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The 2 cm VLBA Survey

J. A. Zensus, E. Ros, M. Kadler
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

K. I. Kellermann, M. L. Lister, D. C. Homan
National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA

M. H. Cohen
Department of Astronomy, Mail Stop 105-24, California Institute of Technology, Pasadena, CA 91125, USA

R. C. Vermeulen
Netherlands Foundation for Research in Astronomy, Postbus 2, NL-7990 AA Dwingeloo, The Netherlands

Abstract. We report on the status of the 2 cm VLBA Survey, a program to study the kinematics of parsec-scale jets in active galactic nuclei (AGN). Over 200 sources have been observed at multiple epochs since 1994 with the Very Long Baseline Array (VLBA) at 15 GHz. The survey is restricted to flat-spectrum, bright sources ($S_{15\,\mathrm{GHz}} \geq 1.5$ Jy for $\delta > 0°$ and $S_{15\,\mathrm{GHz}} \geq 2$ Jy for $-20° < \delta < 0°$) with strong VLBI cores. More than 1000 images have been made so far and can be accessed from on-line archives at `http://www.nrao.edu/2cmsurvey` and `http://www.cv.nrao.edu/~mlister/MOJAVE`.
We present the distribution of apparent velocities measured for the 86 sources for which we have sufficient multi-epoch data, and we discuss the differences between the various classes of AGN (QSOs, BL Lacs, and galaxies).
We have initiated a new long-term project, MOJAVE (**Mo**nitoring of **J**ets in **A**GN with **V**LBA **E**xperiments), based on a statistically complete flux-limited sample which also includes studies of linear and circular polarization.

1. Introduction

The term Active Galactic Nucleus (AGN) refers to the energetic phenomena found in the central regions (nuclei) of galaxies which cannot be attributed directly to stars. Emission is associated with the existence of a super-massive black hole with an accretion disc from which bi-directional relativistic outflows ('jets') emerge. AGN radiate throughout the complete electromagnetic spectrum and their radio morphologies can usually be classified as being either 'extended' (e.g., spatially resolved) or 'compact' (e.g., unresolved at 1″ resolution). The extended sources can be as large as Megaparsecs and are transparent to their own radio synchrotron emission, whereas, due to self-absorption, the compact sources can have flat or even inverted spectra. Very Long Baseline Interferometry

(VLBI) probes the compact regions typically with resolutions of the order of 1 milliarcsecond (mas), which correspond to parsec scales (see Zensus 1997). VLBI is thus the key tool to study the relativistic outflows. Parsec-scale jets often show apparent superluminal motions, when those motions are oriented nearly along the line of sight (see sect. 3.1).

There have been various surveys to study the nature of AGN physics (see Table 1 and Green, Khachikian, & Sanders 2001). In spite of the extensive body of observational data and the sophisticated theoretical models which have been discussed in the last decades, major questions remain unanswered related to the nature of AGN jets. For example, it is not clear whether the flows are ballistic, that is, if individual features have straight trajectories, or if they follow the curvature of the jet. It also remains unclear if the changes in speed or direction of features as they propagate down the jet are typical or if they occur only under special circumstances. The different classes of AGN may present different characteristic Lorentz factors.

Table 1. Selected AGN Surveys

	Name	Refs.
Radio		
VLBI ($\lambda\lambda$ 18/6 cm)	Pearson-Readhead & Caltech-Jodrell Bank	Pearson & Readhead (1988); Taylor et al. (1994, 1996); Polatidis et al. (1995); Thakkar et al. (1995); Xu et al. (1995); Henstock et al. (1995); Vermeulen et al., these proceedings, page 43
VLBI (13/3.6/2)	Radio Optical Reference Frame	Fey, Clegg, & Fomalont (1996); Fey & Charlot (1997, 2000)
VLBI (6)	VSOP Pre-Launch	Fomalont et al. (2000)
VLBI (0.7)		Jorstad et al. (2001)
VLBI (0.3)	MPIfR	Lobanov et al. (2000)
Variability (6/3.6/2)	UMRAO	Aller et al. these proceedings, page 159
Variability	Effelsberg	Kraus et al. (2003)
Variability (1.3)	Northern 2 Jy	Valtaoja, Lähteenmäki, & Teräsranta (1992)
X-Ray		
ROSAT		Brinkmann et al. (1997); Lamer, Brunner, & Staubert (1996); Ciliegi & Maccacaro (1997); Miyaji, Hasinger, & Schmidt (2000)
*Beppo*SAX		Padovani et al. (2002)
γ-Ray		
EGRET	3rd Catalog	Hartman et al. (1999)

