THE HOST GALAXY AND THE EXTENDED EMISSION-LINE REGION OF THE RADIO GALAXY 3C 79

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1. INTRODUCTION

Low-redshift quasars are often surrounded by massive ionized nebulae showing filamentary structures on scales of a few tens of kpc. More specifically, about 40% of the quasars at $z < 0.5$ that are also steep-spectrum (i.e., usually FR II type) radio sources show such extended emission-line regions (EELRs) with an [O III] $\lambda$5007 luminosity greater than $4 \times 10^{41}$ ergs s$^{-1}$. Here we focus our discussion on these steep radio spectrum quasars, because (1) they are possibly the counterparts of FR II radio galaxies like 3C 79 and (2) the presence of a powerful radio jet seems to be a necessary (although not sufficient) condition for producing a luminous EELR, as implied by the correlation between the radio spectral index and the extended optical emission (Boroson & Oke 1984; Stockton & MacKenty 1987).

An EELR typically has a mass of $10^9$–$10^{10} M_\odot$, displays globally disordered kinematics, and shows a complex morphology that bears no obvious relation either to the host galaxy or to the extended radio structure (Stockton & MacKenty 1987; Fu & Stockton 2006, 2007b; see Stockton et al. 2006 for a review). In terms of quasar luminosity, host galaxy luminosity, and black hole mass, the quasars that show EELRs (hereafter the “EELR quasars”) do not differ significantly from non-EELR quasars. But the former are all low-metallicity quasars. The gas metallicity in their broad-line regions (BLRs) is significantly lower ($\leq 0.6 Z_\odot$) than that of non-EELR quasars ($> 1 Z_\odot$; Fu & Stockton 2007a). Although this gas-phase metallicity is unexpectedly low for galaxies with the masses found for these quasar hosts, it is consistent with that in their EELRs. Combining all of the pieces together, the most likely scenario for the origin of an EELR is that it comprises gas that is native to a gas-rich galaxy that merged with the quasar host and triggered the quasar activity, after which a large fraction of the gas was impulsively swept out by a large–solid-angle blast wave (i.e., a superwind), in a manner similar to that envisioned for quasar mode feedback in the early universe (e.g., Di Matteo et al. 2005).

3C 79 ($z = 0.256, 1'' = 4$ kpc)$^2$ is a narrow-line radio galaxy having FR II radio jets with a central component (Hes et al. 1995; Spangler et al. 1984; Hardcastle et al. 1997). Hubble Space Telescope (HST) WFPC2 broadband images show a complex optical morphology—a bright elliptical galaxy with an effective radius of 7.5 kpc, accompanied by multiple tidal arms and two distinct “cores” other than the nucleus (Dunlop et al. 2003; de Koff et al. 1996). As we show in § 3.1, only the galaxy and the “core” south-west of the nucleus are true continuum sources; the rest are all line-emitting regions. The nuclear spectra of 3C 79 show stellar absorption lines and a red continuum, indicating an old stellar population (Miller 1981; Boroson & Oke 1987). A line-emitting region...
region in a curving filament extending 12" to the northwest of the galaxy was seen in an Hα image and was subsequently confirmed by a slit spectrum covering the [O III] λλ4959, 5007 region (McCarthy et al. 1995, 1996). The spectrum also shows emission-line clouds between the filament and the nucleus, as well as clouds extending 5" to the southeast. An [O III] λ5007 image taken in much better seeing (Stockton et al. 2006) shows a very rich morphology and an emission-line luminosity comparable to that of the EELRs around steep-spectrum radio-loud quasars, establishing that 3C 79 is associated with an EELR.

In line with the orientation-based unification schemes of FR II radio galaxies and radio-loud quasars (Barthel 1989), we believe that 3C 79 belongs to the same class of object as the EELR quasars, such as 3C 249.1 and 4C 37.43, but it is viewed at a different angle with respect to the molecular torus surrounding the central engine. If this is true, then the unique geometry of radio galaxies such as 3C 79 could afford us a natural coronagraph blocking the blinding glare from the central engine. Such objects can be especially useful for studies of their host galaxies, which potentially preserve a large amount of information regarding the forces that have sculpted these spectacular emission-line regions.

In this paper, we study the host galaxy and the EELR of 3C 79 with extensive ground-based spectroscopy in combination with a reanalysis of archival *HST* WFPC2 multiband images. First, we briefly describe our observations and data reduction procedures in § 2. In § 3 we study the morphology, stellar kinematics, and stellar populations of the host galaxy. We then demonstrate the similarities between the 3C 79 EELR and the ones around quasars, in terms of gas kinematics, pressure, ionization mechanism, and metallicity, in § 4. Finally, we discuss our main results in § 5 and close with a summary in § 6.

2. OBSERVATIONS AND DATA REDUCTION

2.1. GMOS Integral Field Spectroscopy

We observed 3C 79 with the Gemini Field Unit (IFU; Allington-Smith et al. 2002) of the Gemini Multiobject Spectrograph (GMOS; Hook et al. 2004) on the Gemini North telescope. The observations were performed on the night of 2006 December 21 (UT). Three exposures of 2880 s were obtained using the half-field mode with the B600/G530 grating at a central wavelength of 6242 Å. With this setting, we had a field of view (FOV) of 3.5′ × 5′, a wavelength range of 4100–6900 Å, a dispersion of 0.46 Å pixel−1, and an instrumental full width at half-maximum (FWHM) of 4.5 pixels (2.1 Å). The host galaxy was placed at the lower left corner of the IFU field so that a large fraction of the western part of the EELR could be covered (Fig. 1). Feige 34 was observed for flux calibration.

