The Impact of Low-luminosity AGNs on Their Host Galaxies: A Radio and Optical Investigation of the Kiloparsec-scale Outflow in MaNGA 1-166919

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Abstract

One way an active galactic nucleus (AGN) influences the evolution of its host galaxy is by generating a large-scale (kiloparsec-scale) outflow. The content, energetics, and impact of such outflows depend on the properties of both the AGN and host galaxy, and understanding the relationship between them requires measuring the properties of all three. In this paper, we do so by analyzing recent radio and optical integral spectroscopic observations of MaNGA 1-166919. Our results indicate that the biconical outflow in this galaxy is powered by a low-luminosity, low Eddington ratio AGN ejecting material that drives ∼100–200 km s^{-1} shocks into the surrounding interstellar medium—producing the hot, ionized gas and relativistic particles associated with the observed outflow. The energetics of the relativistic and ionized gas material produced at this shock are comparable, and both the mass outflow and kinetic power of the ionized gas in this outflow are higher than other AGNs with similar bolometric luminosities. Lastly, while the host galaxy’s total star formation rate is comparable to that of other star-forming galaxies with a similar stellar mass, there is evidence that the outflow both suppresses and enhances star formation in its immediate surroundings.

Unified Astronomy Thesaurus concepts: AGN host galaxies (2017); Active galactic nuclei (16); Low-luminosity active galactic nuclei (2033); LINER galaxies (925); Radio continuum emission (1340)

1. Introduction

The observed correlation between the properties of a galaxy and its supermassive black hole (SMBH) suggests that the evolutions of the two are related (e.g., Kormendy & Ho 2013). In current models for galaxy evolution, an important component of this relationship is kiloparsec-scale outflows powered by accretion onto the SMBH, resulting in an active galactic nucleus (AGN; see, e.g., King & Pounds 2015 for a recent review). There are believed to be two different classes of outflows: “winds,” produced by the radiation emitted by the accreting material (e.g., King & Pounds 2015), and “jets,” highly collimated streams of relativistic particles. Observations of X-ray binaries and low-luminosity AGNs suggest a possible connection between the type of outflow and mode of accretion onto the black hole (e.g., Körding et al. 2006), with (e.g., Heckman & Best 2014)

1. winds primarily resulting from “radiative-mode” accretion, where the inflowing material is primarily constrained to a geometrically thin, optically thick accretion disk that extends all the way to the innermost stable circular orbit (ISCO) of the SMBH, while
2. jets are often produced by “jet-mode” accretion, in which the thin accretion disk does not reach the ISCO, but instead is converted into a geometrically thick structure near the event horizon.

In both cases, the interaction between these outflows and the surrounding medium generates shocks (e.g., Faucher-Giguère & Quataert 2012) that can propagate through and affect the properties of the entire galaxy (e.g., Nelson et al. 2019). In most models, the primary role of these outflows is to suppress future star formation in these galaxies—though whether they do so is uncertain (e.g., Bae et al. 2017).

Such outflows are believed to have multiple constituents, such as hot ionized gas produced at the shock, neutral and molecular material entrained in the resultant cosmic rays (e.g., Oosterloo et al. 2017; Richings & Faucher-Giguère 2018; Hall et al. 2019; Murthy et al. 2019 and references therein), and cosmic rays—highly relativistic particles accelerated at the shock. Recent results suggest that, under certain conditions (e.g., $M_* \lesssim 10^{10} M_{\odot}$ galaxies; Hopkins et al. 2020), the pressure of the resultant cosmic rays can actually play an important role in driving massive amounts of material from a galaxy (e.g., Mao & Ostriker 2018; Hopkins et al. 2021). An important way of studying these particles is to measure the morphological and spectral properties of the radio synchrotron emission resulting from the interaction between cosmic rays and magnetic fields (e.g., Zakamska & Greene 2014; Alexandroff et al. 2016; Hwang et al. 2018).

In this paper we present a detailed study of the radio and optical emission of MaNGA 1-166919 (Figure 1), a fairly nearby ($z \sim 0.07$; Table 1) galaxy whose optical colors suggest that it lies within the “green valley” (see Figure 2). Such galaxies are believed to be transitioning from the “blue” (star-forming) cloud to the “red” (quiescent) sequence, possibly as a result of a large-scale outflow removing and/or reheating the gas needed to form additional generations of stars. A previous study of this galaxy by Wylezalek et al. (2017) showed that it indeed hosts such an outflow. As demonstrated below, analyzing the multiple properties
of the outflow and host galaxies provides important insight into how the outflow is produced by the central AGN and how it interacts with the surrounding galaxy.

In Section 2, we discuss our analysis of recent radio observations of this galaxy, presenting our measurement of its radio morphology (Section 2.1) and spectrum (Section 2.2). In Section 3, we discuss the analysis of recent MaNGA (Section 3.1) and GMOS (Section 3.2) integral field unit (IFU) observations of this source. In Section 4.1, we present our measurements of the relativistic material (Section 4.1.1), kinematics (Section 4.1.2), and ionized gas (Section 4.1.3) in this outflow. In Section 4.2, we discuss the relationship between this outflow and the AGN in this galaxy, while in Section 4.3 we discuss the interaction between this outflow and the surrounding medium. In Section 5 we summarize our results and their implications. Throughout the paper we use a luminosity distance \( D_L = 330 \) Mpc, an angular-size distance \( D_A = 287 \) Mpc, and cosmology-corrected scale \( 1.397 \) kpc arcsec\(^{-1}\) according to the NASA/IPAC Extragalactic Database\(^8\) (NED), assuming a flat \( \Lambda \)CDM cosmology \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.279 \), and \( \Omega_\Lambda = 0.721 \).

### 2. Jansky Very Large Array Observations

To better measure the properties of the radio emission of MaNGA 1-166919, we analyzed the data collected in the three Very Large Array (VLA) observations of this galaxy listed in Table 2. For each observation, the raw ASDM files were converted into a measurement set (MS) using the \texttt{import-tevla} task included in Common Astronomy Software Application (CASA; McMullin et al. 2007), version 5.1.2–4, and were calibrated using the VLA CASA Calibration Pipeline 5.1.2. The delays, bandpass, and flux density scale were calibrated using short observations of 3C 286 (J1331+3030), while the gains were calibrated using observations of quasar J0920+446 (B3 0917+441). The calibrated data were then imaged using the CASA task \texttt{tclean} using natural weighting to maximize the sensitivity (at the expense of angular resolution). The large fractional bandwidth of these data sets results in substantial differences in the primary and synthesized beams and the intrinsic source flux across the band, which can create artifacts in the resultant images. To mitigate these effects, we deconvolved the image using a two-term, multifrequency synthesis (MTMFS) algorithm (Rau & Cornwell 2011). During the deconvolution process, the residual maps were smoothed on scales of 0, 4, and 20 pixels to better identify sources of different angular sizes. Furthermore, at L and S bands sufficient flux was detected in the field to use the CASA task \texttt{gaincal} to recalculate the phase calibration assuming the intensity model generated from this imaging, with the new gain table applied to

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Notes.

8 https://ned.ipac.caltech.edu

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### Table 1

| Parameter                        | Value |
|----------------------------------|-------|
| R.A. decl.
J2000                           | 09:46:50.18 +43:25:25.8 |
|                                  | 146.709110 43.423861 |
| IDs                              | SDSS J094650.17+432525.8 |
|                                  | WISEA J094650.18+432525.8 |
| MaNGA-ID                         | 1-166919\(^a\) |
| Plate-IFU                        | 8459-3702 |
| Redshift                         | 0.07221 |
| Luminosity distance \( D_L \)     | 330 Mpc |
| Angular-size distance \( D_A \)  | 287 Mpc |
| Scale                            | 1.39 kpc arcsec\(^{-1}\) |
| Galactic \( A_V \)               | 0.0478 mag |
| \( R_{\text{eff}} \) (r band)\(^b\) | 4.90 |
| \( M_{g}^* \)                    | \( 6.1 \times 10^{10} \) \( M_\odot \) |
| \( g' - r^e \)                   | 0.658 |

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**Figure 1.** Composite RGB image of the Blob Source extracted from the DESI Legacy Imaging Surveys (Dey et al. 2019; legacy surveys.org). The MaNGA field of view is shown in orange. The gray box corresponds to the GMOS field of view.

**Figure 2.** Location of studied galaxy (green star) in the color–magnitude diagram. The gray distribution is shown as a reference based on the \( K \)-corrected photometry taken from the Reference Catalog of galaxy Spectral Energy Distributions (http://cosmicsai.edu) (RCSED; Chilingarian et al. 2017).
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| Table 2
| VLA Observations of MaNGA 1-166919
| Parameter | Value | Value | Value |
|-----------|-------|-------|-------|
| Observation date | 2016 Nov 13 | 2016 Oct 3 | 2017 Dec 30 |
| Band (frequency) | L (1–2 GHz) | S (2–4 GHz) | C (4–8 GHz) |
| Configuration | A | A | B |
| Time on source | 16 min 24 s | 21 min 52 s | 24 min 40 s |
| Thermal rms$^a$ | 17 mJy$^b$ | 8.0 mJy$^b$ | 4.5 mJy$^b$ |
| Field of view$^c$ | 30$^a$ | 15$^a$ | 7.5$^a$ |
| L.A.S.$^d$ | 18$^a$ | 9$^a$ | 14.5$^a$ |
| Number of spectral windows | 16 | 16 | 32 |
| Number of spectral channels/windows | 64 | 64 | 64 |
| Width of spectral channels | 1 MHz | 2 MHz | 2 MHz |

Notes.
$^a$ The image rms due to thermal noise, calculated using the VLA Exposure Calculator (https://obs.vla.nrao.edu/ect/) assuming “natural” weighting.
$^b$ Calculated assuming a bandwidth of 0.6 GHz to account for radio frequency interference (RFI) in this band.
$^c$ Calculated assuming a bandwidth of 1.5 GHz to account for RFI in this band.
$^d$ Calculated assuming a bandwidth of 3.35 GHz to account for RFI in this band.

