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4C 40.36: A RADIO GALAXY AT A REDSHIFT OF 2.3

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ABSTRACT

We present long-slit spectroscopy of a faint extended optical object which we have identified with the radio source 4C 40.36. Three emission lines are detected. Their wavelengths match those of C IV $\lambda1549$, He II $\lambda1640$, and C III] $\lambda1909$ to within 0.5% for a redshift of $z = 2.269$. The extended continuum emission (~ 20 kpc) together with the large equivalent widths (~ 100 Å) and narrow profiles (~ 1500 km s^{-1}) of the emission lines, all show that 4C 40.36 is a galaxy with properties similar to those of other distant radio galaxies. The redshift of 4C 40.36, however, considerably exceeds that of the most distant radio galaxy (3C 326.1 at $z = 1.825$) known to date. 4C 40.36 is of additional interest as an excellent example of the recently discovered phenomenon of alignment between the optical and radio axes of powerful distant radio galaxies. The object was investigated as part of our survey of ultra–steep spectrum radio sources, and we show that the selection criteria used to discover 4C 40.36 result in a sample of objects having a relatively low dispersion of monochromatic radio luminosities.

Subject headings: cosmology — galaxies: redshifts — radio sources: galaxies

I. INTRODUCTION

During the last three decades, the presence of strong radio emission has been one of the most effective ways of pinpointing distant galaxies. Optical identification of the 3CR sample of radio sources is now nearly complete, and careful spectroscopic investigation of these objects has resulted in the discovery of several radio galaxies with redshifts larger than one (Spinrad *et al.* 1985*a*; Spinrad 1987; Djorgovski *et al.* 1988). The most distant object reported until now, 3C 326.1, has $z = 1.825$ (McCarthy *et al.* 1987*a*). As yet, studies of fainter radio sources (e.g., the "1 Jy" sample of Allington-Smith *et al.* 1982) have resulted in no radio galaxy with $z > 1.8$ (e.g., Spinrad and Djorgovski 1987). Moreover, there have been indications from statistical analyses of radio source counts that the supply of powerful radio galaxies might "cut off" above a redshift of ~ 2.0 (e.g., Windhorst 1984).

Much of the motivation for studying distant radio galaxies has come from their potential use as cosmological probes (Spinrad and Djorgovski 1987; Lilly and Longair 1984). Recent evidence for an alignment between the optical/infrared and radio axes in high-redshift radio galaxies (Chambers, Miley, and van Breugel 1987; Chambers, Miley, and Joyce 1988; McCarthy *et al.* 1987*b*) strongly suggests that these objects are highly peculiar and that it is overly optimistic to use them as optical/infrared "standard candles." The high-redshift radio/optical correlations, on the other hand, may yield unique information on the physical nature of nuclear activity and on the conditions of the surrounding (protogalactic?) medium at early epochs. It has therefore added an additional and important incentive for studies of distant radio galaxies.

The sample of ultra–steep spectrum 4C radio sources, as described in Chambers, Miley, and van Breugel (1987), was expected to provide an efficient way to preselect such radio galaxies (e.g., Blumenthal and Miley 1979). Our preliminary results indeed identify 28 out of 33 of these objects with very faint galaxies. Here we describe spectroscopic observations of a source from our sample, 4C 40.36 and show that it has a redshift of $z = 2.269 \pm 0.005$.

II. OBSERVATIONS AND DATA REDUCTION

We observed 4C 40.36 several times at various frequencies and resolutions with the VLA as part of our multifrequency study (Chambers and Miley 1988). Figure 1*a* shows a high-resolution (0".4 FWHM) radio intensity map made at 4885 MHz in 1987 August (Chambers and Miley 1988). The radio data were reduced in the standard way using AIPS, the NRAO image processing system.

