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HIGH SPATIAL RESOLUTION IMAGING OF SOME OF THE MOST DISTANT 3CR GALAXIES

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ABSTRACT

New high spatial resolution, deep imaging of very distant 3CR radio galaxies has been obtained. The average seeing of the sample is ~0″8 FWHM with the best images reaching 0″6, thus allowing us to find new and unsuspected morphologies.

The observed galaxies all show complex morphologies with multiple components. In two cases, 3C 238 and 3C 356, very compact objects have been found. When color information was available, strong color variations were observed among the individual components of the galaxies.

For some of the sources we suggest gravitational amplification by foreground clusters of galaxies or galaxies as a possible interpretation. The radio galaxy 3C 238 seems to be an excellent gravitational lens candidate since two compact components with similar profiles and colors are located on either side of an extended object with a very different color index. 3C 241 and 3C 305.1 show an excellent radio/optical correspondence and we suggest that they may be affected by gravitational lensing.

From these new data, we argue that the high-redshift 3CR radio-galaxies sample cannot be used in a simple way to test for galaxy evolution by means of a standard magnitude/color-redshift relationship.

Subject headings: galaxies: formation — gravitational lenses — radio sources: galaxies

I. INTRODUCTION

The high-redshift 3CR radio-galaxy sample is of great interest as these galaxies are distant probes in the far universe and should enable us to learn more about the early stages of galaxy evolution. However, it has never been clearly established by direct evidence that the high-redshift 3CR galaxies are the progenitors of low-redshift radio galaxies and ellipticals and that they can be used in the same sample to test for galaxy evolution (Chambers, Miley, and van Breugel 1987). The differences are indeed numerous: radio power, optical luminosities, colors, sizes, and so on. The link is in fact done *a posteriori* when a galaxy evolution model seems to correctly fit the brightest cluster galaxies (BCG) and the high-redshift 3CR galaxies (Spinrad and Djorgovski 1987).

A methodological approach for such an analysis needs to consider first the possibility that this sample could be biased before addressing the question of evolution. This sample is a small one with 20–30 galaxies above $z \approx 1$, which all have a very high radio-flux close to the 9 Jy detection limit. As in any flux-limited sample, one has to look for any bias possibly affecting the understanding of the general properties of these galaxies. The high-redshift 3CR sources may have been selected because of their very high intrinsic radio luminosities (1–10 times more powerful than Cygnus A) *or* because their luminosities are enhanced by gravitational amplification due to the presence of foreground galaxies or clusters of galaxies close to their line of sight. Hammer and Nottale (1986) have shown that a strong selection effect due to gravitational amplification by rich clusters of galaxies may alter seriously the observations of distant sources. We have suggested that gravitational amplification may play an important role in the high z 3CR galaxy sample from the presence of foreground galaxies and distant Abell or Zwicky clusters of galaxies on the source line of sight (Hammer, Nottale, and Le Fèvre 1986, hereafter HNL; Hammer, Le Fèvre, and Nottale 1988). The propagation of a light beam in an inhomogeneous universe is described by two main terms (Dyer and Roeder 1974; Hammer 1985); (1) the Ricci (or "matter") term which describes the effects of matter included in the beam, and accounts for an expansion of the beam, and (2) the Weyl (or "shear") term which describes the effect of matter distributed outside of the beam and account for a change in the shape and location of the beam. For clusters or superclusters of galaxies considered as a whole as lenses, the Ricci term is predominant (Hammer 1985), which means that they should in general gravitationally amplify background sources (at all wavelengths), without the occurrence of multiple images. On the contrary, the Weyl term is not negligible when the lens is a galaxy, explaining most of the known observed gravitational *mirages* (Bourassa and Kantowski 1975; Young *et al.* 1980). Part of the 3CR radio galaxies may then have entered the 3CR sample simply because they have been gravitationally amplified by foreground galaxies or clusters of galaxies. Additionally the optical counterparts of these gravitationally amplified galaxies may in some particular cases be gravitationally multiply imaged, possibly leading to large modifications of their general properties. Following this analysis, we have proposed a gravitational lens interpretation to explain the observed properties of the radio-galaxy 3C 324 (Le Fèvre *et al.* 1987, hereafter LHNM) and from further

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observations we have also suggested that the radio-galaxy 3C 13 may be affected by gravitational amplification (Le Fèvre *et al.* 1988).

In another way, a merging/outflow picture (Djorgovski *et al.* 1987; McCarthy *et al.* 1987*a*) have been proposed and take into account the radio/optical correlation observed for some of the high *z* 3CR galaxies (McCarthy *et al.* 1987*a*; Chambers, Miley, and van Breugel 1987). In order to assess the possible role played by gravitational amplification and other interpretations excellent image quality is a necessity; as shown by previous observations, the 3CR galaxies appear in some cases elongated under good image quality (Spinrad 1986) but really exhibit their morphology only under a sub-arcsecond spatial resolution and for some of them their multiple structure is only seen at very faint brightness levels (Djorgovski *et al.* 1987; Le Fèvre *et al.* 1987*a*, 1988). Broad-band imaging of six galaxies, with identifications taken from Spinrad *et al.* (1985), are presented here. The excellent image quality allows us to reveal for the first time the complex morphologies of 3C 238, 3C 241, 3C 305.1, 3C 326.1, and 3C 356, most of them being resolved into multiple components.

