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Millimetre - VLBI Monitoring of AGN with Sub - milliarcsecond Resolution

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Abstract. Global millimetre VLBI allows detailed studies of the most central jet regions of AGN with unprecedent spatial resolution of a few 100–1000 Schwartzschild radii to be made. Study of these regions will help to answer the question how the highly relativistic AGN jets are launched and collimated. Since the early 1990s, bright mm-sources have been observed with global 3 mm VLBI. Here we present new images from an ongoing systematic analysis of the available observations. In particular, we focus on the structure and structural evolution of the best observed AGN jets, taking 3C 454.3 as a characteristic example. This core-dominated and highly variable quasar shows a complex morphology with individual jet components accelerating superluminally towards the outer structure. We briefly discuss the X-ray properties of 3C 454.3 and present its radio- to X-ray large-scale brightness distribution.

1. Introduction

After demonstration of the technical feasibility of Very Long Baseline Interferometry (VLBI) at the short wavelength of 3 mm (Readhead et al. 1983) in the early 1980s, it took about 10 years, before regular and systematic VLBI observations at this wavelength were performed. During 1993–1996 global 3 mm VLBI observations were organised and performed on an ad hoc basis, with a limited number of 3-7 participating antennas. In the second half of the 1990s, the Coordinated Millimetre VLBI Array (CMVA) was established, which facilitated larger global 3 mm VLBI experiments and gave easier user access. In early 1997, the first Very Long Baseline Array (VLBA) stations joined the global 3 mm VLBI observations. With the subsequent addition of more VLBA antennas, the CMVA improved its performance and the resulting images got continuously better. In 2002 the funding of the CMVA stopped, but at the same time the IRAM interferometer on Plateau de Bure became available as a phased array for mm-VLBI. To take advantage of the superior sensitivity of the IRAM instruments and continuing major investments at this and other observatories, the Global 3 mm VLBI Array (GMVA) was founded as a successor of the CMVA (`http://web.haystack.mit.edu/cmva/`).

The GMVA started operation in 2003, and now combines all available antennas of the VLBA (eight in 2004) with the following stations in Europe: Effelsberg, Pico Veleta, Plateau de Bure, Onsala and Metsähovi. It is hoped that in the near future more antennas will join the GMVA. The present GMVA is 3-4 times more sensitive than the VLBA alone, now allowing detailed studies of a much larger number of compact radio sources than before to be made (Agudo et al. 2004).

With an angular resolution of up to 50 μas, global 3 mm VLBI observations allow imaging the innermost regions of AGN and their emanating jets. With such high angular (and spatial) resolution and via a frequent monitoring of the variability, one can hope to learn more about the origin of jets and their 'driving engine'.

2. The Observations

The λ 3 mm observations presented here were performed at 6 epochs different numbers of antennas (see 1). All the data were recorded with the 'MKIII' VLBI recording system and were correlated in Bonn or Haystack. The output from the correlator was fringe-fitted with the HOPS-package (`http://web.haystack.mit.edu/vlbi/hops.html`) and with the standard correlator software at the MPIfR. Hybrid maps could be produced using the intercontinental baselines to achieve a resolution of 50 μas. The amplitude calibration was done in the standard manner using frequent system temperature, gain, and opacity measurements and by applying opacity corrected antenna temperature measurements of the source flux density obtained at Pico Veleta and Effelsberg. The hybrid mapping and model fitting was done in the DIFMAP package.

Our sample of mm-bright AGN presently consist of 24 sources[1]. Some of these sources were observed only in snap-shot mode, with only a few VLBI scans. Other sources were observed with full (u, v)-coverage. Many of the sources were observed repeatedly during 1993–1999. Results of the observations of 1993 are published by Lobanov et al. (2002). Preliminary results for some other sources were

