CIRCUMGA-LACTIC ENRICHMENT IN LOCAL DWARF GALAXIES AS PROBED BY STAR-FORMATION DRIVEN OUTFLOWS

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Abstract. Galactic feedback driven by massive stars and active galactic nuclei plays a fundamental role in regulating galaxy formation and evolution. In particular, intense starburst episodes can generate strong outflows able to suppress star formation by expelling large amount of dust and metals out of the galaxies, possibly enriching their circum (or even inter) galactic media. Local dwarf galaxies are particularly sensitive to feedback processes and offer a unique opportunity to study these phenomena in great details. We search for outflow signatures in a sample of ∼30 local dwarf galaxies drawn from the Dwarf Galaxy Survey. We make use of Herschel/PACS archival data to detect atomic outflows in the broad wings of observed \([\text{CII}]\) 158 \(\mu\)m line profiles. We find that atomic outflows in these galaxies have typical mass-loading factors consistent with unity and velocities high enough to bring gas and dust outward. Our results can be used as input for chemical models, posing new constraints on the processes of dust growth and destruction in the interstellar medium of galaxies.

Keywords: galactic winds, dwarf galaxies.

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I. INTRODUCTION

Galactic winds play a fundamental role in regulating the formation and evolution of galaxies across cosmic time (e.g., [1]). Both stellar processes (such as star formation and supernova (SN) explosions) and active galactic nuclei (AGNs) could exert a feedback on their host galaxy, heating its internal reservoir of gas and expelling material through powerful outflows. They are ubiquitous in high-redshift (\(z > 1\)) starbursts and AGNs, but they are also found to affect the growth of normal star-forming galaxies (SFGs) at early times, when the major phase of the galaxy mass-assembly
was in place. On the other hand, nearby sources offer a unique opportunity to study in detail galactic outflows and their impact on galaxy evolution. Local dwarf galaxies are of particular interest for this kind of studies as they are much more sensitive to feedback which, in the low stellar mass regime typical of such objects (i.e., \( \log(M_*/M_\odot) \lesssim 10 \)), is mostly due to the radiation from young stars and SN explosions, producing the so-called star-formation driven outflows (e.g., [2]).

Several techniques have been exploited so far to probe the prominence of galactic outflows at different cosmic times. Rest-frame UV and optical blue-shifted absorption lines have been extensively used to identify outflowing atomic and ionized gas, especially at \( z \gtrsim 1 \) (e.g., [3]), while nebular emission lines such as H\( \alpha \) or [OIII]\( \lambda 5007 \) are also invoked in both local and high-\( z \) massive SFGs to trace the expelled material (e.g., [4]). Another method consists in decomposing emission line profiles into a narrow and broad Gaussian component, with the latter considered as a tracer of outflowing gas. Recently, this procedure was applied to the [CII] line at 158 \( \mu \)m rest-frame, which is one of the strongest fine-structure lines in the far-infrared (FIR) spectra of SFGs (e.g., [5]). High-velocity outflows have been detected in the broad wings of the [CII] line profile in individual high-\( z \) luminous quasars (QSOs; e.g., [6]) and via stacking analysis in normal SFGs at \( z > 4 \) [7] thanks to IRAM and ALMA observations, respectively. In the local Universe, Herschel data have been exploited to trace atomic (and possibly molecular) outflows in the broad [CII] wings of ultra-luminous infrared galaxies (ULIRGs; [8]), as well.

In this work, we further investigate the importance of stellar feedback in the framework of galaxy evolution by constraining the efficiency of galactic outflows in local dwarf sources. We make use of archival spectroscopic [CII] observations as collected by Herschel/PACS in the sample of local dwarf galaxies drawn from the Dwarf Galaxy Survey (DGS; [9]). We derive both individual and average properties of outflows in these sources, in order to to characterize their efficiency, origin, and impact on their host galaxies. Our results can be used as input in state-of-the-art chemical evolution models (e.g., [10]) which attempt to reproduce the processes shaping the evolution of galaxies at different cosmic times.

Throughout this work, we adopt a \( \Lambda \)-CDM cosmology with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.3 \) and \( \Omega_\Lambda = 0.7 \). Section II presents our sample and the data reduction. In Section III we show the methods used to identify galactic outflows. Our results are discussed in Section IV and summarized in Section V.

