NEAR-INFRARED SPECTROSCOPY OF POWERFUL RADIO GALAXIES AT $z = 2.2-2.6$

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ABSTRACT

Near-infrared spectroscopy ($\lambda_{\text{rest}} \sim 3700-6800$ Å) of eight high-redshift powerful radio galaxies (HzPRGs) at $z = 2.2-2.6$ is presented. Strong forbidden lines and Hz emission were detected in all sources; the data show evidence that the emission lines of the HzPRGs may contribute a substantial fraction ($\sim 25\%-98\%$) of their total observed H- and/or K-band light. Diagnostic emission-line ratios—[O III] $\lambda 5007$/H$\beta$ versus [S II] $\lambda 6716, 6731$/Hz—for three of the eight HzPRGs are consistent with the presence of a Seyfert 2 nucleus; the [O III] $\lambda 5007$/H$\beta$ and [S II] $\lambda 6716, 6731$/Hz ratios and/or limits of the remaining five galaxies are inconclusive. Furthermore, all six of the galaxies for which both H- and K-band spectra were obtained have observed [O III] $\lambda 5007$/Hz + [N II] $\lambda 6548, 6583$ ratios consistent with Seyfert 2 ionization. Much of the inability to detect the weaker emission lines of [S II] $\lambda 6716, 6731$ in three of the galaxies and H$\beta$ in any of the galaxies may be caused by moderate amounts of dust: for the two sources with previously measured Ly$\alpha$ fluxes, the observed Ly$\alpha$/Hz ratios are $\sim 1.5$, much less than the value of 16 expected for gas in a dust-free medium photoionized by a hard, nonthermal continuum. If such a discrepancy is caused solely by dust, this ratio translates into $A_V \sim 0.5-1.0$ mag (depending on which extinction curve—Milky Way, SMC, or LMC—is used) at the rest frame optical wavelengths of the galaxies and a corresponding factor of $\sim 1.6-2.5$ reduction in optical flux.

None of the eight HzPRGs at $z = 2.2-2.6$ has a broad ($\Delta \lambda_{\text{FWHM}} > 1500$ km s$^{-1}$) emission-line core, and it is not clear whether any have broad emission-line wings. However, the near-infrared spectrum of 3C 22, a $z = 0.937$ radio galaxy with 1 $\mu$m luminosity comparable to that of the radio galaxies at $z = 2.2-2.6$ and a radio luminosity only 3-5 times less, shows direct evidence for broad Hz emission wings. Such a feature is indicative of the presence of a partially obscured Seyfert 1 nucleus. Given that 3C 22 is at $\sim 1/3$ the luminosity distance of the sample of HzPRGs at $z = 2.2-2.6$, a thorough search for such a faint feature in the more distant galaxies may require 8-10 m class telescopes.

These new data, along with recent UV-to-optical polarimetry showing evidence of high polarization in many HzPRGs, provide evidence that many HzPRGs are predominantly ionized by an active nucleus, and that a significant fraction of their spectral energy distribution may be caused by nonthermal emission from an active galactic nucleus (AGN).

Subject headings: galaxies: active — galaxies: ISM — galaxies: Seyfert — infrared: galaxies — radio continuum: galaxies

1. INTRODUCTION

High-redshift powerful radio galaxies (HzPRGs; $P_{408 \text{ MHz}} > 10^{27}$ $h^{-2}$ W Hz$^{-1}$, $z > 1$) are potentially important probes of galaxy evolution at early epochs. The recent detections of strong emission lines from HzPRGs at observed near-infrared wavelengths (see, e.g., Rawlings, Eales, & Lacy 1991; McCarthy, Elston, & Eisenhardt 1992; Eales & Rawlings 1993, 1996) has provided a new diagnostic tool with which to study these objects, although the nature of line emission in HzPRGs is currently a subject of great debate. Part of the difficulty in interpreting line emission in HzPRGs has been that the use of standard optical diagnostic emission-line ratios (see, e.g., Baldwin, Phillips, & Terlevich 1981; Veilleux & Osterbrock 1987), commonly used to differentiate between thermal ionization and low or high-excitation ionization from a nonthermal source, has until recently been problematic because rest frame optical emission from galaxies at $z > 1$ is redshifted to near-infrared wavelengths at current epochs.

A new generation of infrared spectrographs has now made it possible to begin systematic studies of the dominant ionization mechanisms in HzPRGs via their rest frame optical emission-line spectra. In particular, the new K-band spectrograph (KSPEC; Hodapp et al. 1994) on the University of Hawaii (UH) 2.2 m telescope on Mauna Kea provides the unique capability of simultaneous coverage of the $\sim 1.0-2.4$ $\mu$m wavelength band at typical spectral resolution $\lambda/\Delta \lambda \sim 700$, while the infrared spectrograph (CGS4) on the 3.8 m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea can provide coverage of either the full J-, H-, or K-band near-infrared windows at a spectral resolution of $\lambda/\Delta \lambda \sim 860$.

A nearly complete sample of HzPRGs in the redshift range $z = 2.2-2.6$ has been selected. An attempt has been made, in so much as is possible, to obtain near-infrared spectra with similar sensitivity and coverage in rest frame wavelength. The choice of the redshift range and wavelength coverage was designed to maximize the number of rest frame optical diagnostic lines observed. As far as the author is aware, this is the first such study that obtains both H- and K-band spectra for a fairly complete sample of HzPRGs.
The outline of this paper is as follows: sample selection and observing procedures are discussed in § 2 and § 3, respectively. Data reduction methods are summarized in § 4. The discussion in § 5 focuses on the observed emission-line spectra and calculated extinction in the HzPRGs, as well as on how the properties of HzPRGs compare with the properties of local radio galaxies and optically selected Seyferts, LINERs, and H II region–like galaxies.

2. SAMPLE SELECTION

The study of HzPRGs at near-infrared wavelengths from the ground is optimized for redshifts in the range \( z \sim 2.2\text{--}2.6 \), which simultaneously places the largest number of rest frame optical diagnostic emission lines (e.g., H\(\beta \), [O \(\text{iii} \)] \(\lambda \)5007, H\(\alpha \), [N \(\text{ii} \)] \(\lambda \)6583, and [S \(\text{ii} \)] \(\lambda \)6716, 6731—hereafter [S \(\text{ii} \)] \(\lambda \)6724) directly in the \( H \)-band and \( K \)-band atmospheric windows. When this project was started in early 1993, relatively few HzPRGs were in the literature with redshifts in this range and with \( \delta > 0^\circ \) (as required by this study for ease in observing from Mauna Kea). Nine galaxies were ultimately selected; five of these objects (B3 0731+438, 3C 257, 53W002, MG 1744+18, and 4C 40.36) were selected from a list compiled by Eales & Rawlings (1993), who presented observed \( K \)-band spectra of HzPRGs with relatively low sensitivity, and four (TX 0200+015, TX 0828+193, 4C 48.48, and 4C 23.56) were selected from the ultrasteepest spectrum (USS) radio galaxy survey (see, e.g., Röttgering 1993; van Ojik 1995; Röttgering et al. 1995; Chambers et al. 1996). With the exception of 53W002, all of these HzPRGs were observed as part of this survey. The positions and redshifts of the eight observed sources are listed in Table 1.

The final observing list included one additional object, 3C 22, which was added during the very first phases of this study. The galaxy 3C 22 has a 1 \( \mu \text{m} \) luminosity comparable to the other eight HzPRGs in the sample and a radio luminosity only \( 3\text{--}5 \) times fainter; however, it has a redshift \( (z \approx 0.94) \) only approximately one-half that of the others. It was originally included in the list mainly as a hedge against the possibility that most of the higher redshift objects would be too faint to obtain spectra with the signal-to-noise ratios necessary to make reasonable measurements of emission-line ratios. If this had indeed turned out to be the case, a more limited spectroscopic study of HzPRGs at redshifts \( z \sim 1 \) would have been carried out. However, both KSPEC and CGS4 provided sufficient sensitivity for studying the \( z \approx 2.2\text{--}2.6 \) sources, although the data obtained for 3C 22 did have a significantly higher signal-to-noise ratio than all of the other sources. The data for 3C 22 is therefore interesting in its own right as an example of how the data for the higher redshift sources might appear if higher sensitivity near-infrared data is eventually obtained.

