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Fourteen extragalactic radio sources mapped at 2.3 and 8.4 GHz with a 24-hour Crustal Dynamics Program VLBI experiment

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Abstract. Fourteen extragalactic radio sources have been mapped at 2.3 and 8.4 GHz with a 24-hour Crustal Dynamics Program VLBI experiment on North-Pacific baselines in May 1985. Among these sources, five have never been previously mapped by the VLBI technique and seven are superluminal sources. By comparing our maps with others at close or previous epochs, our main results are: a tentative proposition that the components of the newly mapped source OQ 208 evolve along a highly curved jet, a determination of the proper motion of the recently ejected jet component C_5 in 3C 345, evidence for a high spectral index gradient in the core region of 3C 454.3, and marginal indication for superluminal motion in DA 193. These maps also emphasize the great potential of Crustal Dynamics Program VLBI experiments to monitor radio source structures on intervals as short as a few months since ~1980.

Key words: interferometry – radio sources: general – quasars: general – quasars: jets of – BL Lacertae objects – galaxies: active

1. Introduction

The VLBI celestial reference frame is defined by the positions of extragalactic radio sources. Its accuracy has reached the milliarcsecond (mas) level with the dual frequency (2.3 and 8.4 GHz) VLBI experiments of the past ten years. At this milliarcsecond level, most of the radio sources show extended structures which limit further improvements in the accuracy and stability of the VLBI celestial reference frame. The positions determined by VLBI depend on the lengths and orientations of the baselines used. Moreover, source structures change with epoch and some radio sources (e.g. 3C 273, 3C 345) exhibit superluminal motion along jets (e.g. Pearson et al., 1981; Biretta et al., 1986), which may shift their positions (determined by their brightness centroid) on a time scale of a few months.

For the purpose of establishing a stable VLBI celestial reference frame with a sub-milliarcsecond precision, it is necessary to account for radio source structures. The position of each source should be referenced to a specific feature of its morphology that is stable and easily recognizable over time. Consequently, radio source structures have to be monitored at both 2.3 and 8.4 GHz. It is likely that for sources with very stable structure, a single map is sufficient at each frequency, while several maps per year might be required for sources which show rapid structural changes (e.g. BL Lac, 3C 273, 3C 454.3). There is no systematic program for mapping the radio sources used in astrometry yet. Some sources have been intensively studied for astrophysical purposes; others have never been mapped at any frequency with the VLBI technique. Even for the well-known superluminal sources, it is often difficult to find maps with proper epoch to correct for the structure effects in a given astrometric/geodetic experiment. It is necessary to develop a systematic program for mapping astrometric radio sources.

As a first contribution to this program, we study the possibility of making maps with astrometric/geodetic experiments themselves. Mapping in astrophysics is based on data acquired during a full u–v track of a source by a VLB array and on complete calibration information for each radiotelescope. During astrometric/geodetic experiments, the u–v coverage is instead sparse (although often uniform), and calibration information is incomplete. However, it has been recently demonstrated that such experiments can provide valuable maps (Charlot et al., 1989; Charlot et al., 1988; Schalinski et al., 1988a and b; Shaffer et al., 1987; Tang et al., 1987). Crustal Dynamics Program (CDP) VLBI experiments are of particular interest. They are conducted several times a year on various networks with up to 7 stations (Ryan and Ma, 1987; Coates, 1988). Fifteen sources are usually observed simultaneously at 2.3 and 8.4 GHz in 24 or 36-hour experiments, providing a sparse but uniform u–v coverage for each source.

We have chosen a 24-hour North-Pacific experiment as a first test for mapping with CDP VLBI data. The overall u–v coverage provided by this experiment is generally good and moreover, the u–v plane for low declination sources is enhanced by the north-south baseline between Kauai (Hawaii) and Gilmore Creek (Alaska) which has a length of $\sim 100 \times 10^6 \lambda$ at 8.4 GHz. We have successfully mapped fourteen sources at both 2.3 and 8.4 GHz. Among these sources, five have never been previously mapped (0229+131, CTD 20, 0528+134, OQ 208, 1548+056), and seven are known as superluminal radio sources (0212+735, OJ 287, 4C 39.25, 3C 273, 3C 345, BL Lac, 3C 454.3). The two others are DA 193 and 1803+784. We emphasize the potential of Crustal Dynamics Program VLBI data for mapping radio sources. They can be used to monitor source structures for astrometry and be of significant value for astrophysics. For example, with CDP data, it would be possible to map radio sources over intervals as short as ~3 months to avoid misidentifications of jet components which might cause large errors in determining superluminal velocities (see Blandford, 1987).

2. Observations and data reduction

The observations were made simultaneously at 2.3 and 8.4 GHz during a 24-hour experiment on 1985 May 15–16 with a 6-station VLBI array. The telescopes were: *Mojave*, the 12 m antenna operated by the National Geodetic Survey and located at the NASA Goldstone complex near Barstow, California; *Vandenberg*, the 9 m antenna operated by the CDP and located at the Vandenberg Air Force Base near Lompoc in California; *Hatcreek*, the 26 m antenna of the Hat Creek Radio Observatory located in Hat Creek, California; *Gilcreek*, the 26 m antenna operated by the CDP and located at Gilmore Creek, Alaska; *Kauai*, the 9 m antenna of NASA's Spaceflight Tracking and Data Network located near Kokee Park on Kauai island in Hawaii; and *Kashima*, the 26 m antenna of the Kashima Space Research Center located at Kashima, Japan. The BWS VLBI technique used was based on simultaneous recording of 6 channels at S band, spanning 2.21799 GHz to 2.30299 GHz, and 8 channels at X band, spanning 8.21099 GHz to 8.57099 GHz, with the Mark III data acquisition system (Rogers et al., 1983). Each channel was 2 MHz wide and received the right circularly polarized radiation. The data were correlated at Kashima Observatory with the K3 processor (Kawaguchi et al., 1982). Effective integration time for an individual scan was between 30 s and 400 s.

The correlation amplitudes and closure phases were retrieved from the CDP data base at Goddard Space Flight Center. The system temperatures and sensitivity at each radiotelescope were combined to produce correlated flux densities by the usual VLBI calibration scheme (Cohen et al., 1975). System temperatures recorded at least once per hour were found for all the stations except for *Vandenberg* where they were recorded only once at the beginning of the experiment. For the initial calibration of the data, the sensitivity of each station was approximately estimated from the VLBI data acquired on DA 193. At 2.3 GHz, DA 193 is assumed as a point-like source. At 8.4 GHz, the a priori model used for the structure is a single elliptical Gaussian component (FWHM = 0.5 mas, PA = 110°, axial ratio = 0.25) which is a compound of the various models and maps in Schilizzi and Shaver (1981), Spangler et al. (1983), and Fey et al. (1985). The adopted total flux densities for DA 193 are 3.0 Jy at 2.3 GHz and 4.3 Jy at 8.4 GHz as extrapolated from the daily measurements at 2.695 GHz and 8.085 GHz of this source by Fiedler et al. (1987) with the spectral shape reported by Fey et al. (1985). No dependence of sensitivity on the telescope elevation was used. Table 1 lists the average system temperature and sensitivity for each antenna at 2.3 GHz and 8.4 GHz. This set of antenna parameters was used for the initial calibration of the data only. The final calibration relied on self-calibration, possible with the 6-station array of this experiment. Since the signal to noise ratios of our data are generally high, a 5% error was added to the original uncertainties of the correlated flux densities and a 5° error was added to the original phase uncertainties before making the maps. The data from the relatively short baselines *Mojave-Vandenberg* (350 km), *Mojave-Hatcreek* (730 km) and *Vandenberg-Hatcreek* (700 km) were removed before making the hybrid maps since they were somewhat inconsistent with the data from the long baselines. It was not understood if this was related to technical problems at one of the California stations or if large scale source structures (between 10 and 100 mas), especially at 2.3 GHz, were involved. The limited number of stations in California (3) was not sufficient to attempt to map such structures.