Individual, selected sources have been observed intensively in order to address these questions (e.g., 3C 345: Ros, Zensus, & Lobanov 2000; 3C 273: Lobanov & Zensus 2001; 3C 120: Gómez, Marscher, & Alberdi 1999; 3C 279: Homan et al. 2003, and these proceedings, page 35; 4C +12.50: Lister et al. 2003a). In particular, variability studies, multi-frequency monitoring, and observations of polarized emission have been important in understanding the physical conditions within individual sources. Our intent here is to study a representative sample of objects, carrying out a long-term, systematic monitoring of relativistic motion in AGN jets on parsec scales. We seek a significant improvement over previous surveys in terms of image resolution and fidelity, sample size, and statistical completeness. The goals of our program are to test and characterize the kinematics of these AGN jets and to determine how these are related to other source properties. We try to provide the basis for a comprehensive physical theory to relate the distribution of Lorentz factors and bends and other morphological characteristics, the internal temperatures, and the spectral behavior.

2. The Survey

Since 1994, we have been using the NRAO Very Long Baseline Array (VLBA) at 15 GHz (2 cm) to study the relativistic outflows in a sample of AGN (see description in Kellermann et al. 1998a and Zensus et al. 2002). Our sample is based on the 1 Jy catalog (Kühr 1981), and considers sources with flat spectra ($\alpha > -0.5$ for $S_\nu \propto \nu^{+\alpha}$ above 500 MHz) and flux densities $S_{15\,\mathrm{GHz}} > 1.5$ Jy for $\delta > 0°$, and $S_{15\,\mathrm{GHz}} > 2$ Jy for $-20° < \delta < 0°$. Some additional sources have been added, particularly those classified as compact symmetric objects or lobe-dominated sources with a strong core. The current 2 cm survey source list (complete up to February 2003) is shown in Table 2. The sources observed so far are tabulated under the column labeled with 'O'. The redshift distribution for the different classes of objects is presented in Figure 1 (a).

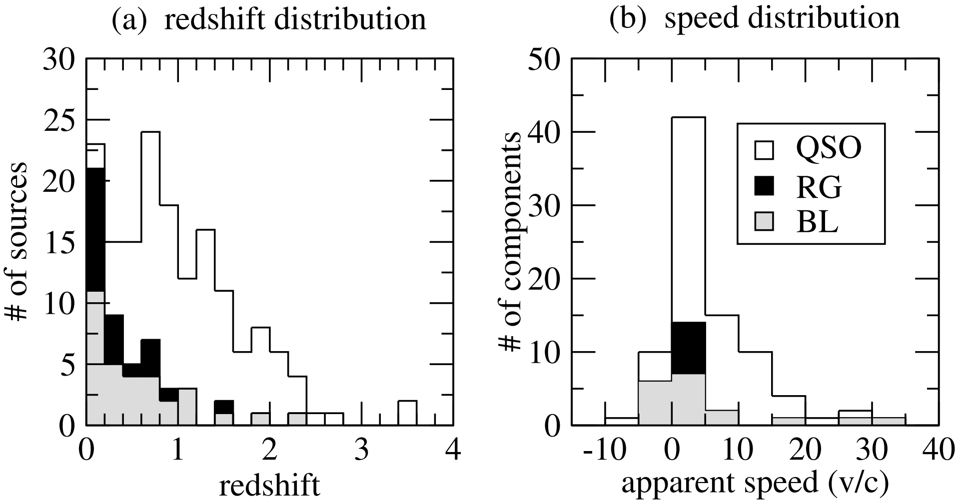

Figure 1. **(a)** Redshift distribution for the different classes of objects from the 2 cm survey. **(b)** Apparent speed distribution for the brightest components for which 3 or more data points were measured and a well-determined speed (18 BL Lac objects, 7 radio galaxies, and 61 QSOs).

