The Physics of the Coronal Line Region for Galaxies in MaNGA

JAMES NEGUS,1 JULIA M. COMERFORD,1 FRANCISCO MÜLLER SÁNCHEZ,2 JORGE K. BARRERA-BALLESTEROS,3 NIV DRORY,4 SANDRO B. REMBOLD,5,6 AND ROGEMAR A. RIFFEL5,6

1The University of Colorado Boulder, 2000 Colorado Avenue, Boulder, CO 80309, USA
2The University of Memphis, 3720 Alumni Avenue, Memphis, TN 38152, USA
3Instituto de Astronomía, Universidad Nacional Autónoma de México, A.P. 70-264, 04510 México, D.F., México
4McDonald Observatory, The University of Texas at Austin, 1 University Station, Austin, TX 78712, USA
5Departamento de Física, CCNE, Universidade Federal de Santa Maria, 97105-900, Santa Maria, RS, Brazil
6Laboratório Interinstitucional de e-Astronomia - LineA, Rua Gal. José Cristino 77, Rio de Janeiro, RJ - 20921-400, Brazil

ABSTRACT

The fundamental nature and extent of the coronal line region (CLR), which may serve as a vital tracer for Active Galactic Nucleus (AGN) activity, remain unresolved. Previous studies suggest that the CLR is produced by AGN-driven outflows and occupies a distinct region between the broad line region and the narrow line region, which places it tens to hundreds of parsecs from the galactic center. Here, we investigate 10 coronal line (CL; ionization potential $\gtrsim 100$ eV) emitting galaxies from the SDSS-IV MaNGA catalog with emission from one or more CLs detected at $\geq 5\sigma$ above the continuum in at least 10 spaxels - the largest such MaNGA catalog. We find that the CLR is far more extended, reaching out to 1.3 - 23 kpc from the galactic center. We cross-match our sample of 10 CL galaxies with the largest existing MaNGA AGN catalog and identify 7 in it; two of the remaining three are galaxy mergers and the final one is an AGN candidate. Further, we measure the average CLR electron temperatures to range between 12,331 K - 22,530 K, slightly above the typical threshold for pure AGN photoionization ($\sim 20,000$ K) and indicative of shocks (e.g., merger-induced or from supernova remnants) in the CLR. We reason that ionizing photons emitted by the central continuum source (i.e. AGN photoionization) primarily generate the CLs, and that energetic shocks are an additional ionization mechanism that likely produce the most extended CLRs we measure.

Keywords: Active galactic nuclei (16), Photoionization(2060), Emission line galaxies (459).

1. INTRODUCTION

An Active Galactic Nucleus (AGN), fueled by accretion onto its central supermassive black hole (SMBH; $M_{BH} > 10^6 M_\odot$), is one of the most energetic phenomena in the observable universe; it can generate a bolometric luminosity $> 10^{46}$ erg s$^{-1}$, which can outshine the collective light of an entire host galaxy. The most powerful can also heat and photoionize gas tens of kpc away (e.g., Heckman et al. 1981; McCarthy et al. 1987; Keel et al. 2012; Liu et al. 2013; Comerford et al. 2017).

Moreover, feedback - the mechanism by which AGN processes (e.g., photoionization, radio jets, and winds) impact nearby matter - has been shown to influence the evolution of the host galaxy (e.g., Fabian 2012; Johnson et al. 2015; Kalfountzou et al. 2017; Rudie et al. 2017). On one hand, AGN feedback may quench star formation and limit the host galaxy’s growth (e.g., Hopkins et al. 2008). On the other, AGN feedback can impart extreme pressure on the neighboring interstellar medium and generate high density conditions favorable for star formation (e.g., Silk 2005).

To unravel the dynamics of AGN-galactic co-evolution, reliable AGN identification is an essential first step. To address this, we consider the Unified Model of AGNs (Antonucci 1993). In this framework, an AGN is classified as either Type I or Type II. Type I are viewed pole-on and are observed to have broad (FWHM $> 1,000$ km s$^{-1}$) and narrow (FWHM $< 1,000$ km s$^{-1}$) emission lines, whereas Type II are viewed edge-on and are observed to only have narrow emission lines. The physical structures that correspond to these regions are the broad line region (BLR) and the narrow line region (NLR), respectively.
The NLR is the largest observable structure in the UV, optical, and near-IR that is directly impacted by the ionizing radiation from an AGN. Measurements from a Hubble Space Telescope snapshot survey, in addition to ground based [OIII] observations, suggest this region extends hundreds of pc to several kpc from the nuclear core (e.g., Mulchaey et al. 1996; Schmitt et al. 2003; Müller-Sánchez et al. 2011). However, the NLR surrounding an AGN may feature active star formation, which can also produce narrow lines (e.g., [NII] λ6584 and [OIII] λ5007; see Santoro et al. 2016). As a result, the NLR is not always an ideal tracer for exclusive AGN activity.

Comparatively, the BLR resides much closer to the SMBH (within ∼ 0.1 kpc; e.g., Laor 2004; Czerny, & Hryniewicz 2011). The enhanced cloud velocities found in this region, near the accreting SMBH, provide reliable signatures for nuclear AGN activity. However, the BLR is not spatially resolved in most existing spectroscopic surveys. Further, for Type II AGN, the BLR is often obscured by a dusty torus that can attenuate optical and UV emission (e.g., Hernández-García et al. 2019).

For most AGNs, though, highly ionized species of gas with ionization potentials (IPs) ≥ 100 eV (termed “coronal lines”; CLs; e.g., [FeVII] and [NeV]) are proposed to exist in the nuclear region between the compact BLR and the more extensive NLR (e.g., Seyfert 1943; Gildden et al. 2016). These lines require extremely high energies for production, above the limit of stellar emission (55 eV; Haehnelt et al. 2001), likely trace the strong ionizing continuum of an AGN (Seyfert 1943), and have been linked to AGN-driven outflows (e.g., Müller-Sánchez et al. 2011; Mazzalay et al. 2013; Rodríguez-Ardila & Fonseca-Faria 2020; Cerqueira-Campos et al. 2021). As a result, detecting CLs may help identify AGNs and AGN-driven outflows in large spectroscopic galactic surveys, which are essential for understanding the influence of AGN feedback on the host galaxy.

CLs have been observed in the spectra of some AGNs; however, their nature and physical extent are still not very well understood (e.g., Penston et al. 1984; Oliva et al. 1994; Prieto et al. 2005; Müller-Sánchez et al. 2011). Prior studies (e.g., Rodríguez-Ardila et al. 2011) suggest that they reside in a distinct zone of extremely hot and collisionally ionized plasma between the BLR and the NLR, in the coronal line region (CLR). Further, Mazzalay et al. (2010) analyzed the structure and physical properties of the CLR for 10 pre-selected AGNs. They used the Hubble Space Telescope/Space Telescope Imaging Spectrograph to study [NeV] λ3427, [FeVII] λ3586, λ3760, λ6086, [FeX] λ6374, [FeXIV] λ5303, [FeXI] λ7892, and [SXII] λ7611 emission in their sample. They determined that the CLR extends between 10 - 230 pc from the nuclear core (similar to Müller-Sánchez et al. 2011 and Riffel et al. 2021). They also measured CLR electron temperatures to vary between 10,000 K - 20,000 K (below the pure AGN photoionization threshold of ∼ 20,000 K) and compared the ionization properties of the CLR to varying photoionization and shock models (e.g., Binette et al. 1996; Dopita & Sutherland 1996). They concluded that AGN photoionization from a central source is the sole physical mechanism producing the lines in their sample. Moreover, Gelbord et al. (2009) scanned the sixth Sloan Digital Sky Survey (SDSS) data release (Adelman-McCarthy et al. 2008) and investigated the CLR in 63 AGNs with [FeX] λ6374 emission (IP = 233.60 eV), without an a priori assumption that emission would only be found in AGNs. They also studied [FeXI] λ7892 (IP = 262.10 eV) and [FeVII] λ6086 (IP = 99.10 eV) emission in these AGNs. They determined that photoionization is also the source of the CLs (inferred using X-ray observations from Rosat; Voges et al. 1999, 2000). The authors then measured the extent of the CL emitting clouds in their sample and found that the lines with higher IPs (e.g., [FeX] and [FeXI]) feature larger FWHM values, consistent with the lines occupying a region closest to the BLR, at a scale comparable to the dusty torus. They determined that the lower IP [FeVII]-emitting regions feature narrower lines and likely merge with the traditional NLR.

Here, we use the SDSS’s Mapping Galaxies at Apache Point Observatory (MaNGA) integral field unit (IFU) catalog, from the survey’s fifteenth data release in its fourth phase (SDSS-IV), to further evaluate the ionization mechanism(s) of the CLR and to better understand the relationship between CLs and AGN activity. Large IFU spectroscopic surveys are critical for studying CLs because they provide spatially resolved galactic spectra that can trace the full extent of the CLR. Additionally, MaNGA has observed ∼ 10,000 nearby galaxies, and the eighth data release of the catalog contains 6,263 unique galaxies, making it one of the largest IFU survey of galaxies currently available. With our custom pipeline, we detect 10 galaxies with emission from one or more CLs detected at ≥ 5σ above the continuum in at least 10 spaxels (∼ 0.16% of the sample), which makes it the most extensive such catalog of MaNGA CL galaxies to date.

