The Zeldovich Universe:
Genesis and Growth of the Cosmic Web
Proceedings IAU Symposium No. 308, 2014
R. van de Weygaert, S. Shandarin, E. Saar & J. Einasto, eds.

doi:10.1017/S174392131601067X

Molecular Gas and Star Formation in Void Galaxies

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Abstract. We present the detection of molecular gas using CO(1–0) line emission and followup Hα imaging observations of galaxies located in nearby voids. The CO(1–0) observations were done using the 45m telescope of the Nobeyama Radio Observatory (NRO) and the optical observations were done using the Himalayan Chandra Telescope (HCT). Although void galaxies lie in the most underdense parts of our universe, a significant fraction of them are gas rich, spiral galaxies that show signatures of ongoing star formation. Not much is known about their cold gas content or star formation properties. In this study we searched for molecular gas in five void galaxies using the NRO. The galaxies were selected based on their relatively higher IRAS fluxes or Hα line luminosities. CO(1–0) emission was detected in four galaxies and the derived molecular gas masses lie between $(1-8)\times10^9$ $M_\odot$. The Hα imaging observations of three galaxies detected in CO emission indicates ongoing star formation and the derived star formation rates vary between from 0.2 – 1.0 M$_\odot$ yr^{-1}, which is similar to that observed in local galaxies. Our study shows that although void galaxies reside in underdense regions, their disks may contain molecular gas and have star formation rates similar to galaxies in denser environments.

Keywords. ISM: molecules, galaxies: evolution, galaxies: ISM, cosmology: large-scale structure of universe.

1. Introduction

Voids contain a sparse but significant population of galaxies that are usually small, gas rich, late type galaxies (kreckel etal. 2012). The smaller voids are dominated by low surface brightness (LSB) dwarfs and irregular galaxies (karachentsev etal. 1999) but the larger voids also have a population of relatively bright galaxies that are often blue in color. These galaxies have ongoing star formation and are often interacting with companion galaxies in pairs or small groups along filaments in the voids (Beygu *et al.* 2013). Many questions remain regarding star formation in void environments; what is its nature - is it sporadic or continuous, what drives it and how is the star formation related to the location of the galaxies with respect to the filaments, walls and void interiors ?

One of the key elements for supporting star formation in galaxies is the presence of molecular hydrogen (H_2) gas. Although neutral hydrogen has been both detected and mapped in several voids, not much is known about the distribution of H_2 gas in void galaxies. There have been two studies that have detected CO emission and estimated molecular gas masses in a total of five void galaxies (Sage *et al.* 1997; Beygu *et al.* 2013). These results indicate that the H_2 gas masses in void galaxies are comparable to those found in nearby star forming systems. In this study we searched for molecular gas in void galaxies to obtain a larger sample of such H_2 rich galaxies and carried out followup Hα imaging observations of some of the detected galaxies. Our main motivation was to understand how the cold gas masses relate to the star formation properties of these

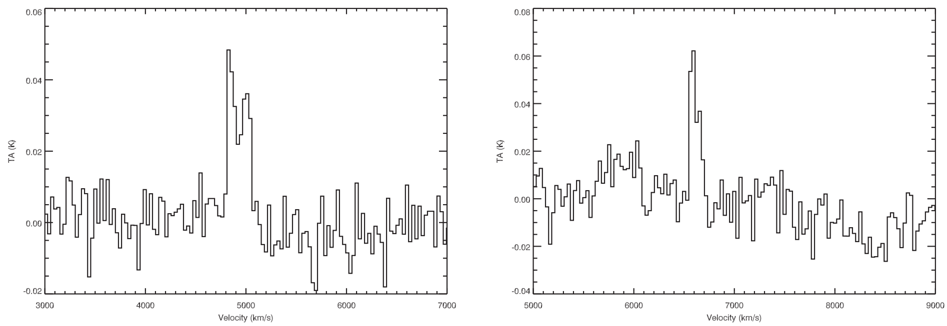

Figure 1. (a) Figure on the left shows the CO(1–0) line emission detected from the galaxy SBS 1325+597 that lies in the void Ursa Minor I. The line has a distinctive double horned profile indicative of a rotating disk and the peak separation is approximately 200 km s^{-1}. (b) Figure on the right shows the CO(1–0) line emission detected from the void galaxy SDSS 153821.22+331105.1. The gas is concentrated in the center of the galaxy and has a line width of ∼100 km s^{-1}.

systems. In the following sections we present our observations, results and discuss their implications. For all distances we have used $H_0 = 73 \; km \; s^{-1} \; Mpc^{-1}$ and $\Omega = 0.27$.

