Ionized Gas Outflows in Low-excitation Radio Galaxies Are Radiation Driven

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Abstract

Low-excitation radio galaxies (LERGs) are weakly accreting active galactic nuclei (AGNs) believed to be fueled by radiatively inefficient accretion processes. Despite this, recent works have shown evidence for ionized and neutral hydrogen gas outflows in these galaxies. To investigate the potential drivers of such outflows, we select a sample of 802 LERGs using the Best & Heckman (2012) catalog of radio galaxies. By modeling the [O III] λ5007 profile in Sloan Digital Sky Survey spectra of a sample of 802 LERGs, we determine that the ionized outflows are present in $\sim$1.5% of the population. Using 1.4 GHz imaging from the Faint Images of the Radio Sky at Twenty Centimeters survey we analyze the radio morphology of LERGs with outflows and find these to be consistent with the parent LERG population. However, we note that unlike the majority of the LERG population, those LERGs showing outflows have Eddington-scaled accretion rates close to 1%. This is indicative that ionized outflows in LERGs are driven by the radiation pressure from the accretion disk of the AGN rather than the radio jets. We report specific star formation rates in the range of $10^{-12} < sSFR < 10^{-9} \text{ yr}^{-1}$. Moreover, we observe higher mass outflow rates, $\sim 150 M_\odot \text{ yr}^{-1}$, for these LERGs than luminous quasars for a given bolometric luminosity, which could possibly be due to the radio source in LERGs boosting the mass loading. This scenario could indicate that these outflows could potentially drive feedback in LERGs.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Radio active galactic nuclei (2134); Radio jets (1347); Galaxy accretion disks (562); AGN host galaxies (2017)

1. Introduction

One of the most fascinating discoveries in modern astronomy is that all massive galaxies have central supermassive black holes (SMBHs), having masses that are proportional to that of the stellar velocity dispersion of their host galaxies (e.g., Kormendy & Richstone 1995; Magorrian et al. 1998; Tremaine et al. 2002; Gültekin et al. 2009; Kormendy & Ho 2013). The growth of these SMBHs through the accretion of matter is an observable phenomenon known as an active galactic nucleus (AGN). Contemporaneously, research explaining the bright end of the galaxy luminosity function (Bower et al. 2006) gave rise to the idea that the AGN is somehow affecting the host galaxy’s evolution. In order to explain these results, theoretical models of galaxy formation and evolution came up with the idea of “AGN feedback,” during which AGN activity injects energy into the gas in the larger-scale environment, in order to reproduce the properties of local massive galaxies, intra-cluster gas, and the intergalactic medium ($M-\sigma$ relations; the sharp cutoff in the galaxy luminosity function; e.g., Silk & Rees 1998; Churazov et al. 2005; Bower et al. 2006; Hopkins et al. 2006; McCarthy et al. 2010; Gaspari et al. 2011). Placing observational constraints on how AGN activity couples to the gas in galaxies and haloes, and where these processes are most prevalent, is an important area of ongoing research (for reviews see, e.g., Cattaneo et al. 2009; Alexander & Hickox 2012; Fabian 2012; McNamara & Nulsen 2012).

Many successful galaxy formation models require a dramatic form of energy injection (“radiation driven” or “quasar mode feedback”), where AGNs drive galaxy-wide (i.e., 0.1–10 kpc) energetic outflows, where the wind generated close to the AGN flowing through the galaxy pushes the gas out from its host galaxy and consequently shuts down future BH growth and star formation and/or enriches the larger-scale environment with metals (e.g., Silk & Rees 1998; Fabian 1999; Benson et al. 2003; Hopkins et al. 2006; Fabian 2012). While there is little doubt that star formation processes (e.g., stellar winds and supernovae) drive galaxy-wide outflows (e.g., Heckman et al. 1990; Lehnert & Heckman 1996; Swinbank et al. 2009) and are an integral part of galaxy evolution (e.g., Hopkins et al. 2006; Dalla Vecchia & Schaye 2008), it is believed that AGN activity is required to drive the highest velocity outflows and is particularly important for the evolution of the most massive galaxies (e.g., Benson et al. 2003; McCarthy et al. 2011). AGNs with high accretion rates (Eddington ratio, $\lambda_{\text{Edd}} > 0.01$) are thought to be radiatively efficient. They typically have thin, bright accretion disks (Shakura & Sunyaev 1973; Malkan 1983; Blaes 2007; Best & Heckman 2012). A fraction of these AGNs are radio-loud with powerful radio jets that could possibly extend to tens or a few hundred kiloparsecs (Miley 1980; Blundell et al. 1999; Hardcastle et al. 2019). Aside from the radiation pressure from the accretion disk, the outflows may well be driven by the acceleration caused by the interaction of the radio jets and the surrounding medium (e.g., Morganti et al. 2003a, 2005; Emonts et al. 2005; Labiano et al. 2013; Schulz et al. 2018). Another possibility is that the gas is swept up and compressed as the radio jets hollow out a cocoon-like structure (e.g., Capetti et al. 1999; Tadhunter et al. 2001). Villar-Martín et al. (1999) mentioned that outflow velocities $>1000 \text{ km s}^{-1}$ could be easily explained if the clouds are entrained in hot, shocked gas that expands out behind the bow shock, similar to the expansion of an interstellar bubble (e.g., Stone & Norman 1992; Dai & Woodward 1994; Klein et al. 1994; O’Dea et al. 2002). This energy-driven mechanism could explain the large amounts of neutral gas involved in the outflow (Emonts et al. 2005).

This is in contrast to the mechanical feedback where radio jets, launched by the AGN, control the level of cooling of the
hot gas in the most massive haloes ("radio mode feedback"); see Bower et al. 2012; Harrison et al. 2014). In this feedback mode, the accretion of material onto the black hole leads to a much larger radiative energy, but can lead to the production of highly energetic radio jets (Best & Heckman 2012). It is widely believed that the radiatively inefficient ($\dot{\lambda}_{edd} < 0.01$) AGN accretion flows (advection-dominated accretion flows, or ADAFs), which are optically thin, geometrically thick (Narayan & Yi 1995), emit the bulk of their energy through radio jets (Merloni & Heinz 2007).

The current understanding is that the AGNs in low-excitation radio galaxies (LERGs) drive galaxy evolution mainly via heating up the ambient gas by launching hot plasma jets (Best & Heckman 2012; Mingo et al. 2016), while the high-excitation radio galaxies (HERGs) could drive galaxy evolution by expelling gas out of the host galaxies through outflows (e.g., Morganti et al. 2005; Gupta & Saikia 2006; Couto et al. 2017), or by launching hot plasma jets and heating up the ambient gas (e.g., Fabian et al. 2003; Wilson et al. 2006; Gendron-Marsolais et al. 2017). The situation is further complicated as the photoionization from AGN radiation highly ionizes the surrounding gas along the jet's axis in HERGs (Couto et al. 2017). The ambient gas could further be accelerated by radiation pressure and possibly be heated by radiative heating (Liu et al. 2013). Classically, LERGs and HERGs have been divided based on the relative intensity of high and low-excitation lines in their optical spectra (e.g., Hine & Longair 1979; Laing et al. 1994; Buttiglione et al. 2010), and are believed to represent intrinsically different types of objects (e.g., Best & Heckman 2012; Miraghaei & Best 2017). HERGs show high accretion rates ($\lambda_{edd} > 0.01$), whereas LERGs show low accretion rates ($\lambda_{edd} < 0.01$; e.g., Heckman & Best 2014; Yuan & Narayan 2014). It has been widely assumed that the accretion mode in HERGs tends to be radiatively efficient, whereas LERGs are mostly radiatively inefficient (Best & Heckman 2012).