3. OBSERVATIONS

In planning the observations of the sample of HzPRGs, the first priority was to obtain simultaneous \( H \)-band and \( K \)-band spectra with KSPEC, and then to obtain \( H \)-band and \( K \)-band spectra using CGS4 of those sources that, for whatever reason, could not successfully be observed with KSPEC. In the end, because of weather and equipment availability, three sources were observed with both spectrometers and five with CGS4 alone. The galaxy 3C 22 was observed only with KSPEC.

Table 1 presents a complete journal of the near-infrared observations. \( K \)-band spectra of eight HzPRGs were obtained with better sensitivity than any previously published \( K \)-band data, \( H \)-band spectra were obtained for five sources, and one object was also observed at the \( J \)-band. Except for the recent publication of \( H \)-band data for one source, these are the first \( H \)-band and \( J \)-band spectra of HzPRGs in this redshift range published to date. Observing parameters are also listed in Table 1. Details of the observing procedures at each of the two telescopes used are discussed separately below.

### 3.1. UH 2.2 m Telescope

Observations with the infrared spectrograph, KSPEC (Hodapp et al. 1994), on the UH 2.2 m Telescope were made during four observing periods between 1993 July and 1994 December. KSPEC is a cross-dispersed echelle spectro-

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**TABLE 1**

| Source          | R.A.   | Decl.  | z    | Telescope | Instrument | P.A. (deg) | Aperture (arcsec) | \( \lambda^a \) | Sample | Date   | Band  | Time\(^b\) (hr) |
|-----------------|--------|--------|------|-----------|------------|------------|------------------|--------------|--------|--------|-------|-------------|
| TX 0200+015.....| 02:00-08.20  | 01:34:45.95 | 2.232| UH 2.2 m  | KSPEC      | 133        | 0.8 \times 760  | 1 \times 1   | 1993 Sep | H – K  | 0.3   |
| UKIRT           | 133     |        |      | KSPEC     | 0.8 \times 760 | 1 \times 1   | 1993 Sep | H – K  | 0.3   |
| B3 0731+438.....| 07:31:41.12 | 43:50:59.0 | 2.429| UH 2.2 m  | KSPEC      | 0.8 \times 760 | 1 \times 1   | 1994 Mar | H – K  | 1.7   |
| TX 0828+193.....| 08:28-01.22 | 19:23:23.8 | 2.572| UH 2.2 m  | KSPEC      | 144        | 1.2 \times 860 | 4 \times 2   | 1995 May | K     |
| MG 1744+18.....  | 17:44:55.34 | 18:22:10.8 | 2.284| UH 2.2 m  | KSPEC      | 56         | 1.2 \times 860 | 4 \times 2   | 1995 May | K     |
| 4C 40.36.........| 18:09:19.42 | 40:44:38.9 | 2.270| UH 2.2 m  | KSPEC      | 80         | 1.5 \times 860 | 6 \times 1   | 1993 Aug | K     | 3.9   |
| 4C 48.48.........| 19:31:40.03 | 48:05:07.1 | 2.344| UH 2.2 m  | KSPEC      | 0          | 0.8 \times 760 | 1 \times 1   | 1993 Jul  | J – H – K | 2.6  |
| 4C 23.56.........| 21:05:00.96 | 23:19:37.7 | 2.480| UKIRT     | KSPEC      | 52         | 1.5 \times 860 | 6 \times 1   | 1994 Oct | H, K  | 6.9   |
| 3C 22           | 00:48:04.23 | 50:55:48.4 | 0.937| UH 2.2 m  | KSPEC      | 0          | 1.0 \times 620 | 1 \times 1   | 1994 Dec | J – H – K | 1.2  |

\(^a\) At 2.2 \( \mu \text{m} \).

\(^b\) On-source time.

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*H*-band observations of 4C 40.36 were obtained by Iwamuro et al. 1996 using the UH 2.2 m telescope equipped with an OH-airglow suppression spectrograph.
graph configured to cover the wavelength range 1.1–2.5 \( \mu m \) in three orders (\( J, H, \) and \( K \)) on a 256 \( \times \) 256 NICMOS-3 HgCdTe detector array. The wavelength resolutions (at 2.2 \( \mu m \)) for each of the observations are listed in Table 1. Additionally, the wavelength range 0.7–1.0 \( \mu m \) is also dispersed in several orders on the array. However, the order crowding at 0.7–1.0 \( \mu m \) is such that only spectra of pointlike sources can effectively be extracted, and this wavelength range is also compromised because of the fact that KSPEC is only in focus at \( \lambda > 0.85 \mu m \). In addition to its spectral capabilities, KSPEC also provides simultaneous imaging of approximately 1 arcmin\(^2\) of sky around the slit on a second NICMOS-3 array. For the 1994 December observing period, the new UH tip-tilt system (Jim et al. 1998) was also implemented, notably improving the tracking, offsetting, and seeing of the observations and data.

For the 1995 November observing period, an upgraded version of KSPEC was used in combination with the UH tip-tilt system. The new device uses a HAWAII 1024 \( \times \) 1024 HgCdTe array as the spectral detector, and provides coverage over the wavelength range 0.81–2.54 \( \mu m \) without confusion due to overlapping orders.

Each observing night began with a series of dome flats with incandescent lights turned on, then off. Once the telescope was guiding with the source in the slit, a 180 s exposure was taken, followed by a second 180 s exposure with the slit positioned 10\(^\circ\) off-source. For all observations, except during 1995 November, each spectrum exposure was accompanied by a 140 s image exposure. No image exposures were taken for the 1995 November observations except to occasionally check the position of stars in the field. For observations prior to 1994 December, the observing pattern was source-sky-source-sky, but the pattern was changed to source-sky-sky-source for the 1994 December observations to minimize spurious features created by changing sky conditions. Observations of standard AV stars near each source were made for flux calibration and to remove telluric lines. Observations of an argon lamp were used for wavelength calibration.

3.2. United Kingdom 3.8 m Infrared Telescope

Observations were made with the infrared spectrometer CGS4 on UKIRT during the observing periods 1993 August 5–9 and 1994 October 3–7. CGS4 is a 1–5 \( \mu m \) two-dimensional grating spectrometer with a 58 \( \times \) 62 InSb array. For all observations, a 75 line mm\(^{-1}\) grating was used in first order. The wavelength resolutions and sampling scheme used for each source is listed in Table 1. For most sources, sampling was done over 2 pixels in 6 or 8 steps in the wavelength direction. A 1 pixel wide (1.5") slit was used for all observations.

Observations with an upgraded version of CGS4 were made during four observing periods from 1995 May to 1996 April. The 1995 May observations were done under shared-risk time. The new detector was a 256 \( \times \) 256 InSb array. A 75 line mm\(^{-1}\) grating in first order was used for the first three observing periods, and a 150 line mm\(^{-1}\) grating in first order was used for the last observing period. A 1 pixel wide (1.2") slit was used for all observations except for the B3 0731 + 438 and 3C 257 observations, which were obtained using a 2 pixel wide 2.5" slit.

