Mon. Not. R. Astron. Soc. **280**, L9–L12 (1996)

Evolution of the aligned structures in $z \sim 1$ radio galaxies

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Accepted 1996 February 22. Received 1996 February 5; in original form 1995 November 24

ABSTRACT

Hubble Space Telescope observations are presented of eight 3CR radio galaxies in the redshift interval $1 \lesssim z \lesssim 1.3$. The optical morphologies of these galaxies change dramatically as the radio size increases. It is shown that this evolution is entirely consistent with large-scale star formation induced by the radio jet, and it is argued that this mechanism could be the predominant cause of the observed alignment of the optical emission along the radio axis.

Key words: galaxies: active – galaxies: evolution – radio continuum: galaxies.

1 INTRODUCTION

In 1987, McCarthy et al. and Chambers et al. discovered that the optical emission of powerful radio galaxies with redshifts $z \gtrsim 0.6$ is elongated and aligned along the direction of the radio axis, a phenomenon which has become known as 'the alignment effect'. Many theories have been proposed to explain this alignment, the most promising involving massive star formation induced by shocks associated with the radio jet, and the scattering of light from an obscured active galactic nucleus, either by dust or by electrons (see McCarthy 1993 and references therein). Understanding the alignment effect is of key importance to cosmology: it will allow the content and properties of the interstellar and intergalactic media to be studied; it will provide details about the interaction of radio sources with their environment; by measuring accurate colours for the underlying old stellar population, the age of the galaxies can be determined, and hence constraints can be placed on the age of the Universe and the choice of cosmological model.

We have made observations with the *Hubble Space Telescope* (*HST*) of an almost complete sample of 28 3CR radio galaxies which lie in the region of sky $|b| \geq 10°$, $10° \leq \delta \leq 55°$, and which have redshifts in the range $0.6 \leq z \leq 1.8$. The first results of this programme were presented by Longair, Best & Röttgering (1995), who concluded that the observations could not be explained by any single theory of the alignment effect.

In this Letter we describe the properties of a complete subsample of these radio galaxies, with redshifts in the range $1.0 \lesssim z \lesssim 1.3$. By restricting attention to such a narrow range, not only are any redshift evolutionary effects negligible, but also, since the radio flux densities of these sources are all about 10 Jy, we eliminate any radio luminosity dependence. Furthermore, at redshifts $z \gtrsim 1.3$, the signal-to-noise ratio of the *HST* observations begins to limit the definition of the extended structures, whilst at lower redshifts, $z \lesssim 1.0$, the alignment effects are less pronounced.

The eight galaxies in this redshift range show a clear evolution of optical morphology with increasing radio size, and this result provides insights into the nature of the alignment effect and the evolution of double radio sources.

2 OBSERVATIONS

The galaxies were imaged with the Wide Field Planetary Camera 2 (WFPC2) of the *HST* for one orbit, approximately 30 min, in each of two filters, selected to be roughly equivalent to the rest-frame *U* and *B* bands of the galaxy. In general, the *B*-band filter contained the strong [O II] 3727 emission line, whilst the *U* band was free of major emission lines. The morphologies of the two images are remarkably similar, although in some sources small differences in colour do exist between different knots. It is not immediately apparent whether these are due to intrinsic differences in the continuum colour, differential reddening by dust associated with the source, or a non-uniform spatial distribution of the emission-line gas. However, even in the third case the colour differences are small enough that the distributions of line and continuum emission must be broadly comparable. This subject will be discussed further in a later paper.

The sources were mapped at 8.4 GHz using the VLA in A-array configuration with a spatial resolution of 0.18 arcsec, comparable to that of the *HST*. The observations consisted of 22-min exposures, giving an rms noise level of about 50 μJy. Radio sources over 10 arcsec in extent were also observed using the *B*-array to provide details of the large-scale radio structures. The galaxies were also imaged at 2.2 μm using UKIRT.

