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Letter to the Editor

215 GHz VLBI observations of bright Active Galactic Nuclei

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Abstract. We report the detection of 6 active galactic nuclei, and also the marginal detection of the galactic center radio source SGR A*, in 215 GHz VLBI observations between the IRAM 30 m telescope on Pico Veleta and one 15 m antenna of the IRAM Plateau de Bure interferometer ($\sim$ 0.3 mas fringe spacing). In this (second) 1.4 mm VLBI-experiment we find source dependent ratios between the total and correlated flux densities in the range of 10–35 %, indicating partly resolved brightness distributions on sub-milliarcsecond scales. In view of the calibration uncertainties and the limited uv-coverage at this high frequency this needs further confirmation. The present detection limit of $\sim 0.4 - 0.5$ Jy opens the possibility for more extended 1.4 mm VLBI experiments, in particular with phased millimeter arrays.

1. Introduction

Very Long Baseline Interferometry (VLBI) at centimeter wavelengths is an established observational tool for investigations of parsec and sub-parsec scale structures and their kinematics in active galactic nuclei (AGN) (eg. Zensus et al. 1995). However, VLBI observations at shorter wavelengths are required to overcome source intrinsic opacity effects and to facilitate more detailed investigations at higher angular and spatial resolution (eg. Krichbaum & Witzel 1992, Krichbaum 1996). VLBI observations at millimeter wavelengths began in the early 1980's (eg. Rogers et al. 1984) and are now performed regularly at 43 GHz with the VLBA and the EVN and – with some limitations of calibration accuracy and map-fidelity – also at 86 GHz with the 'Coordinated mm-VLBI Array'. Global 3 mm VLBI observations with angular resolutions of up to 40-50 μas revealed the existence of compact structures and one-sided jets in many – if not all – AGN (Bååth et al. 1992, Krichbaum et al. 1993, Lerner et al. 1993, Schalinski et al. 1994, Standke et al. 1994, Krichbaum et al. 1995). VLBI observations at even shorter wavelengths are stimulated by the wish for higher spatial resolution and the hope to directly image the expected microarcsecond sized nuclear region where powerful radio jets are produced. The first single baseline VLBI tests at the so far shortest wavelength of 1.3–1.4 mm were made in 1990, resulting in a marginal detection (signal-to-noise ratio of SNR = 5) of the quasar 3C 273 on the 845 km baseline OVRO - Kitt Peak (Padin et al. 1990), and in 1994 with clear detections ($SNR = 7 - 10$) of the sources 3C 273, 3C 279, and 2145+067 on the 1150 km baseline between the IRAM 30 m telescope at Pico Veleta and a single 15 m antenna of the IRAM Plateau de Bure interferometer (Greve et al. 1995). In order to confirm these previous detections and to further expand the number of observable objects, we performed a second VLBI-experiment at 215 GHz, which we report below.

2. Experiments and Data Analysis

The 1.4 mm VLBI observations between Pico Veleta and a single antenna on Plateau de Bure were made on March 1-2, 1995. Because of degrading weather conditions on Plateau de Bure, only data of March 2, 0h00-08h00 UT, could be used for correlation. The observational setup was similar to the earlier 1.4 mm experiment performed in December 1994 (see Greve et al. 1995 for a description). On Plateau de Bure we used again the hydrogen maser from the CNRS (France) and the VLBA terminal from the Yebes observatory (CAY, Spain).

The data were recorded with the MK III VLBI system (Rogers et al. 1983) in mode A at a tape recording speed of 270 inches/s (double speed). This allows 6.5 min continuous VLBI scans with a bandwidth of 112 MHz (ie. 14 bands at 8 MHz each) at frequencies between 215530.99 MHz and 215642.99 MHz. The observations were made in left circular polarization (LCP). We recorded 3-4 scans per hour, using the time between VLBI

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Table 1. Antenna Characteristics at 215 GHz

Station	D [m]	η_A	G [Jy/K]	Tsys [K]	τ_0
Pico Veleta	30	0.35	10.5	250-350	0.06-0.17
Pl. de Bure	15	0.34	40	250-600^a	0.20-0.40^a

^{a}: extrapolated from quasi-simultaneous 86 GHz measurements

scans for focus checks, pointing and calibration (determination of T_{ant}, T_{sys}, opacity τ).

