Carnegie Observatories Astrophysics Series, Vol. 1:
Coevolution of Black Holes and Galaxies, 2004
ed. L. C. Ho (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium1/proceedings.html)

The AGN Content of the NOAO Deep Wide Field Survey at Milliarcsecond Resolution

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Abstract

We are using the NRAO Very Long Baseline Array (VLBA) at 5 GHz to observe compact FIRST sources stronger than 10 mJy in the NOAO Deep Wide-Field Survey (NDWFS). Our study of 206 sources at milliarcsecond resolution overcomes two limitations of past VLBI surveys for active galactic nuclei (AGN), namely biases introduced by targeting flat-spectrum sources stronger than 200 mJy, plus the difficulty of obtaining deep optical identifications and redshifts. Half of the VLBA survey is complete, with almost one in three sources being detected above a typical threshold of 1.5 mJy beam^{-1}. Once complete, the VLBA detection rate will have enough statistical precision to constrain evolutionary models for radio source populations, such as a recent promising one based on a unification scheme for AGN (Jackson & Wall). Since the VLBA survey targets sources without spectral pre-selection, the detections will have implications for the interpretation of VLBA images of sources thought to be gravitationally lensed, and could potentially lead to the discovery of new types of AGN. All VLBA non-detections will still have astrophysical value, because of the visibility-function constraints from the VLBA and the identification information from the NOAO and *Chandra* surveys.

1.1 Our Survey

We used the NRAO VLBA to image 100 sources from the VLA FIRST survey (White et al. 1997) that are within the NDWFS Boötes field (Jannuzi & Dey 1999), and are compact ($\Omega_M < 5''$) and bright ($S_{peak} > 10$ mJy beam^{-1} at 1.4 GHz). Results for the first 27 objects are presented in Wrobel et al. (2001). Phase-referenced observations were made with a switching time of five minutes and a switching angle of 2.5° or less. Each FIRST source was observed for a total of eight minutes spread over six hours to improve (u,v) coverage. Figure 1.1 shows the Boötes field (shaded area) and FIRST sources (circles in the field). The phase calibrators (squares) are shown with a dashed circle outlining the maximum switching angle. Thus all of the FIRST sources within the Boötes field are accessible to the VLBA. For each source, a region of 1600 milliarcsecond (mas) on each side was imaged to enclose the 4σ error ellipse for the FIRST position. The RMS of each image is roughly 0.25 mJy beam^{-1}; however the size of the region imaged (about 10^5 beam areas) imposes a 6σ detection threshold.

With a typical beamwidth of 1.5 x 3.3 mas, and an observing frequency of 5 GHz, the flux density limit of 1.5 mJy implies that all detected sources must have brightness temper-

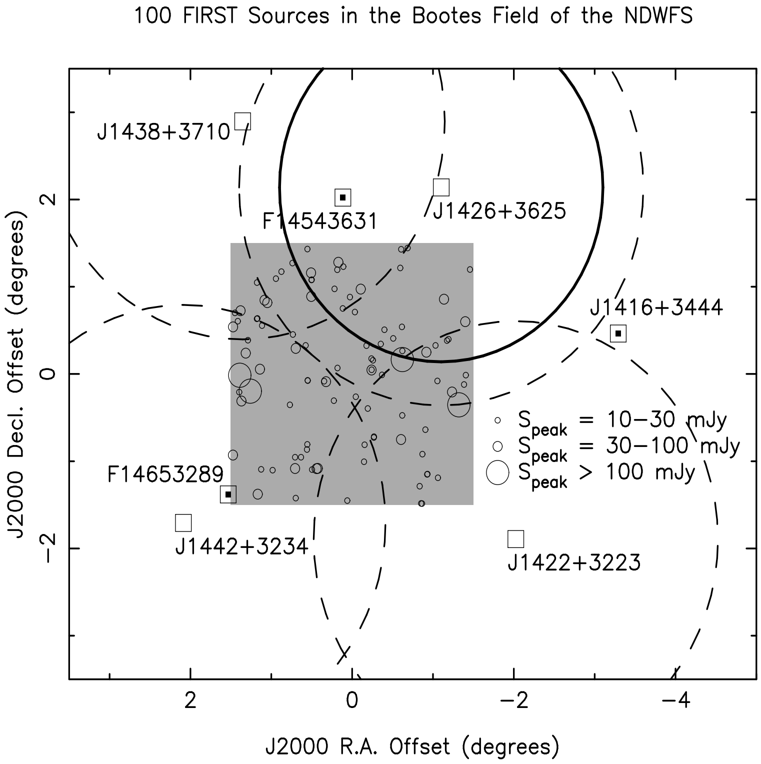

Fig. 1.1. Shaded square is 3° on a side and shows the Boötes field. Circles in the field show 100 FIRST sources, with bigger circles encoding stronger sources. Calibrators outside the field are marked as simple squares for phase calibrators and as squares with inner symbols for astrometric check sources. Two check sources closest to the survey region are weak CLASS sources. Dashed circle of radius 2.5° is centered on each phase calibrator, showing a plausible switching angle for phase referencing at a frequency of 5.0 GHz.

atures of 10^7 K or higher, which, at cosmological distances, can only be AGN. Four FIRST sources were known to be jet or hotspot components; these four were not expected to be detected with the VLBA but were observed for control purposes. Discounting these four, 28 FIRST sources (or $29 \pm 4\%$) were detected with the VLBA above a threshold of 1.5 mJy. All VLBA detections have been astrometrically anchored to the ICRF. We note that non-detections still have value because of the visibility-function constraints on mas scales and identification information from other surveys. Figure 1.2 illustrates some of the VLBA morphologies observed, including a possible compact symmetric object (lower right). The same VLBA methodology is now being applied to an additional 106 compact FIRST sources in the NDWFS Cetus field.

