The CO-CAVITY project: Molecular gas in void galaxies

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Abstract. Galaxies in voids have experienced a different environment than those in denser environments during their entire existence. Their properties are possibly different from galaxies in denser media. The CO-CAVITY project aims at studying the molecular gas contents of void galaxies and compare with non-void ones. To this end, 106 galaxies drawn from the mother CAVITY Integral Field Unit (IFU) sample have been observed with the EMIR receiver at the IRAM 30m telescope in Pico Veleta targeting the CO(1–0) and CO(2–1) lines. The data gathered allows deriving the star formation efficiency, molecular-to-atomic gas mass ratio and molecular-to-stellar mass ratio. The preliminary results presented here suggest that in general, there are no significant differences (within the errors) in the molecular gas content of void and control samples, although some deviations are observed in certain ranges when splitting the samples in stellar mass bins.

1 Introduction

Large galaxy surveys as the Sloan Digital Sky Survey (SDSS; [18]) have shown that galaxies are not distributed in a uniform manner, but forming the so-called "cosmic web" characterised by nodes (clusters), filaments, walls, and vast regions almost devoid of galaxies called voids (see for instance [7]). These regions constitute the lowest-density environments in the Universe and represent an ideal place to study galaxy formation and evolution as they are largely unaffected by the complex physical processes that transform galaxies in high-density environments.

The Calar Alto Void Integral field Treasury Survey (Pérez et al., in prep.; CAVITY)[1] is a legacy survey aimed at filling the gap of large, systematic studies of void galaxies. It is aimed at: *(i)* determine how the environment has influenced the mass assembly (baryonic and dark) of void galaxies; *(ii)* establish how galaxy formation and its properties are dependent on the larger-scale environment; and *(iii)* find the main driver of galaxy transformation, from star-forming to quiescent, passive systems in voids.

CAVITY is observing a sample of ~300 galaxies using the Postdam Multi Aperture Spectrograph (PMAS, [12]) in the PPaK mode [17] at the 3.5m telescope of the Centro Astronómico Hispano Andaluz de Calar Alto (CAHA). The first observations started in January

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[1]`https://cavity.caha.es`

2021, and the first public data release is expected by mid 2024. The CAVITY sample comprises galaxies distributed over 15 cosmic voids in the redshift range $0.005 < z < 0.05$, and has been specifically designed to probe voids of different sizes and dynamical stages, namely the state of expansion of voids, as a result of matter flow towards denser environments; the void galaxies have been chosen in such a way that their $B = 25$ magnitude isophote fits within the field of view of the instrument to ensure that the properties analysed are properly compared.

The star formation properties of void galaxies are fundamental parameters to be investigated, and star formation is strongly regulated by the molecular gas contents; the CO-CAVITY project was conceived in the framework of the CAVITY project as a comprehensive exploration of void galaxies targeting the easily observable CO rotational lines that are a proxy of the H_2 content. This proceedings briefly describes CO-CAVITY and summarises its preliminary results. The full details of this study will be presented in Rodríguez et al. (in prep.).

2 Observations, data reduction and ancillary data

The observations targeting the CO(1–0) and CO(2–1) lines in 106 galaxies drawn from the CAVITY sample were carried out at the IRAM 30-meter telescope using the EMIR receiver in dual-band mode (E0 and E2) and the Fourier Transform Spectrometer (FTS) backend in the wide resolution mode (200 kHz resolution). The observing mode was wobbler switching to allow an effective background cancellation and exposure times ranged from 30 min to 4 h. The observations were performed in several runs (projects 170-21, 083-22, and 164-22) spanning from December 2021 to February 2023.

The files produced by the IRAM `MRTCAL` pipeline were used as input for the data reduction process that was performed with the `CLASS` package from the `GILDAS` suite. This included discarding noisy scans by individual inspection, correcting platforming effects, adjusting and subtracting a linear baseline and finally adding up scans and smoothing them to a resolution of $v_{res} \approx 20$ km/s. The detection rate is as follows: in the CO(1–0) line, 64 galaxies have been clearly detected ($S/N > 5$), 9 galaxies have been tentatively detected ($3 < S/N < 5$) and 33 galaxies were not detected. For CO(2-1), there are 63 detections, 8 tentative detections and 35 non-detections. In four galaxies the CO(1–0) emission was not detected, but the CO(2–1) was clearly detected.

