

LETTER TO THE EDITOR

Superluminal non-ballistic jet swing in the quasar NRAO 150 revealed by mm-VLBI[★]

I. Agudo^{1,2}, U. Bach², T. P. Krichbaum², A. P. Marscher³, I. Gonidakis⁴, P. J. Diamond⁵, M. Perucho², W. Alef², D. A. Graham², A. Witzel², J. A. Zensus², M. Bremer⁶, J. A. Acosta-Pulido⁷, and R. Barrena⁷

¹ Instituto de Astrofísica de Andalucía (CSIC), Apartado 3004, 18080 Granada, Spain
e-mail: iagudo@iaa.es

² Max-Planck-Institut für Radioastronomie, Auf dem Hügel, 69, 53121, Bonn, Germany

³ Institute for Astrophysical Research, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA

⁴ National and Kapodestrian University of Athens, Dept. of Astrophysics, Astronomy and Mechanics, 157 83 Athens, Greece

⁵ University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire SK11 9DL, UK

⁶ Institut de RadioAstronomie Millimétrique, 300 rue de la Piscine, 38406 Saint Martin d'Hères, France

⁷ Instituto de Astrofísica de Canarias, C/Vía Láctea s/n, 38200, La Laguna, Tenerife, Spain

Received 8 August 2007 / Accepted 24 October 2007

ABSTRACT

Context. NRAO 150, a compact and bright radio to mm source showing core/jet structure, has been recently identified as a quasar at redshift $z = 1.52$ through a near-IR spectral observation.

Aims. To study the jet kinematics on the smallest accessible scales and to compute the first estimates of its basic physical properties.

Methods. We have analysed the ultra-high-resolution images from a new monitoring program at 86 GHz and 43 GHz with the Global mm VLBI Array and the VLBA, respectively. An additional archival calibration VLBA data set, covering the period from 1997 to 2007, has been used.

Results. Our data show an extreme projected counter-clockwise jet position angle swing at an angular rate of up to $\approx 11^\circ/\text{yr}$ within the inner ≈ 31 pc of the jet, which is associated with a non-ballistic superluminal motion of the jet within this region.

Conclusions. The results suggest that the magnetic field could play an important role in the dynamics of the jet in NRAO 150, which is supported by the large values of the magnetic field strength obtained from our first estimates. The extreme characteristics of the jet swing make NRAO 150 a prime source to study the jet wobbling phenomenon.

Key words. galaxies: active – galaxies: jets – galaxies: quasars: general – galaxies: quasars: individual: NRAO 150 – radio continuum: galaxies – techniques: interferometric

1. Introduction

An increasing number of jets in active galactic nuclei (AGN) have been reported to show either regular or irregular swings of the innermost jet structural position angle in the plane of the sky (e.g., in OJ 287, Tateyama & Kingham 2004; in 3C 273, Savolainen et al. 2006; in 3C 345, Lobanov & Roland 2005; in BL Lac, Stirling et al. 2003; in S5 0716+71, Bach et al. 2005). Time scales of between 2 and 15 years, and structural position-angle oscillations with amplitudes from $\sim 25^\circ$ to $\sim 45^\circ$, are typical for the reported cases. We will call this phenomenon *jet wobbling* hereafter. Parsec scale AGN jet curvatures and helical-like structures, also at larger distances from the central engine, are also believed to be triggered by changes in direction at the jet ejection nozzle (e.g., in 3C 84, Dhawan et al. 1998).

The physical origin for the observed jet wobbling is still poorly understood. Among the various possibilities, regular precession of the accretion disk is frequently used for modelling at present. Most AGN precession models are driven either by a companion super-massive black hole or another massive object inducing torques in the accretion disk of the primary (e.g.,

Lister et al. 2003, for 4C +12.50; Stirling et al. 2003, for BL Lac; Caproni & Abraham 2004 for 3C 120), or by the Bardeen-Peterson effect (e.g., Liu & Melia 2002; Caproni et al. 2004). However, other AGN scenarios that have yet to be explored extensively, such as the orbital motion of the jet nozzles (also involving binary systems) or other kinds of more erratic disk/jet instabilities (e.g., similar to those thought to produce the quasi periodic oscillations [QPO] in X-ray binaries), can not be ruled out yet. Note that, in support of these erratic instabilities, there is at present debate as to whether the observed jet wobbling is strictly periodic or not (see Mutel & Denn 2005, for the case of BL Lac).

There is still no paradigm to explain the phenomenon of jet wobbling in AGN, but it is likely that, as it is triggered in the innermost regions of the jets, it must be tied to fundamental properties of the inner regions of the accretion system. Hence, there is ample motivation to study the jet wobbling phenomenon, to place our understanding of the jet triggering region and the super-massive accretion systems on firmer ground.

VLBI observations at millimetre wavelengths are a powerful technique for imaging the innermost regions of AGN jets (which are self-absorbed at longer wavelengths) with the highest angular resolutions: $\sim 50 \mu\text{as}$ at 86 GHz (3.5 mm) and ~ 0.15 mas at

[★] Tables 1–3 and the movie are only available in electronic form at <http://www.aanda.org>

43 GHz (7 mm). Here, we report the discovery of an extreme case of jet swing in the quasar NRAO 150, through the first ultra-high-resolution VLBI set of images obtained from this source at 86 GHz and 43 GHz. NRAO 150 is a strong radio-mm source. At radio wavelengths, on VLBI scales, NRAO 150 displays a compact core plus a one-sided jet extending up to $r \gtrsim 80$ mas, with a jet structural position angle (PA) of $\sim 30^\circ$ (e.g., Fey & Charlot 2000). NRAO 150 was not detected by the early optical surveys, most probably due to obscuration through the Milky Way (Galactic latitude = -1.6°). Almost 40 yr after its discovery at radio wavelengths (Pauliny-Toth et al. 1966), NRAO 150 has been identified as a quasar at redshift $z = 1.52$ through a near-IR spectroscopic project (Acosta-Pulido et al., in prep.).

Throughout this paper we assume $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. Under these assumptions, the luminosity distance of NRAO 150 is $d_L = 11025 \text{ Mpc}$, 1 mas corresponds to 8.5 pc in the frame of the source, and an angular proper motion of 1 mas/yr translates into a speed of $69.4 c$. These parameters are used here for the first time to make quantitative estimates of the basic physical properties of the jet in NRAO 150.