The radiatively inefficient and efficient AGNs clearly have fundamental differences, but the precise origin of these differences remains uncertain. Some authors have argued that it relates to the origin of the fueling gas, with accretion of cold gas leading to a stable accretion disk and a radiatively efficient accretion; the accretion of hot gas via the Bondi mechanism would produce the jet dominated radiatively inefficient AGNs (e.g., Hardcastle et al. 2007; Yuan & Narayan 2014). Others argue that the spin of the black hole is important (Martinez-Sansigre & Rawlings 2011; McNamara et al. 2011; Blandford et al. 2019). One of the most widely accepted hypotheses is that the radio jet is driven by the Eddington-scaled accretion rate onto the black hole, with the ADAF mode occurring when the accretion rate is well below the Eddington limit. This was the prediction in the original work of Narayan & Yi (1995), and support for this picture has come from recent work indicating that broad-line AGNs (i.e., quasar-like AGNs seen face-on) have lower limits to their accretion rates at around 1% of the Eddington limit (Kollmeier et al. 2006; Trump et al. 2009, 2011), and indications that a switch between flat-spectrum radio quasars and BL Lac objects (which are believed to be beamed versions of the radiatively inefficient sources) also occurs at that Eddington rate (Ghisellini et al. 2011; Wu et al. 2011). This hypothesis is used by synthesis models for AGN evolution (e.g., Merloni & Heinz 2008) that have been constructed based upon the two different accretion modes.

Despite the difficulties in observing gaseous outflows in galaxies that are intrinsically weak-lined, there is some observational evidence of outflows in LERGs. Morganti et al. (2003a) detected an outflow in H I in the LERG 3C 293. Emonts et al. (2005) further reported an asymmetric [S II] $\lambda\lambda 6717, 6731$ line profile ("blue wing"), indicating an ionized outflow ejecting low-density gas (300 cm$^{-3}$) in 3C 293. Emonts et al. (2005) detected similar kinematics in the ionized gas ([S II]) compared to the H I, concluding that the acceleration from the bow shock of the radio jet is driving the outflows. Morganti et al. (2005) further reported an outflow in H I in the LERG 3C 236, where Labiano et al. (2013) also saw signatures of asymmetry in the [O III] line profile. They stated that the AGN activity could be triggered due to a recent merger.

Chandola & Saikia (2017) studied a sample of 91 radio galaxies at low redshift ($0.02 < z < 0.23$) with low radio luminosity ($10^{23} < L_{1.4 \text{GHz}} < 10^{26}$ W Hz$^{-1}$), among which 80 are LERGs. They investigated the absorption profiles of H I to look for possible feedback by radio jets. They found that the most blueshifted gas cloud has a velocity shift with respect to the optical systemic velocity, $\sim -310$ km s$^{-1}$. Additionally, these 80 LERGs show large line widths (full width at 20% of the peak) of $\sim 500$ km s$^{-1}$, which are associated with radio sources with higher $L_{1.4 \text{GHz}}$. This gas could possibly be disturbed by the radio jet causing the large line width and shock accelerated in their host galaxies causing this blueshift in H I. Chandola & Saikia (2017) concluded that LERGs with relatively higher radio luminosities show evidence of outflows interacting with the interstellar medium that may affect the star formation rates (SFRs) as the sources evolve. Recently, another study by Schulz et al. (2018) with very-long-baseline interferometry of 3C 236 suggested that the outflow could be driven by a jet as the radiation will be inefficient to drive the outflows in LERGs.

The asymmetric and high-velocity [O III] $\lambda 5007$ line profiles are commonly used to trace outflows over tens of parsecs (e.g., Mullaney et al. 2013; Harrison et al. 2014). As [O III] is a forbidden transition line, it cannot be produced in the high-density subparsec scales of the broad emission-line region, which makes it a good tracer of narrow-line region kinematics, and it can be observed from tens of parsecs to tens of kiloparsec scales (e.g., Wampler et al. 1975; Boroson et al. 1985; Stockton & MacKenty 1987).

Labiano et al. (2013) reported remarkably large widths in H I and the optical emission lines of [O III] $\lambda 4959, 5007$ in the Sloan Digital Sky Survey (SDSS; York et al. 2000) spectrum of 3C 236 (FWHM $\sim 900$ km s$^{-1}$, full width at zero intensity, FWZI $\sim 2000$ km s$^{-1}$), taken from the SDSS archive. This large width was also seen in the optical emission of H I, [N II] $\lambda\lambda 6548, 6583$, [S II] $\lambda\lambda 6716, 6731$ lines, as well as in the infrared lines [Ne II] and [Ne III] (Dasyra & Combes 2011; Guillard et al. 2012). An overlay of the [O III] $\lambda 5007$ line and a Gaussian fit to the $^{12}$CO (2 $\rightarrow$ 1) line revealed the existence of extreme red and blue velocities (red and blue wings) $\sim 400$ km s$^{-1}$, which is far beyond the range allowed by the rotation of the disk (Labiano et al. 2013). The authors also found that the FWZI value $\sim 3$ times the value measured for the $^{12}$CO (2 $\rightarrow$ 1) line; the FWZI values are similar for the red and blue wings, suggesting that the red wing is produced in the receding side of the same outflow system. Labiano et al. (2013) concluded that these extreme red and blue velocities and the large line width clearly indicate the presence of an outflow.

Labiano et al. (2013) further reported that a comparison with the H I outflow component shows that the blue wing of the ionized gas emission lines covers a comparable velocity range,
suggesting that the ionized gas outflow may have started to recombine and form H I (Morganti et al. 2003b). One drawback of the study by Labiano et al. (2013) was that they lacked any physical spectral modeling of the [O III] λλ4959, 5007 line and therefore, their measured red and blue velocities may not represent the exact velocity offset of the respective ionized gas cloud from the rest frame of the host galaxy.

A spectroscopic study of optical [O III] lines in ~39,000 type II AGNs by Woo et al. (2016) reported that the outflows are strongly correlated with the [O III] luminosity (which is related to the AGN bolometric luminosity as per Heckman & Best 2014) and the Eddington ratio. The AGNs in the sample of Woo et al. (2016) consisted of both low-ionization nuclear emission-line regions (LINERs) and Seyferts, which imply that the connection of the AGN accretion disk to the outflows could possibly be applicable to LINERs too. There is a possibility that a subpopulation of LINERs could potentially represent a radio-quiet analog of LERGs, but it is difficult to come to any conclusion without a proper spectroscopic analysis of LERGs. Unfortunately, the studies of outflows in LERGs are mostly single-object based, and there is almost no systematic study on the outflows in [O III] λλ4959, 5007. We therefore pursue a systematic spectroscopic analysis to investigate the outflows in ionized gas.

In this paper, we are interested in measuring the properties and determining the potential driving mechanism of the warm (~10^4 K), ionized outflows in LERGs and to see the effect of these outflows on their host galaxies. We present an SDSS spectroscopic analysis of a sample of 802 LERGs with 0.01 < z < 0.3 drawn from the parent sample of Best & Heckman (2012). Importantly, this means that we can place our spectroscopic observations into the context of the overall nearby LERG population.

