UNRAVELING THE COMPLEX STRUCTURE OF AGN-DRIVEN OUTFLOWS. I. KINEMATICS AND SIZES

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ABSTRACT

Outflows driven by active galactic nuclei (AGNs) are often invoked as agents of the long-sought AGN feedback. Yet, characterizing and quantifying the impact on their host galaxies has been challenging. We present Gemini Multi-Object Spectrograph integral field unit data of six local (z < 0.1) and luminous (L_{OIII} > 10^{42} \text{ erg} \text{ s}^{-1}) type 2 AGNs. In the first of a series of papers, we investigate the kinematics and constrain the size of the outflows. The ionized gas kinematics can be described as a superposition of a gravitational component that follows the stellar motion and an outflow-driven component that shows large velocity (up to 600 km s^{-1}) and large velocity dispersion (up to 800 km s^{-1}). Using the spatially resolved measurements of the gas, we kinematically measure the size of the outflow, which is found to be between 1.3 and 2.1 kpc. Owing to the lack of a detailed kinematic analysis, previous outflow studies likely overestimate their size by more than a factor of two, depending on how the size is estimated and whether the [O III] or Hα emission line is used. The relatively small size of the outflows for all six of our objects casts doubts on their potency as a mechanism for negative AGN feedback.

Key words: galaxies: active – galaxies: Seyfert – ISM: jets and outflows – quasars: emission lines

1. INTRODUCTION

Astrophysical outflows can be found in a number of diverse environments and have been associated with different processes that span several orders of magnitude in spatial and temporal scales and energetics. Beyond those associated with stellar processes (e.g., Herbig 1960; Crowther 2007; Humphreys & Davidson 1994; Woosley & Bloom 2006), some of the most energetic outflows are linked to supermassive black holes (SMBHs) during the accretion phase. Such outflows have been observed in different phases of the interstellar medium (ISM): hot plasma (radio jets; Akiyama et al. 2015), ionized gas (e.g., Konigl & Kartje 1994; Murray et al. 1995; Crenshaw et al. 2003), and molecular gas (e.g., Cicone et al. 2014), although the connection of the latter to active galactic nuclei (AGNs) is still under debate. Galaxy-wide star formation or compact starburst regions are alternative drivers of such outflows (e.g., Chevalier & Clegg 1985; Veilleux et al. 2005). AGN-driven outflows are considered to be channels of the AGN feedback, which appears as necessary to explain the present-day scaling relations between black hole mass and host galaxy properties (e.g., Di Matteo et al. 2005; Springel et al. 2005; Croton et al. 2006; Somerville et al. 2008; Schaye et al. 2010; but also see Hopkins et al. 2014).

Outflows in AGN host galaxies are prevalent, as suggested by extensive observational studies of the ionized gas kinematics using large samples (e.g., Heckman et al. 1981; Whittle 1985; Nelson & Whittle 1995; Greene & Ho 2005; Crenshaw et al. 2010; Villar-Martín et al. 2011; Mullaney et al. 2013; Bae & Woo 2014; Woo et al. 2016). Corroborating evidence for these outflows also comes from studies of absorption lines in the rest-frame UV spectrum of AGNs in the local universe (e.g., Arav et al. 2012; Borguet et al. 2012; Crenshaw & Kraemer 2012; Liu et al. 2015) and at higher redshift (e.g., Moe et al. 2009; Lucy et al. 2014; Chamberlain & Arav 2015). While these studies provide convincing evidence for strong nongravitational motions affecting the ionized gas of luminous AGNs, they were unable to properly constrain either the detailed physical properties of these outflows or their impact on the host galaxies owing to the lack of spatially resolved information.

The recent development of powerful integral field unit (IFU) spectrographs has allowed us an unprecedented view of the spatially resolved properties of these outflows. A number of detailed investigations on the kinematics of AGN ionized gas in both the local universe (e.g., Sharp & Bland-Hawthorn 2010; Storchi-Bergmann et al. 2010; Riffel et al. 2013, 2014; Rupke & Veilleux 2013; McElroy et al. 2015) and at higher redshifts (e.g., Nesvadba et al. 2006, 2008; Harrison et al. 2012; Carniani et al. 2015) have elucidated the geometry and the kinematics of AGN-driven outflows.

Despite the significant progress in understanding AGN outflows, studies of gas kinematics based on IFU data have often suffered from the lack of information about the underlying gravitational potential as manifested by stellar kinematics. Without characterizing the gravitational potential within which the ionized gas is moving, precise determination of any nongravitational kinematics, i.e., an outflow, is impossible. In fact, Woo et al. (2016) showed the presence of such a nongravitational component in an increasing fraction of type 2 AGNs with increasing [O II] luminosity and Eddington ratio. This nongravitational kinematic component would be otherwise watered down without removing (or correcting for) the gravitational component as traced by stellar motions. Thus, proper spatial and kinematic decomposition of the ionized gas emission is the key to constraining both the size and the kinetic energy of the outflows, which in turn allows the fundamental understanding of the AGN feedback.

Here we present the analysis of Gemini Multi-Object Spectrograph (GMOS) optical IFU data for six luminous type 2 AGNs, drawn from our previous study of a sample of \(\sim 39,000\) SDSS type 2 AGNs (Bae & Woo 2014; Woo et al. 2016). We characterize the kinematics and size of the outflows in these objects, by taking into account the gravitational and nongravitational kinematics.
Section 2 describes the sample selection, observations, and data reduction. In Section 3 we discuss our method of measuring kinematics, including continuum and emission line fitting, as well as measurement uncertainties. In Sections 4 and 5 we present the main results. Section 6 provides discussion, and Section 7 presents the summary and conclusions. Finally, in the Appendix we provide comments on individual sources. We use the following cosmological parameters for a ΛCDM universe: $h_0 = 0.71$, $Ω_m = 0.27$, and $Ω_Λ = 0.73$.

2. SAMPLE AND OBSERVATIONS

2.1. Sample Selection

In our previous statistical study using $39,000$ type 2 AGNs at $z < 0.3$ based on the archival spectra of the Sloan Digital Sky Survey (SDSS; Woo et al. 2016), we identified AGNs with extreme kinematic signatures by analyzing the velocity and velocity dispersion of the [O III] λ5007 emission line. Among them, we selected six AGNs for a pilot study using the following criteria. First, we limited the redshift range to $z < 0.1$ to obtain subkiloparsec spatial resolution. Second, since the outflow kinematics is closely linked to AGN luminosity, we focused on high-luminosity AGNs by selecting 902 type 2 AGNs with extinction-corrected [O III] luminosity $L_{[\text{O III}]} > 10^{42}$ erg s$^{-1}$. Third, out of 902 objects, we selected 29 AGNs with an [O III] velocity shift $|v_{\text{[O III]}}| > 250$ km s$^{-1}$ (with respect to the systemic velocity measured from stellar absorption lines) and an [O III] velocity dispersion $σ_{\text{[O III]}} > 400$ km s$^{-1}$, based on measurements using SDSS spectra (Woo et al. 2016). We argue that these AGNs with strong outflow signatures are the best candidates for detecting spatially resolved outflows and for understanding the impact on their host galaxies.

In Figure 1, we present the [O III] velocity–velocity dispersion (VVD) diagram for the luminosity-limited sample of 902 AGNs with $L_{[\text{O III}]} > 10^{42}$ erg s$^{-1}$ along with the kinematically selected 29 AGNs. The selection criteria of the [O III] kinematics (gray box) indicate that the kinematically selected 29 AGNs have extreme velocities compared to the majority of AGNs with similar luminosities. The fraction of the selected AGNs based on the kinematic criteria is 3.2%. If we do not apply the luminosity limit, a total of 95 objects (0.4%) out of the $\sim23,000$ AGNs at $z < 0.1$ satisfies the [O III] kinematic criteria. Given its completeness in terms of the [O III] luminosity and kinematics, we will use this sample to understand AGN-driven outflows, including kinematics, energy budgets, and the impact on the ISM for high-luminosity AGNs in the local universe.