2. Observations, images and their modelling

The data set presented here consists of 5 VLBI images at 86 GHz taken with the Global mm VLBI Array (GMVA¹, and its predecessor, the CMVA) covering the time range from October 2001 to April 2004, and 34 Very Long Baseline Array (VLBA) images taken at 43 GHz from June 1997 to February 2007. Among these 34 images, 20 obtained from June 1997 to May 2002 were taken as calibration measurements of the SiO maser monitoring program of TX Cam (Diamond & Kemball 2003). A new 8.4 GHz VLBA image obtained in June 2002 is also presented here. Information about each single observation and its resulting image is provided in Table 1.

The 86 GHz and the 43 GHz data were correlated by the Max-Planck-Institut für Radioastronomie and by the VLBA correlators, respectively. Subsequent phase and amplitude (including opacity) calibration were performed using standard procedures within the AIPS software. Further phase and amplitude self-calibration, as well as the final imaging, were performed through standard procedures within the Difmap software.

Examples of the resulting images at 86 GHz, 43 GHz, and 8.4 GHz – obtained in mid 2002 – are presented in Fig. 1, together with a 2.3 GHz VLBA image obtained in July 2005 by Kovalev et al. (2007). At the four observing frequencies, the images show the typical core plus one-sided jet structures of radio-loud quasars. However, the orientation of the sub-mas scale jet (Figs. 1a and b) differs by $>100^\circ$ with respect to that at larger scales (Figs. 1c and d). This suggests a bent structure of the inner jet oriented within a very small angle to the line of sight. The series of 43 GHz images in Fig. 2 shows evidence of motion in the North-West to South-East direction. More intriguing is the fact that this motion is accompanied by an evident counter-clockwise rotation of the jet on the plane of the sky, which will be the subject of discussion later.

Difmap was also used to model the images of NRAO 150 as sets of 3 or 4 circular-Gaussian intensity distributions (model components, e.g., Fig. 1). Elliptical Gaussian fits were also tested, but they did not improve the results. Only the minimum number of model components describing jet regions considerably brighter than the image-background rms, and at close positions during contiguous epochs, were allowed. All fitted model

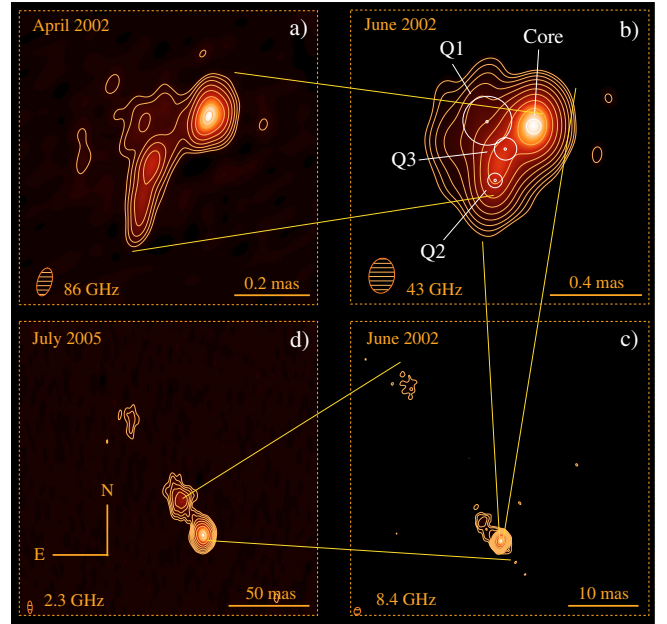


Fig. 1. VLBI images of NRAO 150 at 86 GHz **a)**, 43 GHz **b)**, 8.4 GHz **c)**, and 2.3 GHz **d)**. The 2.3 GHz image was obtained by Kovalev et al. (2007). In images **a)–d)**, the lower contours correspond to 1.0%, 0.2%, 0.15% and 0.5% of the corresponding image peak of 1.05 Jy/beam, 3.84 Jy/beam, 5.55 Jy/beam, and 0.69 Jy/beam, respectively. The upper contours increase by factors of 2. Other image parameters of the **a)**, **b)** and **c)** maps are given in Table 1. The 2.3 GHz convolving beam is $(7.4 \times 2.6) \text{ mas}^2$ with major-axis position angle at -2° . The 86 GHz image illustrates the capability of the GMVA to achieve angular resolutions of up to $40 \mu\text{as}$, with dynamic ranges of up to 100:1 and notable image fidelity, as suggested by the matching 86 GHz and 43 GHz source structures. In the 43 GHz image, the circles are centred at the positions of the Gaussian model components. The radius of such circles symbolise the FWHM size of the corresponding model component.

components were found to have flux densities $S_{\text{comp}}(86 \text{ GHz}) > 90 \text{ mJy}$, $S_{\text{comp}}(43 \text{ GHz}) > 50 \text{ mJy}$, $S_{\text{comp}}(8.4 \text{ GHz}) > 60 \text{ mJy}$. This characterised reliably each of the most significant jet regions by its flux density, relative position, and a FWHM size measurement at each observing epoch. Table 2 lists the results from such fits, using the position of the (typically) brightest modelled Gaussian component – the VLBI core – as reference.

3. Superluminal motion and non-ballistic jet swing

The 43 GHz jet structure evolution is illustrated in Fig. 2, whereas Fig. 3 shows the 86 GHz and 43 GHz inner jet axis evolution, the projected trajectories of the three identified model components Q1, Q2, and Q3 with respect to the core position, and the total flux evolution of these components. We modelled these trajectories, taking into account their curvatures, by fitting second order polynomials to them (e.g., as in Homan et al. 2001 and Jorstad et al. 2005); see the results in Table 3. The mean measured proper motions are $(0.047 \pm 0.002) \text{ mas/yr}$, $(0.042 \pm 0.001) \text{ mas/yr}$, and $(0.034 \pm 0.002) \text{ mas/yr}$, for Q1, Q2 and Q3, with corresponding superluminal apparent speeds ($\beta_{\text{app}}^{\text{obs}}$) of $(3.26 \pm 0.14) c$, $(2.85 \pm 0.07) c$, and $(2.29 \pm 0.14) c$, respectively. Figure 3 shows that the motion of features Q1, Q2 and Q3 outwards from the core is accompanied by counter-clockwise rotation of their position vector, projected onto the plane of the sky, with extremely fast angular speeds $\langle \dot{\Theta}(Q1) \rangle = (10.7 \pm 0.7)^\circ/\text{yr}$, $\langle \dot{\Theta}(Q2) \rangle = (5.8 \pm 0.3)^\circ/\text{yr}$ and $\langle \dot{\Theta}(Q3) \rangle = (8.0 \pm 0.5)^\circ/\text{yr}$.