This paper is outlined as follows: Section 2 details the technical components of the SDSS-IV MaNGA survey and its data pipeline, Section 3 describes the methodology we use to build the CL catalog and to analyze the physical properties of the CLR, Section 4 reviews our results, Section 5 provides interpretations of our findings,
and Section 6 includes our conclusions and intended future work. All wavelengths are provided in vacuum and we assume a $\Lambda$CDM cosmology with the following values: $\Omega_M = 0.287$, $\Omega_{\Lambda} = 0.713$, and $H_0 = 69.3$ km s$^{-1}$ Mpc$^{-1}$.

2. OBSERVATIONS

2.1. The MaNGA Survey

To conduct our analysis, we utilize the largest IFU spectroscopic survey of galaxies to date, the SDSS-IV MaNGA catalog (Bundy et al. 2015; Drory et al. 2015; Law et al. 2016; Yan et al. 2016; Blanton et al. 2017; Wake et al. 2017). MaNGA began taking data in 2014 using the SDSS 2.5 m telescope (Gunn et al. 2006), and has logged the spectra for $\sim 10,000$ nearby galaxies (0.01 $< z < 0.15$; average $z \approx 0.03$) with stellar mass distributions between $10^9$ $M_\odot$ and $10^{12}$ $M_\odot$. The spectra were taken at wavelengths between 3622 Å - 10354 Å, with a typical spectral resolution of $\sim 2000$ and a velocity resolution of $\sim 60$ km s$^{-1}$ (see Bundy et al. 2015).

MaNGA relies upon dithered observations using IFU fiber-bundles, assembled individually from the Baryon Oscillation Spectroscopic Survey Spectrograph (Smeee et al. 2013). The IFUs are grouped into hexagonal grids with field-of-view (FoV) diameters between 12.$''$5 to 32.$''$5 - each distribution is matched to the apparent size of the target galaxy (Bundy et al. 2015). The exact configuration of the fiber-fed system consists of two 19-fiber IFUs (12.$''$5 FoV), four 37-fiber IFUs (17.$''$5 FoV), four 61-fiber IFUs (22.$''$5 FoV), four 91-fiber IFUs (27.$''$5 FoV), and five 127-fiber IFUs (32.$''$5 FoV). The resulting pluggable science and calibration IFUs generate galactic spectroscopic maps out to at least 1.5 times the effective radius; the typical galaxy is mapped out to a radius of 15 kpc. Each MaNGA spatial pixel, or spaxel, covers 0.$''$5 $\times$ 0.$''$5 and the average full-width half maximum (FWHM) of the on-sky point spread function (PSF) is 2.$''$5, which corresponds to a typical spatial resolution of 1 - 2 kpc (Drory et al. 2015).

2.2. MaNGA Data Reduction Pipeline

The MaNGA Data Reduction Pipeline (DRP) generates flux calibrated and sky-subtracted data for each galaxy in a FITS file format that is used for scientific analysis (Law et al. 2016). The resulting DRP data product is run through MaNGA’s Data Analysis Pipeline (DAP: Westfall et al. 2019) that provides spectral modeling and science data products, such as stellar kinematics (velocity and velocity dispersion), emission-line properties (kinematics, fluxes, and equivalent widths), and spectral indices (e.g., D4000 and Lick indices). The data products are publicly released periodically as MaNGA Product Launches (MPLs).

To construct our catalog of CL galaxies in MaNGA, we use MaNGA’s eighth data release (MPL-8), which contains data for 6,263 unique galaxies.

3. ANALYSIS

3.1. Spectral Fitting

The MaNGA DAP provides fits for prominent emission lines (e.g., Hα, Hβ, and [OIII] $\lambda 5007$). However, it does not offer fits for the CLs of interest in this paper (Table 1), which we select due to their high ionization potentials ($\gtrsim 100$ eV), their presence within the wavelength range of MaNGA, and for comparison with prior CLR studies that featured these lines (e.g., Korista, & Ferland 1999; Appenzeller, & Wagner 1991; Oliva et al. 1994; Rodriguez-Ardila et al. 2006; Mullaney et al. 2009; Mazzalay et al. 2010; Rose et al. 2015). As a result, we construct a custom pipeline to scan for [NeV] $\lambda 3347$, $\lambda 3427$, [FeVII] $\lambda 3586$, $\lambda 3760$, $\lambda 6086$, and [FeX] $\lambda 6674$ emission at $\geq 5\sigma$ above the background continuum in the 6,623 galaxies in MPL-8. We use this high 5σ threshold to ensure we identify unambiguous CL emission.

We first access the DRP to extract the necessary data cubes for each MaNGA galaxy. The data cubes provide a spectrum for each individual spaxel across the FoV of each galaxy (spaxel arrays vary between 32 $\times$ 32 spaxels to 72 $\times$ 72 spaxels, depending on IFU configuration). We then use the spectroscopic redshifts of each galaxy, adopted from the NASA Sloan Atlas catalogs using single-fiber measurements (Blanton et al. 2011), to shift the spectra to rest vacuum wavelengths and to impose a minimum redshift threshold ($z_{\text{min}}$) for CLs near the lower wavelength limit of MaNGA ($3622$ Å; Table 1). In some instances, CL rest wavelengths are redshifted out of MaNGA’s spectral range.

Once the spectra are wavelength corrected, we analyze each individual spaxel for each galaxy and perform a polynomial fit on a narrow spectral region, $\sim 300$ Å wide, of continuum near the CL to model the background stellar continuum and subtract it. We then attempt a single Gaussian fit on a $\sim 30$ Å region centered on the rest wavelengths of the CLs. This wavelength range was shown to sufficiently capture the full extent of CL emission in our preliminary scans, even for CLs with FWHM $> 1,000$ km s$^{-1}$. We subsequently determine the root mean square (RMS) flux of two continuum regions ($\sim 60$ Å wide) that neighbor each target CL, free of absorption or emission lines, and require that CL amplitudes are detected at $\geq 5\sigma$ above the mean RMS flux values in these continuum regions. We consider the spectral resolution of MaNGA ($R = \lambda/\Delta \lambda \sim 1400$ at $3600$ Å; $R \sim 2000$ at $6000$ Å; Smeee et al. 2013) to eliminate fits with $\Delta \lambda < 2.4$ Å (for [NeV] $\lambda 3347$, $3427$), $< 2.6$ Å (for
Table 1. Target CLs

| Emission Line | Wavelength (Å) | IP (eV) | \( z_{\text{min}} \) |
|---------------|---------------|----------|-----------------|
| \([\text{NeV}]\) | 3347 | 126.22 | 0.088 |
| \([\text{NeV}]\) | 3427 | 126.22 | 0.063 |
| \([\text{FeVII}]\) | 3586 | 125.0 | 0.016 |
| \([\text{FeVII}]\) | 3760 | 125.0 | - |
| \([\text{FeVII}]\) | 6086 | 125.0 | - |
| \([\text{FeX}]\) | 6374 | 262.1 | - |

Note: Columns are (1) emission line, (2) rest wavelength, (3) ionization potential, and (4), minimum redshift value required for MaNGA detection.

\[ \text{FeVII} \lambda 3586, 3760 \), and \(< 3 \text{ Å} \ (\text{for [FeVII} \lambda 6086 \) and \([\text{FeX}] \lambda 6374; \text{we do not detect the [FeX} \lambda 6374 \text{line using this criteria). We also require that each galaxy in our catalog features} > 10 \text{ CL-emitting spaxels to ensure we are detecting sources with definitive CL emission. We show an example of a single Gaussian fit for the [FeVII} \lambda 3760 \text{ line in Figure 1.} \]

3.2. Coronal Line Flux Maps

We use flux maps to trace the strength and distribution of the CLs in the CLR. To generate these maps, we use the integrated CL flux value from each spaxel for each CL galaxy. We show an example flux map in Figure 2.

For each MaNGA observation, the photometric center corresponds to the galactic center (Yan et al. 2016). We use this position and the galaxy’s inclination angle to determine the de-projected galactocentric distance of each CL spaxel. The MaNGA DAP provides the ratio of the semi-minor to semi-major axes (b/a) for each galaxy, and we use this value to determine the cosine of each galaxy’s inclination angle (i): \( \cos(i) = \frac{b}{a} \). The de-projected distance of each CL spaxel to the center of the galaxy is then measured by:

\[
D_{\text{Spaxel}} = \sqrt{(x - x_{\text{center}})^2 + \left((y - y_{\text{center}}) \ast \cos(i)\right)^2}
\]

Next, we convert the spaxel distances to a physical unit (kpc) using the astropy.cosmology Python package. The resulting value corresponds to the distance of each CL emitting spaxel, and the coronal line distance (CLD) corresponds to the distance of each galaxy’s most extended CL-emitting spaxel (from the galactic center).