[1] B0234+285 (4C 28.07), B0316+413 (3C 84), B0355+508 (NRAO 150) B0420–014, B0528+134 (OG 147), B0607–157, B0827+243, B0851+202 (OJ 287), B0923+292 (4C 39.25), B1156+295 (4C 29.45), B1226+023 (3C 273B), B1228+12 (3C 274), B1546+027 (OR 178), B1611+343 (OS 319), B1633+382 (4C 38.41), B1638+398 (NRAO 512), B1641+399 (3C 345), B1957+405 (Cyg A), B2005+403, B2145+067 (4C 06.69), B2200+420 (BL Lac), B2201+315 (4C 31.63), B2230+114 (CTA 102), B2251+158 (3C 454.3)

Table 1. λ 3 mm VLBI array used at the observations of 3C 454.3 – Antenna Characteristics

Name	D^{a}	G^{b}	$T_{sys}{}^{c}$	Sessions[d]					
	[m]	[K/Jy]	[K]	1993.26	1994.01	1996.78	1997.28	1999.30	1999.81
Effelsberg	100	0.14	130	√	√	√	√	√	√
Onsala	20	0.05	300	√	√	√	√	√	√
Pico Veleta	30	0.14	180	√	√	√	√	√	√
Kitt Peak	12	0.02	220			√	√	√	√
Quabbin	14	0.02	220	√		√			√
Ovro	6 × 10.4	0.02	500			√	√	√	√
Plateau de Bure	15	0.18	180				√		
Hat Creek	9 × 6.1	0.01	300			√	√	√	√
Haystack	37	0.05	250	√	√	√	√	√	
Metsähovi	14	0.02	350				√	√	
Sest	15	0.05	250				√	√	
VLBA (several)	25	0.28	150				√	√	√

[a] is the diameter in metres, [b] is the Sensitivity in [K/Jy], [c] the typical single-sideband system temperature in [K], [d] sessions in with the telescop participates

also published in the 'Millimeter-VLBI Science Workshop' (Barvainis & Phillips 1996) and the '2[nd] Millimeter-VLBI Science Workshop' (Greve & Krichbaum 1999). A more detailed discussion of the individual sources will follow in subsequent papers.

3. 3C 454.3

Here we focus our analysis on the source 3C 454.3. In the first subsection we present the results of mm-wavelengths observations, in particular at 43 GHz and 86 GHz. In the second subsection, we link our results in the μas-regime to the X-ray properties of 3C 454.3 and present its radio- to X-ray large-scale brightness distribution.

3.1. mm-Wavelengths Observations

The Optically Violent Variable 3C 454.3 is a core-dominated, highly active, superluminal radio source at a redshift of $z = 0.859$. At this redshift 1 milliarcsecond correspond to 7.7 parsec[2]. Owing to its activity and structural complexity it is one of the prime candidates for high resolution imaging (e.g., Krichbaum et al. 1996, Jorstad et al. 2001). VLBI images at longer cm-wavelengths show a pronounced and complex core-jet structure extending to the west and bending to the north (Pauliny-Toth et al. 1987).

Multi-epoch VLBA monitoring at 43 GHz and 22 GHz (Jorstad et al. 2001) report a stationary component at a core distance of ~0.6 mas. Emission in this region was seen already earlier by Pauliny-Toth (Pauliny-Toth et al. 1998). The flux density of the stationary component varies between 3.2 Jy (1995.31) and 1.2 Jy (1997.19). Observations between 1995.01 and 1997.58 indicate that three jet components were ejected. The ejection direction seems to vary between a position angle range of −74° to −88° relative to the VLBI core.

The inner jet (r ≃ 2 mas) is oriented mainly to the west. Further out, the jet bends to the north and extends up to 10 mas (P.A.= −95°). From early 3mm-VLBI images obtained in 1993 and 1994, Krichbaum et al. (1996) reported detection of apparent superluminal motion of two inner jet components with apparent speeds of $\beta_{\rm app} \simeq$7–8 c at r ≤ 1 mas. This correspond to the proper motion measured by Pauliny-Toth et al. (1998) who found apparent velocities of $\beta_{\rm app} \simeq$ 8c at r ≥ 5 mas with VLBI at cm-wavelengths[3]. In a geometric interpretation this behaviour can be explained as an ultra-relativistic flow moving along a spatially bent path.