II. NEW DATA: DEEP HIGH SPATIAL RESOLUTION IMAGING

Our deep high-resolution imaging on high-redshift 3CR galaxies was carried out in two observing runs in 1987 May. Most of the frames were obtained during the first run, where we used the RCA2 CCD at the Canada-France-Hawaii Telescope (CFHT) prime focus (0".21 pixel^{-1}) while for the second one we used the same CCD with a f/2.7 focal reducer at the cassegrain focus (0".28 pixel^{-1}). Exposure times ranged from 20 minutes to 1 hr in the broad-band filters. The image quality is a prime factor in our investigation and ranges from excellent values of 0".6 FWHM to a mediocre 1".3 for one frame with a mean of 0".83. The raw CCD output images have been processed in a standard way and the transformation to magnitudes have been done using calibration fields from Christian *et al.* (1985). When data was available, color indices for individual components were computed as described in Le Fèvre *et al.* (1988). In Figures 1–6 (Plates L1–L6) we display the final frames 10.5 × 10.5 arcsec^2 centered on the radio-galaxies (north is up, all taken at CFHT prime focus).

Let us examine the galaxies one by one ($H_0 = 50$ km s^{-1} Mpc^{-1}, and $q_0 = 0$ are assumed throughout the paper).

—3C 238, $z = 1.405$.—This galaxy has a very elongated morphology resolved into three components with the 0".7 seeing FWHM in R (0".8 in *V*), and extended over ~80 kpc (Fig. 1*a*). The brightest component *a*, as well as *c*, have a compact structure and a fit to a star image in the field shows that their profiles are indeed stellar at a 99% confidence level (χ^2 test; see Fig. 1*b*). The color indices for the three distinct components are reported in Table 1: *b* has an unusually blue color index while *a* and *c* have similar colors. The strong similarity of *a* and *c* and the projection of a distant Abell Cluster A949 with an estimated redshift $z = 0.142$ along the line of sight lead us to suggest that they may be two images of a compact source (less than 8.5 kpc from the seeing disk) gravitationally lensed by *b*. If the central component *b* ($R = 23.73 \pm 0.15$) is assumed to be a galaxy at that redshift then it may gravitationally multiply a background compact source provided that its mass is higher than $M = 2 \times 10^{10}$ $M_\odot$, leading to a M/L ratio of $100h_{50}$ (condition for multiple imaging from Subramanian and Cowlings 1986), the role of the cluster of galaxy being to increase the splitting of the gravitational images (Young *et al.* 1980; Hammer *et al.* 1988). The high M/L ratio needed is comparable or lower to what is required for the gravitational lenses 2345+007 and 1635+267 for which dark halos have been considered for the lensing galaxies (Subramanian, Rees, and Chitre 1987; Tyson *et al.* 1986). Moreover, the very blue color index and the 3 × 6 kpc size of the galaxy are compatible with dwarf blue compact galaxies (Thuan 1985) which may have high M/L ratios (Sargent and Lo 1985). 3C 238 seems therefore to be a strong candidate for a gravitational lens. However, this interpretation should be investigated further with deep spectroscopy to obtain the individual redshifts of the three observed components.

TABLE 1

COLOR INDICES

Galaxy	Color index
3C 238 *a*	$V-R = 0.80 \pm 0.20$
3C 238 *b*	$V-R = 0.23 \pm 0.30$
3C 238 *c*	$V-R = 1.03 \pm 0.40$
3C 356 *a*	$B-R = 1.47 \pm 0.15$
3C 356 *b*	$B-R = 1.22 \pm 0.15$
3C 368 *a*	$B-R = 1.64 \pm 0.15$
3C 358 *b*	$B-R = 1.12 \pm 0.22$
3C 368 *c*	$B-R = 1.24 \pm 0.22$
3C 368 *d*	$B-R = 1.84 \pm 0.35$

—3C 241, $z = 1.617$.—We observed this galaxy under excellent seeing conditions at ~0".6 FWHM. Nevertheless, its optical structure is not yet resolved into individual components, but the shape is obviously elongated with an axis ratio of ~0.7 (Fig. 2). A double compact radio source has been detected at VLA (Pearson, Perley, and Readhead 1985); moreover, with VLBI techniques Fanti *et al.* (1985) have been able to resolve the western component into two parts connected by a bridge of emission. When comparing the radio and optical data we find that the separation of the two radio emitting regions and the position angles are in excellent agreement with the detected optical size and the position angle of the galaxy (i.e., 82°, 0".9 peak to peak in radio, vs. 79° ± 10°, 2" total extension in the optical). This agreement may be interpreted under our gravitational amplification framework. If we assume that a foreground object is superposed over a single compact steep spectrum radio-galaxy (0".1, i.e., less than 1.2 kpc, unresolved even with VLBI), then the radio map should only show the three gravitational images predicted in a simple model of gravitational lensing by a spherically symmetric galaxy (Young *et al.* 1980), which is seen in the VLBI radio map. Moreover, the optical imagery should show the blend of the gravitational images of the single source with the deflecting galaxy, i.e., more than three objects in 1", and the system should be hard to resolve even with our image quality. However, this interpretation remains speculative before new data are obtained and other interpretations like outflow of matter along the radio axis (McCarthy *et al.* 1987*a*) which leads also to the observed radio/optical correlation may also be consistent with the data.