A deep CCD image of the blank optical field around 4C 40.36 was taken with the 2.1 m KPNO telescope in 1986 August, under good seeing conditions ($\sim 1".0$). The optical identification was made by accurate ($\pm 0".5$) astrometric measurements of faint stars on the Palomar Sky Survey which were visible in the CCD image. Figure 2 (Plate L2) shows the entire *R*-band CCD image (smoothed to 3 pixels, 1".14, with a limiting magnitude ~ 23.5) with the object we associate with 4C 40.36 marked between two bars in the northeast region of the image at position of the radio source, $18^h09^m19^s.424$, $+40°44'38".88$.

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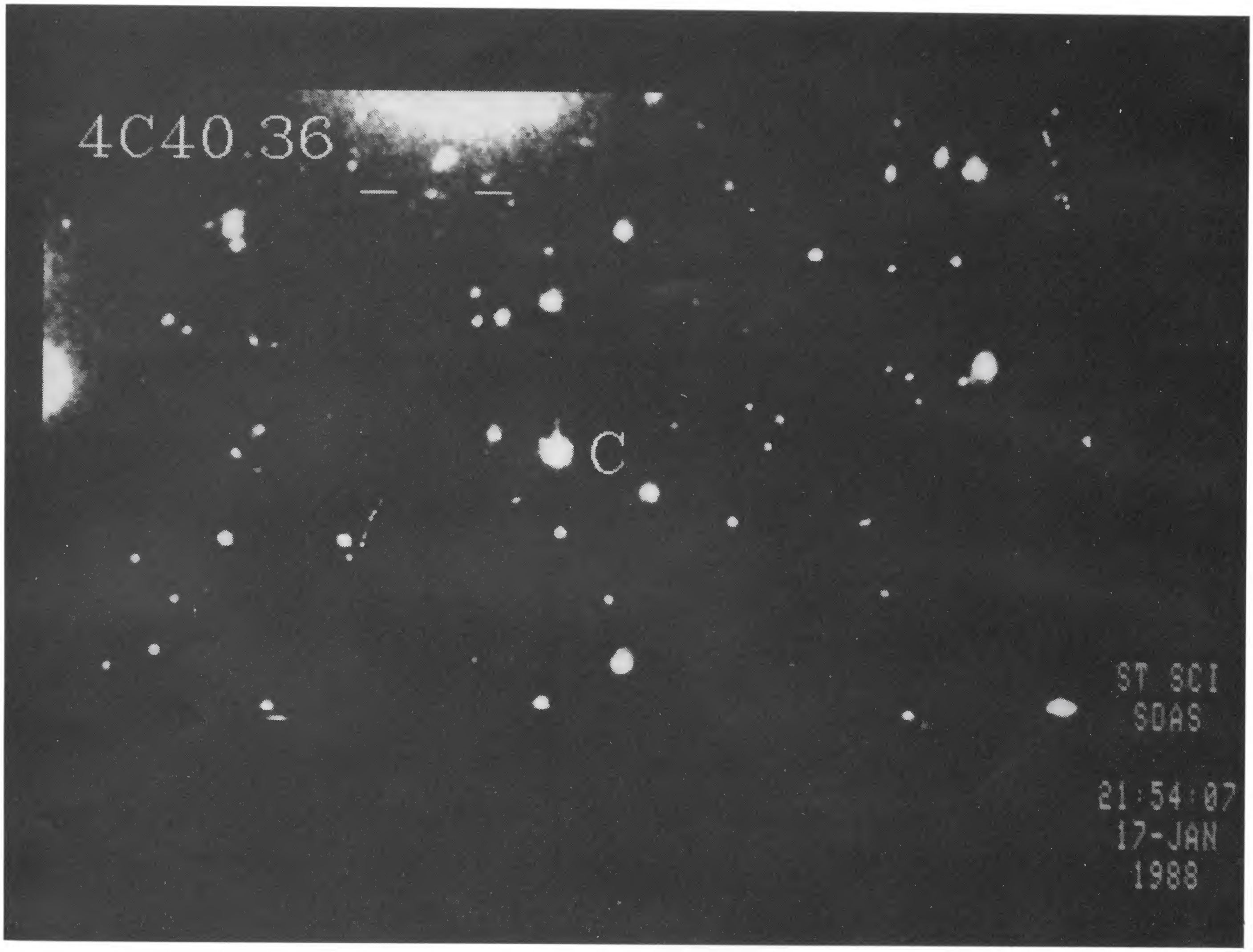

FIG. 2.—Entire R-band CCD image (smoothed to 3 pixels, 1".14), with a limiting magnitude ~23.5. The object we associate with 4C 40.36 is marked between two bars in the northeast region of the image at the position of the radio source, $18^h09^m19^s.424$, 40°44'38".88.