In Section 2, we first briefly describe our sample-selection criteria and the sample itself. We detail our method for detecting outflows in Section 3, while in Section 4 we attempt to explain the key driving force behind the launching of the outflows, and what role these outflows play in terms of AGN feedback. We summarize our conclusions in Section 5. Throughout this paper we adopt the standard Λ cold dark matter cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_\Lambda = 0.7 \).

2. Data

The sample of radio sources was constructed by combining the seventh data release (DR7; Abazajian et al. 2009) of the SDSS spectroscopic sample with the National Radio Astronomy Observatory (NSRAO) Very Large Array (VLA) Sky Survey (NVSS; Condon et al. 1998) and the Faint Images of the Radio Sky at Twenty Centimeters (FIRST; Becker et al. 1995) survey, from the sample of Best & Heckman (2012) for the earlier second data release of SDSS (Abazajian et al. 2004). The parent sample for the DR7 matching is the 927,552 galaxies in the value-added spectroscopic catalogs produced by the group from the Max Planck Institute for Astrophysics, and Johns Hopkins University (MPA/JHU; Brinchmann et al. 2004). These galaxies are cross-matched with the NVSS and FIRST radio sources following the method of Best et al. (2005), but adopting the refinement described by Donoso et al. (2009) for identification of sources without FIRST counterparts. The cross-matching goes down to a flux-density level of 5 mJy, which means that the sample probes down to radio luminosities of \( L_{1.4 \text{ GHz}} \sim 10^{23} \text{ W Hz}^{-1} \) at redshift \( z = 0.1 \).

We initially retrieve radio information from the data catalog of Best & Heckman (2012). This data catalog consists of the characterization of the 18,286 radio sources, among which 9863 radio sources are LERGs. Explicitly, for this work, we limit ourselves to LERGs with signal-to-noise ratio (S/N) > 3 for each of the H β, [O III] λλ5007, [N II] λλ6584, H α, [S II] λλ6716, and [S II] λλ6731 emission lines for confirmed detection. We additionally select only LERGs with \( z < 0.3 \) to ensure that the H α line does not go out of the SDSS wavelength coverage.

Buttiglione et al. (2010) defined a parameter, called “excitation index”:

\[
EI = \log \left( \frac{[\text{O III}]}{H_\beta} \right) - \frac{1}{3} \left( \log \left( \frac{[\text{N II}]}{H_\alpha} \right) + \log \left( \frac{[\text{S II}]}{H_\alpha} \right) + \log \left( \frac{[\text{O II}]}{H_\alpha} \right) \right)
\]

They demonstrated this parameter to be bimodal and mentioned that the approximate separation between LERGs and HERGs is around excitation index (EI) ~ 0.95. The lack of [O I] information restricts us estimating EI to select the LERGs. However, we adopt the classification of LERGs from the diagnostic diagrams of Buttiglione et al. (2010) based on emission lines that are available:

\[
\log([\text{O III}] / H_\beta) - \log([\text{N II}] / H_\alpha) \lesssim 0.7,
\]

\[
\log([\text{O III}] / H_\beta) - \log([\text{S II}] / H_\alpha) \lesssim 0.9.
\]

In order to trace outflow signatures in highly ionized lines, we require the emission lines to be strong enough for the detection beyond the noise level. We also aim for a single consistent approach, unlike Best & Heckman (2012), who carried out a multiple approach, combining different methods to classify the radio AGNs until a classification was achieved. Consequently, we confine our analysis to radio sources that could be selected as LERGs by the analysis of Best & Heckman (2012) and Buttiglione et al. (2010). We therefore only choose the sources that are identified as LERGs by both Best & Heckman (2012) and Buttiglione et al. (2010). We further put special emphasis on their accretion rates. LERGs have been shown to have weak accretion rates (Best & Heckman 2012). As the accretion rate goes up, beyond 1% of the Eddington accretion rate, the radiation will become more efficient to drive the feedback. Therefore, we selected the LERGs that have Eddington ratio \( \lambda_{\text{Edd}} < 0.01 \). This selection process gives us 802 LERGs.

We use the data from the AGN Line Profile and Kinematics Archive (ALPAKA; Mullaney et al. 2013) catalog in order to put our results in context with respect to the work by previous spectral studies connecting outflows and radio sources. The ALPAKA catalog consists of spectroscopic measurements of 24,264 type I and type II AGNs (Seyferts only—LINERs were excluded; Mullaney et al. 2013), including both strongly accreting (\( \lambda_{\text{Edd}} > 0.01 \)) and weakly accreting (\( \lambda_{\text{Edd}} < 0.01 \)) AGNs. We additionally use imaging from FIRST to determine the radio morphology of our LERG sample.
3. Analysis and Results

3.1. [O III] Profile Modeling

We use the stellar continuum-subtracted spectra provided by SDSS throughout the analysis. As we look for the signs of outflows in [O III] line emitting gas, we mainly focus on modeling the [O III] λ5007 line shape. In order to get a better constraint on the fit, we extended our spectral modeling to [O III] λ4959. We therefore consider the rest-frame wavelength region from 4900 to 5050 Å, which covers the [O III] λλ4959, 5007 doublet. This large wavelength window enables us to account for all of the spectral lines covering narrow emission-line region (NLR) components, especially any asymmetry in the line shape (if present) that could potentially affect our measurement of [O III] kinematic parameters.

In order to implement our spectral model, we assume that the velocity centers and the line widths of the narrow [O III] λ4959, 5007 are exactly the same, because they likely originate from the same physical region with similar kinematics. We further put two constraints on the line fluxes in addition to our previous assumptions of emission-line kinematics. The first constraint states that the [O III] λλ4959, 5007 complex has a line flux ratio of one-third (Storey & Zeippen 2000) as expected from subatomic physics. Second, we approximated the continuum with a linear model as the wavelength range of interest was a very small part of the wavelength range covered by the spectrograph. In order to use only high S/N lines and clarify potential asymmetries, we further calculated the average S/N within the wavelength range from 4997 to 5017 Å, which contains the emission line [O III] λ5007. If S/N > 3, we proceeded with modeling the data.

We model the [O III] λ4959, 5007 doublet using a nonlinear Levenberg–Marquardt algorithm with a single or double Gaussian function accounting for each of the emission lines. We only adopt a double Gaussian profile if the skewness within the rest-frame wavelength range from 4980–5025 Å is outside the range [−0.5, 0.5]. This shows a prominent asymmetry in the [O III] line profile. We assume that the narrowest [O III] λ5007 component lies at the systematic redshift. Mullaney et al. (2013) found that the redshift derived from the [O III] λ5007 line is in very good agreement with the redshift provided by the SDSS database. We define the velocity shift, Δv, as Δv = v₂ − v₁, where v₁ and v₂ are the line centers of the first (core) and second Gaussian (wing) components, respectively. A velocity shift Δv > 0 indicates the presence of a blue wing, while a red wing has Δv < 0. Furthermore, we create 100 mock spectra by fluctuating the spectroscopic data with their respective uncertainties and repeat the modeling process, and then estimate the uncertainty in individual model parameters by taking the standard deviation of the distribution. In order to avoid erroneously fitting the noise as the second Gaussian component, we adopt the following criterion:

1. If the amplitude of a Gaussian component is A with an associated uncertainty N, then both Gaussian components must have A/N > 3;
2. The fractional error in velocity dispersion in each of the Gaussian components must be < 1.

We describe the second Gaussian component to indicate an outflow only if the fractional error in Δv < 1.

In summary, we only describe the visible asymmetry in the [O III] λλ4959, 5007 doublet as being indicative of an outflow when both fitted Gaussians are significant and they are offset from each other beyond the uncertainty level.

