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FURTHER 7 MILLIMETER VLBI OBSERVATIONS OF 3C 84 AND OTHER SOURCES WITH 100 MICROARCSECOND ANGULAR RESOLUTION

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ABSTRACT

Second-epoch observations of the nuclear region of 0316+413 (3C 84, NGC 1275) were made at 7 mm wavelength with an angular resolution of 100 μas. They confirm the existence of almost perpendicularly oriented components close to the "core" of the galaxy. A part of the nuclear region expanded along an angle of $\sim 200°$, suggestive of its being the inner portion of a jet that further out bends into the 10 mas southerly oriented jet known from earlier observations with a lower angular resolution. Eight more extragalactic sources were detected with transoceanic interferometers, five of them for the first time, promising a bright future for millimeter VLBI.

Subject headings: galaxies: jets — galaxies: nuclei — interferometry

I. INTRODUCTION

Since our first global 7 mm VLBI observations with an angular resolution as fine as 100 μas in 1986 May 9–10 (Dhawan 1987; Bartel *et al.* 1988), we have continued to map the nucleus of the active radio galaxy 0316+413 (3C 84, NGC 1275) and to search for other promising targets for imaging with our VLBI array (see Bartel 1990 for a review of the development of 7 mm VLBI and Krichbaum and Witzel 1990 and Zensus 1990 for the latest preliminary results). The source 0316+413 promised to be particularly interesting for further investigations, both from a technical and from a scientific point of view. 0316+413 is the strongest known compact continuum source at a wavelength of 7 mm in the northern sky and thus allows optimal antenna pointing checks to be made at each antenna of the array during the observations. Scientifically, 0316+413 is one of the most intriguing extragalactic radio sources. It is associated with the galaxy NGC 1275, the brightest galaxy in the Perseus cluster, believed to be a conglomerate of two galaxies in a stage of collision.

At radio wavelengths, the galaxy is dominated by a compact nuclear region of a size of only ~ 1 mas. From this region, a ~ 10 mas long jet of emission emanates with a speed of ~ 0.5 to $\sim 0.8c$ in a southerly oriented direction (e.g., Romney *et al.* 1982; Marr *et al.* 1988; here and hereafter $H_0 = 60$ km s^{-1} Mpc^{-1}, $q_0 = 0$ are assumed, equivalent to 1 mas = 0.4 pc for this galaxy). Further south at a distance of several arcseconds from the core, knots of emission were found (Pedlar, Boder, and Davis 1983); and finally at a distance of $\sim 30''$ both north and south of the nucleus there are extended emission regions (Noordham and de Bruyn 1982), suggesting that these regions are outer lobes caused by the flow of charged particles from an active galactic nucleus. The nuclear region is therefore of particular interest.

The image of this nucleus obtained from our previous global 7 mm VLBI observations at epoch 1986 (Bartel *et al.* 1988) is indeed intriguing (see also Marcaide *et al.* 1985 for a model of this source). It shows a compact core and two elongated, mutually almost perpendicularly oriented components straddling the southerly oriented jet known from earlier observations with coarser angular resolution. The nature of these components is unknown. In our first paper (Bartel *et al.* 1988), we speculated about possible interpretations, assuming that our results could be confirmed (*a*) in terms of the morphology being caused by a curvature of magnetic field lines in the environment of a rotating black hole (Camenzind 1986), or (*b*) in terms of a jet emanating from an accretion disk around a center of activity. Here, we present an image of the nuclear region at an epoch ~ 1 yr later and compare it with our previous one. Data from a third epoch (1988) are already being analyzed and will later be published, together with an extensive comparison of the results from all three epochs (Krichbaum *et al.* 1991).

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II. OBSERVATIONS AND DATA REDUCTION

We observed the radio galaxy 0316+413 and nine other active galactic nuclei at 7 mm wavelength (43.123 GHz) with a global array of antennas in a session on 1987 June 10–11. The abbreviations, locations, and characteristics of the antennas are given in Table 1. At each site, a hydrogen maser frequency standard and a Mark III VLBI system in recording mode A (Rogers *et al.* 1983) were used. The observations were correlated with the Mark III processor at Haystack Observatory. Fringes were searched for as described by Dhawan (1987) and Bartel *et al.* (1988). Data were calibrated in the usual manner. In Figure 1, we show the correlated flux densities, self-calibrated with a gain correction factor constant for each station, and the closure phases for 0316+413.

