Systematic study of outflows in the Local Universe using CALIFA: I. Sample selection and main properties

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Accepted 2018 October 26. Received 2018 October 26; in original form 2018 July 30

ABSTRACT

We present a sample of 17 objects from the CALIFA survey where we find initial evidence of galactic winds based on their off-axis ionization properties. We identify the presence of outflows using various optical diagnostic diagrams [e.g. EW(Hα), [N II]/Hα, [S II]/Hα, [O I]/Hα line-ratio maps]. We find that all 17 candidate outflow galaxies lie along the sequence of active star formation in the M⋆ versus star-formation rate (SFR) diagram, without a clear excess in the integrated SFR. The location of galaxies along the star-formation main sequence does not influence strongly the presence or not of outflows. The analysis of the SFR density (ΣSFR) reveals that the CALIFA sources present higher values when compared with normal star-forming galaxies. The strength of this relation depends on the calibrator used to estimate the SFR. This excess in ΣSFR is significant within the first effective radius supporting the idea that most outflows are driven by processes in the inner regions of a galaxy. We find that the molecular gas mass density (Σgas) is a key parameter that plays an important role in the generation of outflows through its association with the local SFR. The canonical threshold reported for the generation of outflows – ΣSFR > 0.1 M⊙ yr−1 kpc−2 – is only marginally exceeded in our sample. Within the Kennicutt–Schmidt diagram we propose a domain for galaxies hosting starburst-driven outflows defined by ΣSFR > 10−2 M⊙ yr−1 kpc−2 and Σgas > 101.2 M⊙ pc−2 within a central kiloparsec region.

Key words: ISM: jets and outflows – galaxies: ISM – galaxies: star formation – galaxies: structure.

1 INTRODUCTION

Galactic outflows have been invoked in many astrophysical problems to explain some local and global properties of galaxies like the tight correlation in the stellar mass and metallicity (Heckman 2002; Tremonti et al. 2004), the metal enrichment of intergalactic medium (Pettini et al. 1998; Veilleux, Cecil & Bland-Hawthorn 2005), and in the current models of galaxy formation, where the amount of feedback from outflows is a key ingredient that is not well constrained (e.g. Aguirre et al. 2001; Springel & Hernquist 2003; Scannapieco et al. 2006). Even their global effect, either in preventing or triggering star formation is under discussion (e.g. Silk 2013).

Outflows are driven either by supernovae explosions (SN), stellar winds, or by active galactic nuclei (AGNs), or some combination of these – we refer to such objects collectively as active galaxies. Nuclear star formation is found to occur in the nuclear regions of most Seyfert galaxies (Esquej et al. 2014) and so both may act in concert to generate outflows, although just how this works is mysterious (Hopkins & Quataert 2010). The scale of these outflows depends partly on the escape velocity via the gravitational potential well...
(Tanner, Cecil & Heitsch 2017). A high fraction of active galaxies with lower total mass are expected to host outflows because of their lower escape velocity (Martin 1998; Bland-Hawthorn, Sutherland & Webster 2015). This favours the loss of large fractions of gas and metals in these galaxies (e.g. Barrera-Ballesteros et al. 2018). Massive galaxies retain their baryons more effectively although considerable recycling throughout the halo can take place (Cooper et al. 2008; Tanner, Cecil & Heitsch 2016).

Although there has been an extensive effort on the theory of outflows, the observational counterparts are far from being understood, mainly because their multiphase nature makes them hard to detect and interpret. Numerical simulations today are far from capturing the full complexity of galactic winds too (e.g. Martel 2011). Outflows have been detected at high redshift (Coil et al. 2011; Genzel et al. 2014), in the nearby Universe (e.g. Franx et al. 1997; Fogarty et al. 2012; Ho et al. 2014, 2016), even in the Local Group (Bland-Hawthorn & Cohen 2003; Su, Slattery & Finkbeiner 2010; Fox et al. 2015). Galactic winds have also been detected across most galaxy types (e.g. Axon & Taylor 1978; Bland & Tully 1988; Heckman, Armus & Miley 1990; Lehner & Heckman 1996; Martin 1998; Rupke, Veilleux & Sanders 2005a). In spite of all these studies, the nature, properties, and influence of outflows in galaxy evolution are still unclear. How, why, and where outflows are produced in a galaxy, as well as the loss rates of mass, metals, and energy that they produce are still open questions that have not been completely understood (see Veilleux et al. 2005, for an extensive review). High quality spatially resolved spectroscopic data could bring some light in the understanding of these processes.

A primary problem when studying outflows is the detection itself. Outflows are commonly studied in starburst galaxies or in ultraluminous infrared galaxies due to their large star formation rates (SFR), making them more prone to develop outflows. This means that studies of outflows are biased towards galaxies with high star formation rates. Other studies analyse outflows directly associated with strong AGNs, in particular with those ones directly pointing towards the observers (e.g. BL Lacs or Blazars, Antonucci & Ulvestad 1985; Scarpa et al. 2000; Celotti & Ghisellini 2008), being biased towards these particular kind of objects. Thus, there are few systematic studies of the presence of outflows in an unbiased population of galaxies (cf. Sharp & Bland-Hawthorn 2010; Ho et al. 2016).

Early studies of galaxies with bona fide outflows have constructed the basis in the methodology to detect and characterize them (e.g. Heckman et al. 1990; Lehner & Heckman 1996; Rupke et al. 2005a; Rupke, Veilleux & Sanders 2005b). This methodology is based on the study of the spatial distribution of certain emission line ratios over the extraplanar regions of disc galaxies, and their comparison with certain kinematic properties. Although these studies provide moderate samples of outflows, they do not provide well-defined statistics about the frequency of galaxies hosting outflows and their properties in comparison with those not hosting them. In this study, we address the search and characterization of the statistical properties of galaxies hosting outflows. For this purpose, we exploit the CALIFA integral field spectroscopic survey (IFS) that achieved a large sample (835) of galaxies observed from the Calar Alto telescope in Spain.

Different optical IFS surveys (e.g. SAMI, MaNGA, AMUSING, Allen et al. 2015; Bundy et al. 2015; Gallbany et al. 2016) have already taken advantage of this technique to study the spatially resolved properties of the warm ionized gas component of outflows (e.g. Sharp & Bland-Hawthorn 2010; Rich, Kewley & Dopita 2011; Fogarty et al. 2012; Ho et al. 2014; Wild et al. 2014; Rich, Kewley & Dopita 2015; Ho et al. 2016; Prieto et al. 2016; López-Cobá et al. 2017; Maiolino et al. 2017). The use of larger samples allows us to perform statistical analysis not only on the outflowing galaxies, but on those that do not present outflows, i.e. a properly selected control sample typically overlooked in resolved galaxy surveys.

The layout of this article is as follows: In Section 2, we present the data and physical properties (data products) extracted from them used along this article; describing the analysis of the stellar population in Section 2.1 and of the ionized gas in 2.2. The outflow sample analysis of these data products is presented in Section 3. It includes the selection of candidates that host outflows in Section 3.1, and a description of their distribution along the colour-magnitude diagram (CMD) in Section 3.2.1, their masses and morphologies in Section 3.2.2, and source of the ionization in the central regions in Section 3.2.3. All of these properties are presented in comparison with those of galaxies without a host outflow. The comparison of the integrated SFR (Section 3.2.4), the radial distribution of the SFR density (Section 3.3), and their central values (Section 3.3.1), have lead to the main results of this investigation, discussed in Section 4. The conclusions and future perspectives are presented in Section 5. In this work the standard ΛCDM cosmology with $H_0 = 70 \text{km s}^{-1}\text{Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_L = 0.7$ is adopted.

2 DATA CUBES AND DATA PRODUCTS

The analysed sample comprises all galaxies in the CALIFA survey1 (e.g. Sánchez et al. 2012) up to January 2018, i.e. those with good quality spectroscopic data observed at the 3.5-m of Centro Astronómico Hispano-Alemán (CAHA). It includes the 667 galaxies comprising the 3rd CALIFA Data Release (e.g. Sánchez et al. 2016c), and in addition we include those galaxies with good quality data that were excluded from DR3 because either they did not have SDSS-DR7 imaging data (a primary selection for DR3) or they were observed after the final sample was closed, as part of the CALIFA-extended programs (e.g. García-Benito et al. 2017; PISCO: Galbany et al. 2018). The final sample comprises a total of 835 galaxies. All galaxies were selected following the same primary selection criteria of the main CALIFA survey, i.e. that their optical extent fits within the field-of-view (FoV) of the instrument, relaxing other selection criteria outlined in Walcher et al. (2014) like the redshift range or the absolute magnitude. Thus, this compilation is essentially a diameter-selected survey.

