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HIGH SPATIAL RESOLUTION IMAGING OF 10 3CR GALAXIES WITH $z \geq 1$ AND STATISTICAL EVIDENCE FOR SELECTION EFFECTS FROM GRAVITATIONAL AMPLIFICATION

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ABSTRACT

We present here broad-band filter imaging of 10 3CR galaxies with $z \geq 1$ and narrow-band filter imaging of three of these, with high spatial resolution (0".6 ≤ FWHM ≤ 1".2, mean FWHM = 0".76). New data in favor of the gravitational lensing interpretation of 3C 324 are presented, and the existence of an extremely distant cluster of galaxies around 3CR 239 at $z = 1.78$ is suggested.

So far we have observed 27 3CR galaxies with $z \geq 1$ with an unprecedented mean image quality FWHM = 0".74 (σ = 0".15). It reveals the very unusual morphologies of these galaxies: $\frac{3}{4}$ of them are resolved in two to six components over $\sim 50(H_0/50)$ kpc at a flux level 4 σ above the sky noise, with sizes and luminosities of each component comparable to bright galaxies.

We present statistical evidence of an excess of bright foreground galaxies on the lines of sight of the 3CR galaxies with $z \geq 1$, in the sense that there is as much as 9 times more high-z 3CR galaxies around $R \leq 21$ mag galaxies than would be expected from a random distribution. An excess of foreground distant clusters of galaxies is also found at a lower statistical level. A case-by-case analysis shows that the foreground bright galaxies, and one of the foreground clusters, actually gravitationally amplify the background 3CR galaxies by 0.5–2 mag. Finally, we investigate how the contamination by foreground fainter galaxies, and the gravitational amplification/lensing effects they can induce, could affect the observed properties of the high-z 3CR galaxies, and hence their current interpretations.

Subject headings: galaxies: clustering — galaxies: structure — gravitational lenses

I. INTRODUCTION

Our knowledge of distant galaxies is based upon only ~ 40 radio galaxies with $z \geq 1$. Among them, the ~ 30 3CR galaxies are by far the best studied sources, since almost all of them have a measured spectroscopic redshift up to $z = 2.47$ (Spinrad *et al.*, 1985; Djorgovski *et al.*, 1988; McCarthy 1989). They are currently used in models to test for evolution of galaxies (see, e.g., Spinrad 1986; Guiderdoni and Rocca-Volmerange 1987; Wyse and Silk 1987; Dunlop *et al.* 1989) or even to test cosmological models. All these $z \geq 1$ 3CR galaxies are extremely powerful radio sources ($P_{178\,\mathrm{MHz}} \geq 10^{28}$ W Hz^{-1} sr^{-1}), and there is certainly some danger to derive conclusions on the normal population of galaxies from the properties of such peculiar objects. Indeed, comparison between these high-redshift galaxies and low-redshift ones is a hard task since from a comoving volume argument, the 40 $z \geq 1$ galaxies are the parent population of only one galaxy at $z \leq 0.2$. Selection effects are therefore expected to affect the properties of the high-z 3CR galaxies (Hammer, Nottale, and Le Fèvre 1986): the 30 $z \geq 1$ 3CR galaxies have been selected over half the sky from their high radio power, because they are either very powerful sources ("monsters") or are gravitationally amplified by foreground matter.

Previous studies have shown that the probability to find gravitationally amplified sources in a flux-limited sample is much higher than in a nonbiased one (Turner, Ostriker, and Gott 1984; Hammer, Nottale, and Le Fèvre 1986). This is relevant to the $z \geq 1$ 3CR galaxies sample because all of the galaxies have a radio flux just above the 9 Jy radio flux limit. They could be gravitationally amplified radio sources which originally belonged to a population of radio sources of lower radio power, typically a few Jy, which has a much higher number density than the 3CR sources (Wall and Peacock 1985; Katgert, Oort, and Windhorst 1988). If we consider the 4.5 Jy $\leq S_{178\,\mathrm{MHz}} \leq$ 9 Jy radio source population, there are ~ 15 times more sources than in the 3CR sample (Katgert, Oort, and Windhorst 1988), a good number of them are at $z \geq 1$ (Allington-Smith *et al.* 1988; Lilly 1989), and it seems reasonable to assume that most of their optical counterparts are galaxies as in the 3CR. Several facts then lead us to consider the possibility that a part of them could have their radio fluxes gravitationally amplified by intervening foreground matter: (1) intervening foreground rich clusters with $z \geq 0.1$ or foreground galaxies with $z \geq 0.05$ could gravitationally amplify background sources by a factor 2 or even more, (2) 5% of the sky is covered by Abell type clusters of galaxies with $0.1 \leq z \leq 0.5$ (for which we assume $R = 3$ Mpc for $H_0 = 50$), and (3) galaxy counts from Tyson (1988) show high values of galaxies densities up to $R = 27$. It is of interest to note that the number density of the radio source population with 4.5 Jy $\leq S_{178\,\mathrm{MHz}} \leq$ 9 Jy is 0.2 galaxies deg^{-2} and roughly correspond to the $B \leq 18$ QSO number density (Véron 1983). This QSO population contains several obviously gravitationally multiplied QSOs, even after correcting their magnitude by the gravi-

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tational magnification expected (see, e.g., the review by Turner 1988). Gravitationally multiplied QSOs are due to macro-lensing, i.e., due to gravitational lensing by intervening galaxies and/or clusters of galaxies, which implies that there is an even larger number of QSOs that are simply gravitationally amplified by several tenths of a magnitude without multiple imaging. We therefore also expect that a part of the radio source population with 4.5 Jy $\leq S_{178\,\mathrm{MHz}} \leq 9$ Jy could be gravitationally magnified by intervening foregound galaxies and/or clusters of galaxies. These simple arguments lead to a scenario where some of the 4.5 Jy $\leq S_{178\,\mathrm{MHz}} \leq 9$ Jy sources are gravitationally amplified in such a way as to become part of the 3CR catalog. It seems then reasonable to expect that at least a part of the 3CR high-z galaxies is affected by gravitational amplification due to intervening foreground matter and to investigate the extent of such an effect and the consequences on their observed properties.

Several mechanisms have been invoked to explain the main properties of the high-z 3CR galaxies, such as merging of galaxies (Djorgovski *et al.* 1987), triggering of stellar formation by the radio jet (McCarthy *et al.* 1987), or cooling flow (Fabian *et al.* 1986). A gravitational amplification scenario as described above could affect the current interpretations and has also been considered (Hammer, Nottale, and Le Fèvre 1986; Le Fèvre *et al.* 1987, 1988; Le Fèvre, Hammer, and Jones 1988; Le Fèvre and Hammer 1988). To tackle these issues, a data base providing consistently good image quality is a necessity: high spatial resolution is crucial to the understanding of these objects, since at $z = 1$, $1'' = 11\,(50/H_0)$ kpc ($q_0 = 0$). Imaging is a preliminary to deep and high spatial resolution spectroscopy to be performed on galaxy components with magnitudes $m_R = 23$ at angular separations of a typical $1''$ and which will probably need the next generation of giant telescopes.

We report here on the high spatial resolution imaging of 10 $z \geq 1$ 3CR galaxies in broad-band filters as well as interference filter imaging for three of them. The new photometric properties are presented in conjunction with existing radio and spectroscopic data from the literature, and a short discussion is given for each galaxy. Combined with previously published data, we have observed so far 27 3CR galaxies with $1 \leq z \leq 1.84$ with image quality ranging from $0\farcs5$ to $1\farcs2$ FWHM (mean = $0\farcs74$ FWHM). We discuss the individual and global properties of these 27 galaxies, as seen at the subarcsecond level. Finally, we present a statistical analysis which shows that the $z \geq 1$ 3CR galaxies are not distributed at random with respect to the foreground bright galaxies and clusters of galaxies.

II. HIGH SPATIAL RESOLUTION IMAGING AND DISCUSSION ON INDIVIDUAL SOURCES

All observations reported here have been obtained at the prime focus of the 3.6 m Canada-France-Hawaii Telescope using the 640 × 1024 pixel^2 RCA2 CCD, except for 3C 210 observed at f/8 with the same detector. We experienced consistently good seeing in 1987 June, 1987 October, and 1988 January with final images with FWHM as good as $0\farcs6$ and with a mean of FWHM = $0\farcs76$ for this subsample. The 3CR galaxies have been taken from the updated 3CR catalog from Spinrad *et al.* (Spinrad 1987). CCD frames were reduced in a standard way using IRAF, while the photometry was performed with a faint galaxy photometry package to compute isophotal magnitudes and colors in the $R = 26.5$ mag arcsec^{-1} isophote. To calibrate the data we used the calibrated fields of Christian *et al.* (1985). All the photometric data given here have been corrected for Galactic absorption using the Galactic absorption maps of Burstein and Heiles (1982) and the extinction coefficients of Riecke and Lebofsky (1985). $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$ will be used in the following.

