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EVN observations of Seyfert galaxies

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In this contribution, we report on dual-frequency EVN observations of six nuclei of Seyfert galaxies imaged previously at arcsecond resolution with the VLA. These galaxies are part of a distance-limited sample of Seyferts, for which VLBI observations are available only for the brightest objects. Our observations consider for the first time sources with flux density around $S \sim 1$ mJy (VLA cores), which represents a significant step to lower flux density levels with respect to previous works. They are thus an important step towards an understanding of the emission mechanism in Seyfert galaxies as a population.

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1. Introduction

Active Galactic Nuclei (AGN) are traditionally divided in radio quiet (RQ) and radio loud (RL). The latter are common targets of VLBI observations: they are typically powerful radio sources ($L_r > 10^{22}$ W Hz^{-1}), with bright compact cores (showing in some cases superluminal motions) and large scale radio lobes. Radio quiet AGNs are much fainter radio sources and their radio emission is confined to the sub-kpc scale. However, moderately deep VLA surveys show that most AGN are radio sources at some level [4, 6].

While the radio emission in RL AGN is certainly due to the synchrotron process, the case for RQ AGN is much less clear. A clue about the nature of the radio emission in Seyfert galaxies comes from the study of scaling relations. Recent works have found a correlation between X-ray and radio luminosity extending over 8 orders of magnitudes, down to the regime of Low-Luminosity AGNs (LLAGN) [7]. This correlation holds for both RQ and RL sources, although the two groups are separated by an offset in X-ray luminosity.

Moreover, there is evidence for a trend of increasing radio-loudness with decreasing Eddington ratio [3, 9]. This suggests a similarity to the case of X-ray binaries (XRB), in which jets are more dominant at lower accretion, while disks become less prominent [5].

In order to discuss possible relations between the formation of jets in LLAGN and the accretion rate, we need to look at the radio emission to see if it is actually radiated by a jet. This requires high resolution and superior sensitivity, which explains why this topic has not been challenged before.

We have selected and presented elsewhere [8] a complete sample of 27 nearby Seyfert galaxies. The sample is distance limited ($d < 27$ Mpc) and XMM data are available in the X-ray band [1]. VLBI images are available in the literature only for a few bright objects (the really nearby ones) and we are interested in extending the dataset to fainter sources. In this contribution, we shortly summarize some results on the literature data (Sect. 2) and present the results of new European VLBI Network observations for 6 objects with VLA cores at the milliJansky level (Sect. 3). Finally, we summarize preliminary conclusions and future prospects in Sect. 4.

2. Literature data

Very Long Baseline Interferometry observations of LLAGN and Seyfert galaxies are traditionally difficult due to the low radio luminosity of this sources. Nevertheless, the really nearby sources are bright enough to be imaged and several works have reported the results. Among the sources in our sample, some interesting facts have recently been found.

NGC 4151 is a radio-quiet Sy 1.5 nucleus studied with the VLBA at 15 GHz [10]. The radio source size is < 0.035 pc, i.e. comparable to the broad line region (BLR) scales. The VLBI compact flat-spectrum radio component has a brightness temperature $T_b > 2 \times 10^8$ K and is located within a two sided structure extending to the large scale radio jet. Sub-relativistic motions have been found, suggesting only mild jet velocities or a large viewing angle.

Another remarkable case is NGC 1068 [2], characterized by a central elongated structure with lower brightness temperature ($T_b = 2.5 \times 10^6$ K) and closely aligned to a well detected maser disk. This suggests that the radio emission could arise from thermal free-free process in an X-ray-heated corona or from a wind arising from a molecular disk.

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Table 1: Log of observations. Stations listed in *italics* were affected by major recording or weather problems.

