Mon. Not. R. Astron. Soc. **314**, 849–857 (2000)

The large-scale distribution of warm ionized gas around nearby radio galaxies with jet–cloud interactions

C. N. Tadhunter,[1★] M. Villar-Martin,[1,2] R. Morganti,[3] J. Bland-Hawthorn[4] and D. Axon[2]
[1]*Department of Physics, University of Sheffield, Sheffield S3 7RH*
[2]*Division of Physics and Astronomy, Department of Physical Sciences, University of Hertfordshire, College Lane, Hatfield, Herts AL10 9AB*
[3]*NFRA, PO Box 2, 7990 AA Dwingeloo, the Netherlands*
[4]*Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia*

Accepted 2000 January 14. Received 2000 January 10; in original form 1999 August 20

ABSTRACT
Deep, narrow-band Hα observations taken with the TAURUS Tunable Filter on the 4.2-m William Herschel Telescope are presented for two nearby radio galaxies with strong jet–cloud interactions. Although the brightest emission-line components are closely aligned with the radio jets – providing nearby examples of the 'alignment effect' most commonly observed in high-redshift ($z > 0.5$) radio galaxies – lower surface brightness emission-line structures are detected at large distances (tens of kpc) from the radio jet axis. These latter structures cannot be reconciled with anisotropic illumination of the interstellar medium by obscured quasar-like sources, because parts of the structures lie outside any plausible quasar ionization cones. Rather, the distribution of the emission lines around the fringes of the extended radio lobes suggests that the gas is ionized either by direct interaction with the radio components, or by the diffuse photoionizing radiation fields produced in the shocks generated in such interactions. These observations serve to emphasize that the ionizing effects of the radio components can extend far from the radio jet axes, and that deep emission-line imaging observations are required to reveal the true distribution of warm gas in the host galaxies. We expect future deep imaging observations to reveal similar structures perpendicular to the radio axes in high-z radio galaxies.

Key words: galaxies: active – galaxies: jets – quasars: general.

1 INTRODUCTION

Powerful radio galaxies are frequently associated with extended emission-line nebulosities which extend on radial scales of 5–100 kpc from the nuclei of the host early-type galaxies (Hansen, Norgaard-Nielsen & Jorgensen 1987; Baum et al. 1988). The morphological and kinematical properties of these nebulae provide important clues to the origins of the gas, and the origins of the activity as a whole. The study of such gas is, for example, important for our understanding of the building of galaxy discs and bulges by infall since their epoch of formation. Therefore, it is crucial to determine the extent to which the observed emission-line properties reflect the intrinsic distribution of the warm gas in the haloes of the host galaxies, and the extent to which they reflect the effects of the nuclear activity and interactions with the extended radio sources.

In most low-redshift ($z < 0.2$) radio galaxies the optical emission-line regions are broadly distributed in an angle around the nuclei of the host galaxies, the correlations between the optical and radio structural axes are weak, and the gas kinematics are often quiescent, with linewidths and velocity shifts consistent in most cases with gravitational motions in the host early-type galaxies (Tadhunter, Fosbury & Quinn 1989; Baum, Heckman & van Breugel 1990). However, optical observations reveal a dramatic change in the properties of the nebulosities as the redshift and radio power increase: the emission-line kinematics become more disturbed (compare Tadhunter et al. 1989 with McCarthy, Baum & Spinrad 1996) and the optical/UV structures become more closely aligned with the radio axes of the host galaxies (McCarthy et al. 1987; McCarthy & van Breugel 1989). The most recent high-resolution *Hubble Space Telescope* (*HST*) images of $z \sim 1$ radio galaxies show that the structures are not only closely aligned with the radio axes, but they are also highly collimated, with a jet-like appearance (Best, Longair & Rottgering 1996). The nature of the 'alignment effect' is a key issue for our general understanding of powerful radio galaxies, of particular relevance to the use of radio sources as probes of the high-redshift Universe.

★ E-mail: c.tadhunter@sheffield.ac.uk

Of the many models that have been proposed to explain the alignment effect, the two that have received the most attention are the *anisotropic illumination* and the *jet–cloud interaction*[1] models.

In the case of anisotropic illumination it is proposed that the gaseous haloes of the host galaxies are illuminated by the broad radiation cones of the quasars hidden in the cores of the galaxies (e.g. Barthel 1989), with the emission lines resulting from photoionization of the ambient ISM by the EUV radiation in the cones (e.g. Fosbury 1989), and the extended optical/UV continuum comprising a combination of the nebular continuum emitted by the warm emission-line clouds (Dickson et al. 1995) and scattered quasar light (Tadhunter, Fosbury & di Serego Alighieri 1988; Fabian 1989). The alignment of the obscuring tori perpendicular to the collimation axes of the plasma jets then leads to a natural alignment of the extended nebulosities with the radio axes. The best evidence to support the anisotropic illumination model is provided by polarimetric observations of powerful radio galaxies at all redshifts, which show evidence for high UV polarization and scattered quasar features (e.g. Tadhunter et al. 1992; Young et al. 1996; Dey & Spinrad 1996; Cimatti et al. 1996, 1997; Ogle et al. 1997). It would be difficult to explain these polarimetric results in terms of any mechanism other than scattering of the anisotropic radiation field of an illuminating quasar or active galactic nucleus (AGN). However, despite the success of the illumination model at explaining the polarization properties, a significant fraction of radio galaxies – comprising $\sim$30–50 per cent of radio galaxies at $z \sim 1$, and a smaller proportion at lower redshifts – are dominated by jet-like UV emission-line structures, which are more highly collimated than would be expected on the basis of the 45–60° opening half-angle illumination cones predicted by the unified schemes for powerful radio galaxies (Barthel 1989; Lawrence 1991). Moreover, the highly disturbed emission-line kinematics observed in many high-z sources are also difficult to reconcile with quasar illumination of the undisturbed ambient ISM of the host galaxies.