—3C 305.1, $z = 1.132$.—Despite being observed with the worst seeing in our sample (1".3 FWHM) the galaxy is resolved into two components, *a* and *b* (Fig. 3). Its size of 75 × 60 kpc places it among the biggest 3CR galaxies. Again compared to the VLA radio map (Pearson *et al.* 1985) there is an excellent agreement between the components in radio and optical

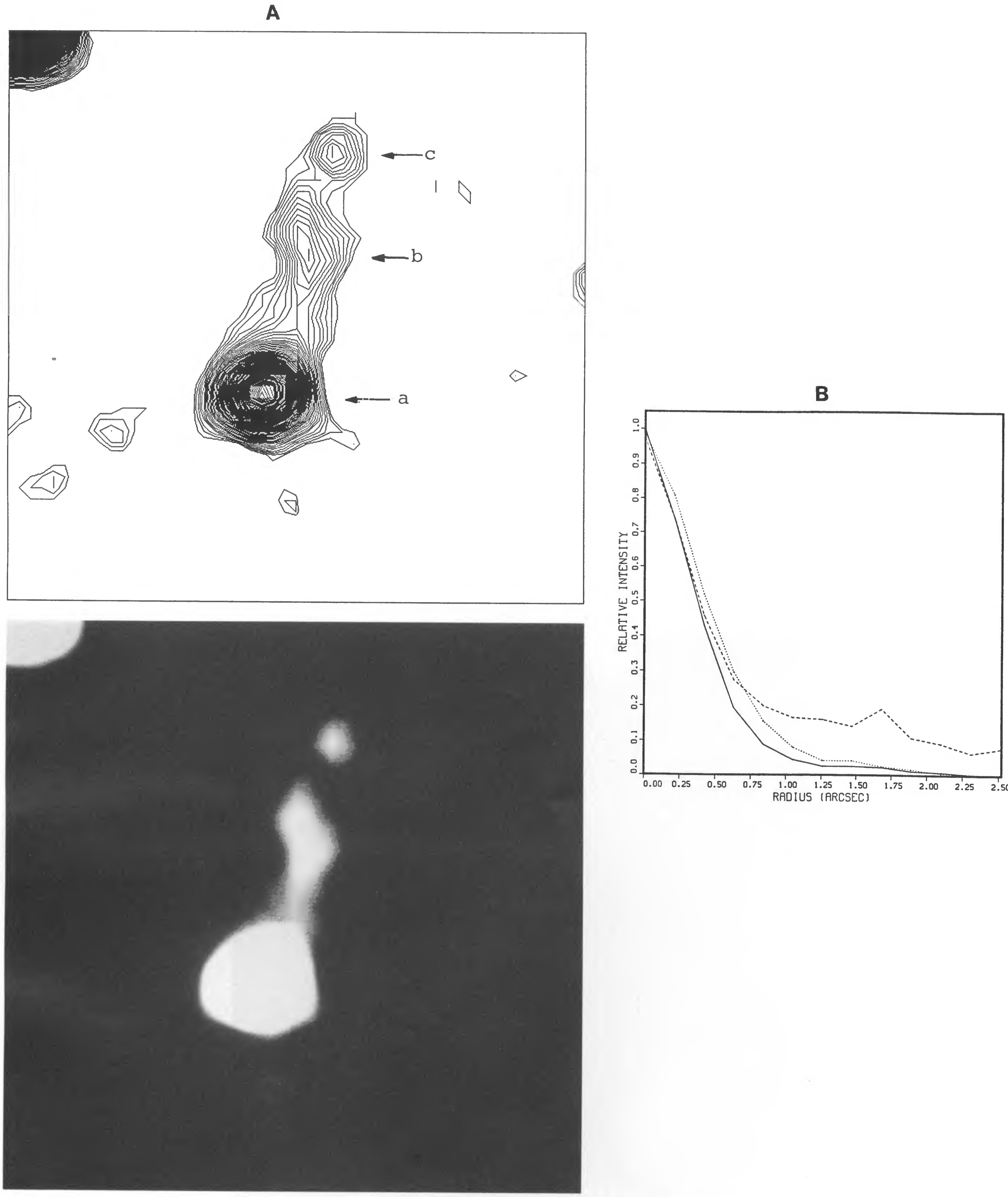

FIG. 1.—(*a*) 3C 238 ($z = 1.405$), 2400 s exposure in *R*, seeing 0″.7, 10.5×10.5 arcsec^2; north is up. The lowest isophote is 0.6% of the sky brightness and the spacing is 0.2% of the sky brightness between the contours. The galaxy is resolved into three components *a*, *b*, *c*, *a* and *c* have similar stellar luminosity profiles and color indices, while *b* is extended and much bluer. (*b*) Luminosity profiles in *R* for component *a* (*dashed line*), *c* (*dotted line*), and a star in the field (*solid line*). The difference in profile above 1″.3 for *c* is due to high contamination by the close *b* component.