III. SECOND-EPOCH IMAGE OF 0316+413 AT 7 MILLIMETERS

Using the California Institute of Technology mapping package we produced from the data a CLEAN image (Fig. 2*a*)

TABLE 1

DESCRIPTION OF ANTENNAS

Antennas	Diameter (m)	Polarization (IAU convention)	Peak Aperture Efficiency (K Jy^{-1})	System Noise Temperature (K)	Affiliation
B	100	Linear	0.370[a]	400	Max-Planck-Institut für Radioastronomie
K	37	LCP	0.034	220	NEROC, Haystack Observatory
O	40	LCP	0.03	300	Owens Valley Radio Observatory
T	20	LCP	0.053	400	Onsala Space Observatory
X	45	LCP	0.306	550	Nobeyama Radio Observatory

[a] The effective aperture efficiency for our VLBI observations was half as large as given.

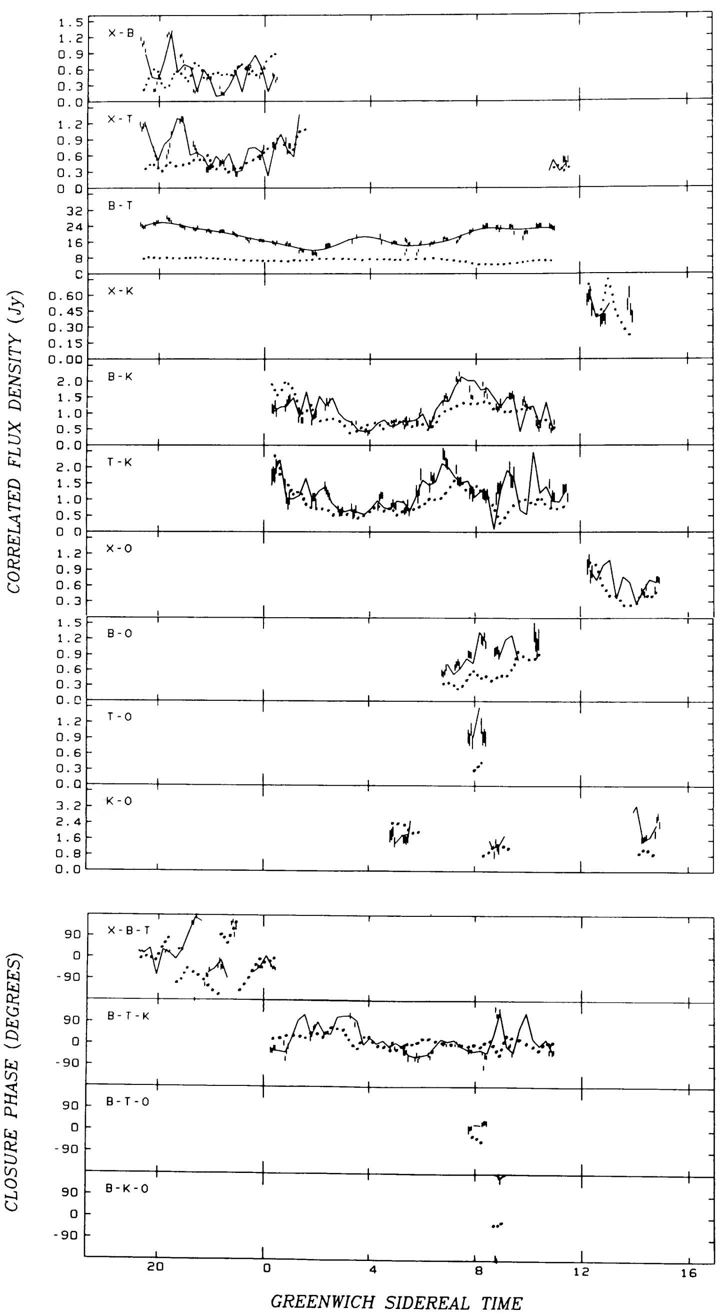

FIG. 1.—Correlated flux densities and closure phases for 0316+413 shown with $\pm 1\ \sigma$ statistical standard errors. Nondetections, caused by sensitivity limitations, are not plotted. The solid lines represent the predictions from the CLEAN components used to produce the image shown in Fig. 2*a*. The dotted lines show the predictions from the equivalent components from the image at epoch 1986 May 9–10.

and, for comparison, a maximum entropy image (Fig. 2*b*). The predictions from the CLEAN image are shown as solid lines in Figure 1. The predictions from the maximum entropy image are not plotted, since they do not differ significantly from the observed data points shown in Figure 1.