Spectral data were taken using exposure times between 60 to 540 s, with 20 to 90 s of each exposure made at each detector position during the sampling. The slit was then moved 15°–30° in the spatial direction on the array for the next multisampling exposure. Thus, the source appears on the array as a positive and negative spectrum after the first frame is subtracted from the second. The source-sky observation sequence was the same as that used in the 1994, December KSPEC observations. Flux calibrations were again made using AV standard stars located near each source, and a krypton lamp was used for wavelength calibration.

For the 1995 May observations of MG 1744 +18, a problem was encountered: the source flux of the positive spectrum was more than that of the negative spectrum flux, implying that the source was only partially in the slit in the second position. Alternatively, the flux of the positive A star spectrum was less than the negative spectrum flux. The slit also appeared to be tilted relative to the array as evident by the position of the OH sky lines. Because of this, only half the data had enough flux to be usable, and no photometry was possible for MG 1744 +18.

4. RESULTS

All data reduction was done within IRAF. For KSPEC data, the procedure was as follows. Sky frames were first subtracted from the source frames. The result was then divided by an appropriate flat field and then averaged. Since there were only a few bad pixels, and none were on the spectral area containing the source spectrum, the bad pixels were individually set to zero before the spectral orders were extracted with the APALL package. The extracted spectra were then wavelength calibrated and divided by the standard star spectrum (which had been averaged, flat fielded, and extracted in the same manner as the source spectrum) to remove any instrumental effects and atmospheric lines. Because of the narrow width of the slit, no photometry was determined for any of the KSPEC observations. Finally the spectrum was multiplied by a Planck blackbody spectrum with the same temperature as the standard star. The CGS4 data were reduced in a same manner as the KSPEC data, except that flat fielding and masking of bad pixels was done automatically after each observation. Photometry was determined for all galaxies except B3 0731 + 438, which was observed at the end of a observing period of variable weather, and MG 1744 +18 (see § 3.2).

The near-infrared spectra for all eight HzPRGs at \( z = 2.2–2.6 \) that were observed are plotted in Figure 1. Measured emission-line properties are summarized in Table 2. For most of the sources, [\( \text{[O III]} \) \( \lambda \lambda 4959, 5007 \), H\(_z\) + [\( \text{[N II]} \) \( \lambda \\lambda 6548, 6583 \), and [\( \text{[S II]} \) \( \lambda \lambda 6724 \). The emission line [\( \text{[O II]} \) \( \lambda \lambda 3727 \) was also detected in 4C 48.48. H\(_{\beta}\) and [\( \text{[O I]} \) \( \lambda \lambda 6300 \) were not detected in any of the HzPRGs. Taking into account the signal-to-noise ratio of any individual galaxy spectrum, all of the HzPRG emission-line spectra plotted in Figure 1 (with the exception of the anomalous source TX 0828 + 193SW) look similar, and the lines have similar widths.

For 4C 23.56, there is a discrepancy in the Hz flux measured from two separate observing periods. During the 1993 August observations, the telescope was positioned on the source by offsetting from a nearby faint star. For the 1994 October observations, the telescope was first peaked up on a relatively nearby star whose position is known to high accuracy, then the telescope was slewed to the radio coordinates of the source. Because the Hz flux measured in the latter observations is 3 times stronger than the line mea-
Fig. 1a

Rest frame optical spectroscopy for the sample of eight HzPRGs at redshifts 2.2–2.6. (a) TX 0200 + 015; (b) B3 0731 + 438; (c) TX 0828 + 193; (d) 3C 257, MG 1744 + 18, 4C 40.36; (e) 4C 48.48; and (f) 4C 23.56. The resolutions and the samplings of all of the observations are listed in Table 1. For the KSPEC observations, the pixel sampling for the J-, H-, and K-bands are 12, 14, and 20 \( \mu \text{m} \) pixel\(^{-1}\), respectively. For the CGS4 observations, the pixel samplings are as follows: 6.6 \( \mu \text{m} \) pixel\(^{-1}\) for B3 0731 + 438, MG 1744 + 18, and TX 0828 + 193; 5.6 \( \mu \text{m} \) pixel\(^{-1}\) for 4C 48.48, 4C 40.36, and the 1993 August observations of 4C 23.56; 11 \( \mu \text{m} \) pixel\(^{-1}\) for TX 0200 + 015 and the 1994 October observations of 4C 23.56. The CGS4 spectra of TX 0200 + 015, 4C 40.36, and TX 0828 + 193SW (K band) have been smoothed an additional 10 pixels, 10 pixels, and 100 pixels, respectively.

For 4C 40.36, the observing conditions were variable for the period the data were obtained. Photometry for the standard star (HD 166208) observed during the night in question was compared to the standards (BS 7503 and BS 8143).
observed on the two photometric nights, and the flux of HD 166208 was found to be 20% lower than the flux expected under photometric conditions. The spectrum in Figure 1 and the emission-line flux values in Table 2 for 4C 40.36 have been scaled appropriately to take this factor into account.

Figure 2 shows the spectrum of the lower redshift radio galaxy 3C 22 that was obtained during 1994, December. The signal-to-noise ratio of this spectrum is significantly better than that of the objects in Figure 1. The Hα + [N II] λ6548, 6583 line wings for 3C 22 are remarkably broad, characteristic of Seyfert 1 galaxies. Emission-line ratios for 3C 22 are also summarized in Table 2, but their discussion will be postponed until after the discussion of the higher redshift objects.

Several of these sources have been observed by others (McCarthy et al. 1992; Eales & Rawlings 1993, 1996). Of the two HzPRGs for which photometric values can be compared with previous measurements, the Hα + [N II] λ6548, 6583 flux value of $2.9 \times 10^{-18}$ W m$^{-2}$ reported by Eales & Rawlings (1996) for 3C 257 agrees well with the value of $2.6 \times 10^{-18}$ W m$^{-2}$ in Table 2, while the value of $3.4 \times 10^{-18}$ W m$^{-2}$ for 4C 40.36 (Table 2) is higher than value of $2.6 \times 10^{-18}$ W m$^{-2}$ reported by Eales & Rawlings (1993). The Eales & Rawlings (1993, 1996) observations made use of a 3″ × 3″ aperture, thus the agreement in 3C 257 line flux and lack of agreement in 4C 40.36 line flux may indicate that the Hα + [N II] λ6548, 6583 emission-line region of 3C 257 is compact and that of 4C 40.36 is extended, or that the Hα + [N II] λ6548, 6583 flux for 4C 40.36 presented in this paper is an overestimate. The resolution, sampling, and integration times (Table 1) for the spectra presented in this paper have allowed for a better determination of rest frame optical line profiles of $z > 2$ HzPRGs than previously published. In addition, the Hα + [N II] λ6548, 6583 profile of 3C 22 (Fig. 2) is consistent with recently published data of this source (Economou et al. 1995; Rawlings et al. 1995).

5. DISCUSSION

5.1. Emission-Line Diagnostics

Figure 3 shows the log ([O III] λ5007/Hβ) versus log ([S II] λ6724/Hα) diagram commonly used to distinguish between galaxies with Seyfert, LINER, and H II region emission-line spectra. Emission from [S II] λ6724 can emanate from ionized hydrogen regions, as well as from semi-ionized regions where collisional ionization is signifi-
cant. Enhancement of forbidden lines such as $[\text{O I}] \lambda 6300$, $[\text{N II}] \lambda\lambda 6548, 6583$, and $[\text{S II}] \lambda 6724$ occurs in active galactic nuclei (AGNs) because, unlike H II regions, they have extended partially ionized zones created by an excess of X-rays (the absorption cross sections of neutral hydrogen, helium, and all ions are small for X-rays; thus X-rays tend to escape the ionized region before interacting; Veilleux & Osterbrock 1987). $[\text{O III}] \lambda 5007$ is a high-ionization line photoionized by UV photons and thus tends to be strong in Seyfert galaxies.

