NEW HIGH-REDSHIFT RADIO GALAXIES FROM THE MIT–GREEN BANK CATALOG¹

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ABSTRACT

We present optical identifications and redshifts for 17 new high-redshift radio sources. Fifteen of these sources are radio galaxies; the remaining two are high-redshift, steep-spectrum, radio-loud quasars. These objects were discovered as part of an ongoing study of compact (θ < 1⁰), moderately steep spectrum (α₁.₄ GHz > 0.75, S₁.₄ GHz ∝ ν⁻¹) sources from the MIT–Green Bank (MG) radio catalog (S₅ GHz ≥ 50 mJy). Spectra for the optical counterparts were obtained at the W. M. Keck Telescopes and are among the optically faintest radio galaxies thus far identified. Redshifts range between 0.3 and 3.6, with 13 of the 17 at redshifts greater than 1.5. Combining these new radio galaxies with two published MG radio galaxy spectra, we synthesize a composite MG radio galaxy spectrum and discuss the properties of these galaxies in comparison with other, more powerful, radio galaxies at similar redshifts. We suggest a radio power–ionization state relation.

Key words: early universe — galaxies: active — galaxies: distances and redshifts — galaxies: evolution — radio continuum

1. INTRODUCTION

The MIT–Green Bank (MG) survey (Bennett et al. 1986; Lawrence et al. 1986) consists of 5974 radio sources in 1.87 sr of sky in an equatorial strip, which have flux densities ≥ 50 mJy at 5 GHz. Studies of higher flux density radio surveys such as the 3CR (Spinrad & Djorgovski 1987), Molonglo (McCarthy et al. 1996), and B2/1 Jy of Allington-Smith (1982) have yielded many interesting discoveries, such as the radio-optical alignment of high-redshift radio galaxies (Chambers, Miley, & van Breugel 1987; McCarthy et al. 1987), very high redshift galaxies (e.g., Lacy et al. 1994; Spinrad, Dey, & Graham 1995; Rawlings et al. 1996), and rich clusters at high redshift (e.g., Dickinson 1996). The survey probes the parameter space between high flux density surveys such as the 3CR and milli- and micro-jansky surveys such as the Leiden-Becker Deep Survey and its extensions (Neuschaefer & Windhorst 1995). The MG range of radio flux density is also considered by the B3 survey (Vigotti et al. 1989) and recent Cambridge surveys (e.g., 6C: Hales, Baldwin, & Warner 1993), but the MG survey was conducted at a higher frequency than these other surveys. Selecting an intermediate-power sample allows us to study various properties as a function of radio power. In particular, a lower radio power suggests that these galaxies may, on average, be less dominated by their active nuclei and may thus be more representative of giant ellipticals at large redshift (cf. Dunlop et al. 1996; Spinrad et al. 1997; Dey et al. 1999). Fainter flux densities also suggest that a fraction of our sample may be at very high redshift, and indeed the median redshift of radio galaxies in the MG observed to this point is zm ≈ 1.1, compared with zm ≈ 0.27 for the 3CR (McCarthy 1993).

Over the past several years we have been pursuing the optical identification of a subset of 218 radio sources systematically selected from the MG catalog. We restrict our sample to radio sources of small angular size (θ ≤ 1⁰), simple (unresolved, double, or triple) radio morphology, and moderately steep radio spectral index (α₁.₄ GHz > 0.75, S₁.₄ GHz ∝ ν⁻¹). The size and morphological criteria primarily select against objects at low redshift. The angular size limit should also bias the sample to larger look-back times when the higher density of the intergalactic medium is more effective at confining radio lobes. The spectral index criterion eliminates low-redshift interlopers and selects against flat-spectrum quasars and in favor of radio galaxies but is only moderately restrictive among the radio galaxies themselves (Blumenthal & Miley 1979). Resulting identifications are often very distant objects and thus serve as useful probes for the study of galaxy formation and evolution. In

¹ Based on observations obtained at the W. M. Keck Observatory, Lick Observatory, and the MDM Observatory. The Keck Observatory is operated as a scientific partnership among the University of California, the California Institute of Technology, and the National Aeronautics and Space Administration and was made possible by the generous financial support of the W. M. Keck Foundation.

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combination with other complete samples, such as the 3CR, optical and near-IR properties of MG sources can be used in correlative studies that span a range of radio power at any given redshift. Similar studies suggest that weak radio sources ($S_{1.4 \, \text{GHz}} < 50 \, \text{mJy}$) have weaker emission lines and that the alignment effect becomes less pronounced with lower radio flux density samples (e.g., Rawlings & Saunders 1991; Dunlop & Peacock 1993; Eales & Rawlings 1993; Thompson et al. 1994). McCarthy (1993) has recently presented a comprehensive review on the optical and associated properties of radio galaxies.

Preliminary results from our survey are described by Spinrad et al. (1993), Dey, Spinrad, & Dickinson (1995), and Stern et al. (1996; 1997). Currently, we have optical identifications for ~85% of our sample and spectroscopic redshifts for ~60% of the sample. In this paper we report on 17 new identifications and redshifts of MG sources. The spectra were obtained at the W. M. Keck Telescopes and are representative of some of the fainter radio identifications thus far. Typical R magnitudes are 23–24. Many of these sources are in the so-called redshift desert, $1.4 \leq z \leq 2.0$, for which no strong features (e.g., $\lambda\text{Ly}_{\alpha}$, $\lambda\text{Ly}_{\beta}$, or $\lambda\text{Hz}$) are redshifted into the optical window, thus making redshift determinations challenging. Our MG sample currently includes 13 galaxies with $z > 2$; we report on four such galaxies here.

The paper is organized as follows: In § 2 we present the observations and data reductions, followed by a discussion of individual systems in § 3. We construct a composite spectrum and compare it with models and other composite spectra of active galaxies in § 4. A concluding discussion is given in § 5. Throughout this paper we adopt a Hubble constant of $H_0 = 50 \, h_{50} \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, $q_0 = 0.5$, and $\Lambda = 0$ unless otherwise noted.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Imaging and Optical Identifications

Preliminary imaging observations of all sources were made over the course of several years (1988–1998) at the Lick Observatory 3 m Shane Telescope on Mount Hamilton and the Michigan-Dartmouth-MIT (MDM) 2.4 m Hiltner Telescope at Kitt Peak. The Kast Double Spectrograph of Lick Observatory (Miller & Stone 1994) employs UV-flooded Reticon 1200 $\times$ 400 CCDs with 27 $\mu$m pixels, corresponding to a plate scale of 0:78 pixel$^{-1}$. Typical seeing for the Lick imaging was 1:2–1:8. The Charlotte camera of MDM employs a Tek 1024$^2$ CCD detector with a plate scale of 0:275 pixel$^{-1}$. Typical seeing for these images was 1:0–1:5.