1.2 Other Survey Data

Complete NDWFS datsets for the Boötes field are not yet available. However 11 of 100 FIRST radio sources are within the area covered by the first data release, version 2, for which B_w, R and I data are now available. AGN were detected in four of the 11 objects.

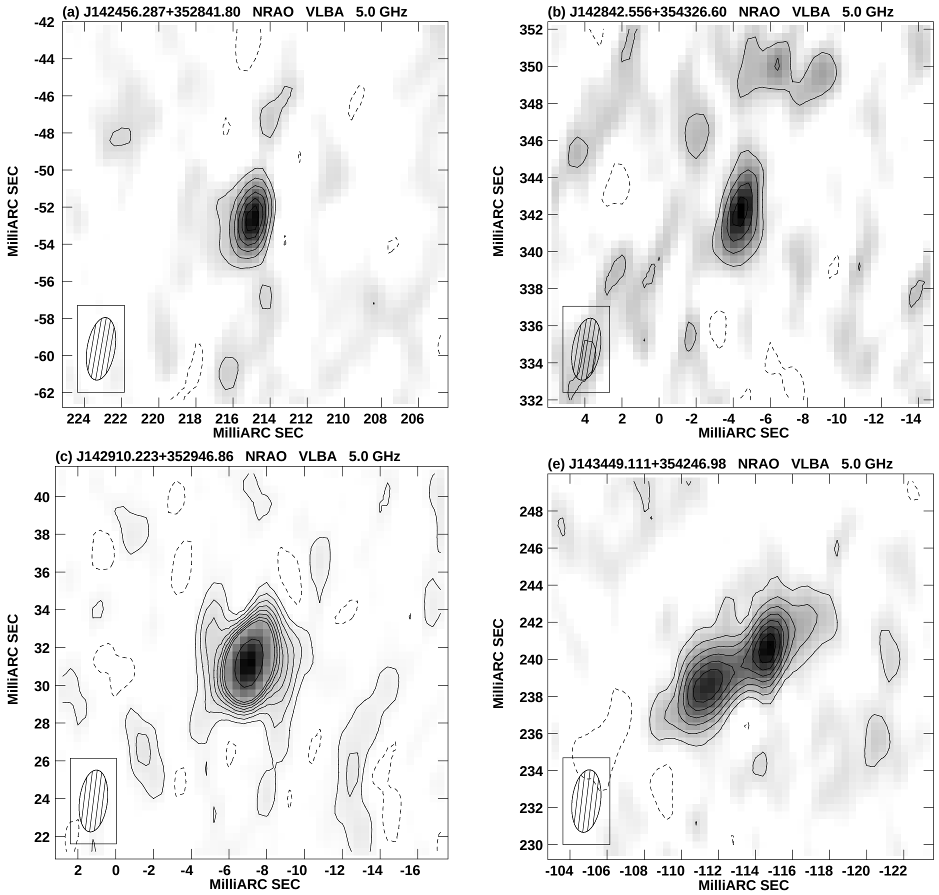

Fig. 1.2. VLBA Stokes I maps at 5.0 GHz of J142456.287+352841.80 (upper left), J142842.556+354326.60 (upper right), J142910.223+352946.86 (lower left) and J143449.111+354246.98 (lower right). For each target, data were acquired in dual circular polarizations with 4-level sampling and bandwidth 32 MHz, and during six 80-second snapshots spread over time to enhance (u,v) coverage. Each cleaned image is centered on the position of the VLBA detection and spans 20 mas. Shaded ellipses show the Gaussian restoring beams at FWHM. Negative contours are dashed while positive ones are solid. Grey scales show positive intensities with darkest values at the image peaks of 3.2, 2.2, 14.8, 1.7, and 4.1 mJy beam^{-1}. Contour levels are at −6, −4, −2, 2, 4, 6, 8, 10, 12, 14, and 16 times the rms noise.

Two of the VLBA detections are coincident with blue ($B_w - R \sim -1$) point sources in the optical data and are identified as quasars. One VLBA detection is coincident with a very red ($R-I$ = +2.5) elliptical and therefore is likely a radio galaxy or BL Lac object. The fourth VLBA detection is coincident with a faint (B_w = 22.7) galaxy at high photometric redshift. Additionally, five of the 100 FIRST radio sources in the Boötes field were detected by the ROSAT All-Sky Survey (RASS), four of which are AGN detected by the VLBA.

A survey of the Boötes field with Chandra (P.I.s C. Jones and S. Murray) is underway to a depth of 5 ksec. Its sensitivity will be 8.0 x 10^{-15} ergs cm^{-2} s^{-1} for extended sources and

3.6 x 10^{-15} ergs cm^{-2} s^{-1} for point sources, roughly 20 times more sensitive than RASS. In addition, the positional accuracy of the survey will be on average $\sim$40 times better, allowing more accurate source identifications at other wavelengths. Once the complete NDWFS and Chandra survey data are available it will be possible to determine the broadband SEDs for AGN to a depth several magnitudes fainter than similar prior surveys. It will also allow more precise methodologies to be developed to search of AGN and other classes of radio sources in other large surveys (e.g., SDSS; Anderson et al. 2001).

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