One of the best observed sources in the sample reported above is the quasar 3C 454.3, which is one of the brightest Active Galactic Nuclei at 3 mm wavelengths. It was observed with global 3 mm-VLBI at the following epochs: 1993.26, 1994.01, 1996.78, 1997.28, 1999.30, 1999.81. In the following we present our results of this quasar and combine it with observations from other wavelengths.

We present in Fig.1 six 3 mm VLBI maps of 3C 454.3. The source shows a one–sided core jet structure with an ultra-compact core (≤0.07mas) and several distinct emission components located to the west. On the mas-scale, we derive apparent velocities of $\beta_{\rm app} = 3.7 - 7$ c. This is in good agreement with the expected jet velocity and the picture of an outward accelerating jet as suggested by Pauliny-Toth et al. (1998). During our observing interval and on sub-mas scales, we observe even a larger change of the jet ejection angle near the core from –61° in 1993.26 to –123° in 1999.81. In contrast to the identification scheme proposed by Jorstad et al. (2001), we do not see evidence for a stationary component. This, however, depends strongly of the cross-identification of jet components between the epochs, and more data need to be added to obtain a clearer picture. Due to the limited time sampling of the 3 mm-images, it is not yet possible to trace all the jet components unambiguously over time ranges larger than about 2-3 years. The addition of images obtained at other frequencies (15 – 43 GHz) will help to close these gaps and we should be able to obtain an unambiguous component identification, as our data analysis proceeds.

[2] $H_0 = 71 {\rm km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$

[3] all values were recalculated for $H_0 = 71 {\rm km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$

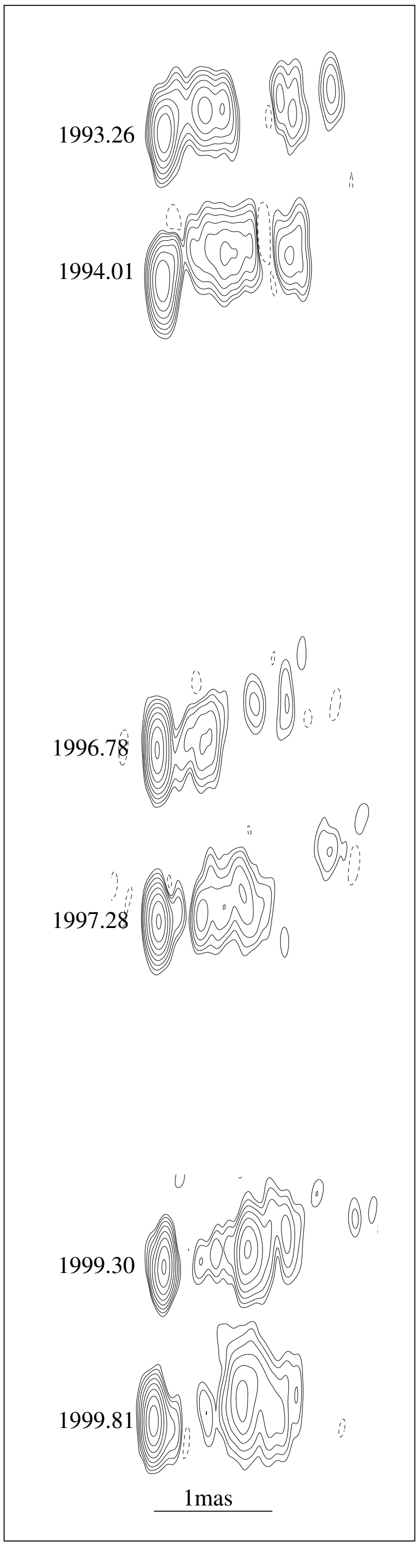

Fig. 1. Global VLBI images at 86 GHz of 3C 454.3. The maps are restored with a common beam size of 0.28×0.07 mas at a P.A. of 0°. 1 mas corresponds to 7.7 pc. Contour levels are: −0.5, 0.5, 1, 2, 4, 8, 16, 32, 64 % of the peak flux density

