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VLA Observations of Hot Spots in High Luminosity Radio Sources

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Abstract. VLA observations at 6 cm have been made of 16 distant luminous 3C sources that appeared to be unresolved or slightly resolved in Cambridge maps but which were known from VLBI observations to contain significant fine structure on the scale of about 1 kpc in their lobes. The general morphology of these sources is very similar to that of their nearby powerful counterparts; most of the lobes contain low brightness tails which are often directed from the hot spots towards the associated optical object. The hot spots are generally unresolved by the VLA observations; in 3C 254, 3C 268.4 and 3C 352, one of the lobes contains two hot spots.

Key words: hot spots—radio galaxies—quasars

1. Introduction

Most of the powerful extragalactic radio sources are known to contain regions of enhanced brightness near the outer edges of their double radio lobes. Such 'hot spots' are believed to represent the ends of beams that supply energy from the nucleus of the associated galaxy or quasar to the outer lobes. The sizes and morphologies of hot spots can therefore provide valuable information on the formation of double sources and on the interaction of beams with the intergalactic medium. Due to the limited angular resolution of aperture-synthesis instruments, hot spots have generally been well mapped only in the relatively nearby sources, in which they appear to have

*Present address: Netherlands Foundation for Radio Astronomy, Dwingeloo, The Netherlands sizes of up to a few kpc. In the more distant (and hence more powerful) sources where the outer lobes themselves are often of the order of ten kpc (or smaller) in size, it has not generally been possible to map any finer-scale structure in the lobes. Single-baseline interferometric observations (*e.g.* Wilkinson 1972) have however suggested such structure on a scale of $\lesssim 0{\cdot}5$ arcsec. More recently, VLBI observations (Kapahi and Schilizzi 1979a, b) have indicated the presence of significant structures on a scale of $< 0{\cdot}1$ arcsec (corresponding to linear sizes of < 1 kpc) in several distant sources selected from the 3CR catalogue. These results suggest that the statistical properties of hot spots derived from observations *with a fixed angular resolution,* of sources covering a large range in redshift, such as the reported strong correlation between the total source luminosity and the fractional flux density in hot spots (Jenkins and McEllin 1977), could be seriously contaminated by resolution effects (see *e.g.* Kapahi 1978; Neff and Rudnick 1980).

In this paper we present synthesis maps, made at 6 cm with the partially completed N.R.A.O.* Very Large Array (VLA), of several 3CR sources that appeared from the VLBI observations to contain significant fine structure in their lobes. The aims of the observations were twofold: firstly to check that the fine structure indicated by the limited VLBI data had been correctly identified with features in the outer lobes and secondly to map the structure of the hot spots when possible. The angular resolution of the present observations is typically in the range of about 0·5 to 1 arcsec, significantly better than was previously available for most of these sources. Our results show the presence of bright regions towards the outer edges of most of the sources and indicate the need for much higher angular resolution to map the hot spots adequately.

2. Observations and results

Measurements of 16 sources were made at 4·885 GHz on 1979 June 29–30 with the partially completed VLA. A maximum of sixteen antennas were in operation, with typically thirteen available for any particular observation. The baselines ranged from 0·1 to 18·25 km. Each source was observed at two to seven different hour angles (see Table 1); individual scans were typically 3 minutes in length, Observations of 17 calibrator sources were interleaved with those of the programme objects to allow a reasonable understanding of the amplitude and phase behaviour of the array during that time.

Table 1. Number of hour angles at which each source was observed.

Source	No. of scans	Source	No. of scans
3C 13	7	3C 263	7
3C 22	5	3C 268·4	6
3C 55	4	3C 270·1	6
3C 186	6	3C 280	6
3C 196	6	3C 330	4
3C 216	7	3C 334	4
3C 220·2	7	3C 352	2
3C 254	6	3C 455	3

*Operated by Associated Universities, Inc., under contract with the U.S. National Science Foundation.