3C 210, z = 1.169.—This radio galaxy has been identified by Grueff and Vignotti (1975), and its redshift has been measured by Djorgovski *et al.* (1988). Our imaging under excellent seeing conditions (FWHM = $0\farcs63$ in R, FWHM = $0\farcs72$ in V) shows an elongated galaxy (axis ratio = 1.5) with possibly two components (Fig. 1) with a global magnitude $R_{26.5} = 21.49 \pm 0.08$ and a blue color index ($V - R = 0.13 \pm 0.15$). No recent high spatial resolution radio map has been published on this source to our knowledge.

3C 230, z = 1.487.—In spite of the very good seeing conditions (FWHM = $0\farcs7$ in both V and R), the observation of this source is difficult due to the proximity of a bright star. However, it is probably resolved into two components (Fig. 2; the object at the southeast of the star is an artifact due to reflection of the bright star image on the CCD window). Again no high spatial resolution radio map is available.

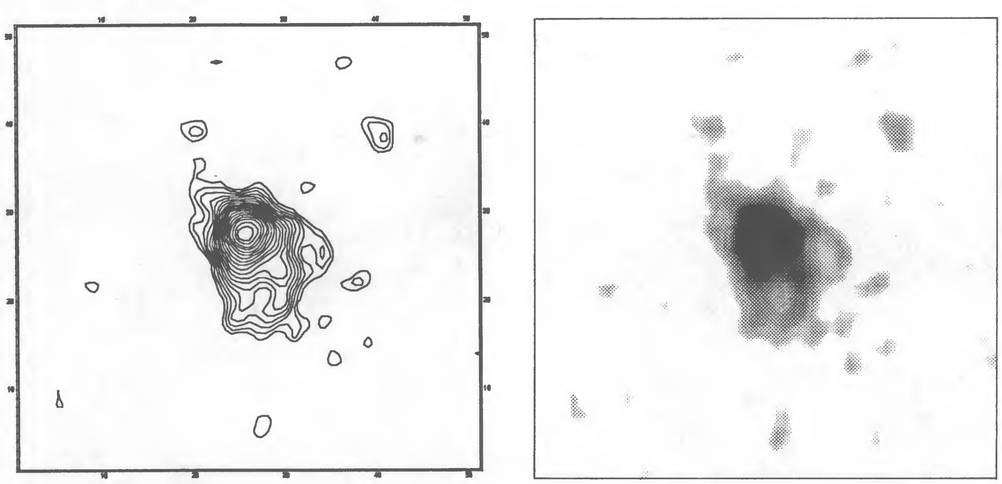

FIG. 1.—3C 210 ($z = 1.169$). 10.5 × 10.5 arcsec^2. R, seeing $0\farcs63$ FWHM. The center of the frame has the following coordinates: $\alpha_{1950} = 8^{\mathrm{h}}55^{\mathrm{m}}10\fs83$, $\delta_{1950} = 28°02'33\farcs6$.

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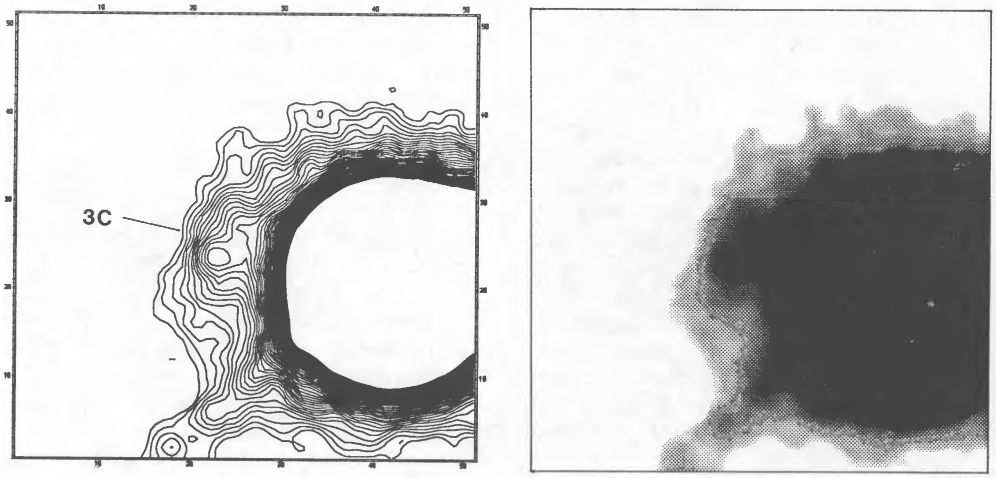

FIG. 2.—3C 230 ($z = 1.487$). 10.5×10.5 arcsec^2. R, seeing 0″.7 FWHM. The center of the frame has the following coordinates: $\alpha_{1950} = 9^h49^m26^s.16$, $\delta_{1950} = 0°12'36''.8$.

3C 239, z = 1.781.—We observed this galaxy under very good seeing conditions in three broad-band filters, R (FWHM = 0″.72), V (FWHM = 0″.83), and U (FWHM = 0″.85). This source is particularly fascinating because it is one of the most distant 3CR galaxies, and its radio power at 178 MHz is the highest of this class of object [P(178 MHz) = 5.3×10^{28} W Hz^{-1}]. The optical identification (Gunn *et al.* 1981) is a slightly elongated galaxy (axis ratio = 1.3) with $R_{26.5} = 21.88 \pm 0.09$, and $V - R_{26.5} = 0.48 \pm 0.2$ (Fig. 3). The optical axis differs from the radio axis by $51° \pm 5°$ and therefore does not follow the radio-optical correlation found by Chambers, Miley, and van Breugel (1987) and McCarthy *et al.* (1987) for other high-redshift radio galaxies. Two galaxies are detected close to 3C 239, b at 5″.5 ($R_{26.5} = 21.78 \pm 0.09$, $V - R_{26.5} = 1.46 \pm 0.23$) and c at 4″ ($R_{26.5} = 24.15 \pm 0.15$, $V - R_{26.5} = 1.10 \pm 0.35$), and 3C 239 lies in a very crowded field (Fig. 4). From the complete photometry performed on the whole field, two different populations of galaxies seem to be present: one verifies $0.2 \leq V - R \leq 0.8$ with several objects detected in U, with $U - V \leq 0.3$ and with a pronounced concentration near 3C 239, the brightest object of this class being the 3C 239 optical counterpart; the other contains redder objects ($V - R \geq 1$) not detected in the U image (Fig. 5). Because Lyα is in the U band at $z = 1.78$ and the high density of galaxies around 3C 239 [more than six galaxies in a $150 \times (50/H_0)$ kpc radius (80 kpc if $q_0 = 1$)], we suggest that the first population belongs to a cluster around 3C 239. We also suspect that gravitational lensing/amplification may affect the 3C 239 source and other background objects because (1) there are several red galaxies around 3C 239 brighter than the 3C 239 optical counterpart, suggesting the presence of a foreground cluster which may gravitationally amplify the background objects around 3C 239 (Nottale and Hammer 1984) and may ease the detection of a cluster of galaxies at $z = 1.78$; (2) the (eastern) brightest radio lobe at 5 GHz (Pooley and Henbest 1974) lies in the "red" galaxy b at only 1″.5 from the brightness peak (from the astrometry of Gunn *et al.* 1981). Since b is bright and red, this suggests that it is foreground and that the compact radio lobe (size $\leq 1''$) is likely to be gravitationally amplified; the alternative of a physical neighbor of 3C 239 seems unlikely due to its brightness and redness; (3) if foreground, c could produce gravitational amplification/lensing on the 3C 239 galaxy. An

