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Negative and Positive Outflow-Feedback in Nearby (U)LIRGs

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The starburst-AGN coexistence in local (U)LIRGs makes these galaxies excellent laboratories for the study of stellar and AGN outflows and feedback. Outflows regulate star formation and AGN activity, redistributing gas, dust and metals over large scales in the interstellar and intergalactic media (negative feedback) being also considered to be able to undergo vigorous star formation (positive feedback). In this contribution, I will summarize the results from a search for outflows in a sample of nearby 38 local (U)LIRG systems observed with VIMOS/VLT integral field unit. For two galaxies of the sample I will detail the outflow properties and discuss the observational evidence for negative and positive outflow-feedback. The assessment of both negative and positive feedback effects represent a novel approach toward a comprehensive understanding of the impact of outflow feedback in the galaxy evolution.

Keywords: galaxies: starburst, evolution, feedback, ISM: jets and outflows, ISM: kinematics and dynamics, techniques: spectroscopic

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1. INTRODUCTION

In the last decade, our understanding of the formation and evolution of galaxies over cosmic time has been significantly enhanced by large scale galaxy surveys. These surveys have drawn a detailed picture of the global properties of the galaxies, establishing the galaxy stellar mass function and scaling relations (e.g., mass-metallicity, Tremonti et al., 2004; Brooks et al., 2006). Galaxy evolution models attempt to reproduce the properties of the galaxies and those of the surrounding Inter Galactic Medium (IGM) invoking the need of feedback mechanisms from starbursts or Active Galactic Nuclei (AGN). In fact, models of galaxy evolution without a strong (stellar or AGN) feedback, lead galaxies to have much higher Star Forming Rates (SFR) and larger stellar masses than observed (e.g., Hopkins et al., 2006). Outflows regulate Star Formation (SF) and AGN activity (negative feedback), and they are also considered the primary mechanism by which dust and metals are redistributed over large scales in the Inter Stellar Medium (ISM), or even expelled outside the galaxy into the IGM (e.g., Aguirre et al., 2001). In addition, it has been recently proposed that outflows can undergo vigorous SF (positive feedback, Ishibashi and Fabian, 2012; Zubovas et al., 2013). In this context, the study of the of feedback mechanisms is of critical importance to trace the build-up of stellar mass and evolution of galaxies in the Universe. Multiphase outflows are ubiquitous at any redshift. Although the bulk of the black hole growth, SF, and galaxy mergers are believed to occur at $z \sim 1$–3, studies of outflows in nearby galaxies offer detailed insights into feedback phenomena as one of the primary drivers of galaxy evolution.

In this context, local Luminous and Ultra-Luminous Infrared Galaxies [(U)LIRGs] are particularly interesting populations. On the one hand these objects show the most conspicuous cases for outflows in the local Universe (e.g., Heckman et al., 2000; Rupke et al., 2002). On the other hand, local (U)LIRGs have a SF-activity similar to that found for "main-sequence" high-z star-forming galaxies, and share with distant galaxies some structural and kinematical properties (e.g., Elbaz et al., 2011; Arribas et al., 2012; Bellocchi et al., 2013). Therefore, local (U)LIRGs allow us to study the outflow phenomenon at environments similar to those observed at high-z, but with a much higher signal-to-noise and spatial resolution.

The large majority of previous outflow studies are based on long slit observations giving only a partial description of the outflow phenomenon (e.g., Rupke et al., 2005). However, Integral Field Spectroscopy (IFS) is well suited for search for and characterize outflows as it allows the spectroscopic measurement of large areas of e.g., interstellar (outflowing) gas and therefore allows to study the 2D structure of outflows.

Outflows are made up of a number of gas phases with a wide range of physical conditions, as the ISM surrounding the starburst and the AGN (see Veilleux et al., 2005 for a review). Of particular interest are the cold phases as cold gas represents the fuel of SF. In the optical range, the cold neutral gas entrained in outflows is detected through the sodium doublet absorption: NaD$\lambda\lambda$5890, 5896.