A subsample of seven of the 17 sources was later reimaged with the Low Resolution Imaging Spectrometer (LRIS) (Oke et al. 1995) at the 10 m W. M. Keck Telescopes on Mauna Kea between 1994 and 1998. The detector is a Tek 2048$^2$ CCD with 24 $\mu$m pixels. Because of a dewar change in 1996 July, the pixel scale changed from 0:214 pixel$^{-1}$ to 0:212 pixel$^{-1}$ at that time. The typical seeing was 0:8–1:0. A journal of our observations is provided in Table 1.

The images were corrected for overscan bias, flattened using a median sky flat, co-added, and calibrated using observations of standard stars. Utilizing astrometry provided by B. Burke and S. Conner, we obtained optical identifications for our candidates based on the radio coordinates. Typically, the optical morphologies are small, faint, and round. We present finding charts in Figure 1. Where available, we present Keck images; the remaining images were obtained at Lick and the MDM as indicated in Table 1. Astrometry for each identification is tabulated in Table 2 with the coordinates of the offset star provided. The estimated uncertainty in the optical positions is 0:3. Optical and radio properties of the sources are in Table 3, where the radio flux densities and spectral indices are from Bennett et al. (1986) and Lawrence et al. (1986). Radio luminosities have been calculated at a rest frame frequency of 4.8 GHz, implementing the spectral index derived from 1.4 and 4.8 GHz observations, a Hubble constant of $H_0 = 50 \, h_{50} \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, $q_0 = 0$, and $\Lambda = 0$. In Table 4 we include more recent 4.85 GHz flux densities for the sample. Many sources may vary at the 10% level over the 10 yr baseline, although MG 2058+0542 apparently varied considerably more over the same period. We therefore indicate its spectral index as uncertain in Table 3. Magnitudes, measured in site-dependent apertures as described in Table 3, are from our CCD photometry and have errors of ~0.1–0.3 mag. Observations obtained at Lick Observatory employed the Spinrad night-sky filter and yield red magnitudes in the $R_s$ system, which is related to commonly used photometric systems by Djorgovski (1985). Typical optical magnitudes are $R \sim 23–24$, probing the fainter envelope of our MG survey.

2.2. LRIS Spectroscopy

We obtained spectroscopic observations with LRIS between 1994 and 1997. We generally used a 300 line mm$^{-1}$ grating (blazed at 5000 Å) to sample a wavelength range $\lambda 4000–9000$, and a 1" wide slit, which yields an effective resolution FWHM of $\sim 10$ Å. The read noise and gain were typically 8.0 $e^-$ and 1.6 $e^-$/ADU$^{-1}$, respectively. However, during the 1994 March run, the LRIS CCD was affected by pattern noise that mimicked extremely high read noise (25 $e^-$ and 65 $e^-$ on the blue and red sides), noticeably degrading the spectrum of MG 1251+1104. Observations were typically done at an air mass $\leq 1.05$. Hence, although the slit position angle was often selected to trace the radio morphology or to include nearby optical sources, we believe our relative spectrophotometry to be accurate for the wavelength considered (cf. Filippenko 1982). The sources attempted spectroscopically at Keck were primarily selected from the fainter ($R \gtrsim 23$) identifications in the MG survey, many having been unsuccessful spectroscopic targets at Lick Observatory. Exceptions are the relatively bright sources MG 0422+0816 ($R \sim 20$) and MG 0511+0143 ($R \sim 22$), which were first observed spectroscopically as a backup project at Keck Observatory on an inclement night. These observations utilized a 600 line mm$^{-1}$ grating (blazed at 5000 Å). The bright quasar MG 2041+1854 ($R \sim 20$) was observed at Keck during twilight on a cirrusy night, whereas the relatively bright ($R \sim 21$) sources MG 0148+1028 and MG 0308+0720 were first surveyed spectroscopically as backup targets on 1997 December 23 UT.

For each observation, we offset the telescope from the reference star listed in Table 2. The data were corrected for overscan bias, flat-fielded using internal lamps taken after

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4 The transformation from Spinrad night-sky $R_s$ into Johnson $VR$ is $(R_v - R) = -0.004 - 0.072(V - R) + 0.073(V - R)^2$. 

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TABLE 1

| Source         | Observation Type | Observation Date | Telescope | Exposure (s) |
|----------------|------------------|------------------|-----------|--------------|
| MG 0018+0940   | I                | 1995 Sep 1       | Keck      | 600          |
| MG 0046+1102   | I                | 1995 Sep 1       | Keck      | 1050         |
| MG 0122+1923   | I                | 1995 Sep 1       | Keck      | 3000         |
| MG 0148+1028   | I                | 1996 Oct 15      | Lick      | 1260         |
| MG 0308+0720   | I                | 1995 Sep 1       | Keck      | 600          |
| MG 0311+1532   | I                | 1994 Jan 11      | MDM       | 600          |
| MG 0422+0816   | I                | 1992 Nov 25      | Lick      | 200          |
| MG 0511+0143   | I                | 1992 Nov 25      | Keck      | 1500         |
| MG 1142+1338   | I                | 1994 Apr 07      | MDM       | 1800         |
| MG 1251+1104   | I                | 1995 Mar 14      | Keck      | 1200         |
| MG 1401+0921   | I                | 1997 Jul 1       | Keck      | 900          |
| MG 2037−0011   | I                | 1994 Sep 30      | MDM       | 1500         |
| MG 2041+1854   | S                | 1996 Jun 16      | Keck      | 300          |
| MG 2058+0542   | I                | 1992 Aug 1       | Lick      | 1400         |
| MG 2109+0326   | I                | 1993 Aug 17      | Lick      | 1500         |
| MG 2121+1839   | S                | 1994 Jul 9       | Keck      | 6550         |
| MG 2308+0336   | I                | 1995 Jul 25      | Keck      | 600          |

* (I) imaging; (S) spectroscopy.

3. NOTES ON INDIVIDUAL SOURCES

**MG 0018+0940.** At $z = 1.586$ this source exhibits a low-ionization spectrum. Unlike more powerful radio sources, the C iii $\lambda 1909$ line is stronger than the C iv $\lambda\lambda 1549$ doublet. Mg ii $\lambda 2800$ is clearly resolved. The optical (R) image of MG 0018+0940 has an extended, chainlike morphology oriented at a position angle of 137° in the optical. The radio source is unresolved in 4.85 GHz observations with the B array of the VLA$^5$ ($\sim 1.2$ beam; Lawrence et al. 1986).

**MG 0046+1102.** At $z = 1.813$ this source also exhibits a low-ionization spectrum, with carbon and magnesium line strengths similar to MG 0018+0940. Mg ii $\lambda 2800$ is again a strong and clearly resolved feature. The optical identification is extended with a position angle of 130° in $R$, whereas the source is unresolved in 4.85 GHz observations obtained with the B-array configuration of the VLA.

**MG 0122+1923.** At $z = 1.595$ this source also exhibits a low-ionization spectrum, with carbon line strengths similar to the two radio galaxies above. The optical identification contains a compact core and diffuse emission to the north oriented at a position angle of 41°.