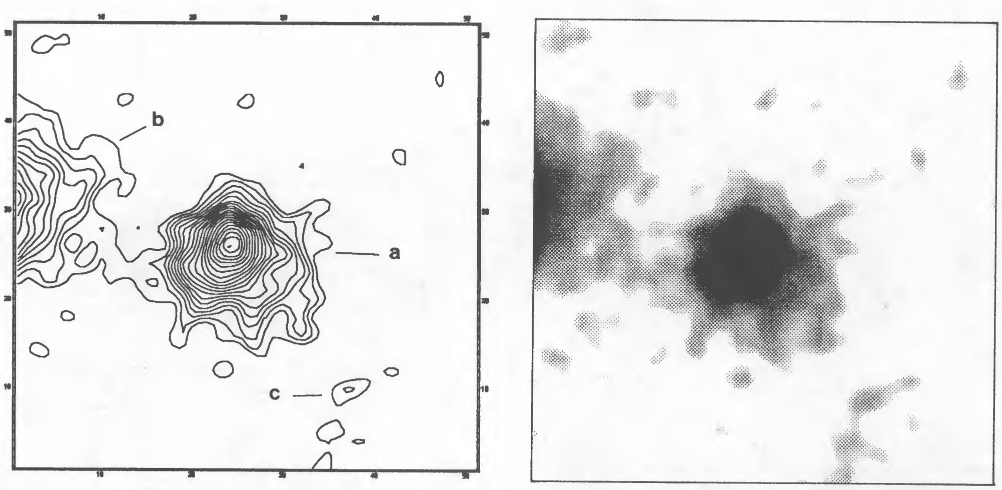

FIG. 3.—3C 239 ($z = 1.781$). 10.5×10.5 arcsec^2. R, seeing 0″.72 FWHM. The center of the frame has the following coordinates: $\alpha_{1950} = 10^h08^m38^s.97$, $\delta_{1950} = 46°43'09''.3$.

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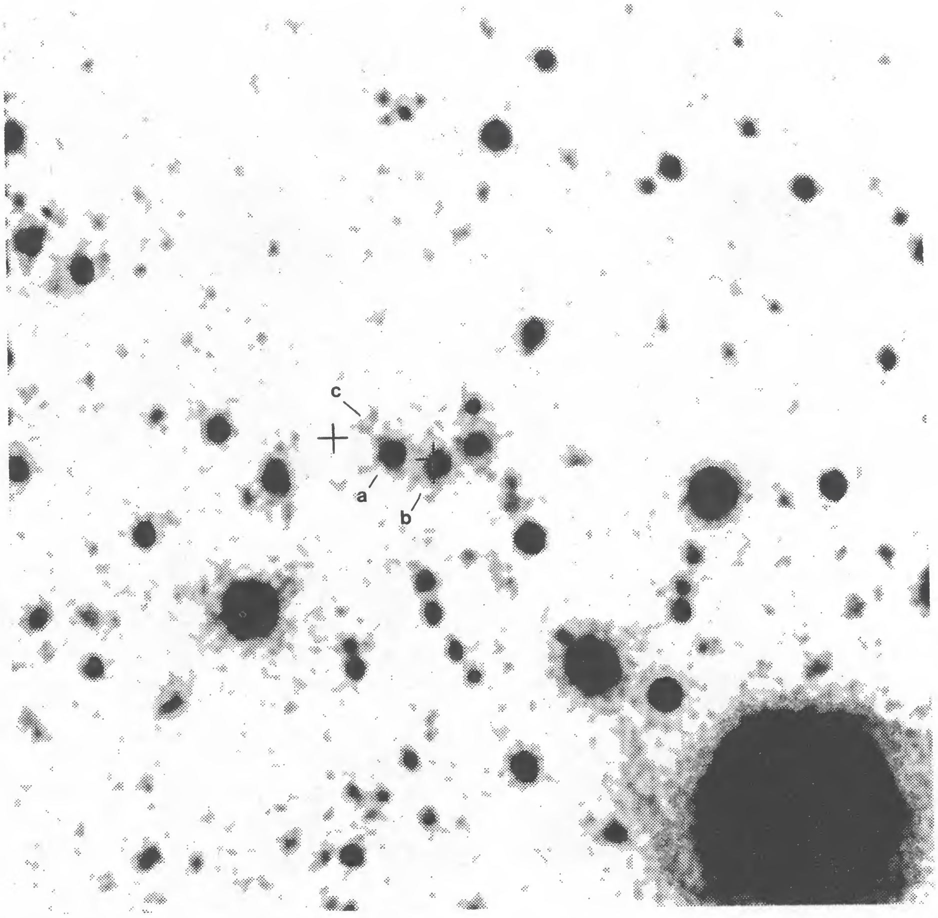

FIG. 4.—3C 239 ($z = 1.781$). 105 × 105 arcsec^2. $V+R$, 2400 s total. The two radio lobes are indicated by crosses. Point a is the optical counterpart to 3C 239; points b and c are close projected galaxies.

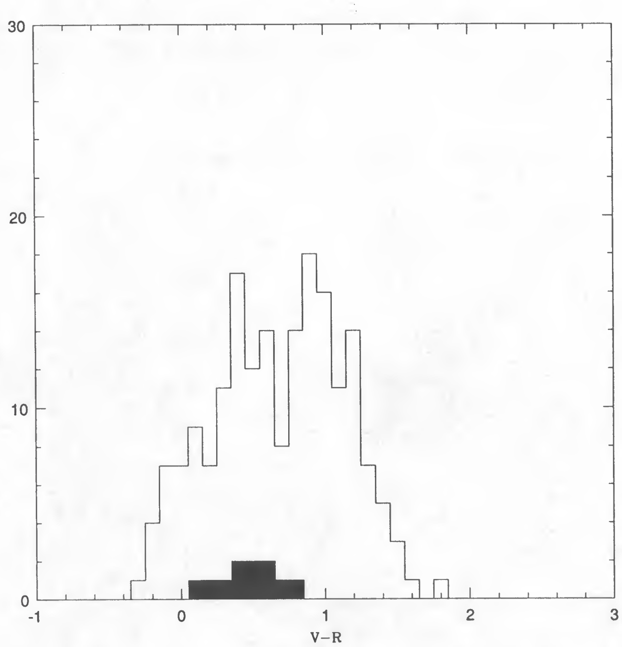

FIG. 5.—Histogram of $V-R$ color indexes in the 3CR 239 field. The galaxies with strong UV excess are indicated by the shadowed area.

alternative to a cluster at the redshift of the radio galaxy may be the projection of nearby very blue compact dwarf galaxies, but it seems difficult to reconcile with the morphologies.

3C 252, z = 1.105.—We observed this radio source identified by Laing *et al.* (1978) under very good seeing conditions in R and V bands (FWHM = 0".64 in R, Fig. 6, 0".81 in V). Close to the position of the radio core (R. A. Laing *et al.*, unpublished), we observe an elongated galaxy a (axis ratio = 1.3) with $R_{26.5} = 21.30 \pm 0.06$ and $V-R_{26.5} = 0.50 \pm 0.14$. The orientation of the radio axis differs from the orientation of the optical axis by $18° \pm 3°$. Only 3" N-W from it, a very faint structure b with $R_{26.5} = 23.68 \pm 0.18$ and with an extremely blue color index ($V-R_{26.5} = -0.36 \pm 0.35$) is detected and looks like the arc structures due to gravitational lensing observed in rich distant clusters of galaxies (Fort *et al.* 1988; Hammer *et al.* 1989). However, spectroscopy of b is needed to go further with this interpretation.

