VLBI observations of galaxies at high redshift

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Abstract

Subsets of fifteen high redshift radio galaxies have been observed with VLBI arrays at 327 MHz, 1.66 GHz or 5 GHz. Here we present results of VLBI imaging of four high redshift radio galaxies, three at 327 MHz and one at 1.66 GHz. Results so far show that 1) compact 1 kpc hotspots dominate the VLA components, 2) the magnetic field strengths in the hotspots are an order of magnitude higher than in Cygnus A, 3) the estimated ages of the sources are considerably longer than the radiative lifetimes of electrons in the hotspots, implying energy resupply, and 4) the ratios of overall size to hotspot size are consistent with the correlations found by Hardcastle *et al* (1998) for FR II radio galaxies and Snellen *et al* (1998) for GPS and CSS radio galaxies. We also investigate the possibility that the misalignment of the components to the southwest in 4C41.17 may be caused by deflection of the jet by an interstellar cloud of mass $\sim 10^8$ solar masses, possibly a proto globular cluster.

1 Introduction

The three most common components of observable emission of radio galaxies at high redshift, IR/optical/UV continuum, optical emission lines, and radio continuum are all highly luminous and spatially extended. Not only can different diagnostics be derived for each of these components, but studies of the relationships between them can place unique constraints on the emission mechanisms, the dynamical state of the thermal plasma, the physical state of the galaxy's environment, and the star formation history.

Radio galaxies are the only objects at z>2 which as a class can be well resolved by ground-based optical telescopes. In many cases the radio structure contains compact features unresolved on the arcsecond scale. In order to investigate the nature of the compact features and their possible role in the alignment of the optical radiation preferentially along the radio axis, we have begun a programme to study the most distant radio galaxies with VLBI. Our specific goals are 1) to investigate the sub-structure in the hotspots observed in VLA observations of these objects, 2) to image the nuclear components at high angular resolution and compare the results with optical data from the HST, 3) to compare the structures in radio galaxies and quasars at high redshift to see whether they can be unified purely on the basis of orientation, and 4) to compare the radio properties of galaxies at high and low redshift and search for evolution in the morphological properties with time.

A total of 15 objects have been observed so far at either 327 MHz (92 cm), 1.66 GHz (18 cm) or 5 GHz (6cm). Three out of nine were detected and imaged at 327 MHz, one has been imaged at 1.66 GHz, a further five have been observed at 1.66 GHz but the data have not yet been reduced, and one of the latter five has also been observed at 5 GHz.

2 Observations and data reduction

At 327 MHz, the sample of nine objects was selected from a list observed at 15 GHz (2 cm) with the VLA by Chambers *et al* (1996) and which showed evidence of compact structure on scales of 200 milliarcsec. The objects were:
0124+495 (4C49.06), 0508+605 (4C60.07), 0630+469 (4C46.12), 0647+416 (4C41.17), 1345+245 (4C24.28), 1803+110 (3C368), 1809+407 (4C40.36), 2105+233 (4C23.56), and 2349+289 (4C28.58).

Observations with a global VLBI array of 10 telescopes were made at 327 MHz (Cai *et al* 1998) in order to take advantage of the steep spectrum of the objects and to allow an order of magnitude increase in angular resolution. Fringes were detected for 3 of the 9 objects; images with centi-arcsecond angular resolution were made of the sub-structure in the lobes of 1345+245, 1809+407 and 2349+289. The remaining six objects were not detected at this angular resolution.

At 1.66 GHz, five objects have been observed from amongst those known to have a nuclear component from VLA observations. Of these only 4C41.17 (0647+415) has been fully reduced (Gurvits *et al* 1997). This source was observed with a five telescope array in the EVN at 18 cm.

One source, 1243+036, was observed at 5 GHz with a six telescope array in the EVN. The data await further reduction.

3 Results

3.1 Images

Figures 1–3 show the images of 1345+245, 1809+407 and 2349+289 obtained at 327 MHz, and Figure 4 the image of the nucleus of 4C41.17 obtained at 1.66 GHz and shown in relation to the VLA image at 5 GHz obtained by Carilli *et al* 1994).

3.2 1345+245 (4C24.28)

The two components detected in our VLBI observations correspond to the two lobes seen in the VLA image by Chambers *et al* (1996) with a separation of 2.44 arcsec. The south-western component is stronger than its north-eastern counterpart which is in the opposite sense to that observed in the VLA images. Both components are slightly extended along position angles different to the line joining them. No emission has been detected at 327 MHz at the position of the weak inner component visible in the VLA 5 and 15 GHz images, thought by Chambers *et al* to be the jet.