The details of the CALIFA survey, including the observational strategy and data reduction are explained in Sánchez et al. (2012) and Sánchez et al. (2016c). All galaxies were observed using PMAS (e.g. Roth et al. 2005) in the PPak configuration (e.g. Kelz et al. 2006), covering an hexagonal FoV of 74 arcsec × 64 arcsec, which is sufficient to map the full optical extent of the galaxies up to two to three disc effective radii. This is possible because of the diameter selection of the CALIFA sample (e.g. Walcher et al. 2014). The observing strategy guarantees complete coverage of the FoV, with a final spatial resolution of full width at half-maximum (FWHM) ~ 2.5 arcsec, corresponding to ~1 kpc at the average redshift of the survey (e.g. García-Benito et al. 2015; Sánchez et al. 2016c). The sampled wavelength range and spectroscopic resolution for the adopted setup ($3745−7500 \, \AA$, $\lambda/\Delta \lambda \sim 850$, V500 setup) are more than sufficient to explore the most prominent ionized gas emission lines from [O II] $\lambda 3727$ to [S II] $\lambda 6731$ at the redshift of our targets,

1http://califa.caha.es
and to deblend and subtract the underlying stellar population (e.g. Kehrig et al. 2012; Cid Fernandes et al. 2013, 2014; Sánchez et al. 2013, 2014, 2016a). The current data set was reduced using version 2.2 of the CALIFA pipeline, whose modifications with respect to previous ones (e.g. Sánchez et al. 2012; Husemann et al. 2013; García-Benito et al. 2015) are described in Sánchez et al. (2016c). The final product of the reduction is a data cube comprising the spatial information in the x and y axis, and the spectral one in the z axis. For further details of the adopted data-format and the quality of the data see Sánchez et al. (2016c).

2.1 Stellar population analysis

The data cubes were analysed using the PIPE3D pipeline (e.g. Sánchez et al. 2016a). PIPE3D performs a combination of multiple synthetic stellar population (SSP) templates, extracted from the MILES (e.g. Sánchez-Blázquez et al. 2006; Vazdekis et al. 2010; Falcón-Barroso et al. 2011) and the gsd156 library (e.g. Cid Fernandes et al. 2013), to determine the best stellar model. These templates cover a wide range in metallicities from subsolar to supersolar, with different stellar ages from 1 Myr to 14 Gyr. Before starting with the fitting process, a tessellation procedure is performed on the data cube in order to increase the signal-to-noise (S/N) of the stellar continuum. This segmentation produces tesselas of different sizes to achieve the desired S/N. All the spectra in each spatial bin is coadded and is treated as individual spectra, and at the end of the fitting analysis, a dezonification of the coadded spectra is applied by taking into account the area of each tessella (see Cid Fernandes et al. 2013). A 2D set of data products, described in Sánchez et al. (2016b), are obtained from the SSP fitting. One of such data products is the cumulative stellar mass at different epochs. The stellar mass (M∗) of a galaxy is estimated by adding the mass in each bin from the tessellation procedure, taking into account the local luminosity of each spectrum and the mass-to-light ratio (see González Delgado et al. 2015). For a given age (that defines a look-back time), the stellar mass is

\[ M_{\ast, age} = \sum_{j=1}^{n} M_{j} \]  

where the \( j \) index runs over the number of templates in the SSP library up to the considered age. Integrated over the complete set of SSP templates, it provides the actual stellar mass of the galaxy. As shown in Sánchez et al. (2016b) and Bitsakis et al. (in preparation), this stellar mass is totally consistent with the one provided using multiband photometric data.

Having estimated the stellar mass at a certain lookback time, it is straightforward to estimate the SFR at this particular time. The SFR would be the differential mass at two adjacent times (Δ\(t_{age}\) over the time range between them Δ\(t_{age}\):

\[ \text{SFR}_{age} = \frac{\Delta M_{age}}{\Delta t_{age}}. \]  

In González Delgado et al. (2017) and Sanchez et al. (in preparation), it has been explicitly shown that this SFR, which we will define as SFR\(\text{SSP}\), correlates very well with other estimations of the SFR.

2.2 Ionized gas analysis

Once obtained the best stellar population model for each spectra in the data cube, it is subtracted from the original cube to obtain a pure-gas cube, following the procedures described in Sánchez et al. (2016a). Then, we analysed each of the detected emission lines in each individual spectrum within this cube using the fitting code FIT3D (e.g. Sánchez et al. 2016b). For this particular study, it was performed by a non-parametric method based on a moment analysis in the pure-gas cube as described in Sánchez et al. (2016b). We recover the main properties of the emission lines, including the integrated flux intensity, line velocity, and velocity dispersion. For this analysis, we assume that all emission lines within a spaxel share the same velocity and velocity dispersion. The result of this procedure applied to each data cube is a set of bi-dimensional maps of the considered parameters, with their corresponding errors, for each analysed emission line.

In addition to these parameters the equivalent width (EW) of each emission line is derived. In particular that of H\(\alpha\) that will be used in our scheme of classification of the ionization source. To derive this quantity the stellar continuum flux density is estimated prior to the subtraction of the stellar model. Then, the integrated flux of each emission line, derived by the moment analysis is divided by this continuum density, at the wavelength of the emission lines, resulting in the required EW.

3 OUTFLOW SAMPLE ANALYSIS

3.1 Candidates selection

Highly inclined galaxies are particularly good candidates to detect extraplanar ionized gas and therefore they are more suitable candidates to host outflows. We started the selection process by considering only those galaxies with high inclination (i > 70°), in order to minimize the effect of mixing of ionization along the line-of-sight due to projection effects. Although we cannot preclude for a certain level of contamination. Using this criterion results in 203 galaxies. Then, we select those galaxies with an increase in the optical line ratios [N II]/H\(\alpha\), [O III]/H\beta, [S II]/H\alpha, and [O I]/H\alpha along the semiminor axis and the disc vertical direction. These increments are characteristic of shocks produced by galactic outflows (Veilleux & Rupke 2002; Veilleux et al. 2005), although they are not exclusive of these processes. Here increase means that the ionization is not compatible with the typical line-ratios observed in SF regions. Outflows are favoured to expand in the direction of the lowest gradient of pressure, which is found along the semiminor axis or in the extraplanar region. As larger the inclination, sharper will be observed the separation between the soft ionization from the SF regions, and the harder would be the ionization produced by shocks in outflows.

Within the high-inclined subsample we find that 39 galaxies present such line ratios enhancement. In Fig. 1 we present one galaxy, NGC 6286, that complies with these criteria. In this figure it is clear how extraplanar gas extends beyond the continuum extension. Hereafter, we will refer to the disc region, regardless of the inclination, as the area located within ±5 arcsec from the semimajor axis, and as extraplanar region to the area located farther than 5 arcsec of this axis. This transition region varies in each galaxy, although it represents a mean value at the average redshift of CALIFA (∼2 kpc). NGC 6286 clearly shows ionized gas in the extraplanar region, with larger line ratios than the ones detected in the disc. Even more, this galaxy presents the archetypal biconical distribution expected in an outflow in both the emission line intensities and ratios. However, this morphological structure does not exist in all outflows. In many cases they present a variety of complex
Figure 1. Example of a wind galaxy selected from the CALIFA sample with the high inclination and line ratio criteria. This galaxy, NGC 6286, is part of the candidates galaxies with a host outflow. The top left-hand panel shows the RGB image of NGC 6286, where red is [N II], green is the V-band, and blue is [O III]. The top central panel is the spatially resolved [N II]/Hα line ratio map. The black contour in this, and in the others maps, indicate the continuum level at $0.1 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, while the intensity colour bar is in the right-hand corner of each map. The top right-hand panel is the spatially resolved [O III]/Hβ line ratio map. The bottom left-hand panel shows the 2D-equivalent width of Hα estimated with the SSP fitting analysis. The bottom central panel shows the [S II] $\lambda\lambda$6717, 6731/Hα line ratio map, and the bottom right-hand panel, the [O I] $\lambda$6300/Hα line ratio map.
of the galaxy inclination, is to move the SF regions towards the composite or the LINER region in the diagnostic diagrams (e.g. Zhang et al. 2017). Therefore, if we had adopted a lower value in the inclination angle, or if we had searched for outflows regardless of their inclination, it would increase the DIG fraction in our sample.