Date	Telescopes	ν (GHz)	Source
2007 Jun 6	Jb, Wb, Ef, On, Mc, Tr, Sh, Ur, Nt	1.6	NGC 4051, 5033, 5273
2007 Jun 1	Jb, *Wb*, *Ef*, On, Mc, Tr, *Sh*, Ur, Nt	5	NGC 4051, 5033, 5273
2008 Feb 28	Jb, Wb, Ef, On, Mc, Tr, *Sh*, Ur, Nt, Hh	1.6	NGC 4388, 4501, 5194
2008 Mar 10	*Jb*, Wb, *Ef*, On, Mc, Tr, Sh, Ur, Nt, Hh	5	NGC 4388, 4501, 5194

Finally, a good case of an extremely weak source though successfully revealed with VLBI is NGC 4395. This radio-quiet type 1 nucleus has an intermediate mass Black Hole ($M_{\rm BH} = 3.6 \times 10^5 M_\odot$), a low Eddington ratio ($L_X/L_{\rm Edd} = 0.004$), and a radio flux density of 0.74 ± 0.04 mJy. Thanks to deep VLBI observations, it has been possible to reveal a high brightness temperature core ($T_B > 2 \times 10^6$ K) and an elongated structure which suggests radio outflow on sub-pc scales [11].

3. New EVN observations

We observed with the EVN at 1.6 and 5 GHz the nuclei of six Seyfert galaxies: NGC 4051, NGC 4388, NGC 4501, NGC 5194, and NGC 5273, between 2007 June and 2008 March. The exact dates and participating telescopes are reported in Table 1. We used the maximum recording rate of 1 Gbps and each source was observed for about 6 hr, switching between targets in order to improve the (u,v)-coverage. Amplitude calibration was done a priori in the standard EVN pipeline; phase corrections were obtained using observations of bright nearby calibrators, in the so-called phase referencing technique.

Phase coherence was clearly detected on the baselines with large sensitive telescopes in four cases at 1.6 GHz and in one case at 5 GHz. Note that the 5 GHz observations were affected by significant failures at some of the largest apertures, thus possibly compromising the detection of the sources. We also found significant displacements (as large as $1''$) from the tentative phase centers adopted in the schedules, owing to the lack of previous high resolution observations.

3.1 Results

We detected with high confidence NGC 4051, NGC 4388, NGC 4501, NGC 5033 at 1.6 GHz and NGC 5033 at 5 GHz. Images of the host galaxy and of the VLBI detections are shown in Figs. 1,2, and 3, and discussed in the following subsections. The image parameters are given in the figure captions and a comparison to the VLA properties is reported in Table 2. In general, the detected galaxies have a flux density on parsec scales that is around 0.5–1 mJy, i.e. between 10 and 50% of the VLA flux density, and estimated sizes < 10 mas (HPBW). The corresponding brightness temperatures are $> 10^8$ K, i.e. suggestive of the presence of Doppler beaming.

3.2 NGC 4051

NGC 4051 is classified as a Sy 1.5 galaxy at $d = 10.2$ Mpc. For this source, the visibility data

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Table 2: Properties of the radio cores. VLBI data (Cols. 1-3) are from the present work; VLA data (Cols. 4-6) are from [4].

Source	$P^{\rm VLBI}_{\rm 1.6\,GHz}$ (mJy beam^{-1})	$P^{\rm VLBI}_{\rm 5\,GHz}$ (mJy beam^{-1})	T_B (K)	$S^{\rm VLA}_{\rm 1.4\,GHz}$ (mJy)	$S^{\rm VLA}_{\rm 5\,GHz}$ (mJy)	$\alpha_{\rm VLA}$
NGC 4051	1.0?	...	1.1×10^5	7.3	3.2	0.7
NGC 4388	0.8	...	1.3×10^6	11.6	7.9	0.3
NGC 4501	0.6	...	1.4×10^6	2.1	1.1	0.5
NGC 5033	1.4	1.0	3.3×10^6	8.0	4.2	0.5
NGC 5194	...	...	...	3.4	1.3	0.8
NGC 5273	...	...	...	2.1	1.3	0.4