3.3. Coronal Line Intensity Profiles

We explore CL intensity as a function of de-projected galactocentric distance to help determine the ionization mechanism(s) producing the CLs. We consider the study conducted by Yan & Blanton (2012), which analyzed ionization sources in galaxies with spatially extended emission line regions. The authors measured integrated flux profiles for a system of ionizing sources and found that the strength of ionizing flux, as a function of galactocentric distance, should decay with a power law index of \( \alpha = -2 \) (i.e. obey the inverse square law) for pure AGN photoionization. They used this model to differentiate AGN photoionization from other sources (e.g., shocks). Tadhunter (2002) also used this model to show that jet-induced shocks primarily ionize extended emission line regions along the axis of radio jets for several AGNs, and that AGN photoionization dominates within the nuclear regions. We fit a power law for each CL galaxy, and measure the best-fit power law index to help determine the ionization source(s) for the CLs. We present a sample power-law fit in Figure 3.

3.4. Stellar Shock Diagnostics

We consider the role of supernova remnant (SNR) shocks in our analysis to determine their role in the production of CL emission. The first SNR identified in an external galaxy was observed by Mathewson, & Clarke (1972, 1973). The authors relied upon the strength of the [SII] \( \lambda \lambda 6717, 6731 \) doublet with respect to the H\( \alpha \) line to differentiate SNR shocks from photoionized regions. Dodorico (1978) and Dodorico et al. (1980) refined this relation empirically, and determined that regions with [SII] \( \lambda \lambda 6717 + 6731 / \text{H}\( \alpha \) > 0.4 feature SNR shocks. The use of this threshold is widely adopted to
identify SNRs (e.g., Raymond 1979; Dopita et al. 1984; Levenson et al. 1995; Blair et al. 2012; Lee, & Lee 2014), and we employ it in our analysis. For each CL galaxy, we also divide the number of CL-emitting spaxels that feature SNRs by the total number of CL-emitting spaxels. The resulting value is the fraction of SNRs in each galaxy’s CLR (“SNR Frac” in Table 2). We calculate this parameter to determine if elevated fractions of SNRs correspond to enhanced CL production, which would suggest that SNR shocks play a major role in the production of CLs. The MaNGA DAP provides flux measurements for the [SII] λ6717, [SII] λ6731, and Hα lines.

3.5. Electron Temperature and Electron Number Density Diagnostics

The electron temperatures and electron number densities of emission line regions provide direct insight into their ionization source(s). Specifically, temperatures between 10,000 K - 20,000 K are typical for photoionization equilibrium, as opposed to collisional shocks, for example, which can induce temperatures up to 10^6 K (e.g., Osterbrock 1984). Furthermore, number densities on the order of ne ≈ 10^2 - 10^4 cm^{-3} are typical of the NLR; ne > 10^9 cm^{-3} for the BLR (e.g., Koski 1978; Peterson 1997).

We measure these parameters for the CL galaxies in our sample using Pyneb, a Python package that evolved from the IRAF package Nebular (Shaw, & Dufour 1995; Shaw et al. 1998; Luridiana et al. 2015). Pyneb’s getCrossTemDen routine iterates over the temperature sensitive flux ratio [OIII] (λ5007 + λ4959)/λ4363 and the density sensitive flux ratio [SII] λ6717/ λ6731 to provide self-consistent temperature and density values (see Osterbrock, & Ferland 2006). For intermediate densities (ne ≈ 10^3 cm^{-3}), which are found beyond the BLR (e.g., Blandford et al. 1990):

\[
\frac{j_{\lambda 6717}}{j_{\lambda 6731}} \propto \frac{n_e}{n_e^2} \propto n_e^{-1}
\]

where j is the emissivity of each line and ne is the electron number density. For the temperature sensitive ratio (e.g., Peterson 1997):

\[
\frac{F(\lambda 4959 + \lambda 5007)}{F(\lambda 4363)} \approx \frac{7.33 \exp (3.29 \times 10^4/T_e)}{1 + 4.5 \times 10^{-4} n_e T_e^{-\frac{1}{2}}} \quad (3)
\]

where F is the flux of each line and T_e is the electron temperature.

We measure these line ratios for each CL emitting spaxel and use getCrossTemDen to determine the CLR temperatures and densities in our sample. The MaNGA DAP provides flux values for the [OIII] λ4959, [OIII] λ5007, [SII] λ6717, and [SII] λ6731 lines. However, it does not provide flux values for the [OIII] λ4363 line. We thus modify our spectral fitting routine outlined in Section 3.1 to measure [OIII] λ4363 in the CL emitting spaxels, if present. We note that the [OIII]
The λ4363 line is often blended with the Hγ line; as a result, we use a double Gaussian fit, where appropriate, to isolate [OIII] λ4363 emission. We show an example of a double Gaussian fit on the Hγ and [OIII] λ4363 lines in Appendix A.

3.6. Galaxy Morphology

To determine the morphological diversity of our sample and to uncover the link, if any, between CL emission and galaxy type, we use the MaNGA Morphologies from Galaxy Zoo value-added catalog, which features data from Galaxy Zoo 2 (GZ2; Willett et al. 2013). GZ2 is a citizen science campaign with more than 16 million visual morphological classifications for > 304,000 galaxies in SDSS.

We use the weighted vote fraction (outlined in Willett et al. 2013), which accounts for voter consistency, to identify CL galaxies as either elliptical (“smooth”; “E” in Table 2) or spiral (“features or disks”; “S” in Table 2). We also use this fraction to determine if a CL galaxy is in the process of merging (“m” in Table 2). We require a weighted vote fraction ≥ 50% for each morphological classification. 4/10 CL galaxies in our sample do not have a GZ2 morphological classification and their morphologies are not apparent from a visual inspection (labeled ‘-‘ in Table 2).

3.7. AGN Bolometric Luminosity

Fueled by the accretion of gas onto supermassive black holes, AGNs emit their energy across the entire electromagnetic spectrum. The AGN bolometric luminosity can thus be a useful gauge for tracing the strength of their emission. If the bulk of CL emission is powered by AGN activity, we anticipate that the AGN bolometric luminosities of the CL galaxies will scale with their CL luminosities.

We determine the AGN bolometric luminosity for each CL-emitting spaxel using the [OIII] λ5007 flux values provided by the MaNGA DAP, and the procedure outlined in Pennell et al. (2017), which assumes [OIII] λ5007 emission comes from the AGN:

\[
\log \left( \frac{L_{\text{bol}}}{\text{ergs}^{-1}} \right) = (0.5617 \pm 0.0978) \log \left( \frac{L_{[\text{OIII}]}}{\text{ergs}^{-1}} \right) + (21.186 \pm 4.164) \tag{4}
\]

4. RESULTS

In this section, we review the strength and spatial distribution of the CLs in our sample, investigate the role of SNR shocks in the production of the CLs, and present electron temperature, electron density, and AGN bolometric luminosity measurements for the CLR. We then compare our sample with the largest existing MaNGA AGN catalog to determine if CL emission is unambiguously linked to AGN activity. Finally, we cross-match our sample with three existing MaNGA BPT AGN catalogs to help uncover if CLs can help identify AGNs in large spectroscopic surveys.

Overall, we detect 10 CL galaxies in our scan of MaNGA’s MPL-8 (0.16% of the catalog) with CL emission detected at ≥ 5σ above the continuum in > 10 spaxels. This detection rate suggests that we will identify ~ 16 CL galaxies in the full survey of ~ 10,000 galaxies. We provide the entire sample of CL galaxies in Table 2.

We measure the CLR to extend between 1.3 - 23 kpc from the galactic center, with an average distance of 6.6 kpc (distances traditionally associated with the NLR). In Appendix B, we present each CL galaxy’s [OIII] λ5007 flux map to demonstrate the similar physical scales (several kpc) of the CLR and NLR.

Further, to ensure that CL emission is sufficiently resolved for each CL galaxy, we investigate the instrument PSF (∼ 2.′5 for MaNGA). We determine that the PSF for our sample varies between 536 pc to 3.2 kpc, with an average PSF of 1.7 kpc. 6/10 CL galaxies show well resolved and continuous emission beyond the instrument PSF. The remaining four CL galaxies, J0752 ([NeV] λ3427), J1535 ([FeII] λ6086), J1714 ([NeV] λ3347), and J2051 ([NeV] λ3427) lack continuous CL emission within a 2.′5 x 2.′5 FoV. As a result, we consider the CLRs within these galaxies to be slightly below the instrument PSF, and not spatially resolved in our analysis. The CL emission in these galaxies may indeed still be spatially resolved (e.g., CL emission may be oriented along an ionization cone); however, we reason that the CLDs we present for these galaxies are upper estimates.

