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IMAGING OF VERY DISTANT 3CR GALAXIES: HIGH SPATIAL RESOLUTION DATA FOR SEVEN GALAXIES WITH $1.176 \leq z \leq 1.841$

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ABSTRACT

This report continues a series of papers discussing a complete high spatial resolution imaging survey of the highest redshift 3CR radio galaxies. We present CCD observations of seven 3CR galaxies with redshifts between 1.176 and 1.841. Excellent seeing conditions have allowed us to resolve most of the galaxies into multiple components.

Two of the galaxies are located less than 4″ from a foreground bright galaxy, and we suggest that they may be gravitationally amplified by more than one magnitude. One of the objects, 3C 194 at $z = 1.779$, is proposed as a gravitational lens candidate.

For the other galaxies observed, different interpretations are considered. Similar to Chambers *et al.* and Le Fèvre *et al.*, we question the use of the high-redshift 3CR radio-galaxies as standard candles for cosmological purposes without further precautions.

Subject headings: cosmology — galaxies: photometry — gravitational lenses — radio sources: galaxies

I. INTRODUCTION

This *Letter* continues a series of articles describing sub–arc second resolution imaging of very distant 3CR radio galaxies obtained with the Canada-France-Hawaii Telescope (CFHT). As is a common feature of our previous papers on this subject (Le Fèvre *et al.* 1987, 1988; Le Fèvre, Hammer, and Jones 1988), all the galaxies observed so far in this sample have been spatially resolved, showing not only elongated shapes but, most of the time, multiple components.

At present, several interpretations have been proposed to explain the properties of the distant 3CR galaxies. First, strong stellar formation may be needed to account for the high observed luminosities. Two different processes have been proposed to trigger a high stellar formation rate: merging of galaxies (Djorgovski *et al.* 1987) or triggering by the radio source along the direction of the radio jet in such a way so as to account for the tendency for an optical/radio morphologies correlation (McCarthy *et al.* 1987*b*; Chambers, Miley, and van Breugel 1987). For such high-redshift objects the possibility of observing galaxies in the process of formation also must be considered, and in this context the galaxy 3C 326.1 has recently been interpreted as a protogalaxy (McCarthy *et al.* 1987*a*).

We also have suggested that some of the galaxies in this sample may be affected by gravitational amplification and/or lensing by foreground galaxies or clusters of galaxies (Hammer, Nottale, and Le Fèvre 1986; Le Fèvre *et al.* 1987, 1988; Le Fèvre, Hammer, and Jones 1988). Several selection effects exist including a 9 Jy radio-flux detection limit for the sample which may bias the detection toward ultraluminous objects at high redshifts, and a significant excess of foreground galaxies and clusters of galaxies observed in the field of several of the ~30 radio galaxies of the sample which may lead to gravitational amplification effects (Hammer, Le Fèvre, and Nottale 1988).

As a step toward understanding these peculiar galaxies, a complete high spatial resolution imaging survey is a necessity. The galaxies are faint, and their typical spatial extensions are on the order or less than 5″, and, as shown by our previous observations, components are seen often at a sub–arc second resolution (1″ = 12 kpc at $z = 1.5$ for $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$). We present here the high spatial resolution images of seven high-redshift 3CR galaxies together with a short discussion for each object.

II. HIGH SPATIAL RESOLUTION IMAGING AND DISCUSSION

The high-redshift galaxies were chosen from the catalog of Spinrad *et al.* (1985) and by considering the new data obtained by Spinrad and collaborators (Spinrad 1987). The photometric observations were done with the RCA2 CCD at the CFHT prime focus with a scale of 0″.21 pixel^{-1}. We observed in 1987 October and 1988 January with excellent seeing conditions ranging from 0″.6 to 0″.9 FWHM (mean = 0″.75 FWHM). The data were reduced and analyzed the same way as in our previous papers to compute magnitudes and color indices. Images of each galaxy are presented in Figures 1–8 (Plates L1–L4) together with contour maps. Each image has north on top, east on the left, and the NS direction is tilted by 1° counterclockwise from the vertical axis of the frame. This, together with the astrometric position of the field center given in each figure legend, allows the comparison with radio data with a typical positional error of less than 1″.

3C 65, z = 1.176.—This double lobe radio-source was first identified by Gunn *et al.* (1981) as a red galaxy at $z = 1.176$ (Spinrad *et al.* 1985). Laing, Riley, and Longair (1983) did not find the identification as secure, giving an estimated chance coincidence probability as high as 0.08, but the radio-core