¹ <http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm>

These are the first superluminal proper motions reported within the innermost 0.5 mas of the jet in NRAO 150. We should also emphasize that the three fitted trajectories are bent and non-radial, which implies that the motion of all the jet features is non-ballistic up to a projected distance from the core of ~ 0.5 mas. Assuming a jet viewing angle $\phi \approx 8^\circ$ (see Sect. 4), it is inferred that the jet features behave non-ballistically up to a deprojected distance from the core ≈ 31 pc. Similar results, in terms of the magnitude of projected angular speeds and non-ballistic nature, are obtained if either Q1 or Q2 is selected as the kinematic centre of the source.

Note also that when the mean projected velocity vectors of Q1, Q2 and Q3 are decomposed in their radial (with respect to the core) and non-radial (i.e. normal, $\beta_{\text{app_norm}}^{\text{obs}}$) components, the latter are $(2.71 \pm 0.21) c$, $(1.39 \pm 0.21) c$, and $(2.01 \pm 0.14) c$, respectively. Thus, we have shown here an extreme case of *superluminal non-ballistic swing* in the jet of an AGN. This is unusual because, in most cases, superluminal motions are only reported in the radial direction relative to the core. Recently however, a growing number of AGN jets exhibiting bent model-component trajectories have been reported (e.g., Homan et al. 2001; Jorstad et al. 2005). NRAO 150 seems to be an extreme case, which reflects the remarkable non-ballistic nature of its jet. Both this non-ballistic nature and projection effects can explain why the trajectories of Q1 and Q3 do not cross with that of Q2 when they are extrapolated back (see Fig. 3).

4. Jet physical parameter estimates

Figure 3 shows the total flux density evolution of the model components. Dramatic increases are displayed by Q2, at ~ 2000 and ~ 2005 , and by Q3, at ~ 2002 and ~ 2006 . Interestingly, a pronounced dip in the core light curve happens shortly before each of the dramatic Q2 flux peaks. These changes can be explained by changing Doppler boosting factors, due to either a jet feature propagating through a bent underlying jet, or to the propagation of such a bend itself along the jet.

The “synchrotron-self-Compton” (SSC) Doppler factor of the source (δ_{SSC}) can be constrained by comparing the observed and the expected first order self-Compton X-ray flux density with the flux density of the source (S_{ν_m}) at the synchrotron turnover frequency (ν_m ; e.g., Marscher 1983; Agudo et al. 2006). Between August 1990 and February 1991, NRAO 150 displayed a flux density $S_{1 \text{ keV}} = (0.35 \pm 0.09) \mu\text{Jy}$ at 1 keV. ROSAT measured a flux $F_{0.1-2.4 \text{ keV}} = (0.22 \pm 0.06) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ corrected for Galactic absorption (assuming a photon index $\Gamma = -1.7 \pm 0.1$) from 1RXS J035930.6+505730 (Voges et al. 2000); its position is fully consistent with the one of NRAO 150, even at the level of the ROSAT 1- σ position error. No other X-ray source or bright radio-mm source is found within 1 arcmin of the position of NRAO 150. At $\nu_m \approx 37 \text{ GHz}$, $S_{\nu_m} = (2.59 \pm 0.21) \text{ Jy}$ (see Reuter et al. 1997; Voges et al. 2000; Chen et al. 2001; Teräsranta et al. 2005). Given that the period between 1990 and 1997 was characterised by a low activity phase and that the VLBI structure of the source was dominated by the core in the 1990s, we assume that the bulk of the 37 GHz flux measured at the beginning of the 1990s was radiated from the core. By taking into account these measurements, the average 43 GHz size of the core in our VLBI maps from 1997 to 2007, $\langle \theta \rangle = (0.10 \pm 0.03) \text{ mas}$, and the typical optically thin synchrotron spectral index $\alpha \approx -0.5$ at the beginning of the 1990s, as well as the assumptions and approximations outlined in Agudo et al. (2006), we obtain $\delta_{\text{SSC}} \approx 6$.

By using expression (2) in Marscher (1983) and the outlined measurements for the core ($S_{\nu_m} \approx 2.59 \text{ Jy}$, $\nu_m \approx 37 \text{ GHz}$,

$\theta \approx 0.10 \text{ mas}$, $\delta_{\text{SSC}} \approx 6$ and $\alpha \approx -0.5$), the magnetic field intensity in the jet can be estimated. In this way we find $B \approx 0.7 \text{ G}$, which is rather large for an AGN jet with the X-ray emission produced by SSC (e.g., Marscher et al. 1979; Ghisellini et al. 1998).

Using now both $\beta_{\text{app}}^{\text{obs}}(\text{Q1})$ as an estimate of the jet plasma speed and $\delta \approx \delta_{\text{IC}}$ in the definitions of δ^2 , and the apparent proper motion of the fluid, β_{app}^3 , we obtain $\gamma \approx 4$ and $\phi \approx 8^\circ$.

Note that all these estimates should still be taken as first approximations, since the measurements used are not as accurate and simultaneous as needed. The results from a coordinated multi-waveband campaign organised in February 2007 will allow better and updated estimates. In addition, the nature of Q1, Q2 and Q3 is still not known. They might be related to pattern speeds of propagating Kelvin-Helmholtz perturbations, which must have smaller speeds than those of the fluid in which they propagate (e.g., Perucho et al. 2006). In contrast, they could be shock waves propagating in a bent underlying jet. In this case, the speed of the shocks must be an upper limit of the plasma speed. Nevertheless, our estimates of γ and ϕ are consistent with those expected from the innermost regions of the quasar NRAO 150, wherein the extreme (projected) jet misalignment implies a very small viewing angle.

5. Summary and conclusions

We have reported the results from the first 86 GHz and 43 GHz VLBI monitoring program of the recently identified quasar NRAO 150. Our observations reveal *a*) a large projected misalignment of the jet by $>100^\circ$ within the inner 0.5 mas to 1 mas from the core, *b*) an extremely fast counter-clockwise rotation of the projected jet axis at a rate of $\sim 6^\circ/\text{yr}$ to $\sim 11^\circ/\text{yr}$, *c*) non-ballistic superluminal motions with mean speeds from $2.3 c$ to $3.3 c$ within the inner 0.5 mas from the core (deprojected distance ≈ 31 pc), *d*) transverse (non-radial) speeds of $2.7 c$, $1.4 c$, and $2.0 c$ for Q1, Q2 and Q3, respectively, *e*) an extreme case of *superluminal non-ballistic jet swing*, and *f*) the first approximations of quantitative estimates of the basic physical properties of the jet in NRAO 150: $\delta \approx 6$, $B \approx 0.7 \text{ G}$, $\gamma \approx 4$, and $\phi \approx 8^\circ$.