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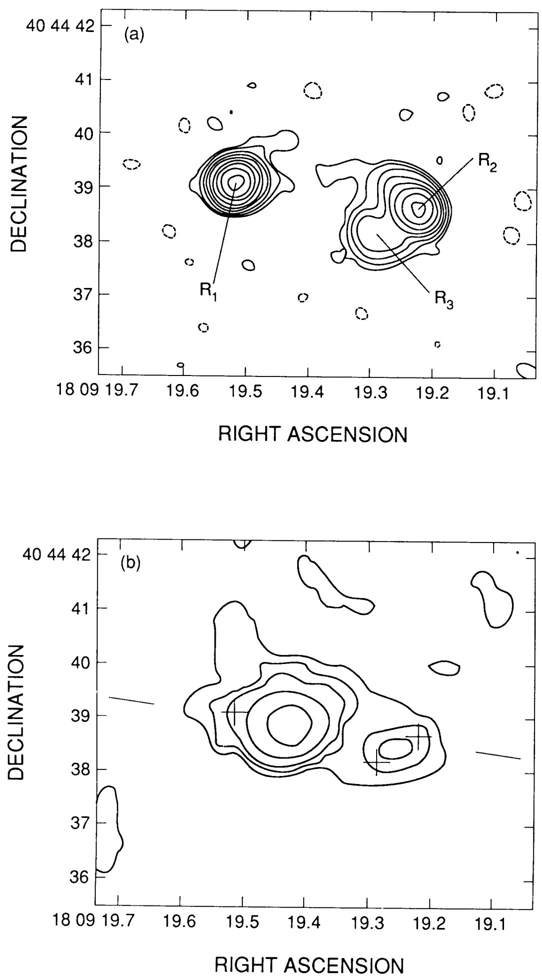

FIG. 1.—Intensity images of 4C 40.36 at the same scale and positioned to within < 1″.0. (*a*) VLA radio intensity image made at 4885 MHz in the A array. Contour levels are 50 μJy per beam × (−2, 2, 4, 8, 16, 32, 64, 128, and 512). (*b*) Broad-band R image, smoothed to 3 pixels (1″.14). Contours are 12, 20, 30, 55, and 90% of the sky-subtracted peak intensity. The crosses on the optical image refer to the fiducial points R_1, R_2, R_3 marked on the radio image.

There are bright stars nearby, whose wings are visible to the north and east. In the center of the image is a star marked "C" which is visible on the Sky Survey, and whose (1950) coordinates we have measured to be $18^h09^m17^s.372$, 40°43′49″.56 (±0″.5). Figure 1*b* shows isophotal *R*-band contours of 4C 40.36. The radio and optical images in Figure 1 have the same scale to within 0.5% and absolute position to ±0″.5.

Our spectroscopic observation was made on 1987 August 22, under poor seeing conditions (~1″.8), with the Cryogenic Camera (De Veny 1985) at the Cassegrain focus of the KPNO 4 m telescope. The telescope was offset from the star marked "C." The 2″.5 wide, 4′.4 long slit was centered at 4C 40.36 with a position angle of 82°, i.e., along the radio source axis. The lowest dispersion grating (810 l mm^{-1}) and red filter GG-420 were used, resulting in a wavelength coverage of 4800–9500 Å with a wavelength resolution of about 30 Å. The pixel separation corresponded to 0″.84 and about 10 Å in the spatial and wavelength directions, respectively. The spectroscopic data were reduced using IRAF, the NOAO image processing system. Data reduction consisted of bias subtraction, flat-fielding illumination correction, distortion correction, wavelength rectification, sky subtraction, atmospheric extinction correction, and flux-calibration relative to the standard star Ross 640. The one dimensional extracted spectrum summed over 4C 40.36 is shown in Figure 3. Because of the sharply falling sensitivity due to the convolution of the CCD sensitivity and the blocking filter cut-off, the flux calibration at the shortest wavelengths (below about 5000 Å) is subject to large uncertainties (about 25%).