4.1. The Strength and Distribution of the CLs

Extended emission line regions (1 kpc to 100 kpc from the galactic center) surrounding AGNs are expected to feature a variety of ionization mechanisms, which include photoionization and shocks (e.g., Tadhunter 2002). To determine the role that these ionization sources play in the production of CLs, we explore the strength and distribution of the CLs.

4.1.1. [NeV] λ3347, λ3427

The [NeV] λ3347 line is produced from the same excitation level as [NeV] λ3427, but its relative flux (100 × CL Flux/Flux (Lyun); based on a composite quasar spectrum from Vanden Berk et al. 2001) is 0.118 ± 0.008, approximately one-third of the [NeV] λ3427 line (0.405 ± 0.012; Vanden Berk et al. 2001). As a result, we expect to detect the stronger [NeV] λ3427 line in a higher fraction of MaNGA galaxies, which we do.
We measure $\text{[NeV]} \lambda 3427$ emission in six galaxies from MPL-8: J1614, J1714, J0736, J0752, J2051, and J2116. In two of these galaxies, J1614 and J1714, we also measure $\text{[NeV]} \lambda 3347$ emission. We present $\text{[NeV]} \lambda 3347, \lambda 3427$ flux maps for J1614 ($z = 0.13$; no G22 classification) and J1714 ($z = 0.09$; elliptical) in Figure 4. For J1614, we identify extended $\text{[NeV]} \lambda 3347$ emission out to 5.9 $\pm$ 2.9 kpc from the galactic center; 8.3 $\pm$ 3.9 kpc for $\text{[NeV]} \lambda 3427$. For J1714, we measure $\text{[NeV]} \lambda 3347$ emission out to 4.3 $\pm$ 2.2 kpc from the galactic center; 3.7 $\pm$ 2.2 kpc for $\text{[NeV]} \lambda 3427$. We show the $\text{[NeV]} \lambda 3427$ flux maps for J0736 ($z = 0.12$; no G22 classification; CLD = 5.4 $\pm$ 2.7 kpc), J0752 ($z = 0.12$; no G22 classification; CLD = 7.1 $\pm$ 2.7), J2051 ($z = 0.11$; spiral; CLD = 2.5 $\pm$ 2.5 kpc), and J2116 ($z = 0.08$; spiral; CLD = 4.3 $\pm$ 1.9 kpc) in Figure 5. In each galaxy, $\text{[NeV]} \lambda 3347, \lambda 3427$ emission is predominantly concentrated within the galactic interior (within $2.9''$ throughout the paper), suggesting that a central source governs CL production in these galaxies. We cross-match these galaxies with the largest existing MaNGA AGN catalog (“MaNGA AGN catalog”; Comerford et al. 2020); AGN classifications determined using WISE mid-infrared color cuts, Swift/BAT hard X-ray observations, NVSS/ FIRST 1.4 GHz radio observations, and SDSS broad emission lines; Section 5), and determine that all $\text{[NeV]} \lambda 3347, \lambda 3427$ galaxies are classified as AGNs.

### Table 2. MaNGA CL Galaxies

| Name                  | SDSS       | Redshift | Mor. | Detected | $L_{\text{bol}}$ | $L_{\text{CL}}$ | CLD   | SNR  | Frac | $\alpha$ |
|-----------------------|------------|----------|------|----------|------------------|-----------------|-------|------|------|----------|
| J073623.13+392617.7   | 0.12       | -        | [NeV]| $\lambda 3427$ | 21.5$\pm$0.1    | 5.2$\pm$0.4     | 5.4$\pm$1.1 | -    | -0.6$\pm$0.1 |
| J075217.84+193542.2   | 0.12       | -        | [NeV]| $\lambda 3427$ | 49.0$\pm$0.2    | 9.8$\pm$0.4     | 7.1$\pm$1.1 | 1.0  | -1.5$\pm$0.1  |
| J090659.46+204810.0   | 0.11       | S(m)     | [FeVII] | $\lambda 3586$ | 4.9$\pm$0.1     | 3.7$\pm$0.03    | 10.0$\pm$1.0 | 0.36 | -0.46$\pm$0.04 |
| J134918.20+240544.9   | 0.02       | -        | [FeVII] | $\lambda 3760$ | 18.4$\pm$0.1    | 7.2$\pm$0.01    | 7.0$\pm$0.2 | 0.38 | -0.84$\pm$0.03 |
| J145420.10+470022.3   | 0.13       | E(m)     | [FeVII] | $\lambda 3760$ | 0.75$\pm$0.09   | 2.30$\pm$0.02   | 23.0$\pm$1.1 | 0.5  | 0.2$\pm$0.1   |
| J153552.40+575409.4   | 0.03       | E        | [FeVII] | $\lambda 6086$ | 7.76$\pm$0.04   | 0.23$\pm$0.01   | 1.3$\pm$0.3  | -    | -1.3$\pm$0.2  |
| J161413.20+260416.3   | 0.13       | -        | [NeV] | $\lambda 3347$ | 78.6$\pm$0.3    | 5.7$\pm$0.3     | 5.9$\pm$1.2  | -    | -0.6$\pm$0.1  |
| J161413.20+260416.3   | -          | -        | [NeV] | $\lambda 3427$ | 126.0$\pm$0.3   | 23.0$\pm$0.3    | 8.3$\pm$1.2  | -    | -1.2$\pm$0.1  |
| J171411.63+575834.0   | 0.09       | E        | [NeV] | $\lambda 3347$ | 5.5$\pm$0.1     | 0.95$\pm$0.10   | 4.3$\pm$0.9  | -    | -0.9$\pm$0.2  |
| J171411.63+575834.0   | -          | -        | [NeV] | $\lambda 3427$ | 9.7$\pm$0.1     | 5.5$\pm$0.1     | 3.7$\pm$0.9  | -    | -0.9$\pm$0.1  |
| J205141.54+005135.4   | 0.11       | S        | [NeV] | $\lambda 3427$ | 4.3$\pm$0.1     | 0.75$\pm$0.03   | 2.5$\pm$1.0  | -    | -0.6$\pm$0.1  |
| J211646.34+110237.4   | 0.08       | S        | [NeV] | $\lambda 3427$ | 41.4$\pm$0.1    | 3.1$\pm$0.1     | 4.3$\pm$0.8  | 1.0  | -1.2$\pm$0.1  |

Note: Columns are (1) CL galaxy SDSS name, (2) redshift from the NASA Sloan Atlas catalogs using single-fiber measurements (Blanton et al. 2011), (3) Galaxy Zoo 2 morphology (if available), (4) detected CL in the galaxy, (5) AGN bolometric luminosity estimated from [OIII] measurements (Pennell et al. 2017), (6) CL luminosity measured in this work, (7) galactocentric distance of the most extended CL-emitting spaxel, (8) fraction of SNRs in the CLR (if available), and (9) slope of the CL intensity profile.

Vanden Berk et al. (2001) analyzed a homogeneous data set of over 2,200 quasar spectra from SDSS and created a variety of composite spectra from this sample. The authors determined that the relative fluxes for [FeVII] $\lambda 3760, \lambda 3586, \lambda 6086$ are 0.078 $\pm$ 0.007, 0.100 $\pm$ 0.011, and 0.113 $\pm$ 0.016, respectively ($\sigma = 0.018$), which feature significantly less scatter than the [NeV] $\lambda 3347, \lambda 3427$ lines ($\sigma = 0.20$). As a result, we expect to find a similar fraction of [FeVII] galaxies that emit each line, which we do.

We measure [FeVII] emission in four MPL-8 galaxies: J1454 ([FeVII] $\lambda 3760$; $z = 0.13$; elliptical; merger), J1349 ([FeVII] $\lambda 3760$; $z = 0.02$; no G22 classification), J0906 ([FeVII] $\lambda 3586$; $z = 0.11$; spiral; merger), and J1535 ([FeVII] $\lambda 6086$; $z = 0.03$; spiral). We present the flux distributions for these galaxies in Figure 5.

Previous studies (e.g., Osterbrock 1981; De Robertis & Osterbrock 1984, 1986; Filippenko & Halpern 1984) posit that the CLR lies within a transition zone between the BLR ($\sim$ 0.1 kpc) and the NLR (several kpc). Here, we measure [FeVII] $\lambda 3760$ flux in J1454 out to 23.0 $\pm$ 2.9 kpc (4.4$\sigma$ above the mean of the CLD distribution; the largest in our sample). We also find that the bulk of the CLR in this galaxy is not spatially coincident with the galactic center. We determine that this galaxy is classified as a merger in G22 and we detect the companion southwest of the galactic center, well-aligned with the [FeVII] $\lambda 3760$ emission. During the merging pro-
cess, companion galaxies can be separated by tens of kpcs (e.g., Farage et al. 2010), which we reason likely accounts for the far-reaching CL emission in J1454 (see Section 4.1.3).

We measure [FeVII] λ3760 emission in J1349 out to 7.0 ± 0.6 kpc from the galactic center. The CL emission in this galaxy is most abundant within the galactic interior, but also extends throughout the southwest and northeast regions. No GZ2 classification is available for this galaxy, but its strong CL emission (1.2σ above the mean of the CL luminosity distribution; Table 2) and its extended morphology make it a galaxy of peculiar interest in our analysis. We further analyze this galaxy in Section 4.4 and determine it to be an AGN candidate.