Reduction of the data will be discussed in more detail elsewhere. The optical data were reduced following the standard Space Telescope Science Institute pipeline (Lauer 1989), and the radio data were reduced using the AIPS software provided by the National Radio Astronomy Observatory (Perley 1989). The absolute positioning of the optical frames was found using one or more unsaturated stars which were present on each frame and also present in the APM data base (Maddox et al. 1990). The astrometric error is typically less than 1.0 arcsec. Hubble's constant is taken to be $H_0 = 50$ km s^{-1} Mpc^{-1}, and the deceleration parameter to be $q_0 = 0.5$.

3 RESULTS

HST images of the eight 3CR galaxies are displayed in Figs 1(a)–(h) (opposite), in order of increasing radio size.[1] Overlaid upon these are contours of radio emission or, in the case of the largest radio sources, the central radio emission plus lines indicating the directions of the radio hotspots.

The galaxies 3C 368 and 3C 324 [Figs 1(b) and (c)] were discussed by Longair et al. (1995), and are not discussed individually here, except to note that the bright knot in the centre of the optical image of 3C 368 is a galactic M-dwarf star. The remaining sources are considered briefly below.

3C 266 is the smallest of the eight radio sources. The *HST* image (Fig. 1a) shows a string of bright knots aligned within 10° of the radio axis and, underlying these, highly elongated diffuse emission which extends from one radio hotspot to the other. Hammer, Nottale & Le Fèvre (1986) suggested that the optical elongation could be a result of gravitational lensing, as the source lies within 3 arcmin of the centre of the rich cluster A1374 ($z = 0.209$). Our image shows no evidence that this is the case. Models of radio spectral ageing suggest that the lobe–hotspot separation velocity of 3C 266 is $\sim 0.18c$ (Liu, Pooley & Riley 1992), indicating that the radio source is 1–2 million years old.

The *HST* image of **3C 280** (Fig. 1d) consists of a number of bright knots aligned along the radio axis, and a bright arc of emission to the north extending from the westernmost knot back towards the centre of the galaxy. A lobe–hotspot separation velocity of $\sim 0.13c$ is proposed by Liu et al. (1992) from radio spectral ageing fits, suggesting an age of a few million years, similar to that of 3C 266.

The most passive object in our sample, **3C 65** (Fig. 1e), comprises a fairly round central object with a blue companion 3 arcsec to the west, along the radio axis. This galaxy is one of the reddest in the 3CR sample ($V-K \sim 6$), and shows little evidence of optical activity associated with the radio phenomenon. Detection of a 4000-Å break in the off-nuclear spectrum by Lacy et al. (1995) and by Stockton, Kellogg & Ridgway (1995) indicates the presence of an old (3–4 Gyr) stellar population in this galaxy.

[1]Strictly, 'projected radio size' is meant. According to unification schemes of radio galaxies and radio-loud quasars, the galaxies have their radio axis orientated within 45° of the plane of the sky, and so their projected and physical sizes should be similar.

The image of **3C 267** (Fig. 1f) consists of three knots misaligned with respect to the radio axis, plus a faint arc of diffuse emission to the north of the westernmost knot. The south-western component is just over a magnitude bluer in $V-K$ than the other knots. A number of other galaxies lying further to the south-west show an excess of emission in a narrow-band filter centred on [O II] 3727, suggesting that 3C 267 may be part of a distant galaxy cluster (McCarthy 1988).

The nuclear region of **3C 252** (Fig. 1g) consists of two, barely separated, bright knots aligned along the radio axis. It is unclear whether this is due to a dust lane running across the central regions, as might be the case for 3C 324 (Longair et al. 1995), or whether they are distinct emission regions. Extending to the east of these components is a triangle of diffuse emission, possibly associated with an ionization cone of scattered light.

There has been much dispute in the literature as to the identity of the host galaxy of **3C 356**, because of the presence of two central radio cores (Fernini et al. 1993), separated by only 5 arcsec, each associated with bright infrared galaxies. The flatter radio spectral index of the southern radio core, together with the unresolved nature of the northern galaxy in ground-based observations, has suggested that the southern galaxy is the radio source host whilst the northern galaxy is interacting with the radio jet (Lacy & Rawlings 1994). However, the *HST* image resolves the northern component into a 'dumbbell'-shaped morphology, characteristic of a number of the 28 galaxies in our sample, whilst the southern galaxy is seen to be very diffuse and unlike any other 3CR source. These observations suggest that the northern component may be the host radio galaxy.