As a supplementary sample, we added CO data of 16 galaxies drawn from the Void Galaxy Survey (VGS; [8]) gathered by our group at the IRAM 30-meter telescope in a pilot survey of CO-CAVITY [2], collecting a total sample of 122 galaxies. However, we excluded four galaxies classified as AGN for the analysis, resulting in a final sample of 118 galaxies, hereafter referred as VOIDS sample.

The control sample of field galaxies was built from xCOLD GASS [13], an IRAM 30-meter H_2 legacy survey comprising 532 galaxies. The HI data for the control sample was obtained from the ALFALFA database. In order to have a control sample as homogeneous in properties as possible, galaxies inhabiting voids [10] and clusters [16], and AGN (constrained by the BPT diagram) were removed from the control sample. In future studies we will compare the properties of void and cluster galaxies.

Ancillary data were gathered from different sources: HI data from the ALFALFA Survey [4] comprising 36 detections (and 20 upper limits); metallicity estimates were derived for this work using the O3N2 estimator [11]; star formation rates (SFR) derived using an H_α model [3]; finally, stellar masses ($M_\star$) were gathered from the MPA-JHU catalogue ([6], [14])[2].

[2] `https://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/`

3 SFR properties, metallicity, and molecular gas contents

The CO-to-H_2 conversion factor α_{CO} was derived following [1]. According to these authors, the conversion factor is correlated with the gas metallicity and the distance to the star-forming main sequence (SFMS), Δ(MS). This parameter has been derived from [5]. More details on the computations will be provided Rodríguez et al. in prep. Finally, the H_2 mass (Figure 2) was computed as $M_{H_2} = f_{ap}\,\alpha_{CO}\,L'_{CO}$, where f_{ap} is the aperture correction computed following [9] and L'_{CO} [K km s^{-1}] $= 3.25 \times 10^7 S_{CO}\,\Delta V\,\nu^{-2}\,D_L^2(1+z)^{-3}$ following [15].

Figure 1 (left panel) shows the distributions of SFR as derived by Duarte-Puertas for our CO-CAVITY (VOIDS) sample and the xGASS control sample, including only SFMS galaxies. It can be seen that both distributions are rather similar. In fact, a Kolmogorov-Smirnov test gives a p-value of 0.16. This can be also observed for the distribution of metallicities as depicted in 1 (right panel).

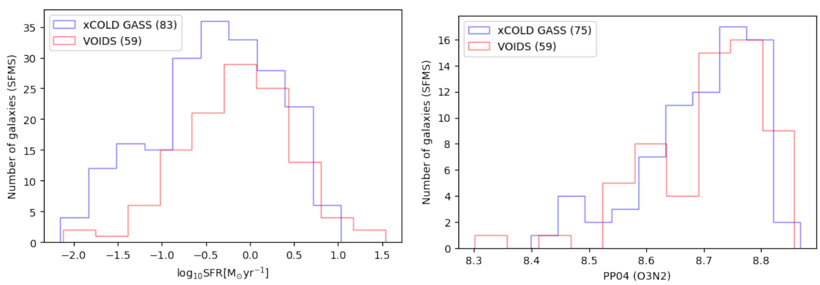

Figure 1. Distribution of SFR (left) and metallicity (right) for our sample of void galaxies and the xGASS control sample.

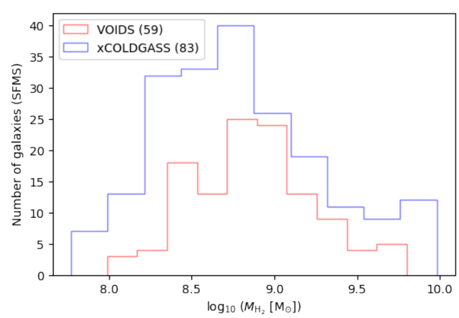

Figure 2. Distribution of molecular gas mass M_{H_2} of the samples of void galaxies and xGASS.