The data were reduced using the Gemini IRAF package (ver. 1.8). The data reduction pipeline (GFRUDEUCE) consists of the following standard steps: bias subtraction, spectral extraction, flat-fielding, wavelength calibration, sky subtraction, and flux calibration. Cosmic-ray rejection was performed by L.A. Cosmic (van Dokkum 2001) before running the data through the reduction pipeline, with careful adjustment of the parameters to avoid misidentification of real data. Spectra from different exposures were assembled and resampled to construct individual data cubes (x, y, λ) with a pixel size of 0.05″ (GFCUBEx). To correct for the differential atmosphere refraction (DAR), we first binned the data cubes along the wavelength direction to increase the signal-to-noise ratio (S/N) of the host galaxy; then the centroid of the galaxy was measured for each bin, and a polynomial was fit to the (x, y) coordinates, restricted by the fact that DAR only causes the centroids to vary along a straight line in (x, y) plane (at the parallactic angle).

2.2. LRIS Long-Slit Spectroscopy

We obtained optical long-slit spectroscopy of 3C 79 on the night of 2007 October 17 (UT) with the Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on the Keck I telescope. The Cassegrain Atmospheric Dispersion Compensator3 (Cass ADC) was used during the observation. We took two 1200 s exposures through a 1″ slit centered on the nucleus at a position angle of 142° (Fig. 1). On the blue arm, we used the 600 groove mm−1 grism blazed at 4000 Å, while on the red arm, we used the 400 groove mm−1 grating blazed at 8500 Å, offering, respectively, wavelength ranges of 3100–5600 Å and 5100–8900 Å and spectral resolutions of 4 and 7 Å (FWHM). The spectra were taken at low air mass (~1.1), and the seeing was about 0.7″ throughout the night.

The spectra were reduced in the standard fashion using IRAF tasks. The blue arm spectra were wavelength-calibrated using observations of arc lamps, while for the red arm spectra we used night-sky lines. Background sky was removed by fitting low-order cubic splines to the regions on each side of the object along the slit direction using BACKGROUND. One-dimensional spectra of 3C 79 were first extracted with a wide (11″) aperture, and they were flux-calibrated and corrected for atmospheric absorption using the spectrophotometric standard Wolf 1346 (taken 5 minutes after the nautical twilight earlier in the night). The calibrated spectra from the two arms agree perfectly in their overlapping region. Then, one-dimensional spectra of high S/N were obtained using a 2″ extraction aperture. These spectra were multiplied by

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3 See http://www2.keck.hawaii.edu/inst/adc/docs.
appropriate smooth curves so that their continua match those of the wide-aperture spectra. Finally, the blue and the red sides, after flux calibration and atmospheric absorption correction, were joined and binned to a common linear dispersion (1.86 Å per pixel) using SCOMBINE. The line-of-sight Galactic reddening ($A_V = 0.421$; Schlegel et al. 1998) was corrected with a standard reddening curve (Cardelli et al. 1989). We obtained an absolute flux calibration by scaling the spectrum to the HST photometry result from § 3.1 ($F_i = 1.8 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$ between 6300 and 7300 Å).

2.3. HST WFPC2 Imaging

To study the host galaxy morphology, we obtained WFPC2/WFC F675W ($4 \times 565$ s) and FR680N ($2 \times 1300$ s) images, and a WFPC2/PC F702W ($2 \times 140$ s) image of 3C 79, available from the archive of the HST. The two broadband images have been previously presented by Dunlop et al. (2003) and de Koff et al. (1996). The linear ramp filter (LRF; FR680N) image has a central wavelength of 6284 Å and a bandpass FWHM of 82 Å at the position of 3C 79; i.e., the filter is centered on the redshifted [O iii] $\lambda$5007 emission line. Images observed with LRFs are not flat-field calibrated in the calibration pipeline, so we flattened the LRF image with an F631N flat-field reference image. Additional cosmic rays after the standard pipeline reduction were identified and replaced by L.A.Cosmic (van Dokkum 2001), again with careful adjustment of the parameters to avoid misidentification of real data.

3. THE HOST GALAXY

3.1. Galaxy Morphology

Although the WFC2 F675W image is dominated by continuum radiation, the H/3 and [O iii] $\lambda$4959, 5007 lines fall on the shortward wing of the filter profile, where the transmissions are about 42%, 76%, and 85%, respectively. To study the morphology of the host galaxy, one has to remove the line-emitting regions from the image. We thus rotated the WFC3 LRF [O iii] image to the orientation of the F675W image, shifted and scaled the image to match the F675W image, and finally subtracted it from the wide-band image to obtain an emission-line–free image (hereafter the F675W* image; Fig. 2). A close companion 0.8" southwest of the major host galaxy is seen in the F675W* image, which we designate 3C 79A. The host galaxy itself is simply called 3C 79 in this section.

3C 79A is better sampled in the PC1 F702W image, so we used this image to study its morphology. We used C. Y. Peng’s GALFIT software (Peng et al. 2002) to fit the two-dimensional galaxy profile, and we used an oversampled Tiny Tim point-spread function (PSF). The result is shown in Figure 3. As indicated by the best-fit Sérsic index of $n = 1.23$, the profile is close to an exponential. As shown by the residuals, the exponential model clearly provides a better fit than the de Vaucouleurs model.