A characteristic that shares both DIGs and HOLMES is their low equivalent width of $H\alpha$ (e.g. Stasińska et al. 2008). As a method to distinguish this ionization from shocks, we adopted the WHAN diagram introduced by Cid Fernandes et al. (2011) that uses the $[\text{N}\,\text{II}]/H\alpha$ versus equivalent width of $H\alpha$ to distinguish between true and fake AGNs [retired galaxies with $\text{EW}(H\alpha) < 3\text{ Å}$]. We impose this additional criterion to select galaxies dominated by shocks by excluding those ones in which the extraplanar ionized gas is largely dominated by regions with $\text{EW}(H\alpha) < 3\text{ Å}$ (i.e. if they are compatible with eDIG, either post-AGBs or HOLMES ionization).

Fig. 2 shows an example of the implementation of the classical diagnostic diagrams ($[\text{N}\,\text{II}]/H\alpha$, $[\text{S}\,\text{II}]/H\alpha$, and $[\text{O}\,\text{I}]/H\alpha$ versus $[\text{O}\,\text{III}]/H\beta$) along with the WHAN diagram, for the spatially resolved components, both disc and extraplanar regions, applied to the archetypal outflow galaxy NGC 6286. Although a fraction of the extraplanar gas falls below the SF demarcation line by K01, probably due to projection effects, and a fraction of the disc gas falls in the sAGN region of the WHAN diagram, it is clear that the extraplanar gas is not compatible with being ionized by old stars but by a strong source of ionization. We have included in these diagrams the locus of AGN and shock ionization from Sharp & Bland-Hawthorn (2010), imposing the condition that the ionized gas should have an $\text{EW}(H\alpha) > 3\text{ Å}$ in these regions, and finally (v) a biconical, bipolar, or a symmetric morphology in the extraplanar gas, not homogeneously distributed at any galactocentric distance above the disc. By applying these criteria we ended up with 17 galaxies candidates to host an outflow.

In summary, to select galaxies that host an outflow we adopt the following selection criteria: (i) high-inclined galaxies, (ii) detection of extraplanar ionized gas, (iii) identification of an enhance in the line ratios along the semiminor axis, (iv) $\text{EW}(H\alpha) > 3\text{ Å}$ in these regions, and finally (v) a biconical, bipolar, or a symmetric morphology in the extraplanar gas, not homogeneously distributed at any galactocentric distance above the disc. By applying these criteria we ended up with 17 galaxies candidates to host an outflow.

We will refer hereafter to this subsample as galaxies candidates with a host outflow. We cannot firmly conclude that they host an outflow since we lack the required high spectral resolution data to perform a detailed kinematics analysis. Thus, we cannot resolve the asymmetries in the emission line profiles, frequently detected in outflows due to the expansion of the gas, or analyse the known correlation between the velocity dispersion and the line ratios, a unique signature of shock ionization (e.g. Dopita & Sutherland 1995; Lehner & Heckman 1996; Monreal-Ibero et al. 2010; López-Cobá et al. 2017). For instance, in the special case of...
NGC 6286 the line-of-sight ionized gas velocity dispersion significantly increases outside the stellar disc (according to fig. 5 in Shalyapina et al. 2004).

In Table 1 we summarize the main properties of this sample of galaxies and in Appendix A we present the same plots shown for NGC 6286 (i.e. equivalent to Figs 1 and 2), for all the outflow candidates in the CALIFA sample. In addition, we list in Table B1 the remaining 26 galaxies that were not classified as outflows by the imposed criteria, although they present eDIG, and in many cases, show an enhancement in the analysed line ratios. Following the criteria indicated before we list in this table the fraction of spaxels in the extraplanar region being compatible with either DIG, AGN-driven, or SF-driven outflows, based on the combination of the classical diagnostic diagrams, the value of the EW(Hα), and the Kewley et al. (2001) and Sharp & Bland-Hawthorn (2010) demarcation lines.

So far, we finish our classification process with three different subsamples: (i) Those galaxies with $i < 70^\circ$, which we will denote as the CALIFA low-inclination sample, or just CALIFA sample for simplicity, since it dominates the number statistics (615 galaxies), and therefore comprises a representative subsample of the original one, (ii) the high-inclination galaxies (203 galaxies), and (iii) the outflow candidates (17 galaxies).

3.2 Properties of outflow candidates

In this section we explore the global properties of the candidates with a host outflows in comparison with those of the other two subsamples of galaxies.

3.2.1 The colour-magnitude diagram

Fig. 3 shows the distribution of the three galaxy samples in the CMD for the $(g − r)$ colour versus the $g$-band absolute magnitude. The galaxies from CALIFA span over the full CMD from the red sequence to the blue cloud and over the intermediate region known as green valley, populated by transition galaxies and AGN hosts (e.g. Sánchez et al. 2018). The global properties of the CALIFA sample have been reported in previous papers for the different data releases (e.g. Sánchez et al. 2012; Walcher et al. 2014; García-Benito et al. 2015; Sánchez et al. 2016c).

Now, we would like to investigate the differences between the three subsamples. In order to quantify these differences, we performed a 2D Kolmogorov–Smirnov test (2D KS, Peacock 1983; Fasano & Franceschini 1987; Press et al. 1992). This test compares two 2D distributions. The null hypothesis is that the observed population of galaxies (the high inclined or the candidates) is drawn randomly from a parent population (CALIFA or the highly inclined galaxies). Typically one assumes a critical $p$-value to reject the null hypothesis. In our case we will adopt a $p$-value of 0.05. As mentioned in Press et al. (1992), the resulting $p$-value in the 2D KS is only an approximation, and the test is accurate enough when $N \sim 20$ and $p$-value $\leq 0.20$. We applied the 2D KS test for the galaxies from the CALIFA subsample and the highly inclined galaxies. The resulting $p$-value is of the order of $10^{-8}$, which is highly significant. This implies that both samples are statistically different. Thus, the highly inclined galaxies are not a representative subsample of the CALIFA galaxies, at least in the space of parameters considered. This is not really surprising, because the full CALIFA sample comprises a wide range of morphological types, with a substantial fraction of elliptical galaxies, that by definition are more roundish and prompt to be rejected from a selection of high-inclined galaxies based on the semimajor to semiminor ratio.

We now applied the 2D KS test for the high-inclination and candidate galaxies. The resulting $p$-value is 0.007, which is also significant at the 0.05 confidence level. In this case it is not obvious why these two samples should be so different. An inspection of Fig. 3 shows that the candidates occupy a narrower region in the CMD diagram, $-20.5 < M_g < -17.0$, which would probably reflect a bias in the luminosity distribution. In other words, we do not find outflow candidates brighter than $-20.5$ mag, although 15 per cent of the highly inclined galaxies are located in this range. We also found that five of the outflow candidates show redder colours. These galaxies also present larger extinction values, $A_v \sim 3$ mag, as a result of their high inclination.

3.2.2 Morphological and stellar mass distributions

Fig. 3, middle panel, shows the distribution in morphology and stellar mass for the three subsamples. The CALIFA subsample is distributed in a wide variety of morphological types, from early- to late-types and irregulars, and stellar masses $6 < \log M_\odot < 12$. The high-inclination subsample is clearly dominated by spiral galaxies (1 elliptical). Their mass distribution seems to follow the same as the CALIFA subsample, but without high-/low-mass galaxies, i.e. restricted to $8.5 < \log M_\odot < 11.5$. Finally, the outflow candidate sample only includes spiral galaxies of types Sa, Sb, Sc, and Sd. The masses in this subsample are distributed in an even narrower range, $9.5 < \log M_\odot < 11$.

In order to quantify the observed differences between the mass distributions of the candidates and the other two subsamples, we applied the 1D KS test (e.g. Press et al. 1992). The KS test compares the maximum difference between two cumulative distribution functions. As larger is the difference between two distributions, larger is the probability that the two distributions arise from different samples.