Jet–cloud interactions have the potential to explain many of the features of powerful radio galaxies that cannot be explained in terms anisotropic quasar illumination. Although the jet–cloud interactions are likely to be complex, at the very least the clouds will be compressed, ionized and accelerated as they enter the shocks driven through the ISM by the jets. Therefore, jet–cloud interactions provide a promising explanation for the high-surface-brightness and extreme emission-line kinematics of the structures aligned along the radio axes of high-z sources. Indeed, recent spectroscopic observations of jet–cloud interactions in low-redshift radio galaxies provide clear observational evidence for the acceleration and ionization of warm clouds by the jet-induced shocks (e.g. Clark et al. 1998; Villar-Martin et al. 1999). Moreover, theoretical modelling work has demonstrated that jet-induced shocks are a viable, if not unique, mechanism for producing the emission-line spectra of radio galaxies (e.g. Dopita & Sutherland 1996).

It is clear that no single mechanism can explain the emission-line properties of radio galaxies over the full range of redshift and radio power; some combination of AGN illumination and jet–cloud interactions is required, with the jet–cloud interactions becoming increasingly important as the redshift and/or radio power increases. However, a major problem with such a combined model is that, while the polarimetric results demonstrate that quasar illumination is important in many high-redshift sources, the extended structures are often dominated by highly collimated jet-like structures, with no sign of the broad cone-like emission-line distributions predicted by the unified schemes for powerful radio galaxies.

How do we explain this dearth of broad cones in the objects with the most highly collimated structures? Possibilities include the following.

(i) *The gas structures are intrinsically aligned along the radio axes of the high redshift sources*, so that the emission-line nebulae reflect the true distribution of warm/cool gas, rather than the ionization patterns induced by the jets or illuminating AGN. For example, West (1994) has proposed that a general alignment of the gas structures along the radio axis may be a natural consequence of the formation of giant elliptical galaxies in a hierarchical galaxy formation scenario, although it is not clear that the structures formed in this way would be quite as highly collimated as those observed in the high-z radio galaxies.

(ii) *The nuclei of the host galaxies do not contain powerful quasars*, and the ionization of the extended gas is dominated by the jets: either by direct jet/cloud interactions or by illumination by the relativistically beamed jet radiation. This scenario is supported by the discovery at low redshifts of a class of powerful radio galaxies with weak, low-ionization nuclear emission-line regions (see Laing et al. 1994; Tadhunter et al. 1998). However, at least some high-z radio galaxies with highly collimated UV structures show direct evidence for powerful quasar nuclei in the form of scattered quasar features in their polarized spectra, so this explanation cannot hold in every case.

(iii) *The broad-cone radiation of the buried quasars does not escape from the nuclear regions of the host galaxies*, because of the absorbing effects of circumnuclear gas. In this case the ionization of the extended gas in the aligned structures is likely to be dominated by jet–cloud interactions, but quasar or beamed jet radiation may also contribute along the jet axis, if the jets punch a hole in the obscuring material. Direct evidence for requisite obscuring material in the central regions is provided by the relatively high occurrence rate of associated C IV and Lyα absorption-line systems in the UV spectra of radio-loud quasars (e.g. Anderson et al. 1987; Wills et al. 1995), the relatively red SEDs of steep-spectrum radio quasars (Baker 1997), and the detection of significant broad-line reddening in a substantial fraction of nearby broad-line radio galaxies (e.g. Osterbrock, Koski & Phillips 1976; Hill, Goodrich & DePoy 1996).

(iv) *The dearth of broad ionization cones in the high-z sources is a consequence of an observational selection effect:* most of the existing emission-line images of the high-z sources have been taken in the light of the low-ionization [O II]λ3727 line, which is emitted particularly strongly by the jet-induced shocks (e.g. Clark et al. 1997, 1998), but is relatively weak in the more highly ionized quasar illumination cones. Thus, given that the published ground-based images of the high-z objects are relatively shallow and have a low spatial resolution, while the published *HST* images have a higher resolution but are insensitive to low-surface-brightness structures, the existing images are likely to be biased in favour of the high-surface-brightness shocked structures along the radio axes. In this case, we would expect deep emission images to reveal gaseous structures outside the main high-surface-brightness

[1] We use ‘jet–cloud interaction’ as a generic term to describe interactions between the warm interstellar medium (ISM) and the radio-emitting components, which could include the radio lobes and hotspots, as well as the radio jets.

structures aligned along the radio axes. If the gas away from the radio axis is predominantly photoionized by quasars hidden in the cores of the galaxies, we would expect the extended low-surface-brightness structures to have a broad distribution, consistent with quasar illumination. Detection of such emission-line morphologies in the objects with the most highly collimated structures would lead to a reconciliation between the anisotropic illumination and jet–cloud interaction models, thereby resolving the outstanding uncertainties surrounding the nature of the alignment effect.

In order to test the latter possibility, it is important to obtain deep emission-line imaging observations for the objects with closely aligned radio and optical structures. We report here pilot observations of two intermediate-redshift radio galaxies – 3C171 ($z = 0.2381$) and 3C277.3 ($z = 0.08579$) – which are nearby prototypes of the high-z radio galaxies, in the sense that they show high-surface-brightness emission-line structures that are closely aligned along their radio axes. The results challenge some commonly held assumptions about the ionization of the extended gaseous haloes around powerful radio galaxies.

2 OBSERVATIONS

Emission-line and continuum observations of 3C171 and 3C277.3(Coma A) were taken using the Taurus Tunable Filter (TTF) on the 4.2-m William Herschel Telescope (WHT) telescope at the La Palma Observatory on the night of 1998 January 27. A log of the observations is presented in Table 1, while a full description of the TTF is given in Bland-Hawthorn & Jones (1998a,b). Use of the $f/2$ camera of TAURUS with the Tek5 CCD resulted in a pixel scale of 0.56 arcsec pixel^{-1}, and the seeing conditions were subarcsec for the observations reported here. The faintest structures visible in the images for both objects have an Hα surface brightness of $\sim 1 \times 10^{-17}$ erg cm^{-2} s^{-1} arcsec^{-2}.

Because of ghosting effects in the flat-field images, no flat-fielding of the data was attempted. However, comparisons between images taken with different filters and/or with the objects placed in different positions on the detector demonstrate that the ghost images of stars and galaxies in the field do not contaminate the images of the main target objects described below.

