KILOPARSEC SCALE STRUCTURE IN HIGH LUMINOSITY RADIO SOURCES OBSERVED WITH MTRLI

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1. INTRODUCTION

The new Jodrell Bank Multi-Telescope-Radio-Link Interferometer system (MTRLI) began operating in January 1980 with four telescopes and with its full complement of six telescopes in December 1980. The location of the telescopes and the baseline lengths (in km) thus obtained are shown in Fig. 1. However, before describing some of the exciting new results it has yielded on high luminosity radio sources it is important to outline the capabilities of the instrument since the maps are produced in a rather different way to those from conventional synthesis instruments.

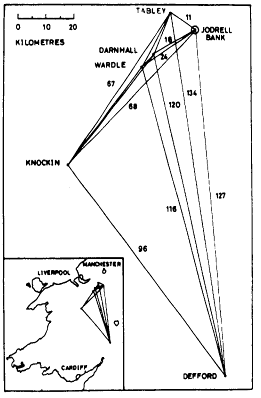

Fig.1 The MTRLI

2. OUTLINE OF THE MTRLI MAPPING CAPABILITY

The technical details of the MTRLI have been outlined elsewhere[1] and need not concern us here since, regardless of the equipment, the phase stability on such long baselines as these is fundamentally limited by the variations in the atmospheric/ionospheric delay over each telescope. And while a few observations have been made using compact sources within the primary telescope beams as phase references to calibrate out these phase variations so far nearly all the MTRLI maps have been produced using 'closure' phase[2]; thus they should more properly be termed "hybrid" maps[3].

Notwithstanding this reliance on closure phase which limits us to mapping only those sources which give fringes above the noise on all baselines, the mapping capability of the system has far exceeded our initial expectations. The methodology we have adopted to analyse the data strongly resembles that of the 'self-calibration' technique now in use for improving VLA maps[4]. We assume that, apart from fixed

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offsets, all the errors in the amplitude and phase of the fringes are associated with the individual telescopes. An algorithm (CORTEL)[5] has been written to correct these telescope errors via an iterative scheme involving CLEAN and we are now routinely obtaining maps whose noise levels approach the limit set by thermal noise (typically ∿1 mJy/beam). This has resulted in maps whose dynamic range is >1000:1 on strong sources dominated by a single compact component.

In the number of telescopes employed and in the use of 'closure' methods the MTRLI should be very like present-day VLBI arrays in its mapping capabilities. Why then are our maps markedly superior in noise level/dynamic range to any VLBI maps published so far? To first order it is because the fringe amplitude calibration on MTRLI (1→2% r.m.s.) is typically five times better than in VLBI where there are rarely a priori unresolved sources to normalise each baseline to the same flux scale. Secondly we believe that the CORTEL algorithm is more sophisticated than the early hybrid mapping methods used in VLBI. The (u,v) coverage obtained with MTRLI is only somewhat better than in many current VLBI experiments and so this cannot be a major contributory factor to the superior dynamic range of MTRLI compared with current VLBI.

Extensive simulations on artificial data have shown that the (u,v) coverage allows us to map linear sources (i.e. Virgo or Cygnus A-like) whose dimensions are ≲50 CLEAN beams. Larger sources must be convolved with a bigger beam until the ∿50-beam criterion is satisfied. At the major observing frequencies of 408, 1666 and 5000 MHz the conventional CLEAN beam is nearly circular at all declinations above 10^{o} and has a FWHM of 1.0, 0.25 and 0.08 arcsec respectively. Thus a rule of thumb is that the MTRLI beam is a factor four smaller than the VLA 'A' configuration beam at the same frequency. Fig. 2 shows a grey

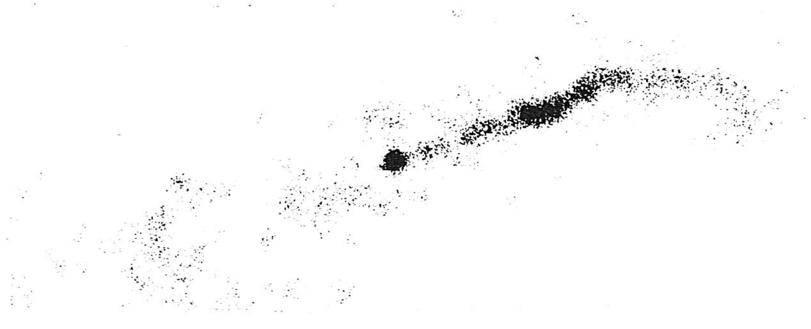

Fig. 2 Four-telescope map of Virgo A at 408 MHz

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scale map of Virgo A at 408 MHz made with only four telescopes and a minimum baseline of 23 km. It shows the compact features in the source, i.e. the nucleus and the knotty radio jet, very well but of course is not sensitive to the smooth extended structure mapped by the VLA[6].