With a resulting $p$-value of 0.02, the KS reveals a significant difference, at the level of 0.05, between the high- and low-inclination galaxies. This is in concordance with the result of the 2D KS estimated for the CMD in the previous section. On the other hand, the resulting $p$-value for candidates and the high-inclined galaxies is 0.25. So, the mass distribution of the candidate subsample is consistent of being drawn from the same mass distribution of the high-inclination galaxies. Thus, the candidates present a similar stellar mass as the highly inclined galaxies. Therefore, the differences found in the CMD are most probably due to a difference in colour, rather than in absolute magnitude (or mass). In summary, the galaxies hosting outflows seem to be slightly brighter, with a similar stellar mass and slightly more evolved stellar populations or with larger dust attenuations than the average inclined galaxies.

3.2.3 Central ionization

In order to investigate the dominant ionization in the nuclear region of the galaxies from the three subsamples, we coadd the emission line fluxes of Hα, Hβ, [O iii], [N ii], [S ii], and [O i] over an area of 3 arcsec $\times$ 3 arcsec at the nucleus of each galaxy. Then, we plot the line ratios in the diagnostic diagrams explained before. This is shown in Fig. 4. We note that the CALIFA and the highly inclined galaxies are distributed following the classical seagull shape, which reflects the variety of ionizing sources in these samples. A large
Table 1. Main properties of the galaxy candidates to host outflows.

| Object                      | $z^{(1)}$ | Hubble Type | $\ell^{(2)}$ | PA$^{(3)}$ | $R_e^{(4)}$ (kpc) | log $M_e^{(5)}$ ($\text{M}_\odot$) | log SFR$^{(5)}$ ($\text{M}_\odot$ yr$^{-1}$) | Nuclear Ionization$^{(5, 6)}$ | $\Sigma_{\text{HI}}^{(7)}$ ($\text{M}_\odot$ yr$^{-1}$ pc$^{-2}$) | $\Sigma_{\text{SSP}}^{(7)}$ ($\text{M}_\odot$ yr$^{-1}$ pc$^{-2}$) | $\Sigma_{\text{gas}}^{(7)}$ ($\text{M}_\odot$ pc$^{-2}$) | Interacting$^{(8)}$ | AGN: Shock: DIG$^{(9)}$ | Per cent |
|-----------------------------|-----------|-------------|--------------|-----------|------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-------------------------|-------------------------|----------|
| IC 2101                     | 0.0149    | Scd         | 79.0         | 55.1      | 4.0              | 10.5                        | 0.5                         | SF                          | $-7.17$                      | $-7.03$                      | 1.55                        | N           | 19:81:0              |          |
| IC 2247                     | 0.0143    | Sab         | 72.1         | 50.9      | 4.6              | 10.7                        | 0.0                         | AGN/SF                      | $-7.48$                      | $-7.45$                      | 1.52                        | N           | 29:69:2              |          |
| MCG-02-02-040               | 0.0119    | Scd         | 76.9         | -40.6     | 2.6              | 10.2                        | 0.1                         | SF                          | $-7.35$                      | $-6.80$                      | 1.42                        | N           | 10:90:0              |          |
| NGC4676A                    | 0.0222    | Sdm         | 77.0         | 89.4      | 8.3              | 10.9                        | 0.2                         | SF                          | $-7.84$                      | $-8.18$                      | 1.35                        | Y           | 32:67:1              |          |
| NGC0216                     | 0.0052    | Sd           | 71.1         | 59.9      | 1.3              | 9.4                         | -0.6                        | SF                          | $-7.60$                      | $-7.05$                      | 0.94                        | N           | 4:96:0               |          |
| NGC6168                     | 0.0088    | Sc           | 79.6         | 18.7      | 2.6              | 9.9                         | -0.1                        | SF                          | $-7.55$                      | $-6.97$                      | 1.30                        | N           | 1:99:0               |          |
| UGC09113                    | 0.0107    | Sb           | 72.4         | -32.8     | 2.4              | 10.1                        | -0.3                        | SF                          | $-7.96$                      | $-7.21$                      | 1.37                        | N           | 1:99:0               |          |
| UGC09165                    | 0.0177    | Sa           | 78.3         | -35.2     | 3.1              | 10.8                        | 0.7                         | SF                          | $-7.10$                      | $-6.77$                      | 1.70                        | N           | 1:99:0               |          |
| UGC10123                    | 0.0126    | Sb           | 77.7         | -35.5     | 2.7              | 10.6                        | 0.3                         | SF                          | $-7.63$                      | $-4.76$                      | 1.44                        | N           | 17:83:0              |          |
| UGC10584                    | 0.0167    | Sb           | 79.7         | 0.5       | 3.0              | 10.6                        | 0.7                         | SF                          | $-4.66$                      | $-4.38$                      | 1.01                        | N           | 10:90:0              |          |
| IC0480                      | 0.0154    | Sc           | 82.3         | 76.7      | 3.5              | 10.3                        | -0.0                        | SF                          | $-7.97$                      | $-7.15$                      | 1.21                        | N           | 0:100:0              |          |
| NGC5434B                    | 0.0190    | Sc           | 82.2         | -19.7     | 5.2              | 10.5                        | 0.6                         | SF                          | $-7.29$                      | $-7.17$                      | 1.45                        | Y           | 45:85:0              |          |
| UGC03539                    | 0.0111    | Sc           | 83.4         | 25.6      | 2.8              | 10.1                        | -0.3                        | SF                          | $-7.89$                      | $-7.15$                      | 1.33                        | N           | 14:84:0              |          |
| UGC10043                    | 0.0074    | Sab          | 82.8         | 60.6      | 3.5              | 9.9                         | -0.7                        | SF                          | $-7.79$                      | $-7.04$                      | 1.40                        | N           | 1:94:5               |          |
| NGC4388                     | 0.0084    | SBB          | 66.3         | -2.4      | 3.5              | 10.9                        | 0.7                         | AGN                         | $-6.61$                      | $-6.62$                      | 1.34                        | N           | 60:40:0              |          |
| NGC6286                     | 0.0183    | Sb           | 75.6         | -55.7     | 6.1              | 11.0                        | 0.7                         | SF                          | $-7.02$                      | $-6.87$                      | 1.51                        | Y           | 4:96:0               |          |
| MCG + 11-08-25              | 0.0136    | Sab          | 54.6         | 23.7      | 5.0              | 10.4                        | 0.3                         | SF                          | $-7.09$                      | $-6.72$                      | 1.44                        | N           | 0:100:0              |          |

Notes: 1 NASA/IPAC Extragalactic Data base. 2 HyperLeda. 3 Estimated from an isophotal analysis on the SDSS $r$-band images as described in Walcher et al. (2014). 4 Estimated from the SSP fitting analysis. 5 Estimated over an area of 3 arcsec $\times$ 3 arcsec around the nuclear region. 6 According to the Kewley et al. (2001) demarcation. 7 Estimated at 0.2 Re. 8 The interaction is refereed as if there are closer companions at the same redshift in the SDSS images or if present evidence of interaction. 9 Excitation mechanism for the observed outflow. The fractions represent the contribution in the ionization of the extraplanar gas (spaxels lying beyond 5 arcsec from the disc) by an AGN, shocks or DIG. These fractions take into account simultaneously all the points lying above the Kewley et al. (2001) curves in each diagnostic diagrams. The shock and AGN fractions was estimated by the amount of spaxels with EW(H$_\alpha$) $> 3$ Å lying at the right-hand and left-hand sides, respectively, of the shock/AGN excitation bisection lines from Sharp & Bland-Hawthorn (2010), in the three diagnostic diagrams. The DIG fraction was estimated from the amount spaxels in the extraplanar region with EW(H$_\alpha$) $< 3$ Å in the three diagnostic diagrams.
fraction of AGN populate these two subsamples. The number of AGN in each subsample varies depending on which diagnostic is used to classify them. An AGN is classified if it lies above the K01 curve and presents an EW(Hα) > 3 Å (Sánchez et al. 2017). From this we obtain that there are 61 and 16 AGN in the CALIFA and high-inclined subsamples, respectively, in the [N II]/Hα diagram, 71 and 28 AGN in the [S II]/Hα diagram, and finally 40 and 14 AGN in the [O I]/Hα diagram. On the other hand, a large fraction of the outflow candidates are grouped in the SF region. Only two galaxies lie above the K01 demarcation, one of them is notably far away from this demarcation, in the AGN region (NGC 4388). As pointed in previous subsections, the classical interpretation of the diagnostic diagrams that attempt to separate between different sources of ionization is no longer valid without other extra parameters like the EW(Hα) or any other physical information about the source of ionization. All candidates present EW(Hα) > 3 Å in their nucleus. This means that according to the diagnostic diagrams and the EW(Hα) criterion, these galaxies are dominated by SF (15 of them) or AGN (1 weak and 1 strong). From the total candidates, 3 out of 17 galaxies are catalogued as X-ray sources, NGC 4676A (log LX = 39.2, González-Martín et al. 2009), NGC 4388 (log LX = 42.45, Corral et al. 2014), and NGC 6286 (log LX = 40.6 Brightman & Nandra 2011). Although only NGC 4388 presents an X-ray luminosity greater than log LX > 42, the classical limit to be considered as an AGN. Indeed, this is the only target that outflowing material is compatible with being ionized by and AGN-driven ionization, based on the scheme described in Section 3.1 (as indicated in Table 1 and Fig. A1). In summary, our selection of highly inclined candidates to outflows seem to bias the sample towards outflows driven by star formation in the vast majority.