The reduction of the images consisted of bias subtraction, atmospheric extinction correction, flux calibration, sky subtraction and registration. From the comparison between the measurements of the flux calibration standard stars taken at various times during the run it is estimated that the absolute flux calibration is accurate to within ± 30 per cent, and the Hα emission-line fluxes agree at this level with the long-slit spectroscopy measurements in Clark (1996). For the emission-line images, the TTF was tuned to the wavelength of Hα shifted to the redshift of the emission lines in the nuclear regions of the galaxies. However, velocity structure in the haloes of the host galaxies may result in the emission lines in the extended structures not being exactly centred in the TTF bandpass, which has a Lorentzian shape. We estimate that, at maximum, this will result in the fluxes being underestimated by a factor of 2 for components with extreme ± 600 km s^{-1} shifts, but this will not affect our main conclusions, which are based largely on the emission-line structures, rather than the emission-line fluxes.

In order to facilitate comparison between the radio and optical structures, radio images were obtained for both sources. The radio and optical images were registered by matching the positions of the core radio sources with the positions of the continuum centroids in the optical continuum images, with the pixel scale and rotation of the optical images calibrated using the known positions of stars in the CCD fields.

The radio image of Coma A was made using data taken with the Very Large Array (VLA) A-array configuration at 1.4 GHz (20 cm). This gives a resolution for the final image of 1.14×1.13 arcsec at PA -72. The data, which were extracted from the VLA archive, were originally presented and discussed in great detail by van Breugel et al. (1985). We therefore refer to that paper for all the radio information about Coma A.

The radio image of 3C171 was kindly provided by K. Blundell. The image was made with the VLA at 8 GHz with a resolution of 1.3 arcsec FWHM. More information about the radio characteristics of this source can be found in Blundell (1996).

3 RESULTS

3.1 3C277.3 (Coma A)

Previous spectroscopic and imaging observations of 3C277.3 by van Breugel et al. (1985) and Clark (1996) show the presence of a series of high-surface-brightness structures along the radio axis. These include a high-ionization emission-line region associated with knots in radio jet some 6 arcsec to the south-east of the nucleus, an enhancement in the emission-line flux close to the hotspot in the northern radio lobe, and an emission-line arc that partially circumscribes the northern radio hotspot. Although the kinematic and ionization evidence for a jet–cloud interaction in this source is less clear than in some other radio galaxies (e.g. 3C171: see below) – the ionization state is relatively high and the emission lines relatively narrow – van Breugel et al. (1985) found evidence for a jump in the emission-line radial velocities across the northern radio lobe, while Clark (1996) noted that the ionization has a minimum, and the electron temperature a peak, at the position of the northern radio hotspot. Note that there is no clear evidence for a powerful quasar nucleus in this source: the nuclear regions show no evidence for scattered quasar light, and the nuclear emission-line region has a relatively low luminosity and ionization state compared with the brightest extended emission-line regions along the radio axis.

Our deep Hα images (Figs 1a and b) show that the emission-line regions along the radio axis form part of a spectacular system

Table 1. Details of the TTF imaging observations for 3C171 and 3C277.3. The second and third columns give the central wavelengths/bandwidths for the blocking filters and the etalon respectively.

Object	Blocking Filter(Å) $\lambda_c/\Delta\lambda$	Etalon(Å) $\lambda_c/\Delta\lambda$	Exposure Time(s)	Seeing($''$) FWHM	Comments
3C171	8140/330	8124/28	1800	0.95	Hα + continuum
	8570/400	–	900	0.95	Continuum
3C277.3	7070/260	7124/19	2×900	0.98	Hα + continuum
	7580/280	–	900	0.98	Continuum

