NICMOS observations of high redshift radio galaxies: witnessing the formation of bright elliptical galaxies?

L. Pentericci[1,3], P.J.McCarthy[2], H.J.A. Röttgering[3], G.K.Miley[3], W.J.M.van Breugel[4] and R. Fosbury[5]

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[1]Max Planck Institute für Astronomie, Konigstuhl 17, D-69117 Heidelberg, Germany

[2]The Observatories of the Carnegie Institution of Washington,813 Santa Barbara Street, Pasadena, CA 91101 USA

[3]Leiden Observatory, P.O. Box 9513, 2300 RA Leiden, The Netherlands

[4]Institute of Geophysics and Planetary Physics, Lawrence Livermore National laboratory,PO Box 808, Livermore, CA 94459 USA

[5]Space Telescope European Coordinating Facility, Karl-Schwarschild-Strasse 2, 85748 Garching, Germany

ABSTRACT

We present the results of a near infrared imaging program of a sample of 19 radio galaxies with redshift between 1.7 and 3.2, using the NICMOS Camera 2 on the Hubble Space Telescope. The galaxies were observed in H band, which for 18 of the 19 targets samples the rest-frame optical emission longwards of the 4000 Å break. For many sources this band contains bright emission lines, but we estimated that this causes relatively little confusion in most cases.
The high angular resolution of the HST allows a detailed study of the host galaxies: the images show a wide range of morphologies, including (i) compact systems, (ii) systems with substructures such as multiple emission peaks and (iii) systems comprised of several components spread over areas of up to 100 kpc. Three galaxies appear unresolved and in two others a nuclear point source dominates the emission in the central region.
While the morphologies of most of the highest redshift galaxies ($z \geq 2.3$) are irregular, those of some of the lowest redshift targets are well represented by de Vaucouleurs profiles, consistent with them being well formed elliptical galaxies.
The near infrared continuum light is generally well aligned with the radio axis and the aligned light is very red with typical V-H colors of ~ 3.5–4. For several galaxies where WFPC2 V or R band images were available we computed a high resolution map of the optical-to-infrared spectral color: all multi-component systems present net color differences between the various clumps, and we argue that most probably the continuum emission has a stellar origin. The ages of these stellar populations as determined by the amplitude of the 4000 Å break vary between 0.5 and 1.3 Gyrs.
Finally in many of the small NICMOS frames we observe nearby faint objects close to the high redshift radio galaxies. The number density of these faint

object s is significantly larger than that observed in the deep NICMOS parallel observations of random fields: furthermore these objects tend to be aligned with the direction of the main axis of the radio sources suggesting that they may be related to the presence of the AGN, and that they might be companion galaxies at the same redshift.

1. Introduction

The study of the early Universe has received a considerable boost in the past few years, due to the development of new techniques for finding large numbers of galaxies at high redshift (e.g. U and B band dropouts, Steidel et al. 1996). Although radio galaxies are no longer the only class of well studied high redshift galaxies, they remain of exceptional cosmological interest, since they are likely to be amongst the most massive galaxies known in the early Universe and may be the progenitors of brightest cluster galaxies observed at low redshift.

Their large masses can be inferred from their K–band luminosities and the near-IR K-z Hubble diagram (e.g. van Breugel et al. 1998). Furthermore there is evidence that they are undergoing vigorous star formation: at least in some high redshift radio galaxies (HzRGs) the UV continuum is dominated by young stars, with estimated star-formation (SF) rates of up to 1000 $M_\odot$ yr^{-1} (Dey et al. 1997). Sub-millimeter continuum dust emission has been detected in several of the highest redshift galaxies (e.g. Papadopoulos et al. 1999), also implying similar large SF rates. These stars are expected to settle on dynamical time-scales and evolve into fully developed elliptical galaxies.

Evidence that HzRGs might be located in proto- cluster environments includes: (i) the detection of luminous X-ray emission from the radio galaxy MRC 1138−262 at z= 2.156, which is probably extended and has been attributed to a hot cluster atmosphere (Carilli et al. 1998); (ii) large Faraday rotation of the polarized radio emission indicating that some HzRGs are surrounded by dense hot magnetized cluster gas (Carilli et al. 1997); (iii) excess of companion galaxies detected along the axes or in the vicinity of the radio sources (Röttgering et al. 1996); (iv) possible excess of Lyman break selected galaxies in the fields of several powerful radio sources (e.g. Lacy & Rawlings 1996) and in particular several candidate companion galaxies (with two objects spectroscopically confirmed) in the vicinity of MRC 0316−257, at z= 3.14 (Le Fevre et al. 1996; McCarthy et al. 1992), and a number

of faint red companions of 4C 41.17 at z= 3.8 detected from deep Keck imaging at 2 μm (Graham et al. 1994).
Having both large stellar masses (e.g. 4C41.17 having M$\sim 10^{11} M_{\odot}$; van Breugel et al. 1998) and high star formation rates (see above), and being located in the densest regions of the early Universe, it is natural to propose that HzRGs will evolve into present-day brightest clusters galaxies (e.g. Best et al. 1997).

In previous papers we have described our studies of HzRGs with the Hubble Space Telescope at optical (UV rest-frame) wavelengths (Pentericci et al. 1998 and 1999). We found that several HzRGs, such as MRC 1138−262 at z= 2.2 and 4C41.17 at z= 3.8 (Dey et al. 1997) are comprised of numerous continuum clumps embedded in giant ($\sim$ 100 kpc) diffuse Lyα halos. Such morphologies are strikingly similar to simulations of forming bright cluster galaxies, made on the basis of the hierarchical models, which predict that the most massive systems are assembled from smaller building blocks (e.g. Baron and White 1987; Dubinski 1998). Indeed the sizes, profiles and luminosities of the *individual* clumps are similar to those of the Lyman break galaxies (LBG) (e.g. Steidel et al. 1996, Giavalisco et al. 1996), indicating that HzRGs could be formed by an assembly of LBGs (Pentericci et al. 1998).
The well known alignment observed between the rest-frame UV morphology and the radio axis (Chambers et al. 1987, McCarthy et al. 1987) implies that the UV emission is strongly effected by the active galactic nucleus, e.g. by scattered light from a QSO or a young population of stars whose formation was triggered by the radio jet. Studies of the near-infrared morphology (rest-frame optical) are particularly important to reveal the nature of the older stellar population (e.g. Lilly 1988), although observations of the continuum emission are made difficult by the presence of strong emission lines in the near-IR bands (Eales and Rawlings 1993).

There have been extensive ground–based near-IR studies of powerful radio galaxies at intermediate and high redshift (e.g McCarthy et al. 1992; Eales et al. 1997; Best et al. 1997; van Breugel et al. 1998). The most important results of these searches are: (i) the morphologies of z$\sim$1 galaxies in the near-IR emission are considerably more relaxed and symmetric than in the optical emission; surface photometry of 3CR z$\sim$1 galaxies has shown that they follow a de Vaucouleurs law (Best et al. 1997), implying that they are dynamically evolved systems (e.g. Rigler and Lilly 1994) with inferred stellar masses of up to $10^{12} M_{\odot}$; (ii) 3CR radio galaxies show a possible excess of emission at large radii, resembling the halo that surrounds nearby cD galaxies (Best et al. 1997); (iii) models of spectral energy distributions of radio galaxies having redshifts between 1 and 3 have been used to infer the ages of their stellar populations, suggesting ages in excess of 1 Gyr and formation redshift of z$\sim$5 or higher (e.g. McCarthy 1993b, Lilly 1988); (iv) deep near infrared (K-band) imaging reveal clustering of red galaxies around some z$\sim$ 1 3CR galaxies (e.g. Roche et al. 1998a and 1998b); (v) van Breugel et al. (1998) found strong evolution of the morphology of HzRGs at rest frame visual ($>$ 4000 Å) wavelengths, from aligned galaxies at redshift $>$ 3 to more symmetrical and compact galaxies at z$<$ 3.

With NICMOS it is now possible to study the near infrared morphology of HzRGs to a resolution comparable to that of our optical WFPC2 images, allowing us to investigate the morphologies of their evolved stellar populations at redshift larger than 2. We can then address questions such as whether there are already well formed ellipticals at those epochs; the importance and the frequencies of merging with sub-galactic clumps at different epochs; how the presence of substructures evolves with redshift; the relationship between the radio source and the near infrared emission in the central regions of the galaxies. In particular, one can examine to what extent the optical/UV alignment effect is also present at near infrared wavelengths.

In this paper we present NICMOS observations of a sample of 19 radio galaxies with 1.8 $\leq z \leq 3.2$. In Section 2 we describe the sample selection and the observations. Section 3 is devoted to the presentation of the results, and a description of the morphologies of the individual objects. In Section 4 we analyze the morphologies of the galaxies, their redshift evolution and their optical-to-infrared colors. Finally, in Section 5, we discuss the implication of our NICMOS results for the study of the alignment effect and we investigate the statistics of (aligned) companion galaxies around the targets.