2. Sample galaxies and observations

Our initial sample comprised of 12 galaxies that were selected based of their relatively high infra-red fluxes or high star formation rates (kreckel et a. 2012; Cruzen *et al.* 2002; Szomoru *et al.* 1996). However due to weather conditions we were able to finally observe only five galaxies from this sample and they are listed in Table 1. Three galaxies have been observed in HI by Kreckel *et al.* (2012) in the Void Galaxy Survey (VGS) (SBS 1325+597, SDSS 143052.33+551440.0, SDSS 153821.22+331105.1) and the remaining two galaxies have been observed in an earlier HI survey of the Bootes void by Szomoru *et al.* (1996). All the galaxies have SDSS data.

The $^{12}CO(J = 1 - 0)$ emission observations were carried out using the 45 m Nobeyama Radio Telescope during 14 - 25 April, 2013. At the CO rest frequency of 115.271204 GHz, the half-power beam width (HPBW) was 15″ and the main beam efficieny was about 30%. The on source time for the first four galaxies varied between 1 to 1.5 hours; due to poor weather conditions SBS 1428+529 was observed for only 25 minutes. We used the one beam (TZ1), dual polarization, double sideband receiver (TZ) and the digital FX-type spectrometer SAM45, that has a bandwidth of 4 GHz (Nakajima *et al.* 2008). Typical system temperatures were 160 - 260 K. The pointing accuracy was about 2″-4″. Only data with a wind velocity less than 5 km s^{-1} were used and data with winding baselines were flagged. The data was analysed using NRO calibration tool NEWSTAR.

The Hα observations were done using the Himalayan Faint Object Spectrograph Camera (HFOSC) which is mounted on the 2m Himalayan Chandra Telescope (HCT) and were carried out on 2014 April 11 & 25. For SBS 1325+597 the redshift is 0.0165, so the Hα filter (band width ∼500 $\AA$) was used to get the Hα line emission. For SDSS 143052.33+551440.0 we used the narrow Hα filter (band width ∼100 $\AA$). The galaxy SDSS J153821.22+331105.1 is at a redshift of $z = 0.022$ and the Hα line is shifted to 6714 $\AA$. Hence we used the narrow band [SII] filter (band width ∼100 $\AA$ and centered around 6724 $\AA$) for this galaxy. To obtain the continuum subtracted Hα images we also obtained broad band images with the R filter centered around the Hα line. The bias frames and twilight flats were used for preprocessing of the images. The data reduction

https://doi.org/10.1017/S174392131601067X Published online by Cambridge University Press

Table 1. Observed galaxies, molecular gas masses and star formation rates

Galaxy	**D_L Mpc**	**Redshift**	**CO flux (K km s^{-1})**	**Molecular Gas Mass(10^9 $M_\odot$)**	Hα Flux (10^{-13} ergs $s^{-1}cm^{-2}$)	**SFR** ($M_\odot yr^{-1}$)
SBS 1325+597	70.4	0.0165	10.7±0.2	1.5±0.03	0.4	0.20
SDSS 143052.33+551440.0	76.6	0.0176	7.0±0.2	1.1±0.03	1.2	0.60
SDSS 153821.22+331105.1	97.6	0.0220	6.4±0.2	1.7±0.05	1.2	1.02
CG 598	248.0	0.0575	5.2±0.1	8.5±0.10	....	.....
SBS 1428+529	191.0	0.0445	< 0.6	< 0.6	....	.....

Notes:
[1] For SBS 1428+529 there was no CO(1–0) detection and no Hα image could be obtained. Upper limits for the molecular gas mass were obtained from the noise which was 0.0024 k and assuming a typical linewidth of 250 km/s.
[2] For CG 598 no Hα image could be obtained.

was done using the standard packages available in IRAF†. The images were corrected for cosmic rays, aligned and corrected for point spread function variations. Flux calibration was done using the spectrophotometric standard star HZ44. The Hα fluxes are listed in Table 1.