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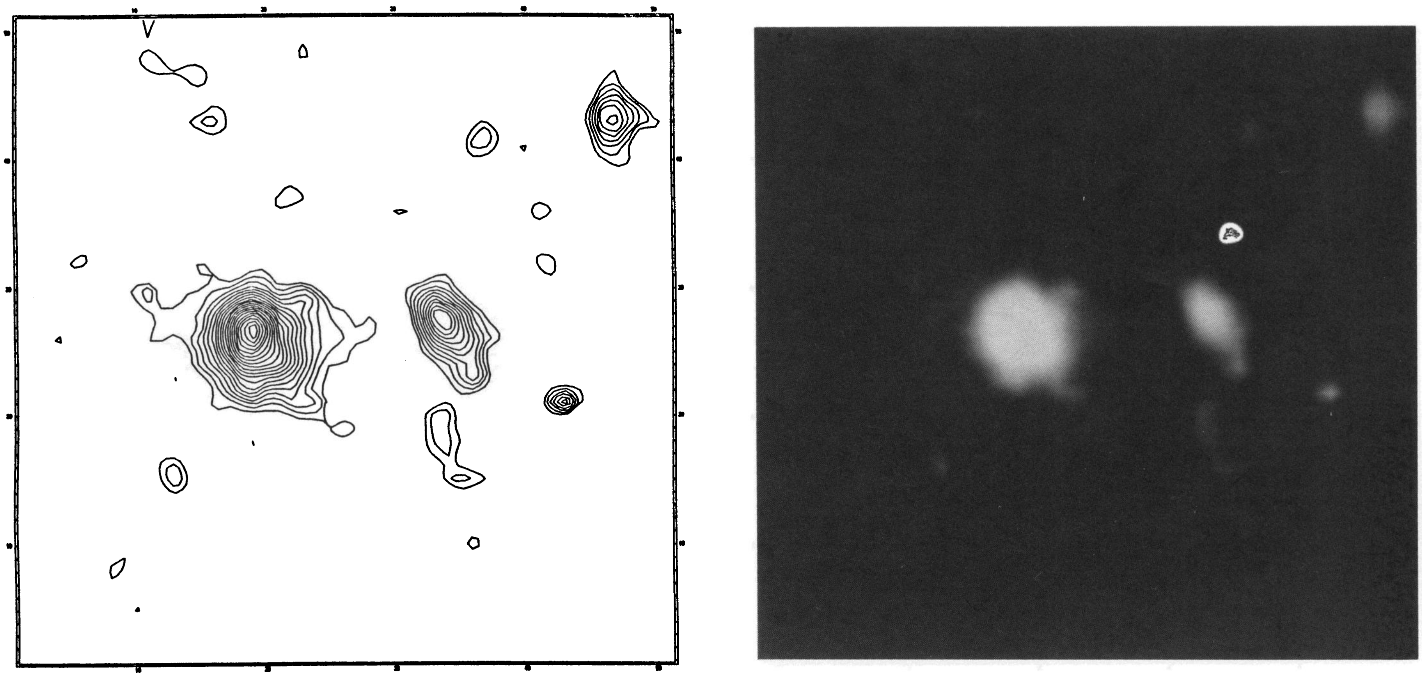

FIG. 1*a* FIG. 1*b*

FIG. 1.—3C 65 (z = 1.176). Contour map (*a*) and gray level picture, 1200 s exposure (*b*) in *R*, seeing = 0″.65 FWHM, 10.5 × 10.5 arcsec^2, north is up, and east is left. The lowest isophote is 1.3% of the sky brightness, and the spacing is 0.5% of the sky brightness between the contours. The center of the frame has the following coordinates: α_{1950} = 02^{h}20^{m}37^s.11, δ_{1950} = 39°47′13″.2 (from the astrometric data of Kristian *et al.* 1974).