III. RESULTS

Figures 1*a* and 1*b* show the radio and optical *R*-band images of 4C 40.36. The radio morphology appears to be a typical Fanaroff-Riley class II edge brightened double (Fanaroff and Riley 1974), consistent with its enormous luminosity (See Table 1). Our unpublished multifrequency images indicate the east lobe is depolarized while the west lobe shows significant polarization and Faraday rotation (Chambers and Miley 1988). The optical morphology is bimodal with the western and eastern maxima separated by 2″. Also indicated on the *R*-band image are fiducial positions from the radio map showing the estimated uncertainty in the relative positions of the radio and optical images. We shall comment on the striking alignment between the radio and optical images below.

Also marked on Figure 1*b* is the position angle of the cryogenic camera slit. The spectrum, integrated over the spatial extent of the object, is plotted in Figure 3. It shows three unambiguous emission lines centered at 5060 Å, 5364 Å, and 6241 Å in the observed frame. These match the redshifted wavelengths of C IV λ1549, He II λ1640, and C III] λ1909 to within 0.5%, for $z = 2.269$. This is within the uncertainty of the relative wavelength calibration. In Figure 4 we show spatial distributions along the slit for the three emission lines and three continuum wavelength regions. The average point spread function (PSF) measured using the offset star is shown for comparison. Although slight variations of the PSF with wavelength are seen (probably due to changes in focus over the uneven surface of the chip), the FWHM of the PSF varies by less than 15% over the regions shown.

The continuum emission is extended and its spatial distribution along the slit is consistent with that observed in the broad-band (better seeing) image. The continuum data also indicate that the region towards the western radio lobe is relatively blue. From the spectrum we estimate the continuum magnitudes integrated along the slit to be 22.1 ± 0.5 and 21.7 ± 0.5 for *V* and *R*, respectively. These values were corrected for the Galactic extinction, by assuming $E_{B-V} = 0.04$ (Burstein and Heiles 1982). This gives a $(V-R) = 0.4 \pm 0.15$.

The C IV and He II lines are also clearly spatially extended, with a distribution similar to the continuum. Their intensity distributions are consistent with bimodal structures, blended

TABLE 1

LOGARITHM OF 178 MHz LUMINOSITY[a] (W Hz^{-1})

Objects	Mean	Standard Deviation
3CR, $\|b\| > 15°$	27.47	1.18
3CR, $\|b\| > 15°, \alpha < -1, \theta < 20''$	29.02	0.23
4C 40.36	29.27	...

[a] Assuming $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$.