We search for outflows in a sample of 38 local (U)LIRG systems (51 individual galaxies) with $z < 0.09$ observed with the VIMOS/VLT integral field unit. This allows us to extend the census of the 2D mapping of neutral outflows in local (U)LIRGs, covering the less studied LIRG luminosity range. In fact, previous IFS studies are limited to a small number of extreme objects, mainly major-mergers (e.g., Rupke and Veilleux, 2013). We exploit these optical IFS-observations to make a significant step forwards in understanding the outflow properties such as their geometry and their connection/feedback with those of the host galaxy. Two galaxies in the sample have been considered as a pilot studies for negative and positive feedback. These were analyzed thoroughly with a multi wavelength approach.

2. SPATIALLY RESOLVED KINEMATICS, GALACTIC WIND, AND QUENCHING OF SF IN THE LIRG IRAS F11506-3851

We choose the nearby LIRG IRAS F11506-3851 as a pilot study, since the availability of both optical and near-IR IFS-data that allows to simultaneously trace different galaxy components (ISM and stars). We have accomplished such a multiwavelength study with VIMOS/VLT and SINFONI/VLT data (Cazzoli et al., 2014). The morphology and the 2D kinematics of the gaseous (neutral and ionized) and stellar components have been mapped in the central regions (<3 kpc) using the NaD absorption doublet, the H$\alpha\lambda$6563 emission line, and the near-IR CO(2-0)λ2.293 μm and CO(3-1)λ2.322 μm absorption bands.

The NaD and the Hα-[NII] emission-line complex profiles were modeled with two kinematic components (i.e., a couple Gaussians per line) on spaxel-by-spaxel basis. The output of the fitting (line flux, central wavelength and intrinsic width) were used to generate spectral maps (**Figure 1**). To obtain the stellar kinematic, we first binned SINFONI/VLT data using the Voronoi 2D-binning method (Cappellari and Emsellem, 2004) and then we used the Penalized PiXel-Fitting method (pPXF; Cappellari and Emsellem, 2004), to fit a library of stellar templates (Winge et al., 2009) to individual spectra to create the spectral maps (**Figure 1**).

The kinematics of the ionized gas and the stars are dominated by rotation, with large observed velocity amplitudes and centrally peaked dispersion maps. In contrast, we have found that the ISM-NaD absorption shows a complex kinematic structure dominated by two main components. On the one hand, we observe an irregular slowly rotating thick disk which lags significantly compared to the ionized gas and stars. On the other hand, we find a kpc-scale outflow perpendicular to the disk, which is ejecting a significant amount of gas (3×10^8 M$_\odot$) from the central regions at a rate of 1.4 times larger than the ongoing SF. The relatively strong emission by SNe in the central regions as traced by the [Fe II]λ1.64 μm emission, indicates a recent ($\sim$7 Myr ago) episode of SF. All these results strongly suggest that we are witnessing (nuclear) quenching due to SF feedback in IRAS F11506-3851 (negative feedback, section 1). However, the relatively large mass of molecular gas detected in the nuclear region via the H_2(1-0)S(1)λ2.12 μm line suggests that further episodes of SF may take place again. In addition, there is evidence of the presence of an ionized outflow that partially overlaps with the neutral one.

Thanks to recent ALMA observations (Pereira-Santaella et al., 2016) we have confirmed the presence of the outflow in molecular gas [via CO(1-0) emission line] with an excellent consistency with that of neutral gas presented in Cazzoli et al. (2014).

3. NEUTRAL GAS OUTFLOW IN NEARBY (U)LIRGS VIA OPTICAL NAD FEATURE

We have performed a systematic study of the properties of the neutral gas in the whole sample of (U)LIRGs, on the basis of spatially integrated, as well as the spatially resolved IFS-spectra of the NaD feature obtained with VIMOS/VLT (Cazzoli et al., 2016).

We have found that neutral outflows are frequent (71 and 55% detection rate for the integrated and spatially resolved analyses, respectively). Outflow (integrated) velocities, V, are in the range: 65–260 km/s and these scale with the SFR as $V \propto SFR^{0.15}$ (excluding AGNs), in rather good agreement with previous results (Martin, 2005). The spatially resolved analysis could be performed for 40 galaxies. In a minor but significant fraction (11 targets) we found disk-rotation signatures, whereas for more than half of the cases (22 targets) the neutral gas velocity fields are dominated by non-circular motions with signatures of cone-like outflows.