We combined the 1.4 mm VLBI observations with 3 mm (86.25 GHz) snap shot VLBI observations of a few strong sources (3C 273, 3C 279, NRAO 530) for a check of the systems and easier fringe search at the correlator. The GPS satellite network was used at both observatories to check the masers and to obtain accurate time information.

The data were correlated at the MK III VLBI correlator of the MPIfR at Bonn using a pre-integration time of 2 s. The data were then fringe fitted (Program: FRINGE), edited, and calibrated using the standard correlator software (eg. Alef 1989), the CalTech VLBI package (Pearson, 1991) and Difmap (Shepherd et al. 1994). To reduce the detection threshold, the fringe fitting of weak scans was performed with search windows reduced in size and centered around rate and delay values extrapolated from neighbouring stronger detections (cf. Krichbaum et al. 1992 for details of the method). In order to confirm weaker detections found with FRINGE, we applied also the new method of incoherent fringe search (Programs: AVERAGE, SEARCH) using the HOPS-package (Rogers et al. 1995): both methods gave consistent results (see table 2).

Phase fluctuations due to the atmosphere severely limit the phase coherence of our data. Coherence times were determined for all detected sources and ranged – depending on elevation and time – between 4 s and 12 s, with a typical value of 8 s which we adopted for the final segmentation. A comparison of the phase fluctuations seen at 215 GHz and 86 GHz in VLBI scans taken under good atmospheric conditions (water vapor $< 1 - 3$ mm H_2O, $\tau_0 \leq 0.15$) shows 2–3 times stronger fluctuations at the higher frequency, consistent with expectations. Phase stability measurements of the LO-chains and inspection of the fringe rate spectrum and visibility phases (showing variations not exceeding 3–4 turns in 6.5 min) leads to the exclusion of severe degradations of the signal on timescales ($\leq$ 2 s) shorter than the segmentation time.

The data were amplitude calibrated using regular system- and antenna temperature measurements from pointing scans across the program- and calibrator sources.

At Pico Veleta, the calibration measurements were made in the 3 and 1 mm bands with SSB tuned SIS receivers ($\sim$ 10 dB sideband rejection). The chopper wheel calibrated pointing cross–scans gave T_{sys}, τ_0 and the single–dish flux densities of the sources, using the planets and standard H II regions as calibrators. At 1.4 mm the accuracy of the T_{sys} measurements is $\sim$ 20 %, the elevation dependent antenna gain curve is accurate to $\sim$ 10 % above 30° elevation, and $\sim$ 20 % at lower elevations.

At Plateau de Bure, only the 3 mm SIS receiver was SSB tuned (rejection $\geq$ 15 dB), while the 1.4 mm SIS receiver was DSB tuned (accurate within 30 %). For the 1.4 mm VLBI-observations we used interlaced 3 mm observations made with the connected array for antenna pointing at 1.4 mm and to extrapolate T_{sys} to 1.4 mm wavelength, using the known antenna characteristics and the IRAM atmospheric model (Cernicharo 1985). While the 3 mm data of T_{sys} are accurate to $\sim$ 20 %, the T_{sys} data extrapolated to 1.4 mm are estimated to be accurate to within 50–70 %. The adopted sensitivity of 40 Jy/K ($\pm$ 5 Jy/K) was later confirmed by absolute flux calibration measurements with the interferometer in the 1 mm band. In table 1 we summarize the typical values of the aperture efficiency (col. 3), effective antenna gain (col. 4), and the range of T_{sys} (col. 5) and zenith opacity (col. 6) during the observations.

The total (single dish) flux densities of the sources at 86 GHz and 215 GHz were measured at Pico Veleta on March 1 and on March 3–4, 1995, shortly before and after the experiment (H. Ungerechts, priv. comm.) using Mars and compact H II regions as flux density calibrators.