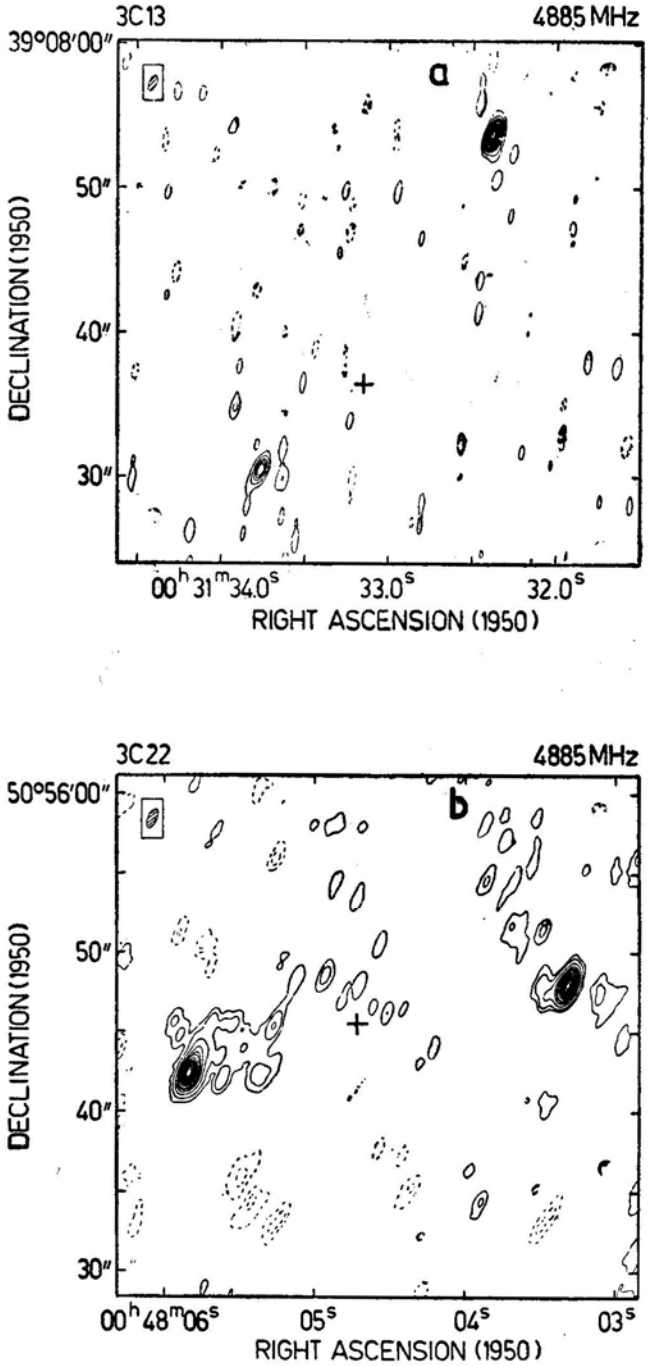


Figure 1. (a) 3C 13: peak flux is 191 mJy. (b) 3C 22: peak flux is 182 mJy. The optical position is from Riley, Longair and Gunn (1980).

Following a point-by-point editing, the data were self-calibrated using an early version of the self-calibration technique of Schwab (1980). The self-calibrated data were then used to produce CLEANed maps of the brightness distribution of the sources. Contour representations of these maps are shown in Fig. 1–9. Maps with a restoring beam of half the dimensions of the main lobe of the dirty beam were also generated to give an indication of the presence of more compact structures in the sources (even though it is known that such 'super-resolution' does not give unique information on source structure). The results of this analysis are mentioned in the following notes.

2.1 *Notes on the Individual Source Structure*

Here we give comments on the source structure, making reference to the VLBI data of Kapahi and Schilizzi (1979a, b), hereafter KS, and to other maps of the sources. The KS data allowed only a rough estimate of angular size, < 0·15 arcsec, to be made. Linear sizes are determined using q_0 = 0·5 and H_0 = 50 km s^{-1} Mpc^{-1}, and redshifts obtained from Smith and Spinrad (1980) and references therein. In the following, N and S refer to 'north' and 'south' ,*p* and *f* to 'preceding' and' following', when referring to the relative positions of components.

Figs 19 show contour maps of the sixteen sources. Contour levels are —5, —2, − 1, 1, 2, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80 and 90 per cent of the peak values in the maps for 3C13, 55, 220·2, 254, 334, 352 and 455. In all of the other maps the lowest contours are at the 2 per cent level except for 3C 270·1, where the 5 per cent contour is the lowest one shown. Beamsizes and orientations are indicated in boxes on each map. The best available optical positions (generally accurate to better than 1 arc-sec unless noted otherwise) are also marked on the contour maps.

3C 13 (Fig. 1a): There is some evidence of extended structure in the 2 and 5 per cent contours of the northern component. This is confirmed by Laing (personal communication) using the complete VLA; his map shows inward extensions in both components at levels below our lowest contour. The point-like components in our map presumably contain the (< 1·3 kpc, z = 1·05) structures observed by KS in both lobes.

3C 22 (Fig. lb): Both components show evidence of unresolved hot spots at the outer edges of the lobes which are probably associated with the compact components (< 0·08 arcsec) found in both lobes by Schilizzi and Seielstad (unpublished observa tion) at 13 cm.

3C 55 (Fig. 2): Fig. 2 is in broad agreement with the maps of Jenkins, Pooley and Riley (1977) at 5 GHz and of Laing (1981) at 2·7 GHz. The map shows that the western lobe has a hot spot at the outer edge, with an inward extension at position angle (PA) ~ 80°; the eastern lobe has a central hot spot with extensions to east and west. The eastern extension, which appears real, was not detected in the Cambridge observation. The VLBI data of KS show that there is compact structure < 0·7 kpc in the western lobe only. Laing (1981) did not detect the hot spots at 15 GHz which implies < 20 mJy in structure < 0·5 arcsec at this frequency. The spectrum of the western hot spot must therefore be steep.