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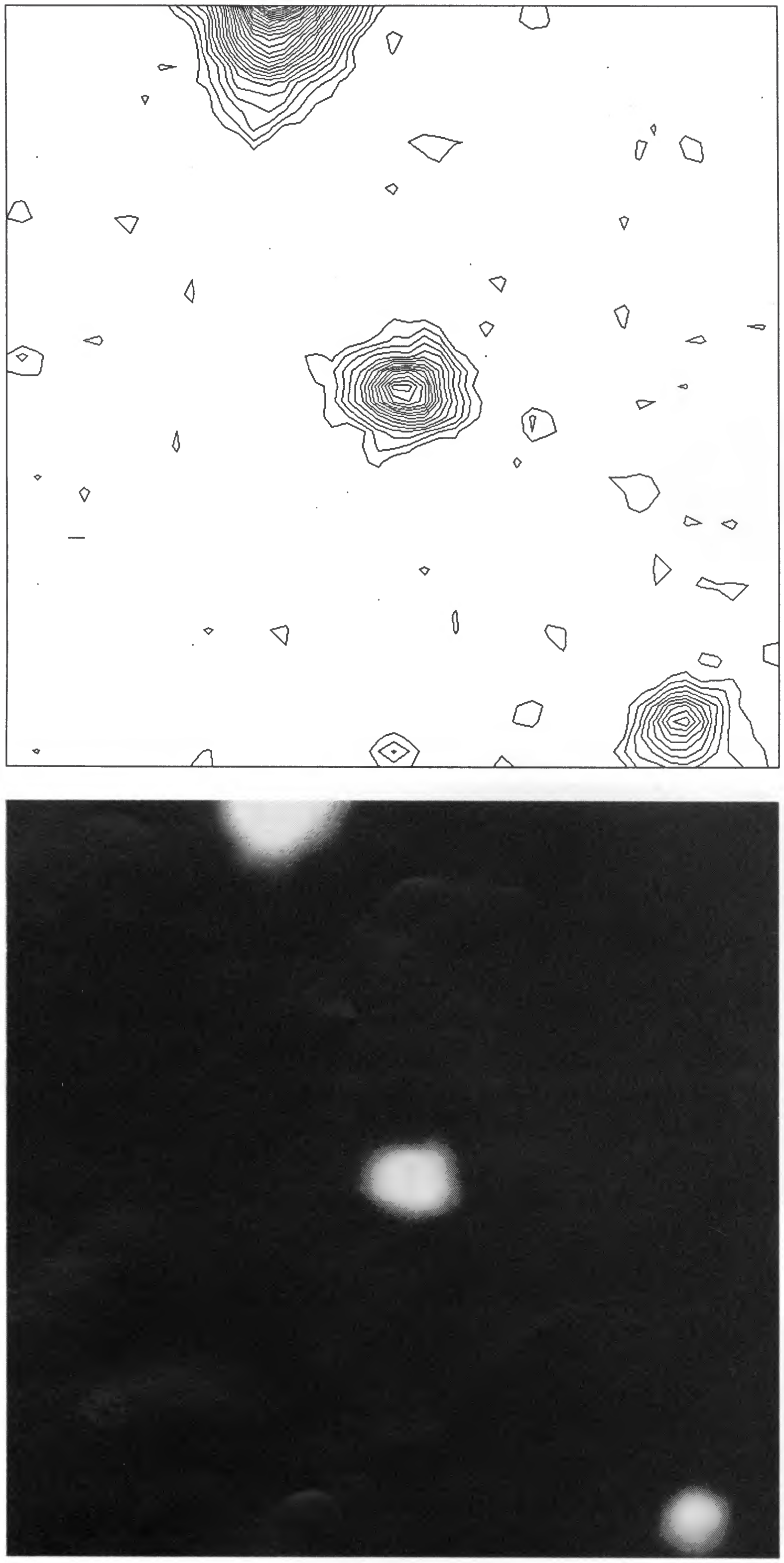

FIG. 2.—3C 241 ($z = 1.617$), 1800 s exposure in *R*, seeing 0".6, 10.5 × 10.5 arcsec^2; north is up. The lowest isophote is 0.6% of the sky brightness, with 0.4% spacing between the contours. The galaxy has an elongated shape with a 0.7 axis ratio. The position angle and the total extension are in good agreement with the radio data of Pearson *et al.* (1985).

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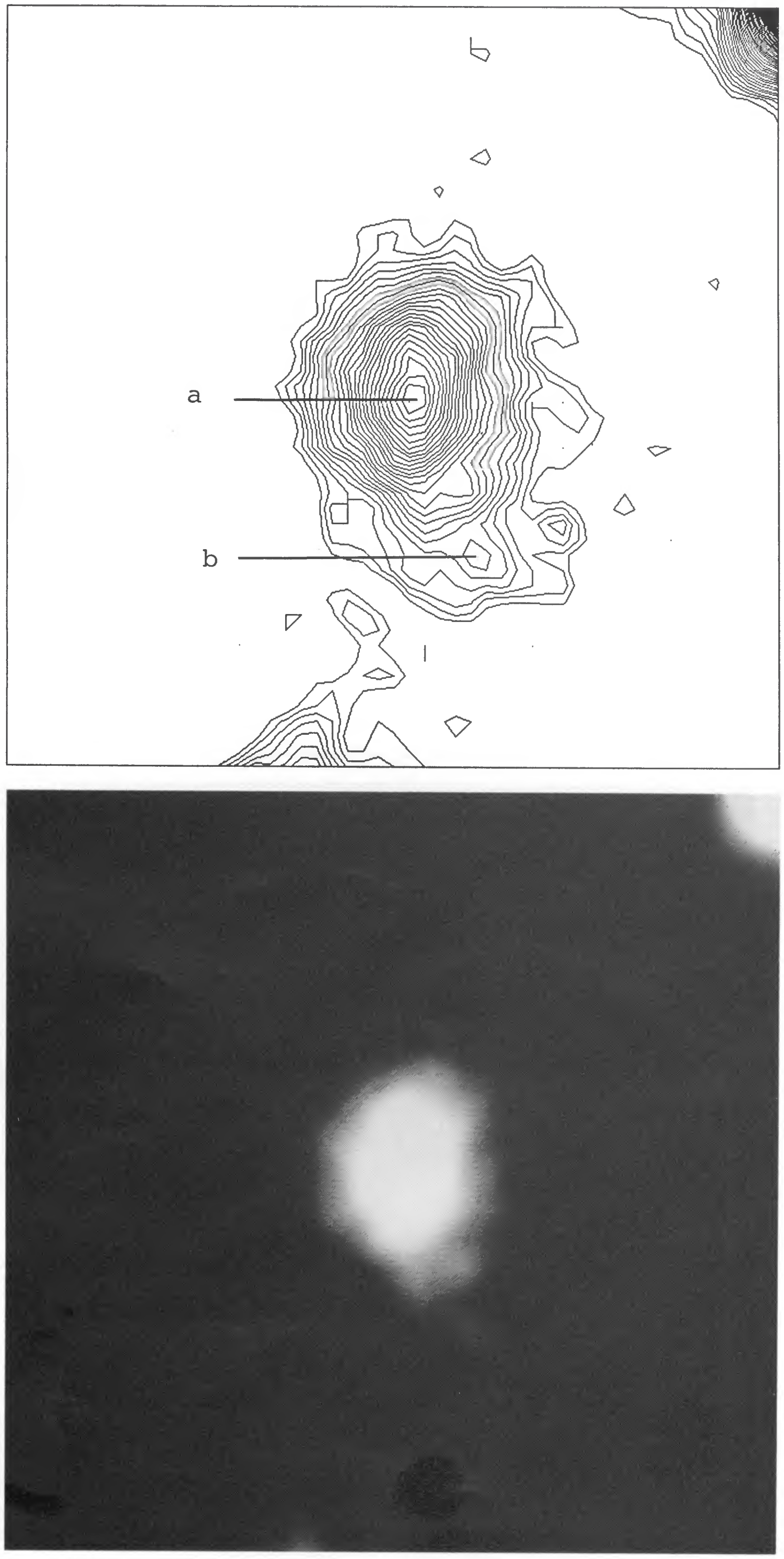