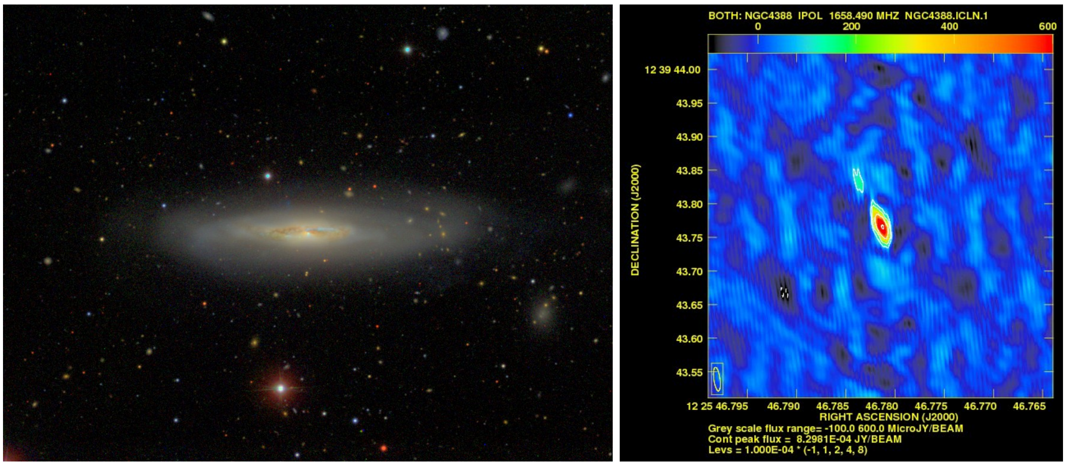

Figure 1: Images of NGC 4388. Left: color image from the Sloan Digital Sky Survey (size $\sim 12'' \times 8''$). Right: 1.6 GHz EVN images of the central region (beam 35×9 mas, in PA 7°).

at 1.6 GHz show that emission on parsec scales is clearly present, although difficult to image or model fit. For this reason, we do not show a clean map, which we hope to produce in a future paper.

3.3 NGC 4388

Classified as a Sy 2 (or 1.9) at $d = 34$ Mpc, this galaxy hosts a central radio source resolved into two peaks, neither of which coincides with the optical nucleus; the northern peak has a flatter, or even inverted, spectral index up to 2 cm, and it has a size upper limit of 70 mas (see [4] and references therein).

Our observations (see Fig. 1) clearly detect compact radio emission from this component, with a 1.6 GHz peak of 0.8 mJy beam^{-1}. It is therefore identified as the "true" core, probably obscured at optical wavelengths. There is also an extension to the NE that could be interpreted as a tentative jet, while no emission is detected from the southern component.

At 6 cm, we lack sensitivity but emission is detected at low SNR ratio.

3.4 NGC 4501

Known also as M 88, NGC 4501 is a Sy 2 galaxy at $d = 31$ Mpc hosting an unresolved VLA

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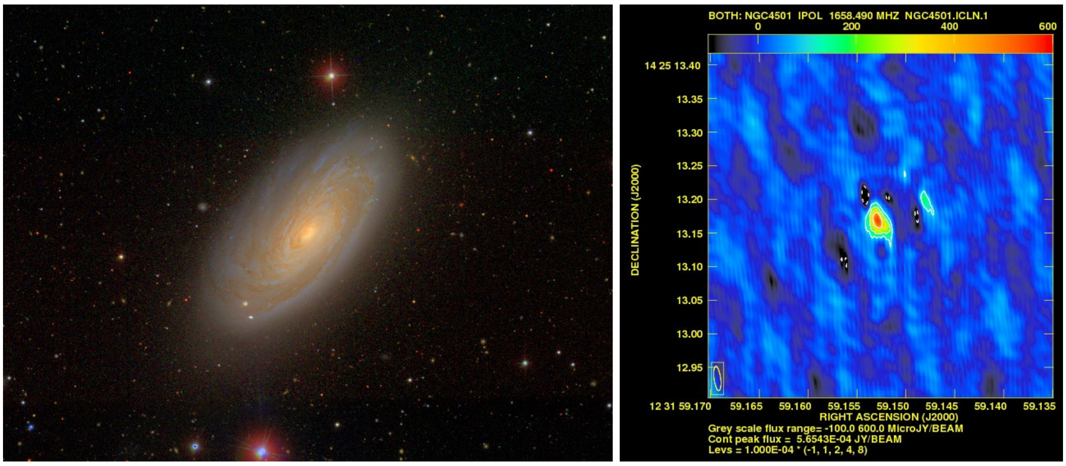