We should stress out that our selection bias the sample against early-type galaxies (as shown in the previous section), and this, by construction, excludes the detection of outflows in these galaxies that in their vast majority should be dominated by the presence of an AGN. In particular, we are excluding the detection of the recently classified as Red Geysers, a kind of object first reported by Kehrig et al. (2012), and confirmed by Cheung et al. (2016), and most probably associated with a weak AGN activity.

### 3.2.4 Star formation rate versus stellar mass

In the previous section we showed that most of our candidates host an outflow present ionized gas in their central regions dominated by star formation (15 of 17). We explore in this section if this star formation is more intense than one of the other two subsamples.

The SFR is a measurement of how much mass in stars is formed during a period of time. Star formation bursts create stars in a wide range of masses following a certain initial mass function (e.g. Salpeter 1955; Kroupa 2001; Chabrier 2003), but only the massive ones will dominate the production of ionizing photons (> 13.6 eV) during a short period of time, ~4 Myr. A common method to estimate the SFR in the optical range is through the luminosity of Hα (SFR = 7.93 × 10^{-44} L_{Hα}; Kennicutt 1998). This method requires that the measured H α flux is produced only by SF process, which is not necessarily true in the presence of an AGN, shocks, or other ionization sources (e.g. Catalán-Torrecilla et al. 2015). To derive L_{Hα}, we integrate the observed H α flux, and after correction by dust attenuation using the extinction law by Cardelli, Clayton & Mathis (1989), assuming the case B of recombination (e.g. Osterbrock 1989) and using the cosmological distance for...
Figure 4. Diagnostic diagrams for the central regions (3 arcsec × 3 arcsec) of the galaxies in the three subsamples: the CALIFA subsample (cyan dots), the high-inclined galaxies (red dots), and the candidates galaxies (green stars). The green colour code in the lower-right of the first panel represents the EW(Hα). We have coded only the EW(Hα) for the candidates. The continuous black curve in the three panels represent the Kewley et al. (2001) demarcation curves. The blue and red lines in the first panel represent the demarcations from Kauffmann et al. (2003) and Stasińska et al. (2006), respectively. The broken line represents the demarcation between Seyfert (up-left) and LINER (up-right) from Kewley et al. (2001).

Figure 5. Star formation rate derived from Hα (left-hand panel) and estimated with the SSPs (right-hand panel) versus the integrated stellar mass for the three subsamples. Cyan and red contours enclose the 90, 68, and 34 per cent of the total data in the CALIFA and the high-inclination galaxies, respectively. Green stars represent the outflow candidate galaxies. The yellow star represent the strong AGN, NGC 4388, found in the candidates as shown in Fig. 4. The continuous and dashed black lines in the left-hand panel correspond to the spatially resolved star formation main sequence (SFMSHα) and the retired sequence of galaxies (RSG) derived by Cano-Díaz et al. (2016). The black line in the right-hand panel correspond to the SFMSSSP derived from the best fit for SF galaxies in the full CALIFA sample [EW(Hα) > 3 Å and line ratios below the K01 curve]. The slope and zero point correspond to 0.71 ± 0.02 and −7.05 ± 0.20, respectively. A chi-squared test was applied for the candidates and the theoretical value given by the SMFS. The reduced chi squares is shown in the top left-hand corner in each panel.

We applied the Kennicutt (1998) law to transform $L_{\text{H}α}$ into SFR$_{\text{H}α}$. In this estimation we ignored the contribution of other sources of ionization. However, as shown by Catalán-Torrecilla et al. (2015) and Sánchez et al. (2017) their effects are limited. Nevertheless, in retired galaxies dominated by old stellar population, this relation must be considered just as a linear transformation between the $L_{\text{H}α}$ to SFR.

In Fig. 5 we show the well-known relation between the SFR and the integrated stellar mass (e.g. Brinchmann et al. 2004; Noeske et al. 2007; Salim et al. 2007). In this figure we plot both the
the transition point where the null hypothesis goes from being rejected to being accepted. In the left inset this occurs at $R_{\text{pl}}$. Plotted in a sample of outflows selected from the SAMI survey. Fig. 5 also shows evidence that using the full optical extension of galaxies, no excess in the SFR of the candidates is appreciated as it would be expected if outflows are driven by strong periods of SF. The outflow candidates seem to be part of the normal star-forming galaxies as expected if outflows are driven by strong periods of SF. The outflow candidates and the other two subsamples. In both panels the CALIFA subsample is distributed in a bimodal sequence shown by the blue contours, one comprising active star-forming galaxies, the so-called star formation main sequence (SFMS; e.g. Brinchmann et al. 2004; Salim et al. 2007), and the other the passive or retired sequence of galaxies (RSG). These sequences have been previously studied spatially resolved for the CALIFA sample (e.g. Cano-Díaz et al. 2016). The high-inclination galaxies are distributed around the SFMS with some galaxies falling in the RSG and the green valley. On the other hand, the outflow candidates are distributed around the SFMS regardless of the calibrator used to estimate the SFR, i.e. no excess is evident. This result has been previously noticed by Ho et al. (2016) in a sample of outflows selected from the SAMI survey. Fig. 5 also shows evidence that using the full optical extension of galaxies, no excess in the SFR of the candidates is appreciated as it would be expected if outflows are driven by strong periods of SF. The outflow candidates seem to be part of the normal star-forming galaxies as revealed by the $\chi^2$ test. Although it seems that outflows are preferentially located along the SFMS, their location in this diagram does not seem to define if a galaxy hosts or not an outflow. Recent studies have pointed out that the local concentration of the SFR might play an important role when driving outflows (e.g. Ho et al. 2016). In other words, the SFR surface density may be a better parameter instead of the integrated SFR to trace or regulate the presence of outflows.

3.3 Radial profiles of SFR surface density

Early studies in local starburst galaxies and high-$z$ Lyman break galaxies have evidenced that outflows are ubiquitous in galaxies with SFR surface densities ($\Sigma_{\text{SFR}}$) larger than $10^{-1} M_\odot \text{yr}^{-1} \text{kpc}^{-2}$ (e.g. Heckman 2001, 2002). Based on these results this value has been adopted in the literature as a canonical threshold for outflows.

Motivated by these results, and the results from the previous section, we proceed to estimate the radial distribution of the $\Sigma_{\text{SFR}}$. One of the great advantages of IFS is its capability to study the spatially resolved properties of galaxies, like $\Sigma_{\text{SFR}}$, instead of deriving it averaged across the entire optical extension of galaxies like it was done in previous analysis. For example, Kennicutt (1998) used the area within the isophotal radius of the galaxies ($D_{25} = 2R_{25}$) to estimate $\Sigma_{\text{SFR}} (= \text{SFR}/\pi R_{25}^2)$. Other authors have adopted the effective radii to estimate the area of the galaxies $\pi R_e^2$ (e.g. Lundgren et al. 2012; Ho et al. 2016) or it has been determined by imposing the Schmidt–Kennicutt law (SK law, Kennicutt, Keel & Blaha 1989).

In some cases in which it was possible to estimate the size of the starburst region (few hundreds of pc) it was adopted as the proper area where star formation is detected (e.g. Wood et al. 2015). These differences in the procedure adopted to derive the $\Sigma_{\text{SFR}}$ introduce clear uncertainties in the absolute scale of the proposed canonical threshold described before.