**MG 0148+1028.** At $z = 2.845$ this is an intriguing source, showing both the bright emission lines typical of high-redshift radio galaxies and the narrow absorption lines

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$^5$ The VLA is a telescope of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.
Fig. 1.—Finding charts for the new identifications. Fields are 1.5 arcmin², with north at the top and east to the left. Identifications are indicated with two dashes. The offset star in each field is marked with A. Note that for MG 2308 + 0336 no bright stars are within the field of view; instead an offset galaxy is indicated.
that characterize high-redshift, star-forming galaxies (cf. Steidel et al. 1996; Lowenthal et al. 1997). These lines, indicated with vertical dashed lines in Figure 2, refer to \text{Si} \text{II} \lambda 1260, \text{O I} \lambda 1302, \text{C II} \lambda 1335, \text{Si IV} \lambda 1394, 1403, \text{S V} \lambda 1502, \text{Si II} \lambda 1526, \text{Fe II} \lambda 1608, \text{and Al II} \lambda 1670 \text{ (e.g., Spinrad et al. 1998). The emission lines of this source are slightly broader than in those sources considered above, with FWHM \sim 1000 \text{ km s}^{-1}, a value commonly seen in quasars,}
although the low C IV $\lambda\lambda1549$/He II $\lambda1640$ ratio leads us to classify this source as a broad-lined radio galaxy. A detailed analysis of MG 0148+1028 is deferred to future publication; note, however, that S V $\lambda1502$, an unambiguous signature of starlight (e.g., Dey et al. 1997), is visible in absorption. The finding chart for this galaxy derives from a short (60 s) exposure obtained through LRIS without a filter to identify the field; this image is superior to the 1260 s Lick image. Slit spectroscopy was done at a position angle of 138° so that galaxies b and c (see Fig. 1) would also be
galaxy b has [O II] λ3727 and [O III] λλ4959, 5007 in emission at z = 0.588, whereas galaxy c has [O II] λ3727 in emission with Mg II λλ2800 in absorption at z = 1.297. The optical identification is marginally resolved: $\text{FWHM}_{\text{Mg}} \approx 1''$, whereas the seeing was $\approx 0''.9$.

$\text{MG 0308 + 0720}$. At z = 2.975 this source is a radio-loud quasar as evidenced by the broad emission lines [e.g., FWHM(C IV) $\sim 5600$ km s$^{-1}$] and unresolved morphology. The Ly$\alpha$–N v λ1240 emission complex is unusual, with narrow Ly$\alpha$ superposed on a broad N v λ1240 emission line. Recent statistical investigations of broad UV lines in luminous (radio-quiet) quasars have suggested that the traditional broad-line region consists of two components—a low-density, intermediate-line region (ILR; FWHM $\approx 2000$ km s$^{-1}$) and a higher density, very broad line region (VBLR; FWHM $\gtrsim 7000$ km s$^{-1}$) blueshifted by $\gtrsim 1000$ km s$^{-1}$ with respect to the ILR (e.g., Brotherton et al. 1994). Differences in the relative contributions of these two components can explain much of the observed variation in quasar broad-line profiles. For instance, Ly$\alpha$ will come predominantly from the ILR, whereas higher ionization lines such as N v λ1240, Si iv λλ1394, 1403, and C iv λλ1549 are dominated by VBLR emission. In this simple model, MG 0308 + 0720 is a quasar whose broad lines are dominated by the VBLR; indeed, the Ly$\alpha$ spectral profile looks similar to that of the composite VBLR presented in Figure 2a of Brotherton et al. (1994). Alternatively, we may be seeing a dusty quasar at high redshift. The Ly$\alpha$–N v λ1240 complex is dominated by broad N v λ1240 emission. Subtracting a Gaussian from the N v λ1240 line, we find the residual Ly$\alpha$ to be extremely weak: the Ly$\alpha$/C iv λλ1549 ratio is $\approx 0.25$, compared with a mean value of 1.2–2.2 in composite quasar spectra (Boyle 1990; Francis et al. 1991). The extremely red continuum is in concordance with this dust obscuration interpretation. Three Mg ii λλ2800 absorption systems at redshifts z $\approx 1.391,1.607,$ and 1.814 are also evident in the spectrum.

$\text{MG 0311 + 1532}$. At z = 1.989 this source exhibits a slightly higher ionization spectrum in comparison with the above radio galaxies. C ii] λ3266 is barely apparent as a faint broad bump near 7000 Å. The red continuum of this source, and particularly the abrupt feature at 7150 Å, are artifacts likely due to scattered light from a bright star $\approx 3.5$ to the northeast. The optical identification consists of low surface brightness emission oriented at a position angle of $135^\circ$, whereas the 4.8 GHz morphology is extended by $5.1'$ at a position angle of $16^1$. 

$\text{MG 0422 + 0816}$. At z = 0.289 this source was observed spectroscopically at Keck as a backup object on a night of poor seeing and thick cirrus, thus making our primary faint targets untenable. The relatively bright optical flux (R $\approx 20$) and unfluxed spectrum are the by-products of these meteorological conditions, which prevented observations of our primary fainter targets. The [O iii] λλ4959, 5007 nebular lines are the most prominent feature of the spectrum. The optical counterpart consists of a marginally resolved core with diffuse emission to the south.

$\text{MG 0511 + 0143}$. At z = 0.596 this source was also observed as a back-up target on an inclement night. This galaxy has a weak-lined spectrum with [O ii] λ3727 of low equivalent width and a prominent 4000 Å break (labeled with an arrow in Fig. 2), indicative of an old stellar population. MG 0511 + 0143 was also imaged in the J and K bands at Lick Observatory on cirrusy nights. Comparing the multiband images suggests the radio galaxy may be part of a cluster at z $\approx 0.6$. The vignetting of the finding chart is due to the small field of view of the Kast imaging spectrometer on the Lick 3 m. The optical identification is oriented at a position angle of $48^\circ$, whereas the 4.8 GHz morphology is extended by $3.9'$ at a position angle of $171^\circ$. 

$\text{MG 1019 + 0534}$. At z = 2.765 this source has an unusual spectrum, which was previously reported by Dey et
TABLE 3