We are performing an integral field spectroscopy survey of these 29 AGNs using three different instruments: the GMOS IFU (Allington-Smith et al. 2002) on Gemini-North (six sources, presented here), the Inamori MALegan Cassegrain Spectrograph (IMACS) IFU (Dressler et al. 2011) on the 6 m Magellan-Baade telescope (nine sources), and the SuperNova Integral Field Spectrograph (SNIFS) IFU (Aldering et al. 2002; Lantz et al. 2004) on the 2.2 m University of Hawaii telescope (14 sources). Given the significant differences in spatial and spectral resolution and the achieved signal-to-noise ratio (S/N) among the three data sets, we present first the results using the highest-quality Gemini GMOS-N data. We provide the properties of the Gemini/GMOS sample in Table 1.

2.2. Observations with the GMOS IFU on Gemini-North

We observed six AGNs using the GMOS-N IFU in 1-slit mode in the 2015A semester (ID: GN-2015A-Q-204, PI: Woo). The field of view (FOV) was $3″ \times 3″$, which corresponds to 3–9 kpc at the redshift of our targets, with a spatial pixel (spaxel) scale $\sim0″.07$. We used the B600 grating, which delivers a spectral resolution of $R \sim 1700$ over the spectral range $\sim4500$–$6800$ Å. Given the configuration of the lenslets, we used a 2 pixel spectral binning, degrading the nominal resolution to $R \sim 1400$, corresponding to an FWHM velocity resolution of $\sim215$ km s$^{-1}$. Exposure times were determined based on surface brightness measurements in $B$ band calculated from SDSS photometry, ranging between 45 and 140 minutes (see Table 1).

During our observations, which were performed as part of the K-GMT Science Program in priority visitor mode, weather conditions were stable with low wind and moderate humidity values. Seeing values ranged between $0″.5$ and $0″.8$, corresponding to subkiloparsec spatial resolutions for most of our targets (e.g., $\sim1$ kpc for the farthest target J172038+294112 at $z = 0.0995$). In Table 1 we provide the log of the observations.

2.3. Data Reduction

We used the Gemini IRAF package for the data reduction, following the standard procedures for the 1-slit mode IFU on the Gemini Web page. First, we subtracted the CCD bias from all frames by using the standard bias frame and removed cosmic rays by using the PyCosmic routine (Husemann et al. 2012), which shows robust results for cosmic-ray removal in fiber-fed IFU data. Second, we obtained the extraction solution based on the flat-field images from the afternoon calibration and corrected for the fiber-to-fiber variation by

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Figure 1. [O III] VVD diagram of the luminosity-limited sample of AGNs with $L_{[\text{O III}]} > 10^{42}$ erg s$^{-1}$ and $z < 0.1$ from Woo et al. (2016). The [O III] velocity dispersion is calculated from the second moment of the emission-line profile based on Equation (1). The sample of six AGNs presented in this paper (green stars), together with the 23 objects (blue squares and orange circles) under investigation with other facilities, are selected based on their high velocity and velocity dispersion (solid box) as the best candidates for follow-up IFU studies.
The Astrophysical Journal, 819:148 (18pp), 2016 March 10

Table 1

Our Sample of Six Type 2 AGNs with Extreme [O iii] Kinematics

| ID          | R.A. (hh:mm:ss) | Decl. (dd:mm:ss) | z  | \(v_{\text{[O \text{ iii}]}_\text{e}}\) (km s\(^{-1}\)) | \(\sigma_{\text{[O \text{ iii}]}_\text{e}}\) (km s\(^{-1}\)) | \(\log L_{\text{[O \text{ iii}]}_\text{corr}}\) (erg s\(^{-1}\)) | \(m_r\) | \(b/a\) | Date       | \(t_{\text{exp}}\) (minutes) | Seeing | AM |
|-------------|-----------------|------------------|----|-----------------------------|-----------------------------|-----------------------------|-------|-------|------------|-----------------------------|--------|----|
| J091808+343946 | 09:18:08         | +34:39:46        | 0.0973 | −419 | 444 | 42.9 | 16.45 | 0.94 | 2015 Mar 18 | 133 | 0.5 | 1.25 |
| J113549+565708 | 11:35:49         | +56:57:08        | 0.0515 | −212 | 400 | 43.1 | 14.72 | 0.82 | 2015 Mar 17 | 45 | 0.8 | 1.13 |
| J140453+532322 | 04:04:53         | +53:23:32        | 0.0813 | −303 | 392 | 42.6 | 16.11 | 0.38 | 2015 Mar 17 | 45 | 0.6 | 1.24 |
| J160652+275539 | 16:06:52         | +27:55:39        | 0.0461 | −268 | 324 | 42.2 | 15.22 | 0.88 | 2015 Mar 17 | 45 | 0.5 | 1.16 |
| J162233+395650 | 16:22:33         | +39:56:50        | 0.0631 | −34 | 556 | 42.4 | 15.61 | 0.76 | 2015 Mar 17 | 45 | 0.5 | 1.11 |
| J172038+294112 | 17:20:38         | +29:41:12        | 0.0955 | −65 | 401 | 42.3 | 16.73 | 0.95 | 2015 Mar 24 | 142 | 0.6 | 1.27 |

Note. Column (1): target ID. Column (2): R.A. (J2000). Column (3): decl. (J2000). Column (4): redshift based on the stellar absorption lines using the SDSS spectra (Bae & Woo 2014). Column (5): [O iii] velocity shift with respect to the systemic velocity. Column (6): [O iii] velocity dispersion measured from SDSS spectra. Column (7): dust-corrected [O iii] luminosity (see Bae & Woo 2014). Column (8): r-band SDSS magnitude. Column (9): \(b/a\) minor-to-major axis ratio. Column (10): date of observations. Column (11): exposure time. Column (12): seeing. Column (13): average airmass.

3. METHODOLOGY

3.1. Emission-line Fitting

To measure the kinematic properties of AGN emission lines, we follow the procedure we adopted for the SDSS AGNs studies (e.g., Bae & Woo 2014; Woo et al. 2016). Here we briefly describe the measurement steps. First, we model the stellar component by fitting the stellar continuum with the best stellar population models using the pPXF code (Cappellari & Emsellem 2004). For the pPXF modeling, we adopted 47 MILES simple stellar population models with different ages, but with solar metallicity (Falcón-Barroso et al. 2011). The best-fit pPXF stellar emission model is then subtracted from the original spectrum to produce a pure emission-line spectrum. The fitting solution provides the line-of-sight velocity of the stellar component in each spaxel. The systemic velocity of each host galaxy is determined from the velocity of the stellar component using the spectrum extracted from the central 3″ spaxels, while the stellar velocity dispersion, \(\sigma_v\), of each galaxy was adopted from the SDSS measurements based on the spatially integrated 3″ fiber SDSS spectrum.

Using the emission-line spectra, we fit the [O iii] and H\(\alpha\) regions, employing the Levenberg–Marquardt least-squares algorithm (Marquardt 1963; More 1978, pp. 105–116) as implemented in the IDL procedure MPFIT (Markwardt 2009). Each individual line is fit with a double Gaussian since for most emission lines two Gaussian components are required except for the outer spaxels in the FOV. We employ an iterative fitting method to decide whether a secondary broad component is needed for fitting each individual line. The secondary component is adopted if its peak flux is at least equal to the noise measured at the continuum near the respective emission line. A more stringent criterion for the retention of broad components (>3 times the noise) does not affect the results presented here. The double-Gaussian profile can be understood as that gas kinematics is characterized by a narrow emission component representing the gravitational potential while a broad emission component reflects the nongravitational potential such as an AGN outflow, as demonstrated by Woo et al. (2016) based on the detailed analysis of the integrated SDSS spectra (see Section 4.2 for details).

For the H\(\alpha\) region, we simultaneously fit the H\(\alpha\) line and the [N ii] doublet, while the redward [S ii] doublet is fitted separately. All lines are fitted with a single- or double-Gaussian profiles as done for [O iii]. To reduce the degrees of freedom from the fitting, we assume the same dispersion and velocity shift (with respect to the systemic velocity) values for the doublets ([N ii] and [S ii]), while velocity dispersion is in turn tied to the dispersion of the individual H\(\alpha\) components. For [O iii] \(\lambda\)5007 and H\(\beta\) we also used a double-Gaussian profile if required, fitting the two lines separately. In Figure 2 we demonstrate the emission-line fitting results for the central spaxel of each galaxy.