For J0906, we identify substantial [FeVII] λ3586 emission out to 10.0 ± 2.5 kpc from the galactic center (1.9σ above the mean of the CLD distribution; the second largest in our sample). We determine that this galaxy is a merger based on the GZ2 classification and identify elongated CL emission along an apparent central bar. We detect the companion in the northern region of this galaxy, partially within the MaNGA FoV.

We scan the MaNGA AGN catalog and find no AGN classification for J1454, J1349, or J0906 (two mergers; one unclassified morphology). We consider the likelihood that these galaxies are AGN candidates, to help determine if AGN processes are producing the CLs in these galaxies, in Section 4.4.

Moreover, prior studies show that gas inflows produced by mergers can generate widespread shocks that ionize gas on kpc and sub-kpc scales (e.g., Medling et al. 2015). As such, we also consider the influence of a companion galaxy to be a potential source of the far-reaching CL emission in the merging galaxies (Section 4.1.3).

For J1535 (a confirmed AGN in the MANGA AGN catalog), we detect [FeVII] λ6086 emission out to 1.3 ± 0.76 kpc. The CL distribution in J1535 strongly resembles the nuclear-bound [NeV] λ3347, 3427 distributions (Section 4.1.1). If CLs are produced predominately by AGN photoionization, then we expect to find the bulk of CLs within the galactic interior, which is the case for this galaxy.

4.1.3. CL AGNs and CL Mergers

We find that the CL galaxies in our sample are either hosting an AGN (7; "CL AGNs"), undergoing a merger (2; "CL mergers"), or are unclassified (1; an AGN candidate; Section 4.4). The strength and distribution of the CL AGNs are consistent with AGN photoionization playing the most direct role in the production of the CLs, with merger-induced shocks being a strong candidate for ionization, too. The CL AGN detection rate (70% - 80%) suggests that CLs are useful for identifying AGN in large spectroscopic surveys.

Additionally, we measure the CLDs of the CL mergers to be the most extended in our sample (10.0 ± 2.5 kpc for J0906 and 23.0 ± 2.9 kpc for J1454). The interactions between companion galaxies, which occur on the scale of tens of kpcs, can create tidal forces that drive gas towards the galactic centers, which can lead to shock excitation (e.g., Farage et al. 2010). These shocks are likely to impact both galaxies and account for the extended CL emission we see in the CL mergers. Moreover, the CL mergers may be relevant for AGN studies because infalling gas can fuel AGN activity, which can produce large-scale outflows and additional shocks that influence the host galaxy’s evolution (e.g., Rich et al. 2015).

4.2. The Role of Stellar Shocks in the CLR

Shock ionization can result from a variety of phenomena, including, but not limited to, AGN activity (e.g., jets), gas inflows produced by mergers, and stellar winds generated by SNRs (e.g., Kewley et al. 2019). We address the role of SNR shock ionization in the CLR, specifically, by investigating the populations of SNRs in the CLR. To execute this analysis, we adopt the approach outlined in Section 3.4.

Further, to better decipher the role of SNRs in the CLR, we plot the CL luminosity for each galaxy in our sample against the fraction of SNRs in their CLRs (Figure 6). We utilize the Pearson correlation coefficient to quantify our results. The coefficient ranges from -1 to +1, where 0 implies no correlation, -1 is indicative of a negative correlation, and +1 signifies a positive correlation. If CL luminosity and the fraction of SNRs are positively correlated, then SNRs likely play a critical role in the production of CLs.

We compute a Pearson correlation value of 0.3, implying a weak positive correlation between the fraction of SNRs in the CLR and the strength of the CLs. This suggests that a higher fraction of SNR shocks, on average, do not increase the strength of CL emission. We reason that AGN photoionization and merger-induced shocks are the dominant ionization mechanisms producing the CLs, even for the CL galaxies that feature a 100% fraction of SNRs in their CL-emitting spaxels (Section 4.4). However, we do acknowledge the sparse amount of data in Figure 6 and a lack of a clear visual trend. While we expect photoionization and merger-induced shocks to have the most impact on the strength of the CLs, further analysis is required to definitively rule out the influence of SNRs in the CLR.
We also inspect the ionizing radiation field of the CL galaxies to determine the ionization mechanism(s) producing the CLR. We consider the $r^{-2}$ ionizing radiation dilution characteristic of pure AGN photoionization (e.g., Tadhunter 2002; Yan & Blanton 2012; Section 3.3), and compare the power law indexes of the CL luminosities to $\alpha = -2$ (Table 2). We measure $\alpha$ to range between $-1.8 \pm 0.3$ to $-0.6 \pm 0.1$ for the CL AGNs (7) and $-0.9 \pm 0.1$ to $0.2 \pm 0.1$ for the remaining sample (3). For both samples, the decay of ionizing radiation with increasing galactocentric distances is shallower than the profile expected for pure AGN photoionization. As a result, we reason that the CLs, even for the CL AGNs, likely feature a blend of ionization mechanisms that include, but are not limited to, SNRs and merger-induced shocks, which account for the extended nature of the CLR (Section 4). Further, we acknowledge that fluctuations in the density profile, as a function of galactocentric distance (Section 4.3; e.g., Revalski et al. 2021), may influence the evolution of the ionizing radiation field, and that merger-driven shocks, AGN photoionization, and SNR shocks may not be the only CL ionization mechanisms; stochastic accretion, AGN light echoes, and AGN outflows are also possible mechanisms that can produce CL emission (e.g., Müller-Sánchez et al. 2011; Winkler 2016).

4.3. Electron Temperatures and Electron Number Densities of the CLs

Previous studies (e.g., Mazzalay et al. 2010) found that temperatures in the CLR range from 10,000 K - 20,000 K, consistent with pure AGN photoionization. However, beyond the $\sim 20,000$ K threshold, up to $10^6$ K, outflowing jets can collisionally ionize and heat gas clouds (via stellar and AGN shocks, for example; see Moy, & Rocca-Volmerange 2002; Section 3.5). For these cases, kinetic energy must be supplied by an additional source (e.g., Osterbrock 1984). Moreover, intermediate electron densities $n_e \approx 10^2 - 10^4$ cm$^{-3}$ are typical of the NLR; $n_e > 10^9$ cm$^{-3}$ for the BLR.

As a result, we measure the temperature and density profiles for the galaxies in our sample to better understand the nature of the CLR (Figure 7). For the density profiles, we acknowledge that recent studies (e.g., Baron & Netzer 2019; Davies et al. 2020) report that electron number densities derived from the [SII] $\lambda\lambda 6717,6731$ doublet may be underestimated. Thus, we consider our electron density measurements to be lower estimates.

For the temperature and density measurements, we require flux values for the [OIII] $\lambda 4363$ line, but we only detect this line in 4/10 CL galaxies, which all host AGNs (Table 3). We also consider the fraction of spaxels in each galaxy’s CLR that we can measure temperatures and densities for (the “Measurement Fraction” in Table 3). We find that the average CLR temperatures vary between 12,331 - 22,530 K, and that the average temper-
Figure 5. From left to right and top to bottom: the SDSS optical image and CL flux maps for J0752, J2051, J2116, J0736, J1454, J1349, J0906, and J1535. The CLDs for the CL mergers are the most extended in our sample (10.0 ± 2.5 kpc for J0906 and 23.0 ± 2.9 kpc for J1454). Merger-induced shocks are likely to be the primary ionization mechanism for these galaxies. The CL galaxies that host AGNs tend to have more compact CL emission that is predominantly within the galactic interior, which suggests AGN photoionization is the primary CL ionization mechanism for these galaxies.
Figure 6. Total CL luminosity for each CL galaxy (with SNR emission in at least one CL spaxel) vs. the fraction of SNRs found in their respective CLRs. We measure a Pearson correlation value of 0.3, which suggests that, on average, higher fractions of SNRs do not produce more abundant CL emission. Due to the few data points and the lack of a clear visual trend, we consider these results preliminary. For some data points, CL luminosity uncertainties are too small to be visualized on the plot.

Figure 8. For galaxies with multiple CL detections, we plot each CL independently. We identify a strong positive correlation between CL and bolometric luminosities for our full sample (Pearson value of 0.9). In general, the strength of the CLR (measured by CL emission) scales with bolometric luminosity.

We then perform a linear regression on the full sample of CL galaxies. We use the $R^2$ statistic to quantify our results. This is a statistical measure that uses the sample’s variance to determine how close the data are to the fitted regression line. It varies between 0 and 1, where 0 implies high variability of the data (i.e. a poor model fit) and 1 suggests low variability (i.e. a good fit). We measure $R^2$ for our sample to be 0.7, which suggests that CL luminosity is dependent on AGN bolometric luminosity, for the majority of our sample. Additionally, we measure the residuals to determine how well the data fit the regression line. We calculate the quantity $R_f$ as the ratio of the residuals to the predicted regression values for each data point (Table 4). This dimensionless quantity measures the deviation of the data points relative to their predicted model values.

