar counterpart or any ongoing star formation. This galaxy is a candidate for the cold flow accretion.

Individually these galaxies and VGS\textsubscript{31} are unusual systems; however, taken collectively they show that the void environment is an extremely interesting site for understanding galaxy formation and evolution.

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