The only exception to the above is source J160652+275539, which upon closer inspection was found to show a very broad H\(\alpha\) component (\(\sigma > 2000\) km s\(^{-1}\)), which seems to originate in the broad-line region. A very broad component of similar width was also seen in the H\(\beta\) emission for some spaxels.\(^5\) As a result, we had to allow for one more Gaussian component for this very broad component in the fitting of H\(\alpha\) and H\(\beta\) of this target. This component was left to have free central wavelength and dispersion. As a result, for the core area of the IFU (\(\sim 2''\) diameter) both H\(\alpha\) and H\(\beta\) are fitted with three components each, while for the outer regions two components were sufficient. The very broad component is excluded from our analysis since we assume that it represents the broad-line region kinematics. For some spaxels, a very broad component and a narrow component were sufficient to fit the observed emission profile. For these cases the intermediate broad component seen in other spaxels and sources may be either truly missing or undetectable owing to the powerful broad emission from the core of the AGN. For these cases, we choose to conservatively assume that for these spaxels the narrow emission can be sufficiently described with a single narrow component.

For each emission line in each spaxel, we measure the first moment, \(\lambda_0\), and second moment, \(\sigma\), of the line profile, which

\(^5\) In general, H\(\beta\) emission is very faint for this object, with reliable H\(\beta\) measurements for only a few tens of spaxels. There are indications of heavy dust extinction as implied by the Balmer decrement of the spaxels where both lines could be measured reliably.
are defined as

\[ \lambda_0 = \frac{\int \lambda f_\lambda d\lambda}{\int f_\lambda d\lambda}, \quad \sigma = \frac{\int \lambda^2 f_\lambda d\lambda}{\int \lambda f_\lambda d\lambda} - \lambda_0^2. \]  

We then calculate the velocity with respect to the systemic velocity (measured from the stellar absorption lines extracted from the central 3″ spaxels) and velocity dispersion after correcting for the instrumental resolution (σ\text{inst} \sim 91 \text{ km s}^{-1}). For some spaxels, emission lines have velocity dispersion consistent with zero after the instrumental resolution correction. These lines are considered unresolved and set to a velocity dispersion value of zero. In addition to the total best-fit model, we also derive the line flux, velocity, and velocity dispersion of the narrow and broad components separately.

The flux-weighted kinematic measures used here present distinct advantages over the peak velocity and FWHM velocity, typically used to study the shape of emission lines, because they better represent the emission-line wings and asymmetric features. Also, velocity dispersion (i.e., second moment of the line profile) is more robust against low-S/N data than measures such as \( W_{60} \), velocity width containing 80% of the total emission-line flux (e.g., Liu et al. 2013; Zakamska & Greene 2014), and \( u_{02} \), the 2nd percentile of the total emission-line flux (e.g., Rupke & Veilleux 2013; Harrison et al. 2014), which are also often used in the literature.

### 3.2. Simulating Uncertainties

We use the noise spectra for each spaxel to derive the uncertainties of the values calculated from our fits, using Monte Carlo (MC) simulations. This is necessary because the lines we want to model are highly asymmetric and require two Gaussian components to be described. The measurement uncertainties of the first and second moment therefore are not straightforward to directly derive from the best-fit model. Instead, for each spaxel we produce 100 new spectra by randomizing the flux using the flux error. We then fit each of these 100 spectra and take the standard deviation of the resulting distributions as the uncertainty for each parameter. We employ an iterative 4σ clipping algorithm to exclude catastrophic fits for determining the final uncertainty. The clipping is stopped once the change in the values of the distribution is less than 10%.

Beyond the uncertainties calculated from the MC simulation, we also employ the estimated peak S/N to exclude spaxels with weak or spurious lines from our analysis. Throughout the paper we use an S/N limit of 3 in an effort to maximize the amount of information extracted from the spectra. Given the high quality of the GMOS data, the choice of S/N limit does not affect our results significantly.

### 3.3. Analysis

The power of IFU data lies in the combination of spatial and spectral information, effectively producing a three-dimensional parameter space within which both morphological and
kinematical features can be traced. Here we briefly lay out the analysis steps and the particular information that we extract from them.

1. Flux maps: We investigate the spatial distributions of the continuum and emission-line flux. Line fluxes are measured by integrating the flux over (a) the whole emission-line profile, (b) the broad component, and (c) the narrow component. Flux maps provide information in terms of both the extent of each component and a measure of trustworthiness of subsequent maps, as all kinematic measurements are flux weighted and S/N dependent.

2. Kinematics maps: We produce stellar velocity maps based on the line-of-sight velocities measured from stellar absorption lines. We also obtain gas velocity and velocity dispersion maps, which are divided into individual emission components (i.e., broad and narrow). Gas velocity dispersion maps are compared to the flux-weighted \( \sigma_v \) measured from the integrated SDSS spectra\(^6\).

3. Kinematic and spatial decomposition: We use the VVD diagram (e.g., Woo et al. 2016) to explore the kinematics of the gas as a function of its spatial distribution. We study the distribution of spaxels with respect to the systemic velocity and \( \sigma_v \), as well as the spaxel distance from the center of the galaxy.

4. Outflow structure: We project the 2D IFU maps on the radial axis and investigate both the [O III] velocity and velocity dispersion as a function of distance from the center of the galaxy. We define the effective radius, \( r_{\text{eff}} \), of the outflow based on either the broad [O III] or broad \( \text{H} \alpha \) emission flux distribution and investigate consistent kinematic patterns as a function of this relative distance unit.

5. Integrated outflow kinematics: Based on the previous steps, we calculate the outflow sizes and the spatially integrated kinematic properties for [O III] and \( \text{H} \alpha \) for total emission profiles, as well as broad and narrow emission components separately.

4. RESULTS

At the redshift of the targets (\( z < 0.1 \)), the GMOS FOV covers \(~3–9\) kpc diameter with a spatial resolution of \(~0.5–1\) kpc, given our seeing-limited observations. Based on their SDSS photometry, all six sources show face-on stellar disks with the exception of J1404, which appears strongly inclined (\( b/a \) major-to-minor axis ratio of 0.38). For at least three sources (J1135, J1606, and J1720) we observe spiral arms in their composite SDSS images (Figure 3, top). The IFU continuum flux maps (second row of Figure 3) show an elongation in the west–east direction due to point-spread function (PSF) effects, as the spectrophotometric star observed during the observing run shows a similar elongation. Integrated \( \text{H} \alpha \) flux maps (third row of Figure 3) show extended emission that follows the continuum emission. In contrast, the [O III] integrated flux maps appear more concentrated with fairly symmetric spatial flux distribution. For all sources we detect [O III] emission (S/N > 3) out to several kiloparsecs. More detailed comments on the individual sources can be found in the Appendix.

4.1. Kinematics of the Ionized Gas

In this section we investigate the kinematics of the ionized gas using the spatial distribution of velocity and velocity dispersion of \( \text{H} \alpha \) and [O III].

4.1.1. Ionized Gas Velocity

All sources show rotation patterns in the stellar velocity maps with maximum velocities ranging between 200 and 250 km s\(^{-1}\) (Figure 4), indicating the presence of a central stellar disk. J0918 may be an exception as its stellar velocity map is very noisy, which is potentially due to its inclination (this is a face-on galaxy).\(^7\)

In contrast, the ionized gas maps show much more diverse kinematic patterns in both their velocity and velocity dispersion distributions. The velocity maps appear to be a superposition of two different kinematic components. While the outer parts of the \( \text{H} \alpha \) velocity maps (second row of Figure 4) appear to trace the stellar kinematics, the inner parts show blueshifted emission (e.g., J1404). For [O III], we do not recover any traces of the stellar rotation but instead find blueshifted emission. The only exception is J1622, which shows redshifted [O III] emission. The velocity dispersion maps show similar behavior, with features of very high dispersion (compared to \( \sigma_v \)) at the center of the galaxies but values similar to \( \sigma_v \) or consistent with zero (unresolved emission line) in the outer parts of the FOV.