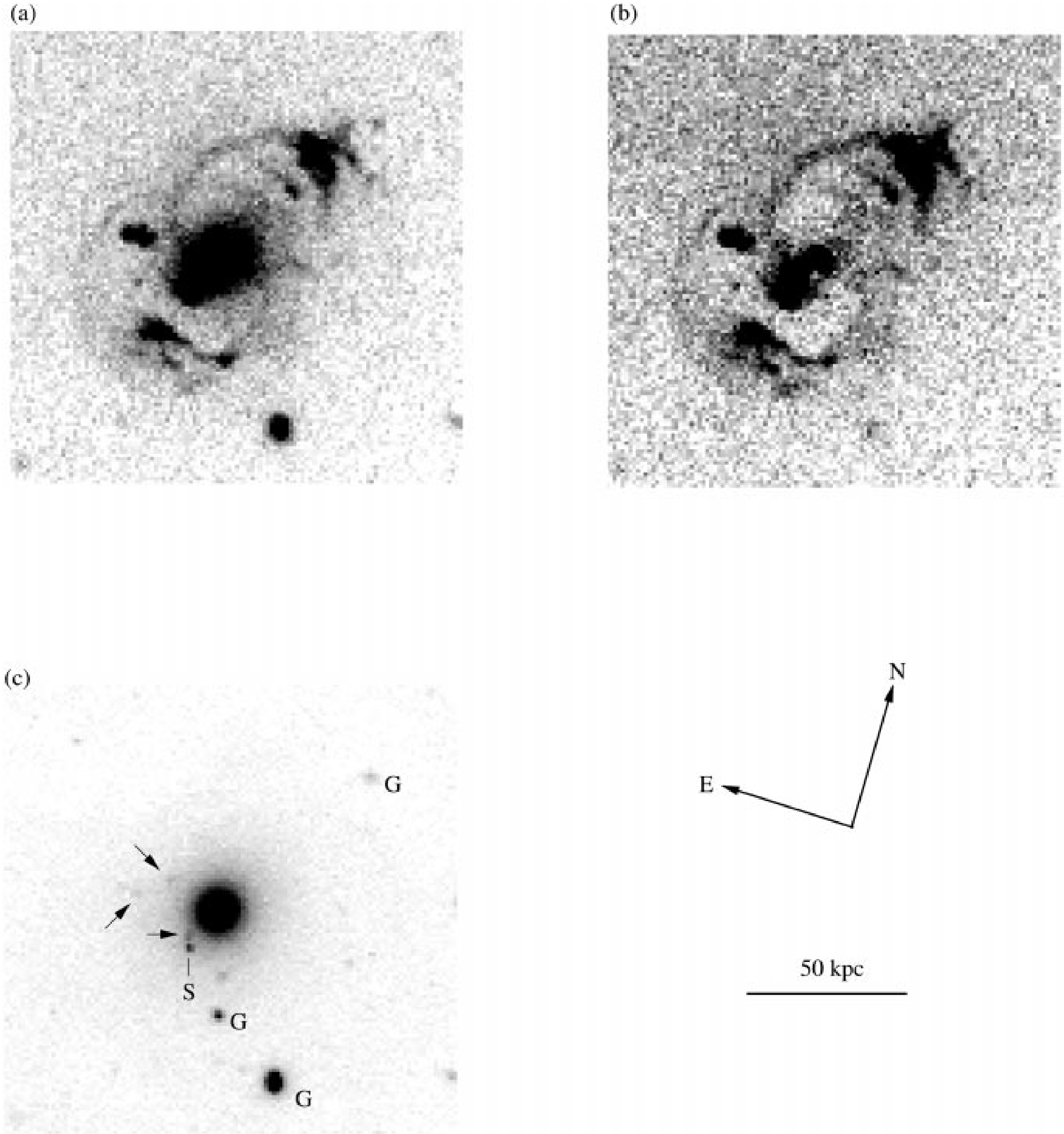

Figure 1. TTF images of Coma A (3C277.3). (a) Hα + continuum; (b) pure Hα; (c) continuum ($\lambda_c = 7580$ Å). In the continuum image the arrows point to faint continuum features associated with the extended Hα filamentary structures, the 'G' symbols indicate galaxies, while the 'S' symbol indicates a faint star (unresolved in *HST* images).

of interlocking emission-line arcs and filaments, which extend almost as far perpendicular as parallel to the radio axis. Of particular interest is the fact that the brightest arc structure wraps a full 180° around the nucleus, with enhancements in the emission-line surface brightness where the arc intercepts the radio axis to the north and south of the nucleus. The spatially integrated Hα fluxes of the bright knots along the radio axis (including the nucleus), the extended low-surface-brightness filaments and the nebula as a whole are 2.5×10^{-14}, 1.6×10^{-14} and 4.1×10^{-14} erg s^{-1} cm^{-2} respectively. For our adopted cosmology,[2] the corresponding Hα emission-line luminosities are 8.6×10^{41}, 5.6×10^{41} and 1.42×10^{42} erg s^{-1} respectively.

The fact that the main arc and filament structures are not visible, or are considerably fainter, in the intermediate-band continuum image (Fig. 1c) – which is at least as sensitive to continuum structures as the narrow-band Hα image – demonstrates that they are predominantly emission-line structures. However, a number of faint galaxies and continuum structures are detected within 100 kpc of the nucleus of Coma A, and at least some of these continuum structures (highlighted by arrows in the figure) are intimately associated with the extended Hα filamentary structures.

Overall, the Coma A system has the appearance of an interacting group of galaxies: the Hα filaments bear a marked resemblance to the H I tails detected in 21-cm radio observations of interacting groups (e.g. the M81 group: Yun, Ho & Lp 1994), and it is plausible that the faint continuum structures represent the debris of interactions/mergers between the dominant giant elliptical galaxy and less massive galaxies in the same group. The X-ray luminosity of Coma A ($L_{0.5\text{–}3\,\mathrm{keV}} < 8.1 \times 10^{42}$ erg s^{-1} : Fabbiano et al. 1984) is also consistent with a group environment.

Fig. 2 shows an overlay of the emission-line image and the

[2] $H_0 = 50$ km s^{-1} kpc^{-1} and $q_0 = 0.0$ assumed throughout.

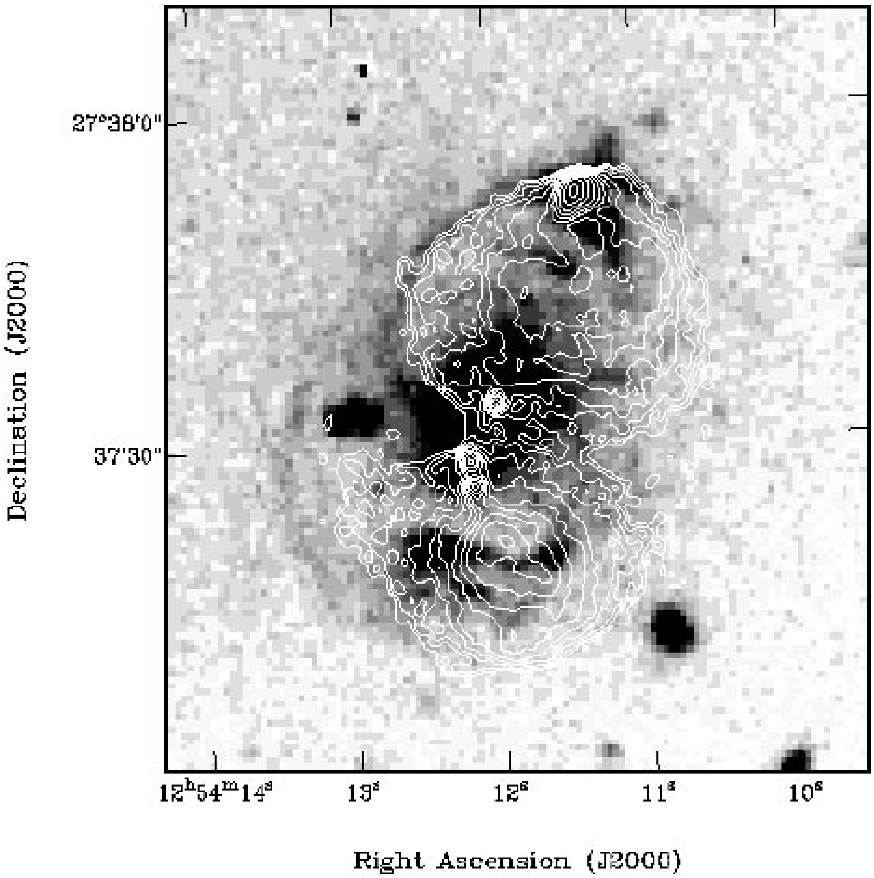

Figure 2. Overlay of the Hα + continuum image for Coma A (grey-scale) with the 6-cm radio map of van Breugel et al. (1985) (contours).