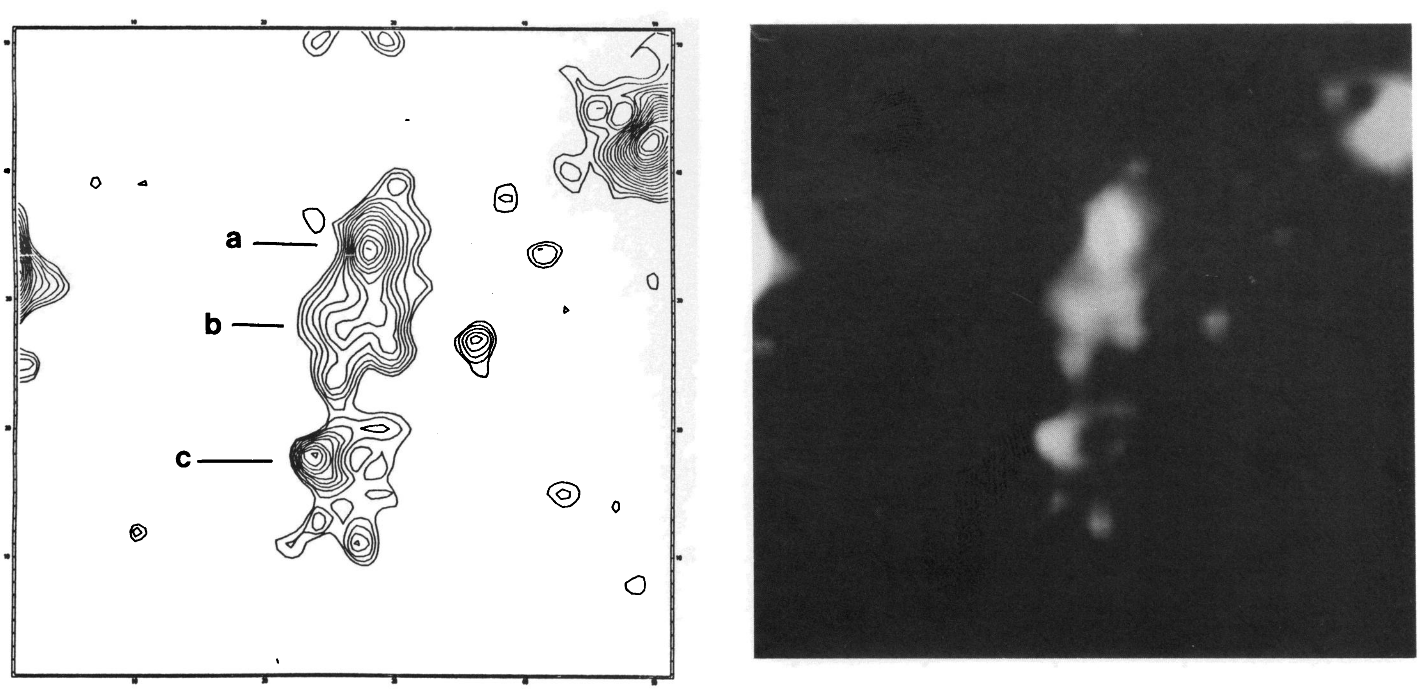

FIG. 2*a* FIG. 2*b*

FIG. 2.—3C 68.2 (z = 1.575). 1800 s exposure in *R*, seeing = 0″.6 FWHM, 10.5 × 10.5 arcsec^2, north is up, and east is left. The lowest isophote is 1% of the sky brightness and the spacing is 0.2% of the sky brightness between the contours. The center of the frame has the following coordinates: α_{1950} = 02^{h}31^{m}25^s.01, δ_{1950} = 31°21′08″.5 (from the astrometric data of Riley *et al.* 1980).

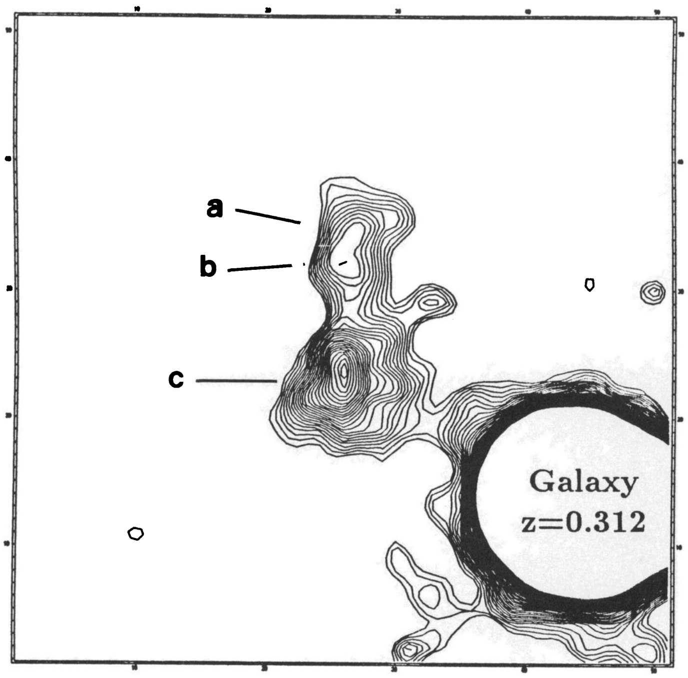

FIG. 3*a*

FIG. 3*b*

FIG. 3.—3C 194 (z = 1.779). 1800 s exposure in *R*, seeing = 0″.75 FWHM, 10.5 × 10.5 arcsec², north is up, and east is left. The old identification, a galaxy at z = 0.312, is on the lower right. The lowest isophote is 1.3% of the sky brightness, and the spacing is 0.15% of the sky brightness between the contours. The center of the frame has the following coordinates: $\alpha_{1950} = 08^h06^m38.06$, $\delta_{1950} = 42°36'58''.6$ (from the astrometric data of Kristian *et al.* 1974).

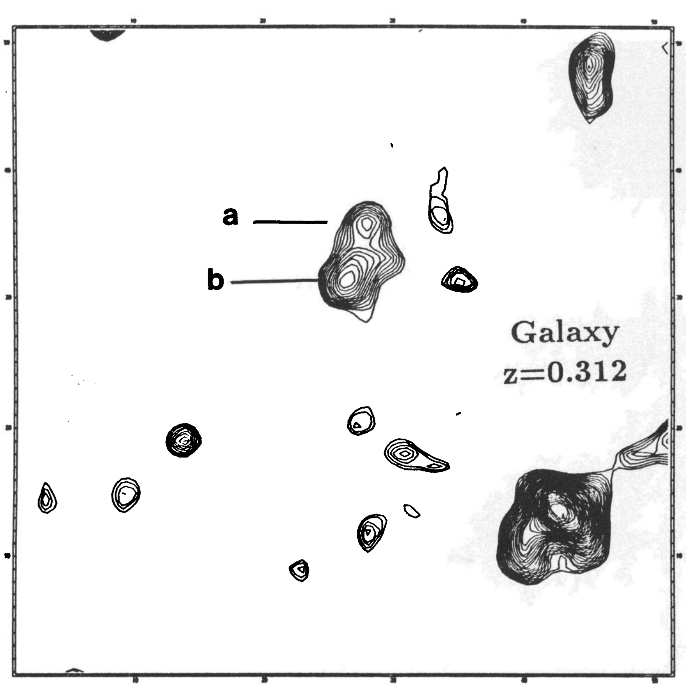

FIG. 4*a*

FIG. 4*b*

FIG. 4.—3C 194, 3000 s exposure in *U*, including the redshifted Lyα line, seeing 0″.92 FWHM 10.5 × 10.5 arcsec², north is up, and east is left. The lowest isophote is 9% of the sky brightness, and the spacing is 0.8% of the sky brightness between the contours.