Instead of attempting to determine the relative contributions of Hα and the $[\text{N II}] \lambda\lambda 6548, 6583$ doublet to the
It is unlikely, given the widths of the [O III] \$\lambda 5007$ lines, that the H$\alpha + [N \, II]$ \$\lambda 6548, 6583$ complex, the smallest ratio of [N II] \$\lambda 6583/H\alpha (= 0.19)$ observed for a sample of luminous infrared galaxies (Kim et al. 1995) has been adopted and plotted (large circles with embedded numerals) for all of the HzPRGs in the sample.\footnote{It is unlikely, given the widths of the [O III] \$\lambda 5007$ lines, that the H$\alpha + [N \, II]$ \$\lambda 6548, 6583$ complexes are pure H$\alpha$. However, if the complexes were purely H$\alpha$, their observed breath ($\Delta v_{\text{FWHM}} \approx 1000$ km s$^{-1}$) would be evidence against H$\alpha$ region-like emission.} Choosing such a ratio tends to bias the data toward the H II region portion of the diagram. To illustrate the extent to which the data are affected by this ratio, the values that result from assuming [N II] \$\lambda 6583/H\alpha = 1.0$, the value adopted by Eales & Rawlings (1993) based on the predictions of photoionization models and the observed value for low-redshift powerful radio galaxies (LzPRGs), and [N II] \$\lambda 6583/H\alpha = 3.74$, the largest value observed by Kim et al. (1995), have also been plotted as small, filled-in circles. Note that in all of the H-band spectra except for the spectrum of 4C 48.48, the estimated H$\beta$ upper limits (3 $\sigma$) provide weak constraints on the lower limit of [O III] \$\lambda 5007/H\beta$. Thus, in all sources except 4C 48.48 and 4C 40.36, the [O III] \$\lambda 5007/H\beta$ ratio is determined assuming H$\alpha/H\beta \geq 3$, and thus [O III] \$\lambda 5007$/H$\beta \geq 3 \times$ [O III] \$\lambda 5007/H\alpha$ (the upper limit for [O III] \$\lambda 5007/H\beta$ in 4C 40.36 is taken from Iwamuro et al. 1996). Three of the eight HzPRGs plotted in Figure 3 clearly fall in the Seyfert region of the plot. The [O III] \$\lambda 5007/H\beta$ and [S II] \$\lambda 6724/H\alpha$ ratios and/or limits for TX 0200, TX 0828 + 193, 3C 257, MG 1744 + 18, and 4C 23.56 are inconclusive.

Additional information about the ionization mechanism is obtained by examining the [O III] \$\lambda 5007/(H\alpha + [N \, II]$ \$\lambda 6548, 6583$) ratios. Table 3 lists the average value for this ratio as a function of emission-line classification for galaxies in the IRAS Bright Galaxy Sample (BGS) and a sample of “warm” IRAS galaxies (Kim et al. 1995; Veilleux et al. 1995), as well as for a sample of LzPRGs with Seyfert 2 emission-line spectra (i.e., Cygnus A: Osterbrock & Miller 1975; PKS 1345 + 12: Grandi 1977; 3C 98, 3C 192, 3C 327: Costero & Osterbrock 1977). Despite the obvious scatter due presumably to extinction and possible metallicity effects, the ratio provides a notable separation between Seyfert galaxies and those of the H II and LINER class. A comparison of these low-redshift, active galaxies with the HzPRGs at $z = 2.2$–2.6 for which both H- and K-band spectra have been obtained show all six HzPRGs to have [O III] \$\lambda 5007/(H\alpha + [N \, II]$ \$\lambda 6548, 6583$) ratios consistent...
with Seyfert 2 galaxies.\textsuperscript{5} The average value of the [O \textsc{iii}] λ\textsuperscript{5007}/(H\textalpha + [N \textsc{ii}]) λ\textsuperscript{6548}, 6583) ratio for these six HzPRGs is also listed in Table 3. Thus, the dominant source of ionization for these galaxies appears to be no different from that observed in most low-redshift, narrow-line radio galaxies.

Because the H\textalpha and [N \textsc{ii}] λ\textsuperscript{6548}, 6583 lines are blended, a direct comparison of the low ionization–H\textalpha line ratio of these high-redshift galaxies to their low-redshift counterparts cannot be made. An alternative is to compare the [S \textsc{ii}] λ\textsuperscript{6724}/(H\textalpha + [N \textsc{ii}]) λ\textsuperscript{6548}, 6583) ratio. For the HzPRGs with [S \textsc{ii}] λ\textsuperscript{6724} detections, [S \textsc{ii}] λ\textsuperscript{6724}/(H\textalpha + [N \textsc{ii}]) λ\textsuperscript{6548}, 6583) = 0.25 ± 0.07, similar to the mean value of 0.27 ± 0.05 observed for a sample of LzPRGs with Seyfert 2 emission-line spectra. Changes in properties such as the elemental abundances of the host galaxy, the shape of the ionizing spectrum, and the electron density of the gas being ionized will act to vary this ratio (note that extinction has little effect on this ratio because these emission lines have similar wavelengths). Table 3 contains a summary of average [S \textsc{ii}] λ\textsuperscript{6724}/(H\textalpha + [N \textsc{ii}]) λ\textsuperscript{6548}, 6583), H\textalpha/[S \textsc{ii}] λ\textsuperscript{6724}, H\textalpha/[N \textsc{ii}] λ\textsuperscript{6648}, 6583, and [N \textsc{ii}] λ\textsuperscript{6648}, 6583/[S \textsc{ii}] λ\textsuperscript{6724} ratios as a function of emission-line classification. Essentially, [S \textsc{ii}] λ\textsuperscript{6724}/(H\textalpha + [N \textsc{ii}]) λ\textsuperscript{6648}, 6583) is a function of H\textalpha/[S \textsc{ii}] λ\textsuperscript{6724} and [N \textsc{ii}] λ\textsuperscript{6648}, 6583/[S \textsc{ii}] λ\textsuperscript{6724}, where H\textalpha/[S \textsc{ii}] λ\textsuperscript{6724} appears to account for most of the variation in the average. On average, [S \textsc{ii}] λ\textsuperscript{6724}/(H\textalpha + [N \textsc{ii}]) λ\textsuperscript{6648}, 6583) is larger for LINERs and Seyfert 2 galaxies than in H\textalpha region–like galaxies (see Table 3), in part because the former have more extended semi-ionized regions (i.e., H\textalpha/[S \textsc{ii}] λ\textsuperscript{6724} decreases as the extent of the semi-ionized region increases). Variations in the metal abundance in the galaxies in the sample undoubtedly contribute to the scatter. For example, a substantial decrease in the metal abundance would cause a substantial decrease in [S \textsc{ii}] λ\textsuperscript{6724}/(H\textalpha + [N \textsc{ii}]) λ\textsuperscript{6648}, 6583) (i.e., H\textalpha/[S \textsc{ii}] λ\textsuperscript{6724} increases as the metal abundance decreases), and vice versa. The observation that LzPRGs and HzPRGs have similar [S \textsc{ii}] λ\textsuperscript{6724}/(H\textalpha + [N \textsc{ii}]) λ\textsuperscript{6648}, 6583) ratios may indicate that, even though HzPRGs are at substantially higher lookback times and possess higher radio luminosities, the properties of the ionizing source and the ionized gas are similar.