We have completed more than 40 observing sessions, usually obtaining 24 images per run. We maintain a data bank of images from these observations, accessible at `http://www.nrao.edu/2cmsurvey`. Each source has been observed at least once per year. The observations typically consisted of multiple snapshots spread over 8 hours with a total integration time of 50 minutes. The root-mean-square noise level in each image is typically less than 1 mJy/beam. In other words, the dynamic ranges achieved are better than 1000:1, sufficient to

Table 2. 2 cm Survey Source List (Status February 2003)

Name	O[a]	K[b]	M[c]
0003−066	√	√	√
0007+106	√		
0016+731	√	√	
0026+346	√	√	
0035+413	√	√	
0048−097	√		
0055+300	√	√	
0059+581			√
0106+013	√	√	√
0109+224			♣
0112−017	√	√	
0119+041	√	√	
0119+115	√		♣
0133+476	√	√	√
0149+218	√	√	
0153+744	√	√	
0201+113	√		
0202+149	√	√	√
0202+319	√	√	√
0212+735	√	√	√
0215+015			♣
0218+357	√		
0221+067	√	√	
0224+671			♣
0234+285	√	√	√
0235+164	√		√
0238−084	√	√	√
0300+470			♣
0310+013	√		
0316+161	√		
0316+413			√
0333+321	√	√	√
0336−019	√	√	√
0355+508	√	√	
0403−132			♣
0405−385	√		
0415+379	√	√	√
0420+022	√		
0420−014	√	√	√
0422+004			√
0430+052	√	√	√
0440−003	√	√	
0446+112			√
0454+844	√	√	
0458−020	√	√	√
0521−365	√		
0528+134	√	√	√
0529+075			♣
0529+483			♣
0552+398	√		√
0602+673	√		
0605−085	√	√	√
0607−157	√	√	√
0615+820	√		
0642+449	√	√	√
0648−165			√
0707+476	√	√	
0710+439	√	√	
0716+714	√	√	
0723−008	√		
0727−115	√	√	√
0730+504			♣
0735+178	√	√	√
0736+017	√	√	√
0738+313	√	√	√
0742+103	√	√	
0745+241	√	√	
0748+126	√	√	√
0754+100	√	√	√
0804+499	√	√	
0805−077			♣
0808+019	√		
0814+425	√	√	
0821+394			♣
0823+033	√	√	
0827+243			√
0829+046	√	√	
0834−201	√	√	
0836+710	√		√
0850+581	√	√	
0851+202	√	√	√
0859+470	√		
0859−140	√	√	
0906+015	√		√
0917+449	√	√	
0917+624			♣
0923+392	√	√	√
0945+408	√	√	√
0953+254	√	√	
0954+658			♣
0955+476			√
1012+232	√	√	
1015+359	√	√	
1032−199	√		
1036+054			√
1038+064			√
1045−188			♣
1049+215	√	√	
1055+018	√	√	√
1055+201	√	√	
1101+384	√	√	
1124−186	√		√
1127−145	√	√	√
1128+385	√	√	
1144+402			♣
1145−071	√		
1148−001	√		
1150+812			√
1155+251	√		
1156+295	√	√	√
1213−172			♣
1219+044			♣
1219+285	√	√	
1222+216			√
1226+023	√	√	√
1228+126	√	√	√
1253−055	√	√	√
1302−102	√	√	
1308+326	√	√	√
1323+321	√		
1324+224			♣
1328+254	√		
1328+307	√		
1334−127	√	√	√
1345+125	√	√	
1354+196	√	√	
1354−152	√	√	
1404+286	√	√	
1413+135	√	√	√
1417+385			♣
1418+546			♣
1424+366	√		
1458+718	√	√	
1502+106	√	√	√
1504+377	√		
1504−167	√	√	√
1508−055	√	√	
1510−089	√	√	√
1511−100	√		
1514−241	√		
1519−273	√		
1532+016	√	√	
1538+149	√		
1546+027	√	√	√
1548+056	√	√	√
1555+001	√	√	
1606+106	√	√	√
1611+343	√	√	√
1622−253	√		
1633+382	√	√	√
1637+574			√
1638+398	√		√
1641+399	√	√	√
1642+690	√	√	
1652+398	√	√	
1655+077	√	√	√
1656+053	√	√	
1656+477	√	√	
1726+455			√
1730−130	√	√	√
1739+522	√		√
1741−038	√		√
1749+096	√		√
1749+701	√	√	
1751+288			√
1758+388	√	√	√
1800+440	√	√	√
1803+784	√	√	√
1807+698	√	√	
1823+568	√	√	√
1828+487	√	√	√
1845+797	√	√	
1901+319	√	√	
1921−293	√		
1928+738	√	√	√
1936−155			♣
1954+513	√		
1957+405	√	√	√
1958−179			♣
2005+403	√	√	√
2007+776	√	√	
2021+317	√	√	√
2021+614	√	√	√
2037+511			√
2113+293	√		
2121+053	√		√
2128+048	√		
2128−123	√	√	√
2131−021	√	√	√
2134+004	√	√	√
2136+141	√	√	√
2144+092	√	√	
2145+067	√		√
2155−152	√		√
2200+420	√	√	√
2201+315	√	√	√
2209+236	√	√	√
2216−038			√
2223−052	√	√	√
2227−088	√		√
2230+114	√	√	√
2234+282	√	√	
2243−123	√	√	√
2251+158	√	√	√
2255−282	√		
2318+049	√	√	
2331+073			♣
2345−167	√	√	√
2351+456			√

