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STRONG LYMAN-ALPHA EMISSION IN THREE DISTANT RADIO GALAXIES[1]

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ABSTRACT

We have discovered very strong (equivalent width ≈ 1000 Å), narrow Lyα emission in the redshifted ultraviolet (UV) spectra of three radio galaxies having $1.62 \lesssim z \lesssim 1.82$. The spectra of 3C 256 and 3C 239 are almost identical; besides Lyα, the strongest UV emission lines are C IV λ1549, He II λ1640, and C III] λ1909. The galaxy 3C 241 exhibits similar features, but the data are of poorer quality. The luminosity of Lyα is typically $\sim 2 \times 10^{44}$ ergs s^{-1} ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$), while its intrinsic full width at half-maximum (instrumental broadening removed) is ~ 1500 km s^{-1}.

Differences between the average spectrum of the radio galaxies and that of QSOs with $z \gtrsim 2$ are briefly discussed. In particular, the C IV and C III] lines in these galaxies are weak compared with He II and Lyα, and all of the features are relatively narrow. Moreover, [Ne IV] λ2424 is unusually strong in 3C 256 and 3C 239, while it is almost never seen in QSOs. The spectral characteristics of nearby type 2 Seyfert galaxies and narrow-line radio galaxies, on the other hand, are similar to those reported here, although the emission lines are somewhat broader in our objects. We note that Lyα itself will probably be a very useful redshift and classification determinant in future spectroscopic surveys of active galaxies having still greater distances.

Subject headings: galaxies: redshifts — galaxies: Seyfert — quasars — radio sources: galaxies — radio sources: spectra

I. INTRODUCTION

Lyman-alpha (Lyα) emission has frequently been detected in the spectra of QSOs during the 20 yr since Schmidt's (1965) study of 3C 9 ($z = 2.012$). It is also seen with the *International Ultraviolet Explorer* (*IUE*) satellite in a few active galactic nuclei (AGNs) having $z \gtrsim 0.04$ (e.g., Fosbury *et al.* 1982; Ferland and Osterbrock 1985*a*, *b*). Successful *ground-based* observation of this hydrogen resonance line in radio galaxies, however, had to await the determination of redshifts exceeding 1.55, because atmospheric ozone and various optical elements in spectrographs severely absorb light below ~ 3100 Å.

In this *Letter*, we report the detection of Lyα emission which dominates the near-UV spectra of the three known radio galaxies with $1.62 \lesssim z \lesssim 1.82$. These are 3C 241 at $z = 1.617$ (Spinrad and Djorgovski 1984, hereafter SD84), 3C 239 at $z = 1.781$ (Spinrad, Windhorst, and Koo 1985), and 3C 256 at $z = 1.819$ (SD84). Since the galaxies are very faint ($m_v \gtrsim 22$), our exploratory spectra are noisy, but they permit the identification and rough flux measurements of several other emission lines normally unavailable to ground-based observers.

[1]Research reported here used the Multiple Mirror Telescope Observatory (MMTO), a joint facility of the Smithsonian Institution and the University of Arizona. Also, based in part on research done at Lick Observatory, University of California.

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II. OBSERVATIONS AND REDUCTIONS

The primary observations were obtained at four telescopes by the entire cast of authors during a three-month interval in the winter and spring of 1985. For spectra near the UV atmospheric limit, we used the Lick Observatory Shane 3 m reflector with an image-tube scanner (ITS; Miller, Robinson, and Wampler 1976), the Multiple Mirror Telescope (MMT) with its blue-sensitive Reticon spectrograph (Shectman and Hiltner 1976), and a similar Reticon plus image-tube system on the University of Arizona 2.3 m reflector. In addition, the Cryogenic Camera (De Veny 1983) was used on the Kitt Peak 4 m Mayall telescope to obtain spectra at wavelengths far to the red of Lyα.

