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PRESENT AND FUTURE MILLIMETER VLBI IMAGING OF JETS IN AGN: THE CASE OF NRAO 150

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RESUMEN

El *Global mm–VLBI Array* es hoy día el interferómetro de VLBI a 3 mm más sensible y proporciona imágenes con resoluciones angulares de hasta 40 micro-segundos de arco. Haciendo uso de este interferómetro, hemos seguirdo la evolución de la rotación en el plano del cielo de la zona más interna del jet en el cuásar NRAO 150, el cual presenta una velocidad angular de $\sim 7°$/año. Los futuros interferómetros de 3 mm podrían incluir estaciones adicionales como ALMA, GBT, LMT, CARMA, SRT, Yebes, Nobeyama y Noto, que permitirían forzar la técnica de VLBI a esta longitud de onda para obtener niveles de sensibilidad y calidad de imagen comparables a las de VLBI en longitudes de onda centimétricas. Esto mejoraría nuestro conocimiento de los sistemas de acrecimiento y la magneto-hidrodinámica de las regiones más internas de los jets en AGN y microcuásares.

ABSTRACT

The Global mm-VLBI Array is at present the most sensitive 3 mm-VLBI interferometer and provides images of up to 40 micro-arcsecond resolution. Using this array, we have monitored the rotation of the innermost jet in the quasar NRAO 150, which shows an angular speed of $\sim 7°$/yr. Future 3 mm arrays could include additional stations like ALMA, GBT, LMT, CARMA, SRT, Yebes, Nobeyama and Noto, which would allow to push VLBI at this wavelength to sensitivity and image quality levels comparable to those of present VLBI at centimeter wavelengths. This would improve our knowledge of the accretion systems and the magneto-hydrodynamics of the innermost jets in AGN and microquasars.

Key Words: **GALAXIES: ACTIVE — GALAXIES: JETS — QUASARS: INDIVIDUAL (NRAO 150) — RADIO CONTINUUM: GENERAL — TECHNIQUES: HIGH ANGULAR RESOLUTION — TECHNIQUES: INTERFEROMETRIC**

1. INTRODUCTION

It has been shown in this conference that fundamental questions related to the nature of the AGN are still open. The accretion of material onto supermassive black holes and the triggering of relativistic jets (including their formation, acceleration and further collimation) are some of the processes that still lack a detailed understanding. Observing with the highest angular resolution instruments offers a good opportunity to learn more about these processes through the study of the time evolution of the jets. An important effort has been made during the last decades to bring the technique of millimeter Very Long Baseline Interferometry (mm-VLBI) to progressively higher sensitivities and shorter wavelengths, offering a powerful tool to observe the innermost regions of the jets and study the physics involved in their behaviour.

During the last years, 7 mm-VLBI observations, with angular resolutions of up to ~ 0.15 milliarcseconds (mas), have addressed the triggering of relativistic jets in AGN and their hydrodynamics. Some particularly important results from these kind of observations are the first size estimation of the radio-visible jet collimation region (~ 1 pc from the core of the jet for M 87; Junor, Biretta, & Livio 1999) and the first measurement of the distance from the central engine to the core of the jet (of ~ 0.3 pc for 3C 120; Marscher et al. 2002). Monitoring programs with adequate time sampling have also allowed tests of relativistic hydrodynamic models in the innermost regions of the jets in AGN (e.g. Gómez et al. 2001 and Jorstad et al. 2005).