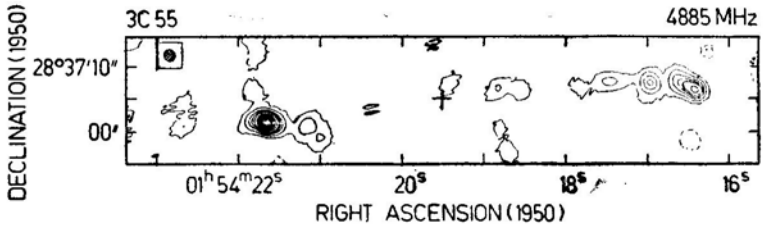


Figure 2. 3C 55: peak flux is 174 mJy.

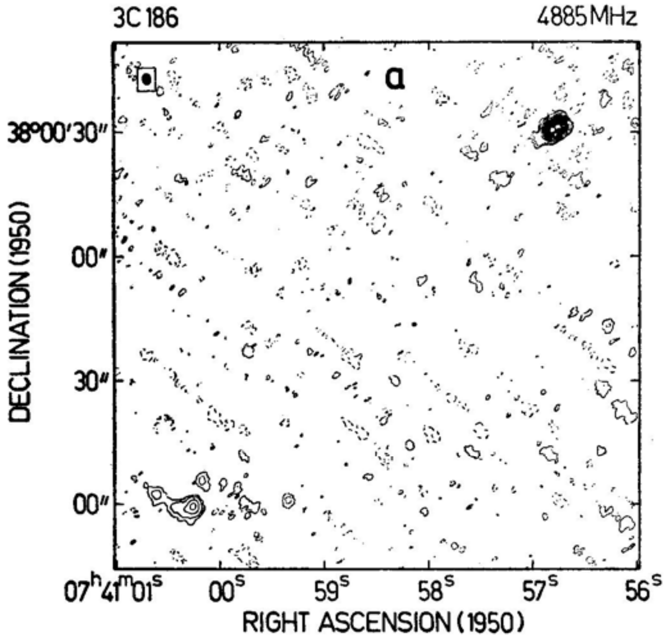
3C 186 (Fig. 3a): Both components are extended and there is no evidence of a link between the N*p* and S*f* components. Fig. 3b shows the N*p* component to be a double separated by 1·2 arcsec in PA 137° with extensions to the north and south (note that Fig. 3a does not have the same scale north-south as east-west). The optical object (17·6 mag quasar, z = 1·0630) lies close to the northern component of the double, which is the weaker of the two. The errors in the radio and optical scales do not, however, preclude the optical object lying between the two lobes, which is the more likely location in view of the steep radio spectrum. The VLBI structure of KS (< 1·3 kpc) is associated with the close double.

3C196 (Fig. 4a): The weak structure seen to the south-east of the N*f* component in the maps by Pooley and Henbest (1974) at 5 GHz and by Lonsdale and Morison (1980) at 408 MHz, is almost completely resolved out by the VLA. Laing (1981) has shown that this component has a steep spectrum. Similarly, the structure to the north-west of the S*p* component seen in the Lonsdale and Morison (1980) map is resolved out here, or its spectrum is too steep for the present dynamic range to retrieve. Laing (1982) gives a recent VLA map in which the extended regions are seen well at 5 GHz. The data of KS indicate substantial resolution on scales of 0·15 arcsec (<1·3 kpc), probably in the southern lobe.

3C 216 (Fig. 4b): The structure appears triple with a central bright component presumably coincident with the optical object (18·48 mag quasar, z = 0·668). Porcas and Pauliny-Toth (personal communication) have detected a 1 milli-arcsec component at 6 cm in 3C 216 with ~ 30 per cent of the flux density; this must surely be associated with the nucleus of the quasar. The variation in flux density observed by KS could well be due to compact structure <0·15 arcsec (< l·2 kpc) in one or both of the lobes on either side of the core. The weak component to the south-west is probably real.

3 C 220·2 (Fig. 5a): Each of the lobes shows a hot spot at the outer edge of the structure. The inward extensions of both lobes curve towards the central component. The VLBI measurements of KS were unable to distinguish which of the three components contained compact structure (<l·3 kpc). It is quite likely that the hot spots in the outer lobes do contain compact structure since there is not sufficient flux density in the core component to account for all the observed 21-cm flux density of KS unless the core has a steep spectrum.

3C 254 (Fig. 5b): Several authors (*e.g.* Pooley and Henbest 1974; Laing 1981) have remarked on the unusual position of the quasar associated with this source which