Figure 2: Images of NGC 4501. Left: color image from the Sloan Digital Sky Survey (size $\sim 12'' \times 8''$). Right: 1.6 GHz EVN images of the central region (beam 36×10 mas, in PA 7°).

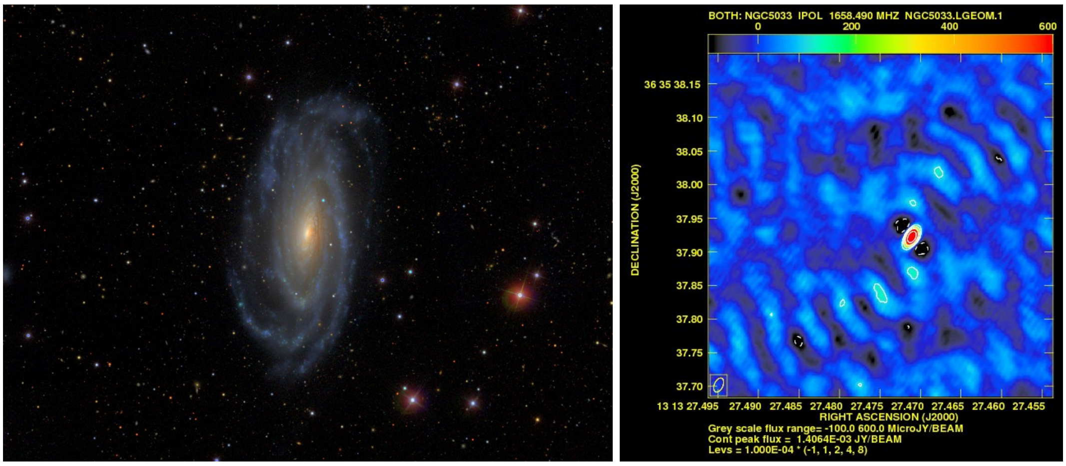

Figure 3: Images of NGC 5033. Left: color image from the Sloan Digital Sky Survey (size $\sim 12'' \times 8''$). Right: 1.6 GHz EVN images of the central region (beam 22×13 mas, in PA -24°).

radio source [4]. We detected this source at 1.6 GHz and show the image in Fig. 2. The peak brightness is 0.6 mJy beam^{-1} and our data account for a large fraction of the VLA detected flux density at 20 cm, suggesting that the radio source is highly compact.

3.5 NGC 5033

VLA data at 6 and 20 cm show an unresolved or slightly resolved core in this Sy 1.9 galaxy at $d = 12.7$ Mpc (see [4] and references therein). We detected this source also on parsec scales; in fact, this is the only object that is detected in our EVN observations at both 1.6 and 5 GHz (the 1.6 GHz image is shown in Fig. 3). Our resulting spectral index is slightly flatter than the one measured on larger scale ($\alpha = 0.5$, [4]). We are probably detecting the inner component of a slightly extended short jet, although the uncertainty in amplitude calibration and possible variability make the error on the spectral index quite large.

3.6 NGC 5194 and NGC 5273

Compact components are not revealed in NGC 5194 and NGC 5273 (a Sy 2 and a Sy 1.5, respectively) within 1" radius from the phase centers. Upper limit peak brightness is around 0.1 mJy beam^{-1} at 1.6 GHz and somehow higher at 5 GHz.

