THE EXTENDED NARROW-LINE REGION OF TWO TYPE-I QUASI-STELLAR OBJECTS

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ABSTRACT

We investigate the narrow-line region (NLR) of two radio-quiet QSOs, PG1012+008 and PG1307+085, using high signal-to-noise spatially resolved long-slit spectra obtained with FORS1 at the Very Large Telescope. Although the emission is dominated by the point-spread function of the nuclear source, we are able to detect extended NLR emission out to several kiloparsec scales in both QSOs by subtracting the scaled central spectrum from outer spectra. In contrast to the nuclear spectrum, which shows a prominent blue wing and a broad line profile of the [O iii] line, the extended emission reveals no clear signs of large-scale outflows. Exploiting the wide wavelength range, we determine the radial change of the gas properties in the NLR, i.e., gas temperature, density, and ionization parameter, and compare them with those of Seyfert galaxies and type-II QSOs. The QSOs have higher nuclear temperature and lower electron density than Seyferts, but show no significant difference compared to type-II QSOs, while the ionization parameter decreases with radial distance, similar to the case of Seyfert galaxies. For PG1012+008, we determine the stellar-velocity dispersion of the host galaxy. Combined with the black hole mass, we find that the luminous radio-quiet QSO follows the local $M_{BH}$–$\sigma_*$ relation of active galactic nuclei.

Key words: galaxies: active – quasars: emission lines

Online-only material: color figures

1. INTRODUCTION

Since the discovery of correlations between the mass of black holes (BHs) and the properties of their host-galaxy bulges (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000), the interplay between active galactic nuclei (AGNs)—thought to represent a stage of galaxy evolution in which BH is actively growing through accretion—and their host galaxies has received much attention. In particular, AGN feedback seems to provide a promising way to drive these relations by quenching both star formation and accretion onto the BH, thus self-regulating BH growth (e.g., Di Matteo et al. 2005; Hopkins et al. 2006; Sironi & Socrates 2010).

Recently, there has been growing observational support for such a scenario for various AGNs, e.g., radio-loud quasars (e.g., Nesvadba et al. 2008; Fu & Stockton 2009), broad-absorption line quasars (e.g., Crenshaw et al. 2003; Moe et al. 2009), local ultraluminous infrared galaxies (e.g., Fischer et al. 2010; Feruglio et al. 2010; Sturm et al. 2011; Rupke & Veilleux 2011), and high-redshift AGNs (e.g., Tremonti et al. 2007; Alexander et al. 2010; Hainline et al. 2011). These observations are, however, often restricted to a handful of sources. Moreover, it is difficult to determine the kinetic energy involved and to prove that the observed outflows are indeed galaxy-scale radiatively driven AGN outflows (compared to outflows driven by, e.g., star formation or jets).

One approach in the quest for observational signatures of AGN feedback is to focus on the emission-line regions in the vicinity of the BH: the so-called broad-line region (BLR) and narrow-line region (NLR), which are photoionized by the central engine. While BLRs are confined to sub-parsec scales around an accretion disk, producing kinematically broadened emission lines with typical velocities of $10^3$–$10^4$ km s$^{-1}$, NLRs, characterized by narrow lines with typical velocities of $10^2$–$10^3$ km s$^{-1}$, can span over kiloparsec scales, which are comparable to the size of the bulge or even the entire galaxy (Boroson & Oke 1984; Stockton & MacKenty 1987). Thus, as a direct interface between the AGN and its host galaxy, the NLR can provide important clues on the impact of BHs on their host galaxies and vice versa.

The NLR of Seyfert galaxies has been studied extensively over the last decades (e.g., Mulchaey et al. 1996; Ho et al. 1997; Schmitt et al. 2003; Falcke et al. 1998; Bennert et al. 2002; Stoklasová et al. 2009). While most earlier studies have focused on the extent and morphology of the NLR, the interplay between radio emission and NLR, and implications for the unified model of AGNs (see Antonucci 1993 for review), the goal of recent studies is to search for imprints of AGN feedback, e.g., in the form of outflowing gas (Schlesinger et al. 2009; Müller-Sánchez et al. 2011).