3. Results and Discussion

For the 9 sources observed in this experiment the projected baseline ranged from 600–800 Mλ (at 215 GHz), which is equivalent to fringe spacings of 0.26 – 0.34 mas. In table 2 we summarize the signal-to-noise ratios and the flux densities. Column 1 & 2 of table 2 give the source names; column 3 the redshift; column 4 & 5 the total flux density at 215 and 86 GHz, respectively; column 6 the number of VLBI scans with significant detections; column 7 & 8 the SNR as obtained after integration over the full scan from standard fringe search (FRINGE) (col. 7) and from incoherent fringe search (SEARCH) (col. 8).

The difference of the SNR-values in columns 7 & 8 is the following: for the standard fringe search (FRINGE) without search windows the typical detection threshold is $SNR \simeq 7$ which, however, can be reduced to $SNR \simeq 5 - 6$ by setting smaller search windows. For the incoherent fringe search (SEARCH) the SNR depends on the number of coherent segments and the search area of rate and multi-band delay. In this experiment we averaged for each 6.5 min scan over about n = 40 segments and searched over a rate-delay grid of 10 mHz $\times$10 μs. Under these conditions significant detections have a $SNR \geq 3$.

In column 9 we give for each source the correlated flux density at 215 GHz. For comparison we give also in col. 10 the correlated flux densities obtained at 86 GHz for 7 sources in another (longer) VLBI-observation performed on March 7–8, 1995 on the same baseline. The range of correlated flux densities does not only reflect the uncertainties of the amplitude calibration, which is of order of $\Delta S_{corr}/S_{corr} \sim 0.4 - 0.6$ at 215 GHz ($\leq$ 0.3 at 86 GHz), but also includes variations most probably caused by source structure. We note, however, that because of the small number of VLBI scans and the remaining calibration uncertainties it is difficult to discriminate between systematic effects from the telescope (eg. focus, pointing, gain-curve), the atmosphere (eg. anomalous refraction, see Altenhoff et al. 1987), and intrinsic variations of the visibilities.

Table 2. Summary of Detections at 215 GHz on the baseline Pico Veleta - Plateau de Bure

Source		z	Total Flux		N	$SNR_{215\,GHz}$		Correlated Flux		Comments
IAU	other		215 GHz[1] [Jy]	86 GHz[2] [Jy]		normal	incoh.[3]	215 GHz[4] [Jy]	86 GHz[5] [Jy]	
0923+392	4C39.25	0.69	3.5± 0.7	6.6± 0.2	-	< 4	2.7	< 0.5	1.2-1.6[6]	not detected
1226+023	3C273B	0.16	9.2± 0.6	17.1± 0.2	1	7	4.3	0.4-0.7	3-6.5	
1253-055	3C279	0.54	11.0± 1.0	19.9± 0.4	5	35	45.7	3-3.8	15-17	
1334-127		0.54	3.1± 0.7	6.0± 0.2	3	12	11.7	0.5-1.1		
1641+399	3C345	0.59	3.0± 0.4	5.6± 0.2	1	6	2.5	≤ 0.4		marginally detected
1730-130	NRAO530	0.90	6.2± 1.1	11.2± 0.3	4	11	11.7	0.5-0.8	8-9	
1742-289	SGR A	-	4.2± 0.5	7.8± 0.4	2	6	4.9	0.5-0.9	1-2	marginally detected
1749+096	OT081	0.32	3.9± 0.3	6.2± 0.1	1	11	12.6	0.9-1.1	3.2-3.8[6]	
1921-293	OV236	0.35	6.4± 0.9	13.0± 0.2	1	7	7.9	0.9-1.1	3.5-5.5[6]	

[1]: on March 4, 1995; [2]: on March 1, 1995
[3]: using a rate multiband delay window of 10 mHz x 10 μs, and 8 s segmentation intervals (Rogers et al. 1995)
[4]: correlated flux for a projected baseline of $600 - 800\mathrm{M}\lambda$ on March 2, 1995.
[5]: from observations performed at 86 GHz on March 7-8, 1995.
[6]: from observations performed at 86 GHz on October 25-30, 1994.