### 2.1. Radio Morphology

As shown in Figure 3, in all three bands the radio emission consists of two lobes on opposite sides of the optical center of the galaxy, with the SE component consistently brighter than the NW. Furthermore, the extent of the radio emission is considerably smaller than the optical size of this galaxy (see Figure 4). The optical half-light radius $R_{90} \approx 4''$ (Table 1) is considerably smaller than the 9”–18” largest angular scale of these observations (Table 2). As a result, this nondetection of larger-scale radio emission is significant. To measure the properties of lobes components, we fit the intensity distribution in the central $12'' \times 12''$ of each image with two Gaussians using the MIRIAD (Sault et al. 1995) task imfit. The resultant properties of both components are listed in Table 4, with the error in integrated flux density calculated using Equation (7) in the documentation of the NVSS Source Catalog.$^9$ The rms of the residual images (Table 4) is comparable to that of the entire image (Table 3), suggesting that no additional components are necessary. This conclusion is supported by the lack of significant structures in the residual images (Figure 3)—with the possible exception at 4–8 GHz (C-band), where there is a $\sim 5\sigma$ excess $\sim 4''$ W of the center of the galaxy. Furthermore, the centers and (deconvolved) extents of the two lobes are consistent across all three bands, suggesting that these results are robust.

### 2.2. Radio Spectrum

In order to measure the physical properties of the radio-emitting plasma, it is first necessary to identify the underlying emission mechanism. This, in turn, requires determining the spectrum of the radio source, which we do using two methods: measuring the flux density of both components in narrowband images of this galaxy (Section 2.2.1), and the spectral index $\alpha$ ($S_{\nu} \propto \nu^{\alpha}$) maps within each band produced by the MTMFS deconvolution described in Section 2.1 (Section 2.2.2).

#### 2.2.1. Narrowband Images

The integrated flux densities of the SE and NW lobes, as measured from the wideband images discussed above, differ significantly between the three observed bands. To better measure how the flux density of these components changes with frequency, we first imaged contiguous subsets of the spectral windows (SPWs) within each band, and then—as in Section 2.1—we fit the resultant image with two Gaussians to measure the integrated flux density of each lobe. The SPWs were grouped such that there would be a $\geq 3\sigma$ change in the flux density of the fainter NW lobe assuming that its continuum radio spectrum in this frequency range is well described by a single power law with spectral index $\alpha \sim -0.9$, the value resulting from fitting a power law to the flux densities derived from the wideband images (Table 4). These images were also produced using the CASA task tclean, as in Section 2.1, again using natural weighting and the same pixel and image size as before, using the “multiscale” deconvolved algorithm (Cornwell 2008) since the decreased fractional bandwidth of the data set made an additional spectral term unnecessary. We again used the MIRIAD task imfit to fit the central $12'' \times 12''$ region of each image with two Gaussians. In these fits, the peak flux, size, and orientation of both ellipses were allowed to vary,
but the positions of the centers were fixed to the size obtained from wideband images given in Table 4. In general, the morphological properties of the two lobes derived from these fits were consistent with the values derived from the wideband images. The resultant integrated flux densities of both the SE and NW lobes are given in Table 5.

The resultant radio spectrum is shown in Figure 5, with the parameters derived from fitting a single power law to the integrated flux densities of both the NW and SE radio lobes given in Table 6. As shown in Figure 5, this model does a good job of reproducing the observed flux densities. We also attempted to fit these flux densities with both a broken power law (as expected if synchrotron cooling is important at higher frequencies) and a power law with exponential cutoff at lower frequencies (as expected from free–free absorption along the line of sight), but these more complicated models did not produce significantly improved fits to the data.

### 2.2.2. Spectral Index Maps

The technique used to get the spectral index maps assumes that the flux density $S$ at a particular frequency $\nu$ and sky position ($\alpha, \delta$) can be accurately expressed as

$$S_\nu(\alpha, \delta) = S_{\nu_0}(\alpha, \delta) + \frac{\Delta S_{\nu_0}}{\Delta \nu} (\nu - \nu_0)$$

and then iteratively solves for the value of $S_{\nu_0}$ and $\frac{\Delta S_{\nu_0}}{\Delta \nu}$ at each location on the sky. As implemented in the CASA command `widebandpbcor`, the derived value of $\frac{\Delta S_{\nu_0}}{\Delta \nu}$ is used to...
calculate the spectral index $\alpha$ within the frequency range of the input data in each pixel of the resultant image.

As shown in Figure 6, in all three bands the spectral index of pixels in the SE and NW lobes is $\alpha \lesssim -0.5$, consistent with the value derived from the analysis described in Section 2.2.1 (Table 6). However, in all three bands the values of $\alpha$ in the SE lobe are, in general, steeper (more negative) than those in the NW lobe.

### Table 4
Parameters of Two Gaussian Fits to the Radio Emission of MaNGA 1-166919

| Parameter | L Band | S Band | C Band |
|-----------|--------|--------|--------|
| Frequency | 1–2 GHz | 2–4 GHz | 4–8 GHz |
| Peak flux density $S_{\text{peak}}$ [mJy/beam] | 1.22 ± 0.05 | 0.52 ± 0.02 | 0.45 ± 0.01 |
| Integrated flux density $S_{\text{int}}$ (mJy) | 1.68 ± 0.11 | 1.01 ± 0.05 | 0.62 ± 0.03 |
| $x$-offset$^a$ | 0°50 ± 0°03 | 0°46 ± 0°02 | 0°44 ± 0°03 |
| $y$-offset$^a$ | $-1°02 ± 0°05$ | $-1°06 ± 0°02$ | $-1°03 ± 0°029$ |
| Major axis $\theta_M$ | $1°71 ± 0°06$ | $1°33 ± 0°04$ | $2°19 ± 0°06$ |
| Minor axis $\theta_m$ | $1°52 ± 0°09$ | 0°97 ± 0°03 | 1°47 ± 0°06 |
| Position angle $\theta_{PA}$ | 86° ± 14° | 43° ± 4° | 75° ± 3° |
| Deconvolved size | 0°99 ± 0°69 | 0°97 ± 0°64 | 1°18 ± 0°71 |
| Physical (deconvolved) size | 1.4 kpc × 1.0 kpc | 1.3 kpc × 0.9 kpc | 1.6 kpc × 1.0 kpc |

**Note.**

$^a$ Measured from the center of the field, $\alpha_{\text{J2000}} = 09:46:50.18$, $\delta_{\text{J2000}} = +43:25:25.83$.

### Table 5
Flux Density of SE and NW Lobes Derived from Narrowband Radio Images

| Band | SPW$^a$ | $\nu^b$ (GHz) | $\Delta\nu$ (GHz) | $S_{\text{int}}^{\text{SE}}$ (mJy) | $S_{\text{int}}^{\text{NW}}$ (mJy) |
|------|---------|---------------|-----------------|-----------------|--------------------|
| $L$ | 0–5     | 1.200         | 0.384           | 1.76 ± 0.02     | 1.08 ± 0.02        |
| $L$ | 6–9     | 1.519         | 0.192           | 1.70 ± 0.02     | 0.90 ± 0.02        |
| $L$ | 10–15   | 1.839         | 0.352           | 1.60 ± 0.02     | 0.91 ± 0.02        |
| $S$ | 0–3     | 2.244         | 0.512           | 1.02 ± 0.01     | 0.60 ± 0.01        |
| $S$ | 4–6     | 2.691         | 0.384           | 0.96 ± 0.01     | 0.54 ± 0.01        |
| $S$ | 7–10    | 3.126         | 0.488           | 0.97 ± 0.01     | 0.51 ± 0.01        |
| $S$ | 11–15   | 3.691         | 0.600           | 0.92 ± 0.01     | 0.48 ± 0.01        |
| $C$ | 0–3     | 4.231         | 0.512           | 0.59 ± 0.01     | 0.33 ± 0.01        |
| $C$ | 4–9     | 4.871         | 0.768           | 0.61 ± 0.01     | 0.31 ± 0.01        |
| $C$ | 10–16   | 5.679         | 0.848           | 0.62 ± 0.003    | 0.30 ± 0.003       |
| $C$ | 17–23   | 6.551         | 0.896           | 0.56 ± 0.01     | 0.26 ± 0.01        |
| $C$ | 24–31   | 7.511         | 1.024           | 0.55 ± 0.01     | 0.23 ± 0.01        |

**Notes.**

$^a$ Range of spectral windows (SPWs) used in the associated band.

$^b$ Central frequency of subband.

$^c$ Range of frequency within subband.

$^d$ Integrated flux density of the SE lobe.

$^e$ Integrated flux density of the NW lobe.

### Figure 5
Radio spectrum of the NW and SE lobes as measured in the narrowband radio images of this galaxy. The integrated flux densities of both components are given in Table 5, and the lines indicate the power-law fit whose parameters are given in Table 6.

### Table 6
Parameters of Power-law Fits to Integrated Flux Density of NW and SE Radio Lobes

| Parameter | SE Lobe | NW Lobe |
|-----------|---------|---------|
| $S_{\nu_{\alpha}}$ | 2.35 ± 0.29 mJy | 1.52 ± 0.40 mJy |
| $\alpha$ | $-0.78 ± 0.09$ | $-0.93 ± 0.18$ |

**Note.**

$^a$ 1 GHz integrated flux density.

with a difference in spectral index $\Delta\alpha \sim 0.1–0.2$ (Figure 6), which may not be statistically significant. However, in $C$ band, this analysis indicates the presence of flat-spectrum ($\alpha \gtrsim 0$)
radio emission. For example, such a spectral index is measured for the $\sim 3\sigma$–$5\sigma$ peak located W of the two lobes. This suggests that this component has a different physical origin than the two lobes that will be discussed in Section 4.3.