In particular, the forbidden [O iii] $\lambda 5007$ (hereafter [O iii]) emission line is well known to show blue wings, which are generally interpreted as a sign of outflow (see Crenshaw et al. 2010 and references therein). To study the kinematics of the ionized gas, spectroscopy of the extended NLR is essential. However, such a study is especially challenging for the most promising candidates to exhibit AGN feedback, high-luminosity QSOs, due to the presence of their bright nuclei.

Recent studies have thus focused on type-II (obscured) QSOs that have been discovered in large numbers from the Sloan Digital Sky Survey (SDSS; Zakamska et al. 2003; Reyes et al. 2008). For example, Greene et al. (2011) studied 15 luminous
type-II QSOs at low redshift ($z < 0.5$) with spatially resolved spectroscopy. Comparing the extent of the continuum and $[\text{O} \text{iii}]$ emission, they argue that the AGN is ionizing the interstellar medium in the entire host galaxy. The large velocity dispersion of this ionized gas out to kiloparsec scales suggests that the gas is disturbed on galactic scale. However, the velocity dispersion is below 500 km s$^{-1}$ for most objects in their sample, and the overall escaping fraction is less than 25% with a median of 2%, even in the most extreme cases. Similarly, Villar-Martín et al. (2011) report blue asymmetry of the $[\text{O} \text{iii}]$ emission line in 11 objects out of a sample of 13 type-II quasars at $0.3 < z < 0.5$. They interpret the asymmetry as a signature of outflows within a few kiloparsec from the central engine. Furthermore, they find an anticorrelation between the degree by which the kinematics of the outflow is perturbed and its contribution to the total $[\text{O} \text{iii}]$ flux, suggesting that only a small fraction of the total mass of the outflow is perturbed and its contribution to the total $[\text{O} \text{iii}]$ flux is dominated by the AGN and thus expected to be spatially under good seeing conditions. To investigate the properties of the NLR based on spatially resolved spectra, we observed PG1012+008 and PG1307+085 with the visual and near-UV Focal Reducer and low dispersion Spectrograph (FORS1) at the VLT on 2005 April 1 and 3. To achieve high spatial resolution, the observations were carried out under good seeing conditions ($<0''7$). A slit width of $0''7$ was chosen to match the seeing. Based on the $[\text{O} \text{iii}]$ narrowband images, we aligned the position angle of the slit with the maximum radial extent of the $[\text{O} \text{iii}]$ emission. The spatial resolution is $0''2$ pixel$^{-1}$. We used grism 300V with an order sorting filter GG375, covering a spectral range of 3300–7180 Å with 2.6 Å pixel$^{-1}$. The instrumental broadening ($\sigma_{\text{inst}}$), determined from arc lamps and skylines, is 216 km s$^{-1}$ at 5000 Å. For flux calibrations, we observed a spectrophotometric standard star G60-54. Table 1 summarizes the observations.

2.2. Observations

To investigate the properties of the NLR based on spatially resolved spectra, we observed PG1012+008 and PG1307+085 with the visual and near-UV Focal Reducer and low dispersion Spectrograph (FORS1) at the VLT on 2005 April 1 and 3. To achieve high spatial resolution, the observations were carried out under good seeing conditions ($<0''7$). A slit width of $0''7$ was chosen to match the seeing. Based on the $[\text{O} \text{iii}]$ narrowband images, we aligned the position angle of the slit with the maximum radial extent of the $[\text{O} \text{iii}]$ emission. The spatial resolution is $0''2$ pixel$^{-1}$. We used grism 300V with an order sorting filter GG375, covering a spectral range of 3300–7180 Å with 2.6 Å pixel$^{-1}$. The instrumental broadening ($\sigma_{\text{inst}}$), determined from arc lamps and skylines, is 216 km s$^{-1}$ at 5000 Å. For flux calibrations, we observed a spectrophotometric standard star G60-54. Table 1 summarizes the observations.

2.3. Data Reduction

Standard data reduction, i.e., bias subtraction, flat-fielding, wavelength calibration, flux calibration, and atmospheric absorption correction, was carried out using a series of IRAF scripts developed for long-slit spectroscopy (e.g., Woo et al. 2005, 2006). Cosmic rays were removed using L.A.Cosmic (van Dokkum 2001). We performed wavelength calibration using arc lines and obtained a spectral resolution of 2.6 Å pixel$^{-1}$ with standard deviation of $\sim 0.25$ Å.