In the experiment we observed 9 sources and clearly detected 6 with signal-to-noise ratios of up to a factor of 4 higher than in the previous 1.4 mm experiment (Greve et al. 1995). For 3C 273 and 3C 279 we confirm the previous detections. In addition to the 6 clearly detected sources, we marginally detected the sources 3C 345 and SGR A*. The observations of SGR A* at 86 and 215 GHz will be discussed in a separate paper. The source 4C39.25 is not detected, while the source 2145+067 detected by Greve et al. (1995) was not observed again. The detection limit at 215 GHz is determined by the lowest correlated flux density in col.9 of table 2, i.e. $S_{cor} \simeq 0.4 - 0.5$ Jy, which is in good agreement with the theoretical expectation based on the antenna parameters of table 1.

In the following we define the degree of compactness of a source by the ratio of correlated flux to total flux (C = max$(S_{corr})/S_{tot}$). For the investigated sources we derive from table 2 a compactness, which ranges between $C = 10 - 35$ % at 215 GHz and $C = 20 - 80$ % at 86 GHz. At 215 GHz, the most compact sources are 3C 279, 1334-127, and 1749+096 with C ≥ 0.25. Since most of the sources exhibit complex structures on sub-mas scales (eg. jets and multiple compact components), the variations of C can be partially attributed to variations of the visibility functions. However, it appears that on average the compactness of the sources at 215 GHz is lower than the compactness at 86 GHz and lower than that typically seen at cm-wavelengths ($C_{5\mathrm{GHz}} = 0.5 - 0.9$). In view of the overall calibration uncertainties and the limited uv-coverage (changes of the visibility function with hour angle could lead to underestimates of C in snap shot type observations) this result must be regarded with caution.

The snap shot type 1.4 mm VLBI observations of 3C 279 of December 1994 and March 1995 were performed at similar ($\pm 5°$) interferometer hour angles (I.H.A.). This allows a direct comparison of the correlated flux densities, which show an increase by nearly a factor of 2 (at I.H.A.= 4.5 h), from 2.2 Jy to 3.8 Jy between both epochs. Such an increase is also seen in the compactness, which increased from C=0.21 to C=0.35, although the total 215 GHz flux density changed only from 10.5 Jy to 11.0 Jy. The 86 GHz VLBI map obtained in March 1995 showed a secondary jet component at $r \simeq 0.1 - 0.2$ mas core separation (Krichbaum, unpublished data). Although the observed variation of the visibility amplitudes and of the compactness are not completely outside the range set by the calibration uncertainties, motion of a jet component (at a speed of $\sim 0.15 - 0.2$ mas/yr typical for 3C 279 (eg. Carrara et al. 1993)) could easily explain the observed changes of the correlated flux densities.

A similar behaviour is also seen in 3C 273. In contrast to 3C 279, however, the compactness of 3C 273 decreased from C=0.14 in December 1994 to C=0.08 in March 1995, while the total flux density decreased from 13.5 Jy to 9.2 Jy. Within a mutual hour angle interval I.H.A.= 2 – 3 h, where data from both epochs are available, the correlated flux density decreased from $\sim$ 1.0 Jy in December 1994 to 0.4–0.7 Jy in March 1995. On sub-mas scales 3C 273 shows a prominent jet with components separating from the core at a typical speed of $\mu \simeq 0.5 - 1.2$ mas/yr (eg. Krichbaum et al. 1990). Again, variations of the correlated flux density and the compactness over timescales of a few months must be expected. In fact, recent 3 mm VLBI monitoring of 3C 273 shows the ejection of a new jet component between January 1994 and March 1995 (Krichbaum et al. 1996). It is worthwhile to note that the relative strength of the changes of the visibility amplitude and the compactness in 3C 279 seem to be larger than in 3C 273, although 3C 273 showed more pronounced variations in total flux density and exhibits a higher angular expansion rate. One possible reason for this may be a more complex sub-mas structure in 3C 273, which on mas-scales shows a more pronounced jet than 3C 279.