| Source          | z   | R  (mag) | 4 × E_{B-V} | S_{1.4 GHz} (mJy) | a_{1.4 GHz} (mJy) | Size (arcsec) | P.A. (deg) | log L_{4.8 GHz} (ergs s^{-1} Hz^{-1}) |
|-----------------|-----|----------|-------------|-------------------|-------------------|--------------|-----------|-------------------------------------|
| MG 0018+0940....| 1.586| 23.0     | 0.237       | 132               | 1.08              | 0.0          | ...       | 34.70                               |
| MG 0046+1102....| 1.813| 23.1     | 0.209       | 74                | 1.07              | 0.0          | ...       | 34.61                               |
| MG 0122+1923....| 1.595| 23.3     | 0.105       | 134               | 1.06              | 0.0          | ...       | 34.70                               |
| MG 0148+1028....| 2.845| 21.4     | 0.157       | 176               | 0.71              | 0.0          | ...       | 35.39                               |
| MG 0308+0720....| 2.975| 21.1     | 0.801       | 164               | 0.95              | 0.0          | ...       | 35.56                               |
| MG 0311+1532....| 1.986| 23.6     | 0.405       | 62                | 1.21              | 5.1          | 161       | 34.72                               |
| MG 0422+0816....| 0.294| 20^a     | 0.721       | 68                | 1.06              | 0.0          | ...       | 32.53                               |
| MG 0511+0143....| 0.596| 22^a     | 0.393       | 98                | 1.06              | 3.9          | 171       | 33.42                               |
| MG 1019+0534....| 2.765| 23.7     | 0.037       | 100               | 1.22              | 1.3          | 103       | 35.40                               |
| MG 1142+0638....| 2.448| 22.3     | 0.093       | 149               | 1.03              | 0.0          | ...       | 34.46                               |
| MG 1251+1104....| 2.322| 24^       | 0.000       | 62                | 1.21              | 0.0          | ...       | 34.94                               |
| MG 1401+0921....| 2.093| 23.3     | 0.013       | 92                | 0.89              | 3.5          | 138       | 34.81                               |
| MG 2037−0011....| 1.512| 24.8     | 0.397       | 119               | 1.03              | 0.0          | ...       | 34.57                               |
| MG 2041+1854....| 3.056| 20^a     | 0.441       | 217               | 0.76              | 0.0          | ...       | 35.10                               |
| MG 2058+0542....| 1.381| 23.7     | 0.425       | 283               | 1.19^              | 0.0          | ...       | 34.90                               |
| MG 2109+0326....| 1.633| 22.0     | 0.281       | 119               | 0.75              | 0.0          | ...       | 34.55                               |
| MG 2121+1839....| 1.860| 22.7     | 0.341       | 69                | 1.09              | 6.3          | 145       | 34.63                               |
| MG 2144+1928....| 3.592| 23.5     | 0.449       | 58                | 1.54              | 8.5          | 177       | 35.76                               |
| MG 2308+0336....| 2.457| 23^       | 0.173       | 148               | 0.85              | 3.0          | 175       | 35.20                               |

**Note.**—Keck magnitudes are in 2" apertures, MDM magnitudes are in 2.5" apertures, and Lick magnitudes are in 4" apertures. Keck and MDM images are through an R filter, whereas Lick observations are through the Spinrad night-sky filter, R_{B} (Djorgovski 1985). We assume H_0 = 50 km s^{-1} Mpc^{-1}, q_0 = 0 to calculate the radio powers. Uncertain numbers are indicated with a colon. Reddening corrections have only been applied to the spectroscopy.

* Estimated from nonphotometric conditions.

al. (1995). L_\alpha, usually the strongest line in high-redshift radio galaxies, is very weak. This is likely due to dust attenuating the L_\alpha emission, implying dust formation at early epochs for this system.

**MG 1142+1338.**—At z = 1.279 this source is a weak-lined radio galaxy with strong [O I] \lambda3727 and high ionization [Ne V] \lambda3426. C II] \lambda1909 is barely visible as a broad feature, whereas neither C II] \lambda2326 nor Mg II \lambda2800 are visible. The optical counterpart is compact.

**MG 1251+1104.**—At z = 2.322 this source was observed during the 1994 March run when the LIRIS CCD was compromised by high pattern noise. L_\alpha is the dominant feature of the spectrum. The continuum slope is untrustworthy and a relic of instrumental problems and leads to uncertain equivalent widths in Table 5. The optical morphology is diffuse and symmetric.

**MG 1401+0921.**—At z = 2.093 this source exhibits a moderate-ionization spectrum radio galaxy with strong

**TABLE 4**

| Source          | 1986 Becker et al. 1991^a Gregory & Condon 1991 Griffiths et al. 1995 |
|-----------------|-----------------------------|-----------------------------|-----------------------------|
| MG 0018+0940....| 132                         | 159 ± 22                    | 190 ± 14                    |
| MG 0046+1102....| 74                          | 100 ± 15                    | ...                         |
| MG 0122+1923....| 134                         | 117 ± 16                    | ...                         |
| MG 0148+1028....| 176                         | 193 ± 27                    | ...                         |
| MG 0308+0720....| 164                         | 165 ± 23                    | 213 ± 15                    |
| MG 0311+1532....| 62                          | 54 ± 9                      | ...                         |
| MG 0422+0816....| 68                          | 116 ± 17                    | 102 ± 12                    |
| MG 0511+0143....| 98                          | 107 ± 16                    | 102 ± 12                    |
| MG 1019+0534....| 115                         | 132 ± 19                    | 100 ± 12                    |
| MG 1142+1338....| 149                         | 127 ± 18                    | ...                         |
| MG 1251+1104....| 62                          | ...                         | ...                         |
| MG 1401+0921....| 92                          | 92 ± 14                     | 66 ± 11                     |
| MG 2037−0011....| 119                         | 179 ± 14                    | ...                         |
| MG 2041+1854....| 217                         | 178 ± 24                    | ...                         |
| MG 2058+0542....| 283                         | 427 ± 59                    | 356 ± 21                    |
| MG 2109+0326....| 119                         | 86 ± 14                     | 75 ± 11                     |
| MG 2121+1839....| 69                          | 65 ± 10                     | ...                         |
| MG 2144+1928....| 58                          | 76 ± 11                     | ...                         |
| MG 2308+0336....| 148                         | 163 ± 23                    | 160 ± 13                    |

**Note.**—All flux densities measured in mJy. The 1986 flux densities for MG 0511+0143 and MG 2308+0336 are from Bennett et al. 1986; the remaining 1986 flux densities are from Lawrence et al. 1986.

^a Becker, Whiter, & Edwards 1991 report a 15% error on all measurements.
Fig. 2.—Spectra for the identifications, with prominent features indicated. Telluric absorption due to atmospheric water vapor (the "A band") is indicated by a cross within a circle. Vertical lines in the spectrum of MG 0148 + 1028 are explained in the text. The arrow in the spectrum of MG 0511 + 0143 refers to the 4000 Å break. Spectra of MG 1019 + 0534 and MG 2144 + 1928 are from Dey et al. (1995) and Maxfield et al. (1999), respectively.
Fig. 2—Continued
C \text{III} \lambda 1909 and weak C \text{II} \lambda 2326. The optical counterpart is slightly elongated with a shell structure to the northwest, whereas the radio morphology has a classic double structure of separation at a position angle of 138°. A similar asymmetric optical structure is observed in 4C 23.56 (Knopp & Chambers 1997). Deep multiband images lead them to interpret the morphology of 4C 23.56 as deriving from a dusty galaxy illuminated by a beam from an active nucleus that is scattered into our line of sight.

MG 2037–0011.—At \( z = 1.512 \) this source is a weak-lined source showing several faint emission lines. Most strikingly, the C \text{III} \lambda 1909 line has a narrow component superposed on a broad component. A comparison with the similar redshift radio galaxy MG 0018+0940 is interesting—in particular, note that Mg \text{II} \lambda 2800 is not seen in the spectrum of MG 2037–0011.