We extract seven spectra along the slit (spatial direction), covering $\pm 3''6$. Positive direction indicates SE and NW for PG1012+008 and PG1307+085, respectively. The aperture size was increased from $0''6$ at the center to $1''8$ at the outer radius by a step of $0''4$, in order to boost the S/N. Figure 1 presents the spectra extracted from the central aperture for both targets. Note that the region near Hα suffers from the atmospheric absorption (A band). We attempted a correction using the standard star spectra. However, we were unable to measure the [N$\text{ii}$] and narrow Hα emission lines, due to the dominance of the broad Hα line.

3. RESULTS

3.1. Extended Narrow-line Region

We analyze spatially resolved spectra to investigate the spatial extension of the NLR. First, to compare the relative strength of the emission between the central and extended regions, we determine the spatial profiles of $[\text{O} \text{iii}]$, continuum, and standard star, respectively. In the case of the continuum, which is dominated by the AGN and thus expected to be spatially broadened by the seeing effect, we collapse the spectra in
Table 1

| Name         | z      | Exposure (s) | P.A. (deg) | Seeing (") | S/N (pixel^{-1}) | Scale (kpc arcsec^{-1}) | $D_L$ (Mpc) | $L_{\text{O} \text{iii}}$ ($\times 10^{42}$ erg s^{-1}) | $L_{\text{B}}$ ($\times 10^{45}$ erg s^{-1}) | $R_e$ (") |
|--------------|--------|--------------|-----------|-------------|------------------|------------------------|-------------|-----------------------------------------------|-----------------------------------------------|---------|
| PG1012+008  | 0.187  | 7400         | 142       | <0.7        | 472–26           | 3.1                    | 909.4       | 4.94                                         | 1.13                                         | 3.4     |
| PG1307+085  | 0.155  | 6800         | 112       | <0.6        | 507–5            | 2.7                    | 739.2       | 4.53                                         | 1.41                                         | 1.3     |

Notes. Column 1: object name. Column 2: redshift determined from [O ii] $\lambda$3727. Column 3: total exposure time. Column 4: position angle of the slit. Column 5: seeing condition. Column 6: signal-to-noise ratio at 5100 Å from the center to the outermost aperture. Column 7: angular diameter distance. Column 8: luminosity distance. Column 9: [O iii] luminosity measured from Bennert et al. (2002). Column 10: B-band luminosity from Elvis et al. (1994). Column 11: effective radius derived from two-dimensional de Vaucouleurs fits to the surface brightness profile given in Bahcall et al. (1997).

Figure 1. Central de-redshifted spectra of PG1012+008 (top) and PG1307+085 (bottom).

Figure 2. Normalized spatial profile of continuum, [O iii] emission line, and the standard star, respectively, for PG1012+008 (top) and PG1307+085 (bottom). For the continuum, the shaded region indicates 3σ errors. (A color version of this figure is available in the online journal.)
Figure 3. Continuum-subtracted central spectrum and residuals after subtracting a scaled central spectrum from the outer spectra, respectively, for PG1012+008 (left) and PG1307+085 (right). Blue and red lines correspond to the minus and plus sides of the center along the slit, respectively, and the number on the upper left corresponds to the distance from the center in units of arcseconds. The best-fit models using several subcomponents are represented by dashed lines (see the text for details), the residuals are presented with an arbitrary offset. The [O\textsc{iii}] emission line is enlarged with the wavelength axis converted to velocity in the right panels. The reference redshift is determined from [O\textsc{ii}] λ3727 line in the central spectrum. (A color version of this figure is available in the online journal.)

The extended NLR emission out to $r > 2''0 \pm 0''.7$ ($6 \pm 2$ kpc), which is larger than the sizes measured by Bennert et al. (2002) since the depth of our observation is roughly 20 times larger.