FIG. 3.—3C 305.1 ($z = 1.132$), 1700 s exposure in R, seeing 1"3, 10.5 × 10.5 arcsec^2; north is up. The lowest isophote is 1.6% of the sky brightness, with 0.6% spacing between the contours. Two components a and b are resolved. The position angle and peak to peak separation are in excellent agreement with the radio data of Pearson *et al.* (1985).

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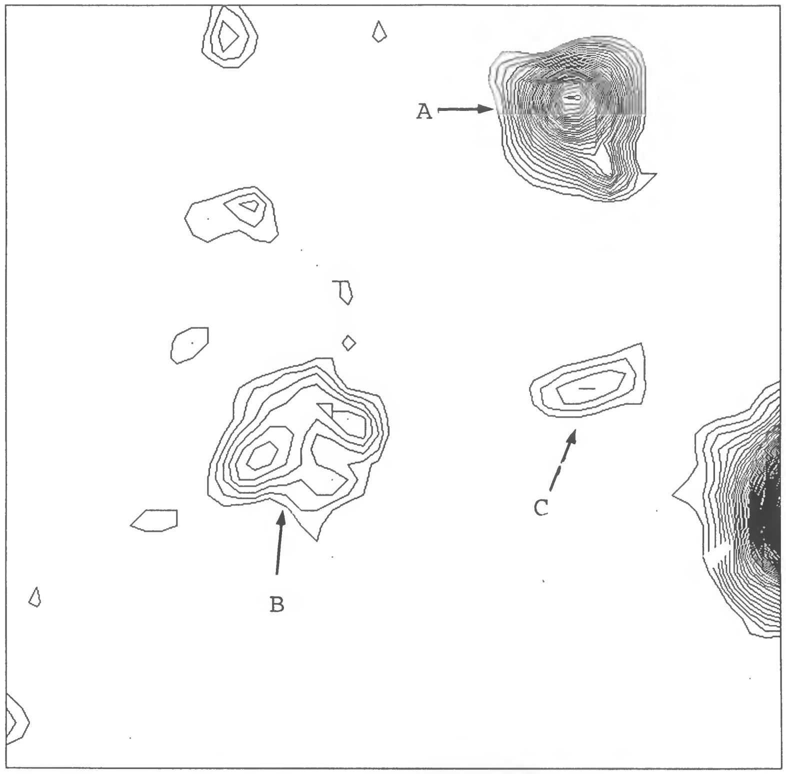
PLATE L4