Figure 1 and Figure 2 show the u–v coverages at 8.4 GHz for the highest and lowest declination sources (1803 + 784, 3C 273). It is interesting that such coverages are more uniform

Table 1. System parameters

Telescope	2.3 GHz T_{sys} (K)	2.3 GHz Sensitivity (K Jy^{-1})	8.4 GHz T_{sys} (K)	8.4 GHz Sensitivity (K Jy^{-1})
Mojave	52	0.018	54	0.0125
Vandenberg[a]	98	0.0068	113	0.0065
Hatcreek	61	0.097	58	0.075
Gilcreek	73	0.105	84	0.082
Kauai	58	0.010	70	0.0088
Kashima	74	0.065	99	0.057

[a] System temperatures at *Vandenberg* were measured only once at the beginning of the experiment.

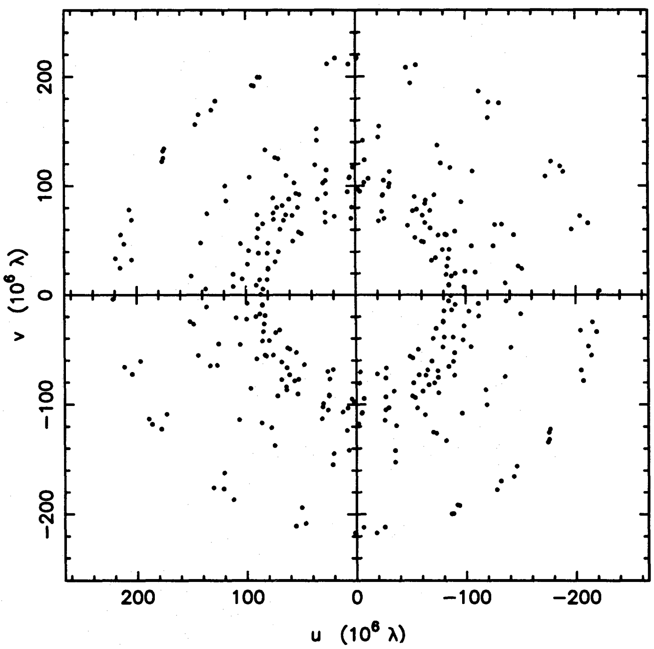

Fig. 1. The u–v plane at 8.4 GHz for 1803 + 784

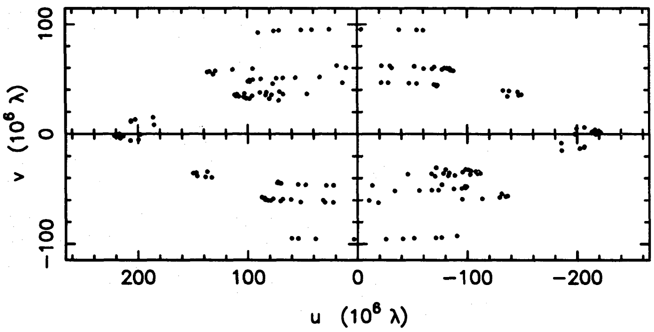

Fig. 2. The u–v plane at 8.4 GHz for 3C 273.

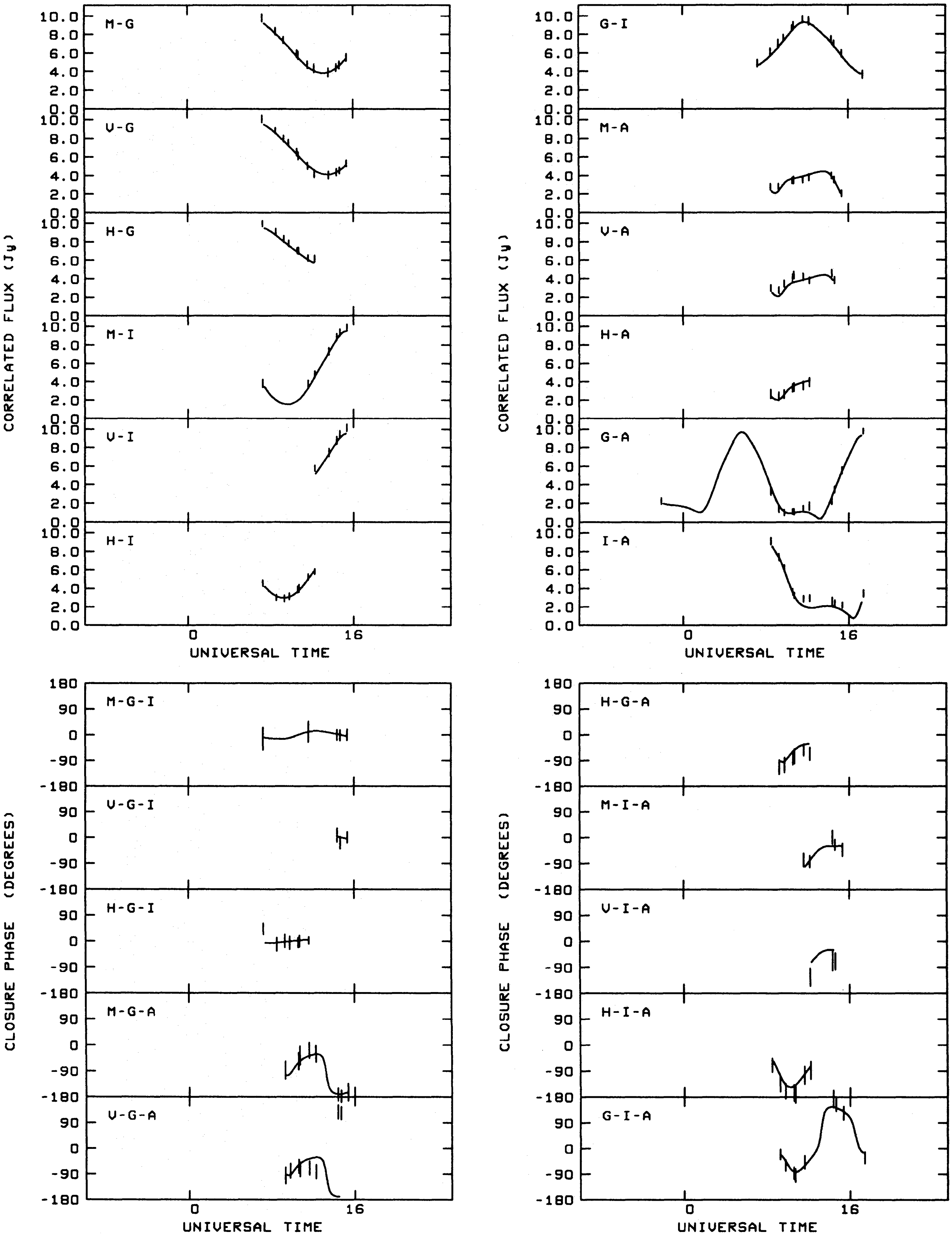

Fig. 3. Fit between the complex visibilities and the hybrid map for 3C 345 at 8.4 GHz. Letters in each plot indicate the individual stations (M = *Mojave*, V = *Vandenberg*, H = *Hatcreek*, G = *Gilcreek*, I = *Kauai*, A = *Kashima*)

than those provided by the predominantly east-west VLBI networks used for astrophysics. For 3C 273, the fringe spacing (λ/B) corresponding to the longest projected baseline in the east-west direction is ~0.9 mas at 8.4 GHz. In the north-south direction, it is ~2.1 mas. The angular resolution in the north-south direction is ~3 times higher than that of the combined European-US VLBI networks used for astrophysics.