3C 266, z = 1.275.—This double-lobe radio source had been optically identified by Kristian, Sandage, and Katem (1978) with a galaxy with strong emission lines including [O II] (Spinrad and Djorgovski 1984). It shows a morphology extended over 58 kpc, resolved into three components a, b, and c, with our 0".62 seeing FWHM in V (Fig. 7a) and 0".95 seeing FWHM in R. Its measured magnitude and color are $R_{26.5} = 20.83 \pm 0.06$, $V-R_{26.5} = 0.45 \pm 0.13$. The optical and radio

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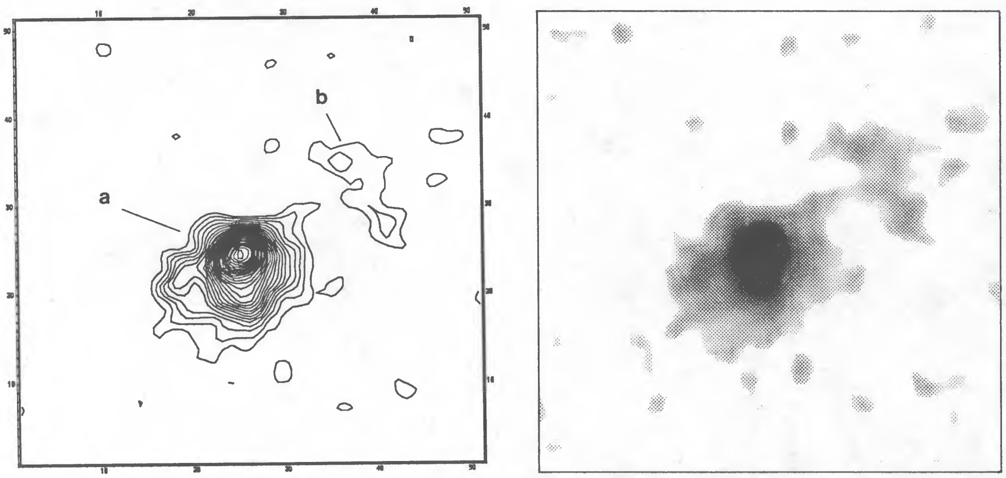

FIG. 6.—3C 252 ($z = 1.105$). 10.5×10.5 arcsec^2. R, seeing 0".64 FWHM. The center of the frame has the following coordinates: $\alpha_{1950} = 11^h08^m48^s.86$, $\delta_{1950} = 35°56'59".4$.

axis orientations are similar with only a 4°.5 difference, and 3C 266 follows the correlation found by McCarthy *et al.* (1987) and Chambers, Miley, and van Breugel (1987) for other distant radio galaxies. A faint galaxy d (FWHM = 1".4, i.e., nonstellar) with $R_{26.5} = 22.49 \pm 0.11$ lies 2".3 east. A check on the astrometry was done with the CERGA Schmidt telescope (Chemin, Heudier, and Pollas 1989) and confirms that a, b, and c are in between the two radio lobes, and d more than 2" from the radio axis. We have also observed the field through a 100 Å wide interference filter around the [O II] 3727 Å line at $z = 1.275$ under very good seeing conditions (FWHM = 0".72, Fig. 7b). We find that the three components a, b, and c have roughly the same relative intensities in R, V, and [O II] filter while d is redder ($V - R = 0.94$) and completely disappears in [O II]. It is therefore possible that d is a foreground or background object, and if foreground it may affect 3C 266 by the mean of optical amplification/lensing. The optical and radio properties of 3C 266 may also be affected in another way by gravitational amplification/lensing since its line of sight is $700 \times (50/H_0)$ kpc from the center of the distant rich cluster A1374 or Zw 243-30 (estimated $z = 0.21$) (see Table 3); a gravitational magnification on the radio/optical source has been estimated by Hammer, Nottale, and Le Fèvre (1986) to be $-0.6 \leq \delta m \leq -0.2$, under the assumption that A1374 is virialized with a density profile following a Hubble law and a projected velocity dispersion between 800 and 1500 km s^{-1} in the cluster's rest frame.

3C 267, z = 1.140.—We observed this source in R and V under excellent seeing conditions (FWHM = 0".62). The optical counterpart of 3C 267 (Gunn *et al.* 1981) is resolved into five components (Fig. 8) with a magnitude $R_{26.5} = 21.56 \pm 0.08$ and a mean color index $V - R = 0.53$. The total size is 69 kpc at $z = 1.140$, and the optical major axis position differs from the radio axis by $26° \pm 3°$. The faint associated radio core (Pedelty *et al.* 1989) is located close to e (astrometry from Gunn *et al.* 1981). It is therefore possible that some of the components are at a different redshift, and that gravitational amplification/lensing plays a role. The alternative is that all the components are at the same redshift and interpretations like merging of galaxies (Djorgovski *et al.* 1987), or triggering of the star formation along the radio axis (Chambers, Miley, and van Breugel 1987; McCarthy *et al.* 1987), have to be considered

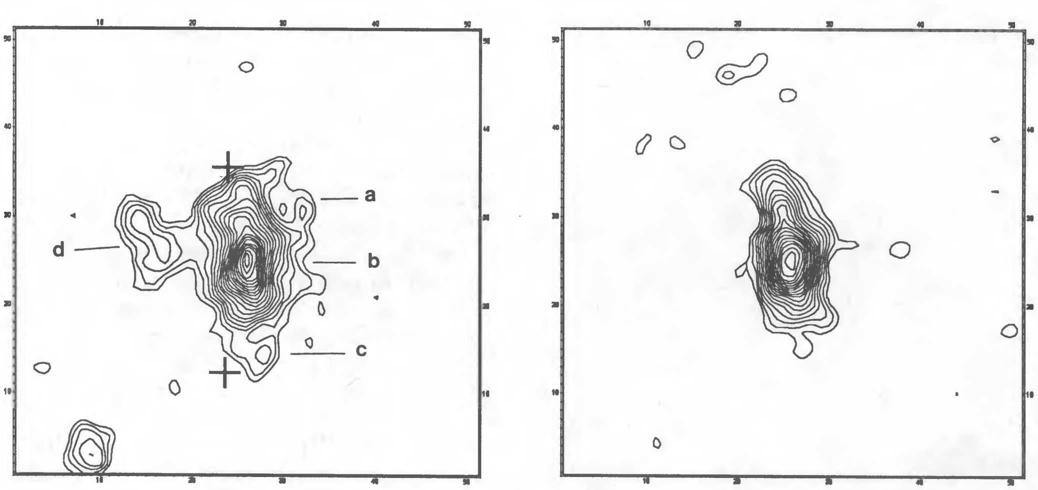

FIG. 7a FIG. 7b

FIG. 7.—(a) 3C 266 ($z = 1.275$). 10.5×10.5 arcsec^2. V, seeing 0".62 FWHM. The center of the frame has the following coordinates: $\alpha_{1950} = 11^h43^m04^s.19$, $\delta_{1950} = 50°02'46".7$. The crosses indicate the position of the radio lobes. (b) 3C 266, [O II], $\lambda = 8479$ Å. Seeing 0".72 FWHM.

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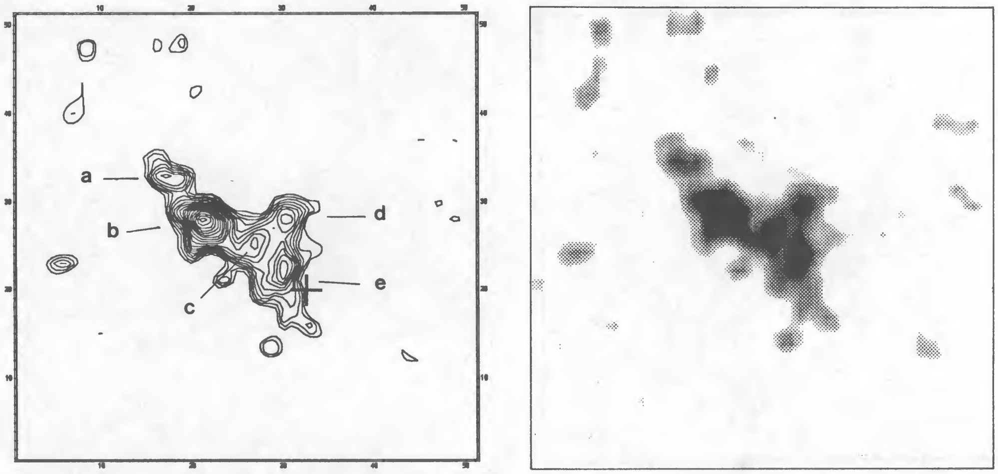

FIG. 8.—3C 267 ($z = 1.14$). 10.5×10.5 arcsec^2. R, seeing 0".62 FWHM. The center of the frame has the following coordinates: $\alpha_{1950} = 11^h47^m21^s.95$, $\delta_{1950} = 13°03'59''.4$. The cross indicates the position of the radio core (Pedelty *et al.* 1989).

keeping in mind the multicomponent morphology. High spatial resolution spectroscopy of the components is needed to go further with these interpretations. Finally, we note that the foreground cluster A1390 or Zw 68-4 ($z = 0.081$; may lead to a gravitational amplification of 3C 267.

