Opacity in compact extragalactic radio sources and the core shift effect

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Abstract. The apparent position of the “core” in a parsec-scale radio jet (a compact, bright emitting region at the narrow end of the jet) depends on the observing frequency, owing to synchrotron self-absorption and external absorption. This dependency both provides a tool to probe physical conditions in the vicinity of the core and poses problems for astrometric studies using compact radio sources. We investigate the frequency-dependent shift of the positions of the cores (core shift) observed with very long baseline interferometry (VLBI) in parsec-scale jets. We present results for 29 selected active galactic nuclei (AGN). In these AGN, the magnitude of the measured core shift between 2.3 and 8.6 GHz reaches 1.4 mas, with a median value for the sample of 0.44 mas. We discuss related physics as well as astrometry applications and plans for further studies.

1. Introduction

Extragalactic relativistic jets are formed in the immediate vicinity of the central black holes in galaxies, at distances on the order of 100 gravitational radii, and they become visible in the radio at distances of about 1000 gravitational radii [1]. This apparent origin of the radio jets is commonly called the “core”. In radio images of extragalactic jets, the core is located in the region with an optical depth $\tau_s \approx 1$. This causes the absolute position of the core, $r_{\text{core}}$, to vary with the observing frequency, $\nu$, since the optical depth profile along the jet depends on $\nu$: $r_{\text{core}} \propto \nu^{-1/k_r}$ [2]. Variations in the optical depth along the jet can result from synchrotron self-absorption [3], pressure and density gradients in the jet and free-free absorption in the ambient medium most likely associated with the broad-line region (BLR) [4]. If the core is self-absorbed and in equipartition, the power index $k_r = 1$ [2]. Density and pressure gradients in the jet and external absorption can lead to deviations in $k_r$ from unity [4]. Changes in the core position measured between three or more frequencies can be used to determine critical physical and geometrical parameters of the relativistic jet origin.

The effect of frequency-dependence of the core position has an immediate connection to several physical and astrometric studies using compact extragalactic radio sources. Systematic observations of the core shift in a sample of compact jets can be used for probing the conditions...
in the compact jets and nuclear regions in AGN and understanding the effect the shift may have on the alignment of the radio and optical reference frames based on extragalactic sources.

Measurements of the core shift have been done so far only in a small number of objects [e.g., 4–12]. In these proceedings, we present and discuss results for 29 compact extragalactic radio sources used in VLBI astrometric studies.

2. Core shift measurements

We have imaged and analyzed 277 sources from geodetic RDV\(^1\) observations made in 2002 and 2003—ten 24 hr-long experiments on 16 January 2002, 6 March 2002, 8 May 2002, 24 July 2002, 25 September 2002, 11 December 2002, 12 March 2003, 7 May 2003, 18 June 2003. Geodetic RDV sessions feature simultaneous observations at 2.3 GHz and 8.6 GHz (S and X bands) with a global VLBI network at right circular polarization. This includes for every session the VLBA and up to nine other radio telescopes from the following list: Algonquin Park (46 m), Gilcreek (26 m), HartRAO (26 m), Kokee (20 m), Matera (20 m), Medicina (32 m), Noto (32 m), Ny Alesund (20 m), Onsala (20 m), TIGO (6 m), Tsukuba (32 m), Westford (18 m), Wettzell (20 m). The data processing technique and imaging results are described by [14].

This long-term RDV program is one of the best choices for a large project to measure two-frequency core shifts on the basis of open archival raw VLBI data for several reasons: (i) it is optimized to have a good \((u,v)\)-coverage, (ii) it has the maximum possible resolution for ground-based VLBI at these frequencies, (iii) the frequency ratio between the simultaneously observed bands is high (3.7), and (iv) the core shift per unit of frequency between 2.3 and 8.6 GHz is larger than that at higher frequencies because of opacity effects [see, e.g., 4].

We have measured the frequency-dependent core shift by model-fitting the source structure with two-dimensional Gaussian components [15] and referencing the position of the core component to one or more jet features, assuming the latter to be optically thin and having frequency-independent peak positions.

Homan D C and Kovalev Y Y (in prep) have made tests comparing core shifts measured in the quasars 1655+077 and 2201+315 with relative astrometry (phase referencing to a calibrator source) to those obtained as here from self-calibrated images by referencing the core to optically thin jet features. The core shifts obtained using these two methods agreed within the errors. This result indicates that self-calibrated images provide sufficient accuracy for measuring the core shift and can be used for a systematic study of this effect. However, the VLBI phase referencing method is required for jets whose structure does not allow the self-referencing technique to be applied.

Other approaches have also been tried. [16] have proposed a “source/frequency phase referencing” method for measuring the core shift, which could be particularly useful while working at higher radio frequencies. [17] performed a 2-D cross-correlation analysis in order to align VLBA images of 3C 84 measured at different frequencies with a formal accuracy less than 5 \(\mu\)as. However, the real error margins of the cross-correlation method are certainly substantially larger, as this method requires the assumption that there are no large variations in observed spectral index along the jet (if the core region is blended) which is not the case for many extragalactic jets.