We chose to use the F675W* image to study the morphology of 3C 79. We converted the geometric parameters from the best-fit exponential model of 3C 79A (effective radius, axis ratio, and position angle [P.A.]) to the WFC image and froze them; however, we allowed the position and magnitude of 3C 79A to vary in the modeling of 3C 79. Figure 4 shows that 3C 79 can be described by a de Vaucouleurs model, as indicated by the high Sérsic index. Table 1 summarizes the morphology results. The P.A. of the minor axis of 3C 79 is aligned within 5° to the direction of the radio jets (as defined by the hot spots; see Fig. 1). The companion galaxy 3C 79A is located 0.84" (3.3 kpc) southwest of 3C 79, and its P.A. is aligned within 7° to the direction of the host galaxy.

Dunlop et al. (2003) modeled the 3C 79 host galaxy with a de Vaucouleurs model (plus a concentric PSF to account for the narrow-line region [NLR]). For comparison, their results are also shown in Table 1. Dunlop et al. used the original F675W image; i.e., the emission-line regions were not removed; thus they overestimated the brightness of the galaxy and had a poor estimate for the axis ratio and P.A. We were able to reproduce their results using GALFIT when modeling the original F675W image.

3.2. Stellar Kinematics

We extracted the host spectrum from the final combined GMOS data cube using a 0.5" (2 kpc) radius aperture. Although the GMOS spectrum shows a poorer S/N in comparison with the LRIS spectrum, it has a better spectral resolution (2.1 Å FWHM as opposed to 7 Å), making it best suited for measuring stellar kinematics. We chose to use the stellar synthesis models of Vazdekis (1999) to fit the data. Although these models have very

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4 See http://www.stsci.edu/software/tinytim/tinytim.html.
5 We chose such a small aperture because (1) it yields the best S/N ratio compared to apertures of other sizes and (2) it avoids hitting the edges of the FOV at short wavelengths.
limited spectral coverage compared with those of Bruzual & Charlot (2003), they have a better spectral resolution (\~1.8 Å), which is similar to that of the GMOS spectrum, and they do cover the spectral region where the spectrum show the highest S/N (S/N \~ 33 at rest-frame wavelengths of 4800 Å \~ 5500 Å). For the modeling we used M. Cappellari’s IDL program,\textsuperscript{6} implement- ing the pixel-fitting method of Cappellari & Emsellem (2004). The program finds the best fit to the data by convolving the model templates with a line-of-sight velocity distribution (LOSVD). Since we used a Gaussian function to parameterize the LOSVD, the program reports the mean stellar velocity (\( V' \)) and velocity dispersion (\( \sigma' \)). In Figure 5 we plot our best-fit model against the data. Following Emsellem et al. (2004), we included a multiplicative Legendre polynomial of degree 6 in the fit to correct the model continuum shape. The kinematics results are insensitive to the assumed model age, although \( \chi^2 \) increases rapidly for models younger than 3 Gyr and the oldest population yielded the minimum \( \chi^2 \). Using a Monte Carlo approach, we found that the 1 \( \sigma \) uncertainties of \( V' \) and \( \sigma' \) are both about 11 km s\textsuperscript{-1}. These errors should be regarded as lower limits, since they do not account for the effect of the template and continuum mismatch. Assuming a negligible amount of systematic rotation, the measured velocity dispersion of \~236 km s\textsuperscript{-1} implies a virial mass of \( 5R\sigma^2/G = 1.3 \times 10^{11} M_\odot \) within 2 kpc from the galaxy center. We estimated the luminosity-weighted velocity dispersion within \( r_{1/2} \) (7.2 kpc) to be \( \sigma_{1/2} = 218 \pm 20 \text{ km s}^{-1} \), with the aperture correction function for SAURON elliptical galaxies, \( (\sigma_{1/2}/\sigma') = (r_{1/2}/r)^{-0.066 \pm 0.035} \) (Cappellari et al. 2006). The viral mass inside \( r_{1/2} \) is then \( M_{1/2}^{\text{vir}} = 4.0^{+0.8}_{-0.6} \times 10^{11} M_\odot \).

3.3. Stellar Population

To study the stellar population of the host galaxy, we have performed detailed continuum modeling on the 3C 79 nuclear spectrum obtained from LRIS. The host galaxy shows a strong UV excess (Fig. 6) and a broad (FWHM \~ 6500 km s\textsuperscript{-1}) Mg \~ \( \lambda 2798 \) line (Fig. 7), but no broad H\textalpha{} or H\beta{} lines are seen. These characteristics seem to closely resemble the radio galaxy Cygnus A (Antonucci et al. 1994; Ogle et al. 1997), implying a significant scattered quasar component. In addition, stellar absorption features are evident (Ca \~ K \~ \( \lambda 3933 \), the G-band \~ \( \lambda 4300 \), the Mg \~ \( \lambda 5175 \), etc.), implying a dominating old stellar population (OSP). As a first guess, we tried to model the continuum with three components: (1) a nebular continuum (at \( T = 10,000, 15,000, \) and 20,000 K), (2) a power law (\( F_\nu \propto \nu^{\alpha} \); \( -0.4 \leq \alpha \leq -1.8 \)) in accordance with the composite UV/optical quasar spectrum; Vanden Berk et al. (2001), and (3) an OSP (7 Gyr \~ \leq \( \leq 10 \) Gyr\textsuperscript{8}; and \( Z = 0.2, 0.4, 1.0, \) and 2.5 \( Z_\odot \); \( Z_\odot = 0.02 \)). The same IDL program was used in the modeling as in \S 3.2, but this time we did not include polynomials to adjust the model continuum shape. Since the nebular continuum scales with the Balmer lines, we required the H\textgamma{} flux from the models to be within 5\% of the measured flux.