It is worthwhile to consider whether the gas in the HzPRGs could be ionized by supernova remnants (SNRs). Indeed, there are a few SNRs that exhibit emission-line

\textsuperscript{5} The [O \textsc{iii}] λ\textsuperscript{5007} measurement of 4C 40.36 by Iwamuro et al. (1996), obtained with a P.A. = 0 and a 1.5 × 60 aperture, is included because their H-band image shows most of the flux to be within 1.5 of the center of the galaxy. The [O \textsc{iii}] λ\textsuperscript{5007} flux is 3.86 × 10\textsuperscript{-18} W m\textsuperscript{-2}, and thus the observed [O \textsc{iii}] λ\textsuperscript{5007}/H\textalpha + [N \textsc{ii}] λ\textsuperscript{6548}, 6583 ratio for 4C 40.36 is 1.1.
### TABLE 2
Emission-Line Properties

| Source          | Instrument | Date      | Line      | $\lambda_{line}$ (\(\mu\)m) | $f(\lambda)$ (Hz + [N II]) | $f(\lambda)$ ([O III]) | FWHM (km s\(^{-1}\)) | S/N |
|-----------------|------------|-----------|-----------|-----------------------------|---------------------------|------------------------|------------------------|-----|
| TX 0200 + 015   | KSPEC      | 1993 Sep  | [O III] \(\lambda5007\) | 1.6183                      | 1.1                       | ...                    | 1080                   | 4.2 |
|                 |            |           | H\(\alpha\) + [N II] | 2.1215                      | 1.0                       | 1040                   | 3.6                    |     |
| CGS4            | 1994 Oct   |           | H\(\alpha\) + [N II] | 2.1211                      | 1.0                       | 2.0 \times 10^{-18}    | 1800                   | 15  |
|                 |            |           | [S II] \(\lambda6724\) | 2.1715                      | 0.16                      | 3.3 \times 10^{-18}    | 1200                   | 4.8 |
| KSPEC           | 1995 Nov   |           | H\(\alpha\) + [N II] | 1.6195                      | 1.2                       | (2.4 \times 10^{-18})  | 860                    | 5.6 |
|                 |            |           |           | 1.2211                      | 1.0                       | ...                    | 2000                   | 5.9 |
| B3 0731 + 438   | KSPEC      | 1994 Mar-Dec | [O III] \(\lambda5007\) | 1.7191                      | 2.7                       | ...                    | 680                    | 8.1 |
|                 |            |           | H\(\alpha\) + [N II] | ...                        | <0.19                     | ...                    | (1000)                 |     |
|                 |            |           | [O I] \(\lambda6300\) | 2.2542                      | 1.0                       | ...                    | 870                    | 5.1 |
|                 |            |           | [O I] \(\lambda6300\) | ...                        | <0.08                     | ...                    | (1000)                 |     |
| CGS4            | 1995 Oct   |           | H\(\alpha\) + [N II] | 2.2489                      | 1.0                       | ...                    | 1600                   | 21  |
|                 |            |           | [S II] \(\lambda6724\) | 2.3024                      | 0.27                      | ...                    | 1180                   | 12  |
| TX 0828 + 193   | CGS4       | 1996 Feb  | H\(\beta\)          | ...                        | <0.36                     | <6.5 \times 10^{-19}   | ...                    |     |
|                 |            |           | [O III] \(\lambda5007\) | 1.7885                      | 1.4\(^a\)                | 2.5 \times 10^{-18}    | 1300                   | 6.9 |
|                 |            |           | H\(\alpha\) + [N II] | 2.3463                      | 1.0                       | 1.8 \times 10^{-18}    | 800                    | 5.0 |
| 3C 257          | CGS4       | 1996 Apr  | [S II] \(\lambda6724\) | ...                        | <0.23                     | 4.2 \times 10^{-19}    | ...                    |     |
|                 |            |           | [O I] \(\lambda6300\) | 2.2857                      | 1.0                       | 2.6 \times 10^{-18}    | 1750                   | 6.9 |
| MG 1744 + 18    | CGS4       | 1995 May  | H\(\alpha\) + [N II] | 2.1552                      | 1.0                       | ...                    | 1750                   | 7.1 |
|                 |            |           | [S II] \(\lambda6724\) | ...                        | <0.14                     | ...                    | (1200)                 |     |
| 4C 40.36        | CGS4       | 1993 Aug  | H\(\alpha\) + [N II] | 2.1462                      | 1.0                       | 3.4 \times 10^{-18}    | 1660                   | 7.1 |
|                 |            |           | [S II] \(\lambda6724\) | 2.1945                      | 0.35                      | 1.2 \times 10^{-18}    | 1320                   | 4.6 |
| 4C 48.48        | KSPEC      | 1993 Jul  | H\(\beta\)          | ...                        | 0.26                      | ...                    | (1000)                 |     |
|                 |            |           | [O III] \(\lambda5007\) | 1.6745                      | 1.8                       | (6.0 \times 10^{-18})  | 640                    | 10  |
|                 |            |           | [O I] \(\lambda6300\) | ...                        | <0.12                     | ...                    | (1000)                 |     |
|                 |            |           | H\(\alpha\) + [N II] | 2.1945                      | 1.0                       | ...                    | 1240                   | 7.7 |
| CGS4            | 1993 Aug   |           | [S II] \(\lambda6724\) | 2.2501                      | <0.12                     | ...                    | (1200)                 |     |
|                 |            |           | [O I] \(\lambda6300\) | ...                        | <0.05                     | <1.8 \times 10^{-19}   | (1000)                 |     |
| 4C 23.56        | CGS4       | 1993 Aug  | H\(\alpha\) + [N II] | 2.1920                      | 1.0                       | 3.5 \times 10^{-18}    | 1110                   | 18  |
|                 |            |           | [S II] \(\lambda6724\) | 2.2440                      | 0.26                      | 9.2 \times 10^{-19}    | 1240                   | 6.2 |
|                 |            |           | [S II] \(\lambda6724\) | ...                        | <1.7                      | <5.9 \times 10^{-18}   | (1000)                 |     |
| 3C 22           | KSPEC      | 1994 Dec  | H\(\beta\)          | ...                        | <0.07                     | ...                    | (1000)                 |     |
|                 |            |           | [O III] \(\lambda5007\) | 0.9696                      | 0.76                      | ...                    | 940                    | 5.6 |
|                 |            |           | H\(\alpha\) + [N II] | 1.2712\(^c\)               | 1.0                       | ...                    | 1730                   | 16  |
|                 |            |           | [S II] \(\lambda6724\) | 1.2746\(^c\)               | 0.07                      | ...                    | 880                    | 4.0 |
|                 |            |           | [O I] \(\lambda6300\) | ...                        | <0.02                     | ...                    | (1000)                 |     |
| He I \(\lambda10830\) |          |           | 2.0996                      | 0.15                      | ...                    | 1660                   | 8.6 |

Note.—All upper limits are 3 \(\sigma\) based on the rms of the given spectrum and the adopted FWHM (in parentheses). [O III] fluxes in parentheses are adopted values based on the CGS4 H\(\alpha\) flux for the radio galaxy and [O III] / [H\(\alpha\)] + [N II], measured with KSPEC.

\(^a\) For TX 0828 + 193 and 4C 23.56, [O III] and H\(\alpha\) + [N II] were not observed simultaneously, so the relative fluxes may be affected by blind offset errors.

\(^b\) Observed wavelength of H\(\alpha\) \(\lambda6563\).

\(^c\) Observed wavelength of [N II] \(\lambda6583\).

**ratios similar to Seyfert 2 galaxies. A conservative estimate of the SNR rate required to explain the observed emission lines can be determined by considering the extreme SNR in NGC 6946, which has log ([O III] \(\lambda5007\)/H\(\beta\)) = 0.85 and log ([S II] \(\lambda6724$/H\alpha$) = −0.06 (Blair & Fesen 1994). The flux of the [O III] \(\lambda5007\) line is 2.5 \times 10^{-17} \text{ W m}^{-2}. At a distance corresponding to \(z = 2.4\), the SNR would have a flux of \sim 2.5 \times 10^{-17} (5.1 Mpc/9330 h^{-1} Mpc)^2 = 7.5 \times 10^{-24} h^2 \text{ W m}^{-2}.$$
W m$^{-2}$. Thus, to produce the average [O iii] $\lambda$5007 flux (i.e., $3 \times 10^{-18}$ W m$^{-2}$) observed in the HzPRGs in the sample would require $4 \times 10^5$ h$^{-2}$ SNRs. Adopting a conservative estimate of 5000 yr for the SNR lifetime, HzPRGs would have to produce SNRs at an implausible rate of $80$ h$^{-2}$ yr$^{-1}$ to maintain their [O iii] $\lambda$5007 flux.