We first analyze the CL AGNs and determine that they fit the regression well, as we expect, with $R_f$ values $< 3$. We then target the CL galaxies that have not been classified as an AGN in the MaNGA AGN catalog, which are either undergoing a merger (J1454 and J0906) or are unclassified (J1349). We do so to identify if these are outliers in our sample of CL galaxies, and to determine if they are potential AGN candidates. J1454 and J0906 are marked by the orange data points in Figure 8; J1349 in green. We measure $R_f$ values for J1454 and J0906 to be 8.1σ and 1.7σ above the mean of the $R_f$ distribution, respectively - the two highest in our sample. This suggests that J1454 is not a strong AGN candidate, and that J0906 requires further analysis to determine if it hosts an AGN. On the other hand, J1349 ($R_f = 1.5$) is within 1σ of the mean of the distribution. We consider this galaxy to be an AGN candidate due to its proximity to the regression line.

We deduce that CLs are strong tracers of AGNs, but perhaps not perfect since we also find that galaxy mergers (which may not host an AGN) can also feature a CLR.

4.5. MaNGA AGN Catalog Comparison

Several authors suggest that CLs are common features in the spectra of AGNs and provide unambiguous signatures for AGN activity due to their high production energies (e.g., Korista, & Ferland 1989; Prieto et al. 2002; Mazzalay et al. 2010; Landt et al. 2011; Müller-Sánchez et al. 2011). We use a catalog of confirmed AGNs in...
MaNGA to test the robustness of CLs as AGN identifiers (Table 5).

Comerford et al. (2020) assembled the largest existing catalog of AGNs in MaNGA to date. The authors used WISE mid-infrared color cuts, Swift/BAT hard X-ray observations, NVSS/FIRST, and SDSS broad emission lines to create their sample. In total, they reported 406 unique AGNs in MPL-8.

Mid-infrared emission, generated by the heated dust which encompasses an AGN, is a reliable probe for obscured and unobscured AGN activity. As a result, they used observations from the Wide-Field Infrared Survey Explorer (WISE; Wright et al. 2010) to help identify AGNs. They considered the four bands observed with WISE (3.4 μm (W1), 4.6 μm (W2), 12 μm (W3), and 22 μm (W4)) and apply a 75% reliability criteria of W1 - W2 > 0.486 exp{0.092(W2 - 13.07)^2} and W2 > 13.07, or W1 - W2 > 0.486 and W2 ≤ 13.07 (Assef et al. 2018) for their analysis. They identified 67 WISE AGNs in MaNGA.

To trace the hot X-ray corona around an AGN, the authors used the catalog assembled by Oh et al. (2018), which consists of ~1,000 AGNs observed by the Swift Observatory’s Burst Alert Telescope (BAT) in the ultra hard X-ray (14 - 195 keV). The authors found 17 AGNs from this catalog in MaNGA.

Further, radio studies are unique in their ability to detect strong emission emanating from AGN radio jets. Best & Heckman (2012) used observations from the 1.4 GHz NRAO Very Large Array Sky Survey (NVSS; Condon et al. 1998) and the Fantail images of the Radio Sky at Twenty Centimeters (FIRST; Becker et al. 1995) to detect AGNs in the SDSS’s seventh data release (DR7). They differentiated AGN activity from star formation emission using the correlation between the 4000 Å break strength and radio luminosity per stellar mass, emission line diagnostics, and the relation between Hα and radio luminosity (Becker et al. 1995). Comerford et al. (2020) found 325 radio AGNs from this catalog in MaNGA.

Broad Balmer emission lines (FWHM > 1,000 km s⁻¹) also serve as useful signatures for AGN activity. The high velocity clouds which produce these lines provide clear evidence of high density gas in close proximity to the SMBH. Oh et al. (2015) assembled a catalog of nearby (z ≤ 2) Type I AGNs in SDSS’s seventh data release using the broad Hα emission line, and Comerford et al. (2020) identified 55 broad line AGNs from this catalog in MaNGA.

We cross match our sample with the 406 unique MaNGA AGNs reported by Comerford et al. (2020) and find 7 CL galaxies in it (70% of our sample). We consider CLs to be a strong tracer of AGN activity since the majority of our CL galaxies are confirmed to host an AGN. Additionally, the remaining 30% of our sample are galaxies of interest. J1349 is an AGN candidate (Section 4.4), and J1454 and J0906 are undergoing mergers, which can induce strong gas inflows that can eventually trigger the activation of AGNs and fuel large-scale AGN outflows (e.g., Rich et al. 2015).

### 4.6. BPT AGN Catalog Comparison

Baldwin-Phillips-Terlevich optical emission line diagnostic diagrams (BPT diagrams; Baldwin et al. 1981; Kewley et al. 2001, 2006; Kauffmann et al. 2003) incorporate line ratios between high and low ionization species (e.g., [OIII] λ5007/Hβ vs. [NII] λ6584/Hα or [OIII] λ5007/Hβ vs. [SII] λ6717 + λ6731/Hα) to distinguish gas ionization sources as star forming, Seyfert (AGN), low-ionization nuclear emission-line region (LINER), or a composite of multiple ionization sources. They serve as the traditional AGN selection tool for most spectroscopic surveys.

Rembold et al. (2017), Sánchez et al. (2018), and Wylezalek et al. (2018) used these diagrams to identify AGN candidates in MaNGA’s MPL-5, which contains data cubes for 2,727 unique galaxies. We scan these catalogs to identify the fraction of CL galaxies found within them. We do so to determine the strength of the BPT diagrams as an AGN selection tool, and to

---

**Table 3.** Average CLR Electron Temperatures and Number Densities

| SDSS Name        | CL     | Electron Temperature | Electron Density | Measurement Fraction |
|------------------|--------|----------------------|------------------|---------------------|
| (1)              | (2)    | (3)                  | (4)              | (5)                 |
| J075217.84+193542.2 | [NeV] λ3427 | 16,680 | 400 | 56% |
| J153552.40+575409.4 | [FeVII] λ6086 | 21,088 | 586 | 3%  |
| J161413.20+260416.3 | [NeV] λ3347 | 22,530 | 355 | 36% |
|                  | [NeV] λ3427 | 19,533 | 244 | 38% |
| J211646.34+110237.4 | [NeV] λ3427 | 12,331 | 414 | 51% |

Note: Columns are (1) CL galaxy SDSS name, (2) detected CL, (3) average CLR electron temperature, (4) average CLR electron density, and (5) the fraction of spaxels in each galaxy’s CLR that we can measure temperatures and densities for.
assess if CLs can help provide accurate AGN identifications in MaNGA (and similar spectroscopic surveys). We acknowledge that each BPT catalog may not have exhaustively scanned MPL-5 (e.g., spectroscopic data may not have been available for all galaxies during each analysis; Rembold et al. 2017). As a result, we consider our findings preliminary.

A primary drawback of BPT diagrams is their inability to distinguish low ionization AGNs from post-AGB stars. Rembold et al. (2017) used the equivalent width of Hα (EW Hα) to mitigate this issue. Cid Fernandes et al. (2010) first determined that galaxies with EW Hα < 3 Å are predominantly ionized by post-AGB stars, rather than AGNs. As a result, Rembold et al. (2017) used this threshold to analyze single-fiber (within the central 3′′) MPL-5 galaxy observations. They identified 62 AGNs above this limit, which were also reported as Seyfert or LINER (which have been shown to strongly link with AGN activity; e.g., Ho 2008) on the BPT diagrams. We scan this catalog for the CL AGNs that are in MPL-5 (J1714; J0736; J2116; J1535) and determine that 0/4 are present.
Figure 8. Total CL luminosity plotted against bolometric luminosity for all CL galaxies. The black line in the linear regression fit to the data. The blue data points are the CL AGNs, the orange are the CL mergers, and the green is the unclassified CL galaxy J1349. For some data points, CL and bolometric luminosity uncertainties are too low to be visualized on the plot.

Table 4. $R_f$ Values for the CL Luminosity vs. Bolometric Luminosity Relationship

| SDSS Name               | CL   | $R_f$ |
|-------------------------|------|-------|
| J073623.13+392617.7     | [NeV] | 0.53  |
| J075217.84+193542.2     | [NeV] | 0.26  |
| J090659.46+204810.0     | [FeVII] | 3.7   |
| J134918.20+240544.9     | [FeVII] | 1.5   |
| J145420.10+470022.3     | [FeVII] | 18.0  |
| J153552.40+575409.4     | [FeVII] | 0.81  |
| J161413.20+260416.3     | [NeV] | 0.54  |
| J171411.63+575834.0     | [NeV] | 0.16  |
| J205141.54+005135.4     | [NeV] | 0.10  |
| J211646.34+110237.4     | [NeV] | 0.52  |

Sánchez et al. (2018) also used BPT diagrams to analyze the spectroscopic properties of ionized gas within the central (within 3″) of the MPL-5 galaxies. The authors similarly used EW Hα values to differentiate AGN from post-AGB star ionization regions. However, they relaxed the 3 Å criteria used by Rembold et al. (2017) and Cid Fernandes et al. (2010), and only considered galaxies with EW Hα < 1.5 Å to be primarily ionized by post-AGB stars (to include weaker AGN). Additionally, the authors excluded galaxies below the Kauffmann demarcation curve, which is an empirical tracer of HII regions - used to isolate star forming sources on BPT diagrams (Kewley et al. 2001, 2006). Using these constrains, they reported 98 AGNs in MPL-5. We find that 1/4 CL AGN, that are in MPL-5, are in this catalog (J2116).