Whereas the ultimate origin of the jet swing must be an intrinsic change of the direction of the inner jet axis (either caused by changes produced at the injection region or by interaction with the medium surrounding the jet), possible causes for the non-ballistic nature of the emitting flow are related to either a small inertia of the jet compared to that of the impacted ambient medium, or to the presence of jet instabilities propagating downstream. However, the superluminal non-ballistic motion of the jet features in NRAO 150 is perhaps too fast and systematic, along tens of parsecs (deprojected) to be induced solely by the ambient medium. In addition, the perturbation that must be produced either by the impact with such medium, or by the changes at the injection region, should imply the growth of disruptive instabilities (e.g., Perucho et al. 2006), in contrast to the remarkable collimation of the jet up to the kiloparsec scale (see Fig. 1). Mizuno et al. (2007) have shown that a magnetic field with the appropriate configuration helps keep a jet collimated against the growth of instabilities. Hence, this possibility, together with the high value for the magnetic field intensity estimated in Sect. 4, suggests that the magnetic field could play an important role in the dynamics of the jet in NRAO 150.

² $\delta = [\gamma(1 - \beta \cos \phi)]^{-1}$ where $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor, β is the speed in units of the speed of light and ϕ is the angle between the direction of the flow and the line of sight.

³ $\beta_{\text{app}} = (\beta \sin \phi) / (1 - \beta \cos \phi)$.

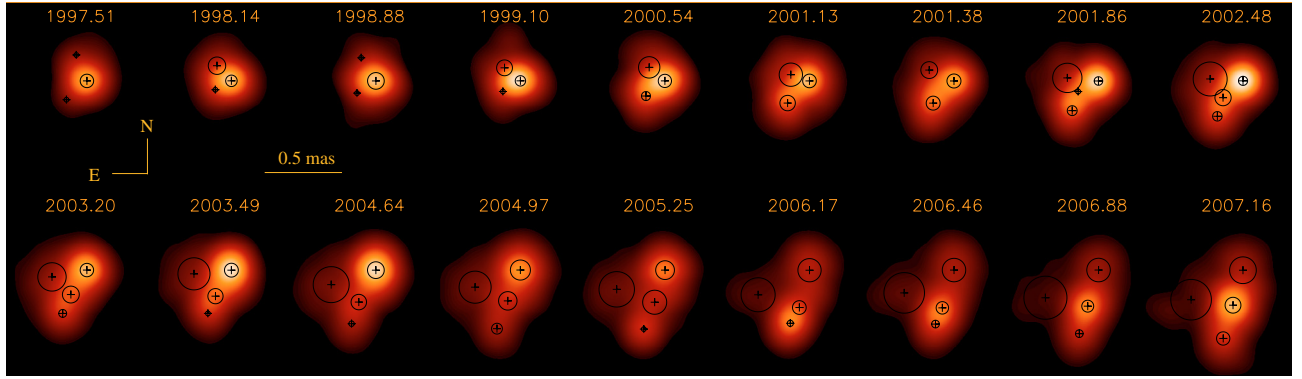


Fig. 2. Selection of 18 of the 34 NRAO 150 images obtained from 1997 to 2007 with the VLBA at 43 GHz. All images have been convolved with the same circular beam of 0.16 mas. The common intensity scale ranges from 0.025 Jy/beam to 4.128 Jy/beam. The positions of the fitted Gaussians are indicated by the black crosses, whereas the black circles (of radius equal to the $FWHM$ of each Gaussian) symbolise their size. A movie corresponding to these images is available with the online version of the article.

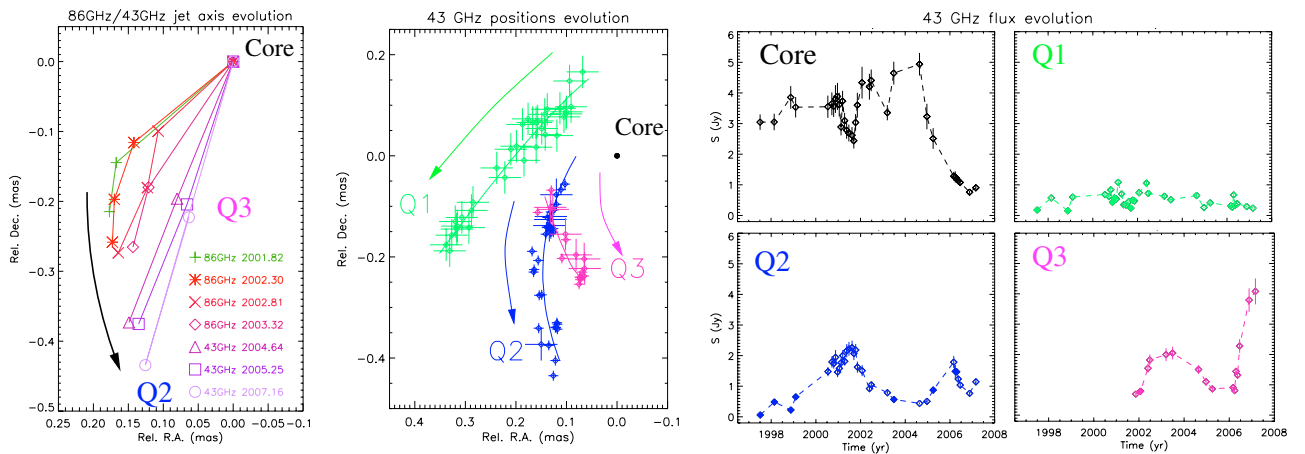


Fig. 3. From right to left, 86 GHz and 43 GHz inner jet axis evolution, projected trajectories of the 43 GHz model components, and their corresponding 43 GHz flux evolution. The crosses in the middle plot symbolise the position errors (computed using the prescriptions by Jorstad et al. 2005), whereas the superimposed bent lines represent the fitted trajectories of each model component (labelled in the Figure). Filled diamonds in the flux evolution plots symbolise upper limits (see Table 2).

It is still unclear whether the reported change of the direction of ejection in NRAO 150 is related to a regular (strictly periodic or not) behaviour or to a single event. This, together with the still unknown nature of the moving jet features (either propagating curvatures or shocks in a bent jet), does not allow us to specify the ultimate origin of this phenomenon in the source. This will be the matter of future studies. Nevertheless, the extreme characteristics of the jet swing make NRAO 150 a prime source for future studies of the origin of jet wobbling.