4 Results

We have compared a number of properties of the VOIDS sample with those of the control one (wall, filament), including specific SFR (sSFR), M_{H_2}, normalised $M_{H_2}/M_\star$, star formation efficiency (SFE), normalised atomic gas mass $M_{HI}/M_\star$ and molecular-to-atomic gas mass ratio M_{H_2}/M_{HI}, as a function of the galaxy stellar mass $M_\star$. To this end, we have created four mass bins, namely $\log M_\star$ [$M_\odot$] = 9.0–9.5, 9.5–10.0, 10.0–10.5, and 10.5–11.0.

Figures 3 and 4 depict the main results. Only galaxies within the SFMS have been included. In all plots, the mean values within each stellar mass bin (horizontal blue lines) and 1σ dispersion around the mean values (grey areas) are represented. Specifically, for the sSFR plot, the mean values of the xGASS sample are slightly higher than the expected from the SFMS [5], however this difference is less than 3 σ. This can be (at least partially) explained by the fact that the SFMS was computed using the full xGASS sample while here we are using a sub-sample excluding void and cluster galaxies. Considering these uncertainties, no outstanding differences are observed between the VOIDS and xGASS (control) samples in the explored parameters. In further detail, such differences can be detected in specific mass bins, as explained below.

In the mass bin ($\log M_\star$ [$M_\odot$] = 9.5–10.0), the average molecular gas mass M_{H_2} is somewhat larger (but less than 3 σ) in void galaxies than in the control sample. This effect is more evident when considering the molecular gas mass normalised with the galaxy stellar mass, $M_{H_2}/M_\star$, being higher in void galaxies. Consequently, the average SFE is lower in the void sample as the SFR is very similar in both groups, and more noticeable in the mass bin ($\log M_\star$ [$M_\odot$] = 9.0–9.5), where the difference between xGASS and void galaxies is $\sim 4\ \sigma$.

The combination of molecular and atomic gas contents was only possible for the subset of VOIDS and xGASS galaxies with ALFALFA detections (and upper limits). Therefore, the results are somewhat hampered by the limited number counts within each mass bin. However, some differences are apparent. The most outstanding is the larger amount of atomic gas observed in the control sample as compared to the void set in the mass bin $\log M_\star$ [$M_\odot$] = 10.0–10.5 (a difference around $\sim 4\ \sigma$). This is also translated to the molecular-to-atomic gas ratio, M_{H_2}/M_{HI}, which is clearly higher in the void galaxies' sample than in the control one.

5 Summary and Conclusions

We have presented the CO-CAVITY survey that observed the CO(1–0) and CO(2–1) lines in 106 galaxies in voids drawn from the CAVITY IFU sample with the IRAM 30m telescope. From the CO data, we have derived the molecular hydrogen masses using standard conversions. These are in the range $8.0 \lesssim \log M_{H_2}$ [$M_\odot$] $\lesssim 9.8$. Combining our data with ancillary data and a control sample of wall and filament galaxies, we have analysed properties as sSFR, M_{H_2}, $M_{H_2}/M_\star$, SFE, $M_{HI}/M_\star$ and M_{H_2}/M_{HI}, as a function of the galaxy stellar mass $M_\star$. In general, these properties are very similar in void and non-void galaxies.