As discussed in Section 3, we find that emission lines require two Gaussian components to be adequately described, owing to strong and sometimes very asymmetric wing components (see Figure 2). Woo et al. (2016), through a rigorous statistical study of a sample of \(~39,000\) type 2 AGNs from the SDSS, concluded that this secondary Gaussian component is a strong indication of the presence of outflows since it is considerably broader than stellar absorption lines and kinematically offset from the systemic velocity of the galaxy. At the same time, its kinematic properties broadly correlate with the AGN luminosity and Eddington ratio. Conversely, the narrow component is found to mostly reflect the gravitational potential of the galaxy. The velocity maps in Figure 4, particularly for \( \text{H} \alpha \), reveal that there is a spatial dependence, with the gravitational (rotation) kinematic component dominating in the outer parts of the FOV. The complex kinematic structure of the emission-line profiles and their spatial trend, as well as the statistical results of Woo et al. (2016), motivate us to look at kinematics maps of each Gaussian component separately, instead of the total emission profile.

The spectrally decomposed broad and narrow components in [O III] and \( \text{H} \alpha \) emission lines are shown in Figures 5 and 6. We first focus on the velocity of the broad and narrow components of \( \text{H} \alpha \) and [O III] (Figure 5). While the broad and narrow decomposition seems a priori arbitrary, we show in the following that there does seem to be a physical distinction between the two. The narrow \( \text{H} \alpha \) and stellar velocity maps agree very well, in terms of both maximum velocities and the rotation structure. This implies that the narrow component of\(^7\)

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\(^6\) The quality of the GMOS data does not allow us to calculate a \( \sigma_v \) at each spaxel.

\(^7\) We remind that stellar velocities are derived based on the fitting of the full spectrum of each spaxel (including the G band and the Mg b absorption triplet) using a combination of stellar population models.
the Hα emission represents the systemic velocity and follows the stellar rotation.

For the narrow [O III], four sources (J0918, J1135, J1404, and J1606) show mostly blueshifted (negative velocity) emission, while two sources (J1622 and J1720) show redshifted emission. [O III] seems to lack rotation signatures and appears to be kinematically decoupled from the Hα-emitting gas. For the cases where narrow [O III] is redshifted, the velocities appear mostly constant over the central part with some hints of increase with radial distances (see Section 4.3 for details). Velocity values nonetheless are consistent with the maximum absolute stellar velocities, ranging up to a few hundred kilometers per second.

The velocity maps of the broad components show markedly different kinematics. For Hα (third row of Figure 5), all sources show blueshifted emission at their centers with velocities that in some cases exceed the maximum stellar velocities. At outer parts, Hα follows the stellar rotation or in some cases is undetected (i.e., the Hα line can be fitted with a single Gaussian). For two of the sources (J1135 and J1622) we observe elongated features near the AGN core with blueshifted emission. J1622 in addition shows a front of redshifted broad [O III] emission at the edge of the elongated feature of blueshifted [O III] emission. The nature of this feature will be investigated further in the following paper.

The broad [O III] emission (bottom row of Figure 5) shows the most extreme kinematics among the different components. Five sources show blueshifted broad [O III] emission with velocities that are up to three times the maximum stellar velocities. One source (J1622) shows redshifted broad [O III] emission with an implied positive gradient with radial distance, unlike the remaining five sources, which generally show decreasing radial trends. We will investigate these radial gradients in detail in Section 4.3. In all cases the broad [O III] velocity distribution appears very symmetric and concentrated around the AGN. The broad [O III] and broad Hα velocity maps show some degree of correlation (in terms of the velocity sign) but the broad Hα is more extended and shows on average lower absolute velocities.

Figure 3. Top: SDSS gri composite images and spectra. The FOV of GMOS IFU (5.0' x 3.5') is shown with blue boxes, while the horizontal blue bars show 5''0 scale. Second row: IFU flux maps integrated over the full wavelength range. Third row: Hα flux maps from the best-fit model profile. Fourth row: [O III] λ5007 flux maps from the best-fit model profile. For the second to fourth rows, contours show the continuum flux at 10% intervals from the peak. Gray spaxels indicate weak or nondetection of continuum or emission line with S/N < 3.

The Astrophysical Journal, 819:148 (18pp), 2016 March 10
Karouzos, Woo, & Bae
4.1.2. Ionized Gas Velocity Dispersion

Next, we present the velocity dispersion maps for \( \text{H} \alpha \) and \([\text{O III}]\) for narrow and broad components in Figure 6. The narrow components of both \( \text{H} \alpha \) and \([\text{O III}]\) show \( \sigma \) of up to a couple of hundred kilometers per second, consistent with \( \sigma_s \). This corroborates our initial assertion that the narrow emission components are mostly dominated by the gravitational potential of the host galaxy rather than the...
nongravitational influence of the AGN, as demonstrated statistically by Woo et al. (2016).

Narrow Hα shows on average smaller velocity dispersion values than narrow [O III], with most sources showing unresolved narrow Hα emission ($\sigma_{\text{narrow}} < \sigma_{\text{broad}}$) beyond the galaxy center. Notable exceptions are J1135 and J1622, which show elongated features of elevated dispersion, tracing similar features seen in the velocity maps of Figure 5. The narrow [O III] component, on the other hand, appears resolved for most spaxels with S/N > 3 and shows consistently symmetric distribution. This may additionally indicate that the narrow [O III] component is affected by the outflow. Thus, the [O III] broad/narrow decomposition does not cleanly separate the two kinematic components.

The broad Hα and [O III] emission components are by definition broader than the narrow components and show values of up to five times the $\sigma_\text{n}$ derived from the SDSS spectra. Broad Hα shows velocity dispersion values of up to 800 km s$^{-1}$. The velocity dispersion maps for broad Hα also reveal interesting features of elevated dispersion: elongated features for J1135 and J1622 (Figure 5) and a ring-like structure for J1404. The broad [O III] appears symmetric and concentrated. Velocity dispersion values for [O III] are on average higher than Hα. The discrepancy between the homogeneity of the [O III] emission kinematics and the kinematic structures seen in Hα emission may be related to PSF smearing effects, given our seeing-limited observations ($\sim$0.5–0.8). Alternatively, these high velocity dispersion Hα features may be unrelated to the AGN-driven outflow but appear co-spatial owing to projection effects.

We note here that for J1404 the ring-like structure in broad Hα emission corresponds to the morphology of the broad [O III]

Figure 5. Velocity maps of the narrow components of Hα and [O III] (top) and the broad components of Hα and [O III] (bottom) from spectral decomposition in each spaxel. Contours are the same as in Figure 3. Gray spaxels indicate nondetection of the emission lines (i.e., S/N < 3).
emission, in that the former seems to spatially coincide with the edge of the latter. As we discuss in the Appendix, these high dispersion features may mark transitions between the outflow-dominated and star-formation-dominated regions around the nucleus.

A first-order qualitative interpretation of the observed kinematics is that we are observing a superposition of two kinematically distinct components. The first one, corresponding to the narrow Hα (and to lesser degree narrow [O III]), is related to the gravitational potential of the galaxy as evidenced by the kinematic similarities with the stellar component. The second one, which is mainly traced by the broad [O III], shows extreme projected velocities and velocity dispersions (which should be indicative of the bulk motion of the ionized gas) and is concentrated around the AGN core.

Hβ shows similar kinematic behavior to Hα and [O III]. A detailed analysis, however, is strongly limited by the low Hβ fluxes, usually more than 10 times fainter than [O III] in the central parts of these AGNs (this will be further explored in Paper II of this series). Nonetheless, for the central-most regions we find that Hβ is asymmetric (see Figure 2) and requires a combination of a narrow and a broad component to be fit. Like Hα, Hβ shows on average smaller velocity and velocity dispersion than [O III].

We note that for both the velocity and velocity dispersion maps, “hot” spaxels exist where the spectral fits of one or both emission lines fail. This can be due to any combination of several confounding factors, including low S/N, peculiar spectral shape, and problematic continuum fitting and subtraction. This leads to spaxels, most often in the outer part of the IFU, with extreme velocity and velocity dispersion values.