The most striking feature of these images is that, whilst the majority display the alignment effect, the morphology of the optical images varies dramatically as the size of the radio source increases: small radio sources consist of a string of bright knots, tightly aligned along the radio axis, whilst more extended sources are generally more compact and contain fewer (generally no more than two) bright components. Our infrared observations of these radio galaxies show that the complex structures associated with the smaller radio sources are comparable in extent to the size of the host galaxy.

The size of a radio source depends upon two factors: its age, and the density of the surrounding medium – or, more precisely, the ratio of the jet ram pressure of the source to the external density. Thus small radio sources may be small either because they are young, or because they are confined by a dense surrounding medium. The second possibility can account for the fact that strong Lyα absorption from radio galaxies at $z \gtrsim 2$ is generally observed only in small radio sources (van Ojik et al. 1996). However, the spectral ageing discussed by Liu et al. (1992) indicates that 3C 266 and 3C 280 (both small sources) have hotspot advance speeds $\gtrsim 0.1c$, and are therefore relatively young. Even assuming that the largest sources have so low a confining density that their hotspots travel outwards at nearly the speed of light, the fact that they are up to 50 times larger in physical size than these small sources would mean that they must be at least five times older. Age effects are therefore important in

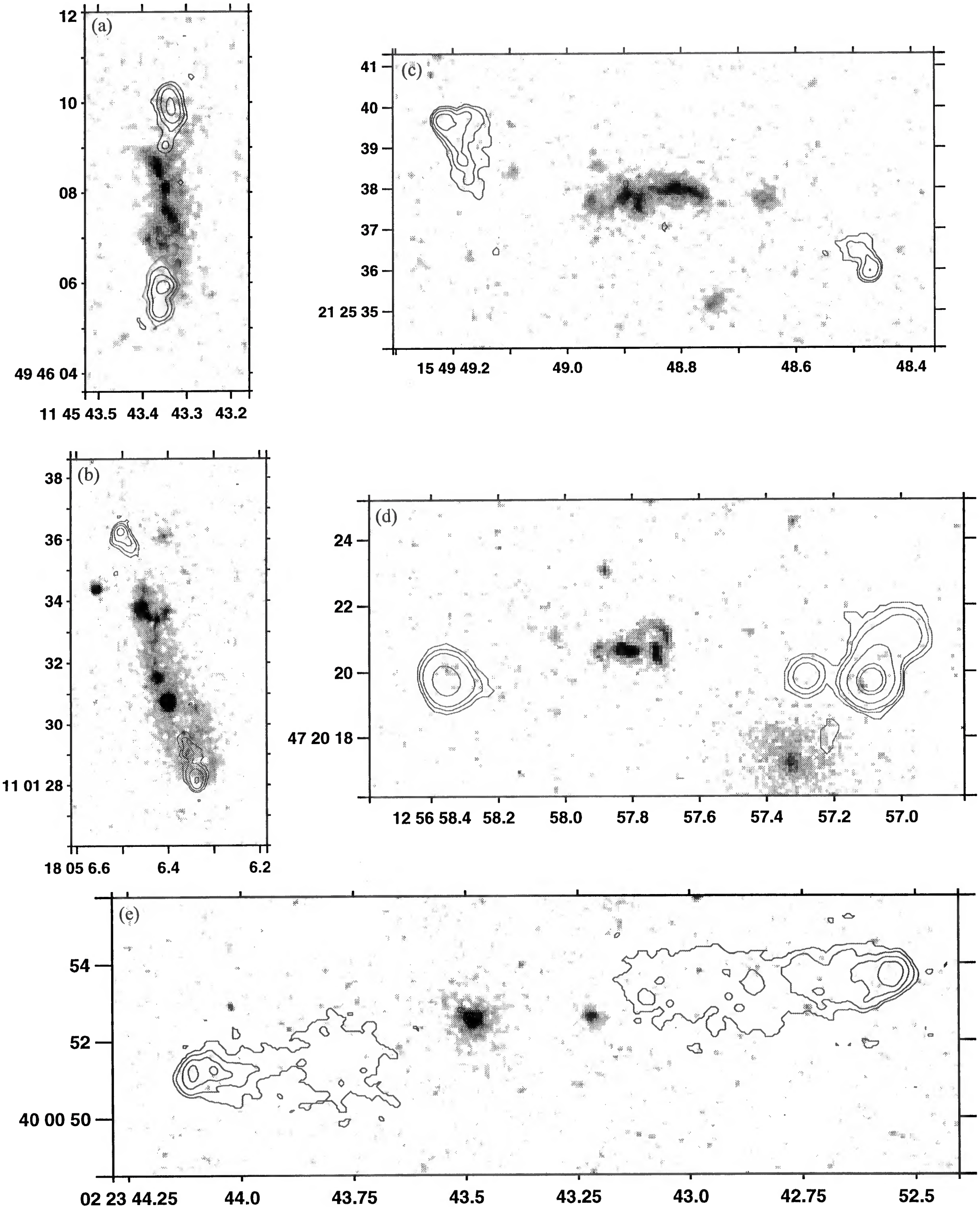

Figure 1. In order of increasing radio size (D): (a) 3C 266 (upper left, $z=1.272$, $D=39$ kpc); (b) 3C 368 (centre left, $z=1.132$, $D=73$ kpc); (c) 3C 324 (upper right, $z=1.21$, $D=96$ kpc); (d) 3C 280 (centre right, $z=0.996$, $D=117$ kpc); (e) 3C 65 (bottom, $z=1.176$, $D=155$ kpc); (f) 3C 267 (overleaf, upper left, $z=1.144$, $D=329$ kpc); (g) 3C 252 (overleaf, lower left, $z=1.105$, $D=488$ kpc); (h) 3C 356 (overleaf, right, $z=1.079$, $D=624$ kpc). 1 arcsec corresponds to approximately 8.5 kpc.