Standard procedures (see e.g., Osterbrock 1977) were followed during the observations, except that the radio galaxies were too faint to see on the TV screen used for guiding. Instead, the positions of nearby stars, from which blind offsets to the radio galaxies had previously been calculated using direct CCD images, were checked periodically to monitor and correct any small tracking errors made by the telescopes. A spectral resolution of ~ 8–12 Å, defined by the full width at half-maximum (FWHM) of emission lines in the night sky, was achieved with the different instruments through entrance apertures of 4″ × 4″ or smaller. The data were reduced in the normal manner; see Djorgovski and Spinrad (1983), Filippenko (1985), and Osterbrock (1977) for further details. No corrections for reddening due to dust were applied to the spectra, since all three objects are at high Galactic latitude ($b \gtrsim 53°$). Although not all the data were obtained under photometric conditions, at least one spectrum could be used to determine approximate absolute fluxes for each galaxy.

Our Lick and MMT spectra of 3C 256, which have the highest signal-to-noise ratios, compare quite well. Integration times of $\lesssim 1$ hr in good conditions were sufficient for strong detections of Lyα and C IV emission in the spectra of 3C 256 and 3C 239. A considerably longer period, however, was spent on 3C 256 at Lick, so that weaker lines could be seen and measured. Observations of the faintest galaxy, 3C 241, were attempted at an air mass larger than usual ($\sec z \approx 1.3$–1.5), and hence are of lower quality than those of the other two radio galaxies. We defer details concerning 3C 241 until better spectra become available, but Lyα was certainly detected at $\lambda \approx 3180$ Å.

III. INTENSITIES AND WIDTHS OF EMISSION LINES

The outstanding qualitative result of this *Letter* is the great strength and relatively narrow width of the Lyα emission line in 3C 256 and 3C 239. This feature is probably a little weaker in 3C 241. Figure 1 illustrates the spectrum of 3C 256, obtained with the MMT (blue) and the Mayall reflector (red); note the narrowness of Lyα, whose intrinsic FWHM is ~ 1500 km s^{-1}. Instrumental broadening of the emission lines was removed to first order by assuming that it adds quadratically to the true (intrinsic) width. Of course, the derived FWHM includes the effects of any mass motion (e.g., rotation) of gas within the entrance aperture. Table 1 gives the intrinsic line widths in 3C 239, whose spectroscopic properties are very similar to those of 3C 256. Since a smaller aperture ($2'' \times 3''$) was used than for 3C 256, instrumental broadening was easier to eliminate, and the contribution of mass motions may have been less significant.

TABLE 1

LINE WIDTHS IN 3C 239

Line	λ_0 (Å)	FWHM (km s^{-1})
Lyα	1216	1400 ± 220
C IV	1549	1700 ± 250
He II	1640	1800 ± 280
C III]	1909	1400 ± 250

As stated by SD84, the emission spectra of almost all radio galaxies having large redshift and high luminosity seem to be dominated by their narrow-line regions (NLRs). The observed equivalent widths (EWs) of Lyα are ~ 1000 Å, perhaps up to ~ 2000 Å in 3C 256, but the faintness of the galaxy continua near rest wavelengths of 1200 Å makes this uncertain by a factor of 2–3. We note that the *flux* of Lyα through the apertures, which can be determined with greater accuracy than its EW, is enormous; the average of the line fluxes for 3C 256 and 3C 239 (Table 2) yield a luminosity of Lyα of $\sim 2 \times 10^{44}$ ergs s^{-1} ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$). The total luminosity for the entire galaxy could differ from this by a factor of ~ 2 because of the relatively small entrance apertures and other effects, but it is comparable to that observed in QSOs (Weedman 1979). Remarkably luminous emission lines (generally [O II] λ3727) have previously been detected in distant radio galaxies by Spinrad (1982) and others.

Figure 2 shows the smoothed, average UV spectrum of the two best observed radio galaxies, while Table 2 lists the emission lines measured in this composite spectrum. The relative fluxes of the stronger, unblended lines should be accurate to $\sim 25\%$–30%, but the weak lines such as N V λ1240, while clearly detected, are difficult to measure quantitatively and hence could be uncertain by $\gtrsim 70\%$.