5.2. $L_{[\text{O} \text{ iii}] \lambda4959,5007}$ versus $P_{151 \text{ MHz}}$

Previous authors have used the [O iii] $\lambda\lambda4959, 5007$ luminosity versus the observed 151 MHz radio power for HzPRGs in an attempt to infer a causal relationship between the ionization source for the gas and the source of the radio emission. Rawlings et al. (1989) have compiled data primarily for LzPRGs, and more recently, Eales & Rawlings (1993, 1996) have added data for HzPRGs. Figure 4a is a plot adapted from Eales & Rawlings (1996) of the [O iii] $\lambda\lambda4959, 5007$ luminosity versus the observed 151 MHz radio power for an unbiased 3C sample of FR II radio galaxies with $z < 0.5$ and a collection of HzPRGs. Data for the HzPRGs TX 0200+015, B3 0731+438, TX 0828+193, 4C 48.48, and 4C 23.56 have also been plotted.

A simple interpretation of Figure 4a would be that there appears to be a correlation between the [O iii] $\lambda\lambda4959, 5007$ emission-line luminosity and the radio power (such a correlation would appear to be even tighter perhaps for the HzPRGs than for the LzPRGs), and that a common excitation source (e.g., the central AGN) is responsible for both. However, the real answer is clearly not so simple. The apparent strong correlation between the [O iii] $\lambda\lambda4959, 5007$ emission-line luminosity and the radio power, $P_{151 \text{ MHz}}$ in Figure 4a is almost entirely an artifact of distance, as evidence by the plot of the ratio
(see Eales & Rawlings 1993, 1996 for discussions on this issue). Evidence for possible AGN contamination of the broadband morphologies of high radio-power galaxies has been demonstrated by Dunlop & Peacock (1993), who show that the rest frame 1.1 μm flux of a sample of 3CR galaxies tend to be more extended and aligned with the radio axis than that of a sample of lower radio-power Parkes galaxies in the same redshift range (z ~ 1). Such extended and aligned morphologies are more pronounced at rest frame UV wavelengths and are undoubtedly connected with the energetics of the central engine, and/or caused by an optically thick, circumnuclear dust/gas torus extinguishing light perpendicular to the radio axis. Rest frame UV spectro-polarimetry (Dey & Spinrad 1996; Cimatti et al. 1996; Manzini & di Serego Alighieri 1996, and references therein) and optical imaging polarimetry (Knopp & Chambers 1997; Knopp 1997), show further evidence of AGN contamination of broadband light in many HzPRGs. Indeed, four of the galaxies discussed in this paper (TX 0200+015, B3 0731+438, TX 0828+193, and 4C 23.56) show rest frame optical polarizations of 10%–45% (Knopp & Chambers 1997; Knopp 1997), indicating that a significant fraction of the rest frame UV-optical continuum emission from many HzPRGs may be scattered/reprocessed AGN light.

5.3. TX 0828+193SW: A Component Dominated by Continuum Emission

In some HzPRGs, there appear to be “components” that are genuinely dominated by continuum emission at observed optical and near-infrared wavelengths. Figure 1 shows two extractions of the southwestern “component” of TX 0828+193. Unlike the northeastern component, TX 0828+193SW has no notable strong emission lines but has comparatively strong continuum emission. Spectroscopy of the radio galaxy at wavelengths near 4000 Å (observer frame) reveals strong Lyz, C iv, He ii, and C iii] emission lines in the northeast component, but no emission lines in the southwest component (van Ojik 1995; Röttgering et al. 1997). Radio, R-band imaging data, and near-infrared imaging data taken of TX 0828+193 show the radio core to be coincident with the northeast component and the southwest component to lie ~5’’ away from the radio core.

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**TABLE 4**

| Source | Band | Magnitude* | Line/Totalb (percent) |
|--------|------|------------|-----------------------|
| TX 0200+015... | H | 18.90 ± 0.05 | 25 ± 2 |
| TX 0200+015... | K | 18.27 ± 0.03 | 28 ± 2 |
| 4C 40.36 .......... | K | 18.01 ± 0.07 | 44 ± 6 |
| 4C 23.56 .......... | H | 19.73 ± 0.10 | 98 ± 21 |
| 4C 23.56 .......... | K | 19.85 ± 0.07 | 77 ± 13 |

*a These broadband magnitudes are determined with the same apertures used for the spectroscopic observations (Table 1).

b Calculation of line contribution to the broadband magnitude of the HzPRGs, where the magnitudes are determined from imaging data by L. Armus (1997, private communication).
but still along the radio axis of the galaxy (Röttgering et al. 1995; Knopp & Chambers 1997; see the Appendix). This raises the possibility that either TX 0828 + 193SW is a cloud being illuminated by continuum emission emanating from TX 0828 + 193NE, or that a buried AGN residing in TX 0828 + 193SW is ionizing gas in TX 0828 + 193NE. The two best examples of ionization of off-nuclear knots in low-redshift radio galaxies are in Coma A (van Breugel et al. 1985) and PKS 2152 − 69 (Tadhunter et al. 1987). In the case of Coma A, the nuclear region has strong continuum emission and relatively weak lines, whereas the off-nuclear knot has relatively strong line emission. In the case of PKS 2152 − 69, both the nucleus and the off-nuclear knot have notable continuum emission, but the line emission from the off-nuclear knot, especially [O III] λ5007, is stronger. Such data would imply that the AGN is in TX 0828 + 193SW and is ionizing the northeastern component. Recent multiwavelength, broadband polarimetry measurements of TX 0828 + 193 show evidence for TX 0828 + 193NE having polarization consistent with scattering due to dust (Knopp & Chambers 1997).

Because TX 0828 + 193SW has no emission-line or absorption features from which its redshift can be determined, there exists the possibility that it is simply an unrelated object along the line of sight. Though the chance of such a superposition is low, there is precedent for concern, most notably the foreground star coincident with 3C 368 (Hammer, Le Fèvre, & Proust 1991). In the recently discovered HzPRG MG 1019 + 0535, a double-component morphology is observed, one component of which shows no sign of strong line emission (Dey, Spinrad, & Dickinson 1995). The authors argue strongly in favor of the lineless component being a foreground object, but unlike TX 0828 + 193, the two “components” of MG 1019 + 0535 are orthogonal to the radio axis. Given the geometry of TX 0828 + 193, the polarimetry measurements, and that such double-component structures aligned with the radio axis are observed in other radio galaxies (e.g., MRC 0406 − 24: Eales & Rawlings 1993), TX 0828 + 193SW is most likely at the redshift of the radio source.

### 5.4. Dust

The evidence to date that HzPRGs as a class contain substantial amounts of dust is mixed but compelling; while polarimetry observations show evidence for scattering by dust in several HzPRGs (Dey & Spinrad 1996; Cimatti et al. 1996; Manzini & di Serego Alighieri 1996, and references therein; Knopp & Chambers 1997; Knopp 1997), far-infrared/submillimeter bolometry (Golombek, Miley, & Neugebauer 1987; Evans et al. 1996; Dunlop et al. 1994; Chini & Kreugel 1994; Ivison 1995; Hughes, Dunlop, & Rawlings 1997) and CO spectroscopy (Evans et al. 1996; Downes et al. 1996; van Ojik et al. 1997b; Scoville et al. 1997) surveys of HzPRGs show evidence for substantial amounts of dust in only a few sources. Regardless of whether or not HzPRGs have comparable or more dust as that inferred by the SEDs and molecular gas masses of many low-redshift radio galaxies (see, e.g., Golombek et al. 1988; Mirabel, Sanders & Kazés 1989; Knapp & Patten 1991; Impy & Gregorini 1993; Mazzarella et al. 1993; Evans 1996), only moderate amounts are required to notably decrease the observed flux of the optical (rest frame) emission lines and continuum. Specifically, the extinction in the HzPRGs may be substantial enough such that the weaker lines of Hβ, [O I] λ6300, and [S II] λ6724, and possible features such as emission-line wings (see § 5.5) fall below the detection threshold of the spectra in Figure 1.