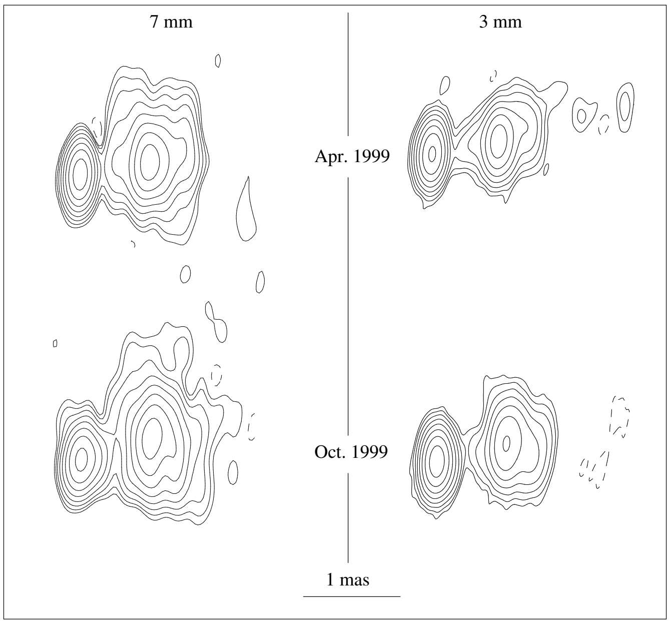

Fig. 2. Comparison between λ7 mm (left side)[A. Marscher, priv.comm] and λ3 mm imaging (right side). All maps are convolved with a beam of the size 0.36×0.16 mas at a P.A. of 3.5°. Contour levels are: −0.5, 0.5, 1, 2, 4, 8, 16, 32, 64 % of the peak flux density

Figure 1 shows that in early 1994, the core appears elongated. This indicates the imminent ejection of a new component. Similar elongations and the ejection of new components can also be observed in 1997.28 and 1999.81. In Figure 3 we show the flux density variability of 3C 454.3 at 22 GHz and 37 GHz over the last 25 years as measured by the Metsähovi group (Teräsranta et al. 1998, and Teräsranta priv. comm.). After the ejection of the new components, the flux increases at both frequencies but with a time delay of about eight weeks for the 37 GHz flux and another four weeks also at 22 GHz.

For two epochs, 1999.30 and 1999.81, we are able to compare the inner part of the jet of 3C 454.3 from our 3 mm VLBI maps with VLBI images obtained at 7 mm (Marscher, priv.comm). This is shown in Figure 2. For the April data we derive a spectral index for the VLBI core of $\alpha = 0.64$ ($S \sim \nu^{+\alpha}$), i.e. a strongly inverted spectrum. In October the spectral index steepened to $\alpha = -0.39$ and a new component appeared west of the core (Fig.1). This new component is still nearly unresolved at 43 GHz. Due to self-absorption of the jet increasing flux is first seen at high frequencies, in this case at 86 GHz and later on at 43 GHz.

3.2. An X-Ray view

A comparably large amount of absorption towards the nuclear X-ray core of 3C 454.3 of $N_{\rm H} = 5\times10^{21}$ cm^{-2} has been reported from a *Beppo*Sax observation of this source (Tavecchio et al. 2002). Alternatively, these authors suggest an intrinsic break in the continuum occurring below ~1 keV to explain the observed lack of soft X-ray photons. In both cases, important insights into the physics of AGN might be provided by the combination of mm-VLBI radio observations on the smallest accessible scales of the nuclear radio jet and the high-energy X-ray spectrum. The most compact region of the nuclear radio jet repre-