2. Observations

2.1. Sample selection

Two sub-samples of objects were observed. The first sub-sample consists of 14 radio galaxies from the Molonglo Reference Catalog (MRC) (McCarthy et al. 1996). The MRC/1Jy sample was defined simply using a flux density limit at 408 MHz of $S_{408} \geq 0.95$ Jy, within a restricted region of the sky ($-30 <$ DEC< -20, $|b| > 15$); 99.5% of the sources in the catalog have been optically identified, and 46 of the 426 radio galaxies in the sample have spectroscopically confirmed redshift $1.6 < z < 3.2$ (see McCarthy et al. 1990 and McCarthy et al. 1991 for the optical identification and spectroscopy of the higher redshift galaxies). The MRC/1Jy survey is one of the largest complete radio sample for which there is a homogeneous and nearly complete set of optical and infrared photometry (see the mentioned papers and McCarthy et al. 1992 for infrared observations).

We then added 5 targets selected from a sample of ultra steep spectrum radio galaxies (USS). This sample comprises the largest set of radio galaxies having redshift larger than 2, which were selected on the basis of the radio spectral indices ($\alpha \leq -1.1$ where $S_\nu = S_0 \nu^\alpha$). This selection technique has proven to be the most effective tool for identifying such radio galaxies. Several samples of USS sources (e.g. Chambers et al. 1996, Röttgering et al.

1994) have led to the discovery of more than 80 radio galaxies with z> 2, about 60% of the 136 such sources known to date (e.g. van Breugel et al. 1999). All the highest redshift radio galaxies (z> 3.5) have been found using this technique (e.g. van Breugel et al. 1999). The USS sample covers a larger area in the sky than the MRC sample, and allows us to probe a wider range of radio sources parameters such as their luminosity and size. Furthermore selecting sources from the USS sample will give a larger overlap with the existing data base of WFPC2 images (Pentericci et al. 1999).

The final sample consists of 19 radio galaxies, uniformly spanning a redshift range between z= 1.68 and z= 3.13, and having a large range of properties, e.g. a range of nearly 3 magnitudes in the infrared luminosity and a factor of 8 in radio power. The radio galaxies are listed in Table 1: for each object we report the redshift, the position of the radio core, the total flux at 4.7 GHz, the spectral index between 4.7 and 8.2 GHz, $\alpha_{8.2}^{4.7}$, the total size in arcseconds and an indication of the radio morphology.

2.2. Observations and data reduction

2.2.1. HST/NICMOS

In Table 2 we list the radio galaxies observed and various observational parameters. All objects were observed with NICMOS Camera 2, which has a plate scale of 0.0762×0.0755 arcseconds per pixel and a total field of view of $19.2'' \times 19.2''$. The filter used was the F160W filter, which is centered at 1.6 μm has a bandwidth of 0.4μm and has the minimum background amongst the available NICMOS filters; we also used the F165M filter which is centered at 1.7μm and has a bandwidth of 0.2μm. We had initially selected this second filter for many of the objects, because it would have provided a bandpass free from line emission for most of the galaxies in the sample, in particular those in the lowest and in the highest redshift ranges (z< 2.09 and z >2.6). Unfortunately using this filter the response was limited by readout-noise and dark current and we had to change our initial observing strategy to use the F160W filter. The wider filter bandwidth included bright emission lines for many of the sources (see Table 2), but we estimate that in most cases this causes relatively little confusion in determining their real continuum morphologies (however see next section). The high sensitivity of this filter allowed the galaxies to be mapped within the allocated 2 to 5 orbits per object.

Each orbit included two 1026 seconds exposures using the MIF1024 Multiaccum exposure sequence and one shorter exposure using the STEP64 sampling sequence. The exposure times for the STEP64 samples were 384, 411, 512 or 576 seconds depending on the orbit. The total integration time for each galaxy is given in Table 2. To facilitate removal of residual flat field and imperfection of the detector, the targets were offset by $\sim 3''$ between each exposure, giving a grid of 15, 12, 9 or 6 exposures.

The NICMOS imaging data were processed in the following manner: the zero level determined from the first read of each exposure sequence was subtracted from all other exposures; then a scaled version of the best dark exposure provided by the HST archive was subtracted. The resulting sequences of "read" in each Multiaccum or STEP64 series were then used to produce a masked, linearized and, to first order, cosmic ray rejected image using an algorithm written by McLeod (1997). Then for the exposures which were obtained before August 1997 the pedestal level (i.e. significant fluctuations of the zero level between sequences) was subtracted separately from each quadrant of the HgCdTe detector and again the cosmic ray rejection algorithm was used. For the observations taken after August 1997 the last two steps could be skipped. Finally, the images were flat fielded using the best flat field provided from the HST archive. The images were then registered using fractional pixel shifts, and were combined using a mask for removal of bad pixels and hot pixels (this mask was constructed directly using the observation frames) and a multi pass $\pm 3\sigma$ cosmic ray rejection algorithm. In combining the images, we weighted them using their exposure times.

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2.2.2. Supporting ground-based observations

For 3 radio galaxies in the sample (MRC 0156−252, MRC 0406−244 and MRC 2104−242) we gathered extensive ground based optical and IR data during the last few years. In Table 3 we summarize the relevant observations. Some results on MRC 0406−244 were already published by Rush et al. 1997. All data were reduced using standard IRAF procedures.

For the spectroscopic observations at the ESO/NTT Telescope, the detector was a Tektronix CCD with 1024^2 pixels and a scale along the slit of $0.37''$ per pixels. The CCD was binned by a factor of two in the wavelength direction. Using a $2.5''$ wide slit with ESO grating #3 we achieved a spectral resolution of 2.8 Å (full width at half maximum, FWHM). The raw spectra were bias subtracted and flat fielded; then the sky contribution was removed by subtracting a sky-spectrum obtained by fitting a polynomial to the intensities measured along the spatial direction, not including the spatial rows/columns where the target was positioned; finally wavelength calibration was performed by measuring the position on the CCD of known lines from a He-Ar calibration lamp, fitting a polynomial function to these data and applying the resultant calibration factors. The resulting accuracy of the calibration is better than 0.3 Å.

The J and K images were obtained with the Las Campanas du Pont 2.5m telescope and its 256×256 HgCdTe array camera, which has a pixel scale of $0.35''$. The integration times ranged from 4000 to 9000 seconds and the objects were moved on the array every

150 seconds. The data were calibrated with standard stars from Elias et al. (1983). The reduction followed standard techniques. The r, I and Lyα images were also obtained at Las Campanas using a 800×800 Texas Instruments CCD detector: the exposures were binned 2×2 resulting in a pixel scale of 0.33 2″. The Lyα images were obtained with interference filters having 1% band-widths. Several 1800 second exposures of each field were obtained with approximately 10″ offsets between each image.

The various images were registered with the NICMOS frames using the position of several point sources in the field, with the AIPS (Astronomical Image Processing System) tasks XTRAN and HGEOM, assuming a linear transformation. The accuracy of the registration is about 0.2″.

All the radio galaxies with the exceptions listed below were imaged with the VLA in A array as part of a high resolution, multi-frequency radio polarimetric study carried out on a large sample of HzRGs; for further details about the observations see the paper by Carilli et al. (1997). For a subset of galaxies, new VLA observations were carried out: the radio galaxies MRC 0324−228 and MRC 0350−279 were observed in the B-array configuration at 4.85 GHz (C-band). The radio galaxies MRC 0152−209, MRC 1017−220, MRC 2048−272 and MRC 2224−273 were observed in the A-array configuration as part of a new high resolution multi-frequency radio survey. Details of these observations will be presented elsewhere (Pentericci et al. in preparation).

2.3. Emission-line contamination

As explained earlier we observed most of our targets with the F160W broad band filter. This resulted in the unavoidable inclusion of bright emission lines normally found in radio galaxies. For the lowest redshift object (MRC 2224−273 at z= 1.68), the strong emission line Hα falls in the observed wavelength range; for the objects in the redshift range 1.9< z <2.6 [OIII] and Hβ become important; finally for the higher redshift objects (z $\geq$ 2.9) the emission line [OII] is within the observed wavelength range. In Table 2 we have listed, for each object, the lines that can contribute substantially to the continuum band flux and the total estimated contribution to the continuum flux.

Since we do not have direct measurements for the line fluxes and their equivalent widths, we have estimated the total contaminating flux using other measured lines (in most cases Lyα and/or Hα). We have used the emission line ratio reported by McCarthy (1993) and Eales and Rawlings (1996) i.e. Lyα/[OII]= 5, [OIII]/[OII]= 3, Lyα/Hα = 1.6. Note however that these are only average ratios. For example, Eales and Rawlings (1993) find that the line emission ratios can vary significantly (within a factor of 10) from object to object, due to the different physical conditions of the gas and/or the presence of dust which can attenuate the Lyα line (e.g. in USS 0211−122, van Ojik et al.1994). Another important source of uncertainty is the difference in the apertures used to derive the continuum and line fluxes: the continuum flux was measured through a fixed 4$''$ diameter aperture, while the line fluxes (mostly taken from the literature) were measured within different apertures and with slits of different sizes: when the apertures used to determine the emission line flux were known (in about half of the cases) we corrected for this by simply scaling the line flux to an aperture of 4$''$. Therefore the values for the emission line contamination given in Table 2 are only indicative. Most important, the line contribution may vary spatially and some parts of the galaxies might be more effected than others, with a much higher line contribution than that listed in Table 2.