6-cm radio map. This reveals a striking match between the emission-line and radio structures. As well as the high-surface-brightness features along the radio axis, the brightest arc to the north of the nucleus closely follows the outer edge of northern radio lobe. The emission-line structures appear to bound the radio structures: the brighter emission-line features have a similar radial and lateral extent to the radio features. It is notable, however, that fainter, more diffuse emission-line structures are detected well outside the radio lobes on the northern and eastern sides of the galaxy.

The detection of arc structures circumscribing radio lobes is not without precedent: the intermediate-redshift radio galaxies PKS 2250−41 (Clark et al. 1998; Villar-Martin et al. 1999), 3C435A (Rocca-Volmerange et al. 1994) and PKS 1932−46 (Villar-Martin et al. 1998), the high-redshift radio galaxies 3C280 (McCarthy, Spinrad & van Breugel 1995) and 3C368 (Best et al. 1996) and the central elliptical galaxy in the cooling flow cluster A2597 (Koekemoer et al. 1999) all show evidence for arcs associated with radio lobes. In many of these cases there is also spectroscopic evidence that the emission-line gas extends beyond the radio lobes.

3.2 3C171

3C171 is another example of an object in which high-surface-brightness emission-line structures are closely aligned along the axis of the radio jets (Heckman, Breugel & Miley 1984; Baum et al. 1988). The spectroscopic evidence for a jet–cloud interaction in this source is strong: the emission-line kinematics along the radio axis are highly disturbed, and the the general line ratios and ionization minima coincident with the radio hotspots to the east and west of the nucleus provide strong evidence that the emission-line gas has been compressed and ionized by jet-induced shocks (Clark et al. 1998). A further possible consequence of the jet–cloud interactions is the highly disturbed radio structure, with the radio lobes showing a greater extent perpendicular than parallel to the jet axis, giving an overall H-shaped appearance (Heckman, Breugel & Miley 1984; Blundell 1996).

Our deep Hα and continuum images of this source are shown in Fig. 3, while an overlay of the optical emission-line image and the radio map is presented in Fig. 4. From the continuum-subtracted Hα image we measure spatially integrated emission-line fluxes of 2.12×10^{-14}, 6.2×10^{-16} and 2.63×10^{-14} erg s^{-1} cm^{-2} respectively for the high-surface-brightness structures aligned along the radio axis (including the nucleus), the faint filament to the north, and the nebula as a whole. The corresponding Hα emission-line luminosities are 6.6×10^{42}, 1.9×10^{41} and 8.1×10^{42} erg s^{-1} respectively.

Although the emission-line structures in 3C171 are clearly different in detail from those detected in Coma A, there are important general similarities. Most notably, as in Coma A, the highest surface brightness emission-line features are closely aligned along the radio axis, yet lower surface brightness structures are also detected in the direction perpendicular to the radio axis. The emission-line structures have a similar radial extent in the directions perpendicular and parallel to the radio axis. Away from the radio axis, the most striking emission-line feature is the filament that extends 9 arcsec (45 kpc) north of the

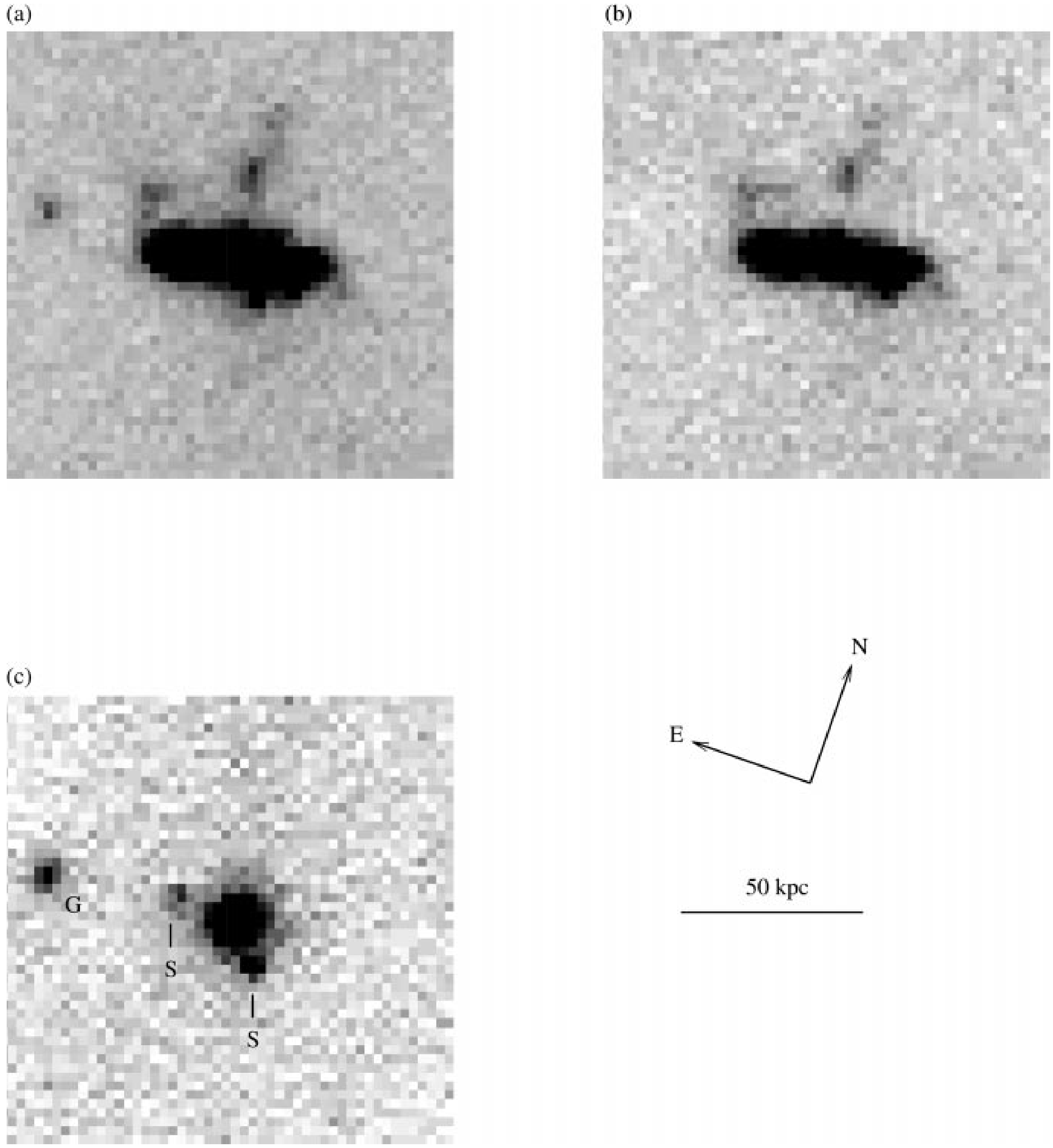

Figure 3. TTF images of 3C171: (a) Hα + continuum; (b) pure Hα; (c) continuum ($\lambda_c = 8570$ Å). The symbols have the same meaning as in Fig. 1.