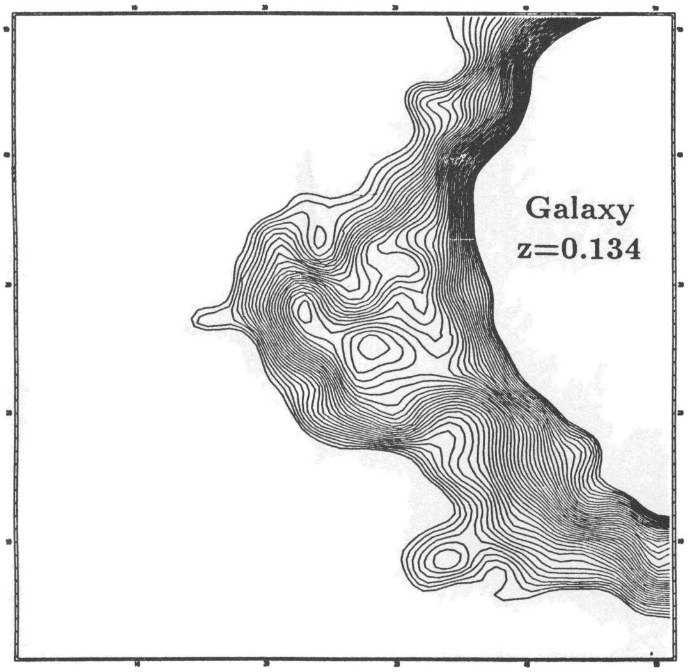

FIG. 5*a*

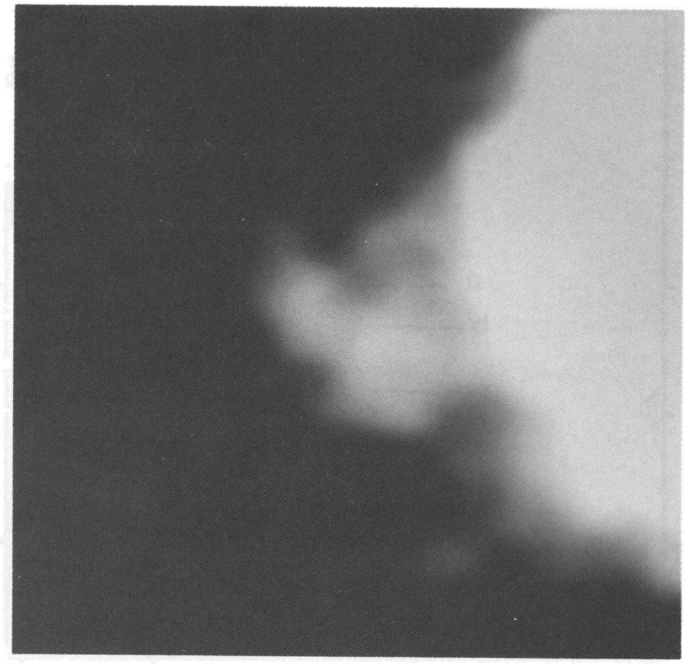

FIG. 5*b*

FIG. 5.—3C 225A (z = 1.565). 1800 s exposure in R,seeing = 0″87 FWHM, 10.5 × 10.5 arcsec^2, north is up, and east is left. The old identification, a galaxy at z = 0.134, is on the right. The lowest isophote is 0.8% of the sky brightness and the spacing is 0.1% of the sky brightness between the contours. The center of the frame has the following coordinates: $\alpha_{1950} = 09^h39^m25^s.26$, $\delta_{1950} = 14°05'35''.0$ (from the astrometric data of Jenkins *et al.* 1977).