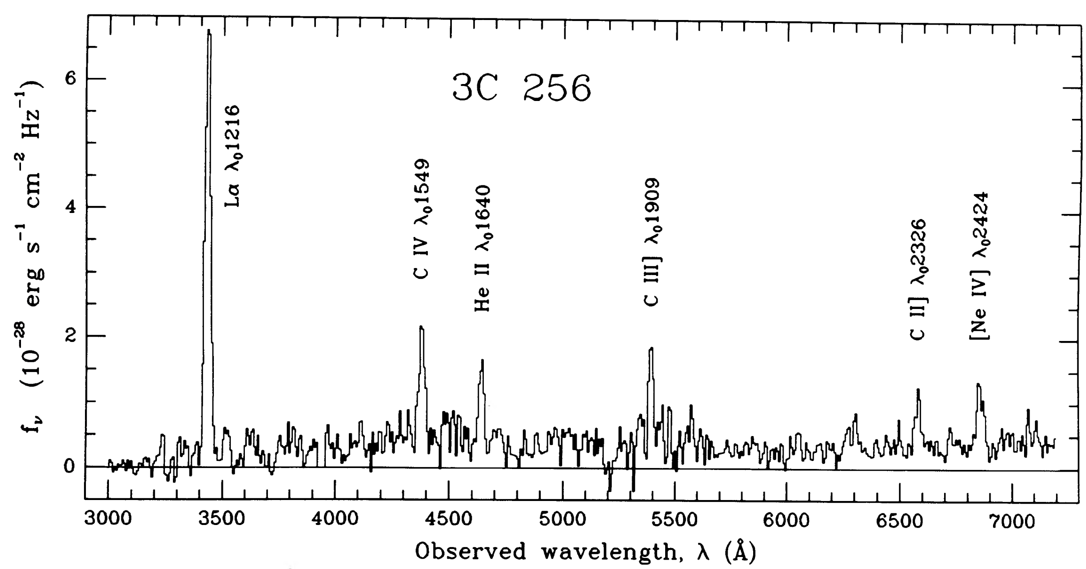

FIG. 1.—Spectrum of 3C 256, obtained with the Reticon spectrograph on the MMT and the Cryogenic Camera on the Mayall reflector. The flux density scale is only approximate. Prominent emission lines, together with their rest wavelengths (λ_0), are labeled.

TABLE 2

AVERAGE SPECTRUM OF 3C 256 AND 3C 239

Line	λ_0 (Å)	EW (Å)	I (10^{-16} ergs s^{-1} cm^{-2})	$100[I(\lambda_0)/I(Ly\alpha)]$
Lyα	1216	340	44.5	100
N V	1240	22:	2.9:	6.5:
C IV	1549	38	6.86	15.4
He II	1640	22	3.5	7.9
O III]	1663	9:	1.4:	3.1:
C III]	1909	28	3.7	8.3
N II]	2142	9:	0.8:	1.8:
C II]	2326	19	1.5	3.4
[Ne IV]	2424	30	2.3	5.2
[O II]	2470	7:	0.5:	1.1:

NOTES—Colon (:) denotes very uncertain value. Equivalent widths are given in the rest frame of the objects. Intensitites are measured in Earth's frame of reference.

IV. BRIEF COMPARISON WITH QUASI-STELLAR OBJECTS AND ACTIVE GALACTIC NUCLEI

Inspection of Figure 2, Table 2, and Table 3 demonstrates the spectral similarities and differences between our radio galaxies and the more familiar quasars (e.g., Baldwin 1979). C IV, He II, and C III] are clearly visible, but in 3C 256 and 3C 239 the carbon lines are weaker with respect to Lyα and He II than they are in the spectra of QSOs. The intensity ratio of Lyα to C IV, for example, is ~ 2.3 times higher in the distant radio galaxies than in the "average" QSO. Relative intensities of the H and He recombination lines, and of lines from different carbon ions, are fairly normal.

Table 3 also shows that 3C 239 and 3C 256 do not resemble H1340 object 10, a high-redshift QSO which has very narrow emission lines (Foltz *et al.* 1983). Although $I(Ly\alpha)/I$(C IV) is approximately the same, He II λ1640 is much too weak in H1340 object 10, and the C IV/C III] ratio differs by a factor of 2.