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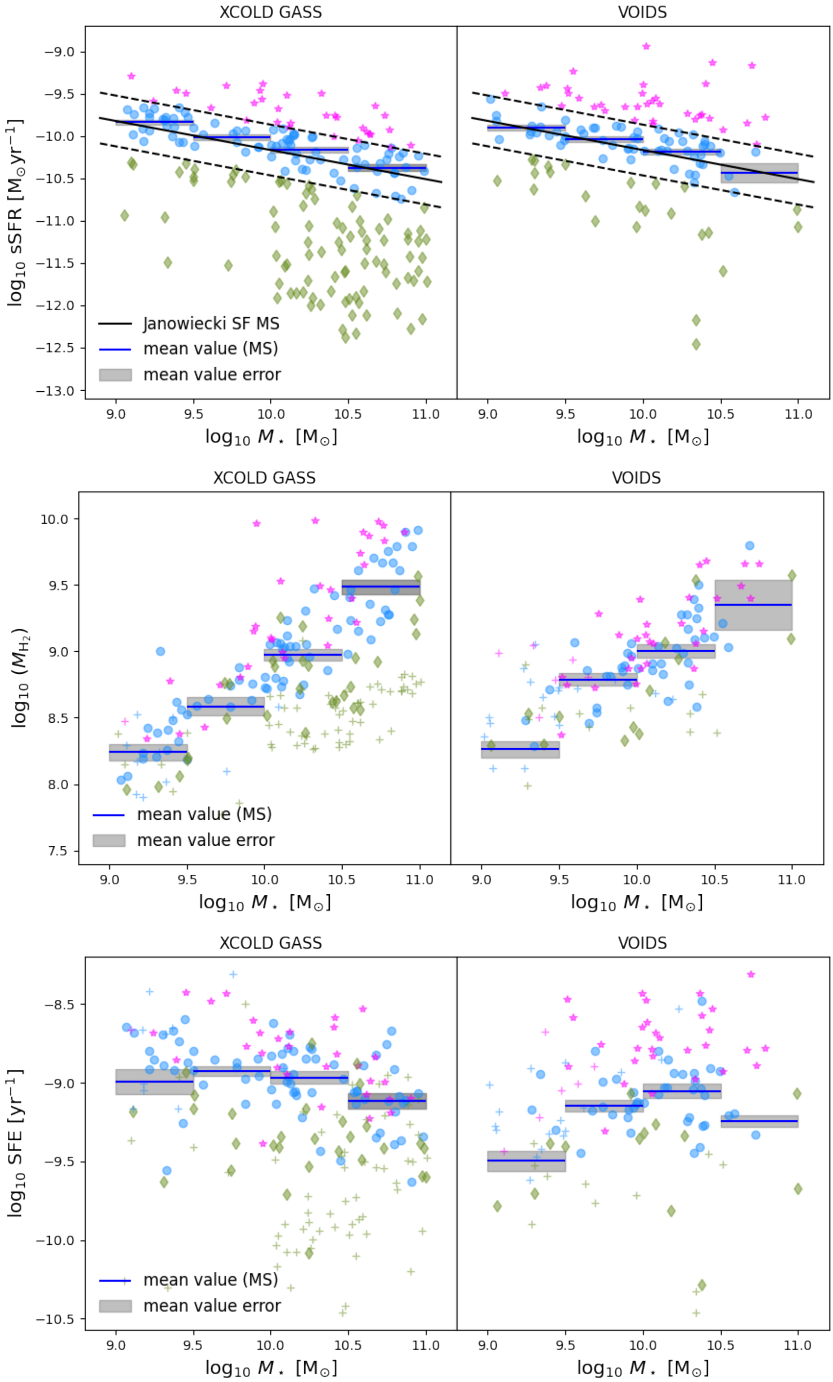

Figure 3. Specific SFR (sSFR), molecular gas content (M_{H_2}) and SF Efficiency (SFE) for the VOIDS and xGASS (control) samples. The solid line in the sSFR plot depicts the MS from [5] and the dashed lines the 0.3 dex boundaries. Pink, blue, and green symbols correspond to galaxies above, on, or below the SFMS (starbursts, normal SF galaxies, and quenched/quiescent galaxies, respectively). The distribution of M_{H_2} (central panel) seems shallower in the VOIDS sample than in the xGASS one. A detailed analysis will be presented in the forthcoming paper.