3.3 1809+407 (4C40.36)

Like the Chambers *et al* (1996) VLA images, the VLBI image contains two components separated by 3.64 arcsec. The western component appears slightly resolved with a size of 150 milliarcsec and the eastern component somewhat more resolved with a size of 220 × 70 milliarcsec. Only a small fraction of the low brightness emission seen in the eastern component in the VLA images is

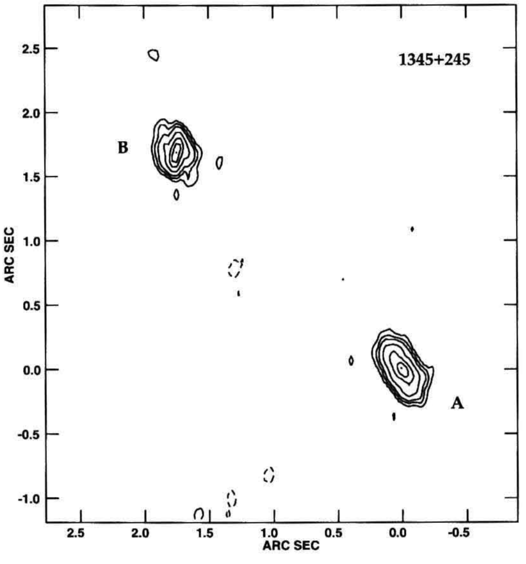

Figure 1. Brightness distribution of the source 1345+245. Contours levels are −2, 2, 5, 10, 25, 50, 75, 99 % of the peak flux density of 1.07 Jy/beam; beam size is 100×100 mas.

detected here. The sum of the flux densities of the two VLBI components is ~90% of the total flux density at 327 MHz of 2.9 Jy. It is clear that the spectrum of the eastern component has turned over, so that its flux density is considerably less than expected from extrapolation from high frequency.

3.4 2349+289 (4C28.58)

Our VLBI image contains two lobes at positions coinciding with those in the VLA images; the separation is 14.50 arcsec. The south-eastern component is resolved at our resolution, with sub-components of angular size less than 100 milliarcsec. The spectra of the two components remain steep down to 327 MHz. The flat spectrum component seen at 5 and 1.4 GHz with the VLA is not visible either in our VLBI images or at 15 GHz with the VLA.

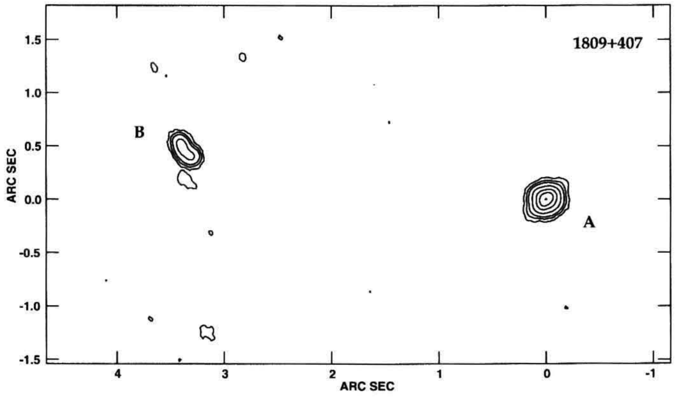

Figure 2. Brightness distribution of the source 1809+407. Contours levels are −2, 2, 3, 5, 10, 25, 50, 75, 99 % of the peak flux density of 0.621 Jy/beam; beam size is 100 × 100 mas.

4 Physical parameters

4.1 Luminosity, size, magnetic field strength and age

The monochromatic luminosities at 327 MHz for the individual components (in fact hotspots) are typically 10^{29} W/Hz while their total radio luminosities range from 10^{46} to 4x10^{49} erg/sec (Gurvits *et al* 1997; Cai *et al*, 1998) – very luminous radio emitters! The sizes of the individual components measured at 327 MHz in 1345+245, 1809+407 and 2349+289 are typically 1 kpc while with the higher resolution at 1.66 GHz for 0647+415 the size of the brightest VLBI component is found to be 65 pc (Gurvits *et al* 1997). The overall sizes of the four objects range from 22 to 107 kpc. The ratio of largest angular size to hotspot size for these sources is consistent with the relationship found by Hardcastle *et al* (1998) for FR II radio galaxies and by Snellen *et al* (1998) for GPS and CSS galaxies. These relationships provide strong evidence for self-similar evolution over a wide range of physical and time scales (*e.g.* Snellen *et al*, 1998: Kaiser and Alexander, 1998) .