The central spectrum of both targets shows an asymmetric [O\textsc{iii}] line profile with prominent blue wings, which can be interpreted as outflows. To properly measure the velocity of [O\textsc{iii}], we model the Hβ–[O\textsc{iii}] region of the central spectrum as follows: first, we use a power law + IZwI template from Boroson & Green (1992) to fit strong Fe\textsc{ii} multiplets in the central spectrum of PG1012+008. For PG1307+085, the Fe\textsc{ii} emission is an order of magnitude weaker (compared to the continuum) and considered negligible. Then, we model the [O\textsc{iii}] line profile with two Gaussians along with broad and narrow Hβ. We use Gauss–Hermite polynomials of order six for the broad component of Hβ, and the ratio of the two [O\textsc{iii}] lines is fixed to the theoretical value (1/3). The best-fit models of the continuum-subtracted central spectra are shown in the top panels of Figure 3.

The “blue” component of [O\textsc{iii}], presumably representing the outflowing gas, is blueshifted from the reference redshift by 1380 km s$^{-1}$ and 173 km s$^{-1}$ for PG1012+008 and PG1307+085, respectively. The FWHM velocity of the total line profile measured from the central spectra is 1050 km s$^{-1}$ for PG1012+008 and 540 km s$^{-1}$ for PG1307+085, respectively. In contrast, as shown in Figure 3, the extended [O\textsc{iii}] emission is narrower than the [O\textsc{iii}] in the central spectrum for both objects, and most of the line flux is coming from low-velocity gas ($V < 500$ km s$^{-1}$). This indicates that the outflowing component with $V > 500$ km s$^{-1}$ is unresolved at the spatial resolution of our current observation and confined to within 0''.7 scale ($\sim 2$ kpc). Thus, the emission-line profile of the extended gas indicates that the extended gas is kinematically quiescent in both QSOs. We conclude that while we detect extended emission out to $r \approx 2''$ (6 kpc), there are no signs of a large-scale ($\sim 10$ kpc) outflow.

We briefly compare our results with those by Leipski & Bennert (2006). The red asymmetry toward the south of the nucleus in PG1012+008 detected by Leipski & Bennert (2006) may correspond to the redshifted residual [O\textsc{iii}] line at 0''.8. We miss some of the complex velocity structure seen by Leipski & Bennert (2006) due to lower spectral resolution. As noted by Leipski & Bennert (2006), PG1307+085 shows a dramatic change in line profile especially to the SE (“minus” in this study) side. The residual narrow line to the SE of PG1307+08 is unresolved at our spectral resolution. Leipski & Bennert (2006) report a velocity dispersion of $\sim 69$ km s$^{-1}$ for this component, which is consistent with our results. While our results are in overall agreement with those presented in Leipski & Bennert (2006), given the differences in spectral resolution and S/N, we find that the broad [O\textsc{iii}] line profile of PG1307+085 toward
the south is consistent with being a PSF wing rather than a true physical extension of outflowing gas.

The [O III]/Hβ line ratio is a diagnostic of the ionization mechanism (Baldwin et al. 1981). In the case of PG1012+008, we cannot rule out that the ionization of the extended gas is at least partially due to star formation. For PG1307+085, however, the high (>5) [O III]/Hβ ratio at r ≤ −0.8 from the center suggests that the QSO is the main source of ionization.

3.2. Physical Conditions

In this section, we measure temperature, density, and ionization parameter of our targets to compare them with other AGNs.

3.2.1. Temperature and Density

We determined the temperature of the NLR gas using the [O III] (λ4959 + λ5007)/λ4363 ratio as outlined in Osterbrock (1989):

\[
\frac{[\text{O III}]}{\lambda 4363} \left( \frac{\lambda 4959 + \lambda 5007}{\lambda 4363} \right) \simeq \frac{7.73 \exp (3.29 \times 10^4 / T)}{1 + 4.5 \times 10^{-3} (n_e / T^{1/3})},
\]

where \( n_e \) is electron density and \( T \) is gas temperature. With typical values of \( n_e = 10^3-10^4 \) cm\(^{-3}\) and \( T = 10^4 \) K, the dependence on \( n_e \) is negligible.