Figure 6. Velocity dispersion maps of the narrow Hα and [O III] (top) and the broad Hα and [O III] components (bottom). Contours are the same as in Figure 3. Gray spaxels indicate nondetection of the emission lines (i.e., S/N < 3).
These “hot” spaxels are usually isolated and have typically larger (factor of two to three) uncertainties than their neighboring spaxels. They should not be confused with spatial conglomerations of several (>10) spaxels that show consistent deviations from the overall kinematic distribution (e.g., the high-velocity, high velocity dispersion feature seen in J1622). The latter are signatures of areas of interest that may trace outflow-driven kinematics, shocked regions, or otherwise regions with different physical conditions.

4.2. VVD Diagram

In this section we focus on the VVD diagram to investigate the kinematics of the ionized gas with respect to the stellar kinematics and the radial distance to the AGN. Figure 7 presents the VVD diagram for the broad and narrow components of [O iii] (shown with orange and green symbols, respectively), with a clear distinction between them. The broad [O iii] components are predominantly found in the upper left corner of the VVD diagram, showing large velocity dispersion and significant offsets from the systemic velocity. In contrast, the narrow [O iii] components are distributed fairly evenly around the systemic velocity and straddle the \( \sigma_s \) range.

We find a negative radial trend of velocity and velocity dispersion for the broad [O iii], while no radial dependence of velocity and velocity dispersion is seen for the narrow component. The broad [O iii] component shows a significant range of both velocities and dispersions, while at large radial distances these values overlap with those of the narrow [O iii] component. The negative radial trend of the broad [O iii] component indicates nongravitational effects such as outflows, whose velocity decreases radially. Thus, velocity and velocity dispersion values eventually become comparable to the systemic velocity and \( \sigma_s \), respectively. In contrast, the narrow [O iii] component in the outer spaxels of the FOV shows a large range of velocities that presumably reflects the rotation. This is supported by the relatively low velocity dispersions of the narrow [O iii] component in these spaxels.

J1622 is the only source in our sample that shows consistently redshifted emission for both broad and narrow [O iii] components (Figure 5). Figure 7 shows that most broad components (orange symbols) have positive velocity (right of the vertical dashed line). However, the velocities of the broad components are consistent with those of the narrow components, implying that the kinematics may be dominantly affected by the gravitational potential.

In Figure 7, we also plot the velocity and velocity dispersion of [O iii] (large gray stars) measured from the spatially integrated SDSS. Compared to the SDSS values, we find that

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8 Radial distance is denoted by the size of the symbols in Figure 7.
while the velocity dispersion of the broad [O\textsc{iii}] component is mostly reflected in the spatially integrated SDSS [O\textsc{iii}] profiles, the velocity is often underestimated, especially for the most extreme kinematics of the central part of the AGN by up to 100%. These differences become clear by comparison with the flux-weighted mean velocity and velocity dispersion of the broad [O\textsc{iii}] components (shown with vertical and horizontal lines in Figure 7).

In the case of H\alpha, the VVD diagrams reveal similar patterns although with less extreme kinematics, as was already shown in Figures 5 and 6. Thus, we do not present the detailed plots. Briefly, the broad H\alpha component is found less offset from the narrow component, with the latter showing very clear bell-shaped rotational patterns in the VVD diagram such that the central spaxels show high velocity dispersion but velocities consistent with the systemic velocity at the top of the bell and outer spaxels at the bottom of the bell having low velocity dispersion and high blueshifts and redshifts, reflecting rotation.

In summary, the VVD diagram for both [O\textsc{iii}] and H\alpha shows a clearly asymmetric distribution in velocities, indicating that both broad components do not follow the rotation owing to a nongravitational effect. This strongly supports a physical distinction between narrow and broad components, the latter reflecting the kinematics of outflows.

**4.3. Radial Profiles of the Outflow**

We present the radial profiles of the outflows, as these can help us estimate the projected size of the outflow-dominated region. This is one of the fundamental parameters for calculating the mass and energy of the gas entrained in the outflow. In Figure 8 we show the normalized absolute velocities and velocity dispersions as a function of the effective radius, \(r_{\text{eff}}\). The radius within which half of the total broad [O\textsc{iii}] emission flux is contained. This definition is motivated by our finding that the broad [O\textsc{iii}] component exhibits the most extreme kinematics in the spatially resolved maps and does not suffer from gravitational effects (e.g., stellar rotation). Velocities in Figure 8 are normalized by the median velocity of the broad [O\textsc{iii}] component within one \(r_{\text{eff}}\) from the nucleus in order to show the relative spatial gradient. Velocity dispersions are normalized by \(\sigma_{0}\) to present the nongravitational effect. Both these normalizations allow us to identify the linear scales within which [O\textsc{iii}] shows “extreme” kinematics with respect to the gravitational potential of the host galaxy.

First, we observe a distinction between the kinematics of the broad and narrow components of [O\textsc{iii}]. Both the velocity and velocity dispersion of the broad [O\textsc{iii}] component decrease with radial distance (except for J1622), while those of the narrow [O\textsc{iii}] component show an almost flat distribution. The velocity and velocity dispersion of the broad [O\textsc{iii}] component converge to the values of the narrow [O\textsc{iii}] component at \(\sim 2-3r_{\text{eff}}\). Second, the extreme kinematics of the broad [O\textsc{iii}] component are prevalent within radial distances of \(\sim 2-3r_{\text{eff}}\), beyond which the decomposition and differentiation of the two components become challenging owing to low S/N. Third, there is an initial plateau of the normalized velocity dispersion for the broad [O\textsc{iii}] component, which is then followed by a fall-off starting at around \(\sim (1.5-2)r_{\text{eff}}\). Since we expect that the velocity dispersion of the stars and gas caused by the gravitational potential decreases with radial distance, the fact that we observe roughly constant velocity dispersion out to \(\sim 2\)
$r_{\text{eff}}$ implies that the outflow is actually experiencing an initial acceleration before decelerating and eventually converging to stellar kinematics (e.g., Crenshaw & Kraemer 2000; Fischer et al. 2013). It is interesting to note that while the velocity dispersion values are different among the sample, all of them show similar radial profiles as a function of their $r_{\text{eff}}$, as well as the decrease of the outflows to the gravitational kinematics.

Lastly, neither the velocity nor velocity dispersion shows an increasing trend with [O III] luminosity. For example, J1606 (lowest [O III] luminosity in our sample) shows larger normalized velocity dispersion than J1135 (highest [O III] luminosity). This implies that the absolute scale of the observed kinematics is mostly influenced by the inclination of the outflow to our line of sight, as well as the outflow opening angle.

In Figure 9 we investigate the mean radial trend of the velocity and normalized velocity dispersion of [O III] with respect to the AGN luminosity and Eddington ratio. We use black hole mass estimates based on SDSS $\sigma_b$ and AGN bolometric luminosities based on the dust-uncorrected [O III] luminosity to derive the Eddington ratios (see Bae & Woo 2014 for details). Given the significant scatter of the $M_{\text{BH}}$-$\sigma_b$ relation and the uncertainties involved in the bolometric correction, these Eddington ratios are highly uncertain.

A mean zero velocity in Figure 9 can be a result of the canceling out of blueshifted and redshifted emission of rotating gas. On the other hand, mean negative velocities imply the presence of a nongravitational component. Similarly, normalized velocity dispersion values significantly above 1 indicate a nongravitational kinematic component. Conversely, mean normalized velocity dispersions around or below 1 are indicative of gas following the gravitational potential of the galaxy. The $\sigma_b$ used for the normalization comes from the SDSS and therefore reflects the flux-weighted stellar kinematics of the nuclear stellar component. This can lead to normalized gas velocity dispersions below 1, especially for the outer parts of the FOV.

We see no obvious trend between $L_{\text{bol}}$ and the [O III] kinematics, with the caveat that the range of the [O III] luminosity is narrow ($\sim$1 dex). In contrast, we detect a weak trend that more extreme kinematics is observed for objects with higher Eddington ratio. Similarly, there is some indication that sources with higher Eddington ratio also show more extended regions, with extreme [O III] velocity dispersion (i.e., $\sigma_{\text{[O III]}} > \sigma_b$). The correlation of the [O III] velocity dispersion with the AGN Eddington ratio is in agreement with previous studies (e.g., Woo et al. 2016) and indicates that the velocity dispersion is more representative of the bulk motion of outflows as it is not affected by projection effects (e.g., Liu et al. 2013; Harrison et al. 2014). Nonetheless, we note that both the inclination angle and the opening angle of the outflows can be different among the six objects, which can dilute any intrinsic correlations with the [O III] luminosity and the Eddington ratio.