3. Results

1. Molecular gas detection : We have detected $^{12}CO(J = 1-0)$ emission from four of the five sample galaxies that we observed (Table 1). The non-detection in SBS 1428+529 could partly be due to the short duration of the scan, which was limited by bad weather. Of the four detections, SBS 1325+597 has the most striking line profile; it has a double horned structure indicating a rotating disk of molecular gas (Figure 1a). The velocity separation of the peaks is $\sim 200\ kms^{-1}$; assuming a disk inclination of 59.3° the disk rotation is 116 km s^{-1}. This is similar to the HI rotation speed from Kreckel *et al.* (2012). In SDSS 153821.22+331105.1 the gas is centrally peaked (Figure 1b); probably driven into the center by the bar in the galaxy. In the other two galaxies (SDSS 143052.33+551440.0 and CG 598) the CO line profile is slightly off center from the systemic velocities of the galaxies, which suggests that their gas disks are disturbed, possibly due to interaction with a companion galaxy (Das *et al.* 2014, in preparation).
2. Molecular masses : The CO fluxes in K km s^{-1} were converted to Jy km/s using a conversion factor (Jy/K) of 2.4. The CO line luminosity was determined using the relation $L_{CO} = 3.25 \times 10^7 (S_{CO} \Delta\ V/Jykms^{-1})(D_L/Mpc)^2(\nu_{res})^{-2}(1+z)^{-1}$ and the molecular gas mass was estimated using the relation $M(H_2) = [4.8\ L_{CO}(K\ kms^{-1})]$ (Solomon & van den Bout 2005). The molecular gas masses lie in the range $(1-8) \times 10^9\ M_\odot$ which is comparable to that observed from bright galaxies in denser environments.
3. Comparison with previous detections and HI masses : Our molecular gas are similar to that obtained for earlier studies of void galaxies by (Sage *et al.* 1997, Beygu *et al.* 2013) that lie in the range $10^8 - 10^9$ $M_\odot$. Although our study and previous detections indicate relatively large H_2 gas masses and a high detection rate, it must be remembered that the sample was biased towards star forming galaxies and those with high FIR fluxes. The molecular gas masses are comparable to the HI masses of these galaxies (Kreckel *et al.* 2012; Szomoru *et al.* 1996).
4. Hα fluxes and star formation rates (SFR) : The SFRs were calculated from the Hα fluxes using the kennicutt formula SFR = L(Hα)/1.26×10^{41} ergs s^{-1} (Table 1).

† Image Reduction & Analysis Facility Software distributed by National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under co-operative agreement with the National Science Foundation.

https://doi.org/10.1017/S174392131601067X Published online by Cambridge University Press

In SBS 1325+597 the Hα is distributed on either side of the galaxy nucleus, possibly in a ring. The distrbution matches the CO line profile (Figure 1a) which indicates a ring like configuration for the molecular gas. In SDSS 143052.33+551440.0 the Hα emission is concentrated about the nucleus. In SDSS 153821.22+331105.1 it is concentrated along the bar. The SFR is highest for SDSS 153821.22+331105.1; it is probably triggered by gas flowing along the bar in the galaxy although the emission is surprisingly faint in the disk.

5. Are these galaxies interacting? : SBS 1325+597 has a disturbed optical and HI morphology. SDSS 143052.33+551440.0 also has a disturbed optical morphology and its CO profile is not symmetric about its systemic velocity. SDSS 153821.22+331105.1 has a bar that may have been triggered by an interaction. CG 598 appears to be accreting a companion in its SDSS g image and its CO profile is also asymmetric about its systemic velocity. Thus all the detected galaxies in our sample show some signs of interaction.

4. Implications

The main implications of this study is that cold gas and star formation are present in voids, even though the overall environment is underdense. Our sample galaxies also show disturbed morphologies, possibly due to interactions with companion galaxies. Our results can be understood in the hierarchical picture of void evolution, in which voids merge leaving behind a filamentary substructure. Galaxies grow along these filaments and in clusters where filaments intersect (e.g. Sahni *et al.* 1994; Sheth & van de Weygaert 2004; Cautun *et al.* 2014). The presence of both molecular gas and star formation in void galaxies indicates that they are probably evolving within this void substructure. Gas flowing along the filaments can be accreted by these galaxies and will contribute to the accumulation of neutral gas in their disks. High enough gas surface densities will result in the onset of star formation, leading to galaxy evolution within the void environment.

Acknowledgements

This paper was based on observations at the Nobeyama Radio Observatory (NRO) which is a branch of the National Astronomical Observatory of Japan, National Institutes of Natural Sciences. The optical observations were done at the Indian Optical Observatory (IAO) at Hanle. We thank the staff of IAO, Hanle and CREST, Hosakote, that made these obervations possible. This research has made use of the NASA/IPAC Extragalactic Database (NED).

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