2.4. Astrometry

The coordinate frame for the NICMOS images determined from the image header information has uncertainties of the order of 0.6$''$ due to the uncertainty in the position of

the guide star (HST data handbook). Since the optical galaxies are generally clumpy on a scale of a few tenths of arcsecond, it is important to obtain the better relative registration between the radio and the optical images for a detailed inter-comparison.
Our radio maps have a typical resolution of $0.2''$ which is comparable to that of the NICMOS images. The exceptions are the radio maps of MRC 0324−228 and MRC 0350−279 which have a resolution of $1.2''$.
To align the NICMOS and the radio VLA images we overlayed the radio cores (for the identification of radio cores see Carilli et al. 1997) on the peak position of the near infrared emission, on the assumption that this IR peak coincides with the galaxy nucleus. In these cases the estimated uncertainty in the overlay is $\sim 0.1''$. In the cases of MRC 0324−218, MRC 0943−242, USS 1707+105 and MRC 2048−272 where no radio core was detected, we used the absolute HST and VLA astrometry to align the maps; in these cases the accuracy achieved is only $\sim 0.8''$.

3. Results

3.1. Summary

In Figures 1 to 19 we present the images of the radio galaxies observed. In most cases we show grey scale representations of the NICMOS emission with VLA contours superimposed (unless the radio emission is unresolved). We also show a contour map of the continuum emission to better delineate the morphology (for all sources except the three unresolved ones).
In Table 4 we list the total NICMOS H band magnitudes for each object, derived using a fixed $4''$ circular aperture. The errors in the magnitudes, reported in column 3, are dominated by the inaccuracy in the sky subtraction. The NICMOS H-band 3σ limiting surface brightnesses achieved ranges from $\mu_{H(3\sigma)} = 24.8$ to $\mu_{H(3\sigma)} = 25.1$ (see Table 2)

for the objects that were imaged with the F160W filter and only $\mu_{H(3\sigma)} = 23.7$ for those observed with the F165M filters and for shorter exposure times. In almost all cases the signal to noise ratio is good and allows us to study in detail the morphology of the galaxies. The exceptions are the very faint radio galaxy MRC 0324−228 at z= 1.89 and the highest redshift object in the sample, MRC 0316−257 at z= 3.13.

Our observations show that HzRGs have a wide variety of near-infrared morphologies. Of the 19 galaxies, 3 are unresolved (MRC 0350−279, MRC 1017−220, USS 2202+128); of these, the first 2 are also unresolved in the radio at all frequencies and one, MRC 1017−220, has been classified as a broad line radio galaxy (BLRG) by Kapahi et al. (1998) on the basis of its emission line spectrum. In two other cases, MRC 1138−262 and MRC 2025−218, a nuclear point source dominates the emission, but subtraction of the point spread function (PSF) reveals underlying extended emission. For all other systems no nuclear point source contributes substantially to the emission.

In Table 2 we have classified the NICMOS morphologies according to the following types: (i) compact or unresolved structures; (ii) systems showing substructures (e.g. two emission peaks within the main body of the galaxy) and (iii) systems comprised of several components spread over large areas (up to 100 kpc). A large fraction of the systems shows close (within $\sim 5''$) emission clumps, that might be part of the systems, but only in few cases, where additional information is available (e.g. narrow band imaging, spectroscopy, etc.) we can conclude that these small components are physically associated to the radio galaxies.

Comparison with the radio sources shows that typically the near infrared emission is well aligned with the radio axis. The alignment effect will be extensively discussed in Section 5. In the next subsection we will make some remarks on the individual objects.

3.2. Individual objects

MRC 0140-257 z= 2.64

The galaxy is shown in Fig. 1: it has 2 peaks of emission with almost the same flux. The orientation of the line joining these peaks is, within a few degrees, along the radio axis. It is possible that the observed morphology is due to an obscuring dust lane. There are a few fainter clumps within 2-3$''$ of the galaxy that could be physically associated with the system.

MRC 0152-209 z=1.89

The galaxy is shown in Fig. 2: it is elongated and it is surrounded by a halo of fainter emission. There is a narrow elongated tail that departs from the southern end of the galaxy. The radio source is unresolved.

MRC 0156-252 z=2.09

The host of this radio galaxy (Fig. 3) is extended. There are 2 small nearby clumps located exactly along the direction of the radio axis but further beyond the point where the radio jet bends. This object is discussed in more detail in Section 3.3

USS 0211-122 z= 2.34

The host galaxy (Fig. 4) of this very large (134 kpc) radio source consists of a nucleus plus faint diffuse emission, having the shape of an arc. The galaxy is misaligned with respect to the radio axis; the radio source shows a jet feature extending from the core towards south and its curvature suggests that the radio axis precesses.

MRC 0316-257 z=3.13

The galaxy is shown in Fig. 5. There are two objects separated by only $\sim 2''$. The identification is the fainter diffuse object to the west. The other object could well be at the same redshift. Given the high redshift of this radio galaxy, the NICMOS image samples rest-frame continuum emission that is mostly below the 4000 Å break, therefore we are not really imaging the older stellar population.

MRC 0324-228 z=1.89

The galaxy is shown in Fig. 6. There are two faint and diffuse objects separated by only $\sim 1.5''$ which could be identified as the host galaxy of the radio source. Ground based observations do not resolve the 2 components (McCarthy et al. 1996), which could be part of the same system; alternatively, one could be the radio galaxy and the other just a foreground object. The VLA snapshot radio image at 4.5 GHz with a resolution of $1.2''$, shows a simple double radio source with no core detected. The direction of the radio axis is at $25°$ with respect to the relative orientation of the two emission clumps.

MRC 0350-279 z= 1.90

The identification of this radio source is the unresolved object in Fig. 7. There are two faint objects at a distance of only $6''$ to the east: one of them is compact and the other one diffuse and elongated. The radio source is unresolved in our VLA B array snapshot observation, so we do not show it.

MRC 0406-244 z=2.44

This galaxy is shown in Fig. 8: it has a main body which shows two emission peaks, and a number of components distributed in a sort of envelope on both sides of the galaxy. The galaxy along the radio axis, which coincides remarkably well with a radio peak, is most probably at a different redshift. For further discussion of this object see Rush et al. 1997 and Section 3.3 below.

MRC 0943-242 z=2.93

This galaxy is shown in Fig. 9: it has a cigar shape and is elongated along the radio axis. The WFPC2 optical image is remarkably similar. The galaxy is extensively discussed in McCarthy et al. 2000 (in preparation).

MRC 1017-220 z= 1.77

The identification of this radio source is the unresolved object in Fig. 10. There are 2 faint diffuse clumps about $5''$ away. The radio source is also unresolved. Kaphai et al. (1998) have classified this radio galaxy as a BLRG on the basis of its emission line spectrum.

MRC 1138-262 z=2.16

The central object of this very large system in Fig. 11 has a large contribution from a point source (the active nucleus), but clearly there is extended emission below it. In addition about 9 other components are visible in a region of about $10'' \times 10''$ around the nucleus: all have WFPC2 optical counterparts, and are embedded in a giant Lyα halo. This galaxy is further discussed in Pentericci et al. 1997 and 1998.

USS 1410-001 z= 2.33

This is a very elongated object (Fig. 12), consisting of the galaxy core plus 2 other clear peaks and diffuse emission extending for more than $4''$ along the galaxy axis. The very red (V-H=5.6) and compact object only $2''$ from the core, might also be part of the system. The galaxy and the radio source are strongly misaligned: the angle between the optical and radio axis is nearly 45°. However, the northern component of the radio source is curved, suggesting the radio axis might be precessing, in which case the elongated near infrared emission could be extended along the previous position of the radio jet.

USS 1707+105 z= 2.35

This is a large multiple system (Fig. 13) consisting of 3 different galaxies (see Pentericci et al. 1999) separated by 3-4$''$, located along the radio axis. The radio core is not detected in the present radio image, however it seems most likely that the radio emission comes from the most luminous and larger galaxy, centrally located between the two radio lobes that is indicated with the letter A in Fig. 13. This galaxy is comprised of a main body plus a few smaller clumps and shows diffuse emission towards north, along the direction of the radio axis. Of the other two emission galaxies, galaxy C is very faint, while galaxy B is slightly more extended.

MRC 2025-218 z=2.63

The galaxy is shown in Fig. 14. The emission is dominated by a nuclear point source. Once this is subtracted there is a large diffuse galaxy roughly aligned with the radio axis. The radio source is small and the southern radio jet has a sharp bent

MRC 2048-272 z= 2.06

The galaxy is shown in Fig. 15. Two bright objects can be seen separated only by 2.5$''$ with a third faint object 2$''$ to the east. With the present astrometry the correct identification is probably the central object. The radio core is undetected in our VLA radio images.