The hybrid maps were produced with the Caltech VLBI package, using the iterative self-calibration algorithm of Cornwell and Wilkinson (1981). They were made in 3 steps: starting with an initial model consisting of one or two Gaussian components, we first did 10 iterations without adjusting antenna gains. Then, we did one iteration adjusting telescope-based gains for each integration period. Finally, we did another 9 iterations with the new gain factors fixed. This 20-iteration procedure produced convergence in all cases. However, convergence could be obtained after only 5 or 10 iterations for sources with simple structure. At the eleventh iteration, the changes of the gain factors were usually less than 10%, indicating that the initial calibration was satisfactory. The fit between the maps and the observations is generally good. Figure 3 shows the fit for 3C 345 at 8.4 GHz as an example.

Among the fifteen sources observed on 1985 May 15–16 by CDP, we have successfully mapped fourteen at both 2.3 and 8.4 GHz. One source (2216-038) could not be mapped because of large systematic errors in the closure phases which were not understood. The optical identification of these sources, as well as their magnitude and redshift, are shown in Table 2. Contour maps for these fourteen sources are shown in Fig. 4. The dynamic ranges of these maps are between 1:100 and 1:15 with an average value of 1:35 at 2.3 GHz and 1:25 at 8.4 GHz. The restoring beam used in all cases is an elliptical Gaussian with FWHM chosen to match as closely as possible the FWHM of the dirty beam produced by the Fourier inversion. The parameters of the restoring beam, the peak brightness and the contour levels used for each map are listed in Table 3. No spectral indices have been derived from these simultaneous 2.3 and 8.4 GHz structures because the angular resolution in our 2.3 GHz maps is three times lower than that in our 8.4 GHz maps.

3. Discussion of individual sources

3.1. New sources

3.1.1. 0229+131

0229+131 is a quasar with redshift $z=2.065$ and optical magnitude $m = 17.7$. It is slightly resolved at the VLA at 1.5 GHz and 4.9 GHz (Perley, 1982). In our VLBI map at 2.3 GHz, its main component is elongated with a position angle (PA) of ~45°. The apparent position angle of this component in Fig. 4 is distorted by the convolution with the restoring beam shape. However, with a circular beam, it is clear that this elongation corresponds to the direction of the two low intensity components seen in the northeast of the map. Although the intensities of these components are close to the noise level of the map, this correspondence might be considered an indication that these features are not spurious. Subsequent observations are needed to confirm the existence of these two components. At 8.4 GHz, 0229+131 is slightly resolved (visibility ≥ 0.7). No indication of the components seen at 2.3 GHz in the northeast direction was found in our 8.4 GHz map.

3.1.2. 0234+285 (CTD 20)

CTD 20 is a quasar with $z = 1.213$ and $m = 18.9$. It is unresolved at the VLA at 1.5 GHz and 4.9 GHz (Perley, 1982). Marscher and Broderick (1983) obtained limited VLBI data on this quasar at 1.7, 5 and 10.7 GHz between April 1980 and August 1982. They could not map the source but noted that the data indicate a multi-component structure. At 10.7 GHz, they proposed very cautiously a model consisting of two components separated by ~3 mas with PA = −9° and a flux ratio of 3. Lawrence et al. (1985) de-

Table 2. Optical data for our 14 sources

Source	Other name	Optical Identification[a]	m	z	References[b]
0212+735		Q, BL?	19	2.367	(1), (2), (5), (6)
0229+131		Q	17.7	2.065	(1)
0234+285	CTD 20	Q	18.9	1.213	(1)
0528+134		Q	20.0	···	(3)
0552+398	DA 193	Q	18	2.365	(1)
0851+202	OJ 287	BL	14	0.306	(1)
0923+392	4C 39.25	Q	17.9	0.699	(1)
1226+023	3C 273	Q	12.9	0.158	(1)
1404+286	OQ 208	G	15.4	0.077	(2)
1548+056		Q	18.5	···	(3)
1641+399	3C 345	Q	16.0	0.595	(1)
1803+784		BL	17	0.68	(1), (5)
2200+420	BL LAC	BL	14.5	0.0688	(1), (4)
2251+158	3C 454.3	Q	16.1	0.859	(1)

[a] Optical identification: Q = quasar, G = galaxy, BL = BL Lac object.
[b] *References:* (1) Hewitt and Burbidge (1987). (2) Véron-Cetty and Véron (1987). (3) Kühr et al. (1981). (4) Burbidge and Hewitt (1987). (5) as quoted in Pearson and Readhead (1988). (6) Biermann et al. (1981).