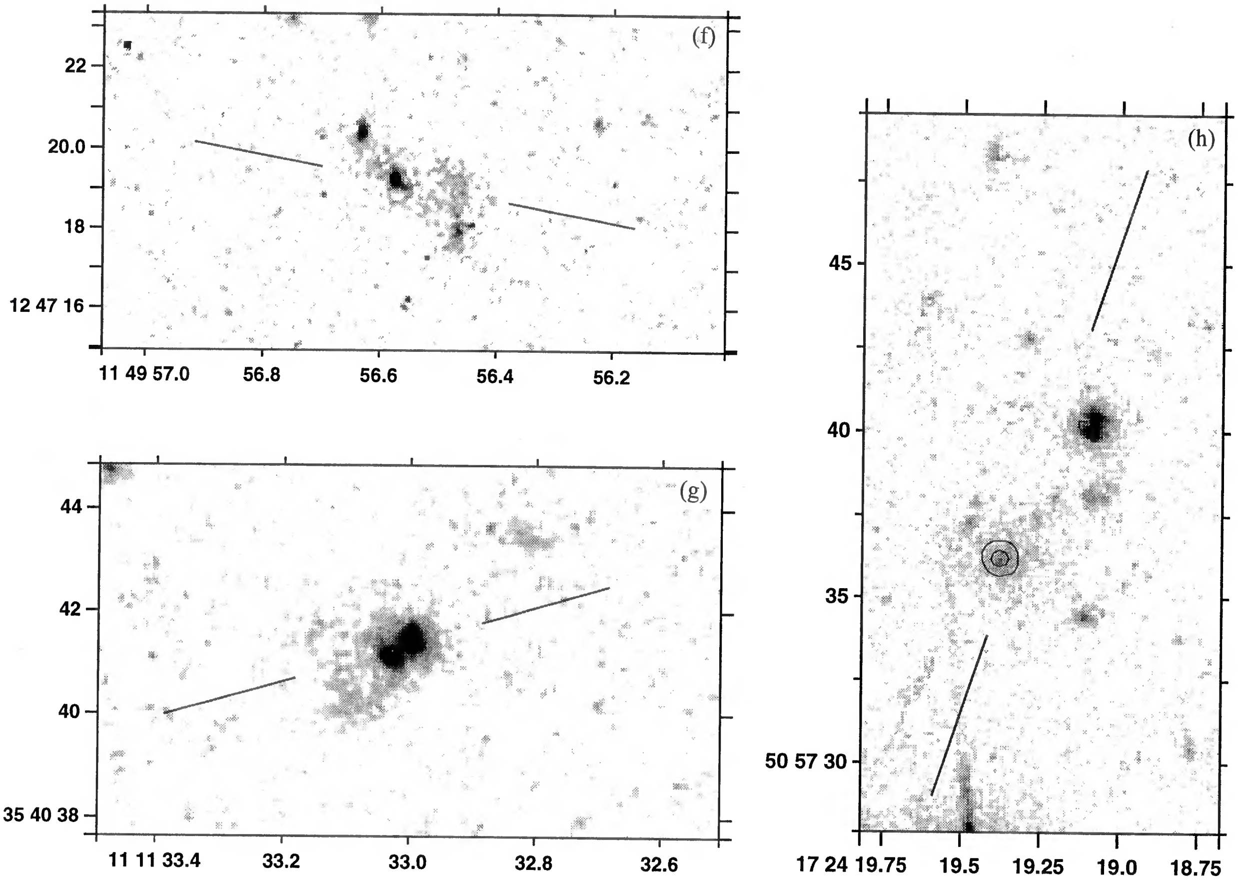

Figure 1 – *continued*

these sources, and a natural interpretation of the sequence of changing morphology with increasing radio size is to associate it with different phases of the interaction of the radio jets with the interstellar and intergalactic medium, as the radio source ages.

One model of the alignment effect that would naturally account for this morphological evolution is vigorous star formation induced by shocks associated with the passage of the radio components (Begelman & Cioffi 1989; De Young 1989; Rees 1989; Daly 1990). Bright strings of star-forming regions would be formed along the radio axis in the smaller sources and then, when the radio hotspots passed beyond the host galaxy, star formation would cease and the clouds of stars would age and relax within the gravitational potential of the host galaxy.

There are two other important alignment models which cannot be discounted by our observations. First, scattering of nuclear light by dust or electrons is important in some of the sources, to account for the observed levels of optical polarization (di Serego Alighieri et al. 1989). Secondly, Dickson et al. (1995) showed that a significant percentage of the ultraviolet light in some radio galaxies is associated with nebular continuum emission from warm line-emitting clouds excited by continuum from the obscured active nucleus.

In Section 4, we consider the possibility that the bright knotty structures are associated with young stars, and show that the time-scales associated with this model are consistent with evolution over the lifetime of the radio source. In this picture, scattering from dust associated with the star-forming regions would be responsible for some or all of the optical polarization.