II. SAMPLE AND OBSERVATIONS

The DGS survey collected Herschel observations for 48 low-metallicity (12+\( \log(O/H) \leq 8.4 \)) dwarf galaxies in the local Universe (\( D \lesssim 200 \) Mpc) with stellar masses \( \log(M_*/M_\odot) \sim 6 - 10 \). The PACS and SPIRE instruments on board of the Herschel Space Observatory provided photometric and spectroscopic coverage of the far-infrared (FIR) emission in these sources. The sample is divided in 37 compact objects and 11 more extended sources. We excluded the latter from our analysis as they have only partial PACS coverage. Additionally, two faint sources were dropped from the PACS spectroscopy program because of time constraints [11]. We downloaded Herschel archival data cubes of [CII] emission for the resulting 35 galaxies. We used the Herschel Interactive Processing Environment (HIPE; [12]), version 15.0.1, on the cubes to extract the best spectrum (with the largest flux and a highest signal-to-noise) for each source. We further avoided 6 objects because of their too much noisy [CII] spectra. Our final sample thus contains 29 dwarf galaxies. For each source, we made a first Gaussian fit of the line to have an initial estimate of its FWHM,
and used this value to define the continuum emission as the region between $2 - 5 \times FWHM$ (both redward and blueward of the line peak), so to avoid the possible wings of the outflow component and the noisy end of the spectrum. Then, we modeled the continuum with a polynomial curve of order 1 or 2, or with a Chebyshev series of third degree, and simultaneously fit the line and continuum for each source. We took as the best continuum modeling the one giving the minimum reduced $\chi^2$ to the fit. Finally, we subtracted the continuum to each spectrum in order to better analyze the line and wings profiles. We searched for outflow signatures in the spectra of each individual galaxy by fitting their [CII] emission lines with a single and double Gaussian profile (the latter including a narrow and broad component), and by inspecting the corresponding residuals. In some cases, the presence of outflowing gas is clearly evidenced by the broad component which, by matching the high-velocity wings of the spectra, improves the fit. We also found that, for three galaxies in our sample, a three-Gaussian fit (with two narrow and one broad components) provided a better $\chi^2$ than obtained from the two-Gaussian modeling (likely because of their evidence for merging activity). We used the latest version of the Code Investigating GALaxy Emission (CIGALE; [13–15]) to compute the physical parameters (e.g., stellar masses) of our galaxies through spectral energy distribution fitting. SFRs were computed from the spectra. In particular, we adopted the prescription presented by [16] (see their Eq. 7), with the observed [CII] luminosity as a tracer of the total SFR.

III. ANALYSIS

We compared the reduced $\chi^2$ of the fit with the single ($\chi^2_{\text{single}}$) and double ($\chi^2_{\text{double}}$) Gaussian profiles, considering the presence of the possible outflow component only when $\chi^2_{\text{double}} < \chi^2_{\text{single}}$. As a result, we found that 11 out of 29 galaxies show clear signs of outflowing atomic gas as traced by the [CII] emission, while in the remaining sources the outflow (if present) is too faint to be individually detected. In the following, we first compute the properties of the 11 sources with outflow evidence, and then we estimate the average outflow features from the entire galaxy sample through line and cube stacking.

III.1. Individual outflow detection

The galaxies with clear outflow detections are characterized by evident wings in the spectra at typical velocities of $\pm 400 \text{ km s}^{-1}$, where the residuals between the single Gaussian model and the line present an excess of emission. In these cases, such residuals are reduced to the noise level by adopting a double Gaussian profile, including a broad component to account for the broad wings in the spectra. We computed the FWHM of the narrow and broad component as $FWHM = (FWHM_{\text{obs}}^2 - FWHM_{\text{inst}}^2)^{1/2}$, where $FWHM_{\text{obs}} = 2.355\sigma$ is the observed width of the line (with $\sigma$ the standard deviation of the corresponding Gaussian function), and $FWHM_{\text{inst}}$ is the PACS instrumental line width (i.e., 240 km s$^{-1}$ for [CII]). We found that the broad component has, on average, a FWHM more than two times larger than the narrow component, with means of $\sim 526$ and 213 km s$^{-1}$, respectively. Then, we obtained the [CII] luminosity of both components by following [17] as:

$$L_{[\text{CII}]} = 1.04 \times 10^{-3} S_{[\text{CII}]} \Delta v D_L (z_{[\text{CII}]})^2 \nu_{\text{obs}} [L_\odot],$$