MG 2041+1834.—At \( z = 3.056 \) this source is a radio-loud quasar. The spectral index of this source is very close to the lower limit of our sample, which was imposed to separate the typically flat-spectrum quasars from the typically steeper spectrum radio galaxies. The relatively bright (\( R \approx 20 \)) source is near the Galactic plane. Therefore, we took advantage of the good seeing conditions at Mauna Kea to take a short exposure spectrum of this source during twilight on a cirrusy night, although, consequently, the spectral fluxes are uncertain. The best image available for this source is from a 5 s exposure through the guide camera at Keck (Fig. 1; 0.275 pixel \(^{-1}\)). The field of view is smaller than for the other objects in Figure 1, and the slit is visible; nevertheless, it is vastly superior to the poor seeing Lick 3 m image. The spectrum shows the typical broad lines of a quasar, with intervening Mg \text{II} \lambda 2800 absorption systems apparent at \( z = 0.875, 1.469, 1.914, \) and 1.946. This source is interesting in terms of being a moderately steep spectrum, radio-loud quasar at \( z \geq 3 \). Few such sources are in the literature and may be interesting in terms of unified models of extragalactic radio sources.

MG 2058+0542.—At \( z = 1.331 \) this source is typical of the sources discussed here. Narrow lines are visible with a faint red continuum, possibly suggestive of star light.

MG 2109+0326.—At \( z = 1.636 \) this source exhibits a slightly higher ionization spectrum than MG 2058+0542, or possibly reflects multiple ionization states, as indicated by the relatively strong [Ne \text{IV}] \lambda 2424 emission line. An emission-line galaxy at \( z = 0.790 \) was also serendipitously discovered on the Keck spectrogram of this target.

MG 2121+1839.—At \( z = 1.861 \) this source shows neither the low-ionization C \text{II} \lambda 2326 nor the high-ionization [Ne \text{IV}] \lambda 2424 lines; the major features are C \text{IV} \lambda \lambda 1549 and C \text{III} \lambda 1909. Ly\( \alpha \) has been detected for this object on the blue camera of the Kast Double Spectrograph of Lick Observatory. Keck/NIRC K-band images of this target are presented in van Breugel et al. (1998) and reveal a relatively smooth morphology, which is not aligned with the radio axis (\( P.A. = 145° \), extended by 6.3'). Serendipitous emission-line galaxies at \( z = 0.353 \) and \( z = 0.859 \) were also discovered on the LRIS spectrogram.

MG 2144+1928.—At \( z = 3.592 \) this source is the highest redshift radio galaxy yet discovered in our MG sample. Its redshift was first measured at Lick Observatory and is mentioned by Spinrad et al. (1993). MG 2144+1928 is an aligned radio galaxy with multiple components showing interesting velocity structure. Detailed discussion and analysis of the optical spectrum, as well as astrometry and a finding chart, are presented by Maxfield et al. (1999). Near-infrared observations of this galaxy are also presented by Armus et al. (1997) and van Breugel et al. (1998). Both the emission-line–free K' image of van Breugel et al. (1998) and the narrowband 2.3 \( \mu \)m image of Armus et al. (1997), selected to target the redshifted [O \text{III}] \lambda 4959, 5007 doublet, show the host galaxy to be extended along the radio axis (\( P.A. = 177° \), extended by 8.5').

MG 2308+0336.—At \( z = 2.457 \) this source is a high-redshift radio galaxy exhibiting a spectrogram indicative of a mixed ionization state. Note that C \text{II} \lambda 2326, the strongest of the carbon lines for this object, is quite broad. Ly\( \alpha \) was also detected at Lick Observatory with the Kast Double Spectrograph. The optical counterpart consists of higher surface brightness core oriented at a position angle of 137°, with fainter emission evident to the south. The 4.8...
### TABLE 5