3. RECENT RESULTS ON HIGHLY LUMINOUS SOURCES

Naturally enough in its first year of operation the MTRLI has concentrated on mapping the strongest compact sources available to it. On average these are intrinsically (but see later) the more luminous sources in the sky. No complete unbiassed sample has yet been fully observed so here I will merely try to show some of the more interesting maps we have made which we hope contain new pointers towards the source physics.

Two of the strongest sources, both apparently and intrinsically, are 3C196 (QSO, Z = 0.87) and 3C295 (galaxy, Z = 0.46) both of which are doubles. However since the component separation in each is only ∿4 arcsec no detailed maps of either object have been available until now. It is important to map many such powerful "normal" doubles, with similar linear resolutions, in order to determine whether at high redshifts there are any differences in structure ascribable either to intrinsic differences in the sources themselves or more likely to the modifying effect of the intergalactic medium whose properties are probably redshift-dependant. The 1666 MHz map of 3C295 shown in Fig. 3 reveals a structure in which the disposition of ridges and hotspots strongly resembles that in the low redshift (Z = 0.056) source Cygnus A as mapped by Cambridge 5 km telescope at 5 GHz[7]. The projected linear size of 3C295 is about half that of Cygnus A, a difference which could merely be due to the effect of projection.

In contrast the 408 MHz map of 3C196 shown in Fig. 4 reveals a very different structure. This can most easily be interpreted as the result of the rotation of its major axis leading to extended (and in fact steep spectrum) trails and hot spots marking the present direction of the putative beams[8]. Until now such rotation symmetries have only been seen in low luminosity objects (see the contribution by R. Ekers) where they are usually ascribed to precession of the rotation axis of the central engine.

The unique characteristics of the MTRLI, i.e. subarcsecond resolution at low frequencies with excellent dynamic range, are particularly apposite for the study of the extended steep spectrum emission near compact flat spectrum components. Many such sources have now been mapped and in the vast majority of them the extended emission is dominated by a one-sided jet often containing barely resolved knots. An illustrative example is shown in Fig. 5 which is the 1666 MHz map of 3C454.3 (QSO, Z =0.86). Here the core contains ∿95% of the total flux and a dynamic range of ∿2000:1 is needed to

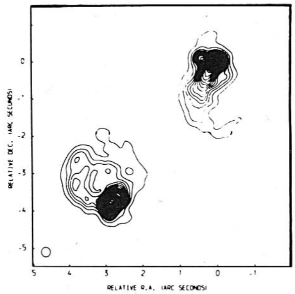

Fig. 3. 3C295 @ 1666 MHz

Contours @ 1,3,5 →25,35→95% of Peak. Bottom Contour ≡ 25 mJy/beam.

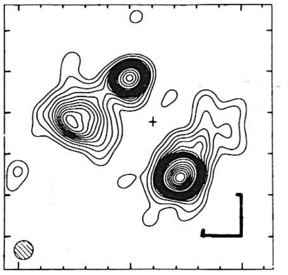

Fig. 4. 3C196 @ 408 MHz

Contours at 1,2,4→24,30→90% of peak. Bottom contour ≡ 82 mJy/beam.
The ⌟ shows 2 arcsec.

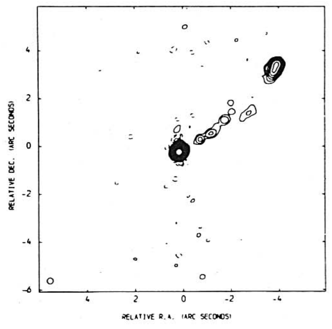

Fig. 5 3C454.3 @ 1666 MHz

Contours at 0.05, 0.1, 0.2→51.2% of peak.
Bottom contour ≡ 4.2 mJy/beam

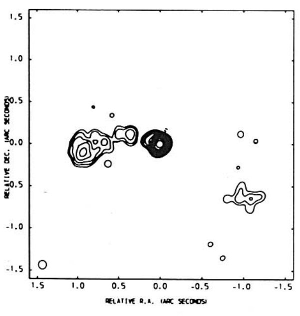

Fig.6a. 3C309.1 @ 1666 MHz

Beam = 0.1 arcsec
Contours @ 0.5,1.0,2.0→64% of peak
Bottom contour ≡ 18 mJy/beam