3C 297, z = 1.4061.—This galaxy has been classified as an N galaxy by Spinrad *et al.* (1985) with a spectrum showing features (moderate Mg II, Ne IV, and C III) similar to those of other 3CR high-z galaxies. Our imaging in the two broad-band filters R and V under good seeing conditions (FWHM = 0".9; Fig. 9*a*) resolve this bright source into at least two components, *a* and *b*, separated by 2".4, with a global magnitude $R_{26.5} = 20.69 \pm 0.05$ [$M_R = -25.1$ without $k(z)$ correction, or -28.74 with a $k(z)$ correction for an elliptical galaxy from Guiderdoni 1986]. None of the components is really a compact source (FWHM = 1".3 and 2".2, respectively); in fact, the brightest component *a* seems itself to be a blend of two subcomponents, because its center in the V image is about 0".3 displaced to the south with respect to its location in the R image. Moreover, in an image through an interference filter centered around the [O II] 3727 Å emission line, a strong emission is observed between *a* and *b*, while the other parts of the galaxy are much fainter (Fig. 9*b*). This source may therefore be a complex blend of objects, and spectroscopy with very high spatial resolution will be needed to go further. Finally this source may be gravitationally amplified, both in terms of radio flux and optical luminosity, due to the foreground medium distant cluster Zw 19-22. No detailed radio map has been published to our knowledge.

3C 322, z = 1.681.—Identified by Riley, Longair, and Gunn (1980), its redshift was measured by Djorgovski *et al.* (1988). Under good seeing conditions (FWHM = 0".81 in R, FWHM = 0".91 in V), it is resolved into two objects (Fig. 10) separated by 2".6 and overlapping at a level fainter than $V = 25.5$ mag arcsec^{-2}. The galaxy *a* has a magnitude $R_{26.5} = 22.77 \pm 0.08$ and $V - R = 0.79 \pm 0.15$, while *b* is fainter with $R_{26.5} = 23.66 \pm 0.15$ and $V - R = 1.13 \pm 0.3$; each of them is elongated E-W with a similar axis ratio of 1.2. From the astrometry of the field (Riley, Longair, and Gunn 1980) it is clear that *a* is on the radio axis (Jenkins, Pooley, and Riley 1977), while *b* is 1".5 from it. The optical axis orientation differs from the radio axis position by 87° ± 3°. Two alterna-

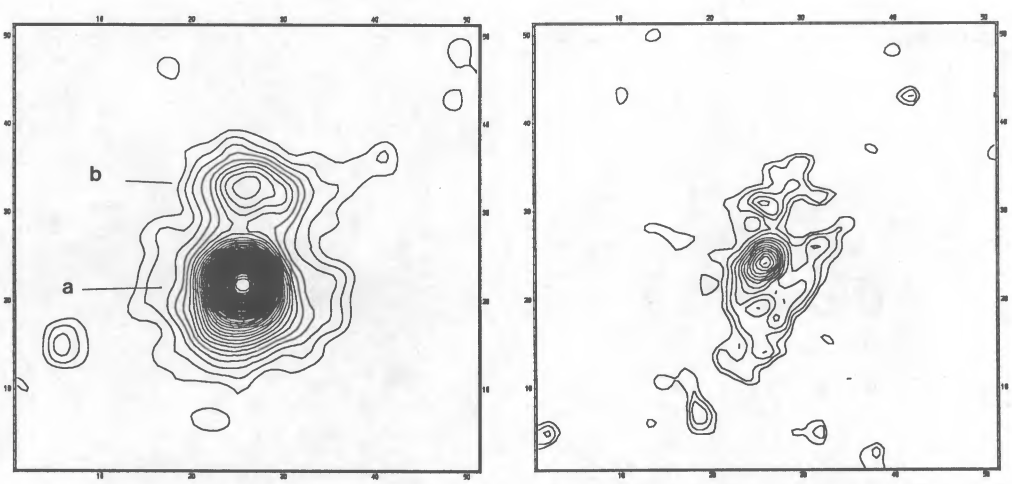

FIG. 9*a* FIG. 9*b*

FIG. 9.—(*a*) 3C 297 ($z = 1.4061$). 10.5×10.5 arcsec^2. R, seeing 0".9 FWHM. The center of the frame has the following coordinates: $\alpha_{1950} = 14^h14^m47^s.78$, $\delta_{1950} = -03°46'57''.8$. (*b*) 3C 297, [O II], $\lambda = 8967$ Å. Seeing 0".85 FWHM.

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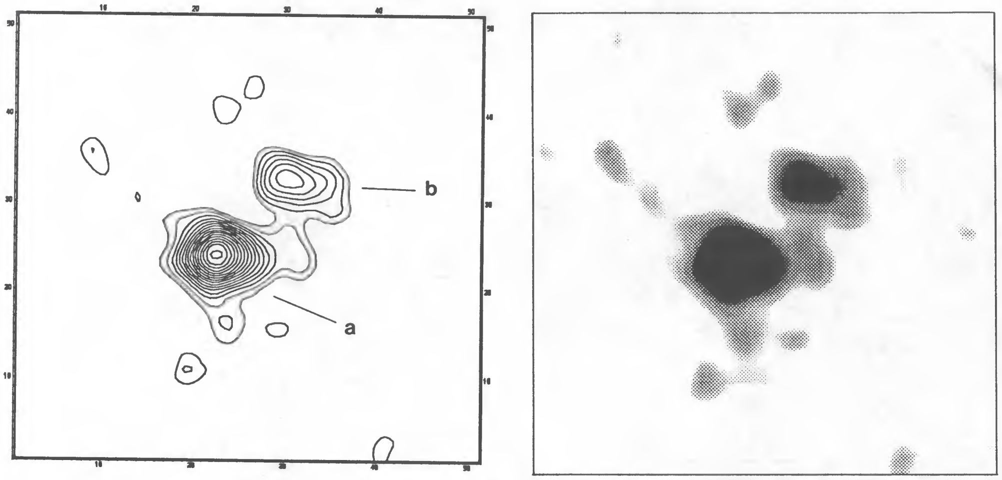

FIG. 10.—3C 322 ($z = 1.681$). 10.5×10.5 arcsec^2. R, seeing 0".9 FWHM. The center of the frame has the following coordinates: $\alpha_{1950} = 15^h33^m46^s.2$, $\delta_{1950} = 55°46'49".2$.

tives need again to be considered here; either the two galaxies are at the same redshift, or they are at different distances, and gravitational amplification/lensing may play an important role. Spectroscopy of b is therefore needed before any attempt to derive 3C 322 intrinsic properties. Finally, the medium distant cluster of galaxies Zw 275-16 is close to the line of sight of 3C 322 (Table 3) and could gravitationally magnify radio and optical fluxes.

3C 324, $z = 1.2063$.—This galaxy has been proposed as a gravitational lens candidate by Le Fèvre *et al.* (1987), on the basis of the presence of a line system at a different redshift $z = 0.845$ (Hammer, Nottale, and Le Fèvre 1986) in the spectrum taken by Spinrad and Djorgovski (1984) and interference filter imaging. More recently, we observed the 3C 324 field through an interference filter corresponding to the [O II] line at $z = 1.2063$ (Fig. 11, FWHM = 1".2). The relative flux ratios betwen the [O II] and R bands are 1.4 and 1.5 for b and c, respectively, if we set the [O II]/R flux ratio to 1 for a: the central component a is faint in [O II] while outer components are detected at locations which correspond exactly to those in the R broad-band filter. Therefore it seems that only the continuum from a was detected while b and c appear much brighter because they are the source of the very strong [O II] 3727 Å emission at $z = 1.206$ (22 times stronger than the C II 2326 Å emission; Spinrad and Djorgovski 1984) and are not likely to be contaminated in this bandpass by a in their positions and shapes. This strongly supports our hypothesis that 3C 324 is a gravitational mirage, with a being a foreground galaxy and b and c being gravitational images of the $z = 1.2063$ background galaxy.

3C 469.1, $z = 1.336$.—We observed this source under the worst seeing of this study: FWHM = 1".2 in the R filter. Our imaging shows the optical counterpart of 3C 469.1 (the object a of Gunn *et al.* 1981) elongated along a SE (axis ratio = 1.9), and a faint object b 3".4 SE of it (Fig. 12).

III. OPTICAL MORPHOLOGIES OF THE HIGH-REDSHIFT RADIO GALAXIES

From our data (Le Fèvre *et al.* 1987, 1988; Le Fèvre, Hammer, and Jones 1988; Le Fèvre and Hammer 1988, and this paper), we find that 75% of the $z \geq 1$ 3CR galaxies have two to six components. These components are defined as resolved features which are detected above the 4 σ level set by the sky noise, and their existence is therefore beyond doubt.