3. Integral Field Unit Data Analysis

As mentioned in Section 1, previous studies of MaNGA 1-166919 suggest that it contains a kiloparsec-scale outflow (e.g., Wylezalek et al. 2017). In this section, we analyze data taken on this source during two IFU observations, one at the Apache Point Observatory as part of the Sloan Digital Sky Survey IV (SDSS-IV; Blanton et al. 2017) Mapping Nearby Galaxy at Apache Point Observatory (MaNGA; Bundy et al. 2015) project, the other using the Gemini-North telescope with the Multi-Object Spectrograph (GMOS; Allington-Smith et al. 2002; Hook et al. 2004). As listed in Table 7, these two data sets are complimentary: the MaNGA data span a wider range of $\lambda$ and cover a larger fraction of the galaxy, while the GMOS data have better angular and spectral resolution. While results from both data sets were previously derived by Wylezalek et al. (2017), we have used a different technique to analyze the MaNGA (Section 3.1) and GMOS (Section 3.2) data as described below—which in general agrees with the earlier work by Wylezalek et al. (2017).

3.1. MaNGA Data

The MaNGA survey consists of IFU (Drory et al. 2015) observations of 10,000 galaxies in the nearby universe chosen to collectively sample a wide range of stellar mass and color (Wake et al. 2017). Each galaxy was observed using bundles of 2" fibers covering (1.5–2.5)× the effective half-light radius of the target, with each galaxy observed with three dithered exposures to fill in the gaps between the fibers in a bundle (Law et al. 2015; Yan et al. 2016a). These data were then calibrated using the procedure described by Yan et al. (2016b) and reduced using the pipeline developed by Law et al. (2016). The flux-calibrated MaNGA spectral cube for MaNGA 1-166919 was made publicly available in the Fifteenth Data Release of the Sloan Digital Sky Survey (DR15; Aguado et al. 2019), as well as results derived from the data analysis pipeline described by Westfall et al. (2019)—which includes measurements of the emission-line properties made using the procedure described by Belfiore et al. (2019). While these results can be accessed using the Marvin toolkit (Cherinka et al. 2019), we analyzed these data sets using the procedure described below aimed at better measuring the properties of the outflowing material. In Section 3.1.1, we describe how we measured the properties of the stellar population of MaNGA 1-166919, and in Section 3.1.2 we describe the method using the measured properties of the ionized gas in this galaxy.

3.1.1. Stellar Fit

We used the NBURSTS full spectral fitting package (Chilingarian et al. 2007a, 2007b) to both derive the properties of the stellar population of this galaxy and determine the stellar contribution to its spectrum. This method uses a $\chi^2$ minimization algorithm to fit the spectrum in each (spatial) pixel with a model derived from broadening the spectrum predicted from a stellar population model with a Gauss–Hermite parameterized distribution (van der Marel & Franx 1993) of the line-of-sight velocity at this position. To avoid systematically biasing the resultant parameters, we masked wavelengths corresponding to strong emission lines (e.g., Figure 7). The stellar spectra were chosen from a grid of PEGASE.HR high-resolution simple stellar population (SSP) models (Le Borgne et al. 2004) based on the ELODIE3.1 empirical stellar library (Prugniel et al. 2007) assuming a Salpeter initial mass function (Salpeter 1955), pre-convolved with the line-spread function provided within the MaNGA data cube in order to account for instrumental effects.
broadening. While the derived properties of the ionized gas do depend on the choice of stellar models, the high signal-to-noise ratio \( (S/N) \) of our data suggests that this will be a small effect (Chen et al. 2018). An example of the results of this procedure is shown in Figure 7.

For each spectrum, this model returns the stellar line-of-sight velocity \( V\lambda \), the velocity dispersion \( \sigma\lambda \), and the equivalent stellar age \( T_{\text{SSP}} \) and metallicity \([\text{Fe}/\text{H}]_{\text{SSP}}\) of the best-fit SSP. To ensure that the derived parameters are reliable, we binned all spaxels with \( S/N > 1 \) (estimated in the stellar continuum spectrum in a narrow 10 Å spectral window centered on 5100 Å in the galaxy’s rest frame) into spatial regions with \( S/N > 20 \) using the adaptive Voronoi algorithm developed by Cappellari & Copin (2003). As shown in Figure 8, the spatial distribution of stellar velocity \( V\lambda \), velocity dispersion \( \sigma\lambda \), age \( T_{\text{SSP}} \), and metallicity \([\text{Fe}/\text{H}]_{\text{SSP}}\) recovered from the MaNGA spectral cube using the NBURSTS full spectral fitting tool (Chilingarian et al. 2007a) and the grid of the SSP models PEGASE.HR (Le Borgne et al. 2004).

As shown in Figure 8, the distribution of the stellar line-of-sight velocity of the stellar component \( V\lambda \) is indicative of a regular rotating stellar population. We modeled this stellar velocity field by assuming that, for a spaxel located at a particular \((x, y)\) measured relative to the center of the galaxy, the emitting stars have a line-of-sight velocity

\[
V_{\lambda}(x, y) = V_{\text{sys}} + V_0(x, y) \cos \phi \sin i \frac{\cos \phi \sin i}{g},
\]

where the azimuthal rotational velocity in the center of the disk (its “galactic plane”) is

\[
V_0(R) = V_0 \left( \tan \frac{\pi R}{R_0} + c \frac{R}{R_0} \right),
\]

where \( V_{\text{sys}} \) is the systemic velocity of the galaxy, \( g = \sqrt{\sec^2 i - \cos^2 \phi \tan^2 i} \) is a geometrical factor converting the projected sky distance \( r = \sqrt{x^2 + y^2} \) between a spaxel at the center of the galaxy to the distance along the galactic plane \( R = gr \), \( i \) is the inclination angle of the disk, \( R_0 \) is a radius where velocity reaches a constant maximum value \( V_0 \) in the case of \( c = 0 \), and \( c \) describes the growth (\( c > 0 \)) or decline
observed in the rotation curve of the two. The predicted spectra of the main and out plane of the sky using a parameterization of a regularly rotating disk is similar to that presented by Chung et al. (2020). As shown in Figure 9, this model is able to reproduce both the observed 1D and 2D stellar velocity distributions.

3.1.2. Emission-line Fit

To measure the properties of emission lines produced by ionized gas in this galaxy, we first subtracted the stellar continuum, as derived in Section 3.1.1, from the observed spectrum in each region, weighting appropriately the contribution of the constituent spaxels. An example of the resulting emission-line spectrum is shown in Figure 10. We then estimate the S/N of the resultant emission-line spectra in each spaxel using the total flux in the Hα+[N II] lines, and we removed from further analyses all spaxels with S/N < 30. As shown in Figure 11, this requirement primarily excluded spaxels in the outer regions of this galaxy—beyond the observed extent of its radio emission (Figure 3). We then used the Voronoi algorithm developed by Cappellari & Copin (2003) to spatially bin the remaining spaxels into regions with S/N ≥ 50.

As shown in Figure 10, the profiles of the emission lines in a particular spaxel were not always well described by a single Gaussian. As a result, we modeled the emission-line spectrum in each spaxel assuming two Gaussian components. Unfortunately, using a $\chi^2$ minimization routine to model the emission-line spectrum in each spaxel with two independent Gaussians yielded unreliable results due—in large part—to the degeneracies inherent in this model. As a result, we developed a procedure to fit the emission-line spectra in all of the spaxels as the sum of two components:

1. a “main” component dominated by regularly rotating gas in the disk of this galaxy; and
2. an “outflow” component.

In this decomposition, we accounted for the per-locus dispersion and assumed that the spatial distribution of the kinematic properties of gas in the “main” component is well described by the prescription for a regularly rotating disk given in Equations (2) and (3).

Initial parameters were derived assuming that the main component dominated the emission in each spaxels, but final values resulted from simultaneously fitting the emission-line spectra for the “main” and “outflow” component, as described below.

We then refit the emission-line spectrum in every spatial bin, assuming that the profile of each spectral line is described by two Gaussians. The free parameters in this model are as follows for both the “main” and “outflow” components:

1. line-of-sight velocity $V_{\text{los}}$ and intrinsic velocity dispersion ($\sigma_\text{gas}$) of a line $\sigma_\text{obs}^2 = \sigma_\text{gas}^2 + \sigma_\text{inst}^2$, where $\sigma_\text{gas}$ is the intrinsic velocity dispersion
and $\sigma_{\text{inst}}$ is the instrumental resolution $\sigma_{\text{gas}}$ of the emitting gas;
2. H$\alpha$ flux;
3. Balmer decrement H$\alpha$/H$\beta$;
4. log [N II] $\lambda$6584/H$\alpha$;
5. log ([S II] $\lambda$6717+[S II] $\lambda$6731)/H$\alpha$;
6. log [O III] $\lambda$5007/H$\beta$; and
7. $\log n_{\text{e}}$, as determined from the [S II] $\lambda$6717/[S II] $\lambda$6731 ratio using the methods described by Osterbrock & Ferland (2006) and Proxauf et al. (2014).