At present, 3 mm-VLBI offers an even better tool to image deeper jet regions (i.e. closer than ~ 0.3 pc from the accretion system). This is because of the lower jet opacities at this shorter wavelength and to

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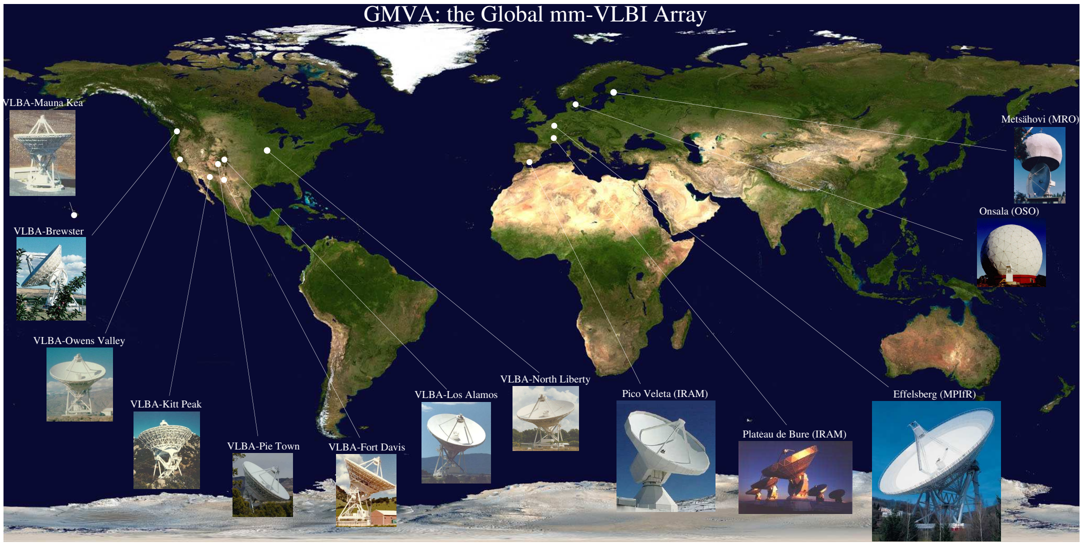

Fig. 1. World distribution of the stations participating in the Global mm-VLBI Array.

the larger resolving power at 3 mm, which can be up to three times higher than at 7 mm.

2. THE GMVA: SENSITIVE ASTRONOMY AT 40 MICRO-ARCSECOND RESOLUTION

The most sensitive 3 mm-VLBI instrument today is the Global mm-VLBI Array (GMVA[5], see Figure 1), composed of the Pico Veleta, Plateau de Bure, Effelsberg, Onsala and Metsähovi stations, in addition to eight of the ten Very Long Baseline Array (VLBA) antennas. The GMVA achieves angular resolutions of up to 40 μas with typical 7σ baseline sensitivities of 80-100 mJy (adopting 20 s coherence time, 100 s segmentation time and the standard GMVA recording rate of 512 Mbps). This yields 7σ image sensitivities of 1-2 mJy/beam (for 12 h of observation and a duty cycle of 0.5). With these characteristics the number of AGN which could be imaged with high dynamic ranges ($\geq$100:1) is now larger than 100.

In an attempt to obtain a deeper knowledge of the physics in the innermost regions of jets in AGN, we have started 3 mm-VLBI monitoring campaigns of some bright sources. In this paper, we present recent results about one of them: NRAO 150.

3. NRAO 150: AN UNUSUAL AGN “HIDDEN” BY THE MILKY WAY

NRAO 150 is an intense radio to mm source, which was first cataloged by Pauliny-Toth, Wade,

[5] http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm

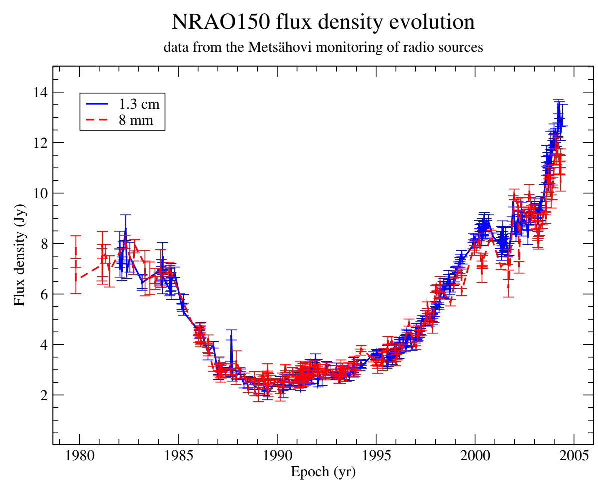

Fig. 2. 1.3 cm and 8 mm long term light curve of NRAO 150 from 1987 to 2005. Data from the Metsähovi monitoring of radio sources.