MRC 2104-242 z= 2.49

This is one of the largest system in the sample, with the emission extending for more than 7$''$ (corresponding to $\geq$ 50 kpc) (Fig. 16). It consists of a main compact object that hosts the radio source, plus at least 3 other smaller clumps (there is some uncertainty due to the presence of a spike from a nearby extremely bright star that might contaminate and cover some other components). Finally there is an extremely narrow feature elongated along the radio axis, which has spectacular Lyα emission (Koekemoer et al. 1996). For further discussion see Section 3.3.

USS 2202+128 z=2.70

The object (Fig. 17) is not resolved on the present image. The radio source is small and s-shaped suggesting the radio axis might be precessing.

MRC 2224-273 z=1.68

This galaxy (Fig. 18) has a simple pear-shaped morphology. There is a small compact object only 2.6$''$ away, located along in the direction of the galaxy main axis. The radio source is unresolved at all frequencies in our VLA observations (Pentericci et al. in preparation).

USS 2349+280 z=2.89

The galaxy is shown in Fig. 19: it consists of 2 components embedded in a halo of diffuse emission. The sharpness of the separation between the two components suggest that is could be due to a dust lane (the NICMOS image samples the emission interval 3600-4630 Å, which can be still affected strongly by dust). The WFPC optical image is very similar (Chambers et al. 1996).

3.3. Detailed multi-wavelength comparisons

MRC 0156-252

In Fig. 20a-c we show the NICMOS image in grey scale overlayed with contours from (a) the I band emission, (b) the K band emission and (c) the Lyα narrow band emission. In

Fig. 20d we show in grey scale the radio jets at 8.2 GHz superimposed on Lyα narrow band contours. The I and K band contain nearly pure continuum emission, while the NICMOS H band contains a contribution from the [OIII] line (see Table 2).

The emission from the ionized gas is very extended ($\sim 9''$) and is not associated with the optical and near infrared emission; the Lyα does not follow the optical/near infrared components, but peaks at the location where the radio jet bends sharply. This case is very similar to that of MRC 1138$-$262 (Pentericci et al. 1997) and 1243+036 (van Ojik et al. 1996): the most likely interpretation is that a cloud of ionized gas is responsible for the deflection of the radio jet, and that the gas emission is strongly enhanced in this region due to shock ionization. Note also that the optical galaxy is located at a minimum of the Lyα emission, a common feature of many HzRGs (e.g. MRC 1138$-$262 and MRC 2104$-$242 below).

Another interesting feature of MRC 0156$-$252 is the presence of two smaller components aligned (within 5°) with the the radio axis but located *beyond* the radio hot-spots. They are of comparable brightness in the H band, but the eastern clump is much redder and is undetected in I, while the other clump (undetected in K) in I band has almost the same brightness as the main galaxy. This difference in colors may be due to a difference in age of the stellar population: McCarthy et al. 1992 argued on the basis of ground-based data that the central galaxy contains a very old stellar populations (~ 2.8 Gyrs) or alternatively a very reddened QSO spectrum. The bluer colors of the aligned component near the bent in the radio jet might be interpreted as enhanced star formation induced by the jet itself.

MRC 0406-244

This galaxy is extensively discussed in Rush et al. 1997. In Fig. 21a-c we show the NICMOS image in grey scale overlayed with contours from (a) the I band emission, (b) the K band emission and (c) the Lyα narrow band emission. In Fig. 21d we show in grey scale the radio jets at 8.2 GHz superimposed to Lyα narrow band contours. The K and H filters contain contributions from line emission: in particular the K-band contain the strong Hα+[N II] $\lambda\lambda$6548, 6584 system and the H band contains the [OIII] $\lambda\lambda$4959,5007 lines. The I band is purely continuum emission.

There is a spatial shift in the peak of the emission at different wavelengths: the peak of the I band coincides with that of H band while the K band peak probably lies in between the two NICMOS peaks, although due to the lower resolution ($0.9''$) and larger pixels size of this image, with the present overlay we cannot exclude that the K band peaks coincides with the brightest H band peak.

The net color gradient between the northern side and the southern was interpreted by Rush et al. (1997) with the fact that most of the emission in the southeast extension is the result of line contamination. The northwest components that appear in the I band are probably true continuum flux.

A high resolution spectrum of the Lyα line taken along the direction of the radio axis is presented in Fig. 22. The spectrum has a total spatial extent of $\sim 8''$, similar to the extent seen in the narrow band image. The emission comes from two components which are offset both in space ($\sim 2''$) and velocity ($\sim$1150 km sec^{-1}); with the help of the narrow band image we identify the brightest component with the main body of the galaxy, while the other component is the northwestern extension. They have both a FWHM of $\sim$ 850 km sec^{-1}. An interesting feature is the deep trough which maybe due to absorption by associated neutral hydrogen, a feature common to many HzRGs (van Ojik et al. 1997). The neutral gas is as spatially extended as the ionized gas and has a velocity gradient of $\sim$ 200 km sec^{-1}.

MRC 2104-242

In Fig. 23a-c we show the NICMOS image in grey scale overlayed with contours from (a) the R band emission, (b) the K band emission and (c) the Lyα narrow band emission. The bright unresolved emission in the Lyα image is probably a cosmic ray hit. Note also the residuals of a spike of a bright nearby star located to the north of the radio galaxy. We do not show an overlay of the Lyα gas with the radio emission since the radio hot-spots are located further beyond the region of the gas emission (see the radio maps in Pentericci et al. 1999). The radio axis is oriented at 12° (counterclockwise), implying that both the continuum and line emission are very well aligned with it. In Fig. 24 we present a high resolution spectrum of the Lyα line.

The galaxy is comprised of several components, each having very different colors: (i) the nucleus of the radio galaxy, (ii) a series of smaller bluer clumps northern of it; (iii) a narrow elongated feature to the south.

The nucleus is bright in K and H but already much fainter in R and in the WFPC2 V band image (Pentericci et al. 1999). As in MRC 0156$-$262, the nucleus coincides with a minimum of Lyα emission. To the north of it, a bright component is clearly seen in R band and is associated with the brightest Lyα emission, which at this position has a FWHM of $\sim$ 500 km sec^{-1}, a rather low value compared with average HzRGs, but consistent with the relation found by van Ojik (1995) that the largest radio sources tend to have Lyα emission with lower velocity dispersion.

Finally, the narrow elongated feature is undetected in K but is detected both in H and in R band. It is associated with spectacular Lyα emission which has 3 different peaks, having velocities of 140 km sec^{-1}, 670 km sec^{-1} and 990 km sec^{-1} blue-wards of the central Lyα emission. The overall velocity dispersion of the system is 1270 km sec^{-1} (FWHM).

Note that the Lyα spectrum shows that the Lyα emission extends beyond that seen in the Lyα image and spans a total region of $\sim$14$''$, as large as the radio source.

4. HST morphologies and colors

4.1. When do the first elliptical galaxies appear?

One of the most intriguing problems in cosmology is at what epoch elliptical galaxies formed. To study this problem using the new NICMOS data, we tried to determine if any of the host galaxies of our distant radio sources has a morphology that resembles that of elliptical galaxies, and if so, determine their characteristic parameters and their dependence with redshift.

When possible, we fitted the radially averaged surface brightness profiles of the host galaxies with the most commonly used model distributions (de Vaucouleurs and exponential). This was not done for (i) the 3 unresolved galaxies and (ii) the 2 galaxies in which the emission in the central region is dominated by a point source. In these last cases, although we could subtract the PSF revealing the extended underlying galaxies, the model of PSF subtracted was not good enough to allow a fit of the residual.

For 9 of the remaining 14 galaxies, the fit gave meaningless results, in particular for those having more than one peak of emission within the main body of the galaxy, for those having extremely close components, and for those with an irregular morphology. Also some apparently regular galaxies (such as MRC 0943−242) are not well represented by any of the above laws. However for 5 of the galaxies (namely MRC 0152−209, USS 0211−122, USS 1707+105A, MRC 2048−272 and MRC 2224−273), the surface brightness profile could be well represented by a de Vaucouleurs law, while the exponential profile gave worst results. In Fig. 25 we show the fit that we have obtained for these 5 radio galaxies and in Table 5 we report the best fit parameters that were determined by minimizing the value of the χ^2.

The PSF of NICMOS might cause a problem for the fitting procedure since it is not a Gaussian. It is difficult to recover accurately the shape of the PSF because the NIC 2 frames are very small and contain at most only few point sources; furthermore it is known that the PSF of NICMOS varies both spatially and with time (Colina and Rieke 1997). Only for 1707+105 we could construct a model of the PSF using 2 point sources near the radio galaxy (in the other 4 frames either there were no point sources or they were saturated). We then de-convolved the image of 1707+105 and fitted again the image obtained: the resulting parameters r_e and μ_e are, within the error, compatible with those obtained by fitting the original image. So we are confident that at least for the 3 largest galaxies (namely USS 0211−122, MRC 1707+105A and MRC 2048−272), the PSF does not influence the results of the fit.