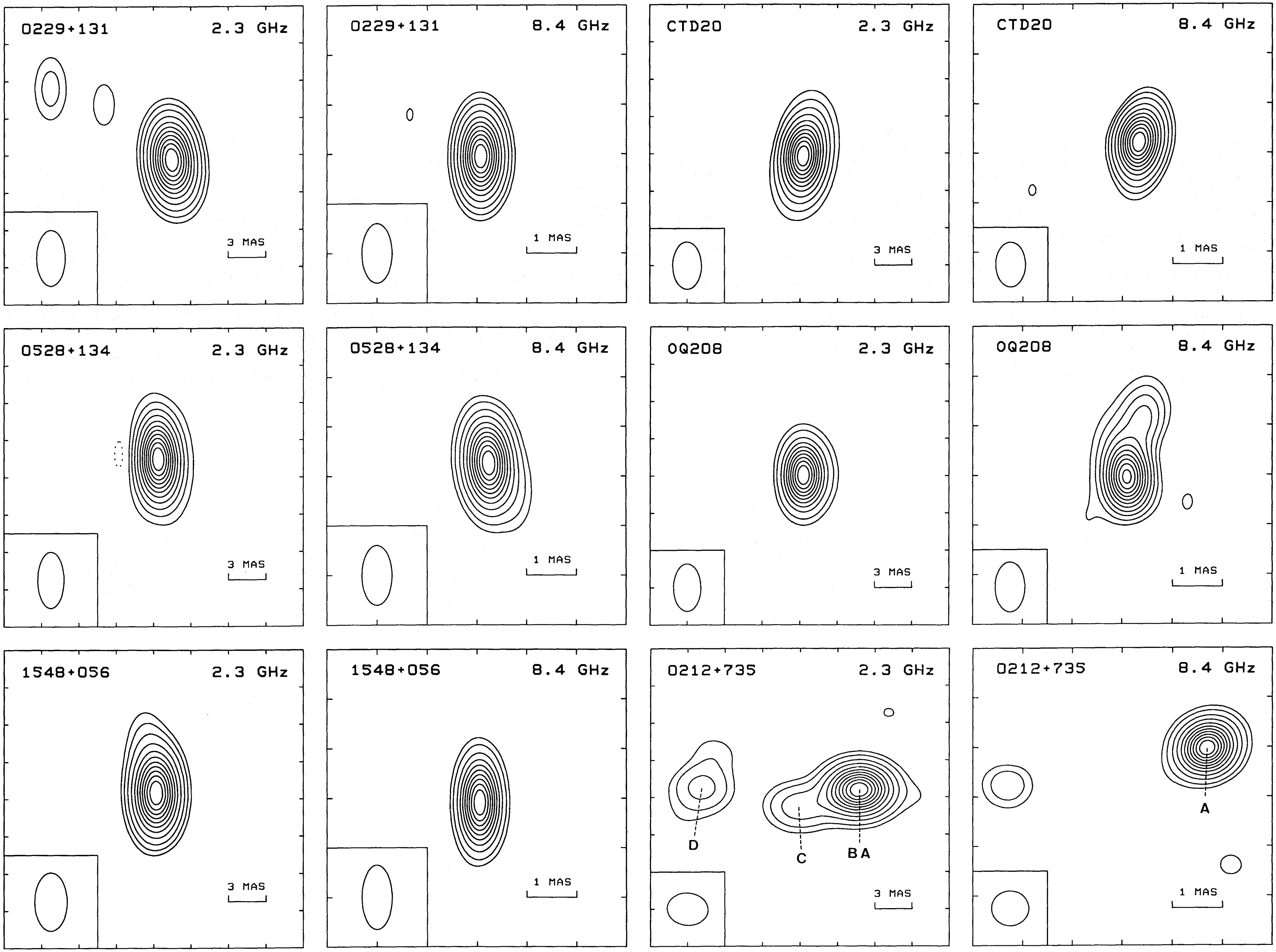

Fig. 4. Hybrid maps of 14 extragalactic radio sources at 2.3 and 8.4 GHz for epoch 1985.37. The scale of each map is indicated in the lower right-hand corner, and the FWHM contour of the elliptical Gaussian restoring beam is shown in the lower left-hand corner. The peak flux density, contour levels, and parameters of the restoring beam used for each map are listed in Table 3

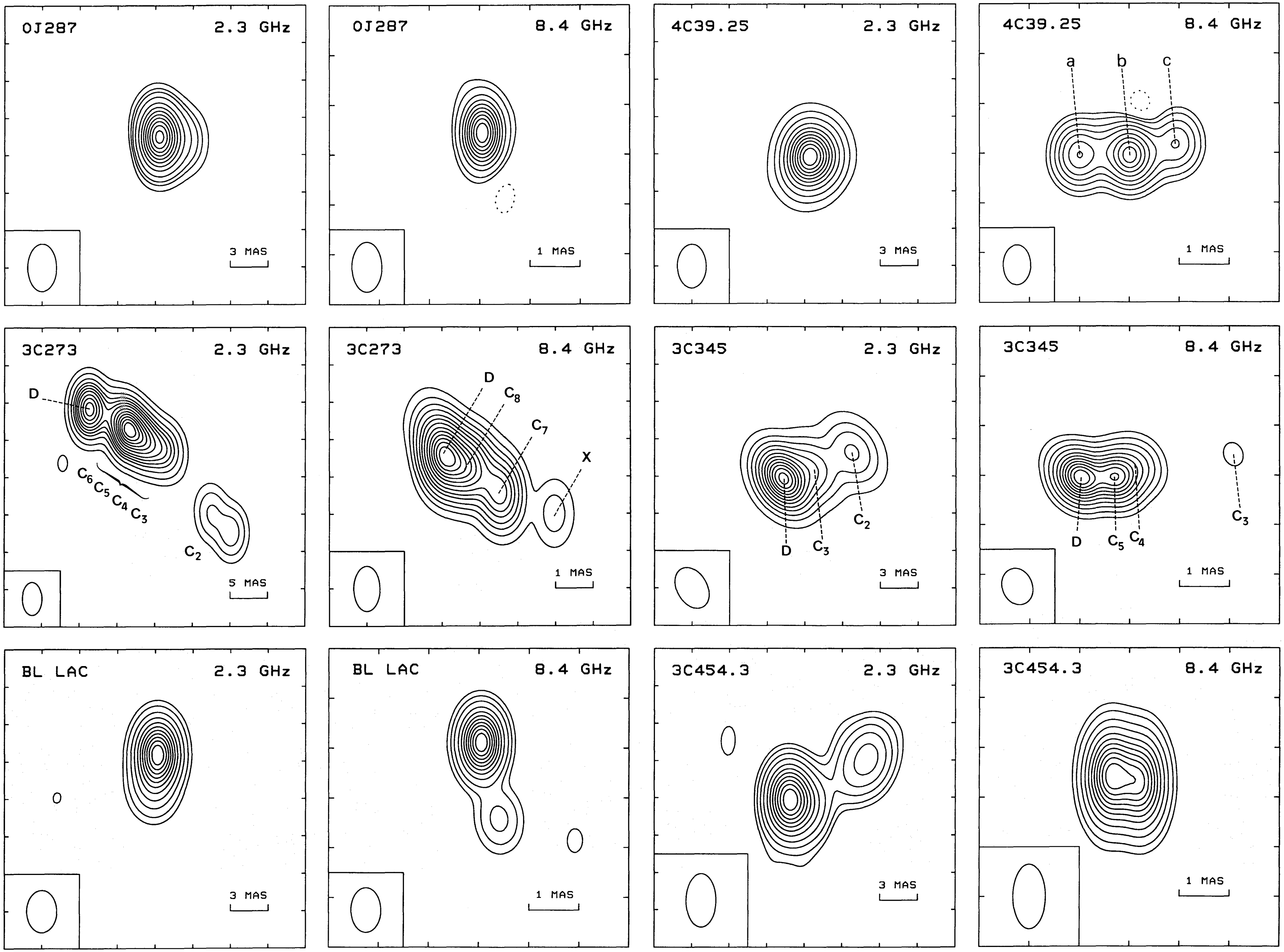

Fig. 4 (continued)

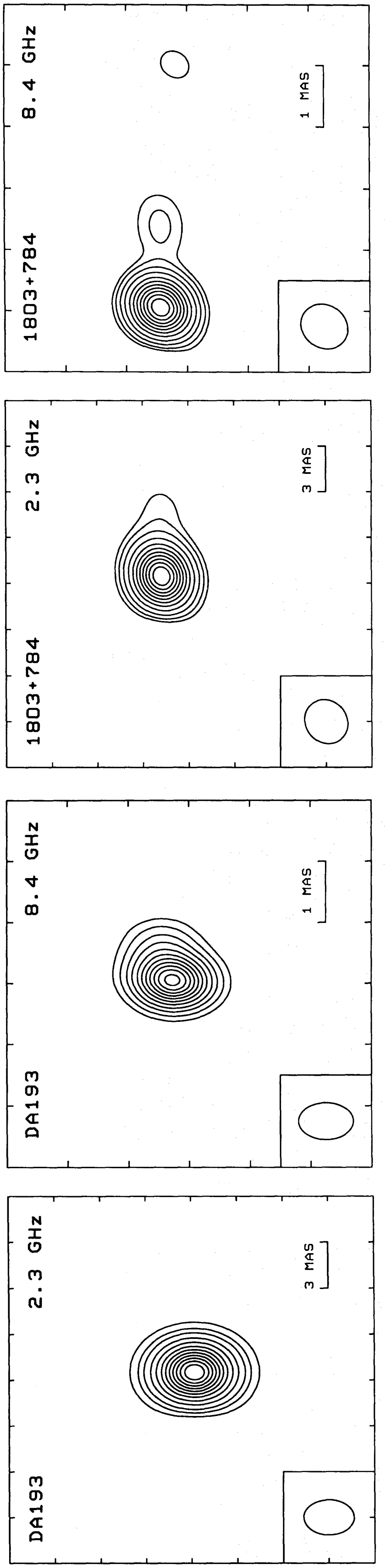

Fig. 4 (continued)

tected CTD 20 at 22.3 GHz in January 1984 and estimated that its angular size was $0.3 \pm 0.2 \times 0.03^{+0.09}_{-0.03}$ mas with PA $= -5°^{+15°}_{-25°}$.

