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Opacity in parsec-scale jets of active galactic nuclei: VLBA study from 1.4 to 15 GHz

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In extragalactic jets, the apparent position of the bright/narrow end (the core) depends on the observing frequency, owing to synchrotron self-absorption and external absorption. The effect must be taken into account in order to achieve unbiased results from multi-frequency VLBI data on AGN jets. Multi-frequency core shift measurements supplemented by other data enable estimating the absolute geometry and a number of fundamental physical properties of the jets and their environment. We have previously measured the shift between 13 and 3.6 cm in a sample of 29 AGNs to range between 0 and 1.4 mas. In these proceedings, we present and discuss first results of our follow-up study using VLBA between 1.4 and 15.4 GHz.

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1. Introduction

In VLBI images of relativistic jets, the location of the narrow end of the jet (branded the "core") is fundamentally determined by absorption in the radio emitting plasma itself (synchrotron self-absorption) and/or in the material surrounding the flow [1, 6, 11] and can be further modified by strong pressure and density gradients in the flow [11]. At any given observing frequency, ν, the core is located in the jet region with the optical depth $\tau_s(\nu) \approx 1$, which causes its absolute position, r_c, to shift $\propto \nu^{-1/k_r}$. If the core is self-absorbed and in equipartition, $k_r = 1$ [1]; k_r can be larger in the presence of external absorption or pressure/density gradients in the flow [11].

Changes of the core position measured between three or more frequencies can be used for determining the value of k_r, estimating the strength of the magnetic field in the nuclear region and the offset of the observed core positions from the true base of the jet [11]. The power index k_r itself can vary with frequency due to pressure and density gradients or absorption in the surrounding medium, most likely, associated with the broad-line region.

If the core shifts and k_r are measured between four, or more, frequencies, the following can be addressed in detail. The magnetic field distribution can be reconstructed in the ultra-compact region of the jet and estimates of the total (kinetic plus magnetic field) power, the synchrotron luminosity, L_{syn}, and the maximum brightness temperature, $T_{b,max}$ in the jet can be made. In addition, the ratio of particle energy and magnetic field energy can be estimated from the derived $T_{b,max}$. This would enable testing the Königl model [6] and several of its later modifications (e.g., [5, 3]). The location of the central engine and the geometry of the jet can be determined. Estimation of the distance from the nucleus to the jet origin will enable constraining the self-similar jet model [12] and the particle-cascade model [2].

Previously, we have found [7] that the shift of the VLBI core position between 2.3 and 8.6 GHz can be as much as 1.4 mas (median value 0.44 mas) for a sample of 29 AGN. It was also found that nuclear flares result in temporal variability of the shift. See [7] and references therein for more discussion of the core shift studies as well as very recent papers by [8, 15]. First selected results from our follow up study of this effect in luminous extragalactic jets are presented in these proceedings.

2. Observational data and core shift measurements

We have selected the twenty most prominent targets from [7] and observed them in a dedicated VLBA experiment in 2007 (code BK 134, 96 hr in total) between 1.4 and 15.4 GHz at nine separate frequencies with 256 Mbps recording rate. Example Stokes I images for one of the targets, the compact steep spectrum (CSS) quasar 3C 309.1 (1458+718) are presented in Figure 1.

In order to test even more sources with high resolution and dynamic range, we also started an analysis of the MOJAVE-2[1] VLBA observations of 192 radio loud extragalactic jets, see sample description in [10]. The MOJAVE-2 observations have happened in 2006 at four frequencies of 8.1, 8.4, 12.1, & 15.4 GHz. Following [7], we applied the self-referencing method to measure the core shift in the data presented.