Excellent agreement in line intensity ratios is found between the distant radio galaxies and NGC 4507 (Table 3), a high-excitation Seyfert 2 galaxy (Bergeron, Maccacaro, and Perola 1981). Unfortunately, little information is available on the complete UV spectra of other type 2 Seyferts and the related narrow-line radio galaxies; most are too faint for *IUE*, and in nearby objects Lyα is heavily contaminated by geocoronal emission. It appears, however, that many of the strong lines have relative intensities similar to those in Table 2 (e.g., Bergeron, Maccacaro, and Perola 1981; Ferland and Osterbrock 1985*b*). One obvious difference, on the other hand, is that the line widths in most type 2 Seyferts and narrow-line radio galaxies are roughly a factor of 3 smaller than those derived here (Koski 1978; Cohen and Osterbrock 1981). This is consistent with the known correlation between line width and radio luminosity (Wilson and Willis 1980; Whittle 1985), since our galaxies are very bright radio sources.

The prominent [Ne IV] λ2424 line in 3C 239 and 3C 256 ensures an NLR of low density, since the critical density for collisional deexcitation of this transition is $\sim 3 \times 10^5$ cm^{-3} (Osterbrock and Parker 1966). Moreover, the simultaneous presence of C II], C III], [Ne IV], N V, and other lines indicates a large *range* of ionization in the two radio galaxies. Recall, however, that SD84 found 3C 256 to be of considerably higher "mean ionization" than 3C 241, 3C 266, and 3C 324 (see also Spinrad and Djorgovski 1983), which are at slightly lower redshifts.

Comparison of published results from various photoionization models (e.g., Davidson 1977; Netzer and Ferland 1984) with the standard QSO and with our average radio galaxy suggests a similar degree of hardness in the UV radiation field,

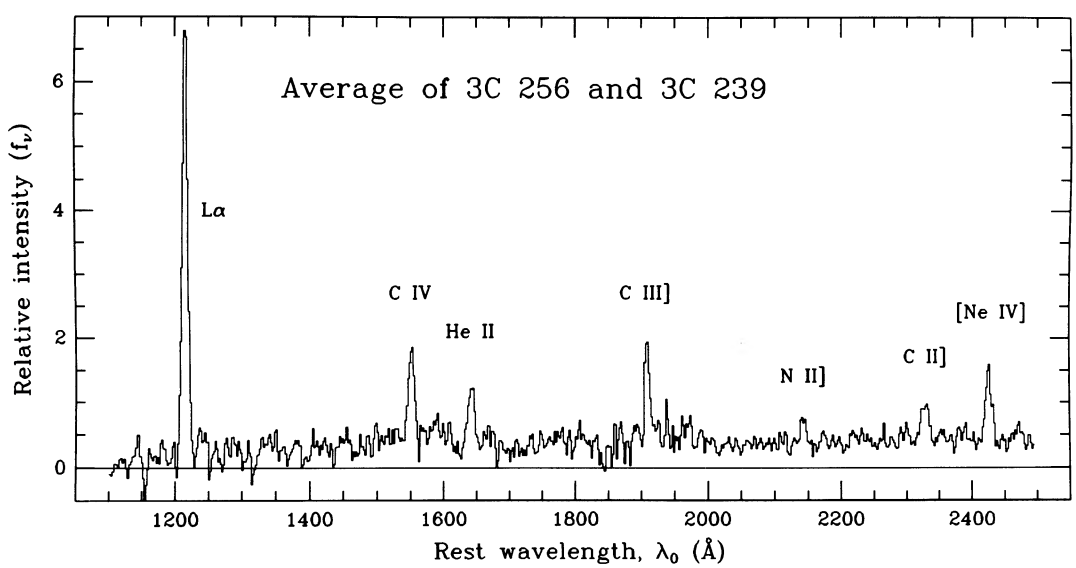

FIG. 2.—Composite spectrum of 3C 256 and 3C 239. The redshift of each object was removed before averaging. Low-frequency undulations in the weak continuum, probably caused by imperfect subtraction of the background sky, are the dominant source of error in the measured equivalent widths of emission lines.

TABLE 3

COMPARISON OF EMISSION-LINE INTENSITY RATIOS

Object	Lyα/He II	C IV/C III]	Lyα/C IV
⟨3C 256, 3C 239⟩[a]	13 ± 7	1.9 ± 0.7	6.5 ± 1
⟨QSO⟩[b]	20 ± 9	2.2 ± 0.8	2.9 ± 1.2
H1340 object 10[c]	114	4.2	5.7
NGC 4507[d]	17.6	2.3	7.1

[a]Average radio galaxy; see Table 2.