Our maps indicate that CTD 20 is elongated in PA $\sim -30°$ at 8.4 GHz and PA $\sim -15°$ at 2.3 GHz. These directions are consistent with those found at other frequencies by the authors mentioned above. By superresolving our maps by a factor of 2, we have indications that the structure at both frequencies might be of the core-halo type.

3.1.3. 0528+134

0528+134 is a quasar with $m = 20.0$ but with no redshift available. At the VLA, a diffuse emission 2″ in extent and centered 1″ north of the core has been detected at 1.5 and 4.9 GHz (Perley, 1982). Our VLBI maps in Fig. 4 show a slight elongation at PA $\sim -140°$ at both 2.3 and 8.4 GHz. By superresolving these maps by a factor of 2, we can see a one-sided extension at 2.3 GHz and a double structure (separation $\sim$0.75 mas, peak intensity ratio $\sim$10) at 8.4 GHz. Hence, we have indications that there might be a core-jet structure at PA $\sim -140°$. We note that the directions of the VLA and VLBI structures are almost opposite as in 3C 147 (see Wilkinson et al., 1977; and Readhead et al., 1980).

3.1.4. 1404+286 (OQ 208)

OQ 208 was optically identified with the Seyfert galaxy Mkn 668 ($m = 15.4$, $z = 0.077$) by Blake et al. (1970). It is unresolved at the VLA at 1.5 and 4.9 GHz (Perley, 1982), but a very faint extended emission surrounding the core has been detected with the Westerbork SRT array at 4.9 GHz (van der Laan et al., 1984). It is unresolved on U.S. continental baselines at 1.7 and 5 GHz (Spangler et al., 1981) and has been used for flux calibration purposes in several VLBI experiments at low frequencies and on short baselines (Jones et al., 1981; Preuss and Fosbury, 1983; Wu et al., 1987).

Our 8.4 GHz map exhibits 2 components separated by $\sim$1.3 mas at PA $\sim -15°$. This is consistent with the 5 GHz one-component model of Zensus et al. (1984) of size of 1.8×0.8 mas with the major axis in position angle $-8°$. Our 2.3 GHz map in Fig. 4 shows a slight extension at PA $\sim -80°$ which is also supported by superresolution of the map. Furthermore, the 1.7 GHz model of Matveenko et al. (1981) shows an elongation at PA $= -120°$. The decrease of the 3 position angles from the highest frequency ($-15°$ at 8.4 GHz) to the lowest frequencies ($-80°$ at 2.3 GHz and $-120°$ at 1.7 GHz) might come from components tracked in a highly curved jet at the 3 different angular resolutions. A similar curved jet has already been observed in 3C 345 (Readhead et al., 1983; Browne et al., 1982). Further observations are needed to test this hypothesis and to detect possible motions of the components.

3.1.5 1548+056

1548+056 is a quasar with $m = 18.5$ but with no redshift available. At the VLA, a small halo surrounding the core has been detected at 1.5 and 4.9 GHz (Perley, 1982). Our VLBI observations show that it is more resolved in the north-south direction at both 2.3 and 8.4 GHz (visibility $\sim$0.5 on the baseline *Gilcreek-Kauai*) than on the longer east-west baselines (visibility $\sim$0.8 on the baselines from California to Japan). A slight extension at PA $\sim 10°$ is seen in our 2.3 GHz map. By convolving with a circular beam, we have indications of a low-intensity component ($\sim$7% of peak brightness) located $\sim$4.3 mas to the north of the main component at this frequency.

Table 3. Map parameters

Source	Frequency (GHz)	Beam[a] Maj. Axis (mas)	Min. Axis (mas)	PA (°)	Peak (Jy/beam)	Contour levels (% of peak)
0229+131	2.3	4.5	2.3	0	0.59	±4, 7, 12, 20, 30, 40, 50, 60, 70, 80, 90
	8.4	1.2	0.6	0	2.76	±4, 7, 12, 20, 30, 40, 50, 60, 70, 80, 90
CTD 20	2.3	3.8	2.3	0	1.73	±2.5, 6, 12, 20, 30, 40, 50, 60, 70, 80, 90
	8.4	0.9	0.6	0	1.53	±4, 7, 12, 20, 30, 40, 50, 60, 70, 80, 90
0528+134	2.3	4.5	2.1	0	1.95	±2, 6, 12, 20, 30, 40, 50, 60, 70, 80, 90
	8.4	1.2	0.6	0	2.39	±3, 6, 12, 20, 30, 40, 50, 60, 70, 80, 90
OQ 208	2.3	3.8	2.2	0	1.01	±5, 10, 20, 30, 40, 50, 60, 70, 80, 90
	8.4	1.0	0.6	0	1.05	±5, 10, 17, 25, 35, 45, 55, 65, 75, 85, 95
1548+056	2.3	4.7	2.6	0	1.73	±4, 7, 12, 20, 30, 40, 50, 60, 70, 80, 90
	8.4	1.3	0.6	0	1.46	±6, 11, 20, 30, 40, 50, 60, 70, 80, 90
0212+735	2.3	3.3	2.6	85	1.05	±3, 6, 12, 20, 30, 40, 50, 60, 70, 80, 90
	8.4	0.75	0.7	90	1.12	±3, 6, 12, 20, 30, 40, 50, 60, 70, 80, 90
OJ 287	2.3	3.8	2.3	0	1.38	±3, 6, 9, 15, 25, 35, 45, 55, 65, 75, 85, 95
	8.4	1.0	0.6	0	6.20	±5, 10, 20, 30, 40, 50, 60, 70, 80, 90
4C 39.25	2.3	3.5	2.3	0	2.63	±1.5, 5, 11, 20, 30, 40, 50, 60, 70, 80, 90
	8.4	0.8	0.55	0	1.42	±3, 6, 12, 20, 30, 45, 60, 75, 90
3C 273	2.3	4.4	2.6	0	7.53	±1, 3, 7, 12, 17, 23, 30, 40, 50, 60, 70, 80, 90
	8.4	1.2	0.7	0	11.4	±1, 3, 6, 10, 16, 22, 30, 40, 50, 60, 70, 80, 90
3C 345	2.3	3.5	2.4	30	4.96	±1.5, 5, 10, 17, 25, 35, 45, 55, 65, 75, 85, 95
	8.4	0.75	0.6	22	4.52	±2.5, 6, 12, 20, 30, 40, 50, 60, 70, 80, 90
BL LAC	2.3	3.4	2.4	0	1.12	±3, 6, 12, 20, 30, 40, 50, 60, 70, 80, 90
	8.4	0.9	0.6	0	1.35	±3, 6, 11, 20, 30, 40, 50, 60, 70, 80, 90
3C 454.3	2.3	4.3	2.4	0	4.63	±5, 8, 13, 20, 30, 40, 50, 60, 70, 80, 90
	8.4	1.15	0.65	0	3.54	±3, 6, 12, 20, 30, 40, 50, 60, 70, 80, 90
DA 193	2.3	3.3	2.3	0	2.60	±1, 3, 6, 12, 20, 30, 40, 50, 60, 70, 80, 90
	8.4	0.9	0.6	0	2.62	±5, 10, 17, 25, 35, 45, 55, 65, 75, 85, 95
1803+784	2.3	3.0	2.7	130	1.36	±4, 7, 12, 20, 30, 40, 50, 60, 70, 80, 90
	8.4	0.8	0.7	145	2.41	±5, 8, 13, 20, 30, 40, 50, 60, 70, 80, 90