Figure 6a shows the best-fit three-component model (i.e., the model that produces the least \( \chi^2 \)), which is a combination of a 9 Gyr old 2.5 \( Z_\odot \) population, a nebular continuum at \( T = 15,000 \) K, and a \( \nu^{\alpha} \) power law with \( \alpha = -1.4 \). This model fits both the continuum shape and most of the absorption features; however, it underpredicts the Ca \~ K line and the G band. This inadequacy can be removed once we introduce a fourth component—an intermediate-age stellar population (1 Gyr \~ \leq \( \leq 3 \) Gyr\textsuperscript{9}; and \( Z = 0.2, 0.4, 1.0, \) and 2.5 \( Z_\odot \)). Figure 6b displays the best-fit four-component model, which successfully reproduces the Ca \~ K line and the G-band absorption. The global best fit to the data is given by stellar population models with a metallicity of 2.5 \( Z_\odot \).

\textsuperscript{8} Applying an additive Legendre polynomial of similar degree led to consistent results.

\textsuperscript{9} At \( z = 0.256 \) the age of the universe is 10.4 Gyr.
absorption features and the overall continuum shape, except that it cannot reproduce the high S/N continuum shape around the Mg\textsc{i}b feature between 5000 and 5500 Å (rest frame), resulting in a 16% increase in the $\chi^2$ value relative to the 2.5 $Z_\odot$ model. Models with subsolar metallicities all fail to give an adequate fit, especially in the continuum below 4300 Å (rest frame). We thus conclude that the stellar population in the host galaxy has a supersolar metallicity. A conservative range of metallicities that can give an adequate fit to the LRIS spectrum is between 1 and 2.5 $Z_\odot$.

We have also attempted to use a young stellar population (<0.1 Gyr) to replace the power-law component, but the best-fit model underpredicts the higher (\textgreater H7) Balmer lines if it correctly predicts the H\textgamma flux (due to the Balmer absorption lines from the young population), and it gives a much poorer fit to the rest-frame UV continuum (2900 Å < $\lambda_0$ < 3800 Å); in particular, it overpredicts the Balmer limit break at 3650 Å.

If we adopt the average total stellar mass from the two best-fit models shown in Figure 6, then the stellar mass inside $r_{1/2}$ is
The compact companion galaxy 3C 79A is detected in the GMOS data cube. The comparison of the spectrum extracted from 3C 79A and a background spectrum from a symmetric location with respect to the minor axis of the host galaxy shows a red continuum, indicating an old stellar population for 3C 79A. This galaxy is reminiscent of the close companion galaxy 1'' away from the EELR quasar 3C 48 (Stockton et al. 2007), which is also elongated toward the active galactic nucleus (AGN). The S/N of the spectrum does not allow a detailed modeling.

4. THE EXTENDED EMISSION-LINE REGION

The HST LRF [O iii] image (Fig. 1) shows not only the filament seen in the Hα image of McCarthy et al. (1995), but also luminous emission-line arms at distances around 2.5'' from the nucleus and an inner arc 1'' to the west. To compare the EELR of 3C 79 with those around quasars, we determined the total luminosity in the [O iii] $\lambda$5007 line within an annulus of inner radius 11.2 kpc and outer radius 44.9 kpc ($L_{[O\ iii]}$). We found a luminosity of $L_{[O\ iii]} = 7.8 \times 10^{42}$ ergs s$^{-1}$, close to that of the most luminous quasar EELR at $z < 0.5$, i.e., that of 4C 37.43, $L_{[O\ iii]} = 9.4 \times 10^{42}$ ergs s$^{-1}$ (converted from Stockton & MacKenty 1987). As a reference, the least luminous detected EELR in the radio-loud quasar subsample of Stockton & MacKenty (1987) has a luminosity about 10 times lower ($PKS\ 2135-147$, $L_{[O\ iii]} = 6.8 \times 10^{41}$ ergs s$^{-1}$).

4.1. Gas Kinematics

The kinematics of the ionized gas can be measured from strong emission lines. Since a single 48 minute GMOS exposure is enough to acquire a good S/N in the [O iii] $\lambda$5007 line region, we derived the velocity fields from the single data cube that has the smallest air mass (AM = 1.172) and the best seeing. To study the velocity structure for the clouds in the inner arc that is only 1'' from the nuclear NLR, we subtracted the light from the NLR and the bright nearby cloud 0.5'' east to the NLR by simultaneously fitting two Moffat PSF profiles at each wavelength in the wavelength range where both clouds are apparent. After trials, it was found that the best subtraction results came from using the best-fit Moffat profile from modeling the Feige 34 data cube over the same wavelength range, indicating that both data cubes have the same resolution (FWHM $\approx 0.5''$ at the [O iii] region). We then fixed the Moffat parameters to those of the standard star and let the positions and magnitudes vary. Finally, we fixed the positions to the average values across the wavelength range from the previous fit and performed the fit with only the magnitudes as free parameters. The resulting PSF-subtracted data cube is presented as a set of velocity channel maps in Figure 8. The velocity field is shown in Figure 9. The velocity dispersion measurements have been corrected for the $\sigma_0 = 42$ km s$^{-1}$ instrumental resolution.

$M_{1/2} = 2.6 \times 10^{11} M_\odot$. The $M_{1/2}/M_{1/2}^{\text{vir}}$ ratio implies a dark matter fraction of $\sim 34\%$ within one effective radius, in agreement with the dark matter fraction of nearby early-type galaxies (Cappellari et al. 2006). We caution that there are significant uncertainties in both the stellar mass derived from single-burst stellar synthesis models and the dynamical mass using the virial theorem. Hence, this straightforward calculation of dark matter content is subject to an error of at least a factor of 2. We note that the absolute R-band magnitude$^9$ of the galaxy is about $-23.2$, which is the same as that of the host galaxies of EELR quasars (Fu & Stockton 2007a).