In the case of H$\alpha$, the velocity and velocity dispersion of the broad component also show a negative gradient with radial distance. We find that the decrease is more rapid, with the velocity values converging to stellar kinematics within $(1-2) r_{\text{eff}}$. We obtain the relation $r_{\text{H}\alpha} = (1.7 \pm 0.3) \times r_{\text{[O III]}}$, reflecting the significantly more spatially extended nature of H$\alpha$ emission. However, the linear sizes of the regions within which broad [O III] and broad H$\alpha$ show nongravitational kinematics ($(1-2)r_{\text{eff}}$ and $(2-3)r_{\text{eff}}$), respectively, are consistent with each other. We caution that broad H$\alpha$ can also originate in star-forming regions (as seen for J1720, for which broad H$\alpha$ is detected at the base of its spiral arms), and therefore we cannot rely solely on the broad H$\alpha$ flux distribution to derive the properties of the outflow.

In Figure 10 we show the averaged kinematics radial profiles for H$\alpha$ broad and narrow components, similar to Figure 9.
Qualitatively, we see the same negative trends with radial distance but with key differences compared to the [O III] radial profiles. First, both the absolute velocities and normalized velocity dispersions reach much smaller values than [O III]. Second, both velocity and velocity dispersion profiles show different shapes below and above ~1.5 kpc. Since both narrow and part of the broad Hα components follow the stellar rotation, this leads to a dilution of the nuclear outflow component that dominates in the central kiloparsec of the Hα profiles. Beyond ~1.5 kpc, the velocity profiles are consistent with zero velocity (as discussed above), while the velocity dispersion profiles show either flatter slopes (e.g., J1135, J1622, J1729) or even an inverse gradient for the case of J1404. Finally, unlike for Figure 9, we find no appreciable trends with either [O III] luminosity or Eddington ratio. This reinforces our previous assessment that even the broad component of the Hα emission is a poor tracer of these outflows.

5. PHYSICAL PROPERTIES OF THE AGN OUTFLOWS

5.1. Outflow Sizes

The effective radius \( r_{\text{eff}} \) measured from the broad [O III] component ranges from 0.4 to 0.7 kpc, while that of the narrow [O III] component goes out to 1.2 kpc. The broad [O III] component is marginally resolved (FWHM \( \sim \) seeing), with the exception of J1622. A direct comparison of the \( r_{\text{eff}} \) of either the broad or narrow [O III] components with both \( r_{\text{Hα}} \) and Eddington ratio does not show significant correlation within the limited dynamic range.

In the case of Hα, the emission region is more extended with \( r_{\text{eff}} \) between 1.8 and 2.1 kpc. The Hα emission is detected out to the edges of the IFU FOV, while the [O III] emission is more concentrated but still significantly detected out to \( \sim 3''-4'' \), which corresponds to a linear scale of \( \sim 7.4 \) kpc, for the highest redshift source in the sample. However, we emphasize that if the maximum size of the emission-line detection is taken as the size of the outflow region, one would significantly overestimate the volume of the ionized gas that is affected by the AGN-driven outflow. This is clearly seen in Figure 9, where at distances >2 kpc, the gas kinematics is consistent with the gravitational stellar kinematics. We therefore argue that a more representative outflow size can be calculated by taking into account both the kinematics and the flux distribution of broad [O III].

Based on Figure 9, for each source we define the region within which the broad [O III] kinematics show evidence for nongravitational motions (i.e., absolute velocity >0 and normalized velocity dispersion >1). This “kinematic” size is found to be between 1.3 and 2.1 kpc (or 2 to 3 times \( r_{\text{eff}}^{\text{O III}} \)). Alternatively, one can calculate the flux-weighted radius of the narrow line emitting gas (e.g., Husemann et al. 2013, 2014), which, however, does not take into account the difference between nongravitational and gravitational kinematic components. Hence, the flux-weighted size can only be considered as an upper limit.

In Figure 11 we compare the measured outflow sizes using the three different methods discussed: (1) based on the kinematics of the broad [O III] and Hα emitting gas, (2) based on the flux-weighted distance (following Husemann et al. 2013), and (3) based on the [O III] detection with S/N > 5. Note that for this exercise we exclude spaxels classified as H\( \pi \) region based on their emission-line flux ratios (Baldwin et al. 1981), but include composite and LINER regions (more detailed analysis will be presented in the following paper). Based on the flux-weighted calculation, we obtain the size of the broad [O III] as 1.5–3 kpc, and the size of the total [O III] emission line or the total Hα emission line as up to 3.7 and 4.1 kpc, respectively, significantly larger than the kinematically estimated size. We find that both photometric methods overestimate the size of the region within which nongravitational outflow kinematics is observed by up to a factor of two for [O III]. On face value, this in effect leads to an overestimation of the outflow lifetimes (which are usually calculated as the size of the outflow divided by its bulk velocity) and consequently to an underestimation of the energy and mass outflow rates. We will explore this effect more in detail in the second paper of this series. In Table 2 we present the flux-weighted mean properties within the \( r_{\text{eff}} \) of each target.

5.2. Outflow Sizes and AGN Luminosity

In this section, we compare the size of the outflows with the AGN [O III] luminosity. In order to increase the dynamical range, we combine our sample with samples taken from the literature. In total, we compile objects from five literature studies, including three samples based on IFU observations (Liu et al. 2013; Harrison et al. 2014; McElroy et al. 2015) and two samples based on spatially resolved long-slit spectroscopy (Greene et al. 2011; Brusa et al. 2015). The combined sample covers more than four orders of magnitude in [O III] luminosity, with our sample being at the lower end of AGN [O III] luminosities. Note that the size of the outflows is defined differently among the different studies. Despite this limitation, we find a well-defined size–luminosity relation (Figure 12). Instead of using AGN bolometric luminosities, we choose to use dust-uncorrected [O III] luminosity to avoid uncertainties related to the bolometric correction and extinction correction and for direct comparison with other literature studies.

We get a Kendall’s \( \tau \) correlation coefficient of 0.46 with very high significance (\( p < 0.0001 \)). We observe, however, that the implied correlation appears to have a varying slope, with AGN luminosities \( \lesssim 10^{42} \) erg s\(^{-1}\) showing a flatter slope compared to their more luminous counterparts.

As shown in Figure 11, for most of the literature samples the actual size of the outflow may be underestimated since it is mostly based on the ionized gas flux distribution, without taking into account the actual spatially resolved kinematics of
In Figure 12 we also plot the size–luminosity relation derived by Husemann et al. (2014) based on a sample of luminous type 1 AGNs (dashed line; Equation (2) from that paper). We find outflow measurements from type 2 AGNs to be largely consistent with the relation. A linear regression fit to the combined sample gives a slope of $0.30 \pm 0.04$.\footnote{We note that in the absence of robust uncertainties and a largely inhomogeneous data set of outflow sizes, the slope uncertainty quoted only reflects the statistical scatter of the size measurements.} This is marginally flatter ($\sim 2\sigma$) than the slope of $0.44 \pm 0.06$ derived by Husemann et al. (2014) but consistent within the uncertainties with the slope of $0.33 \pm 0.04$ derived by Schmitt et al. (2003) for a sample of local Seyfert galaxies observed with Hubble Space Telescope narrowband imaging.

6. DISCUSSION

In this section we discuss the implications of our results concerning the geometry of AGN-driven outflows and the importance of decomposed kinematics in accurately constraining the size of the outflows. The morphology and stellar kinematics of our sample show rotating disks that play a role in determining the kinematics of the narrow-line region. However, an additional kinematic component is clearly present, leading to high velocity dispersion and velocity shift from the systemic velocity. We find that most objects (five out of six) in the sample show negative velocity, which is consistent with previous IFU studies (e.g., Liu et al. 2013; Rupke & Veilleux 2013; Harrison et al. 2014; Carniani et al. 2015). A higher fraction of blueshifted [O III] than redshifted [O III] among high-luminosity AGNs is also found by statistical studies of type 2 AGNs (e.g., Bae & Woo 2014; Woo et al. 2016).