We have measured core shifts between 2.3 and 8.6 GHz in 29 AGN (see Fig. 1, with the resulting values of the shift ranging between \(-0.1\) and \(1.4\) mas and the median value for the sample of 0.44 mas. Errors of the core shift measurements (typical \(1\sigma\) values: 0.1 mas or better) are estimated from the uncertainties of component positions calculated following [18]. The robustness of the measurements is supported by the following observation. In objects with several bright jet components, similar core shift values within errors are obtained from

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\(^1\) Research and Development VLBA experiments [see, e.g., 13].
The derived core shift values for U sources are averaged per source. The median value for the distribution is equal to \( \approx 0.44 \) mas, referencing the core position to different jet features. In objects observed more than once, comparable core shift values are obtained from referencing the core position to the same jet feature at different observing epochs. In both cases, no systematic dependencies are observed, implying that measured core shift values do not depend on the component location and features cross-identified between the two frequency bands S/X have similar position angles (P.A.\(_{S/X}\)).

In order to further ensure the fidelity of the measurements made, we have also performed an independent check by analyzing spectral index images with and without core shift applied and dropping all objects in which application of the core shift resulted in unphysical values of the spectral index (see details below).

The difference in resolution and corresponding angular size of the restoring VLBI beam at 2.3 GHz and 8.6 GHz could lead to a systematical apparent (not real) shift of the core position due to resolution-dependent blending of the core and optically thin parts of the jet. To estimate the magnitude of this effect, we have downgraded the resolution of 8.6 GHz data to the one of the 2.3 GHz band by setting the maximum \((u,v)\)-radius at 8.6 GHz to about 75 M\(\lambda\). Then the 8.6 GHz model was re-fitted for every source and epoch by varying all free parameters. These models were compared to the original 8.6 GHz ones, and the magnitude of the core shift due to blending was calculated. The median value for this blending effect is \( \approx 0.006 \) mas which is much less than the typical error of the core-shift measurements presented in this paper.

**Figure 1.** Histogram of the derived core shift values for 29 sources. One average core shift value per source is used. The median value for the distribution is equal to 0.44 mas.
3. Discussion

If the core shifts and the power index \( k_r \) are measured from VLBI observations at more than two frequencies, the magnetic field strength and distribution can be reconstructed in the ultra-compact regions of the jets \([4]\). The offset of the observed core positions from the true base of the jet as well as the distance from the nucleus to the jet origin can also be derived \([4]\). Estimates of the total (kinetic + magnetic field) power, synchrotron luminosity and the maximum brightness temperature, \( T_{b,\text{max}} \), in the jets can be made. The ratio of particle energy to magnetic field energy can also be estimated, from the derived \( T_{b,\text{max}} \). This information enables testing of the \([3]\) model and several of its later modifications \([e.g., 19; 20]\). The estimated distance from the nucleus to the jet origin constrains the self-similar jet model \([21]\) and the particle-cascade model \([22]\). This approach can also be applied to determine the matter content in parsec-scale jets \([23; 24]\). In case if the core shifts are measured at four or more frequencies, the absolute geometry of the jet can be determined, giving the absolute offset of the core from the central engine. Combined with the value for magnetic field this gives an estimate for the mass of the central black hole \([4]\). It is found that nuclear flares can result in temporal variability of the core shift. Analysis of this effect can shed light on the physics of the flares.

If not taken into account, the core shifts could influence and corrupt both astrophysical (e.g., spectral imaging and Faraday rotation imaging) and astrometric studies. The core shifts are likely to affect the positional accuracy of the radio reference frame and pose problems for connecting radio and optical reference frames. The next steps in this study are to measure core shifts in a complete flux-density-limited sample of bright extragalactic radio sources, to estimate physical parameters from the measured shifts and to look for their temporal variations.

We plan to achieve these goals by combining together further analysis of RDV VLBA S/X datasets, four-frequency \((8.1, 8.4, 12, \& 15 \text{ GHz})\) MOJAVE-2 VLBA observations\(^2\) in 2006, dedicated multi-frequency \((1.4–15 \text{ GHz})\) VLBA observations in 2007 of more than half of the objects discussed in this study, and dedicated \(1.7–8.4 \text{ GHz} \text{ EVN+QUASAR phase referencing observations in 2008 of selected most compact and bright ICRF targets.}\)

We have estimated from theory an average shift between the radio \((4 \text{ cm})\) and optical \((6000 \text{ Å})\) bands to be approximately \(0.1 \text{ mas}\) for a complete sample of radio selected AGN. The robustness of this prediction is supported by the fact that the same method gives an average core shift of \(0.2\) to \(0.3 \text{ mas}\) between \(2.3\) and \(8.6 \text{ GHz}\), which agrees well with the median shift of \(0.44 \text{ mas}\) reported by us here for a non-complete sample of 29 AGN. The estimated radio-optical core shift is comparable to the positional accuracy of GAIA and significantly exceeds that of SIM. It implies that the core shift effect should be carefully investigated, and corrected for, in order to align accurately the radio and optical positions.

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\(^2\) http://www.physics.purdue.edu/astro/MOJAVE/
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