**Observed Emission Lines**

| Source            | Line Identification | \(\lambda_{\text{obs}}\) (Å) | \(f \times 10^{-17}\) (ergs cm\(^{-2}\) s\(^{-1}\)) | \(W_{r}\) (Å) | \(z\) |
|-------------------|---------------------|-----------------|-----------------|----------|-----|
| MG 0018 + 0940    | C IV 1549           | 4004.4          | 8.1             | 145      | 1.584 |
|                   | He II 1640          | 4243.7          | 4.2             | 92       | 1.588 |
|                   | C III 1909          | 4934.6          | 8.7             | 161      | 1.585 |
|                   | C IV 2326           | 6016.7          | 6.5             | 137      | 1.587 |
|                   | [Ne IV] 3426        | 6263.8          | 3.1             | 90       | 1.584 |
|                   | Mg II 2798          | 7236.7          | 8.8             | 227      | 1.585 |
|                   | He II 3203          | 8291.3          | 3.1             | 64       | 1.589 |
| MG 0046 + 1102    | C IV 1549           | 4357.2          | 6.5             | 99       | 1.812 |
|                   | He II 1640          | 4615.8          | 5.5             | 83       | 1.814 |
|                   | C III 1909          | 5366.5          | 7.9             | 124      | 1.813 |
|                   | C IV 2326           | 6542.6          | 7.4             | 120      | 1.813 |
|                   | [Ne IV] 3426        | 6813.2          | 1.9             | 29       | 1.811 |
|                   | O II 2470           | 6947.5          | 2.0             | 30       | 1.813 |
|                   | Mg II 2798          | 7875.6          | 11.8            | 176      | 1.814 |
| MG 0122 + 1928    | C IV 151549         | 4033.9          | 3.2             | 54       | 1.604 |
|                   | He II 1640          | 4262.9          | 3.8             | 81       | 1.599 |
|                   | C III 1909          | 4958.0          | 3.2             | 60       | 1.597 |
|                   | C IV 2232           | 6047.3          | 2.3             | 64       | 1.600 |
|                   | Mg II 22800         | 7273.3          | 3.1             | 77       | 1.598 |
| MG 0148 + 1028    | Ly\(\alpha\)        | 4676.1          | 101.8           | 116      | 2.845 |
|                   | C IV 151549         | 5965.3          | 116.3           | 128      | 2.851 |
|                   | He II 1640          | 6304.9          | 26.0            | 29       | 2.844 |
|                   | O III 1663          | 6040.8          | 8.4             | 9        | 2.849 |
|                   | C III 1909          | 7333.8          | 57.8            | 67       | 2.842 |
| MG 0308 + 0720    | Ly\(\alpha\)        | 4858.3          | 181.8           | 71       | 2.995 |
|                   | N II 12240          | 4905.8          | 529.3           | 221      | 2.956 |
|                   | Si II 121400        | 5587.0          | 56.3            | 26       | 2.991 |
|                   | C IV 151549         | 6162.9          | 155.9           | 75       | 2.979 |
|                   | C III 1909          | 7565.2          | 69.8            | 39       | 2.963 |
| MG 0311 + 1532    | C IV 151549         | 4634.1          | 3.4             | 160      | 1.991 |
|                   | He II 1640          | 4903.5          | 2.0             | 103      | 1.990 |
|                   | C III 1909          | 5703.8          | 2.1             | 97       | 1.988 |
|                   | C IV 2232           | ...             | ...             | ...      | ...   |
|                   | [Ne IV] 3242        | 7239.3          | 1.1             | 50       | 1.988 |
| MG 1019 + 0534    | Ly\(\alpha\)        | 4584.3          | 8.4             | 268      | 2.770 |
|                   | N II 12240          | 4664.8          | 2.3             | 66       | 2.762 |
|                   | C IV 151549         | 5838.9          | 10.4            | 257      | 2.769 |
|                   | He II 1640          | 6174.9          | 8.5             | 170      | 2.765 |
|                   | C III 1909          | 7179.6          | 4.9             | 93       | 2.760 |
| MG 1142 + 1338    | C III 1909          | ...             | <3.0            | ...      | ...   |
|                   | C IV 2236           | ...             | <1.6            | ...      | ...   |
|                   | [Ne V] 3426         | 7783.6          | 5.4             | 112      | 1.272 |
|                   | [O III] 3727        | 8495.1          | 13.6            | 232      | 1.279 |
| MG 1251 + 1104    | Ly\(\alpha\)        | 4040.5          | 23.1            | 148      | 2.324 |
|                   | C IV 1549           | 5148.4          | 3.0             | ...      | 2.324 |
|                   | He II 1640          | 5453.2          | 3.0             | ...      | 2.325 |
|                   | C III 1909          | 6326.7          | 5.2             | 298      | 2.314 |
|                   | C IV 2236           | ...             | <4.5            | ...      | ...   |
| MG 1401 + 0921    | C IV 1549           | 4793.9          | 4.1             | 165      | 2.095 |
|                   | He II 1640          | 5072.8          | 5.0             | 171      | 2.093 |
|                   | C III 1909          | 5901.1          | 3.4             | 83       | 2.091 |
|                   | C IV 2326           | 7187.2          | 1.7             | 89       | 2.090 |
|                   | [Ne IV] 3426        | 7521.8          | 2.9             | 121      | 2.104 |
| MG 2037 − 0011    | C III 1909          | 4782.2          | 4.4             | 123      | 1.505 |
|                   | C IV 2326           | 5843.5          | 1.0             | 39       | 1.512 |
|                   | [Ne IV] 3426        | 6093.9          | 1.0             | 43       | 1.514 |
| MG 2041 + 1854    | Ly\(\alpha\)        | 4986            | 788.5           | 141      | 3.100 |
|                   | Si IV 1400          | 5695.0          | 130.8           | 28       | 3.050 |
|                   | C IV 1549           | 6283            | 417.8           | 54       | 3.056 |
|                   | C III 1909          | 7785            | 68.3            | 25       | 3.086 |
| MG 2058 + 0542    | C III 1909          | 4541.3          | 7.1             | 152      | 1.379 |
|                   | C IV 2326           | 5537.6          | 4.1             | 120      | 1.381 |
|                   | Mg II 2798          | 6667.0          | 6.6             | 206      | 1.381 |
|                   | [Ne IV] 3426        | 5769.6          | 1.3             | 45       | 1.380 |
|                   | [Ne V] 3426         | ...             | <2.0            | ...      | ...   |
Galleries.
of a correlation between radio power and ionization state in distant radio
the weakest of the carbon lines in the MG composite spectrum, suggestive

Note the difference in relative strength of the carbon lines: whereas C
emission line. The 3C/MRC are typically higher radio flux density sources.
Lawrence 1999) radio galaxy spectra, scaled with respect to the C
extremely weak lined MG 1142

MG 1104, whose spectrum is heavily affected by pattern

In Figure 3 we present a composite Keck/MG radio
galaxy spectrum constructed from 11 of the spectra present-
ed here, omitting the unfluxed spectra, the quasars, the
extremely weak lined MG 1142+1338, and MG
1251+1104, whose spectrum is heavily affected by pattern

gHz radio axis is aligned with the fainter emission
(P.A. 4.8 GHz = 175°) and is extended by 3°.

4. EMISSION-LINE PROPERTIES AND IONIZATION STATE

In Figure 3 we present a composite Keck/MG radio
galaxy spectrum constructed from 11 of the spectra present-
ed here, omitting the unfluxed spectra, the quasars, the
extremely weak lined MG 1142+1338, and MG
1251+1104, whose spectrum is heavily affected by pattern
noise. We also include MG 1019+0534 and MG
2144+1928, the only previously published Keck spectra of
MG radio galaxies (Dey et al. 1995; Maxfield et al. 1999), in
order to maintain the integrity of the selection criterion;
namely, we combine all Keck spectra of MG radio galaxies
that we have amassed to date. These selection criteria
ensure that we use only the highest signal-to-noise ratio
data. The composite was constructed by shifting the indi-
vidual spectra into their rest frame, rebinning to a common
linear wavelength scale with 2 Å pixel\(^{-1}\) resolution, and
scaling the spectra by the flux of the C \(\text{III}\) \(\lambda 1909\) emission
line. We select the C \(\text{III}\) \(\lambda 1909\) feature because it is present
in most of the spectra considered here—in objects at both
high and low redshift, as well as objects exhibiting high-
and low-ionization spectra. We justify this algorithm in that our
primary objective is to study the emission-line properties of
the MG sample; normalizing the spectra over a longer
wavelength (line-free) range would give undue weight to the
galaxies with the lowest continua. The current algorithm
warrants the continuum to the weakest lined sources. Accord-
ingly, we deemphasize conclusions drawn regarding the
composite continuum. The red ends of the spectra were then
trimmed to minimize contamination from the telluric OH
features and, in the case of MG 0311 emission line. Instead, we normalized its

![Fig. 3.—Composite MG (top) and 3C/MRC (bottom; McCarthy &
Lawrence 1999) radio galaxy spectra, scaled with respect to the C \(\text{III}\) \(\lambda 1909\)
emission line. The 3C/MRC are typically higher radio flux density sources.
Note the difference in relative strength of the carbon lines: whereas C \(\text{IV}\) \(\lambda\lambda 1549\) is the strongest of the carbon lines in the 3C/MRC composite, it is
the weakest of the carbon lines in the MG composite spectrum, suggestive
of a correlation between radio power and ionization state in distant radio
galaxies.](image-url)
resolution of the spectrograph. For typical line widths of 1100 km s^{-1} observed at 7500 Å, the deconvolution correction is ≈ 75 km s^{-1}. Comparisons with the emission-line strengths determined from composite spectra of higher flux density radio galaxies (McL99), QSOs (Boyle 1990; Francis et al. 1991), Seyfert II nuclei (Ferland & Osterbrock 1986), the LINER nucleus of NGC 4579 (Barth et al. 1996), and models are presented in Table 7. All line profiles in the MG composite were fitted with a simple Gaussian. This simple prescription overestimates the width of the doublet lines, most drastically for Mg II λ2800, whose rest frame separation is 7.2 Å. The typical FWHM for the remaining lines is 900–1100 km s^{-1}, lower than that found by McL99 for their composite radio galaxy spectrum. Unlike McL99, we do not find that the FWHMs increase toward shorter wavelengths. However, the constituent galaxies in the McL99 composite stem from a much larger redshift range (0.16 < z < 3.13), allowing a longer baseline composite spectrum (λ2800–5500). No strong trend is evident in their composite for the restricted wavelength range where both composites overlap. McL99 note that redshift correlates with [O II] λ3727 and [O III] λλ4959, 5007 line width in 3CR galaxies, suggesting that the wavelength–line width trend in McL99 likely reflects a redshift–line width correlation, in the sense that higher redshift radio galaxies have broader emission lines. This is unlikely to be a selection effect, as the 3CR is nearly completely identified.