In our case we estimate the SFR derived from $H\alpha$ and the SSPs at different galactocentric elliptical rings, following the position angle...
and ellipticity of the object. Then we divide each region by the physical area of the corresponding ring, corrected by the inclination angle, to finally obtain the radial distribution of $\Sigma_{\text{SFR}}$ for each galaxy. We selected annular rings of 0.1 $R_e$ width, up to 3 $R_e$, cf. Fig. 6. In addition, we estimate the $\Sigma_{\text{SFR}}$ with the SFR derived from the SSP fitting analysis (SFR$_{\text{SSP}}$), as described in Section 2.1. This method has the great advantage that it does not depend on the physical properties of the ionized gas. However, the SFR$_{\text{SSP}}$ is only estimated where stellar continuum is detected. This means that SFR$_{\text{SSP}}$ traces pure SF with no contamination, at the penalty of a lower precision (due to the limitations of the SSP-fitting procedure, Sánchez et al. 2016a).

PIPe3D estimates the SFR$_{\text{SSP}}$ for the assembled mass in the last $\Delta t = 32$ Myr, as described in Section 2.1. We adopted the same annular rings for this complementary estimation of the star-formation density.

Fig. 6 shows the radial profiles of $\Sigma_{\text{SFR}}$ estimated based on the H$\alpha$ flux and the SSP fitting analysis. These plots were constructed by taking the average value of the $\Sigma_{\text{SFR}}$ for each galaxy in each radial bin, for each subsample of galaxies. The inner 0.2 $R_e$ ($\sim$500 pc) are unresolved due to the PSF size (FWHM $\sim$ 2.4 arcsec Sánchez et al. 2016c). Therefore, any trend below this inner region should be taken with care. In this plot we considered only galaxies dominated by SF in each subsample (i.e. those galaxies with line ratios below the K01 curve in Fig. 4). Adopting this criterion for the high and low inclined and outflow candidate galaxies, the subsamples are limited to 412, 158, and 16 galaxies, respectively.

The radial profiles show that in both cases the candidate galaxies present, on average, higher values of the $\Sigma_{\text{SFR}}$, at least in the inner regions, when compared to the other two subsamples. The $\Sigma_{\text{SFR}}$ estimated with the SSP method has in general larger values in comparison with that estimated with H$\alpha$ because of the different time-scales of both methods. The SFR based on H$\alpha$ traces the SF in the last $\sim$4 Myr, while the SFR estimated with the SSPs traces the SF in the last 32 Myr. Regardless of the method used to estimate the SFR, it is clear that there is a trend in the outflow candidates to present larger values of the $\Sigma_{\text{SFR}}$ in the innermost regions that in the outermost. This comparison between both estimators of the SFR exhibit that the observed excess is not due to a possible contamination by an extra source of ionization of H$\alpha$.

In order to quantify how significant is the difference in the radial distribution of the $\Sigma_{\text{SFR}}$ of the candidates in comparison to the other two samples, we performed an Anderson–Darling test (AD, Press et al. 1992; Feigelson & Babu 2012). In contrast with the KS test that tends to be more sensitive to differences in the central regions of the distributions, the AD test is more sensitive to differences also in the outermost regimes of the distributions. We applied the AD test at each radii, comparing the distributions of $\Sigma_{\text{SFR}}$ for the candidates and the high-inclination subsamples, and the outflow candidates and the low-inclination galaxies. The null hypothesis in both cases is that at each radius both distributions of $\Sigma_{\text{SFR}}$ are subsamples from the same population. The results of these statistical tests are shown in the bottom insets of Fig. 6. By adopting a significance level of 5 percent we see that in the inner radii, the resulting $p$-value for the candidates and the high-inclined galaxies is clearly below the significance level. This is still significant at a 1 percent level. Although the radius at which the null hypothesis is rejected depends on the calibrator used to estimate the SFR, it is certainly clear that below 1 $R_e$ both distributions seem to be different. Indeed at this point the $\Sigma_{\text{SFR}}$ profile presents a clear break and steepening most probably due to the outflow contribution inside this region. As we go to outer regions in the galaxies, the outflow candidates follow the same behaviour of the high-inclination galaxies. On the other hand, the $p$-values for the outflow candidates and the low-inclination CALIFA subsample show that both distributions are different at any radius.

It is interesting to note the low values of the $\Sigma_{\text{SFR}}$ that outflow candidates have, with values always lower log $\Sigma_{\text{SFR}} < -1.0$, which is below the canonical value expected for outflows, described before. We will explore this result in more detail in the next section.

### 3.3.1 $\Sigma_{\text{gas}}$ versus $\Sigma_{\text{SFR}}$: The KS law

The density of SFR has been proposed as one of the main parameters that controls the production of an outflow (e.g. Kennicutt 1998; Heckman 2002). As larger the $\Sigma_{\text{SFR}}$ is, more concentrated would be the energy released by the SN explosions and therefore the overpressured cavity would expand until large-scale galactic winds are driven giving rise to an outflow (e.g. Heckman et al. 1990). To achieve high values in the $\Sigma_{\text{SFR}}$, a high SFR concentrated in small regions (hundreds of pc) is needed. A large SFR is reflected in a large fraction of gas that is transformed into newborn stars, from which only the massive ones (OB stars) will contribute to the formation of the winds required to produce outflows.

It is well known that there is a tight correlation between the $\Sigma_{\text{SFR}}$ and the $\Sigma_{\text{gas}}$ (molecular and atomic) content in galaxies (the so-called KS law, Kennicutt et al. 1989). Although we are not able to measure the gas fraction directly, due to the lack of CO and H$\text{I}$ observations for all galaxies in our sample, it is still possible to have an estimation of the molecular gas content via the dust extinction. Following Sánchez et al. (2018), we proceed to estimate the gas content via the extinction $A_V$:

$$
\Sigma_{\text{gas}} = 15 \frac{A_V}{\text{mag}} \left[ M_\odot \text{pc}^{-2} \right].
$$

This relation presents a scatter of $\sim0.3$ dex when compared with CO measurements (e.g. Galbany et al. 2017), as explored in detail by Barrera-Ballesteros et al. (in preparation), based on the results from the EDGE-CALIFA survey (Bolatto, Wolfire & Leroy 2013).

Fig. 7 shows the relation between the SFR surface density, estimated with both H$\alpha$ and the SSP analysis, and the molecular mass density estimated from equation (3), averaged within the central regions ($R < 0.4 R_e$) of the individual galaxies of our three subsamples. If we focus in the left-hand panel, we observe that the candidates are basically concentrated in the region of galaxies with SF around the KS relation. On the other hand, the high inclination and the CALIFA subsamples are distributed in a cloud, narrower for the first, also around the KS relation. The scatter is larger than that usually reported for the KS law, most probably due to the rough estimation of the gas density (as already noticed by Sánchez et al. 2017). In this panel we observe that only one of the candidate galaxies surpass the threshold of $10^{-1} M_\odot \text{yr}^{-1} \text{kpc}^{-2} (= \Sigma_{\text{SFR, threshold}})$. If we now focus on the right-hand panel, we observe that a large fraction of the candidates are concentrated in a small region close to the canonical value. Indeed $\sim95$ per cent of the candidates present SFR surface densities larger than $10^{-1.5} M_\odot \text{yr}^{-1} \text{kpc}^{-2}$. The galaxies depart from the canonical location of the KS law in the right-hand panel, mostly due to the different time-scale sampled by the SFR derived from the SSP analysis. As indicated before, the SSP analysis traces the SF in a longer period of time (32 and 4 Myr, respectively). Starbursts have typical time-scales of $\sim$100 Myr (e.g. Leitherer 2001). This means that using H$\alpha$ as calibrator to estimate the SFR we only measure the recent SF ($\sim$4 Myr), while adopting...
Figure 7. $\Sigma_{\text{SFR}}$ versus $\Sigma_{\text{gas}}$ for the individual galaxies in three subsamples; left-hand panel shows the $\Sigma_{\text{SFR}}$ estimated with H$\alpha$; right-hand panel shows the $\Sigma_{\text{SFR}}$ estimated with the SSP fitting analysis. The cyan dots represent the SF galaxies in the CALIFA subsample. The red squares represent the SF galaxies in the high-inclined subsample and the green stars the candidates (excluding the AGNs, see Table 1). The green stars represent the outflow candidate galaxies. The horizontal dashed line represents the canonical threshold expected for outflows ($\log \Sigma_{\text{SFR}} = 1.0$). The black straight line represents the Kennicutt (1998) relation.