While the good fit $\mathrm{R}^{1/4}$ law suggests that these galaxies might be morphologically ellipticals or bulges, a knowledge of the spectral energy distribution is also needed to fully determine their nature.

There is a clear redshift evolution in the morphological properties: in particular 5 of the 11 galaxies at z$<$ 2.4 (a lower limit since 2 unresolved objects in this redshift range could also be very small bulges) are well represented by a de Vaucouleurs profile, while none of the 8 galaxies at $z > 2.4$ are (with the possible exception of the unresolved object). The average effective radius is $0.7'' \pm 0.2''$, corresponding to $\sim 5.6 \pm 1.6$ kpc, adopting $H_0 = 50$ km sec^{-1} Mpc^{-1}, and q_0=0.5 (in the redshift range 1.7 to 2.4 with this cosmology the angular size distance is almost constant so we can use an average value).

To fully assess the significance of this morphology evolution, a larger and statistically unbiased sample of high redshift radio galaxies is needed. However this result is also supported by Keck near-IR observations by van Breugel et al. (1998) on a sample of HzRGs (some also belonging to our sample), which showed a strong rest frame visual evolution of the morphologies of HzRGs from aligned systems at z$\sim$ 3, to more symmetric and compact ones at lower redshift.

We can compare this result to what Best et al. (1997) obtained for 3CR z$\sim$ 1 radio galaxies from ground based near-infrared observations and optical HST observations. Best et al. showed that a large fraction ($\sim 80\%$) of the z$\sim$ 1 radio galaxies has profiles which are well fit by a de Vaucouleurs law, with typical effective radii between $1''$ and $2''$, and up to $3.9''$ (31 kpc). The average radius is 15 kpc, i.e. almost a factor of 3 larger than the average effective radius of our z $\sim$ 2 galaxies derived above. Only one high redshift galaxy (USS 1707+105A) has a radius comparable to its lower redshift counterparts. For reference, low redshift brightest cluster ellipticals have an average effective radius of 32 kpc, and values vary from 10 kpc to several tens of kpc (e.g. Schombert 1988).

A limitation to this comparison is the fact that most of the results from Best et al. (1997) were derived from ground based observations with very different spatial resolution ($\sim 1''$ or more) and different rest-frame wavelength ($\lambda_0 \sim 10000$ Å) from our NICMOS images. However, for those few galaxies which do not show a significant aligned ultraviolet component, Best et al. also fitted the HST/WFPC2 images (with resolution $0.1''$, covering a rest-frame emission wavelength just below the 4000 Å break) and found similar results. Furthermore, Zirm et al. (1998) recently observed 11 powerful radio galaxies at redshifts 0.7 $<$ z $<$1.8 with NICMOS and found symmetric optical/near-infrared morphologies consistent with dynamically relaxed elliptical host galaxies.

The above results indicate that a dynamically relaxed and relatively old stellar population is already in place in most of the z$\sim$1 systems, while and it becomes rarer already at redshift z$\sim$ 2 and disappears at redshift higher than 2.5. Furthermore the effective radii of radio galaxies at z$\sim$ 2 are in general considerably smaller (a factor of 3) than those of radio galaxies at z$\sim$1.

A possible evolutionary scenario for the hosts of powerful radio galaxies that can be inferred from these results is the following: at redshift from 3.5 to $\sim$ 2.5 most galaxies show considerable substructures and clumpiness, suggesting strong interactions and mergers. At z $\sim$ 2 about half of the systems start to appear morphologically relaxed; between z$\sim$ 2 and z$\sim$ 1 almost all systems (up to 80 %) evolve into fully developed elliptical galaxies and during this time the characteristic scale length of the galaxies increases on average by a factor of 3. As argued by Best et al. (1997) these galaxies will then continue to accumulate matter through mergers and gas infall: if the mergers occurs homologously (e.g. Schombert 1987), a merger of a large galaxy with a small systems gives as a result a remnant with a larger radius and a more diffuse morphology as compared to the original galaxy. In this way the 3CR galaxies at redshift $\sim$ 1 would then evolve into present day brightest cluster galaxies.

4.2. Colors: comparison between WFPC2 and NICMOS morphologies

For those objects that have both the WFPC2 and NICMOS images, we constructed a color index map to compare their structures in the following way. The optical images were initially convolved to bring them to the same resolution as the near infrared ones ($0.2''$). For the galaxies USS 0211−122, MRC 0943−242, MRC 1138−242, USS 1410−001, USS 1707+105, MRC 2025−218 and MRC 2104−242 that were imaged with the planetary camera (Pentericci et al. 1998,1999) we re-binned both frames on a finer pixel scale; using factors of 3 and 5 for the WFPC2 and the NICMOS respectively, the final pixel scales agreed to better than 1.3%. For the galaxy MRC 0406−242 which has been imaged on the WF3 chip (Rush et al. 1997), the factors used were 4 and 3 respectively for the WFPC2 and the NICMOS, and the agreement between the final scales was better than 2%.
The WFPC2 (or WFPC) and NICMOS images were aligned by comparing the location of stars that were present on both frames. If this was not possible (e.g. because on the small NICMOS frame there were no point sources) we used the location of distinct peaks of the radio galaxy itself. We only applied integer shifts to avoid interpolation. After sky subtraction we calibrated both images to units of flux density in μJy, using the information

in the headers of the WFPC2 images and the calibration of the NICMOS Camera 2 filters derived by Colina and Rieke (1997).

Finally we took the logarithm of each image, excluding all pixels having fluxes less than 3σ (where σ is the rms noise), differentiated the results and re-binned the final image by averaging regions of 2x2 pixels. The resulting image can be calibrated on a scale of two-point spectral index α, where $S_\nu \sim \nu^{-\alpha}$, or alternatively can be scaled to color index via: R-H=1.17+0.91α for those that were images with the F702W filter in the WFPC2 and V-H=1.40+1.08α for those that were imaged with the F606W filter.

The resulting maps of color distribution are presented in Fig. 26-29. Note that there are some spurious color structures, like sharp pixel to pixel variations, especially at the edges of some small components, due to regions with very different signal to noise in the 2 colors, the difference in PSF shape, and the uncertainties of $\sim 0.1''$ in the alignment procedure.

We shall use all these color maps in the next section to study the alignment effect. Here we just examine the distribution of the color indices and their possible relations to other properties of the radio sources.

We limit this study to the clumpiest objects which have a complex color index distribution. Four of the eight galaxies, MRC 0406−244, MRC 1138−262, USS 1707+105 and MRC 2104−242, were classified earlier in this paper as very clumpy objects (see Table 2), while the other 4, (USS 0211−122, MRC 0943−242, USS 1410−001 and MRC 2025-218) have less clumpy structures. We measured the color index of each component of the above galaxies by averaging over a region of $\sim 0.2''$ radius around the peaks in the emission present in the WFPC2 image and/or in the NICMOS image (some components are present only in one of the two bands). We only considered regions of emission that are definitely part of the systems i.e. that emit Lyα at the same redshift and/or are embedded in the Lyα halo of the galaxies. In Fig. 30 we present an histogram with the the distribution of optical to infrared spectral indices. The median color index is around $\alpha = 2$ and more than 75%

of the components have spectral indices between 1.5 and 3 (corresponding to V-H colors between 3 and 4.6), indicating that the radio galaxies contain very red regions.
Note that since the redder bands is in some cases (e.g. MRC 2104−242, see Table 2) contaminated by line emission, a very irregular and clumpy distribution of the emitting gas could produce sharp color gradients between the various components.
Since many properties of HzRGs depend on radio size (e.g. van Ojik et al. 1997) it is interesting to determine if there is a correlation between the color index of the clumps and their distance from the radio core. The results are show in Fig. 31: there's no evident relation between the distance of the component and its color. We also looked at a possible correlation between the color index of a component and the relative position angle of the component with respect to the radio axis: again we see no correlation.
Therefore we conclude that the colors of the aligned components of HzRGs, don't vary much with radio size and orientation, although presenting a large scatter. Note however that the statistics is small and that there is not a large variation in size between the 4 galaxies considered, so this could mask possible relations.

5. The radio/near-infrared alignment effect

Our images show that the near-infrared continuum emission of HzRGs is generally aligned with the main axis of the radio emission. This is the so-called alignment effect which has been studied for more than a decade; several models have been proposed to explain its nature (for a review see McCarthy 1993a and references therein), the most viable ones being: (i) star-formation stimulated by the radio jets as it propagates outward from the nucleus (Chambers et al. 1987; McCarthy et al. 1987; de Young 1989; Daly 1990); (ii) scattering of light from an obscured nucleus by dust or free electrons (di Serego Alighieri et al. 1989; Scarrot et al. 1990; Tadhunter et al. 1992; Cimatti et al. 1993); (iii) nebular continuum emission from warm line emitting clouds (Dickson et al. 1995). There is evidence that all these mechanism contribute to the alignment effect, with strong variations from object to object (e.g. Pentericci et al. 1999). Until recently it was argued that the alignment effect was mainly a characteristic of the observed optical emission from HzRGs (rest-frame UV emission around $\sim$ 1800Å). The NICMOS data reveal that this is not the case: the aligned continuum light contributes also strongly to the near-infrared emission. We will try to asses the contribution of these mechanisms using the new near-infrared images and the color maps constructed in the previous section.