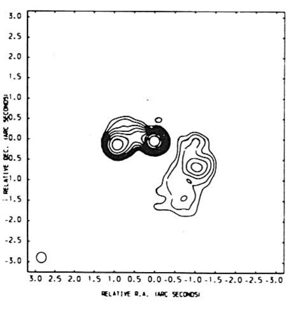

Fig.6b. 3C309.1 @ 1666 MHz

Beam = 0.25 arcsec
Contours @ 0.1,0.2,0.4→51.2% of peak.
Bottom contour ≡ 3.8 mJy/beam

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delineate the jet properly; the knot or hotspot at the end of the jet has a peak brightness $\lesssim 3\%$ of the core.

However, while one-sided jets may dominate the extended emission, high dynamic range maps often reveal components on the opposite side of the flat spectrum core. This is illustrated in Fig. 6a, the 1666 MHz map of 3C309.1 (QSO, Z = 0.90) which incidentally has a resolution of 0.1 arcsec since it was made with European VLBI as well as MTRLI data. This map is typical of many we have obtained of overall flat spectrum sources. However 3C309.1 is a steep spectrum source and comvolving the map to the standard MTRLI resolution (0.25 arcsec) improves the dynamic range (to $\sim$1000:1) and reveals the full extent of the emission to the west of the core (Fig. 6b). It is only because of the relative strength of the steep spectrum emission in 3C309.1 that we are able to see this low brightness structure - a point to bear in mind when trying to interpret similar dynamic range maps of core-dominated sources.

Nearly all the overall flat spectrum objects are quasars and some turn out to have particularly peculiar, twisted, structures. Maps of three such objects 1636+473, 1823+568, and 3C418 are shown in Figs. 7a, 7b,8 & 9. While it is clear that in 1823+568 and 3C418 the extended structure is physically associated with the core in 1636+473 the association can only be said to be statistically very probable, there being no evidence for a tell-tale bridge of emission between the core and the emission to the North.

I must not leave the impression that all the flux density is accounted for in these maps of core-dominated sources[9]. Typically 5-10% of the total flux is missing from the maps and must arise from diffuse low brightness emission with a characteristic scale $\gtrsim 5$ arcsec. The spectral index of this diffuse emission is rather steep ($\alpha \gtrsim -1$ with $S \propto \nu^{\alpha}$).

The crucial question about these core-dominated objects (and the halfway-house cases like 3C309.1) is whether they represent a separate type of radio source to the normal doubles, which also seem to exist at high redshifts vide 3C295, or whether the clear morphological differences between the two types are more apparent than real. For example if there are relativistic bulk motions in the radio-emitting material (and we know that this is almost certainly the case in the nuclei of the superluminals) then the combined effects of relativistic beaming and projection may greatly distort the apparent structure of a source as seen by instruments with limited sensitivity or dynamic range.

Regardless of the detailed physics involved there are a few simple observational facts which must have an important bearing on this question.

1) There must be some doubles seen "end-on" and these must be found among the apparently compact sources.

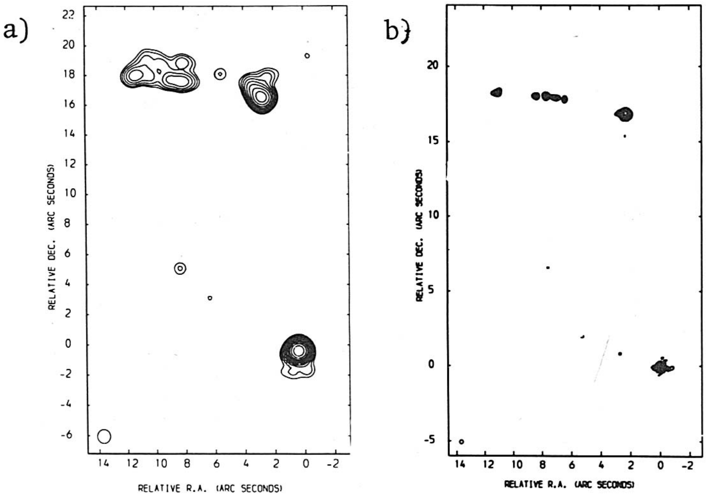

Fig.7a,b. 1636+473 @ 408 & 1666 MHz

Contours at 408 MHz, 10 logarithmically spaced to peak. Bottom contour ≡ 94 mJy/beam