The dominant features seen in both maps are (*a*) a core component; (*b*) two almost perpendicularly oriented components, J1 and J2, close to the core; and (*c*) an elongated halo with the major axis oriented along an angle of $\sim 200°$. Other features are probably not significant.

A comparison with the CLEAN image from our observations at epoch 1986 May 9–10 shows that the properties of the core and the almost perpendicularly oriented components have remained approximately unchanged. Note that the orientation of J1 in Figure 2*a* is similar to that of the inner portion of the slightly curved J1 component in our 1986 image and the orientation of J1 in Figure 2*b* is similar to that of the outer portion. The J2 component is approximately straight, and its orientation is the same in both figures and in the 1986 image. However, the total flux density in the mapped region has increased from 7 to 20 Jy, and the halo expanded apparently into the southerly direction along an angle of $\sim 200°$ at the 10% contour level by $\sim 180\ \mu$as. The significance of the change can be best seen through a comparison of the visibility data obtained at the two epochs. In Figure 1, we added the predictions from our map from epoch 1986 May 9–10 as dots. The properties of the two approximately perpendicularly oriented components are mostly constrained by the correlated flux densities obtained from the BK and TK interferometers. These changed only modestly. The properties of the halo are mostly constrained by the correlated flux densities obtained from the BT interferometer. These have indeed changed considerably.

Another significant change occurred in the correlated flux densities from the XB and XT interferometers. A least-squares fit analysis for this subset of data suggests that two components are embedded in the halo of 0316+413, each ~ 1 Jy strong and separated by 0.6 mas along a position angle of $\sim 200°$–$210°$. Two such components are consistent with the expanded halo in the images of Figures 2*a* and 2*b*. However,

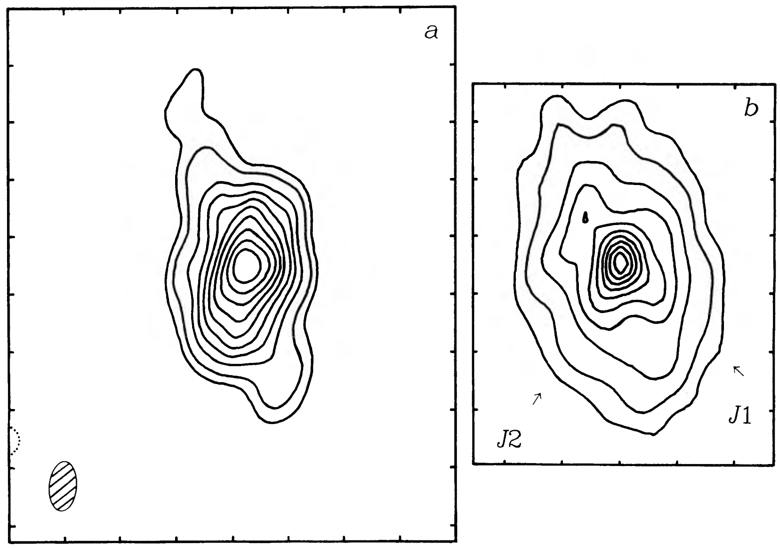

FIG. 2.—A CLEAN image (*a*), and an equivalent image produced with a maximum-entropy convolution algorithm (*b*), of 0316+413 at 7 mm wavelength at epoch 1987 June 10–11. The contours are at −3, 5, 10, 20, ..., 80, and 90% of the peak brightness, 3 Jy per beam area for image (*a*). The 50% contour of the restoring beam for the CLEAN image with a FWHM size of 100 × 170 μas and a position angle of −7° is shown as a striped ellipse in the lower left corner of (*a*). Tick marks in both images are separated by 200 μas. North is up, and east to the left.

because of the sparseness of closure phase information, the significance of the expansion's being asymmetric and going into the southerly direction only, is marginal.

We conclude that the nuclear region has expanded over the course of 13 months. The expansion rate at the 10% contour is ~170 μas yr^{-1} along an angle of ~200° straddled by the orientations of the two almost perpendicularly oriented components. The redshift of the galaxy, $z = 0.018$, along with values of $H_0 = 60$ km s^{-1} Mpc^{-1} and $q_0 = 0$, imply a linear expansion rate of ~0.25*c*. This rate is about 2–3 times smaller than the rate of expansion of the 10 mas long southerly oriented jet found earlier by Romney *et al.* (1982) and Marr *et al.* (1988).