The separation of the outflow component from the gravitational component is demonstrated in the VVD diagram that follows.
(Figure 7), which is a helpful tool in visualizing the different kinematic components. Compared to the systemic velocity and $\sigma_8$, we find that [O \text{ III}] in the central spaxels predominantly shows higher velocity dispersion and high velocity shift, indicating an outflow-dominated region, while the gravity-dominated region is separate in the lower velocity dispersion regime. The outflow may be experiencing an initial acceleration, as indicated by the velocity dispersion radial profiles for [O \text{ III}] (Figure 9), but decelerates beyond a few $r_{pet}$. Together with the dependence on the radial distance in the VVD diagram, these suggest that the outflow kinematics weakens radially.

We expect some degree of dust extinction for all of our targets, as evidenced by the presence of a rotation-dominated stellar disk in at least five of them. Furthermore, with velocity dispersions from 2 to up to 5 times larger than the $\sigma_8$, we find strong evidence for either a wide-angled or quasi-spherical geometry for these outflows. The combination of obscuration and the opening angle of the outflow can, to some degree, dictate the observed kinematics of these outflows. In a separate paper (H.-J. Bae & J.-H. Woo 2016, in preparation) we will use 3D biconical outflow models to explore the position of a source on the VVD diagram.

Determined the size of AGN-driven outflows is a thorny subject that has been approached in many different ways in the literature. Previously, several studies have relied on purely flux-based measurements using, e.g., [O \text{ III}] to define the outflow region size (e.g., Bennert et al. 2006; Nesvadba et al. 2006; Greene et al. 2011; Liu et al. 2013; Rupke & Veilleux 2013; Harrison et al. 2014). Alternatively, some simplified consideration of the kinematics was also included in the calculation of the outflow size (e.g., measuring the size of only the broad Gaussian component of [O \text{ III}]; Rodríguez Zaurín et al. 2013; Brusa et al. 2015; Carniani et al. 2015; McElroy et al. 2015).

However, the size we are interested in is that of the region where the ionized gas kinematics is dominated by the AGN-driven outflow. As we showed in Figure 8, even for the broad component of [O \text{ III}], which exhibits the most extreme kinematics, both the velocity and velocity dispersion radially decrease and become consistent with stellar kinematics beyond $\sim (2-3) r_{eff}$ [O \text{ III}]. Thus, if the size of the region, where the broad component of [O \text{ III}] (or worse, the total [O \text{ III}]) is detected, is taken as the outflow size, this would lead to an overestimation by on average 30%-50% and up to a factor of two (Figure 11). If the H$\alpha$ emission line is used instead of [O \text{ III}], the outflow size would be more severely overestimated since the H$\alpha$ emission line profile can be affected by gas kinematics due to star formation and stellar motion. It is conceivable that AGN-driven outflows extend beyond the GMOS FOV, which covers out to $\sim 4$ kpc from the center. However, since both the velocity and velocity dispersion of the ionized gas drop off and converge with the stellar kinematics within the FOV as shown in Figure 8, it is not likely that the current data are missing larger-scale outflows.

Since we find outflow sizes to be no larger than a couple of kiloparsecs, with most of the extreme kinematics confined within the central kiloparsec of our sources, the impact of the outflows seems to be limited. It is difficult to understand how appreciable amounts of energy can be deposited at galaxy-wide scales to quench star formation or eject gas reservoirs in the galaxy outskirts. Case in point, the Petrosian radii of our six galaxies (based on SDSS photometry) are found to be between 5 and 12 kpc, corresponding to $\sim 5$–10 times the outflow sizes. Even assuming that our kinematic method underestimates the “sphere of influence” of AGN feedback, BPT-based sizes of the AGN photoionized regions (explored in depth in a following paper) are still approximately 3–6 times smaller than the Petrosian radius of their hosts.

7. SUMMARY AND CONCLUSIONS

We have presented a careful analysis of the kinematic properties of six luminous type 2 AGNs based on the wealth of information in the IFU data and kinematically and spatially resolved measurements. We summarize our findings:

1. The emission-line profiles of H$\alpha$ and to a lesser extent [O \text{ III}] appear to be a superposition of two kinematic components (i.e., broad and narrow components): a nongravitational outflow component (high velocity shift and velocity dispersion) concentrated within the central 1.3–2.1 kpc, and a gravitational component in the outer region that follows stellar rotation (Figure 4).

2. The narrow component of H$\alpha$ follows the stellar kinematics closely, while the broad components of both H$\alpha$ and [O \text{ III}], and to a lesser degree the narrow component of [O \text{ III}], show extreme kinematics. These include large velocity dispersion (up to 5 times $\sigma_8$) and mostly blueshifted emission relative to the systemic velocity (Figures 5 and 6).

3. The VVD diagram separates extreme outflow kinematics from gravitational motions. There is a decrease of velocity dispersion and velocity of [O \text{ III}] down to the levels that are consistent with $\sigma_8$ and the systemic velocity, with increasing radial distance (Figure 7).

4. The radial profiles of the velocity and velocity dispersion show negative trends with radial distance. Based on the kinematics and the flux distribution of the outflowing gas, for the first time the size of the outflow can be kinematically determined as 1.3–2.1 kpc (Figures 8 and 9).

5. Size estimation based on the flux (using either the flux distribution or the S/N) is severely overestimated compared to the size of the region where the outflow kinematics dominate over gravitational motion, by up to a factor of two for [O \text{ III}] and by more than a factor of two for H$\alpha$ (Figure 11).

6. There is a positive correlation of the size of the outflow with the AGN [O \text{ III}] luminosity (Figure 12).

Our IFU observations have revealed powerful outflows with more extreme kinematics (velocity and velocity dispersion) than what was implied by their spatially integrated SDSS spectra. This by itself underlines that spatially integrated spectroscopic studies of AGNs may be understimating the incidence of AGN-driven outflows and the kinematics of the gas entrained in them.

We have shown that identifying and characterizing outflows is not straightforward owing to the confounding factors related to physically distinct but co-spatial kinematic components (e.g., stellar rotation, star-formation-driven outflows). Despite the clear presence of strong outflows in these type 2 AGNs, the actual impact in terms of feedback to their host galaxies is unclear, particularly given their relatively small size. Despite the small sample size, as the selected AGNs are extremely rare
objects in the local universe owing to their strong outflow signatures, the potency of AGN-driven outflows as negative feedback agents seems questionable.

In the following paper we will explore the ionization mechanisms at play in these sources and the driving mechanism behind the extreme gas kinematics observed. We will also touch on the star formation properties and their spatial relation to the outflow kinematically dominated region.

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APPENDIX

Here we provide comments specific to individual sources.

A.1. J091808+343946

J0918 is at redshift $z = 0.0973$ (FOV $\sim 8.5 \times 6$ kpc, resolution $\sim 0.85$ kpc). It is a face-on disk with a b/a (major-to-minor axis) ratio of 0.94. The west–east elongation in the IFU continuum flux map is a seeing effect that is also seen in the data of the spectrophotometric star observed during the observing runs. [O III] is significantly detected ($S/N > 3$) only in the central $\sim 1''5 = 2.5$ kpc and appears spatially unresolved. On the contrary, Hα is much more extended, significantly detected out to the edge of the FOV.

There is little evidence for rotation in the stellar velocity map of this source. The broad [O III] component is very compact and appears blueshifted with velocities up to more than $\sim 600$ km s$^{-1}$. The velocity dispersion of the broad component reaches values up to $\sim 700$ km s$^{-1} (\sim 4\sigma_b)$. The broad Hα component is blueshifted in the central region with some hints for redshifted emission at the lower right edge of the IFU, but with velocities consistent with the stellar component.