Acknowledgements. I.A. has been supported in part by an I3P contract with the Spanish “Consejo Superior de Investigaciones Científicas” and in part by a contract with the German “Max Planck Institute für Radioastronomie” (through the ENIGMA network, contract HPRN-CT-2002-00321), which were funded by the EU. The GMVA is operated by the MPIfR, IRAM, NRAO, OSO, and MRO. We thank the staff of the participating observatories for their efficient and continuous support. We acknowledge Y. Y. Kovalev, who provided the data for Fig. 1d. This paper is partially based on observations carried out with the MPIfR 100 m Effelsberg Radio Telescope, the IRAM Plateau de Bure Millimetre Interferometer, the IRAM 30 m Millimetre Telescope, the VLBA, the Onsala 20 m Radio Telescope, and the Metsähovi 14 m Radio Telescope. IRAM is supported by MPG (Germany), INSU/CNRS (France), and IGN (Spain). The VLBA is an instrument of the NRAO, a facility of the National Science Foundation of the USA operated under cooperative agreement by Associated Universities, Inc. (USA). This research has made use of the United States Naval Observatory (USNO) Radio Reference Frame Image Database (RRFID).

References

- Agudo, I., Krichbaum T. P., Ungerechts, H., et al. 2006, *A&A*, 456, 117
 Bach, U., Krichbaum, T. P., Ros, E., et al. 2005, *A&A*, 433, 815
 Caproni, A., & Abraham, Z. 2004, *MNRAS*, 349, 1218
 Caproni, A., Mosquera-Cuesta, H. J., & Abraham, Z. 2004, *ApJ*, 616, L99
 Chen, Y.-J., Jiang, D.-R., & Zhang, F.-J. 2001, *ChJAA*, 1, 507
 Dhawan, V., Kellerman, K. I., & Romney, J. D. 1998, *ApJ*, 498, L111
 Diamond, P. J., & Kembell, A. J., *ApJ*, 599, 1372
 Fey, A. L., & Charlot, P. 2000, *ApJS*, 128, 17
 Ghisellini, G., Celotti, A., Fossati, G., Maraschi, L., & Comastri, A. 1998, *MNRAS*, 301, 451
 Homan, D. C., Ojha, R., Wardle, J. F. C., et al. 2001, *ApJ*, 549, 840
 Jorstad, S. G., Marscher, A. P., Lister, M. L., et al. 2005, *AJ*, 130, 1418
 Kovalev, Y. Y., Petrov, L., Fomalont, E. B., & Gordon, D. 2007, *AJ*, 133, 1236
 Lister, M. L., Kellermann, K. I., Vermeulen, R. C., et al. 2003, *ApJ*, 584, 135
 Liu, S., & Melia, F. 2002, *ApJ*, 573, L23
 Lobanov, A. P., & Roland, J. 2005, *A&A*, 431, 831
 Marscher, A. P. 1983, *ApJ*, 264, 296
 Marscher, A. P., Marshall, F. E., Mushotzky, R. F., et al. 1979, *ApJ*, 233, 498
 Mizuno, Y., Hardee, P., & Nishikawa K.-I. 2007, *ApJ*, 662, 835
 Mutel, R. L., & Denn, G. R. 2005, *ApJ*, 623, 79
 Pauliny-Toth, I. I. K., Wade, C. M., & Heesch, D. S. 1966, *ApJS*, 13, 65
 Peruchio, M., Lobanov, A. P., Martí, J. M., & Hardee, P. E. 2006, *A&A*, 456, 493
 Reuter, H.-P., Kramer, C., Sievers, A., et al. 1997, *A&AS*, 122, 271
 Savolainen, T., Wiik, K., Valtaoja, E., & Tornikoski, M. 2006, *A&A*, 446, 71
 Stirling, A. M., Cawthorne, T. V., Stevens, J. A., et al. 2003, *MNRAS*, 341, 405
 Tateyama, C. E., & Kingham, K. A. 2004, *ApJ*, 608, 149
 Teräsraanta, H., Wires, S., Koivisto, P., Saarinen, V., & Hovatta, T. 2005, *A&A*, 440, 409
 Voges, W., Aschenbach, B., Boller, T., et al. 2000, *IAU Circ.*, 7432, 1

Online Material

Table 1. 86 GHz and 43 GHz image information, including the observing epochs, the total integration times (t_{int}), the observing frequency bandwidth ($\Delta\nu_{\text{obs}}$), the number of bits used for the signal digitalisation sampling, the FWHM minor and major axes of the restoring beam and its orientation angle, the integrated total flux densities, the peak flux density, and the noise levels of the resulting images.

Epoch [y]	t_{int} [min]	$\Delta\nu_{\text{obs}}$ [MHz]	Bits	Beam			S_{int} [Jy]	S_{peak} [Jy/beam]	Noise [mJy/beam]
				μas	μas	$^{\circ}$			
86 GHz images									
2001.82	169	128	1	40	107	-21.1	3.38	1.22	3.3
2002.30	293	128	1	38	77	-18.7	2.85	1.08	1.0
2002.81	228	128	2	41	80	-15.6	3.82	1.30	2.4
2003.32	98	128	2	75	221	-30.1	2.13	1.09	5.7
2004.29	241	128	2	40	82	-14.1	4.57	1.03	1.6
43 GHz images									
1997.51	60	32	1	123	245	-34.6	3.27	2.43	4.8
1998.14	60	32	1	112	251	-9.4	4.06	2.68	4.8
1998.88	60	32	1	154	230	1.1	4.25	3.04	3.6
1999.10	60	32	1	187	292	1.1	4.78	3.80	3.8
2000.54	20	16	2	129	241	-19.0	5.73	3.30	4.0
2000.72	20	16	2	132	244	-19.0	6.04	3.39	3.5
2000.80	20	16	2	132	266	-21.3	6.18	3.42	3.4
2000.88	20	16	2	242	356	-36.7	6.18	4.75	4.4
2000.97	20	16	2	205	329	23.4	5.92	3.85	4.5
2001.05	20	16	2	208	340	13.8	5.72	3.85	4.1
2001.13	20	16	2	206	268	5.7	5.74	3.40	3.7
2001.20	20	16	2	195	261	8.8	5.73	3.35	5.8
2001.29	20	16	2	225	275	12.7	5.59	3.45	4.2
2001.38	20	16	2	134	225	-19.5	5.40	2.49	3.1
2001.48	20	16	2	138	238	-23.6	5.31	2.57	3.2
2001.62	20	16	2	137	256	-31.7	5.41	2.83	4.5
2001.70	20	16	2	129	239	-28.5	4.79	2.28	3.5
2001.78	20	16	2	134	248	-21.3	5.69	2.63	3.6
2001.86	20	16	2	135	243	-20.7	6.76	3.58	2.7
2002.07	20	16	2	160	249	-20.8	7.74	3.99	2.9
2002.40	25	16	2	141	212	-16.0	7.75	4.27	3.0
2002.48	220	32	2	139	184	-3.6	7.60	3.92	0.8
2003.20	220	32	2	147	186	1.1	6.19	2.60	0.9
2003.49	220	32	2	140	186	0.1	7.36	3.42	0.8
2004.64	220	32	2	119	170	-8.3	7.02	3.22	1.1
2004.97	220	32	2	129	196	-26.5	5.37	2.10	0.9
2005.25	220	32	2	121	177	3.1	4.82	1.59	1.0
2006.17	84	64	1	114	190	2.7	4.27	1.91	1.5
2006.24	84	64	1	113	207	1.4	4.31	2.01	1.5
2006.30	84	64	1	111	186	-1.0	4.34	1.91	1.6
2006.37	84	64	1	110	187	-3.8	4.20	1.77	1.9
2006.46	84	64	1	112	188	-14.8	4.21	1.83	1.9
2006.88	42	32	2	130	276	-32.4	4.26	2.33	1.2
2007.16	42	32	2	124	266	-31.4	6.32	3.07	1.7
8.4 GHz images									
2002.48	84	32	2	1180	904	-3.6	6.73	5.65	0.9