& Heeschen (1966). The source has been monitored regularly in the radio and millimeter bands since the beginning of the eighties. Since then, its total flux density light curve has displayed a quasi-sinusoidal behavior with a characteristic time-scale of $\sim$ 20-25) yr (see Teräsranta et al. 2004 and Figure 2). The 1.3 cm light curve of the source peaked at the beginning of 2004, when it displayed $\sim$ 11 Jy (see Figure 2). NRAO 150 lacks, up to now, an optical identification. This is probably due to its low Galactic latitude (-1.6°), which causes strong Galactic ex-

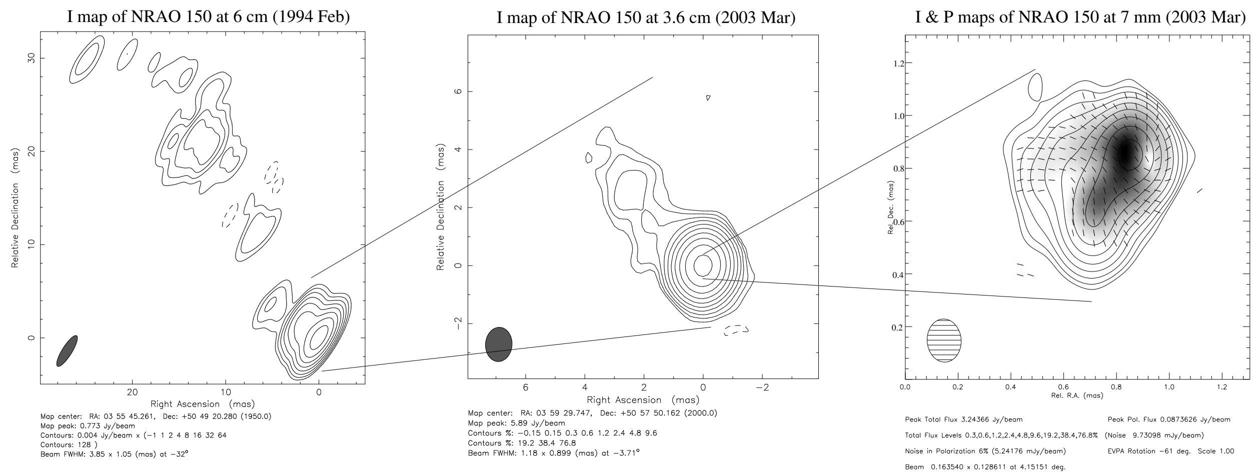

Fig. 3. From left to right, 6 cm, 3.6 cm and 7 mm VLBA images of the jet in NRAO 150 obtained in February 1994 (for the 6 cm map) and March 2003 (for those at 3.6 cm and 7 mm). The contours represent the observed total intensity. For the 7 mm map, the grey scale symbolizes the polarized intensity and the superposed sticks the orientation of the polarization electric vectors. The higher resolution 7 mm image shows a strong misalignment between the cm and the mm jet of $\sim 120^{\circ}$.

tinction. Although its distance is still unknown, we hope to determine its redshift through an ongoing spectroscopic project in the infrared band, at which the source is not strongly absorbed.

On cm-VLBI scales, NRAO 150 shows a compact core plus a one-sided jet extending beyond 20 mas with a structural position angle of $\sim 30^{\circ}$ (see Figure 3). Our new 7 mm-VLBI observations, the first reported at this wavelength, have revealed a strong misalignment, of $\sim 120^{\circ}$, between the inner and outer jet within its first 0.4 mas (Figure 3).