We measure an average rest frame equivalent width of 75 Å for the Lyα emission line in the Keck/MG radio galaxy sample. For comparison, from a sample of 28 radio galaxies with 1.7 < z < 3.5, similar to the redshift range in the current sample, McCarthy (1993) finds a mean rest frame W_{Lyα} of 295 ± 188 Å. Radio-quiet, Lyman-break galaxies with Lyα in emission have a typical W_{Lyα} of 3–20 Å (Steidel et al. 1996). McL99 find that their composite radio galaxy spectrum has very strong Lyα relative to N v λ1240, C iv λλ1549, and C m[i] λ1909, as compared with other active galactic nuclei (AGNs). The MG composite, however, has much weaker Lyα, with line ratios more typical of the other AGNs in Table 7. Most likely the radio galaxy discrepancies stem from the small number of Lyα emitters in the composite spectra. The 3C/MRC composite Lyα is made up of seven galaxies, whereas the MG composite Lyα is made up of only three galaxies, one of which is known to be underluminous in Lyα, likely because of dust absorption (MG 1019+0534; Dey et al. 1995). However,

| Line       | λ (Å) | HzRG MG | HzRG 3C/MRC | Seyfert II | LINER NGC 4579 | QSO Boyle | QSO Francis |
|------------|-------|---------|-------------|------------|----------------|------------|-------------|
| Lyα .......| 1216  | 515*    | 1766        | 1000       | 239            | 485        | 253         |
| N v .......| 1240  | 53      | 88          | ...        | ...            | 128        | ...         |
| C iv .......| 1549  | 131     | 207         | 218        | 81             | 224        | 217         |
| He ii ......| 1640  | 94      | 181         | 37         | 4              | 26         | 62          |
| C m[i] .....| 1909  | 100     | 100         | 100        | 100            | 100        | 100         |
| C m[ii] ...| 2326  | 83      | 52          | ...        | 32             | 19         | 20          |
| [Ne iv] ...| 2424  | 49      | 51          | ...        | <8             | ...        | 8           |
| [O II] ... | 2470  | 17      | 23          | ...        | 7              | ...        | ...         |
| Mg ii ......| 2800  | 116     | 43          | 33         | 113            | 113        | 117         |
| [O III] ...| 3727  | 188     | 207         | 103        | ...            | ...        | 0.3         |

Note.—All line strengths are measured relative to C m[i] λ1909. The MG high-redshift radio galaxy (HzRG) composite derives from the current work, the 3C/MRC HzRG composite is from McL99, the Seyfert II composite is from Ferland & Osterbrock 1986, the UV spectrum of LINER nucleus of NGC 4579 is from Barth et al. 1996, and the QSO composites are from Boyle 1990 and Francis et al. 1991.

* When composite is created without MG 1019+0534, a dusty radio galaxy known to be underluminous in Lyα (Dey et al. 1995), the value of 100 × Lyα/C m[i] λ1909 = 606.
one could also imagine a Lyα–radio power dependency, similar to the known [O II] \( \lambda 3727–1.4 \) GHz–radio power relation (McCarthy 1993), or that the MGs typically reside in dustier or more cold-gas–rich host galaxies.

At longer wavelengths, where the spectra are less affected by small number statistics, there are several significant differences between the radio galaxy composites. Most strikingly, the Mg II \( \lambda 2800 \) doublet is one of the most prominent lines in the MG composite, with Mg II \( \lambda 2800/\) C III] \( \lambda 1909 \sim 1.2 \) and Lyα/Mg II \( \lambda 2800 \sim 4.4 \). In the 3C/MRC composite, however, the Mg II \( \lambda 2800 \) doublet is relatively weak, with Mg II \( \lambda 2800/C \) III] \( \lambda 1909 \sim 0.4 \) and Lyα/Mg II \( \lambda 2800 \sim 41 \). The He II \( \lambda 1640/Mg II \) \( \lambda 2800 \) line ratio also shows significant variation between the composite radio galaxy spectra: He II \( \lambda 1640/Mg II \) \( \lambda 2800 \sim 0.8 \) for the MG sample, whereas He II \( \lambda 1640/Mg II \) \( \lambda 2800 \sim 4.2 \) for the 3C/MRC composite. These strong discrepancies are difficult to interpret, although the MG line ratios are intriguingly more similar to those of LINERs and quasars than to the 3C/MRC composite radio galaxy or Seyfert II galaxies (see Table 7). We note that the Mg II \( \lambda 2800 \) line in the MG composite is composed from five spectra, suggesting that small number statistics may still be the source of these suggestive trends.

The strengths of the various ionization stages of carbon are a more useful diagnostic of the excitation mechanisms in active galaxies: selecting emission lines from the same element avoids metallicity dependencies, whereas the small wavelength separation of the lines considered makes the conclusions relatively insensitive to reddening. In Figure 4 we plot C IV \( \lambda 1549/\) C III] \( \lambda 1909 \) versus C III] \( \lambda 1909/C II \) \( \lambda 2326 \) for individual galaxies in the MG sample, the composite spectra from Table 7, and the models described below. We find that the MG composite appears to be in a lower ionization state than the 3C/MRC composite, with carbon line ratios more comparable to the LINER nucleus of NGC 4579 than to the quasar composites. Again, an alternative explanation is that MGs typically reside in dustier galaxies than 3C/MRC sources. Unfortunately, the limited optical window and high redshift of the current sample deny us access to the line pairs commonly used for dust extinction measurements, such as Hα/Hβ, Lyα/Hβ, and He II \( \lambda 1640/He II \) \( \lambda 4686 \). However, the strength of the Lyα line, which is quite sensitive to dust, implies that there is not an immense amount of reddening in the MG composite, whereas the dramatic change in the Mg II \( \lambda 2800 \) strength between the 3C/MRC composite and the MG composite suggests that there is a significant difference between the emission-line regions in these two radio galaxy populations. Finally, the relatively high C II] \( \lambda 2326/[Ne IV] \) \( \lambda 2424 \) ratio indicates that the MG composite is in a lower ionization state as compared with the higher radio power 3C/MRC composite, despite the [Ne IV] \( \lambda 2424 \) line residing redward of the carbon lines. Therefore, dust reddening alone cannot explain the line ratio difference. This suggests that the ionization state of radio galaxies correlates with radio power. In a detailed study of lower redshift (\( z < 0.7 \)) southern 2 Jy radio sources, however, Tadhunter et al. (1998) find that ionization state, as measured by the [O II] \( \lambda 3727/[O III] \) \( \lambda 5007 \) ratio, does not correlate with radio power.