nucleus. This feature lies along the fringes of the western radio lobe, just as the arc to the north of the nucleus in Coma A skirts the outer edge of the northern radio lobe in that object. A further similarity with Coma A is that, in the radio axis direction, the radio structures are confined within the emission-line structures, which have a similar radial extent. We also find evidence for emission-line gas that is not clearly associated with radio structures: the faint, diffuse Hα emission to the south-east of the nucleus lies well to the south of the extended eastern radio lobe. However, 3C171 is different from Coma A in the sense that the radio lobes extend further than the emission-line structures in the direction perpendicular to the radio axis on the northern side of the galaxy.

4 DISCUSSION

The main aim of the deep emission-line imaging observations was to attempt to detect the broad emission-line cones outside the main aligned structures, and thereby reconcile the AGN illumination and jet–cloud interactions models. The unified schemes predict illumination cones with opening half-angles of 45–60°. Although the extended emission-line nebulosities in low-redshift radio galaxies rarely show the sharp-edged cone structures observed in some Seyfert galaxies (e.g. Pogge 1988; Tadhunter & Tsvetanov 1989), the emission-line distributions are generally consistent with broad cone illumination of an inhomogeneous ISM (Hansen et al. 1987; Baum et al. 1988; Fosbury 1989). The detection of similar emission-line distributions in 3C171 and Coma A would support the idea that the extended ionized haloes are photoionized by quasars hidden in the cores of the galaxies.

The deep imaging observations presented in this paper have confounded our expectations in the sense that, while they do show extended of emission-line gas well away from the radio axis, the

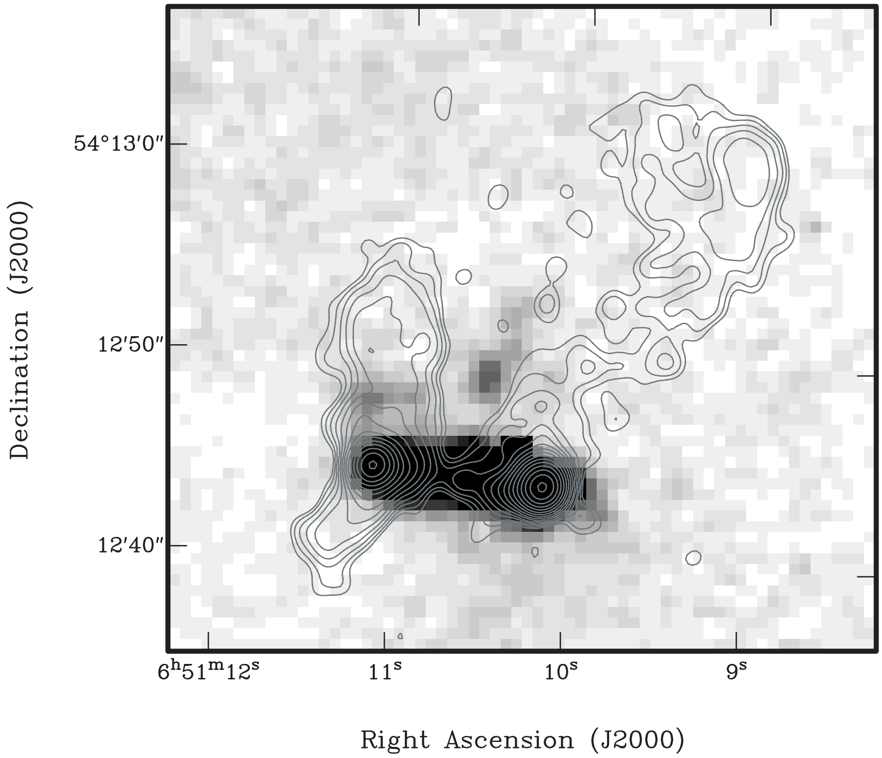

Figure 4. Overlay of the Hα image for 3C171 (grey-scale) with the 6-cm radio map of Blundell (1996) (contours).

emission-line distribution cannot be reconciled with any plausible ionization cone model. Not only do some of the features wrap through a full 180° in position angle around the nucleus of Coma A, but there are no sharp boundaries in the surface brightness of the structures, corresponding to the edges of an ionization cone. It is possible for the emission-line distributions to appear broader than the nominal 45–60° cones predicted by the unified schemes if the cone axes are tilted towards the observer. However, in order to explain the emission-line distributions in 3C171 and Coma A in this way, the cones would have to be tilted to such an extent that the observer's line of sight would lie within the cone and we would see the illuminating AGN directly. Clearly this is not the case, and it appears highly unlikely that the extended filaments away from the radio axis are photoionized by a central source of ionizing photons.

The most plausible alternative to quasar illumination is ionization by the shocks associated with the expanding radio jets and lobes. The emission lines could be produced as the warm clouds cool behind the shock fronts or, alternatively, as a consequence of photoionization of precursor clouds by the ionizing photons produced in the cooling, shocked gas. In either case we would expect a close morphological association between the radio and optical structures, just as we observe in 3C171 and Coma A. By adapting equation (4.4) of Dopita & Sutherland (1996), and assuming a shock speed through the warm clouds of $200\,\mathrm{km\,s^{-1}}$, we estimate that the rate of flow of warm ISM through the shocks would have to be at least $1.9\times10^4\,\mathrm{M_\odot\,yr^{-1}}$ for 3C171, and $3.2\times10^3\,\mathrm{M_\odot\,yr^{-1}}$ for Coma A, in order for the emission-line luminosities of the nebulae as a whole to be produced entirely by shock ionization. Energetically, the shock ionization mechanism appears to be feasible in the sense that the total emission-line luminosities of the sources are <10 per cent of the bulk powers of the radio jets (Clark 1996; Clark et al. 1998).[3]

However, it is not possible to rule out some contribution to the ionization of the extended structures by a central photoionizing source. As discussed in the Introduction, some radio sources with relativistic jets may not have powerful quasar nuclei. If this is the case, the narrow beams of radiation emitted by the jets could contribute to the ionization of the structures along the radio axis, although the ionization of the more extended filamentary structures would continue to be be dominated by interactions with the radio lobes.