To determine the values of these quantities in each spatial region, we used the Levenberg–Marquardt minimization method as implemented by the Python-based LMFIT package (Newville et al. 2016) to determine the combination of values that minimized the $\chi^2$. Furthermore, we required that—for both components—our fits returned values within the following ranges:

1. $2.75 \leq \frac{H\alpha}{H\beta} \leq 10$
2. $-1.2 \leq \log \left( \frac{[O \text{m}] \lambda5007}{H\alpha} \right) \leq 1.3$
3. $-1.0 \leq \log \left( \frac{[N \text{II}] \lambda6584}{H\alpha} \right) \leq 0.4$
4. $-0.9 \leq \log \left( \frac{[S \text{II}] \lambda6717+[S \text{II}] \lambda6731}{H\alpha} \right) \leq 0.25$
5. $0.475 \leq \log \left( \frac{[S \text{II}] \lambda6717}{[S \text{II}] \lambda6731} \right) \leq 1.425$,

as expected from the physical processes governing these emission lines and observations of large samples of other galaxies (e.g., Baldwin et al. 1981; Osterbrock & Ferland 2006; Proxauf et al. 2014). We further required that, for each spatial region, the fitted value $V_{\text{LOS}}$ of the “main” was within 50 km s$^{-1}$ of the value for the “main” component derived from the initial analysis described above. Using this procedure, we simultaneously fit for the properties of the “main” and “outflow” contribution to the emission-line spectrum in each spaxel. An example of the results from this fitting procedure is shown in Figure 10.

Figure 11. Map of the difference between the BIC (Equation (4)) derived from one- and two-Gaussian model fits ($\Delta$BIC = BIC$_1$ – BIC$_2$) and the emission-line spectra of this galaxy. $\Delta$BIC < 0 values suggest that only the “main” component is needed to describe the emission-line spectrum in the spaxel, while $0 < \Delta$BIC < 50 suggests that the addition of the second “outflow” component results in a marginal improvement (such spaxels are marked by transparent colors in other parameter maps). The contours indicate 3 GHz ($S$-band) emission 5, 10, 50× the rms of the image shown in Figure 3.

To assess the statistical significance of the “outflow” component in a given spaxel, we calculated the Bayesian Information Criterion (BIC) statistic (Schwarz 1978; Liddle 2007):

$$\text{BIC} = \frac{N_{\text{data}} \ln \chi^2}{N_{\text{data}}} + N_{\text{vars}} \ln N_{\text{data}},$$

(4)

where $N_{\text{data}}$ is the number of data points, $N_{\text{vars}}$ is the number of free parameters in the model, and $\chi^2$ is the result from fitting the data with said model, resulting from fitting the emission-line spectrum of a given region with a single Gaussian (BIC$_1$) and two Gaussians (BIC$_2$). As shown in Figure 11, BIC$_1$ is substantially higher than BIC$_2$ in the innermost spaxels, strongly implying that the “outflow” component is significant in these regions. These spaxels are also coincident with the radio emission detected from this galaxy, suggesting a physical connection between the ionized gas “outflow” and radio-emitting plasma. In the spaxels beyond the radio emission, BIC$_1$ is either slightly larger or smaller than BIC$_2$—implying that the “outflow” component is either not present or a marginal fraction of the ionized gas at these locations. As a result, in 2D maps of the parameters of the “outflow” component, we mask spaxels with BIC$_1$ < BIC$_2$, while those with BIC$_1$ – BIC$_2$ < 50 are shown in transparent color. Furthermore, in the parameter maps of the main component, we present values from the one-component fit for spaxels with BIC$_1$ ≤ BIC$_2$ and values from the two-component fit for those spaxels where BIC$_1$ > BIC$_2$.

The differences between the “main” and “outflow” components manifests themselves not only in the statistical significance of the fits but also in the derived properties of the ionized gas. As shown in Figure 12, the velocity dispersion $\sigma_{\text{gas}}$ of the “outflow” component is in general higher than that of the “main” component—even for spaxels with similar line-of-sight velocities. The “V” shape of the “outflow” component on the $V_{\text{LOS}}$–$\sigma_{\text{gas}}$ diagram shown in Figure 12 is suggestive of a biconical geometry (e.g., Bae & Woo 2016). Furthermore, as shown in Figure 13, the line ratios measured for the “main” and “outflow” occupy very different regions on the Baldwin, Phillips, and Terlevich (BPT) diagrams—indicating that they are ionized by different mechanisms (Baldwin et al. 1981). The
physical implications of both results will be discussed further in Section 4.1.2.

3.2. GMOS Data

In addition to using MaNGA data to measure the properties of the ionized gas in this galaxy (Section 3.1), we also analyzed the spectrum obtained in recent GMOS IFU observations—whose results were previously presented by Wyilezalek et al. (2017). The GMOS data were taken on Gemini-North in one-slit mode and covered the central $3.5 \times 5.0$ region of this galaxy (Figure 1). The angular resolution of this data set is limited by the atmospheric seeing during this observation, estimated to be $\approx 0.9\arcsec$, and these observations measured the spectrum between $\lambda \approx 4000$ and 7000 Å with a spectral resolution $R \approx 3000$, corresponding to an instrumental dispersion $\sigma_{\text{inst}} \approx 45$ km s$^{-1}$ (Wylezalek et al. 2017) (Table 7). These data were reduced following the procedure described by Wylezalek et al. (2017). The primary differences between our analysis of this data and that presented by Wylezalek et al. (2017) are the modeling of the stellar contribution to the observed spectrum and a different spatial binning of the inferred emission-line spectra—as described below.

Just as in the case for the MaNGA data in Section 3.1, we first determined the stellar contribution to the observed spectrum at a given sky location. We again used the NBURSTS package to fit the observed spectrum with that predicted by the SSP models described in Section 3.1.1. Due to the relatively low S/N in this region, we fixed the equivalent stellar age $T_{\text{SSP}}$ and metallicity $[\text{Fe}/H]_{\text{SSP}}$ in a particular GMOS spaxel to the values derived in the MaNGA spaxel at the same sky position. As a result, this fitting returned the stellar line-of-sight velocity $V_*$ and velocity dispersion $\sigma_*$ for each GMOS sky pixel. We then subtracted the predicted stellar contribution in each sky pixel of the GMOS data cut to determine the emission-line spectrum at each position. To determine the absolute flux calibration of the GMOS data, we compared the total $H\alpha + [\text{N ii}]$ flux within a $3''$ radius inferred from a single Gaussian fit to the value in the Reference Catalog of galaxy Spectral Energy Distributions (RCSED; Chilingarian et al. 2017)—which measured this quantity from an earlier SDSS spectrum using a similar methodology for determining the properties of the emission lines. We found that the flux inferred from the GMOS data was $1.4\times$ lower than that in the RCSED, and we used this factor to adjust the measured fluxes and equivalent widths (EWs) of the aforementioned spectral lines.

Before using these spectra to measure the properties of the ionized gas, it was necessary to first adaptively bin the emission-line spectra into regions of sufficient S/N—as done for the MaNGA data cube (Section 3.1.2). We again used the adaptive Voronoi algorithm developed by Cappellari & Copin (2003) to combine the spectra of adjacent spatial pixels using the maximum S/N per channel measured within the H$\alpha$+[N ii] line complex, such that the combined spectra had an overall S/N $\geq 3$. We then used the Levenberg–Marquardt minimization method implemented by the Python-based lmfit package (Newville et al. 2016) to simultaneously fit single Gaussians to the $H\alpha$, [N ii], and [S ii] emission lines (we excluded the H$\beta$ and [O iii] lines from this analysis owing to the low S/N at the edge of the GMOS bandpass). Again, we required that all three lines have the same line-of-sight velocity $V_{\text{los}}$ and velocity dispersion $\sigma_{\text{gas}}$ at a given sky position, and the resultant spatial distributions of these parameters are shown in Figure 15.

As discussed in Section 3.1.2, the emission-line spectrum measured by MaNGA suggests the ionized gas in this galaxy of two components: a “main” component composed of material rotating within the galactic disk, and an “outflow” component.
which we modeled using two Gaussians. Unfortunately, the S/N of the GMOS spectra is too low to fit a two-Gaussian model to the spectrum in each spaxel as done for the MaNGA data (Section 3.1.2). However, as shown in Figure 12, our analysis of the MaNGA data indicates that the “main” ionized gas has a velocity dispersion $\sigma_{\text{gas}} \approx 100 \, \text{km s}^{-1}$, while $\sigma_{\text{gas}}$ for the outflow component is significantly larger. Furthermore, as shown in Figure 14, the properties of the emission lines in the GMOS data differ significantly between spaxels with $\sigma_{\text{gas}} < 100 \, \text{km s}^{-1}$ and $\sigma_{\text{gas}} > 100 \, \text{km s}^{-1}$. Combined, this indicates that ionized gas in GMOS spaxels with low velocity dispersion ($\sigma_{\text{gas}} < 100 \, \text{km s}^{-1}$) is dominated by the “main” component, while the ionized gas in GMOS spaxels with high velocity dispersion ($\sigma_{\text{gas}} < 100 \, \text{km s}^{-1}$) is dominated by the “outflow” component. As defined using this criterion, the morphology of the GMOS “outflow” component is similar to the radio morphology of this galaxy (right panel of Figure 15), as was also the case for the MaNGA “outflow” component (Figure 11; Section 3.1.2).

To determine the kinematics of the “main” component in the GMOS data, we fit the $V_{\text{LOS}}$ of all spaxels with $\sigma_{\text{gas}} < 100 \, \text{km s}^{-1}$ using the mathematical model for a regularly rotating disk defined in Equations (2) and (3). As shown in Figure 16, this model accurately reproduces both 1D and 2D profiles of $V_{\text{LOS}}$ in these spaxels. Furthermore, as shown in Figure 17, this fit to the GMOS data suggests a regularly rotating disk whose orientation and line-of-sight velocities are similar to what were derived from the MaNGA data.

### 4. Physical Interpretation

In this section, we use the properties measured in the VLA radio (Section 2) and IFU (Section 3) observations analyzed above to measure the properties of material associated with the outflow (Section 4.1) and AGN (Section 4.2) in this galaxy, as well as the impact the outflow has on its host galaxy (Section 4.3).