Even in the smallest, knottiest galaxies in our sample, the sum of the fluxes through apertures enclosing the bright knots amounts to only about 40 per cent of the integrated flux through a 9-arcsec aperture on the *HST* image, indicating a significant level of diffuse extended emission which does not stand out on the *HST* images. This extended emission may be associated with the underlying old stellar population seen in the infrared images, but it could also be the source of any free–free emission, or of additional scattered light.

4 JET-INDUCED STAR FORMATION

We consider a model similar to that of Rees (1989), according to which the interstellar and intergalactic media consist of cold ($T \lesssim 10^4$ K) clumps of material within a hotter ($T \sim 10^6$–10^7 K) gas phase. The passage of the radio components through this two-phase medium is associated with supersonic shocks, arising both from the forward bowshock of the advancing radio jet and from the transverse expansion of the radio cocoon. Hot gas is swept up by these shocks, and raised to such a high adiabat that, were this the only phase present, star formation would be inhibited. This bowshock picture is particularly appropriate to the southern region of 3C 368, which shows an edge-brightened elliptical emission region (see also Meisenheimer & Hippelein 1992). Line emission, free–free emission, and possibly scattering are all likely to be important in this shocked hot gas.

It is the cooled material, not the hot gas, which is important for star formation. Shocks would bypass the cold clouds causing little disruption, and leave them inside the radio cocoon, overpressured by a factor $\sim \mathfrak{M}^2$ where $\mathfrak{M}$ is the Mach number of the shock which is typically ~ 100 along the jet and ~ 10 for the transverse cocoon expansion. This increased pressure would push many of the clouds over the Jeans limit and cause them to collapse, forming a bright string of young star clusters along the radio axis, consistent with that observed in small sources like 3C 266, 3C 324 and the northern arm of 3C 368. After the shocks have passed through the host galaxy, the star formation rate will decrease dramatically.