[1]See `http://www.physics.purdue.edu/MOJAVE/`

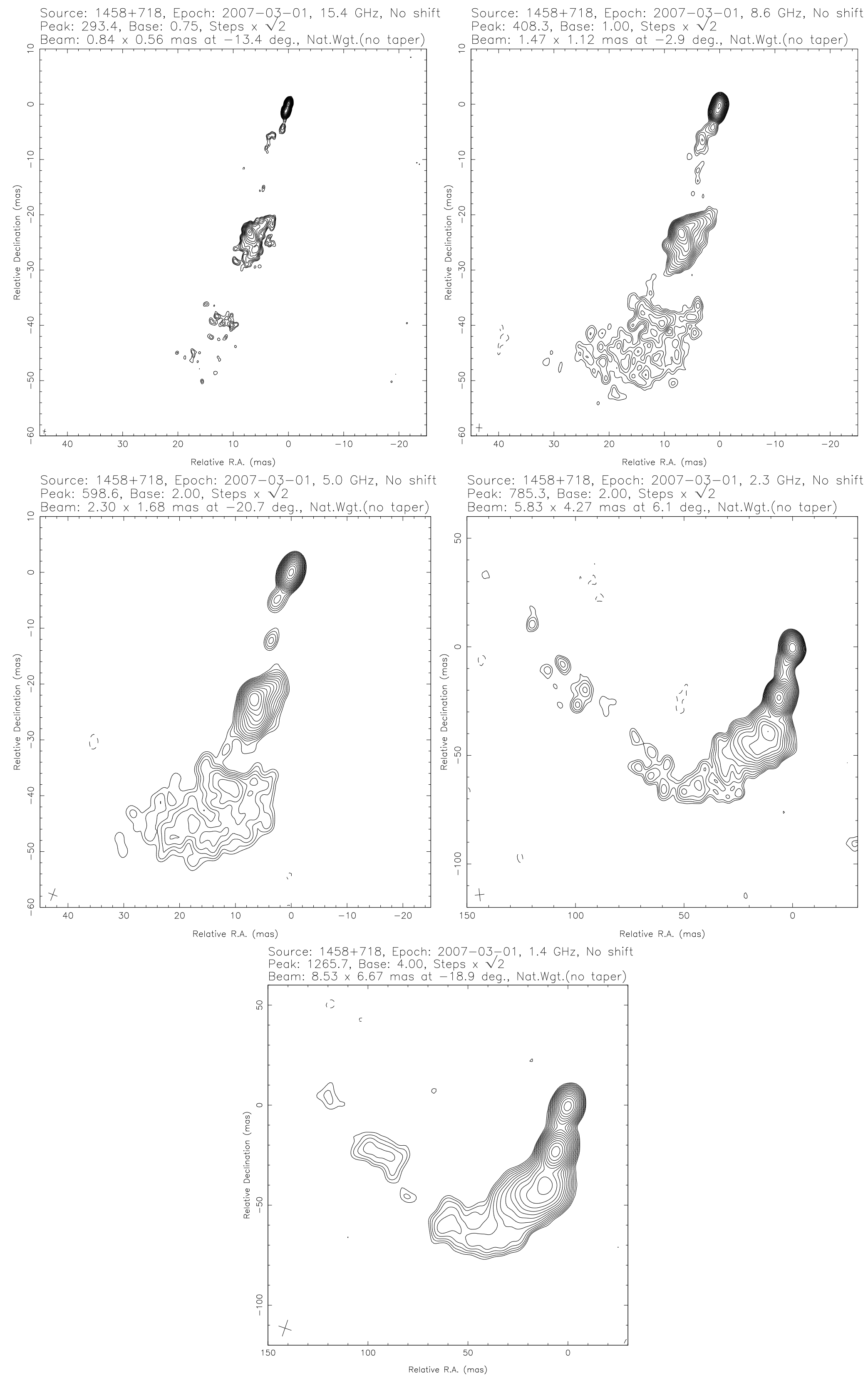

Figure 1: Stokes I images for frequency bands from 15.4 to 1.4 GHz (top to bottom) for the quasar 3C 309.1. Basic parameters can be found on top of each image. The lowest contour is plotted on the level ‘Base’ (mJy/beam). Restoring beam is shown in the left bottom corner of every map.