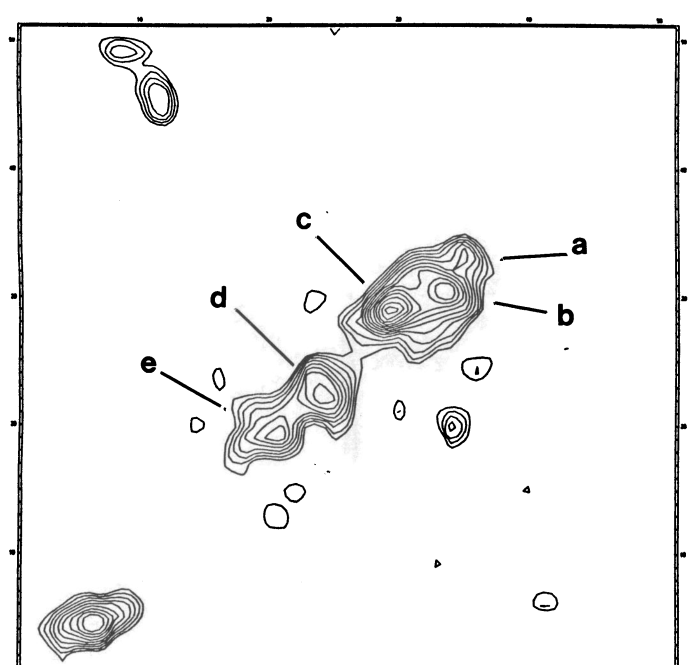

FIG. 6*a*

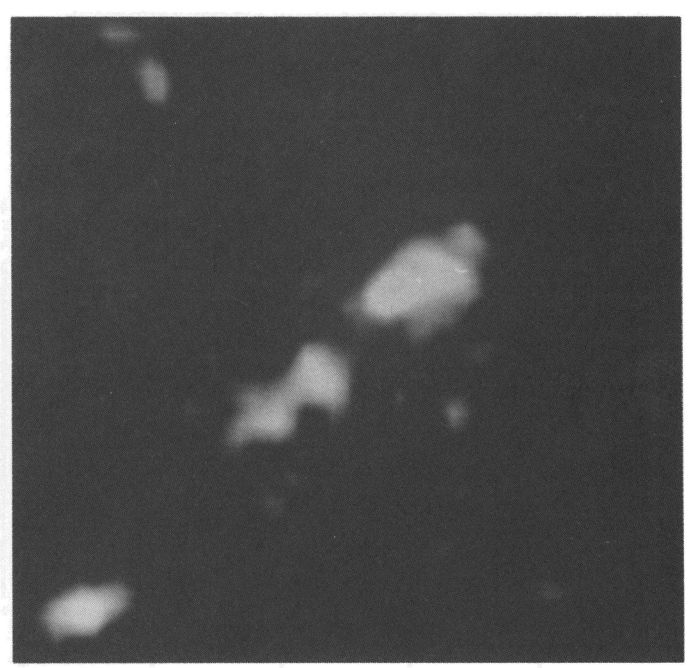

FIG. 6*b*

FIG. 6.—3C 437 (z = 1.480). 1200 s exposure in R, seeing = 0″77 FWHM, 10.5 × 10.5 arcsec^2, north is up, and east is left. The lowest isophote is 1% of the sky brightness and the spacing is 0.2% of the sky brightness between the contours. The center of the frame has the following coordinates: $\alpha_{1950} = 21^h45^m00^s.99$, $\delta_{1950} = 15°06'36''.2$ (from the astrometric data of Kristian *et al.* 1974).

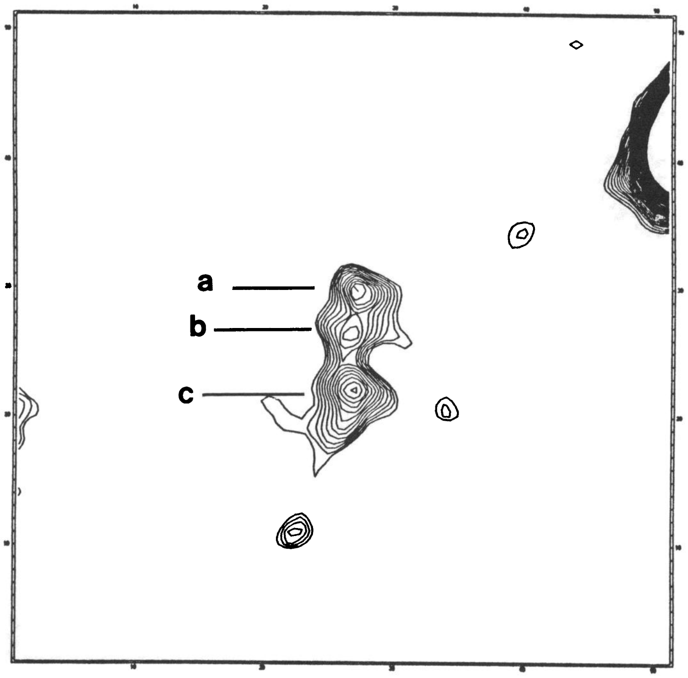

FIG. 7*a*

FIG. 7*b*

FIG. 7.—3C 454.1 ($z = 1.841$), 1800 s exposure in *V*, seeing = 0".85 FWHM, 10.5 × 10.5 arcsec², north is up, and east is left. The lowest isophote is 1.5% of the sky brightness and the spacing is 0.15% of the sky brightness between the contours. The center of the frame has the following coordinates: $\alpha_{1950} = 22^h48^m58^s.96$, $\delta_{1950} = 71°13'23''.5$ (from the astrometric data of Longair and Gunn 1975).