Estimates of extinction in HzPRGs in the sample were made by comparing the observed line ratios of hydrogen recombination lines with their intrinsic ratio (i.e., ratios in a dust-free environment). Intrinsic ratios for low-density gas photoionized by a thermal continuum source are Hα/Hβ = 2.85 and Lyα/Hα = 8.10 (Osterbrock 1989). However, because the evidence presented here and elsewhere (see McCarthy 1993) implies that gas in HzPRGs is heated by a hard nonthermal continuum, enhanced Lyα and Hα emission in predominantly neutral regions heated by X-rays must be taken into account (note that collisions resulting in the emission of Lyα and Hα are comparatively more frequent than those resulting in Hβ). Thus, the intrinsic line ratios applicable to HzPRGs are Hα/Hβ = 3.1 and Lyα/Hα = 16 (Ferland & Osterbrock 1985; Osterbrock 1989).

The Hα emission line was not detected in any of the HzPRG spectra shown in Figure 1. Thus, the Lyα/Hα ratio must be used to calculate the extinction for individual sources. This ratio can be determined for four of eight sources; in the case of B3 0731 + 438 (~2.6) and 3C 257 (~0.1) by using data from Eales & Rawlings (1993), and in the case of TX 0200 + 015 (~1.7) and TX 0828 + 193 (~1.4) by using data from Table 2 and Röttgering et al. (1997). The average observed Lyα/Hα value determined for a larger sample of lower redshift 3CR radio galaxies is ~1.5 (McCarthy 1993), and the observed Lyα/Hα ratio determined for two other z > 2 HzPRGs (Eales & Rawlings 1993) are ~1.4 (MRC 0406 − 24) and ~1.4 (53W002). All of the observed ratios are much less than the value of 16 expected for gas in a dust-free medium photoionized by a hard, nonthermal continuum.

The E(B − V) values determined for the z > 2 HzPRGs B3 0731 + 438, 3C 257, MRC 0406 − 24, and 53W002 using data from Eales & Rawlings (1993) are in the range 0.11 − 0.76. Using the Hz measurements in Table 2, in combination with the Röttgering et al. (1997) Lyα measurements for TX 0200 + 015 and TX 0828 + 193, the E(B − V) of these two galaxies was determined using the following procedure. Because the spectral resolution is insufficient to split the Hα + [N II] λ6583 complex, the values of Hα have been determined using the three ratios of [N II] λ6583/Hα plotted on Figure 3 (i.e., 0.19, 1.0, and 3.74). The observed Lyα/Hα line ratios were first corrected for Galactic extinction, then the extinction in the HzPRGs was determined assuming the extinction curves for the Milky Way (Savage & Mathis 1979), LMC (Nandy et al. 1981), and SMC (Prevot et al. 1984); the corresponding values of E(B − V) are listed in Table 5. Given the redshift of the Hα + [N II] λ6583, 6583 complex and shape of the line emission, it seems quite unlikely that the [N II] λ6583/Hα ratio is as high as 3.74. Thus, using the values from Table 5 and excluding values

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1 McCarthy et al. (1992) have also computed Lyα/Hα for B3 0731 + 438, as well as for the HzPRG MRC 0406 − 24. The discrepancy between the ratios determined by them and those determined by Eales & Rawlings (1993) arise from the fact that the former assume Hα = Hα + [N II] and the latter assume Hα = 2/3(Hα + [N II]).

2 This is the range of E(B − V) for these sources assuming the extinction curves for the Milky Way, the Large Magellanic Cloud, and the Small Magellanic Cloud, and assuming an [N II] λ6583/Hα ratio of 1.0 and 0.19. See the rest of the paragraph for a detailed explanation.
calculated assuming \([\text{[N II]} \lambda 6583/\text{H}α = 3.74]\), feasible values of \(E(B - V)\) range from 0.14 to 0.39. Such \(E(B - V)\) values translate into \(A_β \sim 0.5 - 1.0\) mag (depending on which extinction curve—Milky Way, SMC, or LMC—is adopted) at the observed infrared wavelengths (i.e., rest frame optical wavelengths of HzPRGs at \(z = 2.2 - 2.6\)). and a corresponding factor of ~2 reduction in the emission-line and continuum flux.

Although extinction is commonly determined using the luminous Lyα and Hα emission lines (as done above), there are three concerns in using Lyα for such a measurement. These concerns and their relative applicability to the analysis of HzPRGs are summarized here. First, if there is a sufficient density of atomic hydrogen, the number of Lyα photons along the line of sight can be greatly diminished by resonant scattering or associated absorption. One argument against this is that the measured Lyα emission-line widths are broad enough (\(\geq\) few hundred km s\(^{-1}\)) that most of the photons are in the wings of the line (McCarthy 1996). This can be understood if there exists a large velocity gradient across the gas that is being ionized; Lyα radiation emitted from gas at a given radius from the AGN passes through the gas farther out that is traveling at slower velocities because, to this gas, the Lyα photons do not appear to be resonant photons. However, recent medium-resolution spectroscopy of 15 HzPRGs (van Ojik et al. 1997a), of which TX 0200 + 015 and TX 0828 + 193 are included, show evidence in favor of Lyα absorption. If the intrinsic Lyα profiles fit to the observations are correct, the Lyα emission in these two galaxies may be diminished by up to 50%, making \(E(B - V)\) lower by 0.10, 0.07, and 0.04 for models assuming a Milky Way, an LMC, and an SMC extinction curve, respectively. Second, if the gas is dense enough, Lyα photons can be destroyed by collisional deexcitation of the 2\(^P\) state. This is because the Lyα photons must random walk out of the gas, and thus the lifetime of the 2\(^P\) state is lengthened by the number of steps a Lyα photon must take to escape the gas. However, the densities required for the collisional deexcitation timescale to be shorter than the radiative deexcitation lifetime of the 2\(^P\) state are in excess of \(10^{10}\) cm\(^{-3}\), a density believed to be found only in the densest areas of the broad-line regions of AGNs (Osterbrock 1989). Third, if the alignment of the rest frame UV morphology and the radio axis, as observed in many HzPRGs at \(z > 0.5\), is the result of external illumination of gas and dust clouds by radiation from a central engine, these clouds most likely reflect the majority of the Lyα photons (see, e.g., McCarthy 1996). Given such a geometry, the Lyα luminosity would provide little information on the amount of dust present. However, such a process would also tend to raise, not lower, the Lyα/Hα ratio from its intrinsic value, which is the opposite of what is observed.

5.5. Broad Lines

None of the eight HzPRGs at \(z = 2.2 - 2.6\) were found to have broad emission-line cores (see Fig. 1), nor do they appear to have broad emission-line wings. However, it is entirely possible that the cosmological distances of these galaxies may simply limit the ability to detect such a feature with 2–4 m class telescopes. The emission-line spectrum of the lower redshift HzPRG 3C 22 suggests that this may indeed be the case.