4 RESULTS AND DISCUSSION

We have explored the ionized gas properties for all galaxies from the full CALIFA sample to investigate the presence of outflows in the Local Universe. We imposed a set of criteria in the morphology, on the physical properties of the ionized gas, and in the continuum to select a sample of candidate galaxies with a host outflow. The adopted criteria are (i) highly inclined galaxies, (ii) detection of extraplanar ionized gas, (iii) identification of an enhanced line ratios along the semiminor axis, (iv) a biconical, bipolar, or a symmetric morphology in the extraplanar gas, and (v) $\text{EW}(\text{H}$α$) > 3$ Å in the outflow regions.

Our main result is that only 17 galaxies seem to host outflows that correspond to 8 per cent from the highly inclined galaxies (273) and 2 per cent from the extended CALIFA sample (835 objects). This last fraction is similar to what was found by Ho et al. (2016) in the SAMI galaxy survey. We find that the galaxies hosting an outflow are located in the range of high mass log $M_\star > 9.5$. Although in low-mass galaxies outflows are less frequent, their local impact might be stronger than in galaxies with higher potentials.

The amount of outflows detected in the full CALIFA sample may be a consequence of the short lifetime of these processes. The dynamical time-scale of outflows in starburst galaxies and AGN-driven winds is in the range $\sim 1−10$ Myr (e.g. Veilleux et al. 2005). CALIFA samples galaxies in the Local Universe, in a range of redshift between 0.005 and 0.03. This range translates into a range of time of $\Delta t_{\text{obs}} = 0.34$ Gyr. This means that if the 17 outflows detected in this sample are representative of the full sample, then on average one outflow every 20 Myr is expected. So, it is still possible that all galaxies in the sample have suffered an outflow process in the past, but that these were not observed due to their short lifetime. The detection of outflows with much lower $\Sigma_{\text{SFR}}$ than anticipated and their random location along the SFMS might also reflect the stochasticity of these processes.

Fig. A1 shows that the vast majority of our outflow candidates present shock-excited emission lines in the extraplanar gas. This is quantified in Table 1 by the sharing between different ionization sources of the extraplanar ionized spaxels: most of them are dominated by shock-like SF-driven winds (16 out of 17) and only one is consistent to be an AGN-driven wind: NGC 4388. Indeed, this is the only target that central ionization is completely compatible with the presence of an AGN and with a strong X-ray luminosity. From this analysis, we conclude that most of our selected outflow candidates are consistent with being driven by star formation. However, there is still the possibility that a galaxy hosts both SF and AGN activity causing a mixing in the ionization (e.g. Davies et al. 2014), which will produce a complex distribution of points along the diagram. In addition, the high inclination might produce a strong nuclear obscuration and blur the signal of a possible AGN. This would affect the observed optical emission lines, locating them in the SF region in the considered diagnostic diagrams. Therefore, we cannot reject non of both possibilities. Indeed, we find two targets, IC 2247 and NGC 4676A, with a fraction of $\sim 30$ per cent of their extraplanar ionization being compatible with the ionization by an AGN based on our criteria. The former one has a mixed/composite ionization in the central region (AGN/SF), while the later has clear X-ray emission, although it is not considered to host an AGN (Wild et al. 2014, and references therein).

We found that the global SFRs of the outflow candidates puts all of them along the active star formation sequence, and that there is no significant excess in the SFR. This is contrary to the expectation that this parameter was the major driver for the presence of outflows. Nevertheless, when we explore the spatial concentration of the SFR, we observe that on average, the candidates do present an excess in their $\Sigma_{\text{SFR}}$, when compared with galaxies with SF
activity but without evidence of outflows. This excess in $\Sigma_{\text{SFR}}$ is statistically significant for the innermost regions and it holds up to $\sim 1 R_\odot$ ($\sim 4$ kpc at the average redshift of CALIFA). This constrains a spatial region, which is larger in size compared to the typical acting region of a starburst $10^{2.5} - 10^{2.5}$ pc (e.g., Lehnert & Heckman 1996), where the outflows have a significant signature in the properties of galaxies. For $R > 1 R_\odot$, the outflow candidates behave as normal SF galaxies and within this region, the $\Sigma_{\text{SFR}}$ distribution steepens.

Although on average the candidates do not seem to surpass the proposed canonical threshold for the star formation surface density $\Sigma_{\text{SFR}} > 10^{-1} M_\odot$ yr$^{-1}$ kpc$^{-2}$, when we analyse the individual values of this parameter we observe that all of them lie close to this canonical value. Depending on whether it is used in the H$\alpha$ or the SSPs calibration for the SFR, they can surpass the canonical value only in a few cases. In starburst galaxies, the IR luminosity ($L_{\text{IR}}$) is used as a tracer of the SFR. Indeed, the calibrator used to estimate the canonical threshold in starburst galaxies adopts the $L_{\text{IR}}$ that traces the dust heating due to stars of 10–100 Myr (e.g., Kennicutt 1998). Due to the fact that the $L_{\text{IR}}$ comprises larger periods of SF, compared with H$\alpha$, the SFR$_{\text{SSP}}$ might be used as a better estimator of the SFR in outflows. The sampled time by this calibrator approaches the dust re-emission time-scales.

Our results suggest that the threshold limit in $\Sigma_{\text{SFR}}$ might be more flexible and include galaxies with lower values, in a regime where normal SF spiral galaxies dominate, rather than extreme starbursts. If we go back to the initial studies in outflows, we see that this threshold is achieved only for starburst and high-$z$ Lyman break galaxies, and not for normal disc galaxies that can present values of the star-formation density as low as $10^{-3} - 10^{-1} M_\odot$ yr$^{-1}$ kpc$^{-2}$, when we analyse the individual values of this parameter we observe that all of them lie close to this canonical value. Depending on whether it is used in the H$\alpha$ or the SSPs calibration for the SFR, they can surpass the canonical value only in a few cases. In starburst galaxies, the IR luminosity ($L_{\text{IR}}$) is used as a tracer of the SFR. Indeed, the calibrator used to estimate the canonical threshold in starburst galaxies adopts the $L_{\text{IR}}$ that traces the dust heating due to stars of 10–100 Myr (e.g., Kennicutt 1998; Heckman 2001; Kennicutt et al. 2007). The fact that outflows are ubiquitous in galaxies that exceed the proposed threshold does not exclude the possibility to find outflows in galaxies with $\Sigma_{\text{SFR}} < \Sigma_{\text{SFR,threshold}}$. Indeed, more recent studies have also pointed out that this threshold is quite high for the bulk population of outflows (e.g., Ho et al. 2016).

We have also shown that not only the $\Sigma_{\text{SFR}}$ is a key parameter to generate outflows, but it must be accompanied with large densities of molecular gas (i.e., $\Sigma_{\text{gas}}$). We propose a region for galaxies hosting outflows in the KS diagram: $\Sigma_{\text{SFR}} > 10^{-2} M_\odot$ yr$^{-1}$ kpc$^{-2}$ with $\Sigma_{\text{gas}} > 10^{12} M_\odot$ pc$^{-2}$, in a central region of $\sim 1$ kpc. In summary, it is not only the presence of strong SFR concentrated in a small area, but also the presence of material to be ejected that seems to be needed to generate an outflow.

However, although this seems to be a necessary condition, only 17 galaxies from the highly inclined galaxies present an outflow. This suggests that these are not the only key parameters in driving outflows. Even more, the candidate galaxies are in the high-mass range, contrary to what is expected to an outflow can escape from their local potential. This last is a critical result in the context of the implication in the evolution of the low-mass galaxies. The lack of high spatial resolution in our data and our selection of high-inclined galaxies might be biasing our sample to galaxies hosting large-scale outflows. These are the only detectable in the limit of the spatial resolution of CALIFA. The implementation of the technique introduced in this paper to detect outflows in high spatial resolution surveys is necessary to confirm our results in a more unbiased way. Our search for outflows has been performed without any bias towards the detection of starburst galaxies. In our ‘blind’ classification process we have been able to select galaxies that are previously known to host outflows, like the MICE or UGC 10043 (e.g., Wild et al. 2014; López-Cobá et al. 2017). Another method for detecting outflows that we have not explored in this work is through the interstellar absorption-line Na I λ=5890, 5896 (e.g., Heckman et al. 2000; Chen et al. 2010). Nevertheless, to our knowledge, we have not excluded any previously reported outflow from our explored samples.