This selection process results in 14 sources with confirmed outflows in [O III], with 13 sources showing visible blue wings and one source showing a red wing.

Crenshaw et al. (2010) explained whether there are instances where a combination of outflow geometry and extinction can lead to a redshifted emission line. They showed a test case where the position angle (PA) and inclination of the galactic disk are such that the blueshifted cone in the south is entirely occulted by the disk and the redshifted cone in the north is not. They ran a simulation for every possible combination of disk inclination, bicone inclination (i), and difference in PA in 1° intervals, weighted by the probability of observing a disk or bicone at a particular inclination (xsin i). Assuming a random distribution of these parameters, they found that the percentages of the total population that shows more extinction of the redshifted portion of the bicone than the blueshifted portion are 17.2, 16.7, 15.6, and 13.7% for half-opening angles of the bicone of 30°, 40°, 50°, and 60°, respectively (Crenshaw et al. 2010). They concluded that this model can explain the relatively small occurrences of redshifted emission lines.

In some spectra, we notice a “dip” in the rest-frame wavelength region from 4970–4990 Å, and in some cases, the “dip” is comparable to the neighboring emission line [O III] λ5007. The presence of this “dip” essentially indicates fluctuations in noise in the spectra, and therefore any results from this subsample will be unreliable. To filter out the results from these spectra, we define two regions: region 1, where the rest-frame wavelength is between 4970 and 4990 Å, and region 2, where the rest-frame wavelength is between 4995 and 5015 Å. Region 2 contains the emission-line region. If the absolute value of the amplitude in region 2 was more than three times that in region 1, then we considered it a reliable result. This process eliminates two additional sources.

Consequently, we find 12 LERGs with outflows, representing ~1.5% of the parent sample of 802 LERGs. Plots of the model fits to the nuclear spectra for these 12 LERGs can be seen in Figure 1, with derived parameters tabulated in Table 1.

3.2. Hα + [N II] Profile Modeling

We model the Hα + [N II] λλ6548, 6583 doublet using a nonlinear Levenberg–Marquardt algorithm with a multi-Gaussian function accounting for each of the emission lines, as seen in Figure 2. The Hα + [N II] complex shows a great diversity among the 12 sources. In some sources the line profile does not show any asymmetry, whereas in some cases there is a prominent asymmetry. Further, in some cases we notice a visible broadening in the spectral shape of Hα, suggesting the possible existence of a broad-line region (BLR).

We primarily adopt a double Gaussian model to check for outflows in Hα + [N II] λλ6548, 6583 as seen in their [O III] line shape, where each of the Gaussian triplets represents core and wing components. We again assume that the velocity centers and the line widths of the [N II] λλ6548, 6583 and Hα are exactly the same for each of the core and wings. Additionally, we assume that the [N II] λλ6548, 6583 complex has a line flux ratio of one-third based on subatomic physics, and again use a linear model to account for the continuum. We confirm the necessity of the second Gaussian if both of the Gaussian components have A/N > 3 and the fractional error in velocity dispersion is less than unity. In J003704.10−010908.3 and J124633.75+115347.8, the Hα wing component has
A/N < 3 but A/N > 3 in the [N II] λλ6548, 6583 wings. Therefore, we neglect the Hα wing component in those two sources. In four objects, we see that the FWHM of the second Gaussian component of Hα is >2000 km s⁻¹ with A/N < 3 for the second Gaussian component of [N II]. For these cases, we refit the spectra with a single Gaussian model accounting for all of the narrow cores of Hα + [N II] λλ6548, 6583, and a broad Gaussian accounting for the Hα BLR. We checked that each of the Gaussian components has A/N > 3 and the fractional error in velocity dispersion is less than unity. In J142440.52+263730.4 and J151838.90+404500.2, we see that both the Hα and [N II] λλ6548, 6583 wings have A/N > 3. Therefore,
we do not use any further Gaussian component beyond the Gaussian triplet representing the Hα + [N II] λλ6548, 6583 core.

3.3. SFRs for the LERGs with Outflows

We estimate the SFR for those LERGs with outflows using the Hα core luminosity as derived from the Hα + [N II] spectral modeling using the relation from Kennicutt (1998):

\[
\text{SFR} \frac{M_\odot}{\text{yr}^{-1}} = 7.9 \times 10^{-42} \frac{L_\text{Hα}}{\text{erg s}^{-1}}. \tag{1}
\]

Derived SFRs are listed in Table 2.

3.4. Radio Morphology

We additionally retrieved radio images from FIRST (Becker et al. 1995) for the 12 weakly accreting LERGs with ionized outflows seen in [O III]. In Figure 3 we present total intensity images showing the radio morphology of each object. We find that six of our 12 weakly accreting LERGs are Fanaroff-Riley (FR; Fanaroff & Riley 1974) class 0 objects (compact sources), three are FR I, and three are FR II with faint lobes. The source properties are compiled in Table 1.

3.5. Mass Outflow Rates

The mass, energy, and momentum being carried by galaxy-wide outflows are important quantities to constrain in order to understand the role that outflows play in galaxy formation. Outflows are likely to be entraining gas in multiple phases (i.e., ionized, molecular, and neutral), and multiple gas phase observations are required to fully characterize the outflow properties (e.g., Shih & Rupke 2010; Hardcastle et al. 2012; Mahony et al. 2013; Rupke & Veilleux 2013; Dasyra et al. 2014). However, the warm ionized gas, which we observe in our observations, provides preliminary information on the outflows in this sample and could represent a large fraction of the overall mass and energy of the total outflows, as has been shown for some AGNs (e.g., Rupke & Veilleux 2013). As is often invoked throughout the literature, we can apply some simple outflow models to the whole sample to provide first-order constraints on the mass, energy, and momentum involved in the outflows and to enable a direct comparison to other studies.

The NLR clouds are often driven in outflows by the central engine (Hutchings et al. 1998; Crenshaw & Kraemer 2000; Crenshaw et al. 2000) and are generally in a biconical structure, with the apex of the bicone residing in the central AGN (Pogge 1988; Schmitt et al. 1994). In recent years, Fischer et al. (2013) employed a biconical geometry on Hubble Space Telescope long-slit spectroscopic data for the NLR, where both cones are identical. They found that this biconical geometry best explains how [O III] images often show axisymmetric, triangular NLRs for Seyfert 2s and compact circular or elliptical NLRs for Seyfert 1s, consistent with the unified model (Schmitt et al. 2003), Cano-Díaz et al. (2012) and Cresci et al. (2015) preferred a conical outflow geometry and adopted a simple model for their high redshift (z > 2) quasars. Cano-Diaz et al. (2012) reported the strongly blueshifted regions to the south and to the east of the nucleus of the luminous quasar 2QZJ002830.4-281706, together making a bow-like morphology, suggestive of the envelope of a strong conical outflow. Cano-Díaz et al. (2012) assumed a conical geometry with a given opening angle, uniformly distributed ionized gas clouds with similar density and a constant outflow velocity. Following their work, and with the assumption of constant density clouds and case B recombination with an electron temperature of T ~ 10^4 K, the kinetic power and mass outflow rate become independent of the opening angle and the filling factor of the clouds within the cone; thus, Husemann et al. (2016) derived the following relations:

\[
\frac{M_{\text{ion}}(D)}{3M_\odot \text{ yr}^{-1}} = \left( \frac{L_{\text{Hβ}}}{10^{44} \text{ erg s}^{-1}} \right) \left( \frac{n_e}{100 \text{ cm}^{-3}} \right)^{-1} \left( \frac{\nu_{\text{out}}}{100 \text{ km s}^{-1}} \right) \left( \frac{D}{\text{kpc}} \right)^{-1}; \tag{2}
\]

\[
\frac{\dot{E}_{\text{kin}}(D)}{10^{40} \text{ erg s}^{-1}} = \left( \frac{M_{\text{ion}}(D)}{3M_\odot \text{ yr}^{-1}} \right) \left( \frac{\nu_{\text{out}}}{100 \text{ km s}^{-1}} \right)^2, \tag{3}
\]
where $v_{\text{out}}$ is the outflow velocity. As H$\beta$ has a much lower S/N than [O III] for these LERGs, it is difficult to obtain the luminosity of the H$\beta$ wing component. In fact, even the H$\beta$ core component is difficult to determine. We therefore assume that the [O III]/H$\beta$ ratio for the wing components would be similar to their flux ratios determined by the SDSS pipeline, and obtain the H$\beta$ wing luminosity by simply multiplying the [O III] luminosity by the [O III]/H$\beta$ flux ratio from the MPA/JHU catalog.

One important quantity for estimating the effect of feedback is the outflow size, $R_{\text{out}}$. Unfortunately, one-dimensional spectroscopic data does not allow us to directly estimate the possible sizes of the outflow. Kang & Woo (2018) kinematically measured outflow sizes by estimating the distance from the nucleus where the [O III] velocity dispersion becomes equal to the host galaxy’s stellar velocity dispersion using Gemini Multi-Object Spectrographic data. They determined a relation between outflow size and [O III] luminosity that we employ to establish an upper limit on the outflow sizes from these LERGs.

Figure 2. Multicomponent modeling of the H$\alpha$+[N II] complex for the 12 weakly accreting LERGs, arranged as in Figure 1. Here the green Gaussians represent the fit to the H$\alpha$+[N II] core, the blue Gaussians represent the fit to the wing component, while the dotted black curves denote the fit to the broad H$\alpha$ component. The red and gray curves represent the total model and data (along with shaded 1$\sigma$ errors), while the bottom panels are as in Figure 1.
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Table 2

Feedback Parameters of the LERGs with Outflows

| Object          | log($L_{[O III]}$) | SFR [M$_\odot$ yr$^{-1}$] | log(SFR) [yr$^{-1}$] | log($R_{out}$) [kpc] | log($E_{out}$) [erg s$^{-1}$] | $M_{gas}$ [M$_\odot$ yr$^{-1}$] | $\eta^a$ |
|-----------------|-------------------|-----------------------------|----------------------|----------------------|-------------------------------|---------------------------------|---------|
| J003704.10−010908.3 | 4.12               | 1.54                        | −10.63               | 1.19                 | 42.73                         | 97.77                           | 63.6    |
| J094319.15+361452.1 | 4.13               | 3.39                        | −10.67               | 0.92                 | 42.27                         | 45.62                           | 13.5    |
| J115141.05+334144.5 | 4.47               | 23.19                       | −11.80               | 2.61                 | 42.05                         | 131.62                          | 0.6     |
| J120240.06+544700.3 | 4.83               | 5.29                        | −12.10               | 0.94                 | 42.65                         | 59.74                           | 11.3    |
| J124633.75+115347.8 | 4.20               | 12.56                       | −11.41               | 1.15                 | 42.44                         | 35.41                           | 2.8     |
| J135217.88+312646.4 | 4.12               | 10.45                       | −11.43               | 0.92                 | 42.50                         | 36.82                           | 3.5     |
| J142041.03+015930.8 | 4.33               | 16.79                       | −12.22               | 1.43                 | 42.77                         | 175.58                          | 10.5    |
| J142440.52+263730.4 | 4.48               | 2.53                        | −12.13               | 0.97                 | 42.71                         | 63.94                           | 25.3    |
| J150656.41+125048.6 | 4.86               | 6.08                        | −9.30                | 0.85                 | 42.68                         | 40.81                           | 6.7     |
| J151838.90+404500.2 | 4.69               | 9.22                        | −10.90               | 1.14                 | 42.90                         | 80.27                           | 8.7     |
| J153457.20+233013.2 | 4.28               | 1.51                        | −12.11               | 0.56                 | 41.42                         | 7.22                            | 4.8     |
| J232710.69−004157.7 | 4.97               | 5.75                        | −10.24               | 1.24                 | 42.58                         | 151.11                          | 26.3    |

Notes.

$a$ Logarithm of the narrow H$\alpha$ core luminosity, from the multi-Gaussian modeling of H$\alpha$ + [N II] complex (see Section 3.2).

$b$ Logarithm of the kinetic energy carried out by the outflow per unit time (see Section 3.5). We assume a biconical outflow geometry.

$c$ Mass carried out by the outflow per unit time (see Section 3.5).

$d$ Mass loading factor as obtained from the ratio of mass outflow rate to SFR (i.e., $\eta = M_{out}/$SFR).

(Kang & Woo 2018):

$$\log(R_{out}(\text{pc})) = (0.250 \pm 0.018)\log\left(\frac{L_{[O \text{III}]}^\odot}{10^{42} \text{erg s}^{-1}}\right) + (3.746 \pm 0.028).$$

Another necessary quantity for measuring ionized gas masses, and hence mass outflow rates, is the electron density, $n_e$. As the wing component of [S II] was not detected during our analysis, we use the electron density obtained by Kakkad et al. (2018), where $n_e$ drops exponentially with increasing distance from the nucleus. However, this relation requires a maximum possible $n_e$ representing the $n_e$ near the AGN. Kakkad et al. (2018) found that the electron density for the outflowing gas is $\sim 50 - 200 \text{cm}^{-3}$. We therefore use 2000 cm$^{-3}$ as the maximum allowable electron density, and estimate the electron density at $R_{out}$. We estimate the mass and kinetic energy outflow rates for the LERGs with outflows using Equation (2) and (3), which we list in Table 2.

4. Discussion

In this section, we put our results in the context of previous studies to investigate the possible driving force behind the outflows.

4.1. Do Compact Radio Sources Preferentially Drive Outflows?

Heckman et al. (1984) analyzed 34 moderate-resolution ($\sim 70 - 150 \text{km s}^{-1}$) quasar spectra of the prominent [O III] $\lambda 5007$ emission line using data from three telescopes: the image dissector scanner coupled to the Cassegrain spectrometer on the European Southern Observatory 3.6 m telescope, the High Gain Video Spectrometer coupled to the Ritchey-Chretien spectrometer on the Kitt Peak National Observatory 4 m Mayall telescope, and the intensified photon-counting Reticon spectograph mounted on the Arizona-Smithsonian Astrophysical Observatory Multiple Mirror Telescope. They found that the widths of the [O III] $\lambda 5007$ line from the NLR are correlated with the luminosity of the portion of the steep-spectrum radio emission, which occurs on a size scale $\sim 10^2 - 10^3 \text{pc}$. Whittle (1992) reported that a relatively well-defined group of Seyferts with linear radio morphology and high radio luminosity ($L_{1.4 \text{GHz}} > 10^{22.5} \text{W Hz}^{-1}$) have significantly broader [O III] lines, suggesting an additional acceleration mechanism is present. Long-slit observations of these objects have revealed high-velocity components approximately coincident with the near-nuclear radio lobes, suggesting that the jet that powers the radio source also accelerates ionized gas, creating a super-virial bipolar flow (Whittle 1992). Their studies also supported the idea of a compact radio core that could possibly disturb the [O III] to create such broad line widths. Several spectral studies of small samples of radio AGNs exhibiting compact radio jets reported broadening in the [O III] $\lambda 5007$ emission line that are co-spatial with these compact jets (e.g., Gelderman & Whittle 1994; Tadhunter et al. 2003; Holt et al. 2006, 2008). They suggested that the mechanical energy from the jets is disturbing the [O III] $\lambda 5007$ emitting gas in these cases. An additional spectroscopic study by Mullaney et al. (2013) examined 24,264 optically selected AGNs with $z < 0.4$. Similar to the authors above, Mullaney et al. (2013) reported a connection between the outflows and compact radio cores (for a recent review, see O’Dea & Saikia 2021).