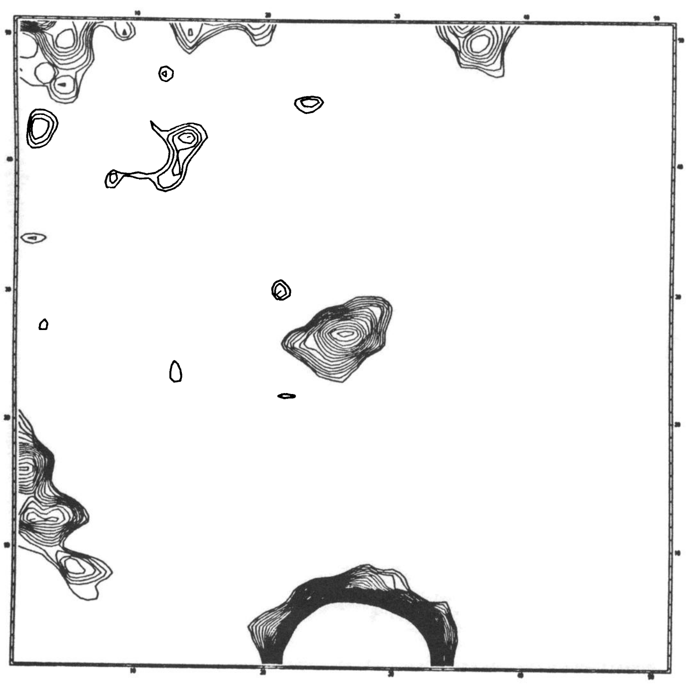

FIG. 8*a*

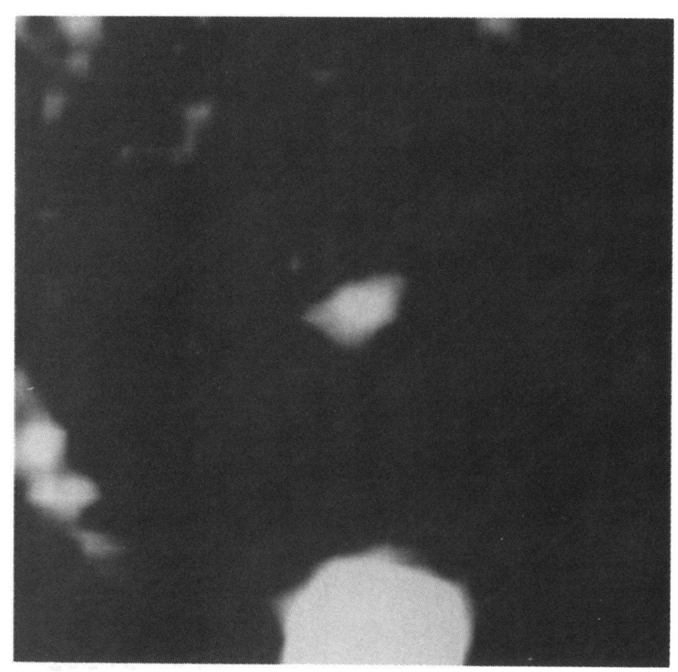

FIG. 8*b*

FIG. 8.—3C 470 ($z = 1.653$), 1800 s exposure in *R*, seeing = 0".65 FWHM, 10.5 × 10.5 arcsec², north is up, and east is left. The lowest isophote is 2.1% of the sky brightness and the spacing is 0.15% of the sky brightness between the contours. The center of the frame has the following coordinates: $\alpha_{1950} = 23^h56^m02''.90$, $\delta_{1950} = 43°48'03''.6$ (from the astrometric data of Jenkins *et al.* 1977).

position (Laing, Owen, and Puschell 1988) is very close to the red galaxy and seems to indicate a correct identification. We have obtained two deep exposures in broad-band V and R filters under excellent seeing conditions, 0".65 in R and 0".80 in V. The Gunn *et al.* (1981) galaxy is easily detected with $R = 22.46 \pm 0.05$ and $V-R = 1.00 \pm 0.1$ and shows an elongated shape but is not resolved into individual components; moreover, a very blue galaxy resolved into two components is detected 3" toward the west with $R = 24.29 \pm 0.15$ and $V-R = -0.14 \pm 0.3$ (Fig. 1). An image in a narrow-band filter including the O II line at $z = 1.176$ obtained in 1988 January gives a good detection of the red galaxy, while the blue galaxy is not detected and probably does not emit in this redshifted line.

3C 68.2, z = 1.575.—This is a very extended galaxy since we detect continuum emission over ~100 kpc, with a measured total magnitude $R = 22.94 \pm 0.08$. It is resolved into three components in R with 0".6 seeing, two of the objects being quite compact and the central one more extended (Fig. 2). $V-R$ color indices are quite blue for the components; 0.36, 0.50, 0.63 for *a*, *b*, and *c*, respectively (typical errors ±0.4 mag). From the radio position of the double radio-source given by Pooley and Henbest (1974), and the astrometry of stars in the field published by Riley, Longair, and Gunn (1980), we find that the midpoint between the radio sources is 1".2 W of component *a*, and that the radio source axis differs from the optical continuum orientation by $10° \pm 2°$. As there is no bidimensional spectroscopic information available for this source, we must discuss the two following possibilities: all the components are at the same redshift, or they are projected galaxies at different redshifts. In the first case, one can compare this galaxy with the protogalaxy simulations described by Baron and White (1987). The total extent and clumpy appearance of the source is similar to the result of their simulation but the galaxy is ~2 mag brighter in surface brightness ($\mu_V = 25.3$, at peak). The well-aligned morphology and the radio/optical alignment seems also difficult to account for under this hypothesis unless star formation is produced along the radio axis as proposed by McCarthy *et al.* (1987*b*) and Chambers, Miley, and van Breugel (1987). In the second case, the presence of galaxies at different redshifts with very close lines of sight could produce gravitational amplification and perhaps lensing of the most distant objects (Hammer, Nottale, and Le Fèvre 1986; Le Fèvre *et al.* 1988; Le Fèvre, Hammer, and Jones 1988) which could account for the optical morphology. Redshift information along the major axis of the observed structure is needed to better define the nature of this source.

3C 194, z = 1.779.—This is one of the most fascinating objects on our list. This radio source has been recently reidentified with a $z = 1.779$ galaxy, only 4" from the old foreground identification of a giant elliptical galaxy at $z = 0.312$ (Spinrad 1987). Two deep V and R exposures were taken under 0".86 and 0".75 seeing, respectively. The new object identified with the radio source appears elongated and resolved into two or three components, as seen in many very distant 3CR galaxies (Fig. 3*a*), with a total magnitude $R = 22.45 \pm 0.05$ (for components *a*, *b*, and *c*). The $V-R$ color indices are very similar for these components as well as for the foreground galaxy: 0.81 for *a*, 0.87 for *b*, 0.78 for *c*, and 0.9 for the foreground galaxy. However, from the recent radio data of Spinrad and McCarthy (Spinrad and McCarthy 1988), the radio data of Pooley and Henbest (1974), and the positions of stars in the field from Kristian, Sandage, and Katem (1974), it appears that the radio core is 2".3 east from the bright elliptical, 3".3 south of *a*, and 2".1 from *c*, which confuses the identification. To investigate the emission line distribution of the galaxy at $z = 1.779$, we obtained in 1988 January an exposure in the broad-band U filter. This filter contains the Lyα emission line redshifted to $z = 1.779$, which from the spectrum obtained by Spinrad and McCarthy (1988), contributes a significant part of the total flux in this filter. The result is astonishing; only the two faintest components, *a* and *b*, are detected in this band while the brightest, *c*, is not detected down to 1 σ above the sky background (Fig. 3*b*).