We can use this model to estimate time-scales associated with the radio source phenomenon. The most massive stars, which in this picture would be responsible for the bright knotty structures in the compact sources, represent only a small fraction of the mass of forming stars, but the strong dependence of luminosity on mass ($L \propto M^{\gamma}$ with $\gamma \sim 3.5$), together with their very blue colours, means that they would produce most of the ultraviolet luminosity of the starburst during their lifetime. If we consider a starburst lasting $\sim 2 \times 10^6$ yr, the approximate time it takes the radio hotspots to pass through the host galaxy, simple modelling using a standard initial mass function shows that its luminosity peaks at the point when the starburst ceases and, by a few $\times 10^7$ yr later, a typical maximum age for a radio source considering hotspot advance speeds to be $\sim 0.1c$, it will have decreased to ~ 10 per cent of the peak value. Thus the contribution of a starburst to the total optical (rest-frame ultraviolet) flux would be dramatically decreased in older radio sources. Note that the radio source's lifetime is comparable to the main-sequence lifetime of a star of mass 4 $M_{\odot}$, and so even the oldest radio sources will still possess noticeably blue colours in this picture.

Similar results were obtained by Chambers & Charlot (1990) who, in an attempt to associate all of the galaxy emission with young stars, demonstrated that the rest-frame ultraviolet flux falls off very rapidly when star formation has ceased. In the infrared waveband the starburst would persist much longer, but there its emission would be overwhelmed by that of the underlying old stellar population.

A second important effect is that the clouds of young stars would be virialized in the surrounding gas, with velocities of $v \sim \sqrt{2GM/r}$, which for typical values of $r \sim 15$ kpc and $M \sim 10^{12}$ $M_{\odot}$ gives $v \sim 750$ km s^{-1}, consistent with detected linewidths for these sources. These speeds are sufficiently high that small clouds of stars would disperse from the immediate vicinity of the radio jet. The crossing time in these sources is $t_c \sim 2r/v \sim (2$–$5) \times 10^7$ yr which, compared with typical source lifetimes, implies that there may be sufficient time for the knots of stars to disperse still further: the arc-like structures in 3C 280 and 3C 267 could represent regions where gas and stars are infalling back towards the nucleus, and the smaller scale of the alignment effect in 3C 252 and 3C 356, the largest sources, could be due to relaxation of the star-forming regions.

5 DISCUSSION

The high-resolution images of powerful radio galaxies at $z \sim 1$ provide new clues to the origins of the alignment effect. The evolution of the optical morphology of these galaxies with increasing radio size can plausibly be explained by models in which the dominant cause of the alignment of the optical and radio axes is star formation induced by the passage of the radio jets.

Although we have discussed the need for cold gas to be present within the radio galaxies in the context of the star formation model, this is also a general requirement of many other models: for example nebular continuum emission can only arise from regions of cold gas, whilst the large quantities of dust required within the body of the galaxy in the dust scattering model indicate the presence of accompanying cold material. These considerations raise the intriguing question of the origin of these cold clumps of material. In Rees' original star formation picture, the radio galaxies were supposed to be in the process of formation, and the clouds condensed out of the infalling pre-galactic material. Infrared observations of the 3C galaxies, however, indicate the presence of an old stellar population. The cold clumps may form as part of a cooling flow towards the central regions of these massive galaxies, which would be consistent with the detection of a number of these objects in the X-ray waveband (Crawford & Fabian 1995, and references therein). If this were the case, it is also reasonable to suppose that this cooling flow is responsible for the fuelling of the black hole and the formation of the radio jets in the first place.

ACKNOWLEDGMENTS

This work is based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA Inc., under contract from NASA. The National Radio Astronomy Observatory is operated by AURA Inc., under co-operative agreement with the National Science Foundation. PNB acknowledges support from PPARC. HJAR acknowledges support from an EC twinning project and a programme subsidy grant by the Netherlands Organization for Scientific Research (NWO). We thank the referee for helpful comments.

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