Based on a simple model, we have found that the outflow mass ranges from 0.4 to 7.5×10^8 M$_\odot$, reaching up to $\sim$3% of the dynamical mass of the host. The mass rates are typically only $\sim$0.2-0.4 times the corresponding SFR indicating that, in general, the mass-loss is small for slowing down significantly the SF. In the majority of the cases, the velocity of the outflowing gas is not enough to escape the host potential well and, therefore, most of it will rain-back into the galaxy disk (fountain scenario).

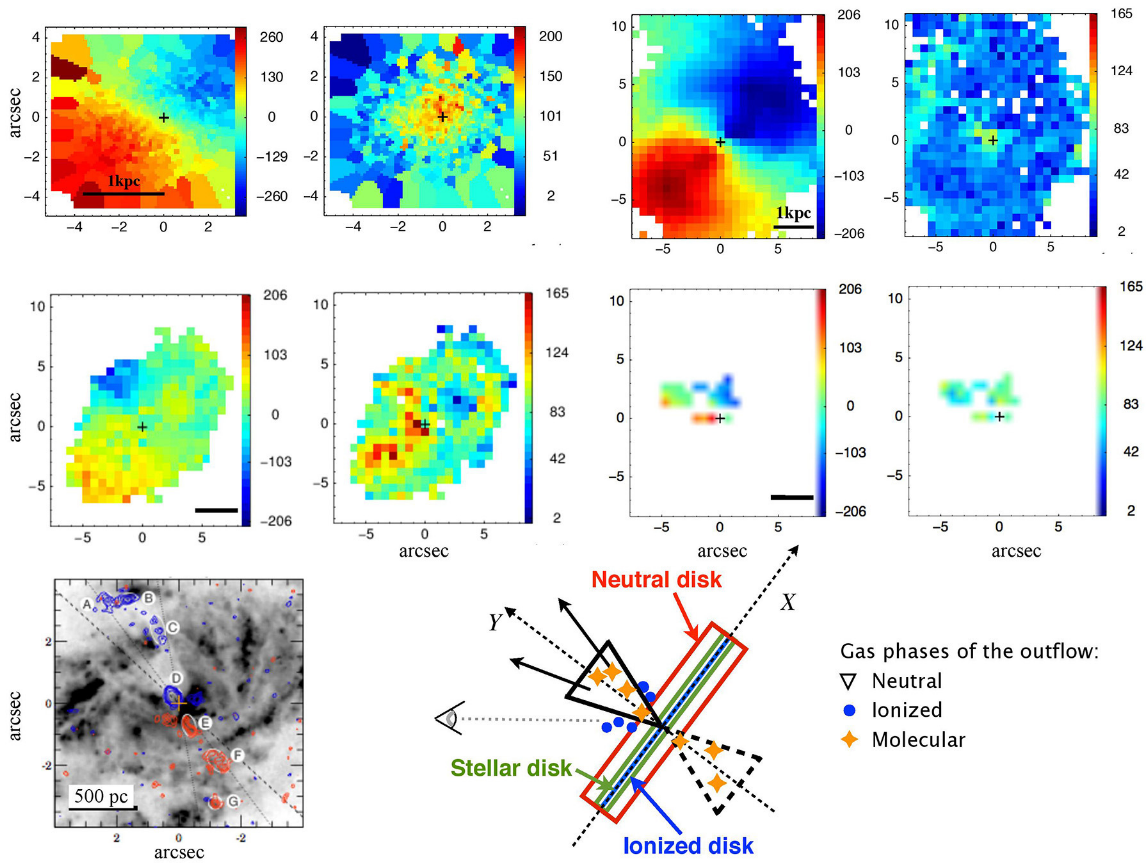

FIGURE 1 | Spectral maps and HST image of IRAS F 11506-3851. **Top-left:** SINFONI/VLT velocity and velocity dispersion maps of stars (CO absorption bands). **Top-right:** the same maps but for the ionized gas (Hα narrow component) obtained using VIMOS/VLT cubes. **Middle:** velocity and velocity dispersion maps of neutral gas (left) and ionized gas (right) obtained analyzing the NaD absorption and the Hα broad component in VIMOS/VLT data. All these maps, from Cazzoli et al. (2014), are in km/s units. The cross marks the galaxy nucleus. **Bottom-left:** A zoomed-in view of the optical morphology (ACS/HST F814W-image) in gray scale with red and blue contours indicating the redshifted and blueshifted, respectively, molecular outflowing clumps detected by ALMA. The dashed lines indicate the minor axis and dotted lines the opening angle. The figure is adapted from Pereira-Santaella et al. (2016). **Bottom-right:** toy model of the outflows and disks summarizing our results, adapted from Cazzoli et al. (2014). Credit: Cazzoli, A&A, 569, A14, 2014, and PereiraSantaella2016, A&A, 594, A81, 2016, reproduced with permission © ESO.

The comparison between the outflow power and the kinetic power of the starburst associated to SNe (**Figure 2**) indicates that only the starburst could drive the outflow in nearly all the (U)LIRGs galaxies, as the outflow power is generally lower than the 20% of the kinetic power supplied by the starburst. Only in two cases the contribution of the AGN is, in principle, significant.

4. STAR FORMATION INSIDE THE OUTFLOW OF IRAS F23128-5919