[a]: Included originally in the 2 cm survey (selection criteria, sect. 2).
[b]: Kinematic analysis performed. (Excludes sources with only one observing epoch or unresolved structure.)
[c]: Included in the MOJAVE sample (see sect. 4). √: confirmed, ♣: candidate.

determine the kinematics of the features in the sources by comparing images made at different epochs. The typical synthesized beam is 1 mas ×0.5 mas in position angle P.A. = 0°. Automatic imaging procedures proved to be sufficient in many of the cases (applying loops of CLEAN and phase self-calibration) using the DIFMAP software package.

The results of the survey have been published in several papers and conference proceedings. A description of the survey including contour plots for each of the sources is given in Kellermann et al. (1998a) and Zensus et al. (2002). General results from the Survey were presented in Kellermann et al. (1997; 1998b; 1999a; 2000; 2003), Kellermann (2002; and these proceedings, page 185), Cohen et al. (these proceedings, page 177), Ros et al. (2002), Ros (2003), and Lister et al. (2003b). Studies on individual sources have been presented: Kellermann et al. (1999b), Vermeulen et al. (2003a; 2003b; and these proceedings, page 43): NGC 1052, Homan (2002), Homan et al. (2003; and these proceedings, page 35): 3C 279; Lister, Kellermann, & Pauliny-Toth (2002), Lister et al. (2003a; 2003b): 4C +12.50; and Lister, Kellermann, & Pauliny-Toth (2002): 2134+004 and OQ 208.

3. Superluminal motions and kinematics

To determine the kinematics, we cross-identified the enhanced emission regions (or 'components') between different epochs. We parameterized their positions using the task JMFIT in AIPS, and with that we established the component motions for more than 100 sources in our sample (see Table 2, column labeled with 'K'). The apparent transverse velocity $\beta_{\rm app}$ of a component is given by the proper motion of the component along the line between it and the "core" (the brightest component), together with the metric distance for our assumed cosmology[1]). Our observations have also revealed non-radial motions, which are present in a ∼30% (16 of 56) of the components (see Homan 2002 and Homan et al., these proceedings, page 35, for the case of 3C 279).