#### 4.1. Outflow

As previously mentioned, the observed radio emission from this galaxy is spatially coincident with the regions where two Gaussians are needed to accurately model the emission-line spectra (Figure 11) derived from the MaNGA data cube (Section 3.1.2), as well as regions where the ionized gas has a high velocity dispersion (Figure 15) as derived from the GMOS data cube (Section 3.2). As a result, in the discussion below we assume that the radio and optical emission is produced by two different, but related, components of the outflowing material. By doing so, we are able to study the relativistic content (Section 4.1.1), kinematics (Section 4.1.2), and thermal content (Section 4.1.3) in this outflow.

##### 4.1.1. Relativistic Component

As described in Section 2.2, the spectrum of the both the SE and NW radio lobes is well described by a power law with spectral index $\alpha \approx -0.7$, consistent with optically thin synchrotron emission resulting from relativistic electrons (and positrons) interacting with a magnetic field (e.g., Pacholczyk 1970; Condon & Ransom 2016). In this case, the observed radio luminosity $L_{\text{rad}}$ depends on the size $R$, the relativistic electron $u_e$, and the magnetic $u_B$ energy density of the emitting region. However, since the synchrotron power $P_{\text{syn}}$ radiated by an electron of energy $E$ in a magnetic field of strength $B$ is (e.g., Pacholczyk 1970; Rybicki & Lightman 1986)

$$P_{\text{syn}}(E) = \frac{4e^4}{9m_e c^7}B^2E^2,$$

where $e$ and $m_e$ are, respectively, the charge and mass of the electron and $c$ is the speed of light, for a given radio luminosity and size there is not a unique solution for $u_e$ and $u_B$. However, there is a minimum in the combined (relativistic electron + magnetic field) energy required to power such a source when $u_e \approx \frac{4}{7}u_B$ (e.g., Pacholczyk 1970; Rybicki & Lightman 1986; Condon & Ransom 2016). The magnetic field strength $B_{\text{min}}$ is (e.g., Pacholczyk 1970; Condon & Ransom 2016)

$$B_{\text{min}} = \left[4.5(1 + \eta)c_{12}R_{\text{rad}}^{-2}ight]^{-\frac{1}{2}} \text{G},$$

where $\eta$ is the ion-to-electron energy ratio; $c_{12}$ is a “constant” whose value depends on $\nu_{\text{min}}, \nu_{\text{max}}$, and $\alpha$ (for $\nu_{\text{min}} = 10^6 \, \text{Hz}$, $\nu_{\text{max}} = 10^{10} \, \text{Hz}$, and $\alpha \approx -0.7$ as derived for both the SE and NW radio lobes; Table 6; $c_{12} \approx 10^8$ in cgs units; Condon & Ransom 2016); $R$ is the radius of the assumed spherical emitting region; and relativistic particle (electrons + ions) energy (e.g., Pacholczyk 1970; Condon & Ransom 2016)

$$E_{\text{min}} = c_{13}\left[1 + \eta\right]L_{\text{rad}}\frac{m_pR_{\text{rad}}^3}{2} \text{erg},$$

where $c_{13}$ is another constant whose value depends on $\nu_{\text{min}}, \nu_{\text{max}}$, and $\alpha$ (for $\nu_{\text{min}} = 10^6 \, \text{Hz}$, $\nu_{\text{max}} = 10^{10} \, \text{Hz}$, and $\alpha \approx -0.7$ as derived for both the SE and NW radio lobes; Table 6; $c_{13} \approx 3 \times 10^4$ in cgs units; Condon & Ransom 2016). Since the 3D geometries of the radio-emitting regions are not known, we assume that $R$ for a particular lobe is between the physical radius inferred by the smallest deconvolved semimajor axis and the largest deconvolved semimajor axis derived from our
modeling of the wideband radio images of this source (Section 2.1), as reported in Table 4. The “minimum energy” magnetic field strengths and relativistic particle energies of both the SE and NW lobes inferred from our measurements of their radio morphology (Section 2.1) and spectrum (Section 2.2) are reported in Table 8.
With this information, we can estimate the energy of the radio-emitting electrons. The synchrotron emission from an electron with energy $E$ in a magnetic field of strength $B$ peaks at a frequency (e.g., Pacholczyk 1970; Rybicki & Lightman 1986)

$$\nu_{\text{peak}} = 0.29 \times \left( \frac{B}{1 \mu \text{G}} \right) \left( \frac{E}{10^9 \text{eV}} \right)^{2/3} \text{Hz}.$$  

(8)

As a result, for a particular $\nu_{\text{peak}}$ and $B$, the energy of the emitting electron is

$$E \sim 6 \left( \frac{\nu_{\text{peak}}}{10^9 \text{Hz}} \right)^{2/3} \left( \frac{B}{1 \mu \text{G}} \right)^{-1/3} \text{GeV}.$$  

(9)

For the observed frequency range of $\nu = 1–8$ GHz and range of $B_{\text{min}}$ given in Table 8, for both lobes the radio emission is dominated by $E \sim 1–4$ GeV electrons. The synchrotron cooling time for such particles $t_{\text{cool}}$ is $t_{\text{cool}} \equiv \frac{E}{\nu B_{\text{min}}} \sim 100–200$ Gyr in both lobes for the estimated particle energies and magnetic field strengths. This suggests that radiative cooling plays a minor role in the evolution of the radio emission from the relativistic particles in this outflow.

Furthermore, the synchrotron spectrum of the observed radio emission can be used to determine the spectrum and origin of the GeV-emitting electrons. Optically thin synchrotron radiation with a power-law spectrum $S_{\nu} \propto \nu^{\alpha}$ is the result of emission from particles with a power-law energy spectrum:

$$\frac{dN}{dE}(E) \propto E^{-\alpha},$$  

(10)

where $\frac{dN}{dE}(E)$ is the number of particles per unit energy at particle energy $E$ and $p$ is the particle index ($p = 1–2\alpha$) (e.g., Rybicki & Lightman 1986; Condon & Ransom 2016). For the spectral index $\alpha \sim -0.85$ measured for both the SE and NW lobes (Section 2.2, Table 6), this suggests $\alpha \sim 2.7$—the value expected from first-order Fermi or diffusive shock acceleration (DSA; e.g., Fermi 1949, 1954). DSA requires that particles cross a shock multiple times (e.g., Bell 1978a, 1978b; Blandford & Ostriker 1978), gaining energy in each shock crossing. The particle spectrum, as well as the spectral index $\alpha$ of its resultant synchrotron emission, generated from this process is dependent on the Mach number $M$ of the shock, where (e.g., Berezhko & Ellison 1999; Guo et al. 2014; Di Gennaro et al. 2018)

$$M = \frac{2\alpha - 3}{\sqrt{2\alpha + 1}}.$$  

(11)

The spectral index $\alpha \sim -0.8$ to $-0.9$ observed from both the SE and NW lobes (Section 2.2, Table 6) suggests that the emitting particles in both components are accelerated in shocks with $M \sim 2–3.5$.

However, such shocks should also efficiently accelerate ions to high energies (e.g., Guo et al. 2014). Recent simulations (e.g., Park et al. 2015) and observations of particles accelerated in shocks with similar Mach numbers $M$ (e.g., S/N 5.7–0.1; Joubert et al. 2016) suggest the ion-to-electron energy ratio $\eta > 100$. If that also occurs in this galaxy, then minimum total relativistic particle energies in the SE and NW lobes are $\sim 10\times$ higher than the values given in Table 8, or on the order of $10^{55}$ erg. Regardless of the true value of $\alpha$, the larger energy in the relativistic component of this outflow suggests that it can have a significant impact on the host galaxy (e.g., Mao & Ostriker 2018; Hopkins et al. 2020).

### 4.1.2. Kinematics

As described in Section 4.1.1, the radio emission observed from MaNGA 1-166919 is believed to be produced by electrons accelerated by a shock propagating through this galaxy. However, theoretical work suggests that $\lesssim 10\%$ of the shocked material is accelerated to relativistic energies (e.g., Caprioli & Spitkovsky 2014; Caprioli et al. 2015), with the bulk of the material heated to a temperature $T_{\text{shock}}$ (e.g., Faucher-Giguère & Quataert 2012; Caprioli & Spitkovsky 2014):

$$T_{\text{shock}} \sim \frac{m v_{\text{shock}}^2}{2k},$$  

(12)

where $m$ is the mass of the particle, $k$ is Boltzmann’s constant, and $v_{\text{shock}}$ is the velocity of the shock relative to the surroundings. If $v_{\text{shock}}$ is high enough, a copious amount of UV and soft X-ray photons will be generated at the shock front (e.g., Raymond 1976; Allen et al. 2008). The spectra from material photoionized by this radiation are expected to have emission-line ratios (e.g., Dopita & Sutherland 1995; Allen et al. 2008) that lie within the LIER of the [S II] BPT diagram (Kewley et al. 2006). In the literature, this emission is often referred to arise from a “low-ionization nuclear emission-line region” [LINER] since they were first and primarily identified in the centers of galaxies; e.g., Heckman 1980; Heckman et al. 1981. However, subsequent work has found that such emission can be detected throughout a galaxy, e.g., Belfiore et al. 2016, and therefore we use the more general term.) Indeed, as shown in Figures 13 and 18, the emission-line ratios of the “outflow” material largely fall within the LIER region of such a diagram. Furthermore, as shown in Figure 18, LIER-like emission is only detected in the center of this galaxy and predominantly found in the “outflow” component of the ionized gas. Therefore, it seems likely that the ionized gas “outflow,” as inferred from our analysis of the MaNGA (Section 3.1.2) and GMOS (Section 3.2) data, is dominated by material photoionized by the shock that also accelerates the relativistic electrons responsible for the observed radio emission.
However, in many galaxies, such line ratios are instead thought to result from photoionization by post-AGB stars (e.g., Yan & Blanton 2012; Singh et al. 2013; Belfiore et al. 2016). Such stars are expected to be prevalent in older ($>1$ Gyr) stellar populations—as inferred for the central regions of this galaxy ($T_{\text{SSP}} \sim 3$ Gyr; Figure 8) from our derivation of its stellar population as described in Section 3.1.1.