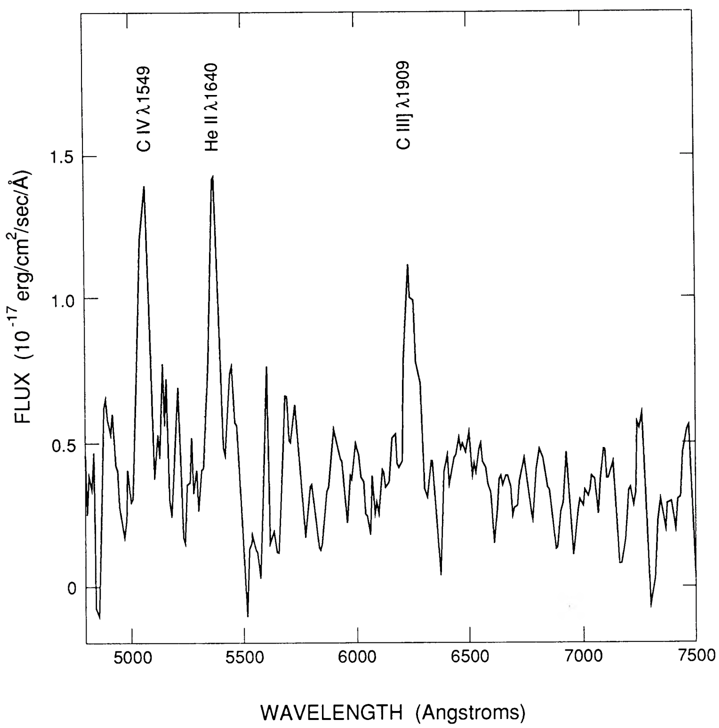

FIG. 3.—Low-dispersion spectrum of 4C 40.36, integrated over the spatial profile and smoothed in dispersion over 3 pixels or ~one resolution element

by the poor seeing. In contrast the C III] line is only barely spatially resolved, showing very little emission from the west component. The C III] line is also broader in wavelength (1700 km s^{-1} compared with 1200 and 1500 km s^{-1} for the C IV and He II lines). Furthermore, the C III] line also exhibits a definite asymmetry due to a red wing extending to more than 1800 km s^{-1}. These results taken together indicate that the physical conditions vary over the object. The lines show large equivalent widths, estimated at 90 Å, 90 Å, and 170 Å for C IV, He II, and C III], respectively. The integrated line ratios, widths, and equivalent widths are comparable to those observed in the "high-ionization" high-redshift radio galaxies 3C 239 and 3C 256, and the observed intensity ratios of the He II line to the C IV and C III] lines are larger than for most QSOs (Spinrad *et al.* 1985*b*).

IV. DISCUSSION

The size of the extended region of continuum emission (20 kpc) as well as the large equivalent widths and narrow profiles of the emission lines show that 4C 40.36 is a galaxy, not a quasar. The line ratios are also similar to those seen in the *IUE* spectrum of the Crab Nebula (Davidson *et al.* 1982). In addition, from the spatial variations in the profiles of the emission lines across the galaxy, we can rule out a gravitational lens scenario for explaining the morphology of 4C 40.36, such as has been applied to 3C 324 by Le Févre *et al.* (1987).

The remarkable morphological correlation between the radio and optical morphologies in 4C 40.36 is prime example of the alignment effect (Chambers, Miley, and van Breugel 1987; McCarthy *et al.* 1987*b*). Although there is evidence that this effect may result from star formation associated with interaction of the radio source with the IGM, the situation is still poorly understood, and other explanations are possible (Chambers, Miley, and van Breugel 1987; Chambers, Miley, and Joyce 1988). However, it is clear from these studies that powerful high-redshift radio galaxies have unique enigmatic properties and that they are certainly not "normal" galaxies.

Nonetheless, because of its extreme redshift, it is interesting to compare the R and V magnitudes of 4C 40.36 (as determined from the spectrum) with the most distant 3CR radio galaxies and brightest cluster members. On the V magnitude versus z diagram (Spinrad and Djorgovski 1987), 4C 40.36 lies on a smooth, virtually horizontal extrapolation of the most distant 3CR galaxies. On the $(V-R)$ versus z diagram (Djorgovski *et al.* 1988; Djorgovski 1987), the $(V-R) = 0.4 \pm 0.15$ of 4C 40.36 is among the bluest of the distant 3CR galaxies, but again it lies on a rather smooth horizontal extension of the data. This places 4C 40.36 in a region that is slightly fainter and redder than the $\mu = 0.5$ exponentially decreasing star formation model of Bruzual (1983). However, it must be emphasized that given the epoch and/or radio luminosity dependence of the alignment effect (Chambers, Miley, and van Breugel 1987; McCarthy *et al.* 1987*b*) the relevance of such models to powerful radio galaxies at high redshifts is unclear. Until the alignment effect is better understood, diagrams of optical/infrared apparent magnitude versus z, and color versus z for high-redshift powerful radio galaxies are of greater utility for determining the intrinsic nature of these unusual objects than for use as cosmological probes.