One further possibility is that the structures are photoionized by young stars associated with the filaments. This is supported by the presence of faint continuum structures associated with the Hα filaments (see Fig. 1c), and the spectroscopic detection of excess UV continuum emission to the north and south of the nucleus along the radio axis above the level expected for the nebular continuum emitted by the warm gas (Clark 1996). Without further information on the nature and spectrum of the extended continuum structures it is difficult to test this model at the present time.

An open question for both 3C171 and Coma A is the extent to which the structures reflect the true distributions of ionized gas in the haloes of the host galaxies, and the extent to which the structures are distorted by their interaction with the radio components. It is possible for shock fronts to sweep up material into shell-like structures. However, given that the clouds are likely

[3] In order to derive this result we have scaled the results of Clark (1996), who considered only the emission-line components along the radio axis, to the total emission-line fluxes for the nebulae as a whole, as derived from our Hα images.

to be destroyed by hydrodynamical interactions with the fast, hot wind behind the shock fronts within a few shock crossing times (e.g. Klein, McKee & Colella 1994), and given also the presence of diffuse Hα emission well away from the radio structures in both Coma A and 3C171, it seems more plausible that these represent pre-existing gas structures. Cloud destruction by shocks may also lead to a relative absence of warm gas in the lobes, further enhancing the shell-like appearance of the emission-line structures. In the case of Coma A it is likely that we are seeing the results of interactions between between the radio-emitting components and the gaseous remnants of mergers/interactions in a group of galaxies.

Clearly, detailed measurements of the kinematics, line ratios and continuum spectra of the filamentary structures are required in order to resolve the outstanding issues concerning the physical state, ionization and origins of the warm gas.

5 IMPLICATIONS FOR HIGH-REDSHIFT RADIO GALAXIES

Our observations demonstrate the presence of extended gaseous structures well away from the high-surface-brightness structures aligned along the radio axes in two nearby radio galaxies. Given that Coma A and 3C171 are similar to the high-redshift radio galaxies in the sense that they show high-surface-brightness emission-line structures closely aligned along their radio axes, as well as evidence for disturbed emission-line kinematics, it seems likely that similar extended gaseous structures also exist in the high-z sources. In this case, the highly collimated structures visible in the existing images of some $z \sim 1$ 3C radio sources may reflect the ionization pattern induced by the radio jets more than the true distribution of warm/cool gas in the host galaxies.

Note, however, that 3C171 and Coma A have radio and emission-line luminosities that are an order of magnitude lower than 3C radio galaxies at $z \sim 1$. Furthermore, the radio lobes in 3C171 and Coma A extend further in the direction perpendicular to the radio jets than is typical in high redshift 3C radio sources. Therefore, it is difficult to predict the detectability of the extended low-surface-brightness structures in the high-z radio galaxies ($z > 1$) based on a straightforward extrapolation of the properties of 3C171 and Coma A. Given the smaller lateral extents of the radio lobes in the high-z sources, the ionization effects associated with the lobes may be less effective at large distances from the radio axes in such objects. In addition, the structures in the high-z sources will be subject to $(1+z)^{-4}$ cosmological surface brightness dimming which will make them more difficult to detect relative to nearby sources for similar intrinsic brightness levels. However, set against this is the fact that, in contrast to Coma A and 3C171, there exists good polarimetric evidence that many of the high-z radio galaxies contain powerful quasars hidden in their cores. Provided that the ionizing photons in the broad ionization cones can escape the nuclear regions (but see discussion in introduction), illumination by the quasar cones will enhance the surface brightnesses of the extended structures and render them more easily detectable.

The extended low-surface-brightness structures may already have been detected spectroscopically in at least one high-z source: deep, long-slit Keck spectra taken along the radio axis of 3C368 ($z = 1.135$) by Stockton, Ridgway & Kellogg (1996) show the presence of a faint emission-line region well outside the main high-surface-brightness emission-line regions closer to the nucleus. The relatively narrow lines and high ionization state measured in this faint, low-surface-brightness region are consistent with quasar illumination of the undisturbed ambient medium of the host galaxy.

Some encouragement may also be drawn from the detection of large Lyα haloes around radio galaxies at $z > 2$ (e.g. Adam et al. 1997). Although the Lyα in these haloes may not be formed by direct photoionization by an AGN, but rather by resonant scattering of Lyα photons produced in the extended regions around the nuclei (Villar-Martin, Binette & Fosbury 1996), these observations at least demonstrate the presence of extensive haloes of cool ISM surrounding the host galaxies of some of the highest redshift radio galaxies.

Thus, we expect future deep emission-line imaging of $z \sim 1$ radio galaxies to reveal the true distribution of the extended ionized gas in the host galaxies, and to provide clues to the origins of the gas and the evolution of the host galaxies.

6 CONCLUSIONS

Deep emission-line imaging observations of two nearby examples of the radio–optical alignment effect have revealed extensive low-surface-brightness emission-line structures well away from the radio axes, thus demonstrating that the intrinsic distribution of warm gas is more extensive than previously suspected.

The general distribution of the gaseous structures is incompatible with the standard quasar illumination picture, while their association with the extended radio structures provides clear evidence that they are interacting with the radio lobes, hotspots and jets. These may be objects in which the ionization of the extended emission-line regions is entirely dominated by shocks induced by interactions between the radio plasma and the ISM.

It is often assumed that the broad distribution of ionized gas observed in low-redshift radio galaxies without clear signs of jet–cloud interactions implies illumination by the broad ionization cones of quasars hidden in the cores of the galaxies. These new observations suggest that this may not always be the case, and that the lobes as well as the jets may have a significant ionizing effect.