The compact companion galaxy 3C 79A is detected in the GMOS data cube. The comparison of the spectrum extracted from 3C 79A and a background spectrum from a symmetric location with respect to the minor axis of the host galaxy shows a red continuum, indicating an old stellar population for 3C 79A. This galaxy is reminiscent of the close companion galaxy 1'' away from the EELR quasar 3C 48 (Stockton et al. 2007), which is also elongated toward the active galactic nucleus (AGN). The S/N of the spectrum does not allow a detailed modeling.

| Galaxy         | Model    | F675W$^a$ | F702W$^a$ | $r_{1/2}$ \((\text{kpc})\) | $n^b$ | $b/a$ | P.A. |
|---------------|----------|-----------|-----------|-----------------|------|------|-----|
| 3C 79A............. | Sérsic   | ...       | 22.19     | 0.22            | 1.23 | 0.49 | 18.2|
| 3C 79 ............... | Exponential | 22.24     | 22.23     | 0.22            | (1)  | 0.48 | 18.0|
| 3C 79 ............... | Sérsic   | 18.06     | ...       | 10.1            | 5.21 | 0.70 | 6.2 |
| Dunlop$^c$............ | de Vaucouleurs | 18.24     | ...       | 7.2             | (4)  | 0.71 | 5.7 |
| Dunlop$^c$............ | de Vaucouleurs | 17.46     | ...       | 7.5             | (4)  | 1.0  | 13  |

$^a$ ST magnitudes corrected for Galactic extinction (for details about the ST magnitude system, see http://www-int.stsci.edu/instruments/wfpc2/Wfpc2_pho/wfpc2_cookbook.html).
$^b$ Sérsic indexes.
$^c$ Converted from Dunlop et al. (2003) Table 3 to our cosmology.

$^9$ Converted from the F675W ST system (see http://www-int.stsci.edu/instruments/wfpc2/Wfpc2_pho/wfpc2_cookbook.html) to the $R$-band Vega ($-0.7$ mag), after applying $k$-correction ($-0.27$) and passive evolution correction ($+0.23$), following Labita et al. (2006).

$^{10}$ The continuum shape did not change much after we corrected it for the fixed-aperture effect (Fu & Stockton 2007b).

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Fig. 5.— Modeling the kinematics of the central part ($r \leq 2$ kpc) of the 3C 79 host galaxy. The GMOS/IFU rest-frame spectrum of 3C 79 host galaxy is plotted in black, with spectral regions excluded from the modeling highlighted in blue (including nuclear emission lines and a CCD chip defect). Overplotted in red is the best-fit instantaneous-burst model of Vazdekis (1999) with the metallicity and age labeled in red. Also labeled are the measured radial velocity of the stars relative to that of the NLR ($v = 0.25632$) and the stellar velocity dispersion. The residual after being offset by $8 \times 10^{17}$ ergs cm$^{-2}$ s$^{-1}$ A$^{-1}$ is shown with diamonds, and the dotted line going through the residual indicates the zero level.

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$^{11}$ This is equivalent to the 10 kpc/40 kpc annulus used by Stockton & MacKenty (1987), since they assumed an empty universe with $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$. $^{12}$ The two clouds have essentially the same velocity at $z = 0.25632 \pm 0.00001$. 

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TABLE 1

MORPHOLOGY OF THE 3C 79 HOST GALAXY AND ITS CLOSE COMPANION
Due to the imperfect PSF subtraction process, no useful kinematics can be extracted from the PSF-subtracted data cube in the nuclear region bordered by the white no-data pixels in Figure 9. Hence, we measured the velocity field in this region from the original data cube and inserted the results into the final velocity field.

Most of the extended emission comes from two main filaments—the inner arc and the outer arm 2.5" from the nucleus. Both filaments show similar velocity gradients, with the northern part approaching us and the southern part receding from us at velocities of $v < 200$ km s$^{-1}$. Together, these two filaments are consistent with a common disk rotation with a flat rotation curve. This sort of locally ordered kinematics of the brighter clouds is reminiscent of that of the three most luminous clouds southeast of 3C 249.1 (Fu & Stockton 2006). However, the much fainter clouds outside the outer arc disrupt this simple picture by showing large approaching velocities.

The velocity dispersion over most of the region is around 50 km s$^{-1}$. The region showing large $(150 - 200$ km s$^{-1}$) between the inner arc and the outer arm, although roughly coincident with the jet direction, in fact also has multiple velocity components that happen to contribute light to the same pixels.
Overall, the velocity field of the 3C 79 EELR is similar to those of the quasar EELRs, in the sense that all of them appear globally disordered but locally ordered, and they all show supersonic velocity dispersions (sound speed $c_s \sim 17 \text{ km s}^{-1}$) within the same range between 50 and 130 km s$^{-1}$ (Fu & Stockton 2006, 2007b).

### 4.2. Spectra of Emission-Line Clouds

To increase the S/N, we have combined GMOS spectra within various regions. The spectra of the clouds in the inner arc ($r \lesssim 1.2''$) are heavily contaminated by light from the nuclear NLR, making it difficult to measure their line intensities accurately. We therefore concentrated on the EELR clouds in the outer arm and beyond. In Figure 8 we have shown the extraction apertures for the four EELR clouds. We have also extracted a NLR spectrum using a circular aperture with a radius of 0.3''. In order to measure the key metallicity diagnostic—the $\text{[N II]}/H\alpha$ ratio—we extracted LRIS spectra from three regions along the slit: a 2'' wide aperture centered on the nucleus was used for the nuclear NLR, and the apertures used for the N1 and S1 regions are shown in Figure 1.