It is possible to distinguish between these models by measuring the kinematics of the putative “outflow” component of the ionized gas in this galaxy, which we identify through deviations from a regularly rotating disk (as derived in Section 3.1.2). For the GMOS data, we estimated this by subtracting the line-of-sight velocity measured in a particular spaxel (left panel of Figure 15) with that predicted by our model for the regular rotating gas in this galaxy (right panel of Figure 17), while for the MaNGA data we calculated the difference in line-of-sight velocity between the “main” and “outflow” components ($\Delta V_{\text{gas,OF}}$) as derived from the modeling described in Section 3.1.2. As shown in Figure 19, the relative line-of-sight velocities show a clear spatial separation of “red” and “blue” components—strongly suggesting a biconical “outflow.” This geometry is consistent with the $V_{\text{LOS}} - \sigma_{\text{gas}}$ of the “outflow” component (Figure 12). Furthermore, the correspondence between the kinematics of the “outflow” ionized gas and the SE and NW radio “lobes,” which is particularly evident in the higher angular resolution GMOS data (left panel of Figure 19), strongly suggests a physical connection between the two. Since the radio emission is produced by shock-accelerated particles, we therefore conclude that these shocks are indeed responsible for producing the LIER-like emission observed from the ionized gas. This conclusion is further supported by the observed dependence between $|\Delta V_{\text{gas,OF}}|$ and the line ratios of the “outflow” gas. As shown in Figure 18, spaxels with higher values of $|\Delta V_{\text{gas,OF}}|$ typically fall above and to the right of spaxels with lower $|\Delta V_{\text{gas,OF}}|$ on the [SII] BPT diagram. This trend is similar to that predicted by models for the emission of material photoionized by shock-heated gas, which find that

Figure 18. Left: [SII] BPT diagram of the “outflow” ionized gas in MaNGA 1-166919, zoomed in on the “LI(N)ER” region as defined by Kewley et al. (2006). The data points are the same as those shown in Figure 13, but are instead color-coded by $|\Delta V_{\text{gas,OF}}|$—the magnitude of the difference in line-of-sight velocity between the “main” and “outflow” components measured at a particular spaxel. Shown is the spatial distribution of star formation (SF), LIER, and Seyfert-like photoionization of the “main” (middle) and “outflow” (right) components, as determined from the location of the line ratios measured in a particular spaxel on the [SII] BPT diagram shown in Figure 13. In the middle and right panels, the contours indicate 3 GHz ($5\text{-band}$) emission 5, 10, 50 times the rms of the image shown in Figure 3.

Figure 19. Difference in line-of-sight velocity between the “outflow” and “main” (regularly rotating) ionized gas in MaNGA 1-166919 as derived from the GMOS (left) and MaNGA (right) data cubes. In both panels, the contours indicate 3 GHz ($5\text{-band}$) emission 5, 10, 50 times the rms of the image shown in Figure 3.
their location on the [S II] BPT diagrams moves up and to right as the shock velocity $v_{\text{shock}}$ increases (e.g., Allen et al. 2008).

If correct, then the relative line-of-sight velocity between the “main” and “outflow” component provides a lower limit on $v_{\text{shock}}$, since this quantity is not sensitive to differences in velocity between these components in the plane of the sky. As a result, we estimate $v_{\text{shock}} \gtrsim 100 \text{ km s}^{-1}$ for the NW lobe and $v_{\text{shock}} \gtrsim 200 \text{ km s}^{-1}$ for the SE lobe—sufficient to photoionize substantial amounts of material both “downstream” (postshock) and “upstream” (preshock) of the shock (e.g., Raymond 1976; Dopita & Sutherland 1995; Dopita et al. 1996; Wilson & Raymond 1999). Furthermore, the observed geometry and differences in extent and shock velocity between the two components of the outflow are consistent with those expected from outflows resulting from high-velocity material ejected from an AGN interacting with a clumpy interstellar medium (ISM; e.g., Mukherjee et al. 2018; Nelson et al. 2019). In fact, simulations suggest that the biconical geometry of this outflow is the natural consequence of a central outflow being confined by the disk of a galaxy (e.g., Wagner et al. 2012). In summary, both the relativistic and ionized components of this outflow appear to be the result of shocks driven into the surrounding ISM by a central engine.

### 4.1.3. Ionized Gas Component

In Section 4.1.1, we presented our measurements for the energy contained in the relativistic component of this outflow. However, this outflow also consists of several nonrelativistic components, including ionized gas, atomic gas, and molecular material. In this section, we use the emission-line spectra derived from MaNGA (Section 3.1.2) and GMOS (Section 3.2) to measure the properties of its ionized component. While studies of similar outflows in other galaxies suggest that atomic and molecular material may constitute the bulk of the entrained mass (e.g., Oosterloo et al. 2017), currently the observational data needed to measure the properties of these components in this galaxy are not available.

The mass of the ionized gas in this outflow $M_{\text{out}}$ can be estimated as (e.g., Soto et al. 2012; Baron et al. 2017)

$$M_{\text{out}} = \mu m_{\text{H}} V n_e f,$$

where $m_{\text{H}}$ is mass of the hydrogen atom, $\mu$ is the average atomic number of the emitting material (assumed to be solar, such that $\mu \approx 1.4$), $V$ is volume of the emitting region, $f$ is the filling factor, and $n_e$ is the number density of electrons. The H$\alpha$ luminosity of this region is equal to (e.g., Baron et al. 2017)

$$L_{\text{H}α} = \gamma_{\text{H}α} n_e^2 f V,$$

where $\gamma_{\text{H}α}$ is the H$\alpha$ emissivity of the ionized plasma. In the case of highly ionized material with an electron temperature $T_e \approx 10^4 \text{ K}$ and optically thick to Lyman line emission (“Case B”; e.g., Baker & Menzel 1938; Burgess 1958), $\gamma = 3.56 \times 10^{-25} \text{ erg cm}^3 \text{ s}^{-1}$ (Osterbrock & Ferland 2006).

As a result, we can calculate $M_{\text{out}}$ by evaluating

$$M_{\text{out}} = \frac{\mu m_{\text{H}} L_{\text{H}α}}{\gamma_{\text{H}α} n_e^2}.$$
than those using other emission lines (e.g., Davies et al. 2020) unfortunately not detected with sufficient spectral resolution or low S/N in our data.

To estimate the extinction along the line of sight toward the outflowing material in both data sets, we use the Balmer decrement (the H$_\alpha$/H$\beta$ flux ratio) of the outflow component measured in the MaNGA data. This is because, as described in Section 3.2, H$\beta$ is not detected in the GMOS data. As shown in Figure 20, this quantity varies significantly, and for the MaNGA outflow we corrected the H$_\alpha$ flux of the outflow in each spaxel with the corresponding Balmer decrement measured for this component. The differing angular resolutions of the MaNGA and GMOS data preclude us from making a similar spaxel-by-spaxel correction. As a result, we estimate the extinction-corrected H$_\alpha$/H$\beta$ ratio (Figure 20) of the outflow component in the MaNGA emission-line spectrum is $\approx 3.9 \times 10^4$ erg s$^{-1}$ for the GMOS data.

Furthermore, we can estimate the total velocity of the outflow $v_{\text{out}}$ as (e.g., Karouzos et al. 2016)

$$v_{\text{out}} = \sqrt{v_{\text{los}}^2 + \sigma_{\text{gas}}^2},$$

where the value of these quantities as measured from the GMOS data is shown in Figure 15 and that as derived for the “outflow” component in the MaNGA emission-line spectrum is shown in Figure 22. Both data sets give similar values of $v_{\text{out}}$ with the ionized gas moving near $\approx 400$ km s$^{-1}$ near the center of the galaxy and slowing to values of $\approx 200$–300 km s$^{-1}$ near the edge of the radio emission.

With this velocity information, we can calculate the kinetic energy and “age” of the ionized gas in this outflow. We determine the kinetic energy $K_{\text{ion}}$ of the ionized gas in the MaNGA data by evaluating $K = \frac{1}{2} M_{\text{ion}} v_{\text{out}}^2$ in each spaxel (Figure 23), and we add together the values to measure a total $K_{\text{ion}} = 2.4 \times 10^{35}$ erg in the MaNGA data and $K_{\text{ion}} = (4.6-8) \times 10^{35}$ erg for the GMOS data. These energies are comparable to the minimum energy estimated for the relativistic content of this outflow (Table 8, Section 4.1.1), suggesting that these two components are in rough equipartition. Furthermore, we estimate the age of the MaNGA outflow in each

\[\text{Table 9}
\text{Properties of the Ionized Gas Outflow and AGN}
\]

| Property          | MaNGA          | This Work       | GMOS*          | Wylezalek et al. (2017) |
|-------------------|----------------|----------------|----------------|------------------------|
| $n_e$             | $\approx 80$ cm$^{-3}$ |               | $\approx 100$ cm$^{-3}$ | $\approx 100$ cm$^{-3}$ |
| $M_{\text{out}}$  | $2.4 \times 10^7 M_\odot$ |               | $(2.2-3.9) \times 10^7 M_\odot$ | $(2.6-8) \times 10^4$ erg |
| $K_{\text{ion}}$  | $2.4 \times 10^{54}$ erg |               | $62$ Myr |
| $\tau_{\text{age}}$ | $\approx 6$ Myr |               | $6.2$ Myr |
| $M_{\text{out}}$  | $\approx 4 M_\odot$ yr |               | $3.5-6.3 M_\odot$ yr |
| $E_{\text{kin}}$  | $\approx 1.3 \times 10^{44}$ erg | $\times 10^{60}$ erg | $1.4 \times 10^{42}$ erg | $1.4 \times 10^{42}$ erg |
| $L_{\text{bol}}$  | $(0.3-9.1) \times 10^{45}$ erg | $\times 10^{65}$ erg | $60 \Delta$ yr |

Note.