Finally, Wylezalek et al. (2018) analyzed each spaxel for every galaxy in MPL-5 and created spatially resolved BPT-diagrams. They weighted the summed fraction of spaxels categorized as either AGN, LINER, or composite in each galaxy (e.g., AGN spaxels were given an 80% weight and composite spaxels were given a 20% weight). The authors then performed cuts on Hα surface brightness and Hα EW. Hα surface brightness is a reliable tracer of diffuse hot ionized gas; however, emission line ratios are often enhanced in regions with low Hα surface brightness (which can mimic AGN and LINER emission; e.g., Haffner et al. 2009). As a result, they excluded spaxels with Hα surface brightnesses < 10^{37} erg s^{-1} kpc^{-2}. They also elevated the minimum EW Hα threshold to 5 Å to further reduce potential stellar contamination (below this limit post-AGB stars are considered to be the primary ionization mechanism). They found 303 AGN candidates, and we identify 2/4 CL AGNs, that are in MPL-5, in their sample (J1535 and J2116). Wylezalek et al. (2018) acknowledged that BPT ionization ratios can be impacted by diffuse ionized gas, extraplanar gas, photoionization by hot stars, metallicity, and shocks. These sources can elevate line flux ratios to produce AGN-like features, potentially leading to misclassification (e.g., Rich et al. 2010, 2011; Kewley et al. 2013).

We determine that the Rembold et al. (2017), Sánchez et al. (2018), and Wylezalek et al. (2018) catalogs feature 0/4, 1/4, and 2/4 CL AGN(s) (in MPL-5), respectively. The low fraction of CL AGNs in these catalogs suggests that CL detections may be useful for identifying AGNs missed by traditional BPT diagrams. We will conduct a more thorough review in a forthcoming publication (Negus et al., in prep) and determine the BPT classifications for all of the CL-emitting spaxels in our sample. We will also compare our findings with future MaNGA BPT AGN catalogs that scan a more complete sample of MaNGA galaxies. This will help us build a deeper understanding of the CL galaxies, and will enable us to more closely evaluate the strength of BPT diagrams as AGN classifiers.
Table 5. CL Galaxies Found in the MaNGA AGN Catalog

| SDSS Name       | AGN Detection Method |
|-----------------|----------------------|
| J073623.13+392617.7 | WISE, Broad          |
| J075217.84+193542.2 | WISE, BAT            |
| J153552.40+575490.9 | WISE, BAT, Broad     |
| J161413.20+260416.3 | WISE, BAT, Broad     |
| J171411.63+575834.0 | WISE, Broad          |
| J205141.54+005135.4 | WISE, Broad          |
| J211646.34+110237.4 | WISE, Broad          |

5. DISCUSSION

In this paper, we analyze 10 CL galaxies from MaNGA’s MPL-8. With our detection rate (0.16%), we expect to find at least \( \sim 16 \) CL galaxies with CL emission at \( \geq 5\sigma \) above the continuum, in at least 10 spaxels, in the final MaNGA catalog of \( \sim 10,000 \) galaxies. We anticipate that the majority of these CL galaxies will be confirmed as AGNs or AGN candidates, and that the remaining will be CL mergers.

We determine that AGN photoionization is likely the dominant ionization mechanism for the CLs in our sample, which is consistent with results found in previous studies (e.g., Gelbord et al. 2009; Mazzalay et al. 2010). As a result, we consider CLs to be a useful tracer for AGN identification, which is a critical step in constraining the role of AGN feedback in the host galaxy’s evolution. On the other hand, we also determine that CLs can be featured in merging galaxies that may not host an AGN (20% of our catalog), likely through gas inflows that trigger shocks and extend the reach of the CLR. However, these CL galaxies may still be useful for understanding feedback within galaxies since mergers can initiate galaxy winds, fuel AGNs, stimulate star formation, and impact a galaxy’s gas supply (e.g., Springel et al. 2005; Comerford et al. 2009; Rich et al. 2015).

Further, Diaz & Rodríguez-Ardila (2019) studied CL emission in four nearby AGNs and reported a co-spatial distribution of CL emission with radio jets. Mullaney et al. (2009) also modeled the location and kinematics of the CLR in a sample of AGNs and declared that the bulk of these regions corresponded to outflows. These AGN processes, in addition to shocks, may be additional CL ionization mechanisms that can account for the extended emission we report.

Finally, prior CL studies measured these lines to lie between the BLR and the NLR (e.g., Mazzalay et al. 2010; Rodríguez-Ardila et al. 2011), or on the order of hundreds of pc (e.g., Müller-Sánchez et al. 2011; Riffel et al. 2021). Here, we measure the CLR to be far more extended, out to distances of 1.3 - 23 kpc from the galactic center and well into the NLR. We do consider the possibility that the CL emission in the CL galaxies can be smeared (to distances much larger than the FWHM of the PSF) by seeing from the atmosphere, the telescope, and/or the instruments (e.g., Chen et al. 2019). In Section 4, we show that beam smearing is possible for 4/10 CL galaxies and consider their CLDs to be upper estimates. However, the remaining population of 6 CL galaxies feature continuous and well resolved CL emission. Among this sample, the CL galaxy with the most extended CL emission is spatially resolved and extends out to 23 kpc. As such, the extent of the CLR that we report (1.3 - 23 kpc from the galactic center) is unlikely to be impacted significantly by beam smearing.

6. SUMMARY AND FUTURE WORK

We assemble the largest catalog of MaNGA CL galaxies to date. With our custom pipeline, we detect 10 CL galaxies exhibiting emission from one or more CLs ([NeV] \( \lambda 3347 \), [NeV] \( \lambda 3427 \), [FeVII] \( \lambda 3586 \), [FeVII] \( \lambda 3760 \), or [FeVII] \( \lambda 6086 \) in this paper) detected at \( \geq 5\sigma \) above the background continuum in at least 10 spaxels. Our primary results are the following:

1. CL emission extends 1.3 - 23 kpc from the galactic center, with an average distance of 6.6 kpc (well into the traditional NLR).

2. Across our entire sample, CL luminosity diminishes exponentially from the galactic center with \(-1.8 \pm 0.3 \leq \alpha \leq 0.2 \pm 0.1\). We compare this to the power law index expected for pure AGN photoionization (\( \alpha = -2 \)), and reason that shocks (e.g., merger-induced and from SNRs) can also produce CLs and increase \( \alpha \) to values > -2.

3. The average CLR electron temperature ranges between 12,331 K - 22,530 K. Shock-induced compression and heating must necessarily elevate these temperatures beyond the threshold for photoionization (\( \sim 20,000 \) K).

4. The average CLR electron number density is on the order of \( \sim 10^2 \) cm\(^{-3} \), consistent with the CLR occupying the NLR, beyond the BLR.

5. CL luminosity strongly correlates with bolometric luminosity (Pearson value of 0.9) for our sample. This is consistent with AGN activity primarily regulating the strength of CLs.

6. The CL mergers (J1454 and J0906) deviate most significantly (\( R_f > 3 \)) from the linear regression fit performed on CL luminosity vs. bolometric luminosity. J1454, 8.1\( \sigma \) above the mean of the \( R_f \) distribution, is not a strong AGN candidate based
on this result. J0906, 1.7σ above the mean of the $R_f$ distribution, requires further analysis to determine if it hosts an AGN.

7. 7 CL galaxies (70% of our catalog) are confirmed AGNs. One CL galaxy is also an AGN candidate. CLs are strong, but perhaps not perfect, indicators of AGN activity.

8. Several CL AGNs are not found in existing BPT AGN catalogs. Our preliminary results suggests that CL detections may be useful for helping to identify AGNs missed by traditional BPT diagrams.

We will conduct a full review of the CLR kinematics in a forthcoming publication to determine the role of outflows in the production of CLs. Specifically, we will trace the bulk motion of galactic outflows (i.e., jets), study the dynamics of gas inflows that result from mergers, and measure the rotation and cloud velocities of gas near the galactic core using MaNGA’s DAP.

We will also scan MPL-11, the final MaNGA data release that contains ~ 10,000 galaxies, in a follow up investigation and append our sample of CL galaxies with any additional CL galaxy detections. Finally, we will analyze the galaxies with emission from one or more CLs detected at ≥ 3σ above the background continuum to ensure we identify all CL galaxy candidates and to ultimately build the most complete sample of CL galaxies in MaNGA.