Given the relatively large number of sources in our sample, we are able to make a statistical analysis of the source kinematics. The distribution of $\beta_{\rm app}$ for the brightest component for the different classes of sources is shown in Figure 1 (b), for those with 3 epochs or more measured, and a well-determined speed. The $\beta_{\rm app}$ median values for each class of sources are 1.72 for BL Lac objects, 0.23 for radio galaxies, and 4.15 for QSOs.

In addition to $\beta_{\rm app}$, we also determine the (isotropic) luminosity, L, from the observed flux density S, and a lower limit to the brightness temperature $T_{\rm b}$ from the peak brightness in the image and the synthesized beam. However, a better limit to $T_{\rm b}$ can be obtained, for the compact sources, by model-fitting the visibilities in (u, v)-space (see the example of 1622−253 in Zensus et al. 2002, reaching values higher than the 10^{12} K limit from Kellermann & Pauliny-Toth 1969). From all these parameters describing the source, we can estimate the relativistic parameters: γ, the Lorentz factor, and δ, the Doppler factor. In addition we can estimate θ, the angle to the line of sight, which is important in

[1]We used a value of $H_\circ = 65\,{\rm km\,s^{-1}\,Mpc^{-1}}$ and $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$.

understanding the geometry of these objects. These values can be compared with those measured at other frequencies, or with other techniques (e.g., variability of the flux density) to study the source physics, including tests of the general paradigm of relativistic beams.

4. Monitoring of Jets in AGN with VLBA Experiments: MOJAVE

Since we established our initial observing list in 1994, we have become aware of more sources which meet the selection criteria described in sect. 2. Also, we have found that other sources which we have been observing do not strictly meet those criteria. Therefore, we have begun a new observing program, MOJAVE, based on a complete VLBI flux density-limited sample of ~ 100 sources covering the same sky region as the original 2 cm survey. The MOJAVE observations, which began in August 2002, (see `http://www.cv.nrao.edu/~mlister/MOJAVE`) will include observations of the changes in linear and circular polarization with time as well as the total power changes.

Our initial selection strategy for MOJAVE involved compiling a list of all northern AGN that have had a measured 2 cm *single dish* flux density greater than 1.5/2 Jy. We began by consulting the Kühr 1 Jy catalog (Kühr 1981; Stickel, Meisenheimer, & Kühr 1994), the VLA calibrator manual, and the JVAS survey. The latter is complete to within $2\overset{\circ}{.}5$ of the galactic plane. Since these combined catalogs are only complete at a wavelength of 6 cm, we included sources from the 22 GHz survey of Moellenbrock et al. (1996) and the high-frequency peaked spectrum samples of Teräsranta et al. (2001) and Dallacasa et al. (2000) that met our flux density criteria. We also included variable AGN from the U. Michigan and RATAN monitoring programs that have displayed sufficient 2 cm flux density at any epoch.

Since we are interested in a VLBI core-selected sample, we eliminated from our candidate list any source whose measured 2 cm VLBA flux had never exceeded 1.5/2 Jy at four epochs over a four year period beginning in 1995. The majority of sources in the previous 2 cm survey have been observed at least on four occasions in order to obtain reliable jet component speeds. For those sources with fewer than four VLBA epochs available, we checked if there were four RATAN or UMRAO flux measurements since 1995 with a similar time spacing to our VLBA epochs, and again rejected those that had never exceeded 1.5/2 Jy. Currently the MOJAVE sample list (column "M" in Table 2) consists of 99 confirmed AGN that meet these strict criteria. We maintain a list of 23 MOJAVE candidates for which we are obtaining VLBA or single-dish observing data that will span the requisite four year time range. The analysis of our VLBA data is currently underway, and new maps are being made available on our website at regular intervals as each epoch is reduced.

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