4. Preliminary conclusions and future prospects

The six sources presented in this paper are part of a larger sample of Seyfert galaxies. The present data set completes the observations of all the galaxies for which radio cores are detected with the VLA at 1.4 and 5 GHz. Parsec scale cores are detected in $\sim$ 80% of the sources. This fraction is still somehow uncertain owing to the faint nature of the sources. In particular, it is possible that some of the non detections are not due to physical reasons but can actually be recovered with a more thorough analysis and/or more accurate positions. The lowest detection rate at 5 GHz is also most likely due to bad observing conditions rather than to peculiar spectral properties.

Overall, the detection rate of compact parsec scale components remains strikingly high and the measured brightness temperatures are also remarkable (generally in excess of 10^6 K, i.e. presumably non thermal). We anticipate that observations of even fainter cores will be doable in the near future and will improve the statistics on the sample. The ultimate goal remains the understanding of the nature of the radio emission in Seyfert galaxies (cores/jet/outflows) and of its coupling to the X-ray emission (disk/corona).

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References

[1] Cappi, M., Panessa, F., Bassani, L., et al. *X-ray spectral survey with XMM-Newton of a complete sample of nearby Seyfert galaxies* 2006, A&A, 446, 459, [arXiv:astro-ph/0509584]

[2] Gallimore, J. F., Baum, S. A., O'Dea, C. P. *The Parsec-Scale Radio Structure of NGC 1068 and the Nature of the Nuclear Radio Source* 2004, ApJ, 613, 794, [arXiv:astro-ph/0406062]

[3] Ho, L. C. *On the Relationship between Radio Emission and Black Hole Mass in Galactic Nuclei* 2002, ApJ, 564, 120, [arXiv:astro-ph/0110440]

[4] Ho, L. C., Ulvestad, J. S. *Radio Continuum Survey of an Optically Selected Sample of Nearby Seyfert Galaxies* 2001, ApJS, 133, 77, [arXiv:astro-ph/0102506]

[5] Körding, E., Falcke, H., Markoff, S. *Population X: Are the super-Eddington X-ray sources beamed jets in microblazars or intermediate mass black holes?* 2002, A&A, 382, L13, [arXiv:astro-ph/0112385]

[6] Nagar, N. M., Falcke, H., Wilson, A. S., Ulvestad, J. S. *Radio sources in low-luminosity active galactic nuclei. III. "AGNs" in a distance-limited sample of "LLAGNs"* 2002, A&A, 392, 53, [arXiv:astro-ph/0207176]

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[7] Panessa, F., Barcons, X., Bassani, L., Cappi, M., Carrera, F. J., Ho, L. C., Pellegrini, S. *The X-ray and radio connection in low-luminosity active nuclei* 2007, A&A, 467, 519, [arXiv:astro-ph/0701546]

[8] Panessa, F., Cappi, M., Pellegrini, S., Barcons, X., Bassani, L., Carrera, F., Ho, L., Giroletti, M. *The X-ray and radio connection in local Seyfert galaxies* 2008, cosp, 37, 2340

[9] Sikora, M., Stawarz, Ł., Lasota, J.-P. *Radio Loudness of Active Galactic Nuclei: Observational Facts and Theoretical Implications* 2007, ApJ, 658, 815, [arXiv:astro-ph/0604095]

[10] Ulvestad, J. S., Wong, D. S., Taylor, G. B., Gallimore, J. F., Mundell, C. G. *VLBA Identification of the Milliarcsecond Active Nucleus in the Seyfert Galaxy NGC 4151* 2005, AJ, 130, 936, [arXiv:astro-ph/0505141]

[11] Wrobel, J. M., Ho, L. C. *Radio Emission on Subparsec Scales from the Intermediate-Mass Black Hole in NGC 4395* 2006, ApJ, 646, L95, [arXiv:astro-ph/0606600]