A.2. J113549+565708

J1135 is at $z = 0.0515$ (FOV $\sim 5.8 \times 3.4$ kpc, resolution $\sim 0.77$ kpc). It is the most luminous galaxy in our sample, with an r-band magnitude of 14.7 AB mag and a [O III] luminosity of $10^{43.1}$ erg s$^{-1}$. It is a face-on disk (b/a = 0.82) with two spiral arms and hints of morphological distortions indicative of a recent ($\sim$Gyr) interaction. A structure observed in the northwest of the galaxy may be a remnant of that interaction. Both [O III] and Hα are detected out to the edge of the IFU FOV. Interestingly, while Hα is slightly more extended than [O III], the two show very similar spatial distributions.

The stellar velocity map of J1135 shows evidence for a rotation pattern in the northwest–southwest direction. The broad [O III] component appears blueshifted, reaching velocities of $\sim 300$ km s$^{-1}$. The [O III] broad component dispersion is $\sim 600$ km s$^{-1}$, three times higher than $\sigma_b (\sim 200$ km s$^{-1}$). The Hα broad component shows a spatial superposition of two components: a rotation component that follows the stellar rotation and an elongated structure in the north–south direction with strong blueshifted emission ($\geq 200$ km s$^{-1}$). The same feature is seen in the broad Hα dispersion map. The maximum dispersion is $\sim 400$ km s$^{-1}$, two times the $\sigma_b$ and larger than the broad [O III] component dispersion.

A.3. J140453+532332

J1404 is at $z = 0.0813$ (FOV $\sim 7.3 \times 5.1$ kpc, resolution $\sim 0.88$ kpc). It has a b/a axis ratio of 0.38 and appears as a highly inclined disk galaxy elongated in the north–south direction. The [O III] emission is concentrated with a somewhat asymmetric shape, although faint [O III] emission is detected out to the edge of the FOV. In comparison, the Hα flux map shows very extended emission, significantly detected out to the edge of the FOV.

The stellar velocity map of J1404 reveals a rotation pattern in a north–south direction. The broad [O III] component shows blueshifted emission. The broad [O III] velocity dispersion takes large values $\sim 400$ km s$^{-1}$ or $\sim 2\sigma_b$. The broad Hα component shows a strong blueshifted core, consistent in shape and average velocity with the [O III] broad component. Gas at the outer part of the FOV appears to follow the stellar rotation. The velocity dispersion of the broad Hα shows values consistent with the [O III] broad component, with a ring of elevated velocity dispersion that is also seen in the narrow [O III] component. Beyond the ring the velocity dispersion drops sharply to values consistent with $\sigma_b$. This is a strong indication that we are observing the terminal region of an outflow driven from the core of the galaxy.

A.4. J160652+275539

J1606 is at $z = 0.0461$ (FOV $\sim 4.4 \times 3$ kpc, resolution $\sim 0.44$ kpc), the closest galaxy in the sample. It has a b/a axis ratio of 0.88 and appears as an almost face-on disk with hints of spiral structure in its SDSS image. The galaxy appears elongated in the west–east direction (beyond the seeing effect).

No [O III] emission is detected beyond $\sim 1''$–$1''5$ from the nucleus.

J1606 shows rotation in the north–south direction. The broad [O III] emission component appears blueshifted across the [O III]-detected spaxels, with velocities reaching values above $\sim 400$ km s$^{-1}$. The velocity dispersion of the broad [O III] is $\sim 2.5$ times the $\sigma_b$. For both the velocity and velocity dispersion of the broad [O III] component, there is evidence for a drop-off beyond $\sim 1''$ distances from the nucleus, approaching the stellar properties. The broad Hα emission component appears very blueshifted in the inner part of the IFU, spatially coinciding.
with the blueshifted broad [O \text{ iii}] emission. There is evidence for rotation along the stellar disk in the outer parts of the broad H\alpha velocity map. The velocity dispersion of the broad H\alpha component is the highest near the nucleus with values of \sim200 \text{ km s}^{-1}.

A.5. J162233+395650

J1622 is at \( z = 0.0631 \) (FOV \( \sim 5.8 \times 4.1 \) kpc, resolution \( \sim 0.58 \) kpc). It has a \( b/a \) axis ratio of 0.76 and appears as a face-on disk. The galaxy appears slightly elongated in the southwest–northeast direction. The H\alpha emission is significantly detected across the full FOV, showing a similar elongation as the continuum. [O \text{ iii}] is centrally concentrated (\( < \sim 2'' \)) with no obvious elongation.

The stellar velocity map of J1622 shows evidence for a rotational pattern in a southwest–northeast direction. The [O \text{ iii}] line is very concentrated and appears redshifted. There is an indication for a ring of elevated velocity around \( \sim 0.78 \) from the continuum center. The velocities are comparable to the stellar maximum velocity, \( \sim 200 \) km s\(^{-1}\). The broad [O \text{ iii}] component is the highest near the nucleus with values of \( \sim 600 \) km s\(^{-1}\).

The very large velocity dispersion for both [O \text{ iii}] and H\alpha emission lines implies a very large opening angle, while the absence of significantly blueshifted emission indicates that there is no obscuring screen and we are observing the outflow with a large viewing angle. An alternative scenario would require a significant overlap (either physical or through projection) between AGN- and star-formation-ionized gas. This would lead to a spreading out of any kinematically distinct components linked to the AGN, especially considering that the massive stars producing the stellar winds should be uniformly distributed across the stellar disk and around the AGN in the galactic nucleus.

A.6. J172038+294112

J1720 is at redshift \( z = 0.0995 \) (FOV \( \sim 8.8 \times 6.2 \) kpc, resolution \( \sim 1 \) kpc), the farthest galaxy in our sample. It is a face-on disk galaxy with two spiral arms and a \( b/a \) axis ratio of 0.95. The continuum IFU flux map shows a core with a northwest–southeast elongation and emission from the base of the spiral arms. The [O \text{ iii}] emission from J1720 is centrally concentrated with no obvious asymmetries (detected out to \( \sim 2'' \)). In contrast, the H\alpha map shows very extended emission with both a bright central component and emission tracing the spiral arms in the northwest and southeast corners of the FOV.

The stellar velocity map of J1720 shows rotation in the northeast–southwest direction. The broad [O \text{ iii}] component shows blueshifted nuclear emission with maximum velocities of \( \sim 200 \) km s\(^{-1}\). The velocity dispersion of the broad [O \text{ iii}] component is very high (up to \( 700 \) km s\(^{-1}\) or \( \sim 5\sigma_b \)), with indications that the maximum velocity dispersion is observed at \( \sim 0.5'' \) from the nucleus. The broad H\alpha component appears blueshifted around the galaxy core, with velocities consistent with the broad [O \text{ iii}] component. The spiral arms also show broad H\alpha emission but with velocities following the stellar velocities. The velocity dispersion of the broad H\alpha component is up to \( 5\sigma_b \) near the galaxy nucleus.

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The outflow sizes based on the flux-weighted size of the narrow-line region, defined by Husemann et al. (2014) and reported in Section 5.1 and Figure 11 of the published version of this article, were miscalculated due to a coding error. The correct flux-weighted photometric sizes based on the total profile of [O III] range between 0.6 and 1 kpc and are significantly smaller than the kinematically defined sizes. This is due to the spatial concentration of [O III], which effectively leads to an underestimation of the size of the region dominated by AGN outflow. Conversely, the comparison between the flux-weighted photometric size and kinematic size for Hα finds them to be roughly similar. Figure 11 shows the updated flux-weighted sizes of the outflows based on both [O III] and Hα. The S/N-based photometric sizes remain unchanged and overestimate the kinematic size of the outflows by at least a factor of 2.

The above changes do not affect our results but instead reinforce our conclusion that photometrically defined outflow sizes reflect the spatial distribution of the flux and can correspondingly lead to either overestimation or underestimation of the size of the region within which the outflow kinematics dominate the gas dynamics.

**Figure 11.** Comparison of the kinematically measured size with the photometrically measured size of the [O III] emission (left) and Hα (right). We plot flux-weighted sizes (blue) and S/N-based sizes (red). The dashed and solid lines indicate the 1:1 and 1:2 ratio between them, respectively. The kinematically measured sizes are based on the broad components, while the photometrically measured sizes are based on the total line profiles.

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