*Ranges reflect the difference resulting from the two ways of estimating the extinction along the line of sight, as described in Section 4.1.3.
spaxel as

\[ \text{age} = \frac{R}{v_{\text{out}}} \]  \hspace{1cm} (17)

where \( R \) is the projected physical separation between the spaxel and the center of the galaxy. As shown in Figure 23, this suggests that the outflow is \( \sim 6 \) Myr old. For the GMOS data, the \( \sim 1.4 \) kpc extent of the outflow coupled with the \( H\alpha + [N\text{ II}] \) flux weighted average outflow velocity \( v_{\text{out}} \) value of \( 222 \) km s\(^{-1} \) suggests \( \text{age} = 6.2 \) Myr—consistent with the results derived from the MaNGA data. As shown in Table 9, this suggests a mass outflow rate of \( \sim 4 \) \( M_\odot \) yr\(^{-1} \) and a kinetic power of \( E_{\text{kin}} \sim (0.2-1) \times 10^{41} \) erg s\(^{-1} \).

### 4.2. Active Galactic Nucleus

The central location and morphology of this outflow are suggestive of an AGN origin. While the emission-line spectra observed by MaNGA (Section 3.1.2; Figures 13, 18 and 24) and the high velocity dispersion measured by GMOS (Section 3.2; Figure 14) of the central gas are consistent with AGN activity, its existence does not directly mean it is responsible for generating this outflow (e.g., Shimizu et al. 2019) or explain how accretion onto the central SMBH results in the \( \sim 100-200 \) km s\(^{-1} \) shocks (Section 4.1.2) responsible for creating its observed relativistic (Section 4.1.1) and ionized components (Section 4.1.3).

Determining whether the AGN can power the observed outflow first requires estimating the AGN’s bolometric luminosity \( L_{\text{bol}} \). Current methods using the emission-line spectra of the AGN assume that the emitting material is photoionized by material accreting onto the SMBH (e.g., Heckman et al. 2004; Netzer 2009, and references therein). As argued in Section 4.1.2, the “outflow” component of the emission-line spectra is believed to be dominated by shock-heated material. Therefore, the “main” component of the observed emission-line spectrum should result in a more accurate estimate of \( L_{\text{bol}} \).

One of the most common techniques for determining \( L_{\text{bol}} \) uses the extinction-corrected luminosity of the [O III] line \( L_{\text{cor}}[O\text{ III}] \) (e.g., Kauffmann & Heckman 2009):

\[ L_{\text{bol}} \sim (600-800)L_{\text{cor}}[O\text{ III}] \]  \hspace{1cm} (18)

where we used the observed Balmer decrements (Figure 25) and Cardelli et al. (1989) attenuation law to calculate the value of \( A_V \) along the line of sight.

This relation was derived by analyzing the SDSS spectrum of the central regions of high-luminosity narrow-line AGNs (Heckman et al. 2004) and did not attempt to separate between the [O III] emission from photoionized and shock-heated material. If large-scale outflows were rare in this AGN sample,
then including the [O III] emission from the outflow in this calculation would significantly overestimate the true value of $L_{\text{bol}}$. However, since this relation did not account for the origin of the [O III] emission, we use it to derive $L_{\text{bol}}$ using both the total [O III] flux and the [O III] flux measured in just the “main” component.

Furthermore, as shown in Figures 18 and 24, only in the central $\sim 1''-2''$ of this galaxy are the line ratios of the “main” component consistent with photoionization by an AGN. This is smaller than the $3''$ aperture used to derive Equation (18) (Heckman et al. 2004). To estimate the possible effect resulting from this discrepancy, we measured the [O III] flux in both regions. The values of $L_{\text{[OIII]}}$ and $L_{\text{bol}}$ resulting from the different choices in region and components are given in Table 10.

Furthermore, the physical relationship between the bolometric luminosity of an AGN and the emission-line spectrum of the photoionized gas depends on the spectrum produced by the material accreting onto the SMBH (e.g., Netzer 2009 and references therein). The considerable diversity in the observed spectral energy distribution (SED) of the AGN (e.g., Elvis et al. 1994) suggests that different relations are appropriate for different types of AGNs. The line ratios of the “main” component in the central regions primarily fall within the LIER region of the S II BPT diagram (Figure 18). Since the “main” component excludes primarily shock-heated material, this emission likely results from material photoionized by the AGN accretion disk. However, LIER AGNs were effectively excluded from the sample of Heckman et al. (2004) used to derive the $L_{\text{bol}}$ vs $L_{\text{[OIII]}}$ relationship given in Equation (18) (Kauffmann & Heckman 2009). As a result, we also estimate $L_{\text{bol}}$ using a relation involving the extinction-corrected H$\beta$ luminosity of the material photoionized by the AGN, which is argued to be less sensitive to the SED of the accretion disk and therefore more appropriate for LI(N)ER AGNs (Equation (1) in Netzer 2009):

$$\log L_{\text{bol}} = \log L_{\text{H}\beta} + C + \max \left[ 0.0, 0.31 \left( \frac{L_{\text{[OIII]}}}{L_{\text{H}\beta}} - 0.6 \right) \right],$$

(19)

where $C$ depends on the extinction law. To account for possible variations in the properties of dust along the line of sight, we repeat this analysis using the same two extinction laws.
discussed by Netzer (2009): optical depth $\tau_\lambda \propto \lambda^{-0.7}$ law originally derived for starburst galaxies (e.g., Wild et al. 2007; C = 3.48), and the Cardelli et al. (1989) extinction law for Milky Way–type galaxies (C = 3.75). Again, we use the same two spatial regions used in the previous method. As shown in Table 10, the values of $L_{\text{bol}}$ derived using this method are comparable to those derived using $L_{\text{O III}}$.

To determine whether this AGN could power the outflow observed in MaNGA 1-166919, we compare its properties with those of “known” AGN-driven outflow. For example, Kang & Woo (2018) found that

$$\log \left( \frac{R_{\text{out}}}{\text{kpc}} \right) + 0.028 \log \left( \frac{L_{\text{O III}}}{\text{erg s}^{-1}} \right) = 11.27,$$

where $R_{\text{out}}$ and $L_{\text{O III}}$ are, respectively, the radius and [O III] luminosity of the outflow. The range of $L_{\text{O III}}$ specified in

Table 10 suggests $R_{\text{out}} \sim 1.1$–$1.5$ kpc—in very good agreement with the size of radio lobes detected in the wideband radio images (Table 4; Figure 3), as well as the high-$\tau_{\text{gas}}$ region inferred from the GMOS emission-line spectra (Figure 15), which suggest $R_{\text{out}} \sim 1.0$–$1.7$ kpc. Additional studies have found that the mass outflow rate $M_{\text{out}}$ of an ionized gas outflow is correlated with the bolometric luminosity $L_{\text{bol}}$ of the AGN (e.g., Fiore et al. 2017; Baron & Netzer 2019; A. Deconto-Machado et al. 2021, in preparation). As shown in Figure 26, the mass outflow rate we estimate for this galaxy is significantly higher than the bulk of galaxies with a similar bolometric AGN luminosity. A similar result is observed for the kinetic power $E_{\text{k}}$ of this outflow, which again is higher than other AGNs with similar $L_{\text{bol}}$.

This suggests that the AGN activity in MaNGA 1-166919 results in an outflow different from most AGNs with a similar bolometric luminosity. If the generation of the outflow is physically connected to the accretion of material onto the SMBH, the accretion mode in MaNGA 1-166919 is different from the others. A key distinguishing parameter between “radiative” and “jet” mode accretion onto an SMBH (as discussed in Section 1) is the Eddington ratio $R$, defined to be

$$R \equiv \frac{L_{\text{bol}}}{L_{\text{Edd}}},$$

where $L_{\text{Edd}}$ is the Eddington luminosity of the central SMBH (e.g., Rybicki & Lightman 1986; Heckman & Best 2014 and references therein),

$$L_{\text{Edd}} \approx 3.3 \times 10^{\frac{M_{\text{BH}}}{M_\odot}} L_\odot,$$

where $M_{\text{BH}}$ is the mass of the SMBH.

To estimate $M_{\text{BH}}$, we use the observed correlation between this quantity and the stellar velocity dispersion $\sigma_v$ of the host galaxy’s central bulge (see recent review by Kormendy & Ho 2013). A decomposition of the surface brightness of this galaxy into a bulge and disk component suggests that its bulge has an effective radius $R_{\text{bulge}} = 3''16$, ellipticity $e = 0.16$, and positional angle $\text{PA}_{\text{bulge}} = 110^\circ$ (Table 2 in Simard et al. 2011). We then estimate the central stellar velocity dispersion by

![Figure 26](image-url)
calculating the light-weighted average of $\sigma_4^2 + \nu_2^2$ (both shown in Figure 8) within $R_{\text{bulge}}$ assuming the above geometry, yielding $\sigma_e = 165.2 \pm 0.5 \text{ km s}^{-1}$. The $M_{\text{BH}} - \sigma_e$ relationship derived by van den Bosch (2016),

$$\log \left( \frac{M_{\text{BH}}}{M_\odot} \right) \approx (-4.0 \pm 0.5) + (5.4 \pm 0.2) \log \left( \frac{\sigma_e}{\text{ km s}^{-1}} \right),$$

(23)

yields $M_{\text{BH}} = 7.5^{+0.8}_{-0.5} \times 10^7 M_\odot$, which has an Eddington luminosity (Equation 22))

$$L_{\text{Edd}} = 2.5^{+0.3}_{-0.2} \times 10^{12} L_\odot \approx 9.5^{+0.9}_{-0.7} \times 10^{45} \text{ erg s}^{-1}.$$  

(24)

For the range of $L_{\text{bol}}$ calculated above (Table 10), this implies $R \lesssim 1\%$—suggestive of “jet-mode” accretion onto the SMBH (e.g., Best & Heckman 2012). Recent theoretical work suggests that, for a given AGN luminosity, “jet-mode” accretion results in a more massive and energetic outflow than “radiative-mode” accretion (e.g., Cielo et al. 2018), consistent with the comparison described above (Figure 26).