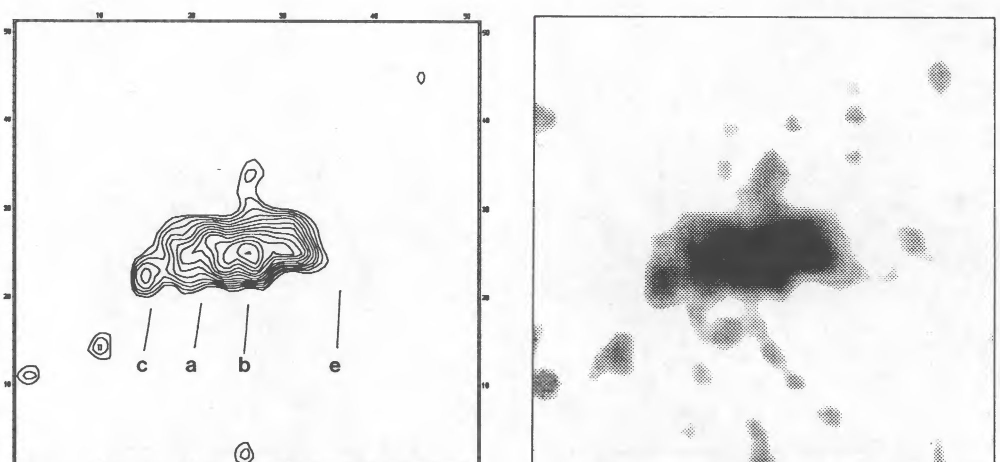

FIG. 11.—3C 324 ($z = 1.2063$). 10.5×10.5 arcsec^2. [O II], $\lambda = 8222$ Å. Seeing 1".2 FWHM. The center of the frame has the following coordinates: $\alpha_{1950} = 15^h47^m37^s.1$, $\delta_{1950} = 21°34'40".2$.

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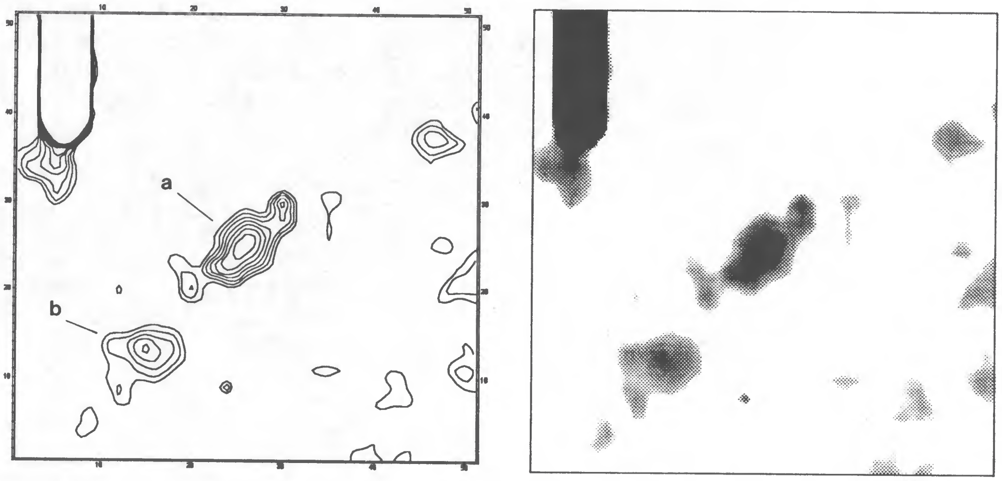

FIG. 12.—3C 469.1 ($z = 1.275$). 10.5×10.5 arcsec^2. R, seeing 1″.2 FWHM. The center of the frame has the following coordinates: $\alpha_{1950} = 23^h52^m58^s.66$, $\delta_{1950} = 70°38'35''.0$.

The total size of the galaxies range from $15(50/H_0)$ kpc to $120(50/H_0)$ kpc, and the components may be aligned (archetype 3C 256, 3C 324) or distributed apparently at random (3C 267). The components are usually spatially resolved under our excellent seeing, and their typical sizes are on the order or less than $10(50/H_0)$ kpc with a mean distance from one component to its closest neighbor ranging from 10 to 40 kpc with a mean of $19(50/H_0)$ kpc. The red magnitudes of a single component range from 19.5 to 26 with a mean of $\sim$23.2, i.e., a mean absolute magnitude $M_R = -22.5 + 5 \log (50/H_0)$ which computed without k-correction or evolution correction, is already comparable to an elliptical galaxy's luminosity.

These basic parameters show how peculiar the morphologies of the $z \geq 1$ 3CR galaxies are. The galaxies have more the appearance of compact groups of bright galaxies than single ellipticals. This property is also shared by other high-z and powerful radio galaxies (Lilly 1988; Chambers, Miley, and van Breugel 1988; Chambers 1989). A comparison with the low and intermediate-redshift radio galaxies samples from Lilly and Prestage (1987) and Yates, Miller, and Peacock (1989) indicate that at redshifts less than 0.6, only one-fourth of the 3CR powerful galaxies have multiple nuclei against $\frac{3}{4}$ for our $z \geq 1$ sample. This is a very fundamental property. A more complete discussion on the morphological properties of the distant radio galaxies is given elsewhere (Hammer 1989).

IV. GRAVITATIONAL AMPLIFICATION/LENSING BY FOREGROUND MATTER

From the presence of foreground objects close to the line of sight of high-z 3CR galaxies, we are able to bring up some statistical evidence that gravitational amplification or lensing actually acts on the general properties of these sources. In the following discussion we consider the 27 $z \geq 1$ 3CR galaxies for which we have imaging among the 31 known (Djorgovski *et al.* 1988).

a) Excess of Foreground Bright Galaxies on the Line of Sight of High-z 3 CR Galaxies

At least four sources are close in projection to a bright foreground galaxy ($R \leq 21$; see Table 1). From red counts of galaxies (Tyson 1988; Karatchensev 1980; Shanks *et al* 1984; Koo 1986) the probability to find a source 5″ from a $R \leq 21$ galaxy is $p \leq 1.6 \times 10^{-2}$. Finding four 3CR sources out of 27 in such a configuration is therefore associated with the small Poisson law probability (with $\nu = 27 \times p$) $P = \sum_{n=4}^{27} e^{-\nu}(\nu^n/n!) = 10^{-3}$, a result consistent with a binomial distribution $P = \sum_{n=4}^{27} C_n^{27} p^n(1-p)^{(27-n)} = 9 \times 10^{-4}$. The location of high-redshift 3CR galaxies with respect to the foreground galaxies is therefore not due to a random distribution at the 99.999% confidence level. We note that these probabilities are likely to be lower estimates for the following reasons: (1) we neglect the effects of gravitational amplification which decreases the probability to find a background source close to a deflecting galaxy by a factor amp^{-1}; (2) the distribution of the high-z 3CR galaxies would appear even more peculiar if we use the parameter $1/\theta \times D_d D_{ds}/D_s$ from the equations of the gravitational optics theory rather than $1/\theta$ (θ being the angular separation between source and deflector [see, e.g., Hammer and Nottale 1986]). It is of interest to compare our result with the study of Webster *et al.* (1988) on 285 QSOs, who found that the surface density of QSOs around $B_J \leq 21$ galaxies is 4.4 higher than would be expected from a random distribution. A similar reasoning shows that the density of 3CR high-z galaxies at less than 5″ from a $R \leq 21$ foreground galaxy is *9 times higher* than would be expected from a random distribution.

Moreover, a case-by-case analysis shows that all these bright foreground galaxies actually gravitationally amplify the background 3CR galaxy. Tables 2A, 2B, 2C, and 2D the expected gravitational magnifications for the four optical sources and their associated radio emission. A set of velocity dispersions and M/L ratios for the intervening galaxies are considered as input into the gravitational amplification formulae, assuming an r^{-2} profile for the mass density of the deflector with a cut at

TABLE 1

$z \geq 1$ 3CR GALAXIES WITH A PROJECTED GALAXY CLOSE TO THE LINE OF SIGHT WITH A MEASURED REDSHIFT

3CR	z and m_R Background	z and m_R Foreground	θ
3C 13	1.351; 21.27	0.477; 20.31	3″.9
3C 194	1.185; 22.57	0.312; 19.30	4.0
3C 208.1	1.02; 19.26	0.158; 20.85	3.9
3C 225A	1.565; 22.54	0.134; 18.79	4.9

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TABLE 2A

AMPLIFICATION FACTORS FOR 3CR 13[a]

M/L	σ_v 300	350	400
12	0.8	1.2	1.6
20	1.3	1.8	3.0
30	7.1	...	...