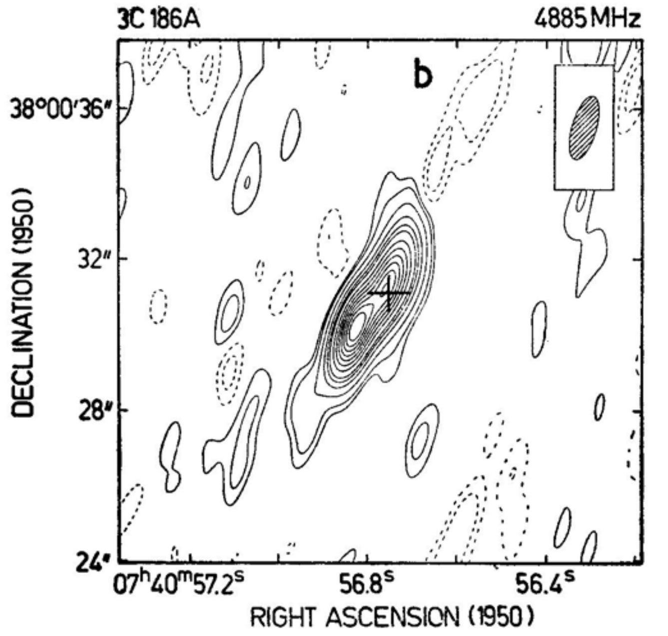
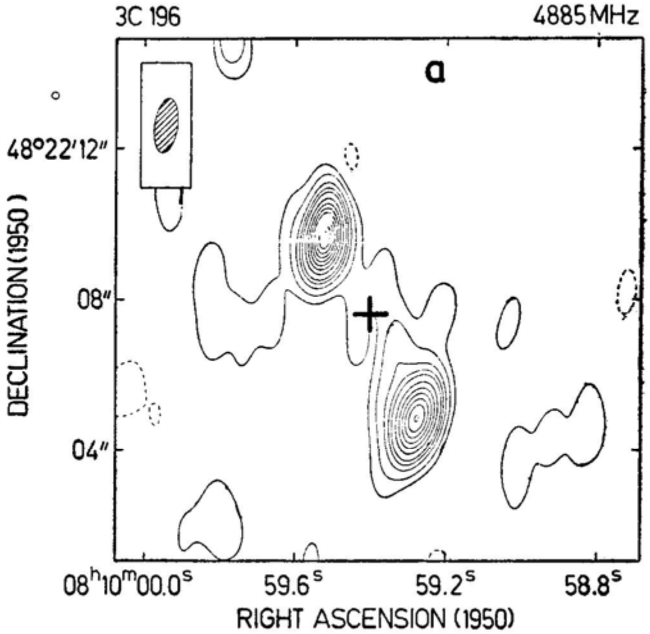


Figure 3. 3C186: peak flux is 128 mJy. The optical position is from Argue and Kenworthy (1972).



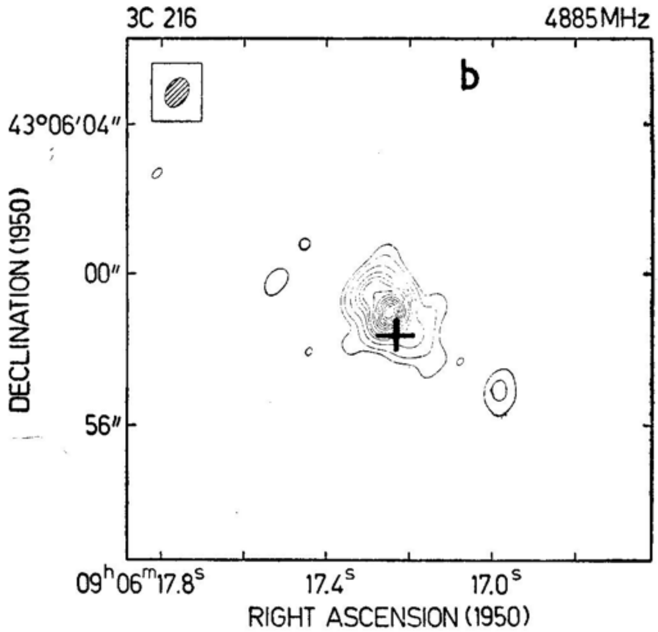
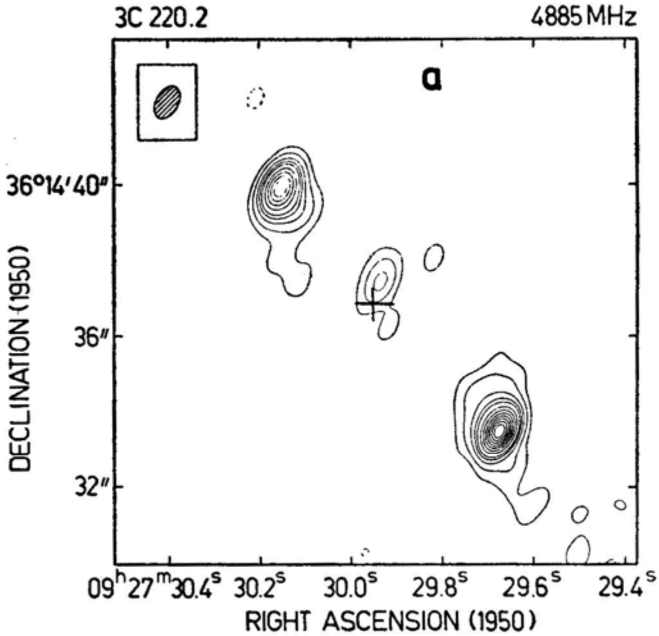


Figure 4. (a) 3C196: peak flux is 1289 mJy. (b) 3C216: peak flux is 1156 mJy. The optical position is from Cohen *et al.* (1977).