To test the hypothesis of a radio power–ionization state relation in high-redshift radio galaxies, we have amassed a sample of 30 radio galaxies with published C IV \( \lambda 1549 \) and C III] \( \lambda 1909 \) fluxes from the literature. In Figure 5 we plot C IV \( \lambda 1549/C \) III] \( \lambda 1909 \) versus rest frame 1.4 GHz radio power. There is a slight tendency for the stronger radio sources to have larger C IV \( \lambda 1549/C \) III] \( \lambda 1909 \) ratios, implying higher ionization states. To test the significance of the correlation, we have calculated the nonparametric Spearman rank correlation coefficient, \( \rho \), for this sample.
and find a value of $\rho = 0.340$. Note that this statistic is independent of cosmology. The null hypothesis, that no correlation exists between radio power and ionization state can be marginally rejected: the probability of obtaining a rank correlation coefficient this high from a sample of 30 uncorrelated variables is 3.5%. If we restrict our analysis to the two larger data sets, i.e., the Keck/MG and ultrasteep source samples, then $\rho = 0.445$ for a sample of 25 sources. The probability of obtaining a rank correlation coefficient this high from a sample of 25 uncorrelated variables is 1.5%, implying that the correlation is significant. We consider these statistical arguments suggestive, but not conclusive, of a radio power–ionization state correlation in the UV spectra of high-redshift radio galaxies. Insufficient sources with both He $\Pi \lambda 1640$ and Mg $\Pi \lambda 2800$ well detected prevented a similar analysis from being done with the He $\Pi \lambda 1640$/Mg $\Pi \lambda 2800$ ratio.

We have computed simple, single-zone photoionization models using CLOUDY (Ferland 1996). The purpose of this exercise is not to fabricate a definitive model of the radio galaxy spectrum, but rather to demonstrate that a simple low-density gas photoionization model can reproduce the overall character of the spectrum and to compare the best-fit parameters with those derived for the 3C/MRC composite. Following McL99, our calculations were made for an ionization-bounded slab of gas with a constant density of $n_e = 100 \text{ cm}^{-3}$ illuminated by a power-law spectrum of ionizing radiation, $F_{\nu} \propto \nu^{-\beta}$. We calculated models with a range of spectral index, $\alpha$, and ionization parameter, $U$. For reference, McL99 found that $\alpha = 1.5$ and log $U = -1.8$ provided the best fit to the composite 3C/MRC spectrum.

We find that the carbon line diagnostics are not well reproduced by these simple models. For example, the best-fit CLOUDY model of McL99 is represented by an asterisk in Figure 4. Although this model does a reasonable job at reproducing the overall character of the 3C/MRC emission-line spectrum, the C $\text{III}] \lambda 1909$/C $\text{II}] \lambda 2326$ ratio is much higher in the model than in the composite spectrum. Figure 2d of Allen, Dopita, & Tsvetanov (1998) is also enlightening: for a given C $\text{IV}] \lambda 1549$/C $\text{II}] \lambda 1909$ ratio, the C $\text{II}] \lambda 2326$ emission line is again too strong in the comparison AGN spectra to be fitted by simple single-zone photoionization models. Photoionization models that incorporate both optically thick (ionization-bounded) clouds and optically thin (matter-bounded) clouds, as described in Binnette, Wilson, & Storchi-Bergmann (1996), are capable of reproducing the observed carbon line diagnostics, as are the shock models of Dopita & Sutherland (1996), implying that (the MG) radio galaxies are more complicated than our basic model. Investigations also reveal that the high equivalent width Mg $\Pi \lambda 2800$ line is difficult to reproduce with the simple model: for $1.0 < \alpha < 1.5$ and $-1.0 < \log U < -2.0$, no model is capable of reproducing the Mg $\Pi \lambda 2800$/C $\text{III}] \lambda 1909$ ratio we find in the MG composite radio galaxy spectrum, indicating that shocks and/or more complicated photoionization scenarios are necessary to explain the emission-line spectra of these galaxies.

5. CONCLUSIONS

We present optical identifications, finding charts, and spectra for 17 new high-redshift radio sources selected from the MG 5 GHz survey. We select targets of moderately steep spectral index to preferentially observe radio galaxies, and, indeed, 15 of the 17 sources discussed here are radio galaxies. The remaining two sources are moderately steep-spectrum, radio-loud quasars, which may be important in terms of unified models of extragalactic radio sources. The spectra were all taken at the W. M. Keck Telescopes and are representative of the fainter MG identifications attempted thus far, with typical $R$ magnitudes of 23–24.

We construct a composite MG radio galaxy spectrum and compare it with the higher radio power composite 3C/MRC radio galaxy spectrum of McL99. We find that the MG radio galaxies typically exhibit lower ionization state spectra than the 3C/MRC radio galaxies. The Mg $\Pi \lambda 2800$ emission line is extremely strong in the MG composite relative to the other rest frame UV emission lines, with Mg $\Pi \lambda 2800$/C $\text{III}] \lambda 1909 \sim 1.5$ and Mg $\Pi \lambda 2800$/Ly$\alpha \sim 0.3$. Extensive modeling with single-zone photoionization models is incapable of reproducing the high Mg $\Pi \lambda 2800$/C $\text{III}] \lambda 1909$ ratio, indicating that shocks and/or more complicated photoionization scenarios are producing the emission-line spectra of these distant radio galaxies.

We have amassed a large sample of high-redshift radio galaxies with published C $\text{IV}] \lambda 1549$ and C $\text{II}] \lambda 1909$ line strengths. Comparing the C $\text{IV}] \lambda 1549$/C $\text{II}] \lambda 1909$ ratio to the rest frame 1.4 GHz radio power, we find evidence for a correlation between ionization state and radio power. A likely interpretation is that the more powerful radio sources are in an active phase when the central engine is emitting more flux across the electromagnetic spectrum with the augmented UV flux leading to higher ionization state spectra. As we progress from the strongest radio sources to weaker sources, we find that the emission-line strengths attenuate, the ionization state of the emission-line region diminishes, and the stellar populations apparently become more dominant. This last effect is seen both in the diminished alignment effect for weak radio sources and the discovery of several weak radio sources at moderate redshift whose spectra are devoid of the UV emission lines that dominate most radio galaxy spectra (e.g., Spinrad et al. 1997). An alternative explanation is to invoke multiple emission-line regions whose relative contributions vary with radio power.

The high-redshift radio galaxies discussed here are faint, and the radio power–line strength correlation implies that long integrations with the new generation of large aperture telescopes is necessary to measure the emission-line strengths and redshifts of these sources. High-redshift radio galaxies from a range of radio flux density will be the key to further investigations of the ionization state–radio power relation.

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