Table 2. 86 GHz, 43 GHz and 8.4 GHz circular-Gaussian model-fit parameters. S , r , Θ and $FWHM$ are the flux density, the projected distance to the core, the position angle with respect to the core and the FWHM size, respectively. Upper limits on the $FWHM$ size and S correspond to fits of unresolved jet regions. For such fits, the upper limit of the sizes were imposed in Difmap to estimate the corresponding flux density upper limits. The latter are close approximations to the actual flux densities of the unresolved regions.

Comp.	S (Jy)	r (mas)	Θ ($^{\circ}$)	$FWHM$ (mas)
86 GHz – 2001.82				
Core	1.937 ± 0.019	...	...	0.053 ± 0.001
W0	0.661 ± 0.020	0.13 ± 0.02	-109.9 ± 9.0	0.137 ± 0.007
W2	≤ 0.244	0.28 ± 0.01	-140.5 ± 2.1	< 0.010
W3	≤ 0.294	0.22 ± 0.01	-130.8 ± 2.6	< 0.010
86 GHz – 2002.30				
Core	1.799 ± 0.018	...	...	0.042 ± 0.000
W0	0.470 ± 0.047	0.18 ± 0.02	-129.2 ± 5.3	0.034 ± 0.003
W2	≤ 0.111	0.31 ± 0.01	-146.2 ± 1.8	< 0.010
W3	≤ 0.159	0.26 ± 0.01	-139.2 ± 2.2	< 0.010
86 GHz – 2002.81				
Core	2.332 ± 0.023	...	...	0.050 ± 0.001
W0	0.933 ± 0.028	0.15 ± 0.02	-132.9 ± 7.8	0.106 ± 0.005
W2	0.278 ± 0.028	0.32 ± 0.01	-149.0 ± 2.1	0.024 ± 0.002
W3	≤ 0.138	0.22 ± 0.01	-145.8 ± 2.6	< 0.010
86 GHz – 2003.32				
Core	1.376 ± 0.014	...	...	0.059 ± 0.001
W2	≤ 0.224	0.30 ± 0.01	-151.6 ± 1.9	< 0.010
W3	0.326 ± 0.033	0.22 ± 0.02	-146.1 ± 4.8	0.037 ± 0.004
86 GHz – 2004.29				
Core	3.663 ± 0.037	...	...	0.092 ± 0.001
W2	0.093 ± 0.009	0.37 ± 0.01	-152.4 ± 1.7	0.021 ± 0.002
W3	0.785 ± 0.024	0.25 ± 0.02	-147.0 ± 4.6	0.111 ± 0.006
43 GHz – 1997.51				
C	3.046 ± 0.253	...	...	0.085 ± 0.001
Q1	≤ 0.180	0.18 ± 0.03	22.2 ± 10.2	< 0.030
Q2	≤ 0.061	0.18 ± 0.03	132.6 ± 10.3	< 0.030
43 GHz – 1998.14				
C	3.051 ± 0.147	...	...	0.073 ± 0.001
Q1	0.573 ± 0.032	0.13 ± 0.03	43.4 ± 13.8	0.111 ± 0.006
Q2	≤ 0.485	0.12 ± 0.01	118.7 ± 4.9	< 0.030
43 GHz – 1998.88				
C	3.855 ± 0.186	...	...	0.106 ± 0.005
Q1	≤ 0.154	0.17 ± 0.03	32.5 ± 10.5	< 0.030
Q2	≤ 0.224	0.14 ± 0.03	122.8 ± 12.9	< 0.030
43 GHz – 1999.10				
C	3.534 ± 0.120	...	...	0.066 ± 0.001
Q1	0.602 ± 0.027	0.13 ± 0.03	50.5 ± 14.0	0.101 ± 0.005
Q2	≤ 0.653	0.13 ± 0.01	121.1 ± 4.4	< 0.030
43 GHz – 2000.54				
C	3.550 ± 0.243	...	...	0.084 ± 0.001
Q1	0.685 ± 0.051	0.13 ± 0.03	49.3 ± 13.8	0.136 ± 0.007
Q2	1.480 ± 0.101	0.15 ± 0.01	128.5 ± 3.7	0.057 ± 0.001
43 GHz – 2000.72				
C	3.645 ± 0.154	...	...	0.087 ± 0.001
Q1	0.619 ± 0.031	0.15 ± 0.03	50.2 ± 12.5	0.133 ± 0.007
Q2	1.794 ± 0.076	0.16 ± 0.01	130.5 ± 3.5	0.078 ± 0.001
43 GHz – 2000.80				
C	3.562 ± 0.187	...	...	0.085 ± 0.001
Q1	0.838 ± 0.050	0.13 ± 0.03	53.7 ± 14.1	0.160 ± 0.008
Q2	1.744 ± 0.091	0.17 ± 0.01	130.4 ± 3.3	0.080 ± 0.001

Table 2. continued.