The different AGN accretion modes are believed to occur in different radio AGNs and host galaxies (e.g., Heckman & Best 2014; Smolčić 2016, and references therein), with radiative-mode accretion typically associated with High Excitation Radio AGNs (HERAGNs), while “jet-mode” accretion is believed to occur in Low Excitation Radio AGNs (LERAGNs). As shown in Table 11, the radio luminosity of this AGN is consistent with an LERAGN (though there are radio-quiet HERAGNs; e.g., Best & Heckman 2012), but the properties of the host galaxy—especially its color—are reminiscent of HERAGNs. This suggests that AGN activity in MaNGA 1-166919 is currently driving the transition of the host galaxy from HERAGN-like to LERAGN-like properties. This requires understanding how the AGN affects the surrounding ISM, which we discuss in Section 4.3.

4.3. Outflow/Host Galaxy Interaction

The appearance of this outflow on the kiloparsec scales probed by the observations described in Sections 2 and 3 is less dependent on its initial geometry and content and more sensitive to the structure of the surrounding ISM (e.g., Wagner et al. 2012, 2013, 2016) and the relative orientation of the outflow to the galactic disk. The offset between the central axis of the outflow (as determined by its radio morphology) and the polar axis of the regularly rotating gas disk projected onto the minor axis of the galaxy (Figure 17) suggests a significant inclination between the two—expected to increase the impact of the jet on the surrounding ISM (e.g., Cielo et al. 2018; Mukherjee et al. 2018; Murthy et al. 2019). This interaction is expected to suppress (“negative feedback”) star formation in some regions and enhance (“positive feedback”) star formation in the other parts of the host galaxy (e.g., Wegner et al. 2015; Dugan et al. 2017; Cielo et al. 2018; Mukherjee et al. 2018).

To understand how this outflow affects its host galaxy, we need to measure the amount and distribution of star formation. This is best done using tracers for the star formation rate (SFR), such as the H$\alpha$ and 1.4 GHz luminosity (e.g., Kennicutt 1998; Kennicutt & Evans 2012 and references therein). As shown in Figure 3, there is little 1.4 GHz emission detected outside the outflow region. Therefore, we can use the nondetection of diffuse 1.4 GHz emission to determine an upper limit on the SFR. The conversion between 1.4 GHz luminosity and SFR is believed to

![Figure 27](image-url)
be (e.g., Murphy et al. 2011; Kennicutt & Evans 2012)

$$\log \left( \frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} \right) \approx \log \left( \frac{L_{1.4 \text{ GHz}}}{\text{erg s}^{-1} \text{ Hz}^{-1}} \right) - 28.20. \quad (25)$$

For the beam size and rms of the 1.4 GHz image (Table 3), a \( < 3 \sigma \) detection of diffuse radio emission in this galaxy corresponds to an upper limit of the SFR surface density \( \mu_{\text{SFR}} \lesssim 0.2 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \). A more sensitive measure of \( \mu_{\text{SFR}} \) is the H\( \alpha \) emission of the “main” component to the ionized gas in this galaxy. We first correct the observed H\( \alpha \) flux for extinction using the spaxel-by-spaxel method described in Sections 4.1.3 and 4.2 for the Balmer decrements shown in Figure 25. To convert the extinction-corrected H\( \alpha \) luminosity of each spaxel into SFR, we use the relation (e.g., Hao et al. 2011; Murphy et al. 2011; Kennicutt & Evans 2012)

$$\log \left( \frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} \right) \approx \log \left( \frac{L_{\text{H} \alpha}}{\text{erg s}^{-1}} \right) - 41.27. \quad (26)$$

We then divide the SFR by the projected area of each spaxel to calculate \( \mu_{\text{SFR}} \). As shown in Figure 27, the most intense regions of star formation in this galaxy have \( \mu_{\text{SFR}} \lesssim 0.025 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \)—significantly lower than the upper limit derived above from the nondetection of radio emission outside the outflow region. Furthermore, as shown in Figure 27, the regions with highest SFR are located near the edge of the outflow. Enhanced star formation near the outflow’s boundary is observed in numerical simulations of such systems, typically concentrated along the jet axis and/or a “ring” around the outflow (e.g., Dugan et al. 2017; Mukherjee et al. 2018)—similar to what is observed here (Figure 27). The region of high SFR \( \sim 3'' \) W of the center of the galaxy is coincident with \( \sim 5\sigma \) emission present in the 6.0 GHz (C-band) image of this source (Figure 27). The flat radio spectrum (\( \alpha \approx 0; \) Section 2.2, Figure 6) detected in this region is suggestive of thermal bremsstrahlung radiation from an \( H \Pi \) region, consistent with the significant SF detected in this region. There is a region of low H\( \alpha \) emission (Figure 27) and low Balmer decrement (Figure 25) located just beyond the W border of the outflow. As mentioned in Section 4.1.2, high-energy photons and particles produced “downstream” of the shock can heat and ionize the pre-shock material—potentially destroying dust molecules (decreasing the Balmer decrement) and fully ionizing the surrounding medium (resulting in a low H\( \alpha \) luminosity if the gas is too hot to recombine).

To assess the global impact of this outflow on star formation in the host galaxy, we compare its total SFR of \( \text{SFR} \approx 3 M_\odot \text{ yr}^{-1} \)—consistent with the SFRSED \( = 3.7 M_\odot \text{ yr}^{-1} \) derived from an independent analysis of its SED (GSWLC-211 catalog; Salim et al. 2018). For star-forming galaxies, the SFR is thought to be strongly dependent on the galaxy’s stellar mass \( M_*, \) with an analysis of star-forming galaxies observed by the SDSS suggesting that (e.g., Elbaz et al. 2007 and references therein)

$$\text{SFR} \sim (5-16) \left( \frac{M_*}{10^{11} M_\odot} \right)^{0.77} M_\odot \text{ yr}^{-1}. \quad (27)$$

For the measured \( M_* \approx 6 \times 10^{10} M_\odot \) of MaNGA 1-166919, this relation suggests SFR \( \sim 3.5-11 M_\odot \text{ yr}^{-1} \)—the lower range of which is consistent with the value derived above. This suggests that the radio-quiet AGN activity at the center of this galaxy has not (yet) quenched star formation, as observed in other such galaxies (e.g., Comerford et al. 2020), and the location of this galaxy in the “Green Valley” of the color–magnitude diagram is due in part to extinction.

5. Summary and Conclusions

In this paper, we present a detailed analysis of the radio (Section 2) and optical (Section 3) properties of MaNGA 1-166919 to determine the origin, content, and impact of its kiloparsec-scale outflow. Together, these data allow us to measure the properties of the central AGN (Section 4.2), the kinematics of this outflow (Section 4.1.2), the energetics of its relativistic (Section 4.1.1) and ionized gas components (Section 4.1.3), and its impact on its host galaxy. Such information is needed to develop a complete model for how the AGN affects its host galaxy.

As shown in Figure 28, our results indicate that the center of this galaxy hosts a low-luminosity AGN powered by low-level \( L_{\text{bol}} \lesssim 0.01 L_{\text{Edd}} \) accretion onto the SMBH at its center (Section 4.2). The material ejected during this accretion drives “biconical,” \( \gtrsim 100-200 \text{ km s}^{-1} \) shocks (Section 4.1.2) into the surrounding medium responsible for producing the observed relativistic electrons (Section 2.2) and ionized gas (Section 4.1.2), which have comparable energies (\( \sim 10^{54}-10^{55} \text{ erg} \); Tables 8 and 9). Furthermore, the kinetic power and mass outflow rate of the ionized gas are observed to be higher than those of other AGNs with comparable \( L_{\text{bol}} \) (Figure 26), suggesting that low Eddington accretion may be more efficient in producing outflows than their high-Eddington counterparts. Lastly, we detect regions of both enhanced and diminished star formation around the outflow.
Figure 27), suggesting that it results in “positive” and “negative” feedback in the host. However, currently the global SFR of this galaxy is consistent with the SFR of star-forming galaxies with similar stellar masses (Section 4.3)—though the relatively small size and young age (∼ 6 Myr) of the outflow suggest that it may, in the future, more profoundly impact star formation in its host.

Such a complete picture of the outflow-mediated interaction between the AGN and its surroundings in MaNGA 1-166919 is only possible by analyzing spatially resolved, multiwavelength data. This is now possible for large samples of outflow galaxies, and similar analyses will allow one to determine how the properties and impact of such outflows are related to the properties of the central AGN, host galaxy, and age of the systems—critical for developing a complete model for the role outflows play in galaxy evolution.

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Facilities: VLA, Sloan, Gemini.

Software: CASA (McMullin et al. 2007), LMFIT (Newville et al. 2016), AstroPy (Astropy Collaboration et al. 2013, 2018), MIRIAD (Sault et al. 1995).

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