[a] The position angle of the major axis is measured from north through east

3.2. Superluminal sources

3.2.1. 0212+735

There have been controversies in the literature about the optical counterpart of 0212+735. It was first reported as a probable BL Lac object by Biermann et al. (1981) and therefore was included in the sample of BL Lac objects studied at the VLA by Antonucci et al. (1986). But recently, Lawrence et al. (1987) reported that 0212+735 looks more like a quasar than a BL Lac object, and Pearson and Readhead (1988) have further emphasized that it is a quasar. VLBI observations of this source at 1.7, 5 and 22 GHz revealed a one-sided core-jet structure (Eckart et al., 1986 and 1987). Three jet components extending 13.5 mas to the east of the core were clearly identified in 5 GHz maps (Eckart et al., 1987; Pearson and Readhead, 1988). Superluminal motion between the core and the first jet component was presumed by Eckart et al. (1987), hereafter E87. It was then confirmed by Witzel (1987).

Our 2.3 GHz map can be compared with the 5 GHz map at epoch 1985.4 of Witzel (1987). Following E87, we have labelled A the core, and B, C, D the three jet components. The separations between C and D (~7.9 mas) agree very well between the two maps, but the separations between the core and the two jet components (C, D) are larger at 5 GHz (~5.7 mas and ~13.5 mas) than at 2.3 GHz (~5.2 mas and ~12.6 mas). This is not really surprising because the separations are measured from the brightness centroid of the blended components A and B in our 2.3 GHz map, whereas they are measured from A in the 5 GHz map of Witzel (1987). Similar discrepancies have already been noticed by E87 after comparing separations in maps at 1.7 and 5 GHz. Such a difficulty has also been discussed from a methodological point of view by Charlot et al. (1989) for NRAO 140.

The directions of the inner jet of 0212+735 are $152\pm20°$ at 22 GHz (E87), $\sim120°$ at 8.4 GHz (our map), $107\pm5°$ at 5 GHz (E87), $\sim105°$ at 2.3 GHz (our map), and $102\pm5°$ at 1.7 GHz (E87). At the lower frequencies (1.7 and 2.3 GHz), the directions of the outer jet components are $\sim90°$ (see our map and E87). When comparing these various values, we note an increase of the position angle of the source elongation with frequency.

In our 8.4 GHz map, a weak emission at PA $\sim$ 100° is seen $\sim$4 mas away from the core. The position of this emission corresponds neither to B or C (respectively located $\sim$1.5 mas and $\sim$5.7 mas away from the core in the 5 GHz map of Witzel, 1987) though its position angle is consistent with the direction of these two jet components. It is interesting that an unlabelled weak component ($\sim$1% of the peak brightness) is at the same position in the 5 GHz map of Witzel (1987) for epoch 1985.4. However, it is rather surprising to detect this feature at the $\sim$6% level in our 8.4 GHz map and fail to see B which is closer to the core at the 3% level. Two interpretations can be put forward: either this is evidence of a jet component with an unusual spectral index $\alpha \geq 0$ ($S(\nu) \propto \nu^{\alpha}$), or the dynamic range of our map is overestimated and this feature is spurious. Further 8.4 GHz observations are needed to clarify this point.

3.2.2. 0851+202 (OJ 287)

This BL Lac object is highly variable at both radio and optical wavelengths (Fiedler et al., 1987; Pollock et al., 1979). VLBI observations at 5 GHz (Pauliny-Toth et al., 1981) and 10.7 GHz (Kellermann et al., 1977) indicated a core-halo structure, while a core-jet structure consisting of 2 components was reported at 1.7 GHz (Matveenko et al., 1981). Superluminal motion was recently suggested by VLBI polarization data (Roberts et al., 1987). Our VLBI maps in Fig. 4 show that OJ 287 is extended to the west at 2.3 GHz, whereas it is nearly unresolved (visibility $\geq$0.9) at 8.4 GHz. By superresolving our 2.3 GHz map by a factor of 2, we have indications of two components with a separation of $\sim$2.5 mas at PA $\sim -95°$ and a peak intensity ratio of $\sim$10.

3.2.3. 0923+392 (4C 39.25)

VLBI observations at 5, 7.5, 10.7 and 14.8 GHz between 1972.3 and 1978.9 showed that this quasar contained 2 stationary components separated by $\sim$2 mas, with time-variable flux densities (Shaffer et al., 1977; Bååth et al., 1980; Pauliny-Toth et al., 1981; Pearson and Readhead, 1981). Then, Shaffer (1984) found that the separation between these 2 components decreased and he discussed possible physical explanations for true or apparent contraction in superluminal sources. Further observations at 8.4 GHz in 1983 (Marcaide et al., 1985) finally revealed that this contraction was apparent and due to the emergence of a new component from the western component. More recently, Shaffer et al. (1987) published a series of maps at 10.7 GHz and 8.4 GHz which show the emergence of this new component and its motion eastward at a superluminal speed, whereas the separation between the 2 extreme components remains constant. Additional VLBI observations at 22 GHz also revealed that this source has presently no well-defined core (Marscher et al., 1987).

In our 8.4 GHz map, the source is completely resolved and the visibility exhibits very deep minima (visibility <0.1). The relative positions and flux densities of the 3 components in our 8.4 GHz map (May 1985) are consistent with those found for July 1984 and July 1985 at the same wavelength by Shaffer et al. (1987). Our map in May 1985 confirms the relative stability of the flux density of "c" ($\sim$30% of peak brightness in all maps), as well as the brightening of "b" (60%, 100%, 100% of peak brightness for the 3 successive dates) and the continuous decay of "a" (100%, 60%, 30% of peak brightness for the 3 successive dates). Further maps at 8.4 GHz in 1986 (Schalinski et al., 1988a) have shown that the brightening of "b" has continued. Tang et al. (1987) have also produced maps at 8.4 GHz which confirm the appearance of a third component between 1980 and 1985. Their map in May 1985 indicates that "a" is the brightest component at this epoch. It is inconsistent with both our map at the same epoch and the one of Shaffer et al. (1987) for July 1985. This inconsistency might be due to the limited u–v coverage they had for this epoch. Their maps for previous epochs, based on more data, are much more similar to those of Shaffer et al. (1987).

In agreement with the 8.4 GHz structure, our 2.3 GHz map appears extended in the east-west direction when the restoring beam is accounted for, but no other emission on scales larger than $\sim$2 mas is seen. This is consistent with the 1.7 and 5 GHz EVN observations of Wu et al. (1987) which indicate that there is no significant structure on scales of 10 to 100 mas above 5% of the peak brightness. This quasar, however, possesses a two-sided core jet structure on arcsecond scales (Browne et al., 1982). By analysing the properties of its radio spectrum together with those of its arcsecond and milliarcsecond scale structures, Marscher et al. (1987) have emphasized that this source is intermediate between typical superluminal sources and symmetric extended sources with weak cores.