The nearby ULIRG IRAS F23128-5919 is a system of two interacting galaxies. The southern galaxy is characterized by a prominent outflow studied by various authors through emission and absorption lines (Piqueras López et al., 2012; Bellocchi et al., 2013; Arribas et al., 2014; Cazzoli et al., 2016). In order to investigate if the multiphase outflow is able to undergo vigorous SF as expected in case of positive feedback (section 1) we have combined archival optical MUSE/VLT data with new X-shooter/VLT observations (Maiolino et al., 2017).

Our strategy enabled the detection of spectral diagnostics over the spectral range from 0.35 to 2.5 µm. The optical nebular emission lines are clearly characterized by two kinematic components: a narrow component tracing the disks of the two merging galaxies and a broad blueshifted component, with velocities up to 600 km/s and width up to 1,000 km/s, tracing the prominent outflow extending for several kpc toward the East. The receding component of the outflow is also seen as broad and redshifted component toward the West, though fainter due dust obscuration in the galaxy disk. The multi-component decomposition of the set of near-IR emission lines we consider: Pa$\alpha\lambda$1.88 µm, Pa$\beta\lambda$1.28 µm, Br$\gamma\lambda$2.16 µm, $H_2$1-0 S(1), [P II]λ1.18 µm, [Fe II]λ1.25,1.64 µm, follows that of optical lines.

By studying multiple diagnostics we obtain independent pieces of evidence that stars are forming in the outflow of IRAS 2312-59. On the basis of optical and near-IR diagnostic

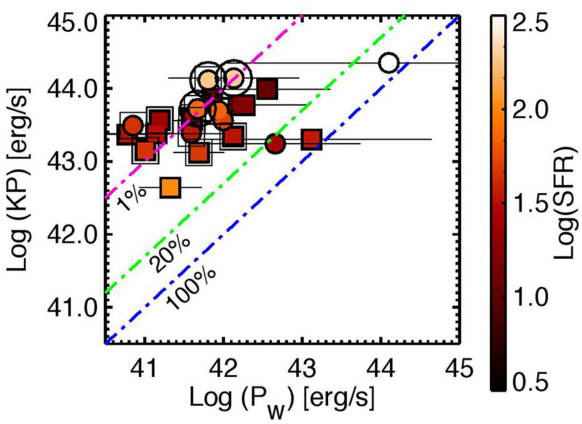

FIGURE 2 | Logarithm of kinetic power of the starburst associated to SNe (KP) as a function of the outflow power (Pw), color coded by their SFR. We identify pure starbursts and AGN-hosts with squares and circles, respectively, while very strong-AGN are marked with an additional circle. Those galaxies for which we were unable to infer in detail the outflow morphology are marked with an additional square. The pink, green and blue lines represent respectively the positions for which the power of the outflow is equal to the 1, 20, and 100% of the kinetic power supplied by the starburst. Credit: Cazzoli, A&A, 590, A125, 2016, reproduced with permission © ESO.