It is conceivable that the expanding portion of the brightness distribution in our image is the inner part of a jet emanating from an active nucleus at an angle of ≳200° and further out bending to an angle of ~170°–180°. However, the difference in the rate of expansion is puzzling. Perhaps our measurement of the relatively slow expansion of the inner portion of the jet is an artifact, caused by the complexity of the brightness distribution combined with a *u*-*v* coverage that is relatively sparse for mapping structure on a scale of ~0.7 to 1.5 mas. An improved mapping capability would, however, be needed to measure expansion velocities of ~0.5 to ~0.8*c* over the course of 13 months. Therefore, to investigate the expansion velocity with more accuracy, observations are needed either with superior *u*-*v* coverage or in a faster time sequence.

IV. OBSERVATIONS OF OTHER EXTRAGALACTIC SOURCES

In addition to 0316+413, we observed nine other extragalactic sources. We detected eight of them with transoceanic interferometers, five of them for the first time. One source, 0615+820, was not detected. Their total flux densities, S_{tot}, maximum correlated flux densities from interferometers with transoceanic baselines, S_{corr}^{max}, and their corresponding visibilities, V^{max}, are given in Table 2. Many of these sources can be mapped (see Krichbaum 1990, Krichbaum *et al.* 1990, and Zensus *et al.* 1991 for maps of some of these sources). One close pair of sources, 1641+399 (3C 345) and 1638+398 (NRAO 512), is of particular interest, since, in case of favorable atmospheric conditions at times of observations, it may allow phase-connection and phase-referencing methods to be applied (e.g., Alef 1988; Bartel *et al.* 1986; Lestrade *et al.* 1990; Marcaide and Shapiro 1983). A least-squares fit of a circular Gaussian model to the 7 mm correlated flux densities of 1638+398 indicates that the source has a FWHM of only ~60 μas. Such a compact source is indeed useful as a phase reference for the superluminal quasar 1641+399. The position of any component, core, or jet, in the brightness distribution of 1641+399 could likely be determined relative to the single compact component of 1638+398 with an accuracy of 20 μas, 2.5 times better than what was achieved recently for this pair of quasars at 8.4 GHz (Bartel *et al.* 1986). Such astrometric accuracy would allow measurements of peculiar movements of the core, as well as of its average proper motion, with unsurpassed accuracy, and therefore increase the potential for astrophysical

TABLE 2

RADIO SOURCES DETECTED WITH VLBI AT 7 MILLIMETER WAVELENGTH ON 1987 JUNE 10–11

Source	S_{tot}[a, b] (Jy)	S_{corr}^{max}[a, c] (Jy)	Baseline[d]	V^{max}[a]
0316+413 (3C 84)	44 ± 4	0.6	KX	0.01
0716+714	1.3 ± 0.2	0.7	BX	0.5
1253−055 (3C 279)	8.9 ± 0.9	1.2	KB	0.1
1638+398 (NRAO 512) ...	1.2 ± 0.2	0.7	BX	0.6
1641+399 (3C 345)	6.2 ± 0.6	0.8	BX	0.1
1803+784	2.1 ± 0.3	0.5	BX	0.2
1928+738	1.9 ± 0.2	0.3	BX	0.2
2007+777	1.8 ± 0.2	0.9	BX	0.5
2251+158 (3C 454.3)	7.7 ± 0.9	1.3	BX	0.2

[a] See text for definitions of column headings.

[b] The values were obtained as the mean of individual measurements made by one of us (T. P. K.) at B. The uncertainties were derived from the standard deviations of the means combined in quadrature with 10% calibration uncertainties.

[c] The uncertainties are ~20%.

[d] See Table 1 for abbreviations.

investigations of the core regions of quasars and studies of the stability of the extragalactic reference frame.

V. CONCLUSIONS

Second-epoch observations of the nuclear region of 0316+413 (3C 84) confirmed the existence of a core and two almost perpendicularly oriented components in its vicinity. The source expanded significantly in a time period of ~ 13 months in a direction of $\sim 200°$, straddled by the two components. This result suggests a bending of the jet, at a distance of ~ 1–2 mas away from the core, by 30°–40° into the direction of the ~ 10 mas long southerly oriented jet. The detection with transoceanic interferometers of five other extragalactic sources for the first time, together with the previous detections of nine other such sources (Bartel *et al.* 1988), indicates a promising future for 7 mm VLBI.

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