3.2.4. 1226+023 (3C 273)

This radio and optically bright quasar is one of the most observed sources for superluminal studies. At least five knots are moving away from the nucleus along a non-monotonic curved jet (Biretta et al., 1985) at superluminal speed (Unwin et al., 1985; Cohen et al., 1987; Zensus et al., 1988). Their angular velocities are between 0.76 mas/yr and 1.20 mas/yr, which correspond to apparent linear velocities from $5.1h^{-1}$c to $8.0h^{-1}$c ($H_0 = 100h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0.5$). Observations at various wavelengths and angular resolutions (Davis et al., 1985; Unwin and Davis, 1988; Zensus et al., 1988) have shown that the radio jet was visible continuously from the pc to the tens of kpc scales and was directed toward the well known optical jet (Greenstein and Schmidt, 1964; Röser and Meisenheimer, 1986) with no evidence for a counterjet.

Our 1985.37 maps at 2.3 and 8.4 GHz are very similar to the 1985.41 and 1985.60 maps at 5 GHz and 10.7 GHz of Zensus et al. (1988) and Cohen et al. (1987). The identification of the jet components of 3C 273 (C_2, C_3, C_4, C_5, C_6, X, C_7, C_8) was based on our two maps superresolved by a factor of 2. The separations between the core and these jet components were presented in detail in Charlot et al. (1988). These measurements are consistent with those predicted for the epoch of our data by Unwin et al. (1985) and Cohen et al. (1987), and confirm that none of these components accelerates significantly. These authors do not identify any of the components found in their maps with C_6 since 1981. However, further evidence of the existence of this component in a later map at 8.4 GHz was found (Charlot, 1989) and makes us believe that our proposed identification is correct. The separation between the core and the jet component C_2 in our 2.3 GHz map is part of the measurements used by Zensus et al.

(1988) to track the superluminal motion of this component. The component C_8 recently ejected from the core and detected at epoch 1985.60 by Cohen et al. (1987) is already visible in our 8.4 GHz map ~3 months earlier. The component labelled X is also seen at 10.7 GHz at epoch 1985.60 (Cohen et al., 1987), but it does not appear in earlier maps and is not yet identified. We also note that some emission exists beyond X in our 8.4 GHz map but it cannot be mapped.

3.2.5. 1641+399 (3C 345)

3C 345 is the best studied of the superluminal sources. An extensive analysis of VLBI observations at 5 frequencies (from 2.3 GHz to 89 GHz) for 20 epochs between 1979.25 and 1984.11 is given by Biretta et al. (1986), hereafter B86. The main results of B86 are the change of the position angle from $-135°$ to $-87°$ of the component C_4 and its acceleration from 0.07 mas/yr to 0.31 mas/yr when it moved away from the core between 1980 and 1984. These results were previously suggested by Biretta et al. (1983) and Moore et al. (1983). Additional VLBI observations at 1.7 GHz reveal that the jet extends to more than 55 mas from the core (Waak et al., 1988). Another important result is that the core of 3C 345 appears stationary relative to the compact quasar NRAO 512 at the level of 20 microarcsec/yr (Bartel et al., 1986).

Our maps at 8.4 GHz and 2.3 GHz extend the sequence of maps of B86 with the additional epoch 1985.37. Comparing the position angles of the components in the two maps gives further evidence for the bend of the jet. The separations between the core and the components C_2 and C_3 are very near those obtained when extrapolating their positions from 1984.11 to 1985.37 with the proper motions derived by B86. Hence, there is no acceleration of these components for the extended period 1979.25–1985.37 (see B86). By superresolving our 8.4 GHz map by a factor of 2, the western bright component appears split into two sub-components of unequal flux densities. The separations between the core and these two sub-components are 0.66 ± 0.04 mas (PA $= -92 \pm 2°$) and 1.13 ± 0.08 mas (PA $= -82 \pm 2°$), as estimated from fitting a three-Gaussian component model to our data. Uncertainties were derived using the method described in B86. The separation of the component C_4 was already ~0.8 mas in 1984.11 (B86) and can be predicted to be ~1.15 mas at our epoch, assuming constant proper motion. Hence we can identify C_4 with the farthest of the two superresolved sub-components, while the nearest one is certainly C_5 reported as emerging from the core by 1983 and detected with a separation of ~0.25 mas at epoch 1984.09 (B86). The addition of our new map yields a proper motion of 0.32 ± 0.05 mas/yr for C_5 (an uncertainty of 0.05 mas was assumed for the separation of C_5 at epoch 1984.09). This proper motion is very close to those reported by B86 for C_3 between 1979.25 and 1984.11 (0.312 ± 0.013 mas/yr), and for C_4 between 1982.86 and 1984.11 (0.295 ± 0.009 mas/yr).

3.2.6. 2200+420 (BL Lac)

This object, which is associated with an elliptical galaxy (Miller et al., 1978), is highly variable both at optical and radio wavelengths (e.g. Pollock et al., 1979; Fiedler et al., 1987). Rapid changes on scale of a few months have been observed in its milliarcsecond structure (Phillips and Mutel, 1982; Mutel and Phillips, 1984; Mutel and Phillips, 1987, hereafter MP87). MP87 have also reported two events with evidence for deceleration of components.

Our 1985.37 map at 8.4 GHz is similar to the one at 10.7 GHz of MP87 for epoch 1985.4 although the separation between the two components is slightly larger in our map (~1.6 mas instead of ~1.4 mas). This is most probably due to the uncertainty in defining the peak of the southern component which is weak and relatively extended in both maps, unless it is due to spectral index gradients. The more compact northern component is presumed to be the core (MP87). Our 2.3 GHz map is elongated at PA ~ 173°. This direction is similar to those reported for previous maps at 5 GHz and 1.7 GHz (Pearson and Readhead, 1981; Padrielli et al., 1986). Superresolution by a factor of 2 indicates the presence of a component located ~2.6 mas to the south of the main component. By comparing our maps at 2.3 and 8.4 GHz which have different angular resolutions, we have clear evidence for a bend of ~20° of the jet. A similar bend was mentioned by Mutel and Phillips (1984).

3.2.7. 2251+158 (3C 454.3)

3C 454.3 has a core-jet structure which was reported at various frequencies by many authors (0.6 GHz: Wilkinson et al. 1979; 1.7 GHz: Pearson et al. 1980, Romney et al. 1984, Padrielli et al. 1986, Pauliny-Toth et al. 1987; 2.3 GHz: Cotton et al. 1984; 5 GHz: Pauliny-Toth et al. 1981, Wu et al. 1986, Pauliny-Toth et al. 1987). This morphology can be seen in our 2.3 GHz map. The position angle of the jet on milliarcsecond scales (~ $-60°$) is relatively close to the one of the outer jet (~ $-45°$) detected with the VLA (Perley, 1982) and MERLIN (Browne et al., 1982). The separation between the compact component and the milliarcsecond jet was reported as stationary by Padrielli (1984). This is confirmed by our 2.3 GHz map which indicates roughly the same separation (~7 mas) as those reported by the authors mentioned above for 1.7 and 2.3 GHz maps at previous epochs. In addition, maps at 10.7 GHz and 23 GHz by Pauliny-Toth et al. (1987), hereafter P87, reveal a misalignment of ~45° between the axis of the core region and the axis of the milliarcsecond jet. This misalignment is clearly seen when comparing our simultaneous 2.3 and 8.4 GHz maps. At 2.3 GHz, the main component of the source appears very slightly extended westward (confirmed by superresolution); this is also an indication of a bend/break of the jet at a separation from the core ≥2 mas. P87 also reported complex and unusual structural changes in the core region between 1981.4 and 1986.2 including both superluminal and stationary features. Those changes are also supported by two-epoch observations at 5 GHz by Wu et al. (1986).