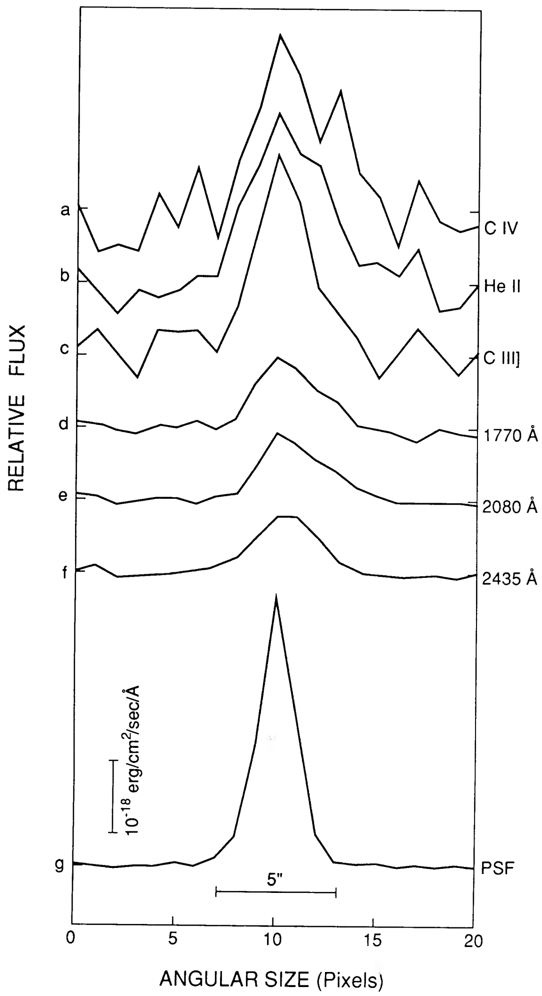

FIG. 4.—Montage of averaged spatial intensity distribution of lines and continuum. Zero levels for each plot are marked by a letter. (*a*) C IV λ1549. (*b*) He II λ1640. (*c*) C III] λ1909. (*d*) Continuum from 1665 Å to 1875 Å in rest frame. (*e*) Continuum from 1925 Å to 2235 Å in rest frame. (*f*) Continuum from 2335 to 2535 Å in rest frame. (*g*) Point spread function obtained from the offset star.

Finally, some brief remarks on the statistics of small ultra-steep spectrum radio sources are in order. In Table 1 we show the mean and standard deviation for the logarithm of the monochromatic radio luminosity at an emitted frequency of 178 MHz. We compare these quantities for all eight ultra-steep spectrum ($\alpha < -1$, where $F_\nu \propto \nu^\alpha$) small ($<20''$) radio sources in the 3C catalog compared with those for 3C sources as a whole (Spinrad *et al.* 1985*a*). It is remarkable that using these selection criteria the standard deviation in the logarithm of the monochromatic radio luminosity is reduced by almost a factor of 6. 4C 40.36 is comparable in luminosity to the most luminous 3C sources, but fainter due to its larger redshift. These considerations suggest that in contrast to the optical/infrared situation, it may eventually be fruitful to use objects such as 4C 40.36 as radio "standard candles."

Several conclusions can be drawn from the observations and results presented here. First, although it is clear that objects such as 4C 40.36 differ from normal galaxies, we have clearly established that such radio galaxies can be detected at redshifts in excess of 2. In addition, we have provided some evidence that objects such as 4C 40.36 have a relatively small dispersion in their monochromatic radio luminosity and therefore might eventually prove to be radio "standard candles" with important applications in observational cosmology.

Further observations of objects such as 4C 40.36 will be of great importance in establishing the nature of high-redshift radio galaxies. For 4C 40.36 itself, comparison of Lyα images with those of C IV and C III] would be particularly valuable for constraining the physical conditions, and we are planning on carrying out such observations in the near future. In addition, we are embarking on a search for more distant radio galaxies by applying our selection criteria to even fainter sources.

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Note added in proof.—Simon Lilly has informed us that he has measured a redshift of 3.395 for a radio galaxy in the "1 Jy" sample.

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