[a] Units: magnitudes.

TABLE 2B

AMPLIFICATION FACTORS FOR 3CR 194[a]

M/L	σ_v 300	350	400
10	1.1	1.6	2.6
20	3.9	...	...

[a] Units: magnitudes.

TABLE 2C

AMPLIFICATION FACTORS FOR 3CR 208.1

PARAMETER	σ_v 150	200	250
Amplification (mag)	0.2	0.4	0.7

TABLE 2D

AMPLIFICATION FACTORS FOR 3CR 225A

PARAMETER	σ_v 200	250	300
Amplification (mag)	0.4	0.6	0.9

a radius $R \gg l$ (Hammer and Nottale 1986):

$$\mathrm{Amp}^{-1} = \left(1 - 3\,\frac{\pi\sigma_v^2 D_d D_{ds}}{c^2 D_s l}\right)^2 - \left(\frac{4GMD_d D_{ds}}{c^2 l^2 D_s}\right)^2 ,$$

where σ_v is the velocity dispersion which can be derived from observations, l is the impact parameter, M is the deflector mass, and D_d, D_s, D_{ds} are the angular diameter distance of the deflector, the source, and between the deflector and the source, respectively. The second term depends on the deflecting mass for which independent estimations are difficult. If the deflecting galaxy is at low z, this term may be negligible, which is the case for the 3CR 208.1 and 3CR 225A configurations. As a way to estimate the minimum gravitational amplification effect, we therefore tried to estimate σ_v and especially its lower limit. In the absence of spectroscopic data with high enough spectral resolution to allow accurate measurements of σ_v, we have estimated its value by indirect means as is described below. Finally, the minimum gravitational amplification will be computed by entering the minimum value of σ_v in formulae (1) and the corresponding virial mass inside the impact parameter $M = 3l\sigma_v^2/G$.

The two elliptical galaxies near 3CR lines of sight to 3CR 13 and 3CR 194 are very bright, $M_R = -23.5$ for both (Le Fèvre *et al.* 1988; Le Fèvre and Hammer 1988) and lie in the upper right-hand corner of the Faber and Jackson (1976) relation. If we use the $L \sim \sigma_v^{3.5}$ relation for elliptical galaxies in the Virgo and Coma clusters from Dressler (1984) and for field elliptical galaxies from Terlevich *et al.* (1981), we can derive the minimum values of σ_v for the foreground galaxies near 3CR 13 and 3CR 194: $\sigma_v \geq 300$ km s^{-1}. Both lead to rather large amplifications of the optical counterparts of 3CR 13 and 3CR 194: $\delta m \leq -0.8$ for 3CR 13 (foreground galaxy with $\sigma_v \geq 300$ km s^{-1} and $M/L \geq 12$), and $\delta m \leq -1.1$ for 3CR 194 (foreground galaxy with $\sigma_v \geq 300$ km s^{-1} and $M/L \geq 10$), while the radio emission is less affected for 3CR 194 and not affected for 3CR 13. Larger values of gravitational magnifications are expected for larger values of σ_v and reasonable values of M/L (Tables 2A and 2B). Our imagery (Le Fèvre and Hammer 1988) shows how 3CR 225A is projected inside a bright foreground spiral galaxy ($M_R = -21$, $z = 0.134$). With the Tully-Fisher relation (Tully and Fisher 1977; Bottinelli *et al.* 1984; Tammann 1986) and assuming the presence of a massive halo (Kent 1987), we obtain an estimate of 250 ± 60 km s^{-1} for the velocity dispersion of this spiral galaxy. Both radio and optical components are therefore magnified at least by 0.34 mag (for a conservative $\sigma_v = 200$ km s^{-1} and a low M/L to 0.6 mag ($\sigma_v = 250$ km s^{-1}). The Seyfert galaxy near 3C 208.1 should have a velocity dispersion typical of spiral galaxies, i.e., likely to be between 150 and 250 km s^{-1}, and for a value of 200 km s^{-1}, it should gravitationally magnify the optical 3CR counterpart by more than 0.5 mag while the radio luminosity should be gravitationally increased by more than a factor of 1.5 (Le Fèvre and Hammer 1990). We therefore conclude that these four distant 3CR galaxies are substantially gravitationally amplified by foreground bright galaxies.

Furthermore, we claim that since these 3CR galaxies are gravitationally amplified, gravitational amplification is the explanation for the strong excess of foreground galaxies that is found in the fields of high-z 3CR galaxies. This is in agreement with our prediction that gravitational amplification affects the high-z 3CR sample by the mean of selection effects (Hammer, Nottale, and Le Fèvre 1986). We did not try to derive a mean gravitational amplification from the number-magnitude relation as done by Webster *et al.* (1988) for their sample of QSOs for the following reasons. They assumed that the excess number of QSOs that have their lines of sight close ($\leq 6''$) to bright foreground galaxies are actually gravitationally magnified sources. Then, they compared the number density of these QSOs with the number density in the rest of the sample, and they derived a gravitational magnification; hence, the mass distribution of the lensing matter associated with the intervening galaxies. However, Webster *et al.* found unrealistic high values for the velocity dispersions of the intervening galaxies, which is probably due to (1) the fact that they obviously miss the configurations where the foreground galaxy is not detected because it is too close to the QSO line of sight (see the case of QSO 1209+107; Arnaud *et al.* 1988) or the configurations where the foreground galaxies are at $z \geq 0.5$, the first case corresponding to the high magnification case; or (2) the implicit assumption that the number-magnitude relation is unaffected by gravitational magnification seems to contradict their results and they probably have to iterate one more time in order to avoid this contradiction. Moreover, such an analysis would need in the 3CR case a much better knowledge of the radio luminosity function of the radio galaxies at relatively low radio fluxes (down to 1 Jy), as well as systematic counts of galaxies around radio lobes (which will be the subject of a future paper).

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b) Contamination of the Lines of Sight from Other Foreground Galaxies

Investigation of the contamination by foreground galaxies on the whole high-z 3CR sample could have some interesting consequence on the properties of these distant radio galaxies. It is worth pointing out that the four bright galaxies mentioned in § IV*a* are quite bright and have been easy to measure spectroscopically; on the other hand, if some of the faint components are also projected foreground galaxies, they may be much more difficult to identify in spectroscopy. Since the morphologies for most of the galaxies show multiple components, it is therefore of interest to investigate the possibility that part of these components is a result of the projection of foreground galaxies on the line of sight. For this we used the galaxy counts of Tyson (1988) for B_J magnitudes up to 25 (or an equivalent R magnitude around 23.5 to match the mean magnitude of the components). We then corrected the counts to take into account only the foreground galaxies with the Schechter luminosity function (Efstathiou, Ellis, and Peterson 1988), and using the $k(z)$ and $e(z)$ corrections from Guiderdoni and Rocca-Volmerange (1988) that are consistent with the counts of galaxies at such magnitudes (Guiderdoni and Rocca-Volmerange 1989). Note that this correction intervenes only at the second-order level, and that it corresponds also to an underestimate of the number of foreground galaxies with respect to the model of rapid starbursts of galaxies at intermediate z recently presented by Broadhurst (1989). We can then compute that the probability of having a foreground galaxy inside the optical radius of one of the distant 3CR galaxies is 0.026, 0.034, 0.041 if we consider the contamination by galaxies with $B_J \leq 24$, 24.5, or 25 mag, respectively. Therefore, we expect that only one of the components of the 20 multiple component galaxies in our 3CR sample is foreground. However, as shown in § IV*a*, selection effects due to gravitational amplification occur in the sample. Under the assumption that there is an excess of 3CR distant galaxies around galaxies with $B_J \leq 25$ g similar to the excess found around galaxies with $R \leq 21$, nine components of the 3CR multiple-component distant galaxies could be foreground objects. The central components of the gravitational lens candidate 3CR 324 may be an example of a foreground component (Le Fèvre *et al.* 1987). Deep high spatial resolution spectroscopy will allow a complete answer to this problem.

c) Excess of Foreground Distant and Rich Clusters on the Sight of High-z 3CR Galaxies

We will use in this section the Abell and Zwicky catalogs; this lead us to consider only the 23 3CR sources having $b \geq 18°$, due to the strong decrease of cluster detection and therefore cluster number below this arbitrary limit. We find that five out of the 23 sources have their lines of sight near the center of a foreground distant cluster of galaxies (see Table 3). We have previously computed the covering factor of the Zwicky clusters (Hammer and Nottale 1986) which are able to gravitationally amplify background sources (i.e., medium or distant clusters; see the formula given by Hammer and Nottale 1986) leading to the probability $p = 0.092$ for a background source to lie behind such a cluster ($\theta/R \leq 1$, where θ is the angular separation between the source and the center cluster, R being the Zwicky cluster radius). Therefore, the probability to find at random five sources out of 23 in such a configuration is $P = \sum_{n=5}^{23} C_n^{23} p^n (1-p)^{(23-n)} = 0.05$ (binomial) or $P = \sum_{n=5}^{23} e^{-\nu}(\nu^n/n!) = 0.06$ (Poisson law with $\nu = 23 \times p$). We obtain a similar result when using foreground distant Abell clusters as gravitational deflectors.