3.1. *The fastest jet rotation in an AGN at $\sim 7^{\circ}$/yr*

Making use of the GMVA (and also of the former Coordinated Millimeter VLBI Array, CMVA), we have monitored the jet evolution since 1999 up to date with observations performed about every six months. Figure 4 shows one of the resulting images from these observations, which demonstrate the capability of the 3 mm array to probe the innermost jet structures with angular resolutions of 40 μas and dynamic ranges of ~100:1. The adequate image fidelity of our new 3 mm observations is also demonstrated by their (u,v)-coverage, which is comparable to that of our 7 mm observations performed with the VLBA (see Figure 5).

The results from our new NRAO 150 images have revealed a clear angular rotation of the inner 0.4 mas jet with a speed of $\sim 7^{\circ}$/year – projected on the plane of the sky – (see Figure 6). To our knowledge, this is so far the fastest jet rotation reported for an AGN.

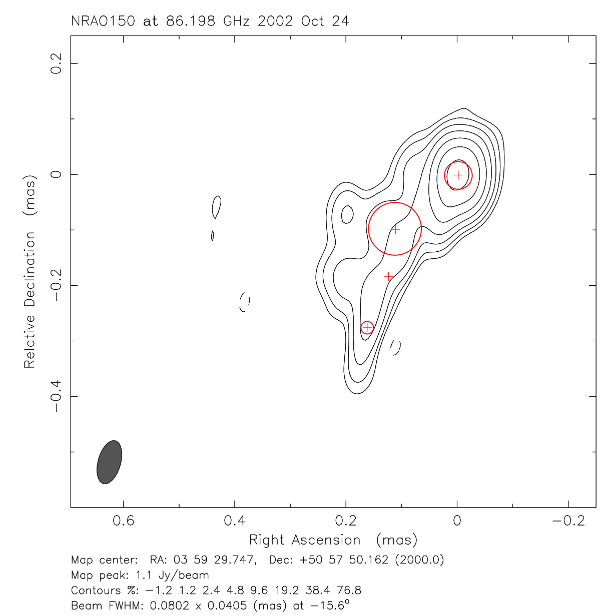

Fig. 4. 3 mm-VLBI image of NRAO 150 taken on October 2002. The positions of the fitted Gaussian components are indicated by the crosses and the circles (of radius equal to the FWHM of each Gaussian) symbolize their size.

This phenomenon not only represents a likely explanation of the large jet misalignment found in

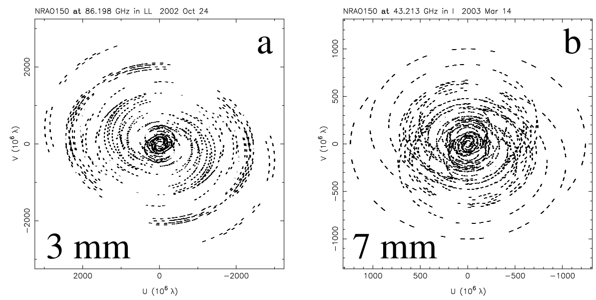

Fig. 5. a) (u,v)-coverage for our 3 mm-VLBI observation performed on 2002 October 24. b) (u,v)-coverage for our 7 mm-VLBI observation performed on 2003 March 14.

NRAO 150, but it also provides clues about the possible origin of the jet rotation. It is reasonable to think that the quasi-sinusoidal light curve of the source, its extreme jet misalignment and the inner jet rotation are related. In this case, a possible explanation of the NRAO 150 evolution would be a precession-like motion of the inner 0.4 mas of the jet. This, together with projection effects and variable Doppler boosting through small viewing angles, could explain the strong jet misalignment, the jet rotation in the plane of the sky and the $\sim$ 20-25 yr variability time-scale of the radio light curves. If, in the future, a significant correlation between these light curves and the position angle of the inner jet is found, the previous explanation will gain stronger support. In that case, the possible period of the behavior of NRAO 150 could be measured from the light curves.

4. ASTROPHYSICS FROM JET WOBBLING IN AGN

Like NRAO 150, several other jets in AGN present wobblings triggered in their innermost regions (e.g., in BL Lac, Stirling et al. 2003, Mutel & Denn 2005; or in OJ 287, Jorstad et al. 2005). These wobblings can be induced by the development of helical instabilities close to the jet base or by the precession of the accretion disk.