Mullaney et al. (2013) used the flux-weighted average FWHM (FWHM$_{avg}$) of the [O III] $\lambda 5007$ line in which the contributions from both fitted Gaussians could contribute, rather than just the broad Gaussian component. FWHM$_{avg}$ is very useful in case there is any significant broadening (FWHM $> 500 \text{km s}^{-1}$) in the narrower Gaussian component. It is defined as:

$$\text{FWHM}_{\text{avg}} = \sqrt{(\text{FWHM}_{c,f_{c}})^2 + (\text{FWHM}_{w,f_{w}})^2},$$

where $f_c$ and $f_w$ are the fractional fluxes contained within the two fitted components (core and wing, respectively), and FWHM$_c$ and FWHM$_w$ are their respective FWHMs. Focusing on the flux-weighted average FWHM, Mullaney et al. (2013) tried to avoid arbitrary definitions such as the threshold above which a broad component constitutes an important contribution to the overall flux of the emission line, or the point beyond which a component is considered “broad.” Mullaney et al. (2013) mentioned that this characterization of the width of the [O III] $\lambda 5007$ line would ensure that all AGNs, whether their
Figure 3. Total intensity radio images, as taken from the Faint Images of the Radio Sky at Twenty Centimeters (Becker et al. 1995) survey for the 12 weakly accreting LERGs with convincing blue wings in [O III]. Images are arranged as in Figure 1. A scale bar is present in each frame showing 100 kpc projected at the redshift of each radio source.
In Figure 4, we plot the flux-weighted average FWHM against the radio luminosity for our outflowing LERGs. We further overplot the weakly accreting AGNs (λrad < 0.01) from Mullaney et al. (2013). We do not see that the FWHMavg of our LERGs increases significantly between the radio-luminosity range 10^{23} < L_{1.4\text{GHz}} < 10^{25} \text{ W Hz}^{-1}, whereas the weak accretors in the sample of Mullaney et al. (2013) clearly show an increase in FWHMavg in that range. For the weakly accreting sources, the sample of Mullaney et al. (2013) has a mean FWHMavg ~ 600 km s\(^{-1}\), whereas our outflowing LERGs have FWHMavg ~ 400 km s\(^{-1}\).

Mullaney et al. (2013) reported that the width of the [O III] \(\lambda5007\) line peaks between $10^{23} < L_{1.4\text{GHz}} < 10^{25} \text{ W Hz}^{-1}$. Those moderate-$L_{1.4\text{GHz}}$ AGNs represent about 3% of the optically selected AGN population at $z < 0.123$ in the sample of Mullaney et al. (2013). Despite constituting only 3% of optically selected AGNs overall, they are ~10 times more common than the more radio-luminous AGNs that are typically the focus of detailed studies of AGN outflows (e.g., Holt et al. 2003, 2008; Tadhunter et al. 2003; Nesvadba et al. 2006, 2008; Cano-Díaz et al. 2012; Harrison et al. 2012).

Mullaney et al. (2013) used the NVSS-detected AGNs in their sample with $3 \times 10^{23} < L_{1.4\text{GHz}} < 3 \times 10^{24} \text{ W Hz}^{-1}$ to cover the region around the FWHMavg peak. They reported that all 71 AGNs in their sample with FWHMavg > 1500 km s\(^{-1}\) and single FIRST matches are unresolved (deconvolved extents <2\(')s), and the more extended radio sources do not have broader [O III] \(\lambda5007\). For the sources with multiple FIRST matches, >80% of the AGNs in their subsample have at least one radio component closer than 1\(')s to the central engine, which suggests the existence of a radio core. Additionally, they found that none of the AGNs in their radio-selected subsample have multiple NVSS matches. Mullaney et al. (2013) concluded that they are unlikely to be FR I and FR II sources.

We investigate the fraction of compact sources in our sample of 802 LERGs. Following Best et al. (2005), the sources with radio class 1 are single-component NVSS sources with a single FIRST match; sources with class 2 are single-component NVSS sources resolved into multiple components by FIRST; class 3 are single-component NVSS sources without a FIRST counterpart; class 4 are those that have multiple NVSS components. If we imagine the extended radio sources to be only contained in class 2, then the compact sources represent ~98% of the LERG population and ~2% of sources are extended radio sources. If we assume class 1 objects to be compact, and classes 2, 3, and 4 to contain extended radio sources, then the compact radio sources represent 87% of the LERG population, and the remaining 13% of sources belong to the extended radio source population. We find for our outflowing LERGs that 50% are compact radio sources (see Table 1, Figure 3), while the remaining outflowing LERGs are extended radio sources. This is in contrast to the parent sample of 802 LERGs where we see that 87% of the population consists of compact radio sources, with the remainder being extended radio sources. If we only consider class 2 objects as extended, the fraction of compact sources rises to ~98%. To summarize, although we find that about 50% of the outflowing LERG populations are compact radio sources, it agrees with compact radio sources dominating the LERG population at $z < 0.4$ where they account for >87% in a large sample of LERGs.

Mullaney et al. (2013) excluded LINERs in their analysis, as LINERs tend to be objects with weak emission lines. It is possible that a subpopulation of LINERs could represent a radio-quiet analog of LERGs. The sample of AGNs analyzed by Mullaney et al. (2013) only included type I and II Seyfert AGNs, with HERGs being their closest counterparts among radio AGNs. Therefore, we primarily focus on the radio morphology of HERGs from the sample of Best & Heckman (2012). In Figure 5, we plot histograms of the radio luminosities for the HERG population for $z < 0.123$ (upper panels) and $z < 0.4$ (the limit of the Mullaney et al. 2013 sample; lower panels). We notice the prevalence of compact radio sources until $z < 0.4$ relative to their extended counterparts (likely FR I/II). In Figure 5 the compact sources represent 91%, 79%, 88%, and 81% of the HERG population, respectively, moving left to right, top to bottom. We further perform a two-sample Kolmogorov–Smirnov test to check whether the compact and extended HERGs from Figure 5 have similar distributions or not. We find the $p$-value $< 10^{-3}$ in each case indicating the compact and extended HERGs have very different distributions. In summary, we find that the compact radio sources account for >80% of the HERG population at $z < 0.4$. This is very similar to what we see for LERGs.

As a next step, we study the radio morphologies of the LERG population by investigating the fraction of compact sources as a function of radio power in LERGs. In Figure 6, we plot the histograms of the radio luminosities for the LERG population for $z < 0.123$ (upper panels) and $z < 0.4$ (lower panels). We again notice the prevalence of compact radio sources until $z < 0.4$ relative to their extended counterparts.