In the standard model of AGN, the radio emission originates from a continuous synchrotron self-absorbed relativistic jet and embedded compact structures, eg. shocks. Determination of the physical parameters of the innermost and most compact jet component (the jet base) yields some constraints for current jet models. If we assume that the observed compact emission results from a homogeneous synchrotron self-absorbed component with a maximum brightness temperature of $T_{12} = T_B/10^{12}$K ≤ 1 limited by inverse Compton cooling, and that this component radiates predominantely near ν_m = 215 GHz, then a lower limit to the magnetic field strength is obtained: from $B = 3.41 \cdot 10^{-5} \nu_m (T_{12})^{-2} \cdot D/(1+z)$ we find $B \geq 7.3 \cdot D/(1+z)$[mG], where D is the Doppler boosting factor. An upper limit for B follows from the observed high Gamma-ray luminosity of AGN (most of the objects of table 2 are detected with EGRET), which indicates that the electron Lorentz-factor γ_0 in blazar jets is considerably higher than previously assumed, eg. $\gamma_0 > 10^3$ (eg. Maraschi et al. 1992). Maximum synchrotron radiation occurs near $\nu_m = 1.2 \cdot 10^{-3} B \gamma_0^2 \cdot D/(1+z)$. This gives $B \leq 0.2 \cdot D/(1+z)$[G]. With an average redshift $< z >= 0.5$ and a typical Doppler-factor $D \simeq 10$ for the sources of table 2, we thus obtain $0.05 \leq B \leq 1.3$ G.

The size of a homogeneous synchrotron self-absorbed component observed at 215 GHz is $\theta_{\mu\text{as}} = 17 \cdot B_{\text{G}}^{1/4} S_{\text{Jy}}^{1/2} [(1+z)/D]^{1/4}$. Single component Gaussian modelfits to the visibility data of the detected sources (tab. 1) result in component flux densities of $S = 0.5 - 4$ Jy and sizes in the range of $\theta \leq 60 - 150 \mu$as, corresponding to brightness temperatures of $T_B \geq 6 \cdot 10^8 - 3 \cdot 10^{10}$ K. With respect to the relation above, these sizes must be regarded as upper limits to the true sizes. Correspondingly the brightness temperatures are minimal brightness temperatures. The fact, however, that only a fraction of the total flux is seen in our VLBI observations ($C \leq 0.4$) indicates the existence of more complex and more extended emission, which must be partly resolved by the interferometer beam. For reasonable magnetic field strengths, the turnover frequency ν_m of the extended emission must be located at $\nu_m < 215$ GHz (otherwise B gets too high). It is therefore likely that the brightness distribution of the objects is not pointlike but consists of several distinct components with sizes ranging from completely unresolved to largely resolved.

4. Future possibilities

The successful detection of 8 out of 9 active galactic nuclei in 1.4 mm VLBI observations between Pico Veleta and Plateau de Bure, and the fact that the sources probably show complex intrinsic source structures on micro-arcsecond scales, stimulate further and more extensive 1 mm VLBI observations. In order to increase the sensitivity, it is highly desirable to use the existing millimeter interferometers as phased arrays (eg. Plateau de Bure, BIMA, OVRO, Nobeyema) and to combine them with existing other mm-/sub-mm telescopes (eg. Pico Veleta, Kitt Peak, Sest). For the present station characteristics (as taken from the literature) and VLBI-observations with 112 MHz bandwidth and an array detection threshold of 3 σ (adopting global fringe fitting, eg. Alef & Porcas 1986), we formally derive detection limits between Pico Veleta and other phased arrays of $\sim 100 - 400$ mJy. This allows the investigation of some 50 Active Galactic Nuclei and compact galactic objects. For the near future 1 mm VLBI experiments also with longer baselines should be envisaged. 215 GHz VLBI interferometry on a 8000 km baseline (eg. Pico-BIMA or BURE-OVRO) would yield an angular resolution of $\sim 35 \mu$as, corresponding to a spatial resolution of 54 lightdays for a source at redshift $z = 1$ ($H_0 = 100$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$). This corresponds to $\sim$ 500 Schwarzschild radii of a black hole of 10^9 solar masses.

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