The giant $R = 19.3 \pm 0.05$ foreground galaxy has an absolute luminosity $M_R = -23.57$ (after K-correction from Guiderdoni 1986, and correction for galactic absorption), and therefore is only 0.5 mag fainter than a brightest elliptical cluster galaxy (Kristian, Sandage, and Westphal 1978). The gravitational amplification of 3C 194 by this galaxy is expected to be more than 1 mag (see Table 1). Furthermore, assuming a mass to light ratio $M/L_R \geq 14$ (or a mass $M \geq 1.7 \times 10^{12}\ M_\odot$) this foreground bright elliptical could gravitationally *multiply* 3C 194 into several images. The M/L value required could even be smaller when taking into account the gravitational effect of the foreground cluster of galaxies Zw 207−22 on the optical beam. This may lead to a substantial decrease of the estimated absolute luminosity of 3C 194.

It is also possible that component *c* is not at $z = 1.779$ but is a foreground galaxy since it is not detected in U (Lyα). If this is indeed the case, additional gravitational lensing effects may be expected and the estimate of the absolute luminosity of 3C 194 may have to be decreased by an even greater amount when correcting the magnitude of 3C 194 from the contamination of *c* and the additional amplification effect. Nevertheless, the confirmation of this speculative idea must wait for faint high spatial resolution spectroscopy.

If *c* is at the same redshift as *a* and *b*, then the important

TABLE 1

AMPLIFICATION IN MAGNITUDE FOR 3C 194 AND 3C 225A

	σ (km s^{-1})				
$(M/L)_R$	200	250	300	350	400
		3C 194			
10.........	−0.3	−0.5	−0.8	−1.1	−1.6
20.........	−0.6	−0.8	−1.2	−1.7	−2.7
30.........	−1.2	−1.6	−2.5	−3.8	−2.0
40.........	−6.8	−2.4	−1.6	−1.1	−0.8
		3C 225A			
10.........	−0.4	−0.6	−0.9	−1.4	−2.1
20.........	−0.4	−0.7	−1.0	−1.5	−2.4
30.........	−0.5	−0.8	−1.1	−1.7	−2.9
40.........	−0.6	−0.9	−1.3	−2.1	−4.9

NOTE.—Amplification is given for a set of M/L and σ combinations for the foreground galaxy. The gravitational magnification is calculated with (Hammer and Nottale 1986; Hammer *et al.* 1988):

$$\delta m = 2.5 \log \left| \left(1 - 3\pi \frac{\sigma^2 \times D}{c^2 \times l}\right)^2 - \left(4G \frac{MD}{c^2 \times l^2}\right)^2 \right|$$

with σ = velocity dispersion in the lens galaxy; $D = (D_d \times D_{ds})/D_s$; D_d, distance to the lens; D_s, distance to the source; D_{ds}, distance lens-source; l, impact parameter; M, mass of the lens.

differences seen between the U band and the V and R bands show the poor correlation of the emission-line gas and the continuum as is observed for 3C 326.1 (McCarthy *et al.* 1987*a*). However, in the case of 3C 194, *a*, *b*, and *c* have the same $V-R$ color indices, i.e., blue continuum properties, so it is then not clear why they exhibit such a difference in U.

Discussions on the luminosity evolution of high-z 3CR galaxies should recall the fact that 3C 194 lies on a very uncommon line of sight, 4″ from a very bright foreground galaxy. This implies that the estimate of its absolute magnitude may have to be reduced by at least 1 mag from the flux amplification by the foreground elliptical galaxy.

3C 225A, z = 1.565.—Spinrad and collaborators have recently reidentified this source with a $z = 1.565$ galaxy (Spinrad 1987). The new galaxy is seen as an object extended over more than 5″ with two components separated by 1″.2 resolved with the 0″.87 seeing in the R frame (Fig. 4). Its measured magnitude is $R = 22.5 \pm 0.1$. 3C 225A is embedded in the outskirts of the previous identification, a galaxy at $z = 0.134$ (Spinrad *et al.* 1985), only 4″.9 from the nucleus, corresponding to 15 kpc at $z = 0.134$. This foreground galaxy with an absolute K-corrected magnitude $M_R = -21.0$ (2.5 mag fainter than a brightest elliptical cluster galaxy) certainly gravitationally amplifies the optical fluxes of 3C 225A by more than 1 mag (Table 1). A similar amplification is also expected in radio since the radio-source extension (less than 4″.4; Jenkins, Pooley, and Riley 1977) seems to correspond roughly to the optical size. The occurrence of gravitational lensing (multiple imaging) seems unlikely since a mass to light ratio greater than 40 is required for the $z = 0.134$ galaxy. The correlation between the optical and radio morphologies may therefore be an intrinsic property of the galaxy and be compared to the correlation found for other radio sources by Chambers, Miley, and van Breugel (1987) and McCarthy *et al.* (1987*b*).