Assuming minimum energy conditions and energy equipartition (Miley 1980), we can calculate (Gurvits *et al* 1997; Cai *et al* 1998) component magnetic field

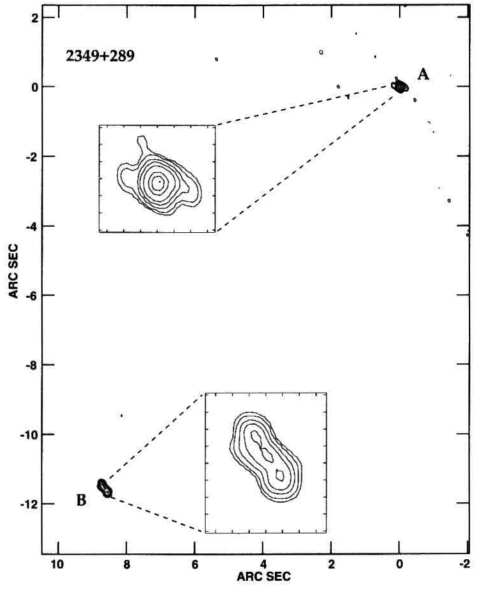

Figure 3. Brightness distribution of the source 2349+289. Contours levels are -2, -1, 1, 2, 5, 10, 20, 50, 75, 99 % of the peak flux density of 1.19 Jy/beam; beam size is 100 $\times$ 100 mas. Tick separation in the insets is 100 mas.

strengths. The magnetic field strengths derived 10^{-2} to 10^{-3} G are significantly higher than typical for lower redshift galaxies *e.g.* Cygnus A, 3×10^{-4} G (Carilli and Barthel 1996). This may indicate that the density of the IGM and the intergalactic magnetic field in the early universe is higher than in the nearby universe.

The overall sizes of the sources imply ages of at least 10^5 years (equivalent to component motion at the speed of light), while the radiative lifetimes of the individual components, assuming no resupply of energy and calculated by dividing the energy in relativistic electrons by the total radio luminosity, are 10^3 to 3×10^4 years. This is evidence for the existence of a continuing supply of energy to the lobes, presumably from the central object.

4.2 The bent jet in 0647+415 (4C41.17)

The only evidence we have for jets supplying the energy to the hotspots in these sources is found in 4C41.17. The lower panel in Figure 4 shows low level components to the west of the main component at an intermediate position angle to that between N and B1 (-103°) and between B1 and A (-126°); this may indicate the path of jet propagation. Assuming the jet is bent at B1 due to interaction with an interstellar cloud, estimates of momentum transfer to B1 suggest that the mass of the cloud is of the order of 10^8 solar masses (Gurvits *et al*, 1997). It is not out of the question that B1 is the pre-cursor to a globular cluster forming in the galaxy some 3 kpc from the nucleus (Fall and Rees 1977, Rees 1977).

Of course many assumptions have gone into this mass estimate, one of which is that the cloud is not displaced by more than its "size" due to momentum transfer from the jet during the radiative lifetime of B1 of 2.2×10^3 years. The size is taken as the distance from the bright eastern component in the VLBI image to the westernmost weak component, (860 pc). Whether this is a valid assumption is not possible to prove or disprove with the current state of our knowledge. If the cloud is not to be disrupted, it may require to be more massive than 10^8 solar masses. Figure 4b gives a sketch of the interaction proposed.

5 Unification of high redshift galaxies and quasars

The radio morphologies of high redshift galaxies are lobe dominated and very different to those of their high redshift quasar counterparts which are strongly core dominated (*e.g.* Frey *et al* 1997). Can they be unified on the basis of orientation alone? The answer is not yet clear, partly because the samples of quasars and galaxies observed so far are not matched in luminosity. The cores in the galaxies are 2 to 3 orders of magnitude weaker than the quasars which is consistent with there being strong beaming in the quasars (and presumably superluminal motion), but it also implies that we should see quasars further from the line of sight with more prominent jets. Perhaps these will be found in samples of fainter high redshift quasars (*e.g.* Britzen and de Bruyn, private communication) which are matched in luminosity to the galaxies.