Assuming that about half of the blue light is scattered light from a central quasar, which is a typical estimate for the objects showing considerable polarization at these wavelengths (see for example Cimatti et al. 1994), we can estimate the percentage of scattered light there would be in the H band. According to unification models the incident spectrum seen by the scattering medium is that of a quasar, $S \propto \nu^{-\alpha}$. As a value for α we take the one derived from the composite spectra of quasars from the MRC catalogue (the same parent catalogue from which most of our sources were taken) compiled by Baker and Hunstead (1995). They found $\alpha = 1$ for the steeper cases. Thompson scattering by thermal electrons is wavelength independent (although in some cases it has serious energetic difficulties, e.g. Eales and Rawlings 1990): in this case the scattered spectrum will be in shape similar to the incident one. For dust scattering, the output spectrum will be bluer than the incident one (for optically thin dust), with the exact shape depending on the size of the grains (e.g. Dey et al. 1996 and references therein).

Assuming 50% of the blue flux (at $\sim$ 1800 Å rest-frame) is scattered light, and that the scattered component has a power-law spectrum with $\alpha = 1$, we can calculate its contribution at $\sim$ 5000 Å for components with different observed optical-to-infrared spectral indices. The fraction of scattered light in the optical will also be 50% for those components with a spectral index $\alpha = 1$; it will be 26% for the the components with an observed optical-to-infrared spectral index $\alpha = 2$; it will be 10% for those with an index $\alpha = 3$; and finally it will be 4% for the components with $\alpha = 4$. These percentage would decrease considerably if the scattering is wavelength dependent; on the other hand they could increase if we allow for some reddening. However it is clear that for components with observed optical-to-infrared spectra steeper than $\alpha = 2$, as most radio galaxies exhibit (see Fig. 30), scattered light cannot be the dominant fraction of the emission at 5000 Å rest-frame wavelength.

We can try to separate the aligned component from the central symmetric one, using the fact that they have different colors: this can be done by subtracting scaled versions of the WFPC2 images from the NICMOS images, and iteratively change the scale factor until the resulting image has very little signature left of the aligned components. This process is not perfect but for the galaxies that have a rather uniform color across the image, the result is a clear separation of the aligned component and the symmetric one (central galaxy). In a companion paper (McCarthy et al. 2000) we show how this is done for MRC 0943−242: in that case we find that the aligned component has a nearly uniform spectral index of $\alpha = 2$, and has a SED that can be well represented by a modified quasar profile. McCarthy et al. conclude that in this specific case a large fraction (up to 60%) of the aligned continuum at 5000 Å is scattered light from the central quasar. Other galaxies for which the separation is good are USS 0211−122, USS 1410+001 and MRC 2025−218 (although this last case is more complicated due to the presence of a strong unresolved nuclear component), where the aligned light has a nearly constant spectral index (~ 2.3 for USS 0211−122 and MRC 2025−218, and ~ 2 for USS 1410+001).

For two of these objects there exist also polarization measurements, showing that the rest-frame UV emission is polarized: USS 1410−001 has a polarization of 10% (Cimatti et al. 1998) and an estimated total contribution of scattered light of 40 to 60% (depending on

the nature of the scatterer) at 1800 Å (rest-frame); MRC 2025−218 has a polarization of 8% (Cimatti et al. 1994), and the total SED of the galaxy can be fit by models in which scattered light accounts for a very large fraction of the emission at 1800 Å.
Then from the uniformity of the spectral indices in the aligned component, and using the calculations above, we conclude that in these objects also a considerable fraction ($\sim$ 30% or more) of the rest-frame optical emission could be scattered light.
For the multi-component objects, the simple separation between the aligned and the symmetric component is not possible because the optical-to-infrared color index varies considerably within the regions of the galaxy, as shown by the color maps. If the emission from these external regions were dominated by scattered light from a central quasar, then we might expect a similar color for all of them. Furthermore, the spectral indices of some components are considerably steeper than $\alpha = 2$, and in addition in some galaxies the components are located beyond the radio source (e.g. MRC 0156−252), or outside the ionization cone (e.g. MRC 1138−262). Hence we conclude that in these systems the contribution of scattered light to the optical continuum must be very small (less than 10%).

If we then assume that in these galaxies all of the emission is produced stellar light, we can determine the approximate age of the bulk stellar population from the observed colors. To do this we have compared the amplitude of the 4000 Å break observed in the clumps with the amplitudes (at the same rest-frame wavelengths) derived from the spectral energy distributions of stellar populations evolving according to the galaxy isochrone synthesis spectral evolution library compiled by Bruzual and Charlot (1993). We use the BC 1995 model, assuming a simple stellar population, and a Salpeter initial mass function (IMF), with star masses ranging from 0.1 to 125 $M_{\odot}$. We find that the instantaneous star-burst model evolves most rapidly and can reproduce the observed 4000 Å break in 0.5 Gyrs for the bluest components of HzRGs, to 1.3 Gyr for the reddest ones.

All other modes of star formation (e.g. star-burst with a finite duration, an exponentially declining star formation mode, etc.) require a longer time to reproduce the same colors. However the inferred ages could be overestimated in those components that have a considerable contribution from line emission in the redder band.

These large ages inferred for the stellar population argue against jet-induced star formation as a possible origin of the clumps, since the typical radiative life-time of a radio source ($\sim 10^7$ yrs, e.g. Carilli et al. 1991) is much shorter than that of the stars. However if the radio activity was recurrent then the observed clumps could have formed during previous phases of activity.

Finally we mention the model proposed by West (1994), in which the anisotropy of the optical and infrared emission around a typical high redshift radio galaxy is due to the anisotropy of the surrounding density distribution (see also Eales 1992). In this model, galaxy formation proceeds along preferred directions which are related to large scale elongated distribution of matter: in the prolate potential of the forming galaxy, the gas will fall and settle into a disk whose axis is along the major axis of the distribution of matter. The radio jets then will be emitted along this axis, hence the alignment between their direction and the distribution of the surrounding material (gas and stars). Within this model the relative ages of the radio jets and stellar components do not have to be matched. However, this model alone cannot explain the alignment effect since, for example, it cannot explain the polarization properties of many HzRGs.

We have shown that the properties of the aligned component vary considerably from galaxy to galaxy. A larger sample is needed to disentangle the possible effects. In particular we will soon obtain WFPC2 images for the complete NICMOS sample, and we will be able to construct the color distribution maps for a statistically significant number of galaxies. Coupling these high resolution data with good (high S/N) polarization information, would be extremely helpful for understanding the nature of the alignment effect.

5.1. Companion galaxies and their relation to the alignment effect

Any model attempting to explain the alignment effect has to take into account not only the morphology of the radio galaxies hosts, but also their surroundings. We will show here that the alignment is also present on a larger scale, with many small companion galaxies of HzRGs showing a tendency to be aligned with their radio axis.

Most HzRGs in our sample show very close companion objects. We define a companion as a small (size $\leq 1''$) object that is located within a region delineated by a 50 kpc radius around the radio source. We exclude objects with a stellar profile (although they might be in some cases high redshift unresolved objects rather than stars) and those which can be recognized as spirals, on the assumption that they are most probably foreground systems. The average number of companion galaxies for the 19 HzRGs is 2.0±0.3 down to a magnitude limit of $m_H = 23.5$. Some of these systems could be foreground objects, however there is an excess of galaxies around HzRGs: from deep counts of NICMOS parallel orbit, Lin et al. (1998) derive an average cumulative density of galaxies in H band down to a magnitude $m_H = 23.5$ of $\sim 1.5 \times 10^5$ galaxies deg^{-2}. The expected number of galaxies in a circular area of radius 50 kpc is 1.4. Therefore there is a marginal excess of objects in the area around HzRGs.

Further evidence that these objects may be associated to the radio galaxies is provided by the distribution of the orientation of companions with respect to the radio axis (or optical axis if the radio source is unresolved). In computing this distribution we have excluded companions of radio galaxies that are unresolved both in the radio and in the near-infrared emission (e.g. MRC 0324−228) since in these cases it is impossible to determine any preferred direction. The result is presented in Fig. 32: the histogram shows that the companion galaxies are predominantly located along the radio axis. A Kolmogorov Smirnov test shows that the distribution differs from a uniform distribution between $0°$ and $90°$ at the 1% level.

Röttgering et al.(1996) reported a similar effect finding a statistical excess of optical companions located along the radio axis of ultra steep spectrum radio sources. While they defined companions as objects that are located within a circle with diameter equal to the radio source extension, we prefer to use a fixed scale, since we do not assume a-priori that the companion galaxies are related to the presence of the radio sources. However it is significant that, even with a different definition of companion galaxies, both groups find an excess density in the direction of the radio axis.