3C 437, z = 1.480.—This source exhibit one of the most peculiar structures with at least five components, spread into two blocs, resolved with 0″.75 seeing in our R frame (Fig. 5). Its total measured magnitude is $R = 22.87 \pm 0.07$. The components are roughly aligned along the 160 kpc total extent of the source, and from the positions of stars taken from Kristian, Sandage, and Katem (1974) and the radio position of the double radio source given by Riley, Longair, and Gunn (1980), we find that the midpoint between the two radio sources falls on component *b*. This may indicate that the two components *d* and *e*, distant by more than 3″.5 from the central radio position, are not physically related to the three northern components, being, for example, foreground galaxies. An alternative is to compare 3C 437 to the simulated appearance of protogalaxies (Baron and White 1987). The size is in agreement with the models, except that it is not obvious how to create an almost perfect alignment of five clumps, and the observed surface brightness $\mu_R = 24.5$ is in excess of ~ 2 mag from what is predicted. Note finally that the optical P.A. differs from the radio P.A. by $32° \pm 2°$, and 3C 437 does not show an optical/radio alignment as found by Chambers, Miley, and van Breugel (1987) and McCarthy *et al.* (1987*b*) for other high-z radio galaxies. Deep two-dimensional spectroscopy along the components will clarify the nature of this source.

3C 454.1, z = 1.841.—This is the highest redshift 3CR galaxy known until now (Djorgovski 1987; Spinrad 1988). The total magnitude has been measured at $R = 22.93 \pm 0.07$. Our moderately good seeing images (0″.9 FWHM in R, 0.85 FWHM in V) shows an elongated structure resolved into three components in the V frame (Fig. 6). From the radio data of Pearson, Perley, and Readhead (1985), and the position of stars in the field given by Longair and Gunn (1975), we find an excellent agreement between the radio images (separation = 1″.6, P.A. = 166°) and the optical images *a* and *c* (separation = 1″.6, P.A. = $169° \pm 3°$), while the central optical component has no detected radio counterpart. Color indices are quite similar for the components, 0.86, 0.90, and 0.79 for *a*, *b*, and *c*, respectively. One possible interpretation may be to consider gravitational lensing of a radio galaxy by a foreground galaxy assimilated to component *b*. In this context, the radio galaxy may be multiply imaged into components *a* and *c*, leading to the excellent agreement between the radio and optical data. Another interpretation may be to consider the galaxy as a result of enhanced star formation along the radio axis as proposed by McCarthy *et al.* (1987*b*) and Chambers, Miley, and van Breugel (1987). High spatial resolution deep two-dimensional spectroscopy will be needed to determine whether the redshifts of the three components are similar or not.

3C 470, z = 1.653.—This galaxy was observed under excellent seeing conditions, 0″.65 FWHM in R, 0″.73 FWHM in V, with a total magnitude $R = 23.34 \pm 0.1$. However, the optical structure is not resolved into individual components despite an obviously elongated shape with an axis ratio ~ 0.6. Note also that the optical P.A. differs by $74° \pm 10°$ from the radio P.A., and 3C 470 differs from other high-z radio galaxies for which correlation between the optical and radio morphologies has been observed (Chambers, Miley, and van Breugel 1987; and McCarthy *et al.* 1987*b*).

III. CONCLUSION

Seven very high redshift 3CR radio galaxies have been observed under excellent seeing conditions, and most of them were resolved into several faint components. These data clearly exhibit the peculiarity of high-redshift radio galaxies in the 3CR sample and show the difficulty of comparing them to lower redshift galaxies.

These observations show two instances of contamination by foreground galaxies close to the line of sight of the distant 3CR object which can be compared to the case of 3C 13 (Le Fèvre *et al.* 1988). The net result is that the distant 3C 194 and 3C 225A are subjected to gravitational amplification effects which may reach more than 1 mag. The case of 3C 194 may be even more complex since we suspect another galaxy in the field, only 2″ from the 3CR object, also to be a foreground object.

Due to the lack of bidimensional faint spectroscopy of 3C 68.2 and 3C 437, we are not able to definitely assess the status of these very extended, multicomponent galaxies. They extend over 100 kpc and 160 kpc, respectively, and only one external component seems to agree with the radio midpoint. Due to this discrepancy, it is possible that we are observing chance associations of projected galaxies at different redshifts and that gravitational amplification effects play an important role. An alternative may be to consider these galaxies as protogalaxies, as discussed in Baron and White (1987), since they exhibit similar morphologies to what is expected from simulations for forming galaxies. However, the observed surface brightnesses are in excess of more than 2 mag as compared to the predictions of the models, and the perfect alignment of components observed in both cases seems difficult to account for.

The excellent radio to optical correlation observed for 3C 454.1 may be interpreted as the result of gravitational lensing by the central of the three aligned components detected, but other interpretations such as enhanced star formation along the radio axis (McCarthy *et al.* 1987*b*; Chambers, Miley, and van Breugel 1987) may also be considered.

We note that for some galaxies like 3C 68.2, 3C 225A, and 3C 454.1, the optical axis is well aligned with the radio axis (perfect correspondence in the compact case of 3C 454.1), while for others like 3C 65, 3C 194, 3C 437, and 3C 470, no alignment is observed. The statistical alignment of optical and radio axis observed by McCarthy *et al.* (1987*b*) and Chambers, Miley, and van Breugel (1987) for some high-redshift 3CR and 4C radio galaxies therefore does not seem to be a general property for the whole high-z 3CR galaxy sample (Hammer, Le Fèvre, and Nottale 1988).

From our observations we consider that more work needs to be done, specifically faint two-dimensional spectroscopy and high spatial resolution narrow-band imaging, to be able to have a complete picture of the very distant 3CR galaxies, and before interpreting the magnitudes and colors of these galaxies in terms of strong evolution of their stellar populations alone (Djorgovski 1988; Wyse and Silk 1987).

All these observations will be discussed and analyzed in more details together with the complete sample of 3CR galaxies with $z \geq 0.8$ for which we have now high spatial resolution imaging (Hammer and Le Fèvre 1988; Le Fèvre and Hammer 1988).

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