Figure 2 shows that the Hα + [\text{N II}] \(\lambda 6548, 6583\) complex for 3C 22 has a line core width, \(\Delta v_{FWHM} \sim 1700\) km s\(^{-1}\), consistent with the higher redshift HzPRGs observed (see Table 2). This emission emanates from extended, low-density gas some distance from the nucleus of the galaxy. However, note the very broad Hα wings (\(\Delta v_{FWHM} \sim 7600\) km s\(^{-1}\)) in 3C 22; such a feature is also visible in additional data (not shown here) from three KSPEC observing periods between 1994 July–September and has also been reported by Economou et al. (1995) and Rawlings et al. (1995). Such a feature is indicative of the presence of a partially obscured Seyfert 1 nucleus and is consistent with the hypothesis that FR II radio galaxies are quasars whose broad-line active nuclei are mostly obscured from the line of sight. The signal-to-noise ratio of the spectra of the higher redshift galaxies shown in Figure 1 is simply insufficient to rule out the presence of a similarly broad component in the \(z = 2.2 - 2.6\) objects.

It is tempting to speculate that broad line wings, such as those observed in 3C 22, may be present in the more distant HzPRGs. However, current efforts using 2–4 m class telescopes suggests that larger apertures (i.e., 8–10 m class telescopes) will be required to detect broad line wings for HzPRGs at \(z > 2\).

6. SUMMARY

The following conclusions are drawn from the near-infrared spectroscopy of a sample of eight HzPRGs at \(z = 2.2 - 2.6\):

1. For three of the eight HzPRGs, the emission-line ratios [O \text{III}] \(\lambda 5007/\text{H}β\) and [S \text{II}] \(\lambda 6724/\text{H}α\) are character-
istic of Seyfert 2 emission, consistent with the spectral type of the majority of low-redshift, narrow-line, powerful radio galaxies. The $[\text{O III}]\lambda 5007/\beta$ and $[\text{S II}]\lambda 6724/\lambda 6583$ ratios and/or limits are inconclusive for the remaining five HzPRGs. Furthermore, of the six galaxies for which both $H$- and $K$-band spectra have been obtained, all six have observed $[\text{O III}]\lambda 5007/(\lambda 6583 + \lambda 6548)$ ratios consistent with Seyfert 2 ionization.

2. Unlike the emission-line spectra of low-redshift, narrow-line, powerful radio galaxies, the emission lines of the eight HzPRGs appear to contribute from $\sim 25\%$--$85\%$ of the $H$- and/or $K$-band light from these galaxies.

3. The southwestern component of TX 0828 + 193 shows no evidence of strong emission lines and comparatively strong continuum emission, whereas the northeastern component shows strong line emission and no noticeable continuum emission. If this featureless component is at the redshift of the radio galaxy, the continuum emission in TX 0828 + 193SW may be illumination from an AGN residing in the northwest component. Alternatively, the AGN may reside in the southwest component and thus ionize gas in the southwest component, creating the strong lines observed. A comparison of these data with low-redshift radio galaxies with off-nuclear knots supports the latter interpretation.

4. The observed $Ly_α/\lambda 6583$ ratios of the two TX sources are $\sim 1.5$, much less than the value of 16 expected for gas photoionized by a hard nonthermal continuum. The discrepancy is most likely caused by extinction by dust, though associated absorption may account for up to a $50\%$ reduction in $Ly_α$. The ratio $Ly_α/\lambda 6583$ corresponds to $A_v \sim 0.5$--1.0 (depending on which extinction curve—Milky Way, SMC, or LMC—is used), and a corresponding factor of $\sim 2$ reduction in emission-line and continuum flux.

5. None of the eight HzPRGs at $z = 2.2$--2.6 have broad emission-line cores, and it is not clear whether any have broad emission-line wings. However, the near-infrared spectrum of 3C 22, a radio galaxy at $z = 0.937$ with 1 $\mu m$ luminosity comparable to that of the eight HzPRGs at $z = 2.2$--2.6 and a radio luminosity only $3$--$5$ times less, shows direct evidence for broad Hz emission wings. Given that 3C 22 is at $\frac{1}{3}$ the luminosity distance of the other galaxies observed, systematic searches for broad emission-line wings in radio galaxies at $z > 2$ should be pursued but may require the use of $8$--$10$ m class telescopes.

These new data, along with recent rest frame UV-to-optical polarimetry of HzPRGs, are consistent with the idea that many HzPRGs are predominantly ionized by an active nucleus and that significant fractions of their SEDs may be caused by nonthermal emission from their AGNs.

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### APPENDIX

#### NEAR-INFRARED FINDER CHARTS

Much of the difficulty in carrying out a HzPRG spectroscopy program on 2--4 m class telescopes is aligning the galaxy and the slit; the galaxies are often too faint to see after short integrations with an imaging array (UH 2.2 m) and too faint to "peak up" on with the spectrometer (UKIRT). With the exception of the KSPEC observations of 3C 22, the galaxies were observed by first blind-offsetting from a star whose position is known to fair accuracy, or by placing the slit on the sky relative to bright stars in the field of view. The latter method is preferable to large offsets, and it also makes it straightforward to check whether or not the galaxy has drifted out of the slit because the positions of the stars in the field can constantly be monitored.

To aid in future observations of these galaxies, $K'$ images of eight of the nine galaxies discussed in this paper have been

### TABLE 6

| Source      | Telescope | Instrument    | Pixel Scale (arcsec pixel$^{-1}$) | Band | Date   | Time (minutes) |
|-------------|-----------|---------------|-----------------------------------|------|--------|----------------|
| TX 0200 + 015 | UH 2.2 m | QUIRC 1024 $\times$ 1024 | 0.1886 | $K'$ | 1995 Dec | 106 |
| B3 0731 + 438 | UH 2.2 m | QUIRC 1024 $\times$ 1024 | 0.1886 | $K'$ | 1995 Dec | 40  |
| TX 0828 + 193 | UH 2.2 m | QUIRC 1024 $\times$ 1024 | 0.1886 | $K'$ | 1996 Mar | 160 |
| 3C 257       | UKIRT    | IRCAM3        | 0.286   | $H$  | 1996 Apr | 20  |
| MG 1744 + 18 | UH 2.2 m | QUIRC 1024 $\times$ 1024 | 0.1886 | $K'$ | 1997 Jul | 45  |
| 4C 40.36     | UH 2.2 m | QUIRC 1024 $\times$ 1024 | 0.06084 | $K'$ | 1997 Jul | 56  |
| 4C 48.48     | UH 2.2 m | QUIRC 1024 $\times$ 1024 | 0.1886 | $K'$ | 1995 Dec | 28  |
| 4C 23.56     | UH 2.2 m | QUIRC 1024 $\times$ 1024 | 0.1886 | $K'$ | 1995 Dec | 40  |
| 3C 22        | UH 2.2 m | QUIRC 1024 $\times$ 1024 | 0.1886 | $K'$ | 1995 Dec | 18  |

* The $H$-band image of TX0828 + 193 is taken from Knopp & Chambers 1997.
Fig. 5.—Near-infrared images of the nine HzPRGs discussed in the paper. A scale bar is provided in each image, and the identification is marked with two ticks. In all images, north is up and east is to the left.

taken (Fig. 5). Also included in Figure 5 is an $H$-band image of TX 0828 + 193 from Knopp & Chambers (1997), which, though the field of view is much smaller than the $K'$ images, shows the distinct double component morphology (see §5.3). A summary of the imaging observations is given in Table 6. All of the $K'$ images of the $z > 2$ HzPRGs have been smoothed $4 \times 4$ pixels to make it easier to see the HzPRGs and other faint sources in the field. When there was some question as to which source was the HzPRG, the radio coordinates of the galaxy were used to perform astrometry with stars visible in the STScI Digitized Sky Survey $^9$ images.

$^9$ The Digitized Sky Survey were produced at the Space Telescope Science Institute under US Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope.
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