Unlike those for the EELR clouds, NLR spectra should be corrected for stellar absorption features. We fitted the continuum using the same stellar synthesis model templates as in §3.3 and...
| Region          | [Ne v] λ3426 | [O ii] λ3727 | [Ne iii] λ3869 | [O iii] λ4363 | Hβ       | Hα      | [O iii] λ5007 | [N ii] λ5199 | [N ii] λ6584 |
|----------------|-------------|-------------|----------------|----------------|---------|---------|---------------|-------------|-------------|
| Gemini GMOS IFU |             |             |                |                |         |         |                |             |             |
| a................ | 0.83 ± 0.19 | 2.45 ± 0.16 | 0.65 ± 0.07    | 0.15 ± 0.05    | 0.33 ± 0.04 | 1.00 ± 0.05 | 9.32 ± 0.03   | <0.18       | ...         |
| b................ | 1.54 ± 0.43 | 3.25 ± 0.35 | 1.18 ± 0.19    | <0.49          | <0.33   | 1.00 ± 0.11 | 8.91 ± 0.08   | <0.47       | ...         |
| c................ | 0.53 ± 0.10 | 2.50 ± 0.16 | 1.01 ± 0.05    | 0.13 ± 0.03    | 0.26 ± 0.02 | 1.00 ± 0.02 | 10.39 ± 0.02  | 0.06 ± 0.02 | ...         |
| d................ | 1.38 ± 0.15 | 2.62 ± 0.09 | 1.19 ± 0.05    | 0.19 ± 0.02    | 0.29 ± 0.02 | 1.00 ± 0.02 | 11.52 ± 0.01  | 0.05 ± 0.02 | ...         |
| NLR............... | 1.057 ± 0.016 | 1.590 ± 0.015 | 0.944 ± 0.004 | 0.176 ± 0.003 | 0.302 ± 0.003 | 1.000 ± 0.004 | 10.923 ± 0.002 | 0.041 ± 0.004 | ...         |
| Keck LRIS Long Slit |             |             |                |                |         |         |                |             |             |
| N1................ | 0.60 ± 0.02 | 2.73 ± 0.02 | 1.09 ± 0.02    | 0.15 ± 0.03    | 0.28 ± 0.02 | 1.00 ± 0.02 | 10.63 ± 0.02  | <0.09       | 3.09 ± 0.03 |
| S1................ | 0.58 ± 0.04 | 2.92 ± 0.05 | 1.31 ± 0.04    | 0.27 ± 0.07    | <0.15   | 1.00 ± 0.04 | 11.83 ± 0.03  | <0.21       | 2.93 ± 0.07 |
| NLR............... | 1.093 ± 0.003 | 1.591 ± 0.015 | 0.921 ± 0.009 | 0.185 ± 0.008 | 0.297 ± 0.007 | 1.000 ± 0.008 | 10.602 ± 0.008 | 0.038 ± 0.017 | 3.100 ± 0.008 |

**TABLE 2**

LINE RATIOS OF 3C 79 LINE-EMITTING CLOUDS RELATIVE TO Hβ
The two instruments agree fairly well. The low intrinsic reddening of an emission line.

The emission-line ratios of the 3C 79 clouds are very similar to those of quasar EELRs. Previously we concluded that the spectra of quasar EELRs are most consistent with being photo-ionized by a quasar continuum and are inconsistent with shock or the self-ionizing shock + precursor models (Fu & Stockton 2007b). Now we reemphasize this point by comparing strong line ratios of the EELRs of the radio galaxy 3C 79 and the quasars 3C 249.1 and 4C 37.43 with emission-line galaxies at a similar redshift range. The Sloan Digital Sky Survey Data Release 4 (SDSS DR4) provides high-quality optical spectra for a large number of galaxies. The emission-line fluxes after correcting for stellar absorption and foreground extinction are publicly available. We first created a subsample of SDSS emission-line galaxies by including only those with S/N > 3 in the strong emission lines [O II] 3727, 3729, Hα, [O III] 5007, Hα, [N II] 6584, and [S II] 6717, 6731. Then we divided the sample into star-forming galaxies and AGNs, using the empirical dividing line of Kauffmann et al. (2003), and corrected for the intrinsic reddening using the Balmer decrement and the standard Galactic reddening curve (Cardelli et al. 1989). The theoretical values for the Hα/Hβ ratio are 2.85 for star-forming galaxies and 3.1 for AGNs. Finally, we classified the galaxies into Seyfert, LINERs, star-forming galaxies, and AGN/star-forming composites, following the classification schemes of Kewley et al. (2006).

Figure 10 compares the locations of our EELRs and the distributions of the SDSS galaxies in two line ratio diagnostic diagrams. As can be seen, the EELRs share the same territory as the Seyfert galaxies, but are clearly distinguishable from star-forming and composite galaxies, indicating that the EELRs are photoionized by an AGN-type ionizing spectrum. The line ratios from the 3C 79 EELR match those from 3C 249.1 and 4C 37.43 very well, thus pure shock and shock + precursor models can be ruled out, since it has been shown (using the same line ratios) that these models do not fit these quasar EELRs (see Fig. 5 of Fu & Stockton 2007b for an example).