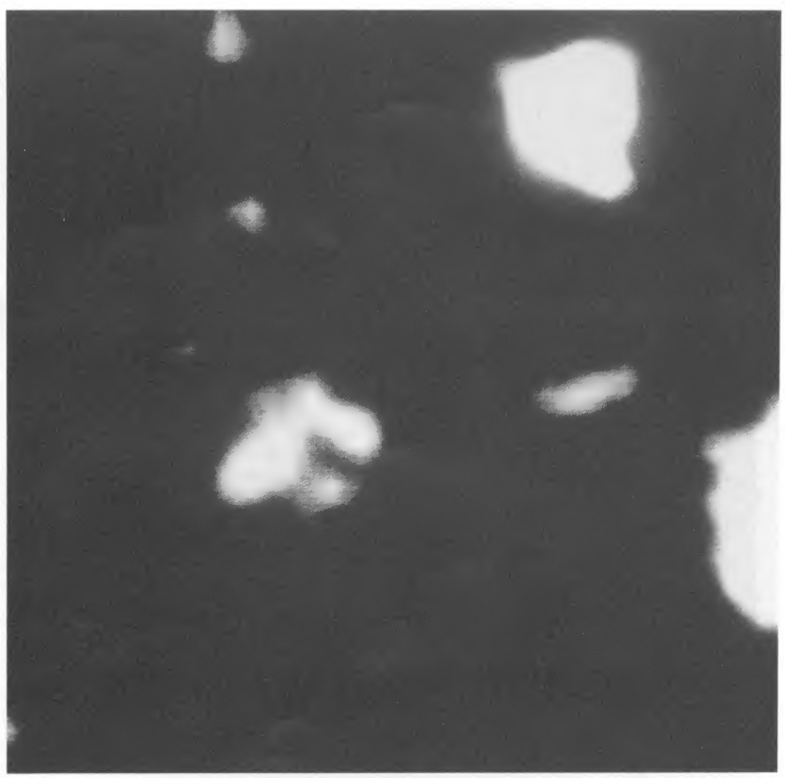


FIG. 4.—3C 326.1 ($z = 1.825$), 3600 s exposure in R, seeing 0"7, 10.5 × 10.5 arcsec^2; north is up. The lowest isophote is 0.9% of the sky brightness, with 0.2% spacing between the contours. The multiplicity of B and the detection of C show the complexity of the continuum emission as opposed to the smooth Lyα emission detected by McCarthy *et al.* (1987*b*).

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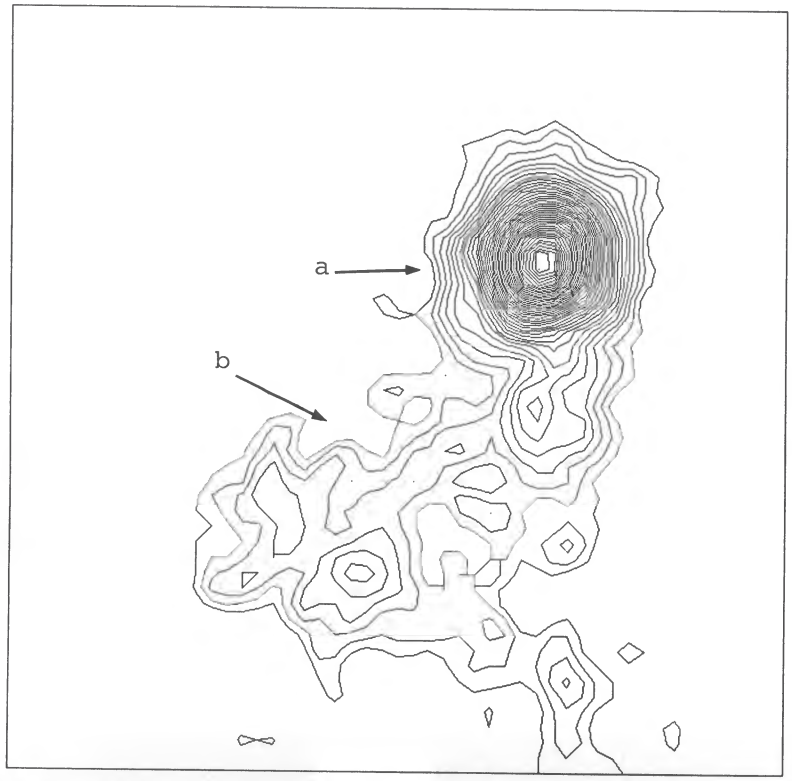

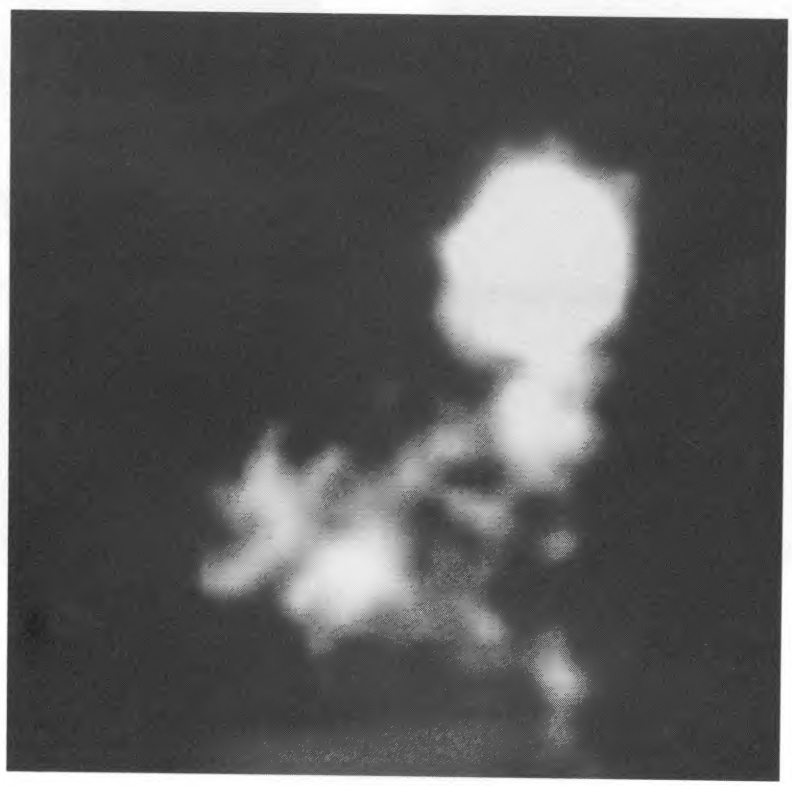

FIG. 5.—3C 356 ($z = 1.079$), 3000 s exposure in R, seeing 0$''$85, 10.5 × 10.5 arcsec^2; north is up. The lowest isophote is 1.7% of the sky brightness, with 0.4% spacing between the contours. The stellar object a is clearly at the edge of the extended faint region b.