ACKNOWLEDGMENTS

J.N. and J.M.C. acknowledge support from NSF AST-1714503. J.N. thanks Mitchell Revalski for useful discussions focused on the physical conditions of ionized gases and emission line diagnostics. RAR acknowledges partial financial support from CNPq and FAPERGS.

Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS web site is www.sdss.org.

SDSS-IV is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, the Chilean Participation Group, the French Participation Group, Harvard-Smithsonian Center for Astrophysics, Instituto de Astrofísica de Canarias, The Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU) / University of Tokyo, the Korean Participation Group, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPG Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatories of China, New Mexico State University, New York University, University of Notre Dame, Observatório Nacional / MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University, and Yale University. Collaboration Overview Start Guide Affiliate Institutions Key People in SDSS Collaboration Council Committee on Inclusiveness Architects Survey Science Teams and Working Groups Code of Conduct Publication Policy How to Cite SDSS External Collaborator Policy

This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

This research has made use of data supplied by the UK Swift Science Data Centre at the University of Leicester.

Software: Astropy (Astropy Collaboration et al. 2013, 2018), IRAF (Tody 1986, 1993), PyNeb (Luridiana et al. 2015).
REFERENCES

Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., et al. 2008, ApJS, 175, 297

Albareti, F. D., Allende Prieto, C., Almeida, A., et al. 2017, ApJS, 233, 25

Antonucci, R. 1993, ARA&A, 31, 473

Appenzeller, I., & Wagner, S. J. 1991, A&A, 250, 57

Assef, R. J., Stern, D., Noirot, G., et al. 2018, ApJS, 234, 23

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33.
doi:10.1051/0004-6361/201322068

Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, AJ, 156, 123. doi:10.3847/1538-3881/aabc4f

Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5

Baron, D. & Netzer, H. 2019, MNRAS, 486, 4290. doi:10.1093/mnras/stz1070

Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559

Vanden Berk, D. E., Richards, G. T., Bauer, A., et al. 2001, AJ, 122, 549. doi:10.1086/321167

Bershady, M. A., Verheijen, M. A. W., Swaters, R. A., et al. 2010, ApJ, 716, 198

Best, P. N. & Heckman, T. M. 2012, MNRAS, 421, 1569

Binette, L., Wilson, A. S., & Storchi-Bergmann, T. 1996, A&A, 312, 365

Blair, W. P., Winkler, P. F., & Long, K. S. 2012, ApJS, 203, 8

Blanc, G. A., Weinzirl, T., Song, M., et al. 2013, AJ, 145, 138

Blandford, R. D., Netzer, H., Woltjer, L., et al. 1990, Active Galactic Nuclei, 97

Blanton, M. R., Kazin, E., Muna, D., et al. 2011, AJ, 142, 31

Blanton, M. R., Bershady, M. A., Abolfathi, B., et al. 2017, AJ, 154, 28

Bryan, J. J., Owens, M. S., Robotham, A. S. G., et al. 2015, MNRAS, 447, 2857

Bundy, K., Bershady, M. A., Law, D. R., et al. 2015, ApJ, 798, 7

Burtscher, L., Orban de Xivry, G., Davies, R. I., et al. 2015, A&A, 578, A47

Cappellari, M., & Emsellem, E. 2004, PASP, 116, 138

Cappellari, M. 2009, arXiv e-prints, arXiv:0912.1303

Cappellari, M., Emsellem, E., Krajnović, D., et al. 2011, MNRAS, 413, 813

Cappellari, M. 2017, MNRAS, 466, 798

Cerqueira-Campos, F. C., Rodríguez-Ardila, A., Riffel, R., et al. 2021, MNRAS, 500, 2666. doi:10.1093/mnras/staa3320

Chen, J., Shi, Y., Dempsey, R., et al. 2019, MNRAS, 489, 855. doi:10.1093/mnras/stz2183

Cid Fernandes, R., Stasinska, G., Schlickmann, M. S., et al. 2010, MNRAS, 403, 1036. doi:10.1111/j.1365-2966.2009.16185.x

Collin-Souffrin, S., Dyson, J. E., McDowell, J. C., et al. 1988, MNRAS, 232, 539

Comerford, J. M., Gerke, B. F., Newman, J. A., et al. 2009, ApJ, 698, 956. doi:10.1088/0004-637X/698/1/956

Comerford, J. M., Barrows, R. S., Müller-Sánchez, F., et al. 2017, ApJ, 849, 102

Comerford, J. M., Negus, J., Müller-Sánchez, F., et al. 2020, arXiv:2008.11210

Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693

Czerny, B., & Hryniewicz, K. 2011, A&A, 525, L8

Davies, R. I., Baron, D., Shimizu, T., et al. 2020, MNRAS, 498, 4150. doi:10.1093/mnras/staa2413

De Robertis, M. M., & Osterbrock, D. E. 1984, ApJ, 286, 171

De Robertis, M. M., & Osterbrock, D. E. 1986, ApJ, 301, 727

de Zeeuw, P. T., Bureau, M., Emsellem, E., et al. 2002, MNRAS, 329, 513

Díaz, Y., & Rodríguez-Ardila, A. 2019, Boletín de la Asociacion Argentina de Astronomia La Plata Argentina, 61, 186

Dodorico, S. 1978, Mem. Soc. Astron. Italiana, 49, 485

Dodorico, S., Dopita, M. A., & Benvenuti, P. 1980, A&AS, 40, 67

Dopita, M. A., Binette, L., Dopita, M. A., et al. 1984, ApJ, 276, 653

Dopita, M. A. & Sutherland, R. S. 1996, ApJS, 102, 161. doi:10.1086/192255

Drory, N., MacDonald, N., Bershady, M. A., et al. 2015, AJ, 149, 77

Eisenstein, D. J., Weinberg, D. H., Agol, E., et al. 2011, AJ, 142, 72

Elhamdhi, A. 2011, AcA, 61, 179

Fabian, A. C. 2012, ARA&A, 50, 455

Farage, C. L., McGregor, P. J., Dopita, M. A., et al. 2010, ApJ, 724, 267. doi:10.1088/0004-637X/724/1/267

Ferland, G. J., Chatzikos, M., Guzmán, F., et al. 2017, RMxAA, 53, 385

Filippenko, A. V., & Halpern, J. P. 1984, ApJ, 285, 458

Gelbord, J. M., Mullaney, J. R., & Ward, M. J. 2009, MNRAS, 397, 172
APPENDIX

A. DOUBLE GAUSSIAN FIT FOR Hγ AND [OIII] λ4363

Figure 9. A sample spectrum showing a double Gaussian fit on the Hγ and the [OIII] λ4363 lines (detected at $\geq 5\sigma$ above the continuum) in a single spaxel for J2116. The dashed black line is the continuum subtracted spectrum, the shaded gray region is the uncertainty, the solid red line represents the best fit, the red dotted vertical lines mark the fitting window, and the blue dotted lines show the rest wavelengths of Hγ and [OIII] λ4363.
B. \[\text{[OIII]} \lambda 5007\] FLUX MAPS FOR THE CL GALAXIES

**Figure 10.** From left to right: SDSS optical image, \([\text{NeV}] \lambda 3427\) flux map, and \([\text{OIII}] \lambda 5007\) flux map for J0736.

**Figure 11.** From left to right: SDSS optical image, \([\text{NeV}] \lambda 3427\) flux map, and \([\text{OIII}] \lambda 5007\) flux map for J0752.

**Figure 12.** From left to right: SDSS optical image, \([\text{FeVII}] \lambda 3586\) flux map, and \([\text{OIII}] \lambda 5007\) flux map for J0906.
Figure 13. From left to right: SDSS optical image, [FeVII] $\lambda 3760$ flux map, and [OIII] $\lambda 5007$ flux map for J1349

Figure 14. From left to right: SDSS optical image, [FeVII] $\lambda 3760$ flux map, and [OIII] $\lambda 5007$ flux map for J1454

Figure 15. From left to right: SDSS optical image, [FeVII] $\lambda 6086$ flux map, and [OIII] $\lambda 5007$ flux map for J1535
Figure 16. Top row (left to right): SDSS optical image and $\text{[NeV]} \lambda 3347$ flux map for J1614. Bottom row (left to right): $\text{[NeV]} \lambda 3427$ flux map and $\text{[OIII]} \lambda 5007$ flux map for J1614.
Figure 17. Top row (left to right): SDSS optical image and [NeV] λ3347 flux map for J1714. Bottom row (left to right): [NeV] λ3427 flux map and [OIII] λ5007 flux map for J1714.

Figure 18. From left to right: SDSS optical image, [NeV] λ3427 flux map, and [OIII] λ5007 flux map for J2051.
Figure 19. From left to right: SDSS optical image, $\text{[NeV]} \lambda 3427$ flux map, and $\text{[OIII]} \lambda 5007$ flux map for J2116.