\footnote{NVSS is complete to $L_{1.4\text{GHz}} > 10^{23} \text{ W Hz}^{-1}$ at this redshift.}
peaks between 10^23 and 10^24 W Hz^{-1}, which is highly dominated by compact radio AGNs, as shown above. Therefore if we analyze the radio AGNs in that region, we will be mostly looking at the compact radio AGNs. We observe that the [O III] line width does not peak within the region 10^{23} < L_{1.4 GHz} < 10^{25} W Hz^{-1} for the LERGs with ionized outflows, and the population of compact radio sources has a peak within 10^{23} < L_{1.4 GHz} < 10^{25} W Hz^{-1} in a sample of low-excitation and high-excitation radio AGNs. Thus, the preference for outflows in compact sources found by Mullaney et al. (2013) may simply be due to the fact that compact sources dominate the radio source population at z < 0.4.

### 4.2. Are Ionized Outflows Related to Accretion Disks or Radio Jets?

Previously the outflows in LERGs were usually connected to the acceleration from the bow shock of the radio jet (e.g., Emonts et al. 2005; Morganti et al. 2005; Labiano et al. 2013; Schulz et al. 2018). However, Woo et al. (2016) analyzed a sample of ~24,000 type II AGNs up to z < 0.3, and concluded that the outflows in AGNs could be linked to AGN accretion rather than their radio luminosity. The AGNs in the sample of Woo et al. (2016) consisted of both LINERs and Seyferts, and the outflows were strongly correlated with [O III] luminosity and Eddington ratio. Some of those LINER AGNs could possibly represent a radio-quiet analog of the LERGs as they tend to have weak emission lines. Therefore, based on our observations, we investigate the key driving force behind these outflows in LERGs. Our key results are as follows:

1. We see that only ~1.5% of the LERGs in our sample show signs of outflows in [O III]. We used the selection criterion
mentioned in Section 3.1 to determine the fraction of the type II optically selected AGNs with ionized outflows in the ALPAKA catalog (Mullaney et al. 2013). We find that \(\sim 35\%\) of the optically selected type II AGNs show signs of ionized outflows. Woo et al. (2016) reported that \(\sim 45\%\) of type II AGNs at \(z < 0.3\) show signs of outflows in [O III]. This indicates that having a radio jet in a low-excitation AGN is neither necessary nor sufficient for generating an ionized outflow.

2. FR I jets are thought to interact strongly with their ambient media (e.g., Laing & Bridle 2014) and might be the best candidates for driving a gaseous outflow. However, we find ionized outflows in LERGs with a range of radio morphologies: compact (FR 0), FR I, and FR II. Therefore there is no preference for any type of radio morphology in order to drive ionized outflows.

3. We calculate the jet power \(P_{\text{jet}}\) using the relation given by Cavagnolo et al. (2010) and present the distribution of jet powers in the right panel of Figure 7. We do not observe any noticeable trend between \(P_{\text{jet}}\) and the occurrence of the outflows. We perform a two-sample Kolmogorov–Smirnov test, and report a \(p\)-value of 0.33, which reveals that the jet powers in the outflowing LERGs could have similar distributions as their parent sample of 802 LERGs.

4. We present the distribution of \(\lambda_{\text{Edd}}\) in the left panel of Figure 7. We see a sharp increase in the number of LERGs exhibiting [O III] outflows as all of the 12 LERGs showing ionized outflows have \(\lambda_{\text{Edd}} > 0.001\) in the left panel. As \(\lambda_{\text{Edd}}\) increases, the number of LERGs with outflows increases. The largest number (eight out of 12) of LERGs with outflows is near \(\lambda_{\text{Edd}} \sim 0.01\). We also perform a two-sample Kolmogorov–Smirnov test, and report a \(p\)-value of \(\sim 10^{-4}\), which reveals that the Eddington ratios in the outflowing LERGs are distributed very differently compared to their parent sample of 802 LERGs.

These findings suggest that the launching mechanism of the ionized outflows could be related to radiation pressure from the accretion disk, rather than the radio jet.

Blandford & Begelman (1999) proposed the idea of an advection-dominated inflow-outflow solution, in which a small fraction of gas accreted onto the SMBH provides the energy to launch outflows. They also stated that the outflows could be self-collimating and form jets. One alternative is that before the accreted material reaches the inner accretion disk, the radiation pressure from accretion disk photons pumps the material outwards. As the ejected material travels farther, it gets further accelerated outwards from the shock of the radio jet (Capetti et al. 1999; Tadhunter et al. 2001). As the material crosses kiloparsec scales carried out by the shock of the jet, it is located on the jet’s axis. This could possibly explain why Emonts et al. (2005), Labiano et al. (2013), and Schulz et al. (2018) observed the outflowing atomic and ionized gas on the radio jet’s axis.

4.3. Feedback from LERGs

AGN feedback has become a necessary ingredient to the various numerical simulations and semi-analytic models of galaxy evolution to quench star formation at higher stellar masses, which is crucial to recover the properties of the local galaxy population (e.g., Di Matteo et al. 2005; Bower et al. 2006; Croton et al. 2006; Somerville et al. 2008; Schaye et al. 2015). In these models, a fraction of the gas escapes from the host galaxy’s potential due to galaxy-wide outflows (Harrison et al. 2014). This suppresses future star formation, regulates the central SMBH growth, and enriches the larger-scale environment with metals (Harrison et al. 2014). In this section we will discuss whether the ionized outflows in LERGs are reaching...
galaxy-wide scales or not, and more importantly, if they have an impact on the evolution of their host galaxies or not.

In order to influence the host galaxy’s evolution, these outflows must necessarily be large enough to expel gas out of the entirety of the host galaxy. In recent years, numerous studies have found that outflows from luminous quasars (10^{41} < L_{[O\text{ III}]} < 10^{44} \text{ erg s}^{-1}) could reach up to ∼10 kpc scales (e.g., Genzel et al. 2014).

We compare outflow sizes against [O III] luminosity, L_{[O\text{ III}]}, for a selection of luminous quasars, as derived by Lonsdale et al. (2003), Davies et al. (2004), Nesvadba et al. (2006, 2008), Reyes et al. (2008), Veilleux et al. (2009), Harrison et al. (2012), Liu et al. (2013a, 2013b), Rupke & Veilleux (2013), Genzel et al. (2014), Harrison et al. (2014), Brusa et al. (2015a, 2015b), Carniani et al. (2015), Cresci et al. (2015), Perna et al. (2015), Brusa et al. (2016), Wylezalek et al. (2016), Bischetti et al. (2017), Duras et al. (2017). Contours denote the distribution of non-outflowing LERGs (small black dots) in the L_{bol} − sSFR plane.