Moreover, at least one of the radio galaxies is likely to be gravitationally amplified by a foreground cluster: 3CR 266 is projected less than 3′ from the center to the distant rich cluster A1374 (Zw 243-30) with an estimated $z = 0.21$ (Leir and van den Bergh 1977). Under the assumption that this cluster is virialized and that its density profile follows a Hubble law, we can compute the gravitational amplification of the optical and radio fluxes with the following formulae:

$$\mathrm{Amp}^{-1} = [1 - 0.1(\sigma_v/1000 \text{ km s}^{-1})^2]^2$$

and $\delta m = -2.5 \log(\mathrm{Amp})$. Using realistic values for the cluster velocity dispersion (Bahcall, Soneira, and Burgett 1986), we find that even for low values of σ_v there is a substantial magnification of both optical and radio fluxes of 3CR 266: $\delta m = -0.2, -0.3, -0.6$ for $\sigma_v = 800$, 1000, and 1500 km s^{-1}, respectively.

V. CONCLUSION

Ten $z \geq 1$ 3CR galaxies have been observed under excellent seeing conditions. The main results from these observations are as follows:

1. New data in favor of a gravitational lensing interpretation for 3CR 324 have been collected.
2. There is a possible identification of a rich cluster of galaxies around 3CR 239 at $z = 1.78$, which could be the most distant cluster known so far.
3. Almost all optical sources are resolved into apparent multiple components (3CR 230, 3C 266, 3CR 267, 3CR 297, 3CR 324) and/or lie 2″–5″ off a brighter galaxy (3CR 239) or a fainter one (3CR 252, 3C 266, 3CR 322, 3CR 469.1).
4. One source, 3CR 266, is found likely to be substantially affected in both radio and optical fluxes by gravitational amplification due to foreground clusters of galaxies, and two others (3CR 239, and 3CR 322) may also be affected.

TABLE 3

$z \geq 1$ 3CR GALAXIES WITH A PROJECTED CLUSTER OF GALAXIES GALAXY CLOSE TO THE LINE OF SIGHT

3CR	z_s	Foreground Zwicky/Abell Cluster	z or Distance Class of the Cluster	θ/R, θ (arcmin): Angular Distance Source-Cluster; R = Cluster Radius (Zwicky)
3CR 266.......	1.273	Zw 243-30	Very distant	0.29
		A1374	0.210	0.75(50/H_0 Mpc)
3CR 238.......	1.405	Zw 36-11	Medium distant	0.48
		A949	0.142	3.5(50/H_0 Mpc)
3CR 194.......	1.185	Zw 207-22	Medium distant	0.56
3CR 305.1.....	1.132	Zw 354-2	Medium distant	0.71
3CR 322.......	1.684	Zw 275-16	Medium distant	0.80

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TABLE 4

3CR GALAXIES HAVING TO BE REMOVED FROM THE 3CR SAMPLE AFTER CORRECTION FOR GRAVITATIONAL AMPLIFICATION

3CR	α	Probable σ(km s^{-1}) of the Deflector	Probable Flux Amplification	Corrected Radio Flux (Jy)
3CR 208.1.....	0.65	200	1.75	5.3
3CR 225A.....	0.93	250	1.7	4.5
3CR 266.......	1.01	1000	1.25	8.8

This new imaging almost completes the high spatial resolution survey of the $z \geq 1$ 3CR galaxies with a mean image quality of 0".75 for 27 galaxies (Le Fèvre *et al.* 1987, 1988; Le Fèvre, Hammer, and Jones 1988; Le Fèvre and Hammer 1988). Their detailed morphologies are now known on scales on the order or less than $10(50/H_0)$ kpc, and 75% are observed to have two to six resolved components which have the typical sizes and luminosities of individual galaxies. Moreover, most of the other galaxies present elongated shapes which may break down into individual components with a better image quality. These peculiar morphologies are a basic property for the high-redshift 3CR galaxies which has to be accounted for by any interpretation.

There are some statistical evidences that the $z \geq 1$ 3CR galaxies are not distributed at random with respect to the foregound matter from the following arguments:

1. There is an excess of a factor of 9 of 3CR sources close to bright $R \leq 21$ foreground galaxies than would be expected from random distribution.

2. There is an excess of distant Abell and/or Zwicky clusters on their lines of sight.

3. 3C 324 is a gravitational lens candidate. Moreover, there is direct evidence that four 3CR optical counterparts are gravitationally magnified by 0.5–1.6 mag due to the close projection of foreground bright galaxies of known redshifts: 3CR 13, 3CR 194, 3CR 208.1, and 3CR 225A. One source, 3CR 266, is probably magnified by a foreground cluster, while four others (3CR 194, 3CR 238, 3CR 305.1, and 3CR 322) may also be affected in a similar way. The radio properties are also affected by these effects since at least three sources (3CR 208.1, 3CR 225A, and 3CR 266) are part of the 3CR catalog only because their radio fluxes are gravitationally magnified by foreground bright galaxies or clusters and after correction for gravitational amplification have radio fluxes below the 3CR catalog flux limit (see Table 4). Five other sources (3CR 194, 3CR 238, 3CR 239, 3CR 305.1, 3CR 322) may be similarly affected. This confirms the prediction that the observations of high-z 3CR galaxies are affected by selection effects coming from gravitational amplification/lensing (Hammer, Nottale, and Le Fèvre 1986).

Interpretations of the main properties of these high-redshift galaxies are then complicated by such effects. Multiple-component galaxies may either be the result of mergers of galaxies (Djorgovski *et al.* 1987), or an interaction between the radio jets and the intergalactic medium (McCarthy *et al.* 1987), both activating the star formation, or it may be due to the contamination of foreground galaxies which is enhanced by the selection effects linked to gravitational amplification/lensing. A contamination by cluster galaxies associated with the 3CR source should also be considered since there are some indications that some 3CR galaxies lie in clusters (Spinrad and Djorgovski 1984; Yates, Miller, and Peacock 1989); this paper). Statistical arguments have been presented to sustain the various interpretations, such as the observed optical/radio alignment for several sources as a result of interaction of the radio jets with the intergalactic medium (Chambers, Miley, and van Breugel 1987; McCarthy *et al.* 1987) and the statistical excess of foreground matter as coming from the selection effects due to gravitational lensing. These latter effects are able to strongly modify most of the properties of these distant galaxies, from radio to optical wavelength, including the infrared. Further developments including detailed counts of galaxies in the fields of high-z 3CR galaxies will be presented in a future paper (F. Hammer *et al.*, in preparation).

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Note added in proof.—We have recently made high spatial resolution spectroscopy of 3CR 368 ($z = 1.135$) at the 3.6 m Canada-France-Hawaii Telescope and at the N.T.T. 3.6 m of the European Southern Observatory. Individual spectra of the four components included in the slit strongly suggest that it is a new gravitational lens (F. Hammer, O. Le Fèvre, and D. Proust, *IAU Circ.*, No. 4920 [1990]). The brightest component is a foreground elliptical, while its two neighbors are gravitational multiple images of a single source. Radio components are also affected by lensing. After removing the lens, the real appearance of 3CR 368 and its actual properties are strongly modified.

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