This result shows that the alignment effect not only holds for the radio galaxy hosts, but also for its neighboring galaxies within a region as large as ~ 100 kpc. The origin of this excess of companion objects preferentially located along the radio axis can be explained in two ways: either there is more material along the radio axis (e.g. West 1994) or the material along the radio axis emits more radiation due to the interaction with the radio jets (see the discussion and the references in the previous section).

6. Conclusion

We have presented the results of a near infrared imaging program on a sample of 19 radio galaxies having redshift between 1.7 and 3.2, observed with NICMOS Camera 2 on the Hubble Space Telescope.

Our observations show that the host galaxies of powerful radio sources have a wide range of morphologies, from systems with simple compact morphologies to systems with substructures such as multiple emission peaks to systems comprised of several components spread over areas up to 100 kpc. Only in few cases the active nucleus dominates the emission in the central region.

Following is a summary of the most important results obtained:

(i) We have shown that at $2 < z < 3$ HzRGs evolve from irregular radio aligned morphologies to more symmetric compact systems which have morphologies often well represented by a de Vaucouleurs profile. This indicates that at z$\sim$ 2 about half of host galaxies of HzRGs have a morphology consistent with them being ellipticals or bulges.

(ii) A comparison between a representative sample of z $\sim$ 2 radio sources hosts and z $\sim$ 1 3CR radio galaxies shows that there is difference of a factor 3 in their effective radii, indicating that the systems must grow considerably between these two epochs.

(iii) The NICMOS data have shed new light on the alignment effect: in almost all extended systems the near infrared continuum light is aligned with the radio axis and the aligned component is much redder than what was thought before. For several galaxies WFPC2 V or R band images were available so we computed a high resolution map of the optical-to-infrared spectral index (or similarly of $R - H$ color). These spectral indices are in general rather steep ($\alpha = 2$ or steeper), indicating most probably a stellar origin for the near-infrared continuum emission. The clumpy systems show net color differences between the various components, which can be explained with different ages for the stellar content. The inferred ages, as determined from the Bruzual and Charlot models, are large, of the order of $\sim$ 1 Gyr in most cases, and seem to rule out jet-induced star formation.

(iv) Finally we find an over-density of faint objects around HzRGs. In the small NICMOS frames we can see in many cases nearby faint objects around the high redshift radio galaxies and their space density is higher than what is observed in the deep NICMOS parallel observations of random fields. Furthermore these objects tend to be aligned with the direction of the main axis of the radio sources suggesting that they are related to the presence of the radio source, and that they might be companion galaxies at the same redshift.

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Table 1. Properties of the radio sources.

Source (1)	z (2)	RA (3)	Decl (4)	$S_{4.7}$ (5)	$\alpha_{8.2}^{4.7}$ (6)	Size (7)	Morphology (8)
MRC 0140−257	2.64	01h42m41.16s	-25d30m34.1s	47	1.3	4.2	double
MRC 0152−209	1.89	01h54m55.77s	-20d40m26.3s	115	1.9	1.6	one-sided
MRC 0156−252	2.09	01h58m33.45s	-24d59m30.2s	112	1.1	8.3	double,distorted
USS 0211−122	2.34	02h14m17.37s	-11d58m46.7s	54	1.5	17.0	double
MRC 0316−257	3.13	03h18m12.06s	-25d35m09.7s	101	1.3	7.6	double
MRC 0324−228	1.89	03h27m04.44s	-22d39m42.6s	131	1.2^a	9.7	double, no core
MRC 0350−279	1.90	03h52m51.64s	-27d49m22.6s	86	1.2^a	$\leq$0.6	unresolved
MRC 0406−244	2.44	04h08m51.44s	-24d18m16.7s	108	1.3	10.0	double
MRC 0943−242	2.93	09h45m32.79s	-24d28m49.8s	55	1.8	3.9	double,no core
MRC 1017−220	1.77	10h19m49.05s	-22d19m58.0s	261	1.1	$\leq$0.6	unresolved
MRC 1138−262	2.16	11h40m48.25s	-26d29m10.1s	153	1.8	15.8	double,distorted
USS 1410−001	2.33	14h13m15.13s	-00d22m59.6s	57	1.3	24.0	double
USS 1707+105	2.35	17h10m06.85s	+10d31m09.0s	64	1.2	22.5	double,no core
MRC 2025−218	2.63	20h27m59.45s	-21d40m57.1s	95	1.1	5.1	double,distorted
MRC 2048−272	2.06	20h51m03.37s	-27d03m04.6s	115	1.6	8.3	double
MRC 2104−242	2.49	21h06m58.16s	-24d05m11.3s	107	1.0	24	double
USS 2202+128	2.70	22h05m14.27s	+13d05m33.7s	52	1.5	4.2	double
MRC 2224−273	1.68	22h27m43.26s	-27d05m01.7s	60	1.6	$\leq$0.6	unresolved
USS 2349+280	2.89	23h51m59.08s	+29d10m28.9s	34	1.6^b	15.2	double

[a] Spectral index between 4.7 Ghz and 408 MHz

[b]Spectral index between 4.7 GHz and 1.4 GHz

Note. — (1) 1950IAU name of the radio galaxy; (2) redshift; (3) and (4) position of the radio core (J2000 coordinates); (5) total flux and 4.7 GHz; (6) total spectral index between 4.7 and 8.2 GHz; (7) total extension in arcsecond; (8) radio morphology at 8.2 GHz

Table 2. NICMOS observations .

Source (1)	Date (2)	N (3)	$\mu_{(3\sigma)}$ (4)	T$_{exp}$ (5)	Filter (6)	λ_0 (7)	Cont. lines (8)	%flux (9)	Cl. (10)
MRC 0140−257	17/10/97	4	25.00	10195	F160W	3850-4950	Hβ	1	2
MRC 0152−209	26/12/97	4	24.48	10259	F160W	4840-6230	[OIII]	6	2
MRC 0156−252	28/09/97	4	24.89	9232	F160W	4530-5830	[OIII],Hβ	5	3
USS 0211−122	19/10/97	4	24.65	10195	F160W	4190-5390	[OIII],Hβ	3	1
MRC 0316−257	17/10/97	4	24.76	10195	F160W	3390-4360	[OII]	10	1
MRC 0324−228	22/06/97	2	24.50	5065	F165M	5540-6230	–	–	2
MRC 0350−279	18/10/97	4	24.63	10195	F160W	4830-6210	[OIII]	–	1
MRC 0406−244	11/08/97	5	24.84	12824	F160W	4070-5230	[OIII],Hβ	17	3
MRC 0943−242	12/06/97	3	24.55	7694	F160W	3560-4580	[OII]	7	1
MRC 1017−220	13/06/97	2	24.25	5065	F165M	5780-6500	[OI]	–	1
MRC 1138−262	27/11/97	5	24.57	12824	F160W	4430-5700	[OIII],Hβ	2	3
USS 1410−001	07/01/98	4	24.76	10195	F160W	4200-5410	[OIII],Hβ	9	2
USS 1707+105	24/10/97	4	25.01	10195	F160W	4180-5370	[OIII],Hβ	2	3
MRC 2025−218	09/09/97	4	24.64	10259	F160W	3860-4960	Hβ	1	1
MRC 2048−272	23/10/97	4	24.65	10259	F160W	4580-5880	[OIII],Hβ	–	1
MRC 2104−242	24/10/97	4	24.61	10259	F160W	4010-5160	[OIII],Hβ	26	3
USS 2202+128	21/06/97	2	24.25	5065	F165M	4320-4860	Hβ	2	1
MRC 2224−273	11/11/97	4	24.68	10259	F160W	5220-6720	Hα,[OI]	28	1
USS 2349+280	24/11/97	4	24.78	10195	F160W	3600-4630	[OII]	2	2

Note. — (1) 1950IAU name of the radio galaxy; (2) observation date; (3) number of orbits;(4) limiting surface brightness in H magnitudes; (5) total exposure time (seconds); (6) filter used; (7) restframe wavelegth range covered by the observations; (8) emission lines falling in the continuum band;(9) percentual of line flux in the total emission measured within a 4″ circular aperture; (10) morphological classification according to Section 3.1.