Contours at 1666 MHz, 10 logarithmically space to peak. Bottom contour ≡ 19 mJy/beam

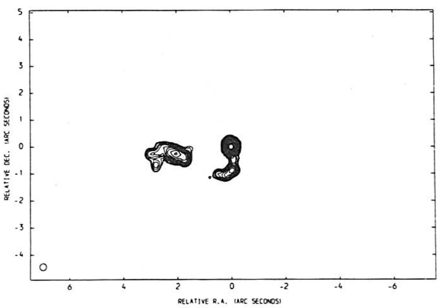

Fig.8 1823+564 @ 1666 MHz

Contours @ 0.30, 0.42, 0.58 (x 1.4) →80.5% of peak.
Bottom contour ≡ 2.3 mJy/beam

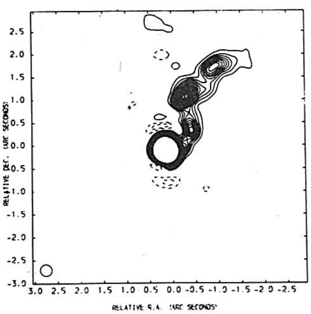

Fig.9 3C418 @ 1666 MHz

Contours @ 1,2,3,4 → 20% of peak
Bottom contour ≡ 8.2 mJy/beam

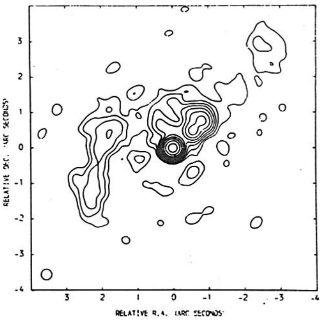

Fig.10 3C380 @ 1666 MHz

Beam = 0.3 arcsec
Contours @ 0.25, 0.5, 1.0 → 64% of peak
Bottom contour ≡ 9.0 mJy/beam

2) We do not observe any compact sources as amorphous "blobs" corresponding to a simple superposition of the outer lobes.

3) All compact sources in fact contain bright cores and have coherent extended structure, often jet-like and one-sided, as well as faint, diffuse "haloes".

4) We do not see "disembodied" jets i.e. without an accompanying core.

From these very general statements it seems almost inescapable first that some aspect-related amplification of the core flux is occurring, this is presumably due to relativistic beaming. Secondly point 4) implies that if the core fluxes are boosted then so, at least to some degree, must be those of the jets otherwise the jets would be swamped and invisible in limited dynamic range maps. Relativistic beaming of the jet emission is the obvious explanation since it also naturally accounts for the one-sidedness which is so prevalent.

A simple working hypothesis to explain the apparently diverse forms seen in highly luminous radio sources is therefore that there is really only one type of object and its appearance is critically dependent on the bulk velocity of the emitting material and its angle to the line of sight. However this pleasing synthesis is almost certainly a gross over-simplification of the real situation a view which is strengthened by the 1666 MHz map of 3C380 shown in Fig. 10. This steep-spectrum source seems to manifest virtually all types of structure and it is difficult to see merely a classical double source lurking amidst this tangle of emission. Further doubts will remain about this unified scheme until 1) maps with sufficient dynamic range ($>10^4$:1) are available to trace out the diffuse emission regions in core-dominated sources to see whether they really are the faint "ghosts" of the outshone outer lobes 2) VLBI techniques have advanced sufficiently in sensitivity to measure the supposed relativistic motions in the extended jets. At least we may have confidence that these observational goals will be met in the forseeable future.

I thank all my colleagues at Jodrell Bank who contributed towards making the MTRLI, and therefore this paper, possible. Among those people who helped me produce these maps or who allowed me to use their maps prior to publication were Mike Charlesworth, Ron Clarke, Marshall Cohen, Tony Foley, Colin Lonsdale, Tom Muxlow, Mark Orr and Althea Wilkinson. I am grateful to them all and to Ian Browne with whom I have had many illuminating conversations.

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