Comp.	S (Jy)	r (mas)	Θ ($^{\circ}$)	$FWHM$ (mas)
43 GHz – 2000.88				
C	3.801 ± 0.177	...	...	0.088 ± 0.001
Q1	≤ 0.430	0.17 ± 0.03	60.1 ± 11.1	< 0.030
Q2	1.944 ± 0.106	0.18 ± 0.03	133.6 ± 10.1	0.101 ± 0.005
43 GHz – 2000.97				
C	3.885 ± 0.145	...	...	0.092 ± 0.001
Q1	≤ 0.576	0.16 ± 0.03	70.2 ± 11.6	< 0.030
Q2	1.461 ± 0.055	0.20 ± 0.01	138.4 ± 2.9	0.067 ± 0.001
43 GHz – 2001.05				
C	3.618 ± 0.111	...	...	0.085 ± 0.001
Q1	0.541 ± 0.023	0.17 ± 0.03	56.4 ± 11.1	0.058 ± 0.003
Q2	1.581 ± 0.048	0.18 ± 0.01	131.6 ± 3.1	0.055 ± 0.001
43 GHz – 2001.13				
C	2.889 ± 0.085	...	...	0.087 ± 0.001
Q1	1.084 ± 0.044	0.12 ± 0.03	71.4 ± 14.6	0.148 ± 0.007
Q2	1.766 ± 0.052	0.20 ± 0.01	135.4 ± 2.9	0.098 ± 0.001
43 GHz – 2001.20				
C	3.733 ± 0.149	...	...	0.120 ± 0.006
Q2	2.001 ± 0.080	0.19 ± 0.03	135.9 ± 9.5	0.114 ± 0.006
43 GHz – 2001.29				
C	3.097 ± 0.104	...	...	0.089 ± 0.001
Q1	0.662 ± 0.029	0.15 ± 0.03	73.7 ± 12.4	0.142 ± 0.007
Q2	1.815 ± 0.061	0.20 ± 0.01	135.8 ± 2.9	0.084 ± 0.001
43 GHz – 2001.38				
C	2.781 ± 0.107	...	...	0.089 ± 0.001
Q1	0.439 ± 0.021	0.17 ± 0.03	66.3 ± 10.7	0.107 ± 0.005
Q2	2.159 ± 0.083	0.19 ± 0.01	136.8 ± 3.0	0.089 ± 0.001
43 GHz – 2001.48				
C	2.692 ± 0.104	...	...	0.091 ± 0.001
Q1	0.344 ± 0.016	0.18 ± 0.03	68.3 ± 10.2	0.065 ± 0.003
Q2	2.219 ± 0.086	0.19 ± 0.01	138.9 ± 3.0	0.097 ± 0.001
43 GHz – 2001.62				
C	2.623 ± 0.12	...	...	0.082 ± 0.001
Q1	0.456 ± 0.02	0.17 ± 0.03	67.6 ± 10.6	0.108 ± 0.005
Q2	2.260 ± 0.10	0.20 ± 0.01	140.1 ± 2.9	0.096 ± 0.001
43 GHz – 2001.70				
C	2.440 ± 0.159	...	...	0.089 ± 0.001
Q1	≤ 0.250	0.19 ± 0.03	67.6 ± 9.6	< 0.030
Q2	2.068 ± 0.135	0.20 ± 0.01	139.6 ± 2.8	0.093 ± 0.001
43 GHz – 2001.78				
C	3.036 ± 0.173	...	...	0.095 ± 0.001
Q1	0.437 ± 0.028	0.20 ± 0.03	71.5 ± 9.3	0.106 ± 0.005
Q2	2.184 ± 0.125	0.21 ± 0.01	137.7 ± 2.7	0.090 ± 0.001
43 GHz – 2001.86				
C	3.600 ± 0.162	...	...	0.054 ± 0.001
Q1	0.594 ± 0.032	0.20 ± 0.03	84.4 ± 9.2	0.186 ± 0.009
Q2	1.625 ± 0.073	0.25 ± 0.01	138.4 ± 2.3	0.063 ± 0.001
Q3	0.944 ± 0.042	0.15 ± 0.01	117.6 ± 3.9	0.031 ± 0.001
43 GHz – 2002.07				
C	4.334 ± 0.145	...	...	0.086 ± 0.001
Q1	0.790 ± 0.035	0.16 ± 0.03	83.9 ± 11.4	0.201 ± 0.010
Q2	1.508 ± 0.050	0.26 ± 0.01	143.0 ± 2.2	0.100 ± 0.001
Q3	≤ 1.069	0.19 ± 0.01	125.6 ± 3.0	< 0.030

Table 2. continued.