Table 3. Ground based observations log

Galaxy (1)	Telescope (2)	Date (3)	Band (4)	λ_0 (5)	T_{exp} (6)	Res. (7)	Ref (8)
MRC 0156−252	du Pont 2.5m	27/10/89	Lyα	3700/50	8100	1.5″	1
	du Pont 2.5m	15/11/96	K_s	2.2μ	4770	0.9″	1
	du Pont 2.5m	9/09/91	I	8100	1800	0.9″	1
MRC 0406−244	du Pont 2.5m	17/02/96	Lyα	4200/100	9000	1.1″	2
	du Pont 2.5m	19/11/96	K_s	2.2μ	9030	0.9″	2
	du Pont 2.5m	8/09/91	I	8100	1300	0.9″	2
	NTT/EMMI	24/11/97	Spectr. Grat 3	2967	4800	2.8Å	1
MRC 2104−242	du Pont 2.5m	29/10/89	Lyα	4265/50	7800	1.4″	1
	du Pont 2.5m	9/09/91	r	6400	3100	0.7″	1
	NTT/EMMI	30/06/97	Spectr. Grat 3	302	7200	2.8Å	1

Note. — (1) Radio galaxy; (2) Telescope used; (3) observation date ; (4) filter or grating used; (5) observed wavelegth covered (in Å); (6) total exposure time (in seconds); (7) resolution; (8) reference 1. This paper; 2. Rush et al. 1997

Table 4. Photometry

Galaxy	M_H	err
MRC 0140−257	20.13	0.07
MRC 0152−209	18.69	0.04
MRC 0156−252	18.39	0.10
USS 0211−122	19.64	0.04
MRC 0316−257	20.23	0.05
MRC 0324−228	19.93	0.03
MRC 0350−279	20.26	0.10
MRC 0406−244	18.93	0.04
MRC 0943−242	19.77	0.08
MRC 1017−220	18.28	0.05
MRC 1138−262	18.04	0.03
USS 1410−001	19.25	0.05
USS 1707+105	20.15	0.04
MRC 2025−218	18.94	0.04
MRC 2048−272	20.18	0.04
MRC 2104−242	19.91	0.10
USS 2202+128	19.80	0.10
MRC 2224−273	19.23	0.05
USS 2349+280	19.94	0.05

Table 5. Parameters of the de Vaucouleurs fit

Galaxy	z	r_e	μ_e
		arcsec	H mag arcsec−2
MRC 2224−273	1.68	0.2	18.6
MRC 0152−209	1.89	0.2	19.1
MRC 2048−272	2.06	0.64	20.8
USS 0211−122	2.34	0.73	21.8
MRC 1707+105	2.35	1.62	23.7

Fig. 1.— *Left*: A grey scale representation of the near infrared continuum emission of the radio galaxy MRC 0140−257 at z= 2.64 with contours from the VLA 8.2 GHz observations super-imposed. *Right*: Contour representation of the continuum emission.

Fig. 2.— *Left*: A grey scale representation of the near infrared continuum emission of the radio galaxy MRC 0152−209 at z= 1.89. *Right*: Contour representation of the same image.

Fig. 3.— *Top panel*: A grey scale representation of the near infrared continuum emission of the radio galaxy MRC 0156−252 at z= 2.09 with contours from the VLA 8.2 GHz observations super-imposed. *Bottom panel*: Contour representation of the continuum emission.

Fig. 4.— *Left*: A grey scale representation of the near infrared continuum emission of the radio galaxy USS 0211−122 at z= 2.34 with contours from the VLA 8.2 GHz observations super-imposed. *Right*: Contour representation of the continuum emission from the host galaxy.

Fig. 5.— *Left*: A grey scale representation of the near infrared continuum emission of the radio galaxy MRC 0316−257 at z= 3.13 with contours from the VLA 8.2 GHz observations super-imposed. *Right*: Contour representation of the continuum emission.

Fig. 6.— *Left*: A grey scale representation of the near infrared continuum emission of the radio galaxy MRC 0324−228 at z= 1.89 with contours from the VLA 4.5 GHz observations super-imposed. *Right*: Contour representation of the continuum emission from the two possible identifications of the host galaxy.

Fig. 7.— A grey scale representation of the near infrared continuum emission of the radio galaxy MRC 0350−279 at z= 1.90.

Fig. 8.— *Left*: A grey scale representation of the near infrared continuum emission of the

radio galaxy MRC 0406−244 at z= 2.44 with contours from the VLA 8.2 GHz observations super-imposed.*Right*: Contour representation of the continuum emission.

Fig. 9.— *Left*: A grey scale representation of the near infrared continuum emission of the radio galaxy MRC 0943−242 at z= 2.93 with contours from the VLA 8.2 GHz observations super-imposed. *Right*: Contour representation of the continuum emission.

Fig. 10.— Grey scale representation of the near infrared continuum emission of the radio galaxy MRC 1017−220 at z= 1.77. The host of the radio source is the unresolved object to the east

Fig. 11.— *Left*: A grey scale representation of the near infrared continuum emission of the radio galaxy MRC 1138−242 at z= 2.16 and its close companions, with contours from the VLA 8.2 GHz observations super-imposed. *Right*: Contour representation of the continuum emission from the central region.

Fig. 12.— *Left*: Grey scale representation of the near infrared continuum emission of the radio galaxy USS 1410−001 at z= 2.33 with contours from the VLA 8.2 GHz observations super-imposed. *Right*: Contour representation of the continuum emission from the host galaxy.

Fig. 13.— *Top panel*: Grey scale representation of the near infrared continuum emission of the radio galaxy USS 1707+105 at z= 2.35 and its close companions, with contours from the VLA 8.2 GHz observations super-imposed. *Bottom panel*: Contour representation of the continuum emission from the host galaxy.

Fig. 14.— *Left*: Grey scale representation of the near infrared continuum emission of the radio galaxy MRC 2025−218 at z= 2.63 with contours from the VLA 8.2 GHz observations super-imposed. *Right*: Contour representation of the continuum emission.

Fig. 15.— *Left*: Grey scale representation of the near infrared continuum emission of the radio galaxy MRC 2048−272 at z= 2.06 with contours from the VLA 8.2 GHz observations super-imposed. *Right*: Contour representation of the continuum emission.

Fig. 16.— *Left*: Grey scale representation of the near infrared continuum emission of the radio galaxy MRC 2104−242 at z= 2.49 with contours from the VLA 8.2 GHz observations super-imposed. *Right*: Contour representation of the continuum emission from the central region. The elongated feature north-west of the galaxy core is a spike from the near by star.

Fig. 17.— Grey scale representation of the near infrared continuum emission of the radio galaxy USS 2202+128 at z= 2.70 with contours from the VLA 8.2 GHz observations super-imposed.

Fig. 18.— *Left*: Grey scale representation of the near infrared continuum emission of the radio galaxy MRC 2224−273 at z= 1.68. *Right*: Contour representation of the continuum emission.

Fig. 19.— *Left*: Grey scale representation of the near infrared continuum emission of the radio galaxy USS 2349+280 at z= 2.89. *Right*: Contour representation of the continuum emission.

Fig. 20.— The NICMOS image of MRC 0156−252 in grey scale overlayed with contours representing the I band emission (top left), K band emission (top right) and narrow band Lyα emission (bottom left). The bottom right panel shows the 8.2 GHz radio emission in grey scale overlayed with contour of the narrow band Lyα emission

Fig. 21.— The NICMOS image of 0406-244 in grey scale overlayed with contours representing the I band emission (top left), K band emission (top right) and narrow band Lyα emission

(bottom left).The bottom right panel shows the 8.2 GHz radio emission in grey scale overlayed with contour of the narrow band Lyα emission

Fig. 22.— A high resolution spectrum of the Lyα emission line from 0406-244, taken with the NTT, having a resolution of 2.8 Å

Fig. 23.— The NICMOS image of 2104-242 in grey scale overlayed with contours of the R band emission (left panel) K band emission (central panel), and narrow band Lyα emission (right panel). The elongated feature on the top right of the images is a spike from a nearby bright star.

Fig. 24.— A high resolution spectrum of the Lyα emission line from 2104-242, taken with the NTT, having a resolution of 2.8 Å

Fig. 25.— Surface brightness profiles for the 5 radio galaxies which are well represented by a de Vaucouleurs law: the dots are the data with relative error bars, while the dotted lines are the best fit laws.

Fig. 26.— The optical to infrared spectral index distribution for the radio galaxies USS 0211−122 (left) and MRC 0406−244 (right). The bar on the top indicates the scale in each case

Fig. 27.— The optical to infrared spectral index distribution for the radio galaxies MRC 0943−242 (left) USS 1410−001 (right). The bar on the top indicates the scale in each case

Fig. 28.— The optical to infrared spectral index distribution for the radio galaxy USS 1707+105 (left) and MRC 2025−218 (right). The bar on the top indicates the scale in each case

Fig. 29.— The optical to infrared spectral index distribution for the radio galaxies MRC 1138−262(left) and MRC 2025−218 (right). The bar on the top indicates the scale in each

case. In these galaxies there is a strong contribution from a nuclear point source which influence the spectral indexes in the center.

Fig. 30.— Distribution of the optical to infrared spectral indices of the components of the 4 clumpy radio galaxies, MRC 0406−244, MRC 1138−262, USS 1707+105 and MRC 2104−242.

Fig. 31.— The optical-to-infrared color indices of the components of the 4 clumpy radio galaxies MRC 0406−244 (triangles), MRC 1138−262 (squares), USS 1707+105 (asterisks) and MRC 2104 −242 (plus), plotted versus their distance from the galaxy radio core (or nucleus).

Fig. 32.— Distribution of the orientation of companion galaxies within 50 kpc of the radio galaxies, with respect to the radio axis