where $S_{[\text{CII}]} \Delta v$ is the velocity-integrated line flux in units of Jy km s$^{-1}$, $\nu_{\text{obs}}$ is the observed peak frequency in Gigahertz, and $D_L$ is the luminosity distance in Mpc at the redshift derived from the
centroid of the single Gaussian fit of the \([\text{CII}]\) line (i.e., \(z_{\text{CII}}\)). We used the \([\text{CII}]\) luminosity of the narrow component to estimate the SFR\([\text{CII}]\) of each galaxy (see Sect. II). The uncertainty on \(L_{\text{CII}}\) was obtained by using the errors on the Gaussian fit parameters of each \([\text{CII}]\) spectrum to perturb the corresponding integrated flux \(N = 1000\) times. We then took the 16th and 84th percentiles of the resulting distribution as the error on \(S_{\text{CII}}\Delta v\), propagating it to \(L_{\text{CII}}\) based on Eq. 1.

III.2. Stacking of the spectra

In order to get the average outflow properties of our galaxy sample and to investigate the possible presence of the outflows in the sources with no individual detection, we performed a stacking of their \([\text{CII}]\) spectra. First, we used the computed \(z_{\text{CII}}\) to align each continuum-subtracted spectrum to the \([\text{CII}]\) rest-frame frequency. Then, we proceeded with a variance-weighted stacking as

\[
S_{\text{stack}} = \frac{\sum_{i=1}^{N} S_i \cdot w_i}{\sum_{i=1}^{N} w_i},
\]

where \(S_i\) is the \([\text{CII}]\) spectrum of the \(i\)-th galaxy, \(N\) is the number of stacked sources, and \(w_i = 1/\sigma_i^2\) is the weighting factor (with \(\sigma_i\) the noise associated to each spectrum). To estimate \(\sigma_i\), we avoided the velocity range \([-800; +800]\) km s\(^{-1}\) in order to exclude contamination from the \([\text{CII}]\) emission and the broad wings.

Fig. 1 shows the result of this procedure. As done for the individual outflow detections, we fitted the stacked spectrum with both a single and double Gaussian profile, comparing the corresponding reduced \(\chi^2\) and residuals. The spectrum shows clear signs of broad wings at velocities \(\pm \sim 400\) km s\(^{-1}\) as evidenced by the corresponding large residuals obtained by using a single Gaussian function to fit the line profile. The two-component Gaussian clearly improves the fit, resulting in a reduced \(\chi^2\) smaller than unity and a residual flux consistent with the noise over the entire velocity range. To ensure that the stacking result is not biased by the presence of a few sources with stronger evidence of outflows, we performed a delete-\(d\) jackknife resampling. We recomputed 500 times the stacked spectrum by excluding each time \(\sim 10\%\) of the sample (i.e., 3 galaxies), in order to get an estimate of the wings variation while still preserving a large enough sample to stack. The resulting FWHM distributions of both Gaussian components are in agreement with what obtained by stacking the whole sample, implying that our results are not affected by outliers. As done for the individual sources showing broad wings, we estimated the \([\text{CII}]\) luminosity of the broad component of the stacked spectrum through Eq. 1, as well as their FWHM.

III.3. Stacking of the cubes

To characterize the average spatial extent of the atomic outflows in our galaxies, we produced a stacked \([\text{CII}]\) cube. As done for the spectra in Sect. III.2, we first aligned the spectral axes of each continuum-subtracted cube to the \([\text{CII}]\) rest-frame emission. Then, we also spatially aligned the cubes by centering them on the peak of the corresponding \([\text{CII}]\) intensity map produced by summing the fluxes from the spectral channels including the emission line. We used a variance-weighted stacking as in Eq. 2, where now the \(\sigma\) in the weighting factor represents the spatial rms estimated in each channel of the cube in regions free of emission. We produced velocity-integrated \([\text{CII}]\) maps of the wings in the low- and high-velocity tails at \([-500, -250]\) and \([250; 500]\) km s\(^{-1}\),
respectively (Fig. 2), which resulted in high-significance detections of \( \gtrsim 20\sigma \). We then summed the two maps together to obtain the total outflow emission, detected at \( \gtrsim 30\sigma \) and that we used to obtain the average outflow radius. In particular, we fitted a 2D Gaussian function to the total intensity map of the wings obtaining the outflow circularized effective radius defined as \( R_{\text{out}} = \sqrt{ab} \), where \( a \) and \( b \) are the best-fit beam-deconvolved semi-major and semi-minor axis of the Gaussian, respectively. We found \( R_{\text{out}} = 0.99 \pm 0.39 \) kpc, where the uncertainty was computed through the errors of \( a \) and \( b \) from the fit. Our result is in good agreement with previous estimations from the literature in local galaxies (e.g., [18]).