For the former, jet-cloud interactions (Gómez et al. 2000) or dense ejections filling only part of the jet section could be possible triggering perturbations. However, they have not been extensively explored from the theoretical point of view. This is most likely due to our lack of knowledge of the jet formation region and the lack of the adequate relativistic magneto-hydrodynamic tools to study it. Nonetheless, the subsequent development of Kelvin-

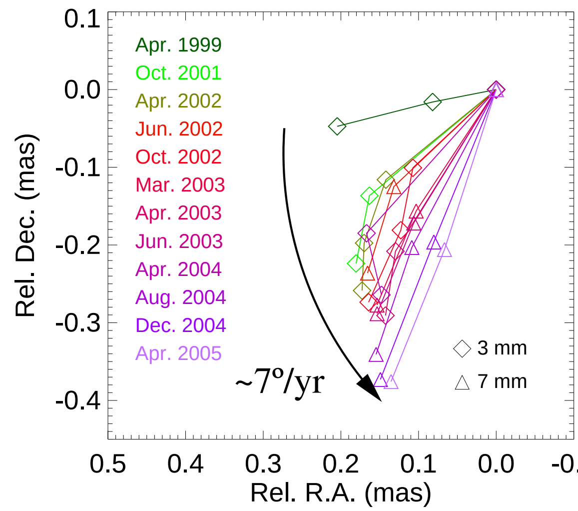

Fig. 6. Position –with respect to the core of the jet emission– of the inner model-fit components in NRAO 150. Only results from observations performed between 1999 and 2005 at 3 mm and 7 mm are drawn. The plot shows a fast change of the jet initial direction with a mean angular speed of $\sim 7^{\circ}$/year.

Helmholtz helical instabilities has been well studied (Hardee 2004, and references therein).

Disk precession seems to be nowadays the preferred mechanism to test and model the quasi-regular jet structural position and integrated emission variability of AGN. Up to now, most precession models applied to AGN are driven by a companion super-massive black hole or another massive object (see e.g. Valtonen, Lehto, & Pietilä 1999, for OJ 287; Lister et al. 2003, for 4C +12.50; Stirling et al. 2003, for BL Lac; Caproni & Abraham 2004, for 3C 120; Lobanov & Roland 2005, for 3C 345). However, alternative possibilities for accretion disk precession – and hence jet precession – have appeared in the literature during the last ten years (e.g., Schandl & Meyer 1994; Pringle 1996; Quillen 2001; Liu & Melia 2002; Lai 2003). Among them, of special interest are the models from Liu & Melia (2002) and Lai (2003) which drive the precession through intrinsic properties of the accretion system. For that reason, they allow one to estimate or constrain the possible black hole spin and accretion disk density profile (for Sgr A*, Liu & Melia 2002; for a set of eight AGN, Caproni, Mosquera-Cuesta, & Abraham 2004) and disk infall time (Lai 2003) from the observational properties of the systems.

Although there is still no general paradigm to explain the accretion disk (and jet) precession and other kinds of wobbling for AGN, it is rather likely that, as they are triggered in the innermost regions of the disks (and jets), their mechanisms have to be tied to fundamental properties of these regions (i.e., close to the accretion system). Hence, further development of models together with the appropriate characterization of the observational properties of the innermost regions of jets in AGN would place our understanding of the jet triggering region and the super-massive accretion systems on firmer ground.

From the observational point of view, high resolution mm-VLBI observations such as those presented here for NRAO 150 are of importance, as they allow to probe the innermost (sub-pc scale) regions of jets in AGN.