4.2.2. Ionization Mechanisms

The emission-line ratios of the 3C 79 clouds are very similar to those of the quasar EELRs. Previously we concluded that the spectra of quasar EELRs are most consistent with being photo-ionized by a quasar continuum and are inconsistent with shock or the self-ionizing shock + precursor models (Fu & Stockton 2007b). Now we reemphasize this point by comparing strong line ratios of the EELRs of the radio galaxy 3C 79 and the quasars 3C 249.1 and 4C 37.43 with emission-line galaxies at a similar redshift range. The Sloan Digital Sky Survey Data Release 4 (SDSS DR4) provides high-quality optical spectra for a large number of galaxies. The emission-line fluxes after correcting for stellar absorption and foreground extinction are publicly available. We first created a subsample of SDSS emission-line galaxies by including only those with S/N > 3 in the strong emission lines [O II] 3727, 3729, Hα, [O III] 5007, Hα, [N II] 6584, and [S II] 6717, 6731. Then we divided the sample into star-forming galaxies and AGNs, using the empirical dividing line of Kauffmann et al. (2003), and corrected for the intrinsic reddening using the Balmer decrement and the standard Galactic reddening curve (Cardelli et al. 1989). The theoretical values for the Hα/Hβ ratio are 2.85 for star-forming galaxies and 3.1 for AGNs. Finally, we classified the galaxies into Seyfert, LINERs, star-forming galaxies, and AGN/star-forming composites, following the classification schemes of Kewley et al. (2006).

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13 See http://www.mpa-garching.mpg.de/SDSS/DR4, and see Tremonti et al. (2004) for a description of the data.
4.2.3. Gas Metallicity

With the knowledge that the EELR of 3C 79 is photoionized by the hidden quasar, we can now estimate the metallicity of the gas using photoionization models. In the following, we compare our data with the dusty radiation-pressure–dominated photoionization models of Groves et al. (2004), with a density of 1000 cm$^{-3}$. Since the diagnostic line ratios we use are almost entirely dependent on the abundances, models adopting a different density will not change our results.

As the metallicity of a photoionized nebula increases, the temperature of the nebula decreases (as a result of the increased metal cooling), and the strengths of lines from heavy elements also increase with respect to hydrogen lines (due to the increased abundance of the heavy elements relative to hydrogen). The latter effect is especially strong for nitrogen lines, since the element is dominated by “secondary” production$^{14}$ at $Z \approx 0.2$ $Z_{\odot}$. Hence, N abundance increases at a much faster rate with metallicity, i.e., N/H $\propto Z^2$. In Figure 11a we use the temperature-sensitive [O iii] $\lambda4363$/H$\beta$ ratio to demonstrate the dependence of nebula temperature on metallicity. The stratification among the grids of different metallicities is further improved by the fact that helium increases linearly with metallicity relative to hydrogen (Pagel et al. 1992). In Figure 11b and Figure 12, respectively, we show the strong dependence of [N ii] $\lambda5199$/H$\beta$ and [N ii] $\lambda6584$/H$\alpha$ on metallicity. At each metallicity, we show models spanning a range of ionization parameters ($-2.3 \leq \log U \leq 0$) and four power-law indices from $\alpha = -1.2$ to $-2.0$, representing the quasar ionizing continuum ($F_\nu \propto \nu^\alpha$). We have converted the modeled total metallicities to gas-phase metallicities using the solar abundances defined by Anders & Grevesse (1989; $12 + \log (O/H)_\odot = 8.93$ and $Z_{\odot} = 0.02$), in order to be consistent with both previous studies on the metallicity of quasar BLRs and metallicity results from stellar populations ($\S$ 3.3). One solar metallicity in Groves et al. (2004) corresponds to $1/3$ $Z_{\odot}$ in our figures, since approximately half of the metals are assumed to be depleted onto dust in the composite galaxies, the background image) in line ratio diagrams: (a) [O iii] $\lambda4363$, 3729/H$\beta$ vs. [O ii] $\lambda5007$/H$\beta$ and (b) [O iii] $\lambda4363$, 3729/[Ne iii] $\lambda3869$ vs. [O ii] $\lambda5007$/H$\beta$. Measurements from the EELRs of 3C 79, 3C 249.1, and 4C 37.43 are shown as red open circles, violet filled circles, and blue squares, respectively (Fu & Stockton 2006, 2007b). Both diagrams clearly show that the EELRs are photoionized by an AGN-type ionizing spectrum.

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$^{14}$ Where nitrogen is synthesized from existing carbon and oxygen (Pagel & Edmunds 1981).
models, and their assumed solar metallicity is about 0.2 dex\(^{15}\) lower than that of Anders & Grevesse (1989).

As can be seen in Figures 11 and 12, the line ratios of the EELR, as well as the NLR of 3C 79, like those quasar EELRs and their BLRs, are most consistent with a low metallicity, about 1/3–2/3 solar. Figure 12 illustrates the peculiarity of 3C 79 more clearly by comparing it directly with SDSS AGNs on the same line ratio diagnostic. The nuclear NLR and the two other regions where we have [N\textsc{ii}] measurements all lie on the lower metallicity side of the main Seyfert branch, overlapping the quasar EELRs. This result supports the orientation-based unification schemes of FR II radio galaxies and radio-loud quasars (Barthel 1989). On the other hand, 3C 79 offers yet another example strengthening (1) the correlation between the presence of EELRs and the metallicity of the nuclear gas (BLRs and/or NLRs) and (2) the similar metallicity in EELRs and the gas in the nuclear region. Both correlations were initially discovered only among steep-spectrum radio-loud quasars (Fu & Stockton 2007a).