Comp.	S (Jy)	r (mas)	Θ ($^{\circ}$)	$FWHM$ (mas)
43 GHz – 2002.40				
C	4.204 ± 0.177	...	...	0.046 ± 0.001
Q1	0.884 ± 0.045	0.18 ± 0.03	92.9 ± 9.9	0.298 ± 0.015
Q2	0.921 ± 0.039	0.28 ± 0.01	144.4 ± 2.0	0.032 ± 0.001
Q3	1.695 ± 0.086	0.17 ± 0.03	127.8 ± 11.0	0.102 ± 0.005
43 GHz – 2002.48				
C	4.409 ± 0.171	...	...	0.058 ± 0.001
Q1	0.576 ± 0.028	0.21 ± 0.03	86.6 ± 8.7	0.216 ± 0.011
Q2	1.045 ± 0.040	0.28 ± 0.01	144.0 ± 2.1	0.060 ± 0.001
Q3	1.540 ± 0.074	0.17 ± 0.03	129.8 ± 11.1	0.103 ± 0.005
43 GHz – 2003.20				
C	3.356 ± 0.145	...	...	0.085 ± 0.001
Q1	0.582 ± 0.030	0.23 ± 0.03	101.0 ± 8.1	0.180 ± 0.009
Q2	0.788 ± 0.034	0.32 ± 0.01	150.8 ± 1.8	0.050 ± 0.001
Q3	1.440 ± 0.074	0.19 ± 0.03	146.7 ± 9.9	0.107 ± 0.005
43 GHz – 2003.49				
C	4.647 ± 0.259	...	...	0.088 ± 0.001
Q1	0.554 ± 0.035	0.24 ± 0.03	95.6 ± 7.7	0.204 ± 0.010
Q2	≤ 0.569	0.31 ± 0.01	151.5 ± 1.8	< 0.030
Q3	1.596 ± 0.089	0.19 ± 0.01	148.5 ± 3.0	0.097 ± 0.001
43 GHz – 2004.64				
C	4.937 ± 0.160	...	...	0.107 ± 0.005
Q1	0.558 ± 0.018	0.30 ± 0.03	108.0 ± 6.1	0.229 ± 0.011
Q2	0.438 ± 0.007	0.38 ± 0.01	155.6 ± 1.5	0.035 ± 0.000
Q3	1.063 ± 0.017	0.23 ± 0.01	151.8 ± 2.5	0.098 ± 0.001
43 GHz – 2004.97				
C	3.229 ± 0.116	...	...	0.128 ± 0.006
Q1	0.475 ± 0.017	0.31 ± 0.03	110.6 ± 6.0	0.204 ± 0.010
Q2	0.507 ± 0.018	0.40 ± 0.03	158.1 ± 4.6	0.069 ± 0.003
Q3	1.160 ± 0.042	0.21 ± 0.03	157.6 ± 8.6	0.117 ± 0.006
43 GHz – 2005.25				
C	2.512 ± 0.093	...	...	0.119 ± 0.006
Q1	0.435 ± 0.016	0.33 ± 0.03	111.7 ± 5.6	0.226 ± 0.011
Q2	≤ 0.875	0.40 ± 0.01	160.3 ± 1.4	< 0.030
Q3	1.009 ± 0.037	0.22 ± 0.03	162.3 ± 8.6	0.153 ± 0.008
43 GHz – 2006.17				
C	1.280 ± 0.049	...	...	0.148 ± 0.007
Q1	0.261 ± 0.010	0.36 ± 0.03	115.6 ± 5.1	0.217 ± 0.011
Q2	1.788 ± 0.045	0.36 ± 0.01	160.2 ± 1.6	0.039 ± 0.000
Q3	0.940 ± 0.024	0.25 ± 0.01	164.8 ± 2.3	0.087 ± 0.001
43 GHz – 2006.24				
C	1.257 ± 0.049	...	...	0.142 ± 0.007
Q1	0.349 ± 0.014	0.34 ± 0.03	113.7 ± 5.3	0.233 ± 0.012
Q2	≤ 1.484	0.36 ± 0.01	160.4 ± 1.6	< 0.030
Q3	1.218 ± 0.033	0.26 ± 0.01	163.5 ± 2.2	0.082 ± 0.001
43 GHz – 2006.30				
C	1.207 ± 0.049	...	...	0.153 ± 0.008
Q1	0.362 ± 0.015	0.34 ± 0.03	112.1 ± 5.3	0.248 ± 0.012
Q2	1.470 ± 0.043	0.35 ± 0.01	160.2 ± 1.6	0.051 ± 0.001
Q3	1.295 ± 0.038	0.25 ± 0.01	163.5 ± 2.2	0.077 ± 0.001

Table 2. continued.

Comp.	S (Jy)	r (mas)	Θ ($^{\circ}$)	$FWHM$ (mas)
43 GHz – 2006.37				
C	1.133 ± 0.047	...	...	0.155 ± 0.008
Q1	0.390 ± 0.016	0.33 ± 0.03	115.8 ± 5.6	0.262 ± 0.013
Q2	1.236 ± 0.037	0.35 ± 0.01	160.6 ± 1.6	0.056 ± 0.001
Q3	1.430 ± 0.043	0.25 ± 0.01	163.4 ± 2.3	0.077 ± 0.001
43 GHz – 2006.46				
C	1.079 ± 0.045	...	...	0.149 ± 0.007
Q1	0.338 ± 0.014	0.35 ± 0.03	114.6 ± 5.3	0.258 ± 0.013
Q2	1.038 ± 0.032	0.36 ± 0.01	161.0 ± 1.6	0.049 ± 0.000
Q3	1.742 ± 0.054	0.25 ± 0.01	162.8 ± 2.3	0.079 ± 0.001
43 GHz – 2006.88				
C	0.760 ± 0.027	...	...	0.150 ± 0.008
Q1	0.253 ± 0.009	0.38 ± 0.03	117.5 ± 4.8	0.274 ± 0.014
Q2	0.769 ± 0.017	0.42 ± 0.01	163.2 ± 1.4	0.049 ± 0.000
Q3	2.465 ± 0.055	0.24 ± 0.01	163.4 ± 2.4	0.076 ± 0.001
43 GHz – 2007.16				
C	0.903 ± 0.052	...	...	0.170 ± 0.009
Q1	0.348 ± 0.020	0.38 ± 0.03	119.7 ± 4.8	0.258 ± 0.013
Q2	1.143 ± 0.057	0.45 ± 0.01	163.8 ± 1.3	0.085 ± 0.001
Q3	3.895 ± 0.222	0.23 ± 0.03	164.0 ± 7.9	0.101 ± 0.005
8.4 GHz – 2002.48				
Core	6.352 ± 0.635	...	...	0.378 ± 0.038
X4	≤ 0.088	0.62 ± 0.24	-98.8 ± 22.3	< 0.180
X5	0.073 ± 0.007	1.73 ± 0.42	-52.5 ± 13.9	0.836 ± 0.084
X6	0.116 ± 0.012	3.59 ± 0.44	-43.0 ± 7.1	0.883 ± 0.088
X7	0.103 ± 0.010	24.71 ± 1.39	-31.8 ± 3.2	2.785 ± 0.278

Table 3. Proper motion results. For each model component, we give the number of data points for the fit of the trajectory (N), the mean position angle ($\langle\Theta\rangle$), the mean angular speed ($\langle\dot{\Theta}\rangle$), the mean proper motion ($\langle\mu\rangle$), and its corresponding $\beta_{\text{app}}^{\text{obs}}(\mu)$, as well as its radial ($\langle\mu_{\text{rad}}\rangle$) and normal component ($\langle\mu_{\text{norm}}\rangle$), and its corresponding $\beta_{\text{app_norm}}^{\text{obs}}$.

Comp.	N	$\langle\Theta\rangle$ °	$\langle\dot{\Theta}\rangle$ °/yr	$\langle\mu\rangle$ mas/yr	$\beta_{\text{app}}^{\text{obs}}$ c	$\langle\mu_{\text{rad}}\rangle$ mas/yr	$\langle\mu_{\text{norm}}\rangle$ mas/yr	$\beta_{\text{app_norm}}^{\text{obs}}$ c
Q1	33	139.5 ± 7.1	10.7 ± 0.7	0.047 ± 0.002	3.26 ± 0.14	0.026 ± 0.002	0.039 ± 0.003	2.71 ± 0.21
Q2	34	175.4 ± 1.3	5.8 ± 0.3	0.042 ± 0.001	2.85 ± 0.07	0.036 ± 0.001	0.020 ± 0.003	1.39 ± 0.21
Q3	16	153.8 ± 2.7	8.0 ± 0.5	0.034 ± 0.002	2.29 ± 0.14	0.018 ± 0.002	0.029 ± 0.002	2.01 ± 0.14