For PG1307+085, we were able to measure temperature and density using [O III] and [S II] line ratios from the center toward the south. The derived temperature is 25,500 ± 11,700 K at 3′′, decreasing with radial distance to 13,400 ± 11,700 K at 3′/6 (∼9.7 kpc). Using the same methods, Bennett et al. (2006a, 2006b) estimated the average temperature of four Seyfert 1 and four Seyfert 2 galaxies in the nuclear region as 33,590 ± 7070 K and 14,470 ± 440 K, respectively, while Greene et al. (2011) estimated a temperature range of \( T = 11,000-23,000 \) K for 15 type-II QSOs. Note that the measurements of the Seyfert galaxies in Bennett et al. (2006a, 2006b) included reddening correction determined from the Balmer decrement, while Greene et al. (2011) and this work did not correct for reddening. Note also that the physical scale in each measurements differs: for the Seyfert galaxies it corresponds to a few pc in the center, while for the type-II QSOs in Greene et al. (2011), it corresponds to 3′ fiber aperture of SDSS spectra, covering ∼11 kpc at the median redshift. Although a direct comparison is not straightforward, the type-I QSO PG1307+085 reaches lower temperature at the center compared to Seyfert 1 galaxies and similar to type-II QSOs.

The density was measured in a standard way from the [S II] λ6716/6731 ratio using the IRAF temden task,\(^8\) correcting for the effect of temperature using the derived values. The derived density ranges between 584 and 169 cm\(^{-3}\), decreasing with radial distance (0″-2″). These values are similar to the mean density \( n_e = 335 \) cm\(^{-3}\) of type-II QSOs estimated by Greene et al. (2011), and slightly lower than the mean nuclear density of Seyfert galaxies: 1070 ± 180 cm\(^{-3}\) for Seyfert 1 galaxies (Bennett et al. 2006a) and 1100 ± 315 cm\(^{-3}\) for Seyfert 2 galaxies (Bennett et al. 2006b). However, one should note that the nuclear density varies in a wide range (∼300-2500 cm\(^{-3}\)) among Seyfert 1 and 2 galaxies studied by Bennett et al. (2006a, 2006b), and it is not yet clear if the difference is significant. The higher and denser NLR of type-I QSOs can be a natural result of a dusty torus blocking the central region in type-II QSOs.

\(^8\) http://stds.stsci.edu/nebular/temden.html
3.3. Black Hole Masses and Stellar-velocity Dispersion

We estimate BH masses from the velocity and size of the BLR based on virial assumptions (e.g., Woo & Urry 2002; Park et al. 2012). In practice, we use the single-epoch virial mass estimator using the AGN continuum luminosity at 5100 Å ($L_{5100}$) and the line dispersion of the broad Hβ line $\sigma_{H\beta}$. From the nuclear spectra extracted with an aperture of 2″ radius, including >99% of the light, we measure $L_{5100}$ and $\sigma_{H\beta}$, after subtracting Fe II contamination. Compared to the values from Vestergaard & Peterson (2006), our $L_{5100}$ is 0.77 dex smaller probably due to slit losses. Therefore, we use $L_{5100}$ from Vestergaard & Peterson (2006).

Assuming a virial factor of $\log f = 0.72$ (Woo et al. 2010), we calculate $M_{BH}$. Recently, Park et al. (2012) reported the systematic difference of the Hβ line profile between the single-epoch and the rms spectra. Correcting for this effect using Equation (13) in Park et al. (2012), the mass estimates of $M_{BH}$ are decreased by $\sim0.18$ dex (Table 2). The estimates are consistent with those given in Vestergaard & Peterson (2006) within the errors of single-epoch BH mass ($\sim0.46$ dex).

For PG1012+008, we can also measure stellar-velocity dispersion since we clearly detect the host galaxy (at 2″ from the center). Due to the combined effect of the contamination from the AGN continuum and emission lines, and the presence of 4000 Å break, we consider the measurement based on the Ca H+K absorption lines as uncertain. In the case of the G-band region, broad Hγ affects the fitting. Thus, stellar-velocity dispersion is determined using the spectral range 5030–5300, including several strong stellar lines such as the Mg i triplet (5172 Å) and Fe (5270 Å) (e.g., Woo et al. 2006, 2008; Greene & Ho 2006).