diagrams (also called BPTs) we discriminate the dominant source of ionization of the kinematic components used to model emission lines (Baldwin et al., 1981; Riffel et al., 2013; Colina et al., 2015). In all the five diagnostic diagrams (**Figure 2** in Maiolino et al., 2017) we have found that the line ratios for the broad outflowing component are typical of HII star-forming regions. Furthermore, on the one hand coronal lines associated with AGN excitation (e.g., S IXλ1.252 and Al IXλ2.045μm) are absent in the near IR spectra. On the other hand, we have found signature of a young stellar population (age a few tens Myr) formed at high velocity in the inner region of the outflowing gas and then decelerated by the gravitational potential of the galaxy (reacting only to gravity and not to radiation pressure as the outflowing gas). This implies that the young stars are formed in situ, i.e., within the outflow, as also indicated by the values of the gas ionization parameter (no photoionization by the UV radiation field of the galaxy disk).

Finally, we translate the luminosity of the broad component of Hα into a SFR of 15 $M_\odot$/yr that is a substantial fraction, i.e., 13 % (up to 25 % if we consider the outflow is biconical) of the total SFR of 115 $M_\odot$/yr of the ULIRG system.

5. SUMMARY

Outflows have been proposed as an effective way to quench and enhance star formation and AGN activities. In (U)LIRGs starburst-AGN coexist and this galaxies represent a transitional phase from star-forming to quiescent galaxies offering a unique insight for the understanding of how feedback mechanisms regulate the gas reservoir. The aim of the works presented in this contribution is to study how negative and positive feedback phenomena, as consequence of starburst and AGN activities, are able to shape the gas life-cycle and observed properties via multiphase outflows. This represent a novel approach toward a comprehensive understanding of the impact of outflow feedback in the galaxy evolution.

The main conclusions of this contribution can be summarized as follows:

- Neutral gas massive SNe-powered outflows are observed frequently in our sample of (U)LIRGs, with velocities V = 65–260 km/s, and loading factors ranging from 0.2 to 0.4 $M_\odot$/yr (Cazzoli et al., 2016). Most of the cold outflowing material is likely falling back to the disk (fountain scenario). We studied in detail the neutral, ionized and molecular phases of the outflow in the LIRG IRAS F11506-3851 (Cazzoli et al., 2014; Pereira-Santaella et al., 2016). The outflow (a galactic fountain) is ejecting a significant amount of gas from the central regions at a rate of 1.4 times larger than the ongoing SF.
  For some of the LIRGs in the sample, we will study the IGM enrichment caused by large scale outflows on the basis of the detection and kinematic of the NaD absorption in background galaxies.
- By studying multiple diagnostics we obtain independent pieces of evidence that stars are forming in the outflow of the nearby ULIRG IRAS 2312-59 (Maiolino et al., 2017). More specifically, these evidence include diagnostic ratios typical of those of star-forming HII regions (as indicated by optical and near-IR diagnostic diagrams) and the detection of young $\sim$10 Myr stars in the outflow which move ballistically. We excluded that the outflowing gas is photoionized by the UV radiation field of the galaxy disk on the basis of ionization parameter arguments. Therefore, for the first time we have unambiguously identifying a case of outflow positive feedback as star formation occurring within the outflow.

Star formation may also be occurring in other outflows. Future works by our group include the increment the census of the cases of positive feedback and the investigation of the properties of the star-forming outflowing-gas.

Finally, we remark that the type of studies presented in this contribution set the ground for future studies. More insights on the outflows feedback will come in the next decade thanks to upcoming ground based telescopes or space missions, as the European Extremely Large Telescope and James Webb Space Telescope.

AUTHOR CONTRIBUTIONS

The analysis of optical VIMOS IFS data come from the PhD thesis by SC (Cazzoli, 2016) and referred papers (Cazzoli et al., 2014, 2016). SC contributed also the analysis and interpretation of SINFONI and X-shooter observations (Cazzoli et al., 2014 and Maiolino et al., 2017, respectively). SC contributed also to interpretation of ALMA data (Pereira-Santaella et al., 2016).

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This manuscript is partially based on the PhD thesis of SC (available online at http://hdl.handle.net/10486/676308, in line with Universidad Autonoma de Madrid policies). This thesis is the only medium that all the work done by SC during her Ph.D. has appeared in. The publication of manuscripts based on SC thesis work is in line with the Universidad Autonoma de Madrid policies.

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