[b]Average QSO (Baldwin 1979).

[c]Narrow-line QSO (Foltz *et al.* 1983).

[d]Seyfert 2 (Bergeron, Maccacaro, and Perola 1981). Dereddened, $E_{B-V} = 0.134$ mag.

and an ionization parameter of $\log U \approx -2.5 \pm 0.4$. We cannot state *a priori* whether the Lyα line is optically thick or thin, but despite this uncertainty it is interesting to note that the rather weak C IV and C III] (relative to Lyα and He II λ1640) may imply a deficiency in carbon, and perhaps other metals, by a factor of 2–4. Davidson's (1977) optically thin, metal-poor photoionization model with an ionizing spectral index of $\alpha = 1.5$ ($f_\nu \propto \nu^{-\alpha}$) and $\log U \approx -2.7$ seems to fit our results best, and optically thick models with a somewhat larger ionization parameter are also satisfactory. Better data, and more realistic calculations which consider a range of U among the narrow-line clouds (e.g., Péquignot 1984), are clearly necessary to confirm our preliminary conclusion regarding the abundances.

V. THE FUTURE: IDEAS AND SPECULATIONS

Thus far we have made only the most basic Lyα "discovery observations," as well as a rough historical interpretation of the UV emission-line intensities in terms of QSO photoionization models. With new data of higher quality we should look into the following topics:

1. Is Lyα often spatially extended beyond the main body of the galaxy, in the same way that the strong [O II] λ3727 line flares out in some radio sources and QSOs (Fosbury *et al.* 1982; Spinrad and Djorgovski 1983; SD84; Hintzen and Stocke 1985)?

We have one new datum concerning this question. Cursory examination of a fairly deep, direct UV plate of 3C 256 obtained with the 4 m Mayall telescope at Kitt Peak indicates that the image, which is *dominated* by Lyα in the UV bandpass, has the same general shape as the blue and red CCD images illustrated by SD84. Thus, the Lyα line is not restricted to a point source near the center of this large galaxy, nor does it have any peculiar filamentary shape which could have been anticipated from the "cooling flow" Lyα line seen in Perseus A (Fabian, Nulsen, and Arnaud 1984) and possibly in several radio galaxies and cluster giant elliptical galaxies (Nørgaard-Nielsen, Jørgensen, and Hansen 1984; Hu and Cowie 1985). If the Lyα isophotes really turn out to have the same shape as those arising from the starlight in 3C 256, we will have to consider the possibility that young stars are at least partly responsible for the ionization of the interstellar medium in this object (Terlevich and Melnick 1985; Djorgovski and Spinrad 1985).

2. Can we use the enormous strength of Lyα in these objects as a tool for discovering galaxies at still greater distances? An idea here might be to initiate a spectroscopic search for galaxies at very accurate (usually central-component) radio positions of undetected ("blank field") optical objects. One example is 3C 470 (Laing, Riley, and Longair 1983). The lore in this subject is that most of the "blank fields" with steep radio spectra ($\alpha \gtrsim 0.7$) will turn out to be distant ($z \gtrsim 1.5$) radio galaxies. A detection of Lyα would simultaneously yield a vital redshift *and* an identification; this line is only ~ 1500 km s^{-1} wide in our prototypical distant galaxies (3C 256 and 3C 239), whereas permitted lines in QSOs generally have widths ~ 2–8 times as great. This technique has already been successfully employed by SD84, but with [O II] λ3727 rather than Lyα.

3. Another hope is that a fair number of primeval galaxies (e.g., Davis 1980) at $z \approx 2$–3 can be detected in the UV and blue spectral regions by some sort of future objective-prism (or grism) survey at faint levels. Perhaps the way to initially try this is to conduct a deep search for young companion galaxies around known quasars ($z \gtrsim 2$). If stars do provide the necessary ionizing photons, then the hypothetical galaxies should appear as narrow Lyα "spikes" superposed on an undetected (or barely detected) continuum. The Lyα line will generally be much fainter than in our spectra of 3C 256 and 3C 239, which are very luminous galaxies.

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