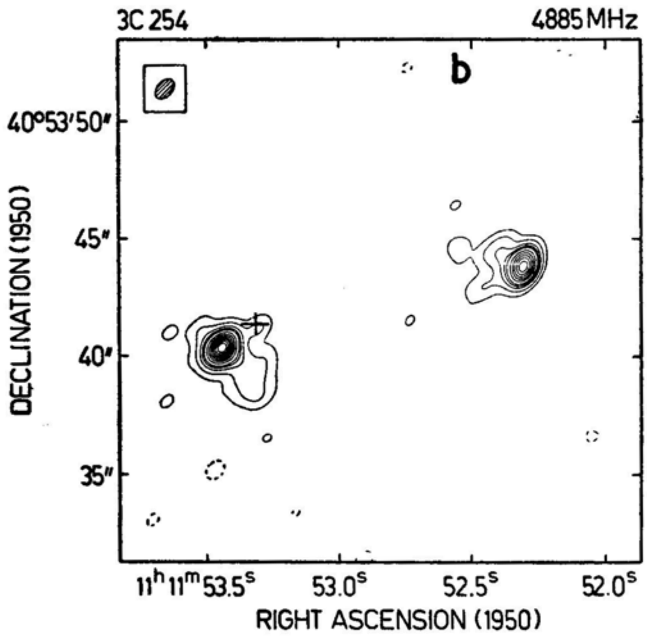


Figure 5. (a) 3C 220.2: peak flux is 212 mJy. (b) 3C 254: peak flux is 216 mJy. The optical position is from Riley, Longair and Gunn (1980).

lies to the northwest of the S*f* component. It clearly has a weak radio emission associated with the nucleus seen here in the lowest two contours. Each lobe is extended, being composed of a hot spot and a low brightness tail pointing approximately at right angles to the source axis. Laing (personal communication) has made a more recent VLA map which shows the N*p* lobe to be double in PA ~ 2° (also indicated by restoration of the present data with a smaller beam). KS found structure < 1·2 kpc in both lobes. There is not sufficient flux in the nuclear component to have been detected by KS if the core spectrum is flat.

3C263 B (Fig. 6a): This is the eastern part of the source only. The N*p* component in this map is unresolved and coincident with a 16 mag quasar (z = 0·6463). The S*f* component is composed of a hot spot and a low brightness extension back towards the nucleus. Both components contain structure on the scale of 1·2 kpc (KS).

3C268·4 (Fig. 6b): Both outer lobes are extended; the *Sp* component appears to have a double structure (separation 0·94 arcsec in PA 122°) as seen in a map restored with a smaller beam. The alignment of the *Sp* double is approximately perpendicular to the overall source axis. At 15 GHz, Laing (1981) detected only a single component in the Sp lobe whose position coincides with the stronger (north-west) component of the double seen by us. It is therefore likely that the weaker component of the double has a steep spectrum. The VLBI data of KS indicate that the *Sp* lobe contains compact structure on the scale of < 1·3 kpc.

3C 270·1 (Fig. 7a): The southernmost component is slightly extended to the west (see Stocke, Christiansen and Burns 1982, for a more recent VLA map). KS could not distinguish between the core component and the southern component for the location of their observed compact structure (<1·3 kpc).

3C280 (Fig. 7b): The structure is quite similar to 3C254 in having a compact, low-brightness component located close to one of the two main lobes. This component does not, however, coincide with the proposed identification (Gunn *et al.* 1981) in contrast to 3C 254. The western component appears extended to the north-west, away from the hot spot. A more recent VLA map by Laing (personal communicaiton) shows this extension in more detail as well as the compact component referred to above. The eastern component in our map appears slightly resolved; again in Laing's map greater detail is seen, the component having a low-level inward extension. The evidence from KS points to the western lobe as containing compact structure on the scale of 0·15 arcsec; though compact, the low-surface-brightness component near the western lobe is not strong enough to contribute all of the flux density seen by KS.

3C330 (Fig. 8a): The overall structure is in broad agreement with that of Jenkins, Pooley and Riley (1977) and Laing (1981). Both components are extended towards each other but there is no central component. The low-brightness inward extension of the N*f* component is more clearly seen in the present map than in the earlier maps. From very limited data KS suggested that the *Sp* component was the more likely candidate for the observed compact structure (< 1 kpc). From our map, the N*f*