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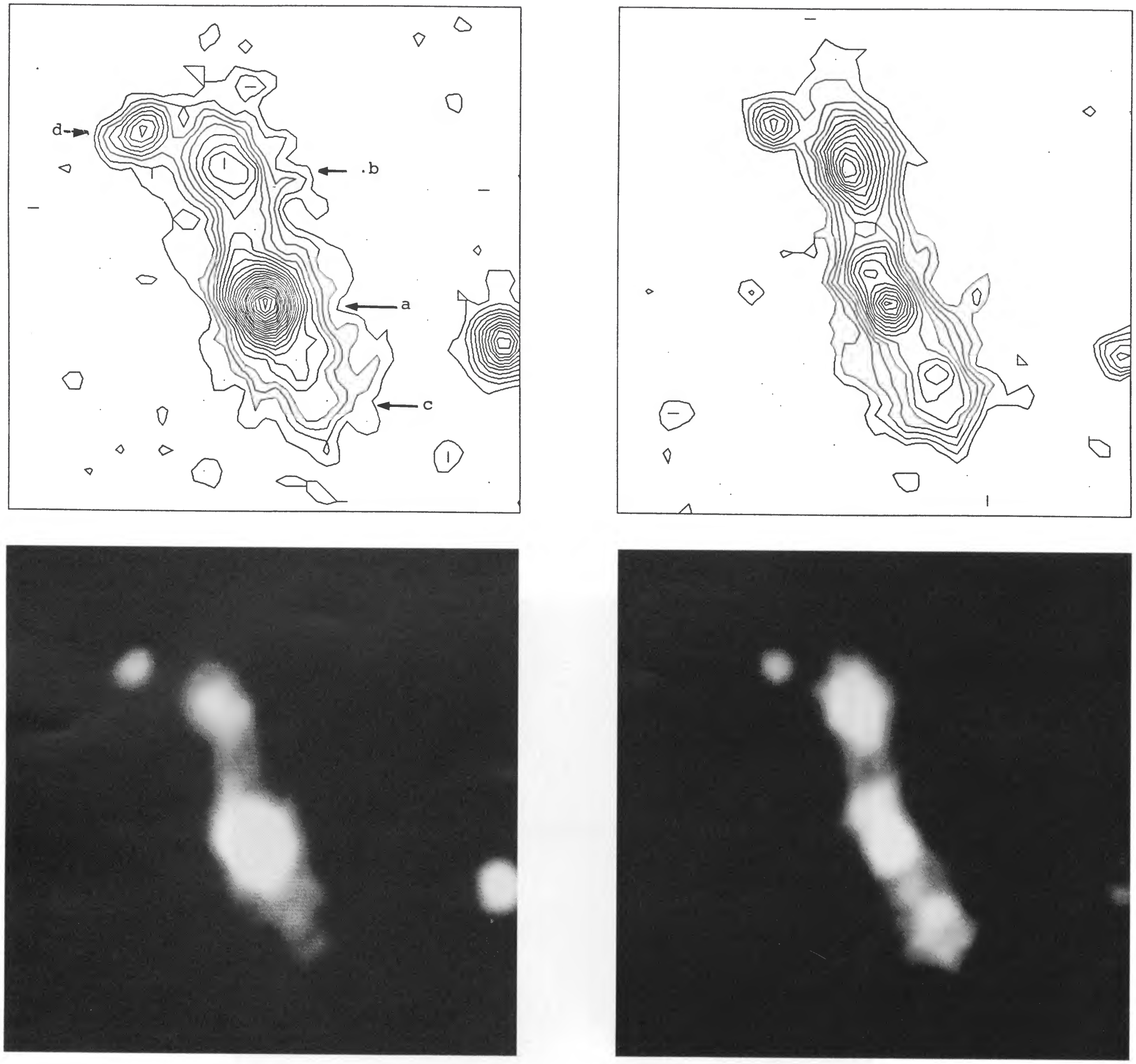

A B

FIG. 6.—(*a*) 3C 368 ($z = 1.132$), 1200 s exposure in *R*, seeing 0″.8, 10.5 × 10.5 arcsec^2; north is up. The lowest isophote is 1.4% of the sky brightness, with 0.9% spacing between the contours. (*b*) 3C 368, 2400 s exposure in *B*, seeing 0″.75. The different color behavior for *a*, *d* as opposed to *b*, *c* is obvious when compared to the *R* frame.

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(separation 2″.2 radio vs. 2.2 optical, peak to peak, P.A. 12° radio vs. 15° ± 5° optical) but the ratios of optical to radio emission are very different for each component. A gravitational lensing interpretation might also be in order since it is consistent with all the available data. The cluster of galaxies Zw 354 − 2, classified as medium distant, is close to the line of sight of 3C 305.1 and could gravitationally magnify radio and optical fluxes (Hammer and Nottale 1986). Moreover, to account for the optical/radio agreement, we propose the following hypothesis: if the line of sight of a compact steep spectrum radio source with associated optical emission lies within $\sim 2''$ from a foreground cluster galaxy with a mass $\approx 5 \times 10^{11}$ $M_{\odot}$ it should be gravitationally split into two (or more) components separated by $\sim 2''$. Note that both radio components have identical spectral indices between 5 and 15 GHz (Pearson *et al.* 1985), whereas the optical/radio flux ratio of the two observed images are very different which is consistent with our interpretation since the optical deflecting galaxy should contaminate the configuration. The available data are presently in accordance with a gravitational lensing interpretation but high spatial resolution narrow band imaging and spectroscopy for each components are needed to confirm or reject this interpretation, and other interpretations must be considered as well.