3. Selected Results

3.1 1.4-15.4 GHz measurements, quasar 3C 309.1

Results of the multi-frequency core shift measurements and spectral index image corrected for the shift are presented in Figure 2 for 3C 309.1. This CSS quasar is located at redshift 0.905 [4]. One milliarcsecond corresponds to 7.82 pc. We adopt the following parameters from [11]: jet Lorentz factor $\Gamma_{\rm jet} = 5$, observing angle of the jet $\vartheta_{\rm jet} = 20^\circ$, jet opening angle $\phi = 2^\circ$. We also use the value $\alpha = -0.6$ for the spectral index of the jet. Applying the model and method by [11] we study the frequency dependence of the opacity in the jet and we derive the basic physical properties of the flow at the location of the VLBI core. The offset measure $\Omega_{r\nu}$ [11] might be slightly affected by the blending below 5 GHz for 3C 309.1. In view of this, the higher frequency measurements can be employed to derive the physical properties of the jet. Using the shifts between 5, 8, and 15 GHz and the jet parameters summarized above, we estimate the distance from the 15 GHz core to the central super-massive black hole to be 5 ± 2 pc. The magnetic field at a distance of 1 parsec from the nucleus is estimated to be 2.3 ± 0.5 G, adopting the electron density $N_e = 17,000$ cm^{-3} [9]. This is comparable with the determined equipartition magnetic field $B_{\rm eq} = 1.7\pm0.8$ G. The estimate above corresponds to a magnetic field of 0.1 ± 0.2 G in the apparent core region observed at 15 GHz. We also estimate the total luminosity $L_{\rm tot} = (1.1\pm0.2)\times10^{47}$ erg s^{-1} and the synchrotron luminosity $L_{\rm syn} = (1.4\pm0.3)\times10^{46}$ erg s^{-1}, for the compact, unresolved section of the jet. The maximum brightness temperature predicted for this section of the jet is $(8\pm6)\times10^{11}$ K, which suggest that the jet emission is dominated by the energy release due to the Compton losses.

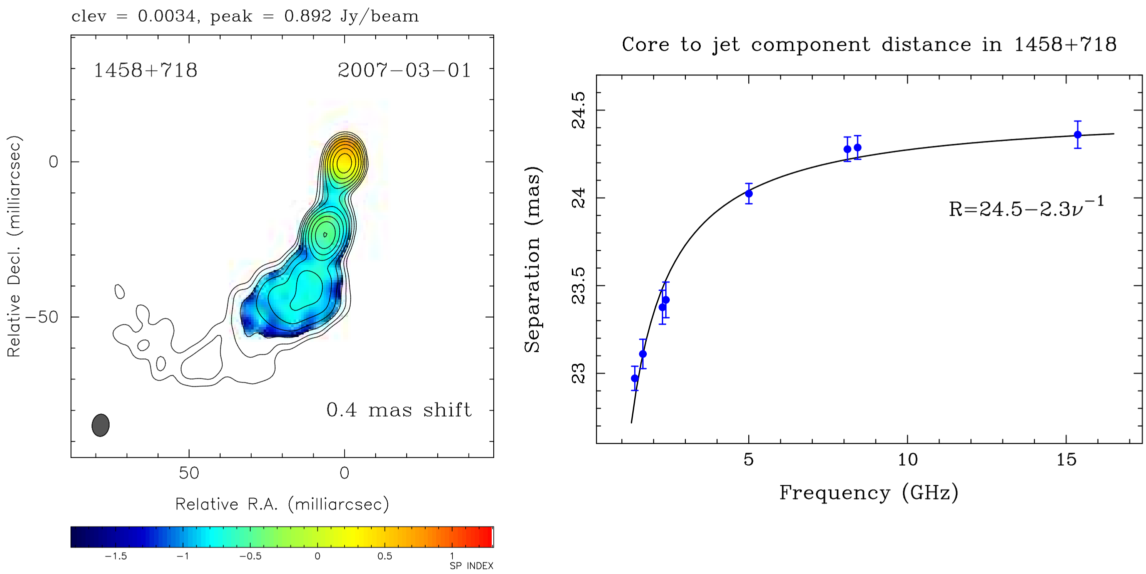

Figure 2: Results for the CSS quasar 3C 309.1. *Left:* Spectral index α ($S \propto \nu^\alpha$) image between 1.4 and 2.4 GHz, 0.4 mas shift applied. The restoring beam is shown in the left bottom corner. Spectral index is shown by color while contours represent the 2.4 GHz CLEAN image. *Right:* Distance between a jet feature centroid position and the core versus frequency. The curve is fitted to the data for the pure synchrotron self-absorption case ($k_{\rm r} = 1$).