**IV. RESULTS AND DISCUSSION**

**IV.1. Outflow efficiency**

To fully characterize the outflows and their impact on the evolution of dwarf galaxies, a key parameter is the so-called mass-loading factor, i.e., the ratio between the rate of gas mass expelled out of the galaxy and the rate of star formation. This quantity is an estimate of the outflow efficiency and it represents a key ingredient for simulations trying to explain the physics of barions in galaxies. We used the [CII] luminosity of the broad component (both for individual outflow detections and stacked spectrum) to estimate the mass of the outflowing atomic gas. In particular, we considered the following relation by [19]:

\[
M_{\text{out}}/M_\odot = 0.77 \left( \frac{0.7L_{\text{[CII], broad}}}{L_\odot} \right) \left( \frac{1.4 \times 10^{-4}}{X_{\text{C}^+}} \right) \times \frac{1 + 2e^{-91K/T} + n_{\text{crit}}/n}{2e^{-91K/T}},
\]

where \( X_{\text{C}^+} \) is the \( \text{C}^+ \) abundance per hydrogen atom, \( n_{\text{crit}} \sim 3 \times 10^3 \text{ cm}^{-3} \) is the critical density of the [CII] transition (e.g., [5]), \( T \) and \( n \) are the gas temperature and density, respectively. Eq. 3 was derived under the assumption of an optically thin [CII] emission (e.g., [7]), and assuming
Fig. 2. [CII] intensity maps of the wings and core of the outflow emission. Contour levels are shown in white at 3, 5, and 7σ, where σ is the rms of the integrated intensity map. The PACS beam is shown in the lower-left corner of the first panel, and a reference scale of 5 kpc is displayed in the central panel.

$X_{C^+} = 1.4 \times 10^{-4}$ [20], $T$ in the range 60-200 K (see [7] and references therein), and $n \gg n_{\text{crit}}$, all typical of PDRs. In addition, the factor 0.7 in the parenthesis of Eq. 3 is the fraction of [CII] emission arising from PDRs, while the remaining 30% is supposed to come from the other phases of the ISM. We thus computed the atomic mass outflow rate within the time-averaged expelled shells or clumps scenario [21]:

$$M_{\text{out}} = \frac{v_{\text{out}} \times M_{\text{out}}}{R_{\text{out}}},$$

where $v_{\text{out}} = \frac{\text{FWHM}_{\text{broad}}}{2} + |v_{\text{broad}} - v_{\text{narrow}}|$ is the outflow velocity (with $\text{FWHM}_{\text{broad}}$ the full width at half maximum of the broad component, while $v_{\text{broad}}$ and $v_{\text{narrow}}$ the velocity peaks of the broad and narrow components, respectively), and $R_{\text{out}}$ is the outflow radius as obtained in Sect. III.3. This model is consistent with a constant outflow rate over time.