5. THE FUTURE GLOBAL MM-VLBI ARRAY

5.1. *Higher sensitivity, higher image fidelity and polarimetry*

Even with the good performance of the GMVA, it is desirable to further improve the sensitivity and the quality of images. This would increase the number of observable sources and astrophysical scenarios. The most direct way to achieve that is to increase the collecting area of the present interferometric array. For the near future, ALMA, the GBT, the LMT, CARMA, SRT, Yebes, Nobeyama and Noto are some of the most sensitive stations suitable to participate in 3 mm-VLBI. Together with them, the present GMVA would be able to achieve 7σ baseline sensitivities of (5 to 10) mJy, and 7σ image sensitivities better than 0.1 mJy/beam. These estimates predict an *increase, by a factor of 10* with respect to the present GMVA sensitivity. At the same time, the development of the VLBI technique is providing ever faster data recording speeds. For the next years, recording rates of at least 2 Gbps are expected (Garret 2003), which will increase the expected sensitivities by an extra factor $\geq \sqrt{2}$. Further improvements in coherence time for mm-VLBI, through atmospheric phase correction methods (see Roy, Teuber, & Keller 2004 and also http://www.mpifr-bonn.mpg.de/staff/aroy/wvr.html), are being developed at present.

But the proposed future array will not only produce an increase in sensitivity. The new stations will also improve the (u,v)-coverage (see Figure 7), and so the image fidelity. In addition, ALMA will improve the (u,v)-coverage for sources with low declination (less than 20°) and will facilitate the VLBI imaging of the Galactic Center source Sgr A*.

Finally, high sensitivity 3mm-VLBI polarimetry is nowadays being tested for the GMVA and it is expected to be offered as a standard observing mode during the next years.

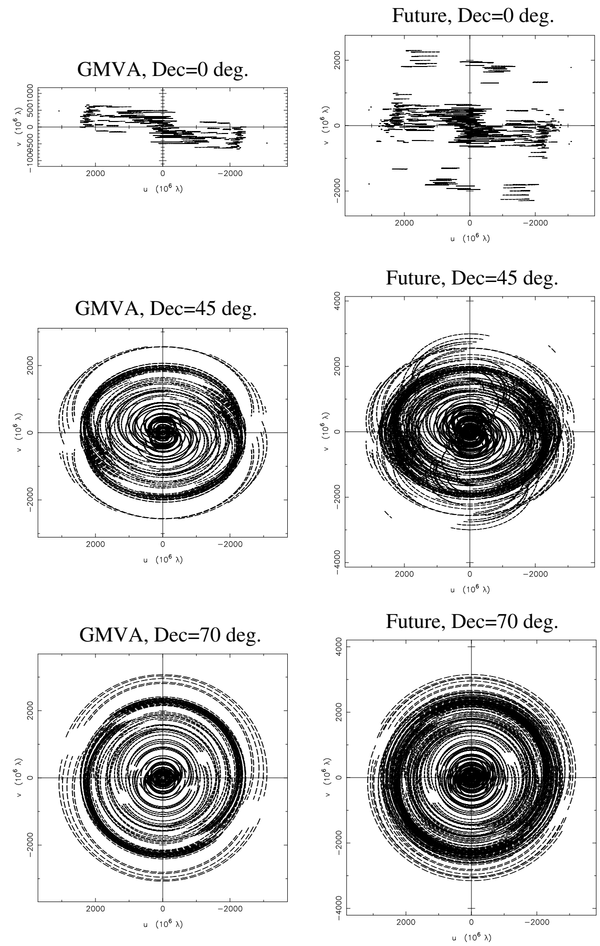

Fig. 7. Simulations of the (u,v)-coverages of the present GMVA (left) and those of the GMVA plus the suitable stations proposed in § 5.1 (right). 0°, 45° and 70° of source declinations are presented from top to bottom.

5.2. *Future science*

If the proposed improvements are achieved in the future, images with dynamic ranges of up to 1000:1 could be easily obtained. This would place the sensitivity and image fidelity of 3 mm-VLBI at comparable levels than those of present cm-VLBI. These achievements, together with the possibility to obtain polarimetric images, would help to (i) to study the triggering mechanisms of relativistic jets, (ii) to probe their initial magnetic field configurations (iii) and to better constrain the properties of their accreting systems, for several hundreds or possibly thousands of jets in AGN and microquasars.

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