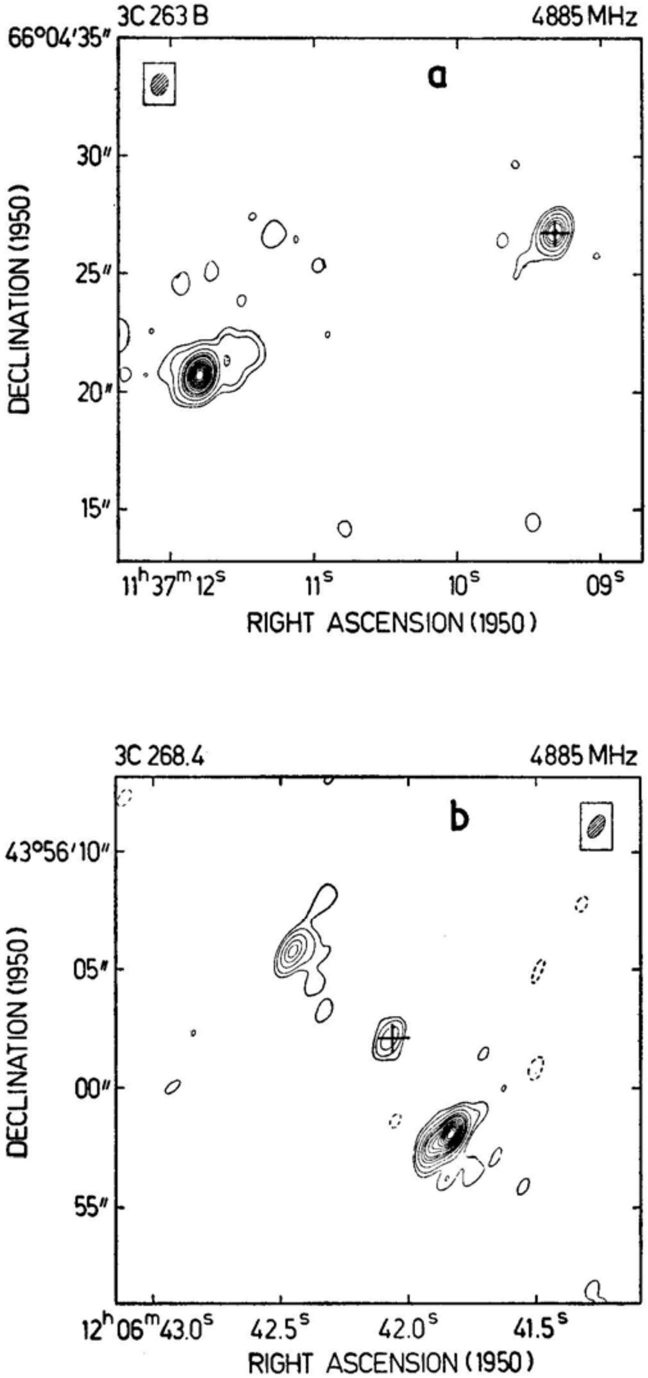


Figure 6. (a) Eastern part of 3C 263: peak flux is 485 mJy. There is little compact structure in the western lobe (Pooley and Henbest 1974). (b) 3C 268·4: peak flux is 302 mJy.

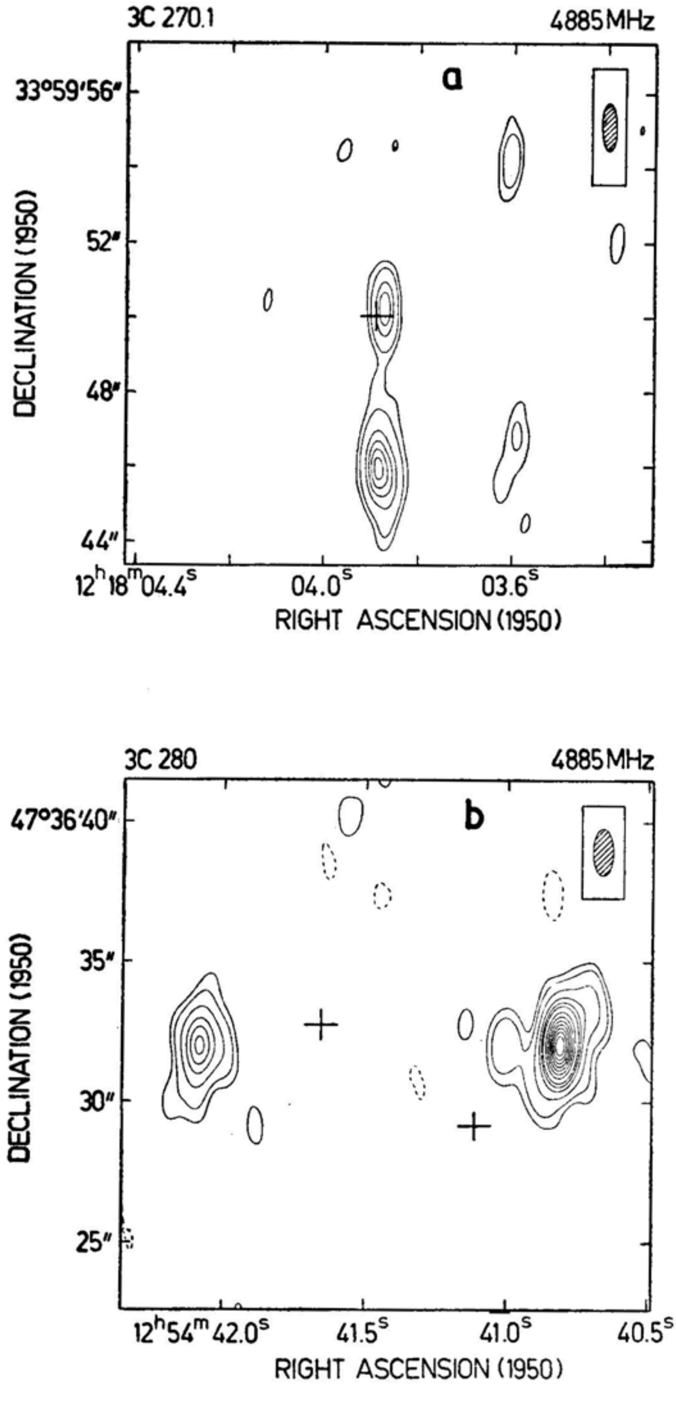


Figure 7. (a) 3C 270·1: peak flux is 247 mJy. (b) 3C 280: peak flux is 904 mJy. The optical positions are from Gunn *et al.* (1981).