ACKNOWLEDGMENTS

The Willian Herschel Telescope is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roches de los Muchachos of the Instituto de Astrofisica de Canarias. We thank Katherine Blundell for allowing us to use her radio image of 3C171. MVM acknowledges support from PPARC.

REFERENCES

Adam G., Rocca-Volmerange B., Gerard S., Ferruit P., Bacon R., 1997, A&A, 326, 501

Anderson S. F., Weymann R. J., Foltz C. B., Chaffee F. H., 1987, AJ, 94, 278

Baker J. C., 1997, MNRAS, 286, 23

Barthel P. D., 1989, ApJ, 336, 606

Baum S. A., Heckman T. M., Bridle A. H., van Breugel W., Miley G. K., 1988, ApJS, 68, 833

Baum S. A., Heckman T. M., van Breugel W., 1990, ApJS, 74, 389

Best P. N., Longair M. S., Rottgering H. J. A., 1996, MNRAS, 280, L9

Bland-Hawthorn J., Jones D. H., 1998a, Publ. Astron. Soc. Aust., 15, 44

Bland-Hawthorn J., Jones D. H., 1998b, in Proc. SPIE Vol. 3355, Optical Astronomical Instrumentation. SPIE, Bellingham WA, p. 85
Blundell K. M., 1996, MNRAS, 283, 538
Cimatti A., Dey A., van Breugel W., Antonucci R., Spinrad H., 1996, ApJ, 465, 145
Cimatti A., Dey A., van Breugel W., Hurt T., Antonucci R., 1997, ApJ, 476, 677
Clark N. E., 1996, PhD thesis, Univ. Sheffield
Clark N. E., Tadhunter C. N., Morganti R., Killeen N. E. B., Fosbury R. A. E., Hook R. N., Shaw M., 1997, MNRAS, 286, 558
Clark N. E., Axon D. J., Tadhunter C. N., Robinson A., O'Brien P., 1998, ApJ, 494, 546
Dey A., Spinrad H., 1996, ApJ, 459, 133
Dickson R. D., Tadhunter C. N., Shaw M. A., Clark N. E., Morganti R., 1995, MNRAS, 273, L29
Dopita M. A., Sutherland R. S., 1996, ApJS, 102, 161
Fabbiano G., Miller L., Trinchieri G., Longair M., Elvis M., 1984, ApJ, 277, 115
Fabian A. C., 1989, MNRAS, 238, 41P
Fosbury R. A. E., 1989, in Meurs E. J. A., Fosbury R. A. E., eds, ESO Workshop on Extranuclear Activity in Galaxies, European Southern Observatory, Garching bei München, p. 169
Hansen L., Norgaard-Nielsen H. U., Jorgensen H. E., 1987, A&AS, 71, 465
Heckman T. M., van Breugel W. J. M., Miley G. K., 1984, ApJ, 286, 509
Hill G. J., Goodrich R. W., DePoy D. L., 1996, ApJ, 462, 162
Klein R., McKee C., Colella P., 1994, ApJ, 420, 213
Koekemoer A. M., O'Dea C. P., Sarazin C. L., McNamara B. R., Donahue M., Voit G. M., Baum S. A., Gallimore J. F., 1999, ApJ, 525, 621
Laing R. A., Jenkins C. R., Wall J. V., Unger S. W., 1994, in Bicknell G. V., Dopita M. A., Quinn P. J., eds, ASP Conf. Ser. Vol. 54, 1st Stromlo Symposium on the Physics of Active Galaxies. Astron. Soc. Pac., San Francisco, p. 227
Lawrence A., 1991, MNRAS, 252, 586
McCarthy P. J., van Breugel W., Spinrad H., Djorgovski S., 1987, ApJ, 321, L29
McCarthy P. J., van Breugel W., 1989, in Frenk C., ed., The Epoch of Galaxy Formation. Kluwer, Dordrecht, p. 57
McCarthy P. J., Spinrad H., van Breugel W. J. M., 1995, ApJS, 99, 27
McCarthy P. J., Baum S., Spinrad H., 1996, ApJS, 106, 281
Ogle P. M., Cohen M. H., Miller J. S., Tran H. S., Fosbury R. A. E., Goodrich R. W., 1997, ApJ, 482, 370
Osterbock D. E., Koski A. T., Phillips M. M., 1976, ApJ, 206, 898
Pogge R. W., 1988, ApJ, 328, 519
Rocca-Volmerange B., Adam G., Ferruit P., Bacon R., 1994, A&A, 292, 20
Stockton A., Ridgway S. E., Kellogg M., 1996, AJ, 112, 902
Tadhunter C. N., Tsvetanov Z., 1989, Nat, 341, 422
Tadhunter C. N., Fosbury R. A. E., di Serego Alighieri S., 1988, in Maraschi L., Maccacaro T., Ulrich M. H., eds, Proc. Como Conf. 1988, BL Lac Objects. Springer-Verlag, Berlin, p. 79
Tadhunter C. N., Fosbury R. A. E., Quinn P., 1989, MNRAS, 240, 255
Tadhunter C., Scarrott S., Draper P., Rolph C., 1992, MNRAS, 256, 53P
Tadhunter C. N., Morganti R., Robinson A., Dickson R., Villar-Martin M., Fosbury R. A. E., 1998, MNRAS, 298, 103
van Breugel W., Miley G., Heckman T., Butcher H., Bridle A., 1985, ApJ, 290, 496
Villar-Martin M., Binette L, Fosbury R. A. E., 1996, A&A, 312, 751
Villar-Martin M., Tadhunter C. N., Morganti R., Clark N., Killeen N., Axon D., 1998, A&A, 332, 479
Villar-Martin M., Tadhunter C. N., Morganti R., Axon D., 1999, MNRAS, 307, 24
West M. J., 1994, MNRAS, 268, 79
Wills B. J. et al., 1995, ApJ, 447, 139
Young S., Hough J. H., Efstathiou A., Wills B. J., Axon D. J., Bailey J. A., Ward M. J., 1996, MNRAS, 279, L72
Yun M. S., Ho P. T. P., Lo K. Y., 1994, Nat, 272, 530

This paper has been typeset from a TEX/LATEX file prepared by the author.