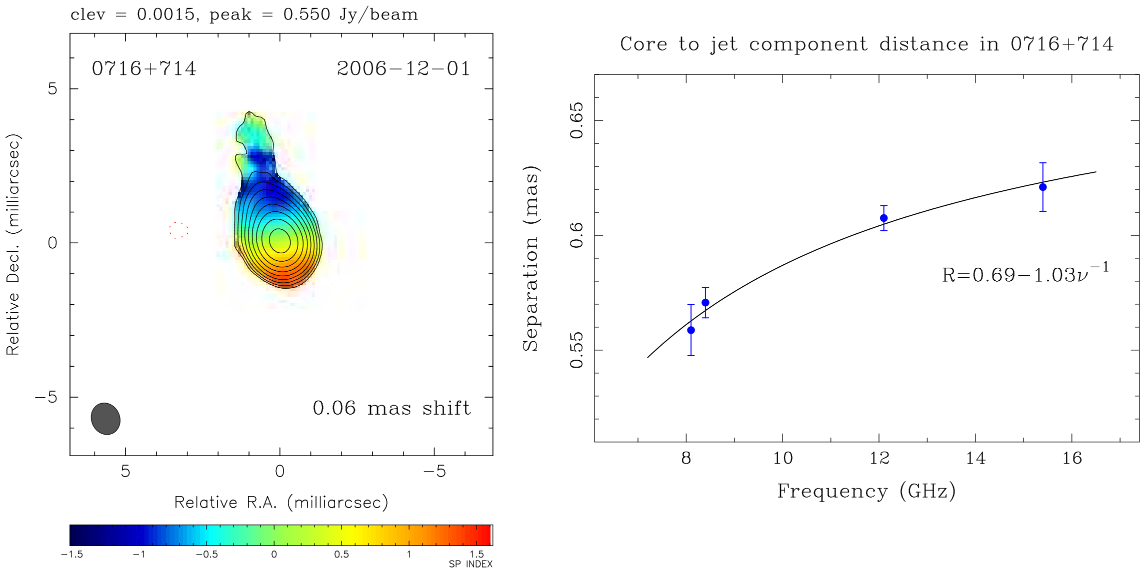

Figure 3: Results for the BL Lac object 0716+714. *Left:* Spectral index α image between 8 and 15 GHz, 0.06 mas shift applied. The restoring beam is shown in the left bottom corner. Spectral index is shown by color while contours represent the 15.4 GHz CLEAN image. *Right:* Distance between a jet feature centroid position and the core versus frequency, $k_r = 1$ is used for the fitted curve.

3.2 8.1 to 15.4 GHz measurements, BL Lacertae object 0716+714

Figure 3 reports successful core shift measurements in the very interesting intra-day variable BL Lacertae object 0716+714 (e.g., [16, 14], and references therein). This source is located at redshift 0.31 [13], one milliarcsecond corresponds to 4.52 pc. The core shift between 8.1 and 15.4 GHz is found to be only about 0.06 mas. However, even this relatively small value affects spectral index imaging significantly if not accounted for.

4. Summary

The core shift effect is important to account for performing multi frequency VLBI analysis of compact extragalactic jets and using these objects as reference points in astrometry. It provides a useful tool to derive and study physical properties of the apparent compact relativistic jet origin and the absolute jet geometry. In these proceedings we described our multi-frequency follow up study of this effect. We reported selected preliminary results and confirmed previous findings.

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