5 CONCLUSIONS

The main conclusions of the exploration of the presence of outflows in the complete sample of galaxies observed by the CALIFA survey are the following ones:

(i) The fraction of galaxies with clear evidence of outflows range between 2 and 8 percent, depending on whether we consider the full sample of galaxies with any possible evidence or those ones that fulfill all our selection criteria.

(ii) The properties of galaxies hosting outflows are similar to that of the non-hosting ones in terms of their distribution along the CMD, mass, morphology, and integrated SFR, when the comparison is restricted to galaxies of the same inclination.

(iii) Galaxies hosting outflows are distributed in a high-mass range of $9.5 < \log M_\odot < 11$.

(iv) Most of our outflow candidates are compatible with being driven by star formation, based both on the dominant ionization in the central regions and their location in the diagnostic diagrams in comparison with demarcation described by Sharp & Bland-Hawthorn (2010). Only in one case we see clear evidence of AGN-driven outflows (NGC 4388).

(v) The highly inclined galaxies hosting an outflow present a significant excess in the SFR surface density in the central regions ($R < 1 R_\odot$), when compared with the non-hosting outflow ones, indicating that at least in these galaxies, outflows are mostly driven by a central increase in the SFR.

(vi) The galaxies hosting outflows in the CALIFA sample only marginally exceed the canonical threshold on the $\Sigma_{\text{SFR}}$, maybe because they present regular star formation that yields lower values in the star formation surface density, and therefore produce weaker outflows compared to those of starburst galaxies.

Our results indicate that outflows are less restricted to extreme star-formation events, either central or integrated, being more frequent events than anticipated. Further studies are needed to explore the outflows in galaxies with lower inclinations, where data with better spatial and spectral resolutions could break the confusion between the different ionization components (e.g., López-Cobá et al. 2017), and over much larger samples, like the ones provided by the MaNGA survey (e.g., Bundy et al. 2015), to provide with better statistics. Even more, we need to explore in more detail the physical properties of the outflows themselves, only outlined in this study, and focus on the detectability of these events in retired/early-type galaxies, mostly excluded in this analysis due to the imposed inclination selection.

ACKNOWLEDGEMENTS

CLC and SFS are grateful for the support of Consejo Nacional de Ciencia y Tecnología (CONACYT, Mexico) for grant CB-285080, and funding from the PAPIIT-DGAPA-IA101217(UNAM), PA-PIT: IN103318, and CONACYT: 168251 projects. ICG, SFS, and CLC acknowledge support from DGAPA-UNAM (Mexico) grant IN11341. CLC acknowledges CONACYT (Mexico) PhD scholarship. JBH acknowledges the support of an ARC Laureate Fellowship.
from the Australian Government. LG was supported in part by the US National Science Foundation under Grant AST-1311862.

This study uses data provided by the Calar Alto Legacy Integral Field Area (CALIFA) survey (http://califa.caha.es/).

CALIFA is the first legacy survey performed at Calar Alto. The CALIFA collaboration would like to thank the IAA-CSIC and MPIA-MPG as major partners of the observatory, and CAHA itself, for the unique access to telescope time and support in manpower and infrastructures. The CALIFA collaboration also thanks the CAHA staff for the dedication to this project.

This work is based on observations collected at the Centro Astronómico Hispano Alemán (CAHA) at Calar Alto, operated jointly by the Max-Planck-Institut für Astronomie and the Instituto de Astrofísica de Andalucía (CSIC).

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SUPPORTING INFORMATION

Supplementary data are available at MNRAS online.

Figure C1. Galaxy with detected extraplanar emission but not selected as outflow candidate.

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APPENDIX A: CANDIDATES GALAXIES

In Fig. A1 the spatially resolved line ratio maps and diagnostic diagrams for all the candidate galaxies with a host outflow listed in Table 1 comprising the same information shown for NGC 6282 in Figs 1 and 2 are shown.

Figure A1. Spatially resolved line ratios and diagnostic diagrams together with the WHAN diagram for the candidate galaxies to host outflows listed in Table 1. In each panel, it has included a false colour image of the galaxy (green: V-band, red: [N II] and blue: [O III]). The two black contours indicate the continuum level at 0.1 and 0.05 $\times 10^{-16}$ erg s$^{-1}$. The meaning of the demarcation curves and the symbols are the same from Figs 1 and 2.
Figure A1 – continued
Figure A1 — continued
Figure A1 – continued
Figure A1 – continued
Figure A1 – continued
Figure A1 – continued
APPENDIX B: GALAXIES NOT CATALOGUED AS OUTFLOWS

In Table B1 we present the remaining galaxies with detected extraplanar ionized gas or some increase in the line ratios, but that were not classified as outflow candidates. Some of these galaxies present eDIG. In some cases the eDIG is dominated by HOLMES or post-AGB. In other cases the extraplanar gas presents EW(Hα) > 3 Å, but it is distributed in a continuous layer of ionized gas above the galactic disc. These ones might be ionized by leaking photons of H II regions that escape from the disc. In galaxies with high SFRs, or starburst galaxies, a fraction of the ionizing photons can escape from the H II regions without being absorbed. It has been suggested that these leaky H II regions photons may escape to the diffuse ISM and the intergalactic medium and ionize regions of kilo parsec scales from the disc (e.g. Ferguson et al. 1996; Hoopes & Walterbos 2003; Wood et al. 2010; Martin et al. 2015).

It is important to emphasize that this work is not focused in the exploration of eDIG in general. There are other studies in the CALIFA survey that focus in the analysis of DIG in all type of galaxies regardless of their inclination (e.g. Singh et al. 2013; Lacerda et al. 2018). Nevertheless we list in here those galaxies that might be probably confused with outflows, which do not imply these galaxies are the only ones with eDIG in the CALIFA sample. It may also be possible that some of these galaxies could be reclassified as outflow candidates with better spatial and spectral resolution data.
Table B1. Galaxies with extraplanar ionized gas, but not classified as outflows because they do not fulfil all the required criteria indicated in Section 3.1. The fraction of spaxels in the extraplanar region compatible with being ionized by an AGN, SF-driven shocks, and old-stars, based on the scheme described in Section 3.1 and Table 1 is included for reference.

| Object            | AGN:Shock:DIG |
|-------------------|---------------|
| NGC 0693          | 9:91:0        |
| PGC 0063016       | 1:99:0        |
| UGC 04730         | 23:77:0       |
| UGC 5392          | 6:94:0        |
| NGC 1677          | 1:99:0        |
| NGC 4149          | 2:80:18       |
| NGC 5908          | 7:63:30       |
| MCG -01-01-012    | 0:50:50       |
| NGC 2480          | 8:92:0        |
| NGC 5402          | 0:100:0       |
| NGC 5439          | 0:100:0       |
| NGC 6361          | 5:88:7        |
| UGC 04550         | 12:88:0       |
| UGC 09262         | 2:98:0        |
| UGC 09665         | 0:100:0       |
| IC 2098           | 0:98:2        |
| IC 4582           | 3:97:0        |
| NGC 0681          | 0:72:28       |
| NGC 1056          | 12:87:1       |
| NGC 5145          | 3:94:2        |
| IC 1481           | 56:43:1       |
| IC 0540           | 30:14:57      |

APPENDIX C: SUPPLEMENTAL MATERIAL

Fig. C1 shows the same plots from Fig. A1 but for a galaxy not classified as an outflow candidate from Table B1. The remaining plots for the galaxies listed in Table B1 are available in the Supporting Information for this article.
Figure C1. Galaxy with detected extraplanar emission but not selected as outflow candidate. In each panel it has included a false colour image of the galaxy (green: Hα red: [N II] and blue: [O III]). The two black contours indicate the continuum level at 0.1 and 0.05 × 10^{-16} erg s^{-1}. Black circles in the diagnostic diagrams indicate EW(Hα) < 3 Å. The meaning of the demarcation curves and the colour code of the symbols are the same from Figs 1 and 2.

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