Both measurements now enable us to place the PG1012+008 on the $M_{BH}$–$\sigma$ relation in Figure 5, where the 24 reverberation-mapped AGNs and the best-fit $M_{BH}$–$\sigma$ relation from Woo et al. (2010) are overplotted for comparison. Note that the stellar-velocity dispersion of PG1012+008 is measured at 2″ from the center, and can thus be considered a lower limit for the luminosity-weighted velocity dispersion of the bulge since the velocity dispersion generally increases toward the center (e.g., Kang et al. 2013). Even when taking into account an expected shift to the right, the object falls onto the local $M_{BH}$–$\sigma$ relation (Figure 5), indicating that at least this low-$z$ high-luminosity QSO is following the same $M_{BH}$–$\sigma$ relation.

4. DISCUSSION AND SUMMARY

We investigated the kinematics and physical condition of the NLR in two type-I QSOs, PG1012+008 and PG1307+085, using spatially resolved spectroscopy. The emission from the NLRs of these two targets is dominated by a central point source with slight deviation from the expected PSFs. However, modeling the Hβ–[O iii] region of the outer spectra clearly reveals the spatially extended weak NLR out to $r \approx 2″$ (6 kpc) from the center, spanning a larger extent than previously reported from HST [O iii] images by Leipski & Bennert (2006) due to the increase in depth of our observations. The [O iii] line of the nuclear spectrum of both targets shows blue wings and broad widths with FWHM velocities exceeding 500 km s$^{-1}$. However, the same feature is not present in the outer spectra, indicating that the outflow is confined within the PSF size ($\sim2$ kpc) and does not extend to galactic scales.

Compared to similar studies of type-II QSOs (Humphrey et al. 2010; Greene et al. 2011), the NLR of the two type-I QSOs studied here appears to be less extended. Due to the small sample size, and the intrinsic difficulty of inferring the true “size” of emission in long-slit observations, we are unable to draw a conclusion on whether type-I QSOs actually have less extended NLRs. Recently, Husemann et al. (2013) carried out an integral-field spectroscopy of a large sample of nearby type-I QSOs revealing a typical size of 10 kpc, similar to that of type-II QSOs studied by Greene et al. (2011). They also caution that the difference between the size determined by long-slit spectroscopy and the size based on a two-dimensional spectroscopy is on average a factor of two, and can be as high as a factor of six. Even so, the mean size of NLRs in type-I QSOs determined by Husemann et al. (2013) seems to be smaller than

![Figure 5. PG1012+008 on the $M_{BH}$–$\sigma$ relation. Black data and fit are taken from Woo et al. (2010). Our target is marked as a red circle with the arrow indicating that the stellar-velocity dispersion measured at $\pm2″$ is a lower limit to the true luminosity-weighted bulge velocity dispersion.](image)

(A color version of this figure is available in the online journal.)
that of type-IIs (28 kpc) based on a comparable integral-field spectroscopy by Liu et al. (2013), although these type-II QSOs are at a slightly higher redshift.

The lack of galactic scale outflows in type-I QSOs has also been pointed out by Husemann et al. (2013). Out of 31 type-I QSOs in their study, only three show kiloparsec-scale outflow, and the spectra of extended emission generally show narrower [O III] line profile than the central QSO spectrum. In the framework of the unified model of AGNs (Antonucci 1993), while the outflow in the projected plane may look less extended in type-Is than type-IIs, the projected velocity is expected to be larger as we look directly into the ionization cone. However, it is not yet clear whether type-IIs have larger projected outflow velocities than type-IIs (see Husemann et al. 2013; Liu et al. 2013). At the same time, although the [O III] emission is expected to be more elongated or biconical for type-II QSOs, the morphology of [O III] emission seems to be more elongated in type-I QSOs (Husemann et al. 2013). It is possible that in a merger-driven evolutionary scenario (e.g., Sanders et al. 1988), AGN feedback in the ionized gas occurs mainly in the obscured (type-II) phase. The sample probed here may still not be quite luminous enough to drive galactic wide energetic outflows that expel gas from the host galaxy and quench star formation as those found at high redshift (e.g., Cano-Díaz et al. 2012). Solid evidence for large-scale outflows related to AGN feedback still remains elusive.

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