We now turn to analyze whether these LERG-driven outflows significantly quench star formation in their host galaxies or not. As outflows are of multiphase gas (Harrison et al. 2014; Husemann et al. 2016, 2019) and the majority of the mass is carried out by molecular outflows, it is difficult to constrain the complex nature of multiphase gas. However, based on our observations of the ionized outflows within the central 1 kpc, we will attempt to infer the effect of these outflows on the star formation within the host galaxies. We previously estimated an SFR of 1−12 M_☉ yr^{-1} (see Table 2). Only one object, J115141.05+334144.5, has an SFR > 232 M_☉ yr^{-1}. If the host galaxy has a large stellar mass, then it is possible it could automatically have a high SFR due to an abundance of cold gas. To mitigate this issue, we investigate the specific star formation rate, sSFR = SFR/M_*, (Behroozi et al. 2013; Schaye et al. 2015), where we adopt the stellar masses from the MPA/JHU catalog. In Figure 8, we plot the sSFR against the AGN bolometric luminosity, L_{bol}, for our LERGs along with the

Figure 8. Specific star formation rate (sSFR) vs. AGN bolometric luminosity (L_{bol}) for our outflowing LERGs (large red stars) along with luminous quasars from the literature (other symbols; Lonsdale et al. 2003; Davies et al. 2004; Nesvadba et al. 2006, 2008; Reyes et al. 2008; Veilleux et al. 2009; Harrison et al. 2012; Liu et al. 2013a, 2013b; Rupke & Veilleux 2013; Genzel et al. 2014; Harrison et al. 2014; Brusa et al. 2015a, 2015b; Carniani et al. 2015; Cresci et al. 2015; Perna et al. 2015; Brusa et al. 2016; Wylezalek et al. 2016; Bischetti et al. 2017; Duras et al. 2017). Contours denote the distribution of non-outflowing LERGs (small black dots) in the L_{bol} − sSFR plane.

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Figure 9. Mass outflow rate ($M_{\text{out}}$) vs. AGN bolometric luminosity ($L_{\text{bol}}$) for our outflowing LERGs along with luminous quasars from the literature. Symbols are the same as in Figure 8. The straight line highlights the increasing trend between $L_{\text{bol}}$ and $M_{\text{out}}$ for the luminous quasars. The outflowing LERGs lie above the straight line.

Figure 9. Mass outflow rate ($M_{\text{out}}$) vs. AGN bolometric luminosity ($L_{\text{bol}}$) for our outflowing LERGs along with luminous quasars from the literature. Symbols are the same as in Figure 8. The straight line highlights the increasing trend between $L_{\text{bol}}$ and $M_{\text{out}}$ for the luminous quasars. The outflowing LERGs lie above the straight line.

The aforementioned studies of luminous quasars. We additionally show the locations of the other 790 LERGs without outflows as points with corresponding contours. Figure 8 shows that the LERGs with outflows tend to have higher $L_{\text{bol}}$ than the LERGs without outflows. We notice that for our outflowing LERGs, the sSFR is in the range $10^{-12} < \text{sSFR} < 10^{-9} \text{yr}^{-1}$. We see a similar range of sSFR for the non-outflowing LERGs, with a concentration of $L_{\text{bol}}$ values between $10^{43} < L_{\text{bol}} < 10^{44} \text{erg s}^{-1}$. For the luminous quasars from the previous studies, the sSFR is in the range $10^{-10} < \text{sSFR} \lesssim 10^{-12} \text{yr}^{-1}$. This discrepancy indicates that the LERGs are a different class of object and have much lower sSFR, possibly due to gas depletion.

Despite the low SFRs observed in the LERGs, the outflow needs to expel significant gas mass out of the galaxy in order to quench star formation and to produce the observable host galaxy properties. We estimate mass outflow rates of $7-150 \text{M}_\odot \text{yr}^{-1}$ (see Table 2) using Equation (2). Comparing it with the SFR, we notice that they are $\approx 3-60$ times greater than the SFRs of the outflowing LERGs, with one exception at 0.5 times for J115141.05+334144.5, where we observe a prominent red wing. These mass loading factors, $\eta$, are often comparable to those of the luminous quasars from the samples of Liu et al. (2013a, 2013b), Genzel et al. (2014), Bischetti et al. (2017), and Duras et al. (2017), but much higher than the sample of Harrison et al. (2012, 2014), who traced the ionized phase of the outflows, and other works looking at the different gas phases (e.g., Martin 1999; Heckman et al. 2000; Newman et al. 2012; Cicone et al. 2014). In the sample of Carniani et al. (2015), we see a diversity in mass loading factors. The quasars at $L_{\text{bol}} < 10^{46} \text{erg s}^{-1}$ have $\eta < 1$, whereas two quasars from the sample have $\eta > 20$ at $L_{\text{bol}} \sim 10^{47} \text{erg s}^{-1}$ (Carniani et al. 2015). Strikingly, one quasar at $L_{\text{bol}} \sim 10^{47} \text{erg s}^{-1}$ in their sample has $\eta < 1$. In Figure 9, we plot the mass outflow rates, $M_{\text{out}}$, against $L_{\text{bol}}$ for our LERGs along with the results from the previously mentioned studies of luminous quasars. We notice an increasing trend between $L_{\text{bol}}$ and $M_{\text{out}}$ for both our LERGs and the quasars. The most striking feature is that the LERGs typically have higher mass outflow rates per $L_{\text{bol}}$ than the other AGNs. This could be an effect due to the existence of the radio source and how the bow shock from the radio jet could sweep material farther out in the galaxy, resulting in a higher $\eta$.

5. Summary and Conclusions

We have presented SDSS optical spectroscopic observations covering the [O III] $\lambda\lambda4959, 5007$ emission lines of 802 LERGs with $0.01 < z < 0.3$. Our targets were selected from a parent sample of 18,286 radio galaxies with $z < 0.3$ from Best & Heckman (2012), and we demonstrate the presence of outflows in the [O III] $\lambda\lambda4959, 5007$ emission lines. In short our findings are as follows:
1. Only 12 out of 802 LERGs display visible broad wings in the [O III] $\lambda$4959, 5007 emission lines. This represents $\sim 1.5\%$ of the parent sample (Section 3.1).
2. Six out of these 12 LERGs are compact radio sources, three are FR I sources, and the remaining three are FR II sources (Section 3.4). The population of compact radio sources represents $\sim 80\%$ of the radio AGN population until $z < 0.4$. Thus there is no preference for outflows to be found in a given radio source morphology (Section 4.1).
3. The numbers of LERGs with outflows show no significant trend with jet power (Section 4.2).
4. The number of LERGs with outflows increases with increasing Eddington ratio. Eight out of the 12 outflowing LERGs have Eddington ratios close to 0.01 (Section 4.2).
5. LERGs with outflows typically have $R_{\text{out}} \sim 1$ kpc, with only one source having $R_{\text{out}} \sim 2.5$ kpc. Although other luminous quasars have higher outflow sizes, there is no correlation between $L_{\text{OIII}}$ and $R_{\text{out}}$ (Section 4.3).
6. LERGs with outflows have lower SFR ($10^{-12} < \text{sSFR} < 10^{-9}$ yr$^{-1}$) than luminous quasars. This is indicative that LERGs are a different class of AGNs (Section 4.3).
7. LERGs with outflows show higher mass outflow rates than other luminous quasars for a given $L_{\text{bol}}$. The existence of a radio source could possibly enhance the mass loading (Section 4.3).

All of these results indicate that the ionized outflows in LERGs may be linked to the accretion disk, not the radio jet.

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This research has made use of NASA’s Astrophysics Data System, as well as TOPCAT, an interactive graphical viewer and editor for tabular data (Taylor 2005), in addition to Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013, 2018).

This research has made use of the VizieR catalog access tool, CDS, Strasbourg, France (DOI:10.26093/cds/vizier). The original description of the VizieR service was published in Ochsenbein et al. (2000).

Facilities: Sloan, VLA.

Software: Astropy (Astropy Collaboration et al. 2013, 2018), Matplotlib (Hunter 2007), NumPy (van der Walt et al. 2011), SciPy (Virtanen et al. 2020), TOPCAT (Taylor 2005).

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6 https://astropy.org
7 http://vizier.u-strasbg.fr/viz-bin/VizieR

Sec. 4.3