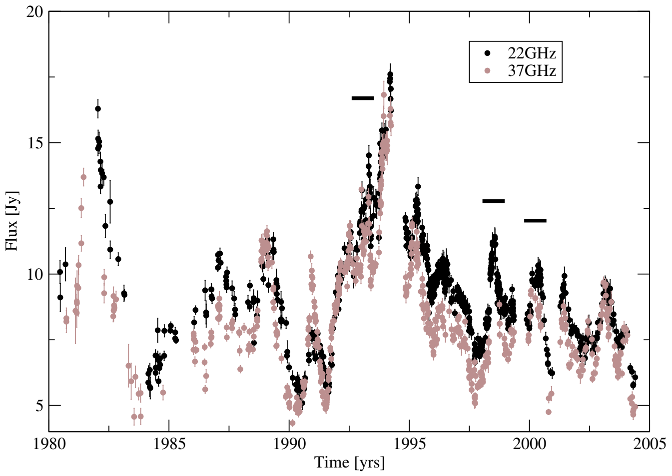

Fig. 3. Single dish radio lightcurve of 3C 454.3 at 37 GHz and 22 GHz taken at the Metsähovi radio telescope. The timeranges of the ejection of the compontents are marked by the bars. (Teräsranta et al. 1998)

sents an attractive candidate for the dominating source of the compact X-ray emission in 3C 454.3. In addition, the angular resolution achieved in our 3mm-VLBI experiments of 50 mas allows us to search for hints of the putative compact absorber on linear scales as small as 0.3 pc. Such an approach is particularly interesting because of the puzzling discrepancy between the expected small angle of the jet axis to the line of sight in superluminal quasars like 3C 454.3 and the occurrence of considerable absorption, more naturally expected from type 2 objects oriented closer to the line of sight.

We present here data from a short snapshot *CHANDRA* observation of 3C 454.3 performed on Nov., 6th, 2002. This observation was done within the scope of a survey of quasar jets (Marshall et al. 2004).Independent of that study, the X-ray properties of 3C 454.3 were analysed as a part of an X-ray spectral survey of radio-loud core-dominated AGN (Kadler et al., these proceedings). The X-ray image (Fig. 4) reveals a resolved core-jet structure of 3C 454.3 with a bright knot of X-ray emission coinciding with strong radio emission emitted about 5 arcsec from the core (Murphy et al. 1993). In addition, a significant unresolved source of X-ray emission is located at the same P.A. at a separation of ~ 1 arcmin from the core. Deeper large-scale radio imaging is necessary to reveal the nature of this peculiar source. The X-ray spectral analysis of the integrated X-ray emission of 3C 454.3 is in agreement with the results of Marshall et al. (2004): we find a strongly piled-up spectrum with an intrinsic photon index of ~ 1.3 and a considerable amount of absorption of $\sim 6\times10^{21}$ cm^{-2} confirming also the results of Tavecchio et al. (2002).

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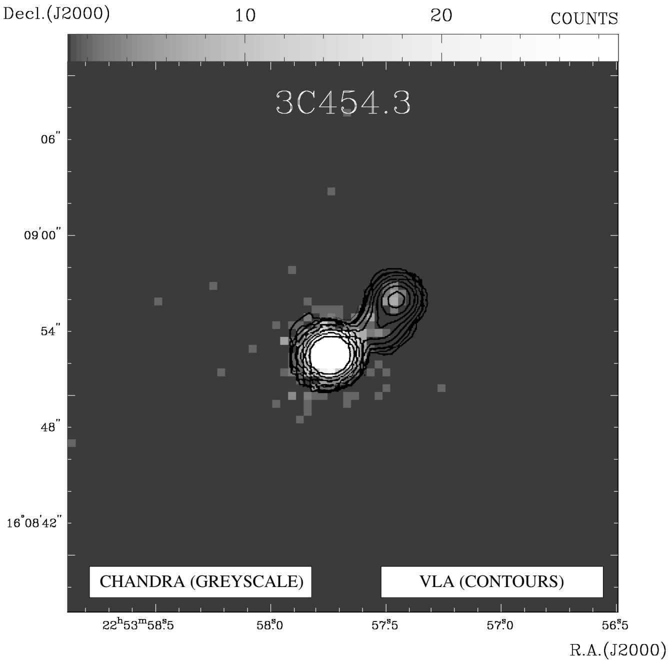

Fig. 4. The kiloparsec-scale radio- and X-ray brightness distribution of 3C 454.3. The radio jet is displayed in contours (taken from Murphy et al. 1993) at a frequency of 1.6 GHz.

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