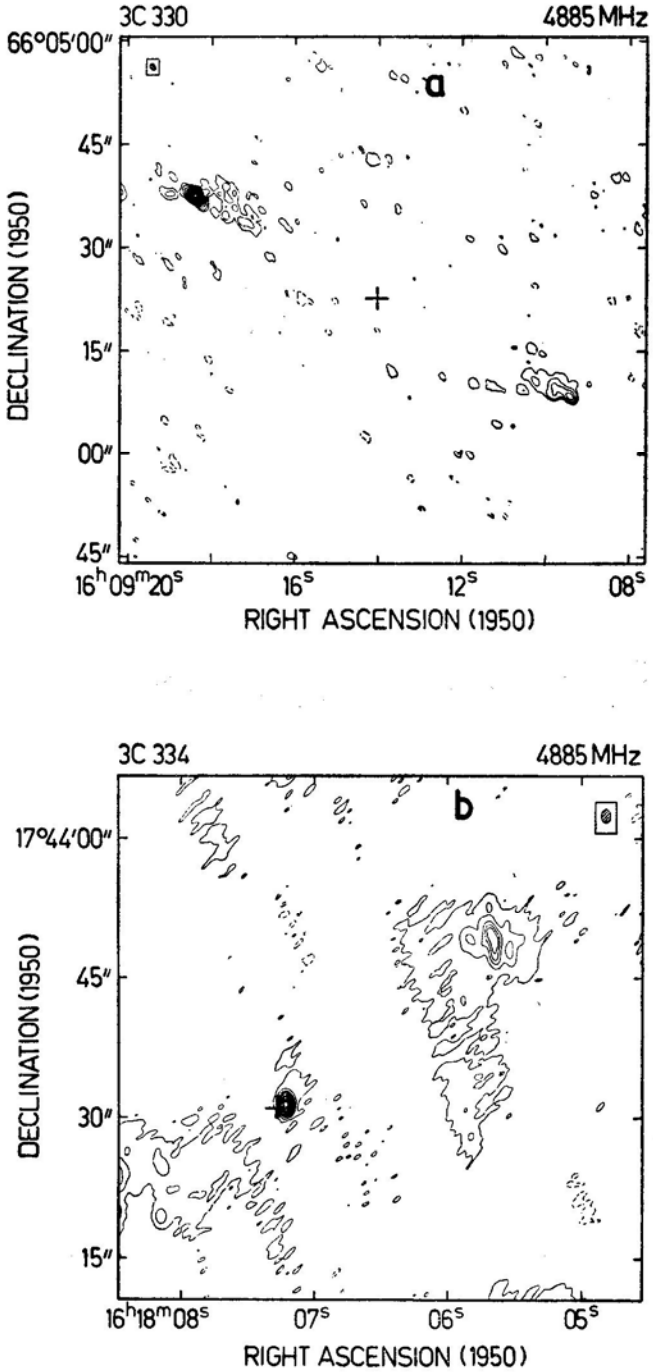


Figure 8. (a) 3C 330: peak flux is 679 mJy. (b) 3C 334: peak flux is 135 mJy. There is no compact structure in the eastern lobe (Jenkins, Pooley and Riley 1977).

component looks more likely than the *Sp* because it is far stronger, although the *Sp* is also edge-brightened. Laing (1981) notes that the N*f* component has a significantly steeper spectral index than the *Sp* between 5 and 15 GHz, but not between 2·7 and 5 GHz. This can be understood from a comparison of the present map with Laing's. The weak extension seen in our map to the north-east of the hot spot in the N*p* lobe is not present in the 15 GHz map, implying a steep spectrum for this feature.

3C334 (Fig. 8b): The structure is similar to the map of Jenkins, Pooley and Riley (1977) except that the northern component here is very much more resolved. The compact component (< 1·1 kpc) detected by KS is clearly associated with the central quasar. The KS structure shows considerable effects of resolution which might be arising from the narrow jet near the core seen in a recent VLA map by Wardle and Potash (1982).

3C352 (Fig. 9a): The Np component is a close double separated by 1·5 arcsec in PA – 22° with extensions to the south-west and north-east seen in the 2, 5 and 10 per cent contours. The strongest feature appears unresolved in this component. The S*f* component has one unresolved feature with extensions towards east and west up to the10 per cent level. There is some evidence of these extension in both components in the map by Jenkins, Pooley and Riley (1977). No emission can be seen at the position of the associated galaxy. KS could not unambiguously determine the location of their detected compact structure (< 1·2 kpc).