5. DISCUSSION

5.1. The Origin of the Low-Metallicity Gas

The great majority of quasars show supersolar metallicities in their nuclear regions (see Hamann et al. 2007 for a recent review); yet, as we have previously shown (Fu & Stockton 2007a), quasars with luminous EELRs are drawn exclusively from the subset of steep radio spectrum quasars that have BLRs with subsolar metallicities. The fact that the quasar host galaxies are almost always very massive and thus are expected to have high metallicities suggests an external source for the low-metallicity gas. Furthermore, the apparent link between the metallicity of the gas in the BLRs and the metallicity of the gas in the EELRs, which have minimum masses of $10^9$–$10^{10}$ $M_\odot$, means that the external source of the gas must itself have been moderately massive.

In 3C 79, we have an FR II radio galaxy that shows the same pattern. Although of course we cannot obtain a broad-line region metallicity in this case, we have used the unresolved nuclear narrow-line region metallicity as a surrogate. Aside from providing a consistency check on unified models for FR II radio galaxies and quasars, the main question of interest is whether the clearer view of the inner region of the host galaxy gives us any insight into the origin of the low-metallicity gas and the mechanism that produced the EELR.

The host galaxy of 3C 79 appears to be a fairly normal elliptical morphologically. The most intriguing feature in the inner region is the extremely compact galaxy 0.8" from the center of the host galaxy. The nearly exponential profile of this galaxy suggests that it could be a tidally stripped “pseudobulge” of a late-type galaxy (e.g., Kormendy & Kennicutt 2004); the interstellar medium of such a galaxy would be quite plausible as a source for the low-metallicity gas in 3C 79. We have suggested elsewhere (Stockton et al. 2007; Fu & Stockton 2007b) that luminous EELRs may result from nearly spherical blast waves connected with the initiation of FR II radio jets. The connection with low-metallicity gas is less clear, although we can speculate that it may have something to do with the lower radiative coupling such gas would have to the quasar radiation field, allowing more efficient accretion. It is interesting to note that related considerations have been invoked recently to explain the link between low metallicity and long-duration gamma-ray bursts (Fruchter et al. 2006) on the scale of massive stars, although the physical mechanisms involved are certainly different.

5.2. Low-Metallicity Radio Galaxies in SDSS

Armed with the latest photoionization models, Groves et al. (2006) identified ~40 (out of ~23,000) candidates of low-metallicity Seyfert 2 galaxies in SDSS. A caveat to note is that authors restricted the sample to galaxies with stellar masses lower than $10^{10} M_\odot$ while selecting their candidates, as guided by the mass-metallicity correlation (e.g., Tremonti et al. 2004). Although the EELR quasars are excluded from the SDSS emission-line galaxy sample, 3C 79 represents a population of low-metallicity AGNs that were missed by Groves et al. These AGNs are host to massive evolved galaxies with $\sim 10^{12} M_\odot$ of stars and harbor $\sim 10^9 M_\odot$ black holes at their hearts, and they are likely to be more powerful than the Seyfert 2 galaxies.

By cross-correlating the TEXAS radio galaxies (Douglas et al. 1996) with SDSS DR4 AGNs, we have identified a sample of low-metallicity radio galaxies. Like that of 3C 79, the spectra of their host galaxies show red slopes and absorption features that are indicative of an old stellar population. Follow-up high-resolution imaging and spatially resolved spectroscopy of these galaxies and a comparable control sample are needed to finally identify the source of the low-metallicity gas and the triggering mechanism for quasar superwinds. In addition, detecting EELRs around these objects would provide a new test for the unification schemes.

6. SUMMARY

Based on extensive ground-based spectroscopy and archival HST/WFPC2 images of the radio galaxy 3C 79, we have conducted a detailed analysis of its host galaxy and the EELR. The host galaxy of 3C 79 is a massive elliptical with $M_R = -23.2$. The UV/optical spectral energy distribution of the host galaxy is best described by a combination of an intermediate-age stellar population (1.3 Gyr), an old stellar population (10 Gyr), a power law, and a nebular thermal continuum. Both stellar populations are

\(^{15}\) The C, N, O, and Fe abundances in the solar abundance set assumed by Groves et al. (2004) are all ~0.2 dex lower than those in Anders & Grevesse (1989). Hence, the mass fraction of metals (i.e., $Z_e$) is about 1.5 times lower, $Z_e = 0.013$, than that of Anders & Grevesse (1989).
metal-rich (2.5 \(Z_\odot\)). This best-fit model indicates a total stellar mass within one effective radius of approximately \(2.5 \times 10^{11} M_\odot\), consistent with the virial mass derived from stellar kinematics (\(\sim 4 \times 10^{11} M_\odot\)).

The EELR of 3C 79 is remarkably similar to the most luminous quasar EELRs. The velocity field, although available in only a small area, is locally ordered but globally disordered. The EELR is almost certainly photoionized by the hidden quasar, and it shows densities of \(\sim 100 \text{ cm}^{-3}\) in the \([\text{O} \text{ ii}]\)–emitting regions and temperatures around 13,000 K. Most interestingly, the metallicity of the gas in both the EELR and the NLR is about 1/3–2/3 solar, matching perfectly the metallicity in both the EELRs and the nuclear BLRs of the EELR quasars.

There is a very compact close companion galaxy 3.3 kpc from and 4 mag fainter than the host galaxy. This companion galaxy shows an exponential profile and is presumably a tidally stripped “pseudobulge” of a late-type galaxy that might be the source for the low-metallicity gas, as well as the star-forming regions in 3C 79.

The exact correspondence between this EELR and the EELRs around quasars joins the already overwhelming evidence in support of the unification schemes for FR II radio galaxies and radio-loud quasars. The definitive trait of subsolar metallicity in the NLR of 3C 79 also provides an efficient tool for selecting FR II radio galaxies that likely host luminous EELRs.

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