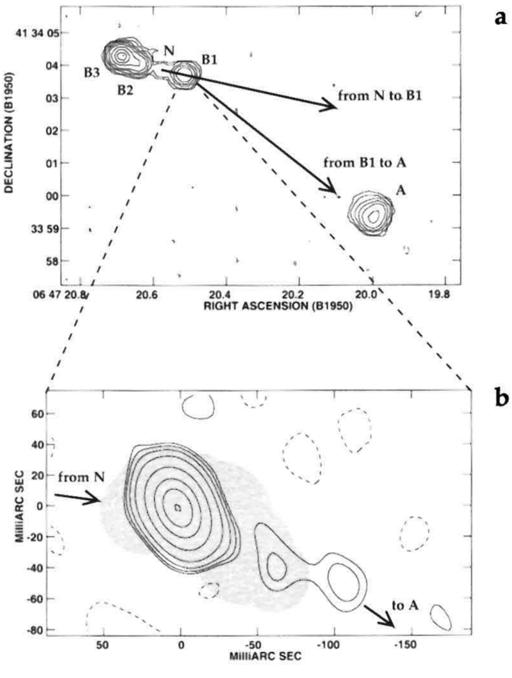

Figure 4. a). VLA image of 4C41.17 at 6 cm (Carilli et al., 1994);
b). VLBI 18 cm image of the component B1. Contour levels: -2, 2, 3, 5, 10, 25, 50, 75, 99 % of the peak brightness of 8.2 mJy/beam; restoring beam is 38.1×26.8 mas in PA 21.4°. The shaded area shows a hypothetical cloud responsible for the jet bending. Arrows indicate directions of the jet propagation before and after the assumed interection with the cloud.

6 Conclusions

Our VLBI study of high redshift radio galaxies has led to the following conclusions:
1) compact 1 kpc hotspots are found dominating the VLA components;
2) no radio cores are detected at 327 MHz which is consistent with their having flat radio spectra and with the sensitivity of the observations;
3) with standard assumptions, the magnetic field strengths in the hotspots are 10^{-2} to 10^{-3} G which is an order of magnitude stronger than in the low redshift galaxy, Cygnus A. Again with standard assumptions, the largest angular sizes of the sources suggest ages which are one to two orders of magnitude longer than the radiative lifetimes estimated from the total electron energy. This implies that there is resupply of energy from the nucleus or that shock reacceleration occurs in the hotspots;
4) the ratio of overall size to hotspot size is consistent with the correlation found by Hardcastle *et al* (1998) for FR II radio galaxies and by Snellen *et al* (1998) for GPS and CSS galaxies.

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References

Cai Z., Schilizzi R. T., Gurvits L. I., Miley G. K., Bremer M. A. R., Röttgering H. J. A., Nan R., Liang H., Chambers K. C., 1998, Astron. Astrophys. (submitted)
Carilli C. L., Owen F. N., Harris D. E., 1994, Astron J. **107**, 480
Carilli C. and Barthel P. D., 1996, Astron. Astroph. Rev. **7**, 1
Chambers K. C., Miley G. K., van Breugel W. J. M., Bremer M. A. R., Huang J.-S., Trentham N. A., 1996, Astrophys. J. Supp. **106**, 247
Fall S. M. and Rees M. J., 1977, MNRAS 181, 37

Frey S., Gurvits L. I., Kellermann K. I., Schilizzi R. T., Pauliny-Toth I. I. K., 1997, Astron. Astrophys. **325**, 511

Gurvits L. I., Schilizzi R. T., Miley G. K., Peck A., Bremer M. N., Röttgering H. J. A., van Breugel W., 1997, Astron. Astrophys. **318**, 11

Hardcastle M. J., Alexander P., Pooley G. G., Riley J. M., 1998, MNRAS, 288, 859

Kaiser C. R., Alexander P., 1997, Mon. Not. R. Astr. Soc. **286**, 215

Miley G. K., 1980, Ann. Rev. Astron. Astrophys. **18**, 165

Rees M. J. , 1977, in Evolution of galaxies and stellar populations, eds. B.M.Tinsley and R.B.Larson, Yale University Press, p. 339

Snellen I. A. G., Schilizzi R. T., de Bryun A. G., Miley G. K., 1998, Proc. IAU Coll. 164 "Radio Emission from galactic and extragalactic compact sources", eds. G. B. Taylor, J. M. Wrobel, J. A. Zensus, ASP (in press)