−*3C 326.1*, $z = 1.825$.—With the highest redshift among the 3CR sample, this galaxy has recently drawn attention with the discovery by McCarthy *et al.* (1987*b*) of a 10″ extended Lyα emission region around the radio position, although not centered on it, and has been interpreted as a protogalaxy. At the central position of the Lyα emission given by McCarthy *et al.* we can identify in our deep *R* frame a cigar-like very faint ($R = 24.53 \pm 0.20$) object labeled as C, while the object denoted B at the east end of the emitting region is resolved into several components under our excellent 0″.7 seeing (Fig. 4). Despite the excellent quality of our frame, we do not detect any other emission in *R* between B and C, nor do we detect an emission NW of C as suggested by McCarthy *et al.* down to an isophotal level $\mu_R \approx 28$ mag arcsec^{-2}. If real, the knots detected by McCarthy *et al.* in a composite *B*, *V*, *R* image must be very blue to be consistent with our image. Therefore the existence of continuum emission other than A, B, and C must be addressed by further observations to understand where the ionizing photons come from and in measuring an overall continuum magnitude. Due to the difficulty for the moment of defining clearly where the continuum magnitude is to be measured this galaxy should not be used in a magnitude-*z* diagram to test for galaxy evolution.

−*3C 356*, $z = 1.079$.—This is a very puzzling object. It is 3 mag brighter than a redshifted brightest cluster galaxy. From its morphology and with a 0″.8 seeing it appears as a star-like image *a* (at the 99% confidence level as compared to stars in the same frame with a χ^2 test) associated with a faint extended region *b* (Fig. 5). The stellar image is not in the central part of this region but clearly at an edge with the extended nebulae starting south of it, the overall optical emission covering ~ 85 kpc. The extended region has the same total luminosity as the compact object ($R = 21.31 \pm 0.10$ vs. $R = 21.26 \pm 0.10$) which is quite atypical, while its $B-R$ color index is bluer by 0.25 mag (Table 1). The spectroscopy of this galaxy made by Spinrad (1982) and the presence of a compact object may suggest its classification as a Seyfert galaxy since it is quite highly ionized (flux ratio [Ne v]/[O II] ≈ 0.32) with an [O II] rest frame width of ~ 240 km s^{-1} (see Veron 1981; Koski 1979). However, the 3C 356 radio power at 178 MHz is roughly the same as for 3C 405 (Cygnus A) which is considerably higher than for Seyfert galaxies (Lawrence 1987) and leads to consider 3C 356 as a very compact narrow-line radio galaxy. Note that the surface brightness of the extended emission, $\mu_R = 24$–25 mag arcsec^{-2}, is brighter than any other optical emitting structure with the same size as seen in powerful nearby radio galaxies (Heckman *et al.* 1986) when the $(1 + z)^4$ brightness dimming due to redshift is taken into account. The compactness of the brightest component (intrinsic size less than 4 kpc) together with the bright extended emission may therefore indicate a problem of classification for this source and that 3C 356 should not be included in a sample of 3CR galaxies and BCGs to test for galaxy evolution at high redshift.

−*3C 368*, $z = 1.132$.—The structure is very complex and spectacular differences are seen from *B* to *R* bands. The components have a differential color behavior, and the central nucleus *a* is split into two components in *B*. In Table 1, we report the measurements of $B-R$ color indices for the four distinct components appearing in the galaxy in *R* with the 0″.75 seeing (see also Figs. 6*a* and 6*b*). We found very different color indices: red for the *a* and *d* components and blue with a 0.4–0.6 mag difference for *b* and *c*. This galaxy has been interpreted as a merger of galaxies by Djorgovski *et al.* (1987); taking into account the excellent radio/optical alignment, outflow of matter along the radio axis (McCarthy *et al.* 1987*a*), or gravitational lensing should also be considered.

III. CONCLUSIONS

Deep, high spatial resolution imaging of several sources from the high-redshift 3CR galaxy sample has been presented here and very complex and unexpected morphologies have been found. Combined with previously obtained data (Le Fèvre *et al.* 1987, 1988), all the galaxies observed so far are resolved and most of them show multimodal structures. When color index information was available, we measured significant color differences for the components of each galaxy.

An interpretation in terms of gravitational amplification/lensing by foreground galaxies or clusters of galaxies is proposed for 3C 238, 3C 241, and 3C 305.1, 3C 238 being the strongest candidate. Before more data is available, other interpretations which also take into account the radio/optical correlations like the merging/outflow picture proposed by McCarthy *et al.* (1987*a*) have also be be considered for 3C 241 and 3C 305.1.

The complexity of the 3CR galaxies like 3C 356, which includes a compact object, and 3C 326.1, shows that they are not normal ellipticals and their use as standard candles to test for galaxy evolution is therefore questionable (see also Chambers *et al.* 1987).

Therefore, if these galaxies have to be used to derive galaxy evolution from a redshift (or color)—magnitude diagram one needs to: (1) exclude from the sample all sources for which classification as a galaxy is in doubt, (2) define without ambiguity which nearby galaxies are the descendants of the distant 3CR galaxies, (3) understand the part played by gravitational amplification and how it might change the apparent properties of the sources, (4) define how and where to measure the magnitudes and color indices of a multicomponent high *z* 3CR galaxy, which would have been considered as several galaxies if seen at low redshift.

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