3C455 (Fig. 9b): The S*p* component is extended towards the N*f* component. The optical object (quasar, z = 0·543) is associated with the unresolved N*f* component; the structure may therefore be of the D2 class, and the compact structure (< 1·1 kpc) of KS would then most likely be in this component.

3. Conclusion

The outer lobes of most of the high-luminosity sources reported here were previously known from maps made with the Cambridge 5-km telescopes (with a resolution of 2 × cosec δ arcsec at 5 GHz) to be unresolved or only slightly resolved, therefore usually appearing to consist of 'naked' hot spots without any associated regions of extended emission. The present VLA observations show that most of the lobes actually have extended emission in the form of low brightness 'tails' which often, though not always, point back towards the associated galaxy or quasar. The hot spots appear in general to be unresolved (<0·3 arcsec). In at least 3 of the sources discussed in this paper, (3C 254, 268·4, and 352) there is evidence for one of the lobes containing two hot spots. Such multiple-hot-spot structure has also been found to be fairly common by Laing (1981) from observations with the Cambridge 5-km telescope at 15 GHz.

From VLA observations at 15 GHz of several powerful but relatively nearby (z < 0·2) radio galaxies, Dreher (1981) has recently noted that the hot spots often have sharp outer edges (< 300 pc wide) oriented perpendicular to the source axis. Because such small features would subtend angles < 0·04 arcsec at high redshifts, it is not surprising that the present observations show little fine structure in the hot

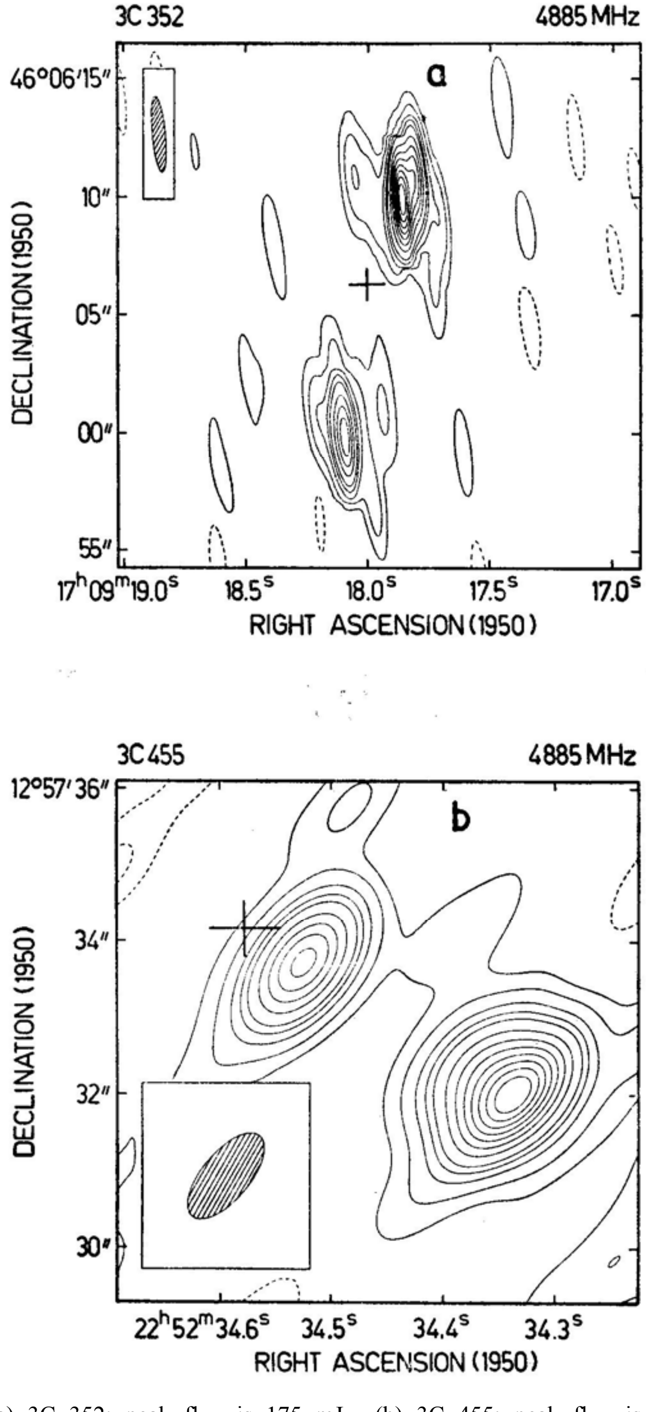


Figure 9. (a) 3C 352: peak flux is 175 mJy. (b) 3C 455: peak flux is 253 mJy.

spots. We plan to look for such fine structure with multi-station observations in the European VLBI network. We expect multiple hot spots to be as common in the powerful, distant sources as they are in the more nearby luminous radio galaxies. If this proves not to be the case, it will have interesting implications for theories of radio-source evolution.

The current observations indicate that the distant, luminous radio sources are morphologically very similar to their nearby, radio-powerful counterparts. Most of the observed structural differences appear to result from observing the distant sources with limited resolution, or limited dynamic range, or both.

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