Our map at 8.4 GHz consists of 2 components of almost the same strength. A slightly superresolved map allows us to separate these 2 components and indicates an intensity ratio of 0.95. We note the intensity ratio in the 10.7 GHz map of P87 for the same epoch (1985.3) is only ~0.50 with the eastern component brighter. This change in the structure of 3C 454.3 from 10.7 GHz to 8.4 GHz requires a spectral index difference of ~2.5 between the two components. Such a difference is unusual in the core region of extragalactic radio sources, but Pauliny-Toth et al. (1981) have already measured spectral indices as different as 2.4 and 0 between features in the core region of this source.

3.3. Other sources

3.3.1. 0552+398 (DA 193)

VLBI observations of DA 193 at 5.0 and 10.6 GHz indicated either a core-halo structure (Schilizzi and Shaver, 1981), or a core-jet structure consisting of two components (Spangler et al., 1983). The position angle of the major axis of the halo ($\sim -70°$) and that of the line joining the two components ($-80 \pm 20°$) were consistent. Additional VLBI observations at 22.2 GHz suggested that this object be rather considered as a highly compact source without a jet (Fey et al., 1985).

Our 8.4 GHz map in Fig. 4 shows an extension at PA $\sim -75°$. This direction is consistent with the previous maps and models at 5.0 GHz and 10.6 GHz mentioned above. By superresolving our map by a factor of 2 (see Charlot et al., 1988), we have indications that there are two components. We estimated the separation between these two components and their flux densities by fitting a two-Gaussian component model to our data. Our best model indicates a separation of 0.52 ± 0.05 mas at PA $= -75 \pm 2°$ with flux densities of 3.0 ± 0.3 Jy and 1.3 ± 0.3 Jy, respectively. The separation we obtained is significantly larger than the one at 5.0 and 10.6 GHz reported for the earlier epoch $\sim$1981.5 (0.37 ± 0.05 mas) by Spangler et al. (1983). These authors actually measured this separation at 5 GHz and adopted it to fit their data at 10.6 GHz because of the limited VLB array used at this frequency (6 stations at 5 GHz and 4 stations at 10.6 GHz). If the two components are correctly identified in the two maps, the inferred proper motion is 0.04 ± 0.02 mas/yr making DA 193 a possible superluminal quasar ($v \sim 1.7$ c) with the standard cosmological parameters. Additional data are being analysed to confirm this finding (Charlot, 1989a in preparation). At 2.3 GHz, DA 193 is only barely resolved (visibility ≥ 0.8), but a slight extension at PA $= -90°$ can be seen when convolving the delta functions with a circular restoring beam.

3.3.2. 1803+784

VLBI observations at 1.7 GHz of 1803+784 reveal a core-jet structure with the jet extending $\sim$30 mas westward of the core (E87). At 5 GHz, the structure of this source consists of a compact core and a jet component separated by 1.2 mas at PA $\sim -90°$ (E87, Witzel 1987, Pearson and Readhead 1988). The two-epoch observations of E87 at 5 GHz indicate that the separation between these two components did not change significantly from 1979.93 to 1983.92. Witzel (1987) has further emphasized that any internal proper motion in this object between 1979.93 and 1985.8 was subluminal ($v < 0.6$c). Additional VLBI observations at 1.7, 5 and 8.4 GHz have also confirmed this finding (Schalinski et al., 1988b).

Our 8.4 GHz map exhibits the two components mentioned above with a separation of $\sim$1.3 mas. Though slightly larger, this value is consistent with those found at 5 GHz by E87 and Pearson and Readhead (1988) when considering their uncertainties (1.2 ± 0.3 mas at 1979.92, 1.24 ± 0.1 mas at 1982.26, 1.16 ± 0.14 mas at 1983.92). In addition, a very weak component is detected $\sim$4 mas away to the west of the core. It is interesting that the position of this 8.4 GHz component corresponds roughly to the tip of the slight extension westward of the core in our 2.3 GHz map. The fact that this feature is seen at these two different frequencies may indicate that it is real. However, it does not appear in any of the 5 GHz maps of E87 and Pearson and Readhead (1988).

Our 2.3 GHz map does not show the long extended $\sim$30 mas jet mentioned above. This is not really surprising because the components of this jet are relatively weak at 1.7 GHz ($<8\%$ of the peak brightness, see E87). Hence, their intensities at 2.3 GHz are below or close to the dynamic range of our map ($\sim 4\%$ of the peak brightness) due to negative spectral indices ($S(\nu) \propto \nu^{\alpha}$). It is also worth noting that our two maps show no evidence of a component to the east of the main component, as suggested by the 5 GHz maps of E87.

4. Conclusion

Fourteen extragalactic radio sources have been mapped at 2.3 and 8.4 GHz with a 24-hour Crustal Dynamics Program VLBI experiment on North-Pacific baselines at epoch 1985.37. Five of these sources have never been previously mapped by the VLBI technique; seven others are superluminal sources. The maps we produced provide simultaneous information at 2.3 and 8.4 GHz, including alignment or misalignment of the structures at these frequencies. We propose that the components of the newly mapped source OQ 208 evolve along a highly curved jet. The positions of the components of the superluminal sources at epoch 1985.37 are generally consistent with those predicted for this epoch by previous authors, hence providing no evidence for acceleration. For 3C 345, we have calculated a proper motion of 0.32 mas/yr for the recently ejected jet component C_5. By comparing our 8.4 GHz map of 3C 454.3 with one at 10.7 GHz for the same epoch (Pauliny-Toth et al., 1987) we have inferred a high spectral index gradient in the core region of this source. For DA 193, we have marginal indication for superluminal motion with $v \sim 1.7$c between 1981.5 and 1985.37; this possible superluminal motion was not previously reported.

The results above illustrate the great potential of Crustal Dynamics Program VLBI experiments to monitor extragalactic radio source structures though they are primarily designed for geophysics. They could be used to supplement the current programs for monitoring extragalactic radio sources. North-Pacific experiments have been conducted at least twice a year since 1985 (Ryan and Ma, 1987). They are well suited for mapping since they provide good overall u–v coverage for all sources even at low declination like 3C 273. Other CDP experiments (e.g. North-Atlantic, East-Pacific) can be used also and the whole CDP data base should be a powerful tool to track superluminal motions of components at both 2.3 and 8.4 GHz over intervals as short as a few months since $\sim$1980. It is also likely that several Crustal Dynamics Program experiments made at close epochs could be processed together in order to improve the u–v coverages and therefore the dynamic ranges of the maps.

The dual frequency maps we produced are also useful to calculate radio source structure corrections for astrometry. These corrections are necessary to achieve a stable VLBI celestial reference frame with a sub-milliarcsecond precision. An analysis of radio source structure effects in astrometric and geodynamic VLBI will be presented in a paper in preparation (Charlot, 1989b, in preparation).

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