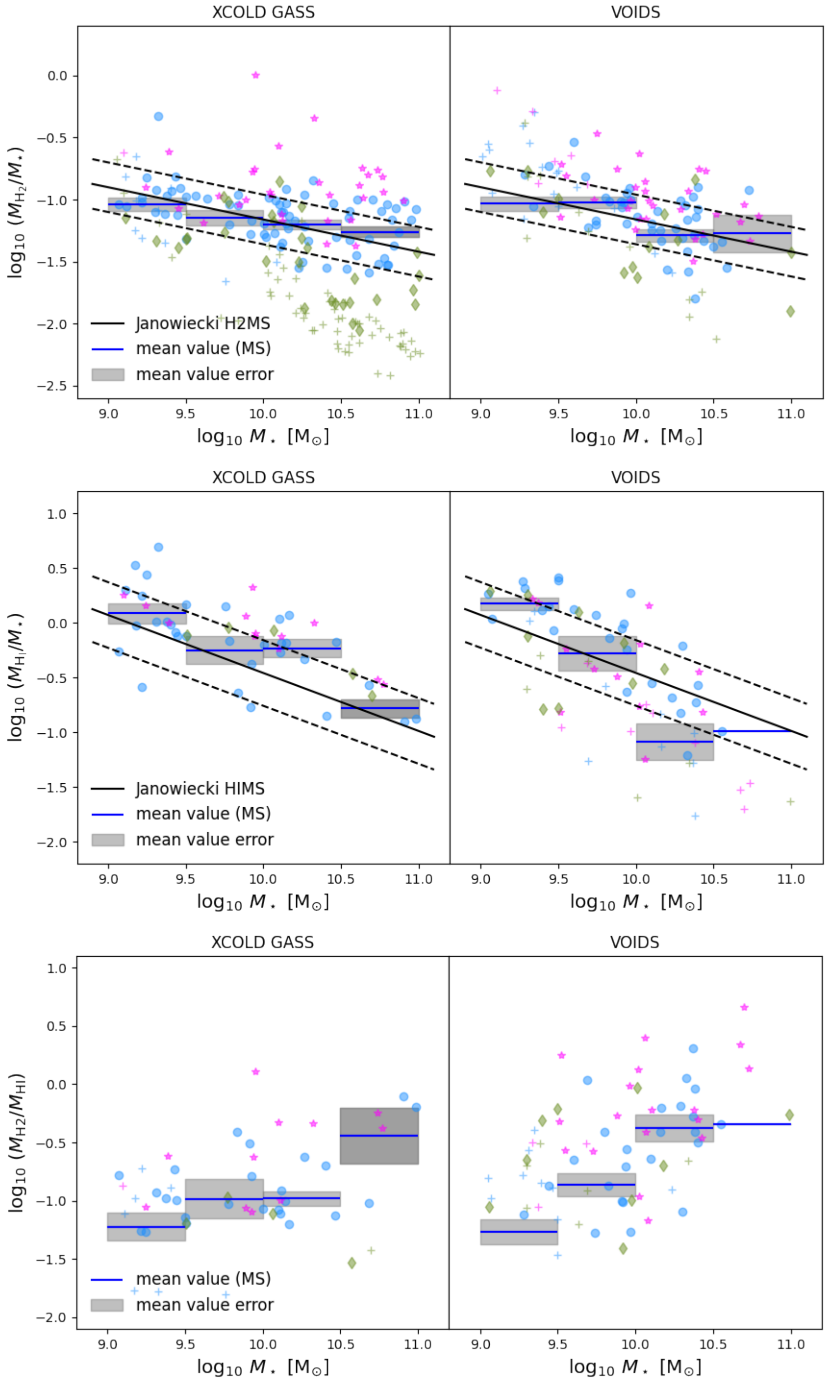

Figure 4. Normalised molecular and atomic gass masses and molecular-to-atomic mass ratio for the VOIDS and xGASS (control) samples. Symbols as in the previous figure. Due to the low sensitivity of the ALFALFA survey, data are available only for a reduced number of galaxies, and, as a consequence, results are inconclusive.