We show in Fig. 3 (left panel) the atomic outflow rate as a function of the SFR as obtained from the spectral stacking of our galaxies and from individual detections of the broad component, and color-coded by their mass-loading factors. We also report the best-fit relations between molecular outflow rate and SFR for both local AGNs and starburst/SFGs as found by [18]. AGN hosts are characterized by $\eta \gg 1$ in the range of SFR spanned by our sample, while SFGs have typically lower outflow efficiencies. Most of our galaxies lie along the 1:1 relation (i.e., $\eta = 1$) as also found in previous observations of local SFGs (e.g., [18, 24]), with an average mass-loading factor $\eta \sim 1.3$. We note that, if we assume that all the phases of the ISM contribute equally to the outflow rate (e.g., [18]), we could obtain an average outflow efficiency three times larger than estimated (i.e., $\eta \geq 3$). From the stacking we found similar results, that is $\eta = 0.97$, obtained by assuming the corresponding median SFR, i.e., $0.22 \, M_\odot \, \text{yr}^{-1}$. The best fit to the individual outflow detections provided $\log(M_{\text{out}}) = 1.13 \log(SFR_{\text{CII}}) + 0.05$, with the slope in agreement with that found by [18] for local SFGs, but closer to the 1:1 relation. Furthermore, we compare our results to those found at high redshift by [22] and [7], who took advantage of [CII] emission detected in SFGs at $4 < z < 6$. Both results are in nice agreement with our low-redshift findings, suggesting that similar feedback mechanisms can be in place in this kind of galaxies.
Fig. 3. Left: Atomic outflow rate as a function of the SFR, for both individual detections of broad wings (squares) and from line stacking of our sample (star). The red and blue lines are the best-fit relations between molecular outflow rate and SFR for local AGN hosts and star-forming/starburst galaxies by [18], while the shaded regions are the corresponding uncertainties. The solid green line with the shaded area represent a linear fit to the DGS galaxies with individual outflow detections and its uncertainty, respectively. The dashed line reports the 1:1 relation. We also show the results from [CII] stacking of $z \gtrsim 5$ SFGs by [22] (hexagon) and [7] (diamond). All markers are color-coded for their mass-loading factors. Right: Relation between the outflow velocity and the escape velocity. Galaxies of our sample with individual outflow detections are shown as circles. Nearby dwarf galaxies are shown as diamonds [23]. The dashed line reports the 1:1 relation. All data are color-coded for their stellar mass.

IV.2. Chemical enrichment of the intergalactic medium

To understand if outflows are able to bring gas outside of low-mass sources, we computed the escape velocities of our galaxies ($v_{\text{esc}}$) needed by outflows to escape their gravitational potential. Following [18], we assumed a Navarro-Frenk-White (NFW) dark matter density profile [25], resulting in:

$$v_{\text{esc}}(r) = \sqrt{2|\Phi(r)|} = \sqrt{\frac{2M_{\text{halo}}G}{r(\ln(1+c) - c/(1+c))} \ln(1 + r/r_s)},$$

(5)

where $G$ is the gravitational constant, $c$ is the concentration parameter$^1$, $M_{\text{halo}}$ is the mass of the halo, and $r_s = r_{\text{halo}}/c$ is the characteristic radius, with $r_{\text{halo}}$ as the virial radius. The halo mass was obtained from the stellar mass of the corresponding galaxy through abundance matching.

$^1$Instead of assuming a single value of $c$ for each galaxy, we used the $z = 0$ relation by [26] to link the concentration parameter to the halo mass as $\log(c) = 0.76 - 0.1 \log(M_{\text{halo}})$. 


techniques [27], while the virial radius is defined as (e.g., [28]):

$$r_{\text{halo}} = \left( \frac{3M_{\text{halo}}}{4\pi 200 \rho_{\text{crit},0}} \right)^{1/3},$$

(6)

with $\rho_{\text{crit},0}$ being the present critical density.

Fig. 3 (right panel) shows the velocity of the outflow as a function of the escape velocity for each galaxy with individual outflow detection. As a comparison, we display the results by [23] for local dwarf galaxies. All of our sources are close or above the relation, with outflow velocities higher than (or comparable to) the escape ones, in agreement with the results for local dwarfs. This suggests that galactic winds in these objects are able to bring material at least in their circumgalactic medium (CGM), having a large impact on their baryon cycle.

V. CONCLUSIONS

In this paper, we present the characterization of galactic outflows in local dwarf galaxies through *Herschel* observations of their [CII] emission. We found clear evidence of outflowing gas in 1/3 of our sample. For each source, we estimated the rate of the gas mass expelled by the outflow and compared that with the SFR to put constraints on the outflow efficiency, finding an average mass-loading factor consistent with unity. This result can be a factor of three larger when accounting for the other phases (i.e., ionized and molecular) of the ISM, that are not included in the atomic gas traced by the [CII] emission. We then computed the velocities needed by outflows to bring the gas outside of the dark matter halos of our galaxies. We found that, despite their low efficiencies, outflows in dwarf galaxies are able to expel large amount of material into the CGM of their host, where gas can be later re-accreted by galaxies and used again for star formation. Outflows in most of our galaxies are even able to enrich their intergalactic medium, making part of the gas no longer available for their baryon cycle. Our results on the outflow efficiencies could be used for tuning chemical evolution models trying to reproduce observational properties of both local and distant galaxies, providing a better description of the physical processes contributing to their evolution through cosmic time.

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