Article

Exploring The Magnetic Field Configuration Close To The Central Engines Using GMVA

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Abstract: The high radio frequency polarization imaging of non-thermal emission from active galactic nuclei (AGN) is a direct way to probe the magnetic field strength and structure in the immediate vicinity of supermassive black holes (SMBHs) and is crucial in testing the jet-launching scenario. To explore the the magnetic field configuration at the base of jets in blazars, we took advantage of the full polarization capabilities of the Global Millimeter VLBI Array (GMVA). With an angular resolution of $\sim$50 micro-arcseconds (μas) at 86 GHz, one could reach scales down to $\sim$900 Schwarzschild radii (for a 10^9 solar mass black hole). We present here the preliminary results of our study on the blazar BL Lac. Our results imply that on sub-mas scales the core and the central jet of BL Lac are significantly polarized with two distinct regions of polarized intensity. We also noted a great morphological similarity between the 7mm/3mm VLBI images at very similar angular resolution.

Keywords: active galaxies; BL Lacertae object: BL Lac; jets; GMVA: high-resolution VLBI; magnetic field; polarization

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1. High-frequency and high-resolution VLBI

Polarization study of non-thermal emission from AGN is a direct way to probe the magnetic field strength and structure in the immediate vicinity of a black hole, i.e., in a region where plasma is being injected and accelerated into the main jet stream. The current GMVA observations offer an angular resolution of 50 μas, which scales down up to $\sim$900 Schwarzschild radii for a 10^9 $M_\odot$ BH. In addition to that, Faraday depolarization effects become negligible at millimeter and sub-millimeter radio bands. Therefore, high-frequency polarimetric observations are essential in order to have a better understanding of the role of magnetic field in AGN accretion and jet production.

High-resolution observations have also been proven to be quite important in pinpointing the radiation processes responsible for the γ-ray emission in blazars [1–5]. Magnetic fields appear to plan an important role in particle acceleration; either particles are accelerated in high-magnetized environments [via relativistic magnetic reconnection and/or magnetoluminescence 6,7], or in low magnetized environments via relativistic shocks [8]. Understanding magnetic-field configurations is therefore essential for probing the high-energy radiation processes.

BL Lacertae, the prototype of the BL Lac class of AGN, is one of the nearest blazars (z=0.068) with the jet aligned within (6–10)° to our line-of-sight, approaching at an apparent flow speed of up to $\sim$10c [9]. Observing campaigns at 7 mm have shown swings in the direction of the innermost ($\leq$ 1.0 mas) region of the jet, which has been attributed to either helical instabilities, and/or jet inlet precession with proposed periods of 2.3 and 26 years [9,10]. The origin of the observed position angle swings and the helical motion in the inner jet region is controversial and still enigmatic. A one-to-one comparison of the jet kinematics with the broad-band flux variability is an important step towards a

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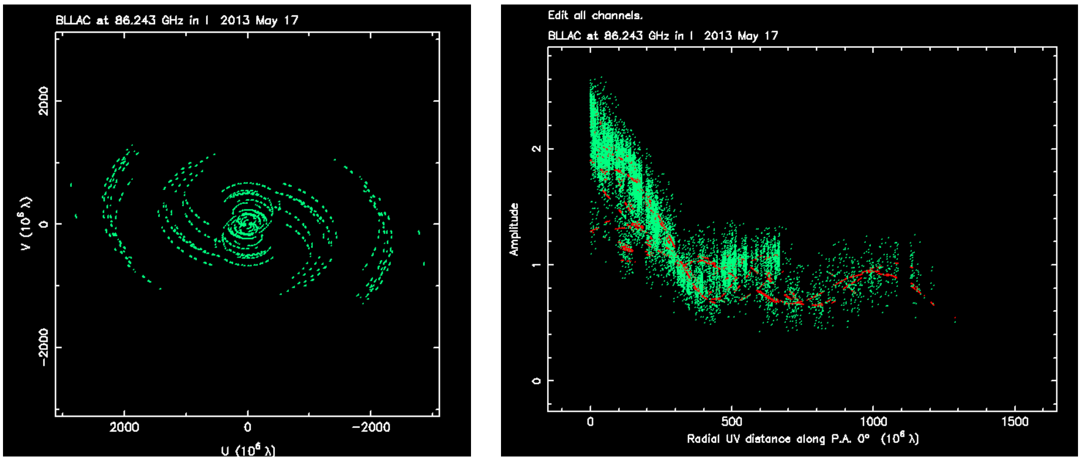

Figure 1. Left: UV-plot for BL Lac at 86 GHz in May 2013. Right: Correlated flux versus projected baseline.

solution of the problem. For a recent flare in 2006, a combination of high-resolution images with the associated broadband flux and optical polarization measurements of the source provided evidence for a helical magnetic field, well within the jet acceleration zone. There are also growing evidences that the observed gamma-ray emission is produced in this region, possibly by the interaction of moving with stationary shock(s) [5]. Therefore, BL Lac is an excellent candidate to study the relation between jet formation, gamma-ray emission, shock propagation and polarization variability.

2. Global 3 mm VLBI observations

The VLBI observations of the source were taken during an unprecedented broadband outburst. The source was detected at its **historic high brightness** in cm and mm radio bands [11,12], at X-ray [13] and in the far-infrared bands in December 2012. On November 2012, the source flux had risen to ∼14.6 Jy at 1.3 mm - the highest measured since SMA (sub-millimeter array) observations began in 2002. On December 5, 2012, BL Lac experienced an X-ray flare several orders of magnitude brighter than any previous flare, accompanied by bright optical and ultraviolet emission. The source also experienced its brightest gamma-ray flare measured by the Fermi-LAT (Large Area Telescope) [Photon Flux at E>100 MeV $\sim 2{\times}10^{-06}$ ph cm^{-2} s^{-1}, 14]. We took advantage of this unique opportunity to search for related structural variations in the core region and on scales of a few ten micro-arcseconds.

To achieve the necessary high resolution and image fidelity, we conducted immediate VLBI observations in dual polarization mode at 22, 43, and 86 GHz radio frequencies in 2013. Bright blazars S5 0716+714, 1749+096, 3C 454.3, and 3C 345 were used as calibrators. In addition to the VLBA, we had participation of Pico Veleta and Effelsberg (both LCP/RCP) and Yebes (LCP). As a result, we had a factor of two increase in angular resolution and a factor of three gain in the sensitivity. Data calibration and imaging were performed using the standard tasks in AIPS and difmap. Figure 1 (left) shows the UV-coverage of BL Lac for the 3 mm data taken in May 2013. The correlated flux versus baseline length plot for the same is shown in the right panel.

Determining the D-terms (often refereed to as polarization leakage) is one of the most challenging aspect of high-frequency polarization imaging. So far there is no optimal way to get an accurate estimation of it. We used the task LPCAL to estimate the D-terms of each antenna for a given experiment. For a consistency check, we compare the estimated D-terms for different sources in a given experiment and also for the same source in different experiments. Except for a few stations, we noticed that the variations in D-term values were ≤15%. For stations like MK, the D-terms variations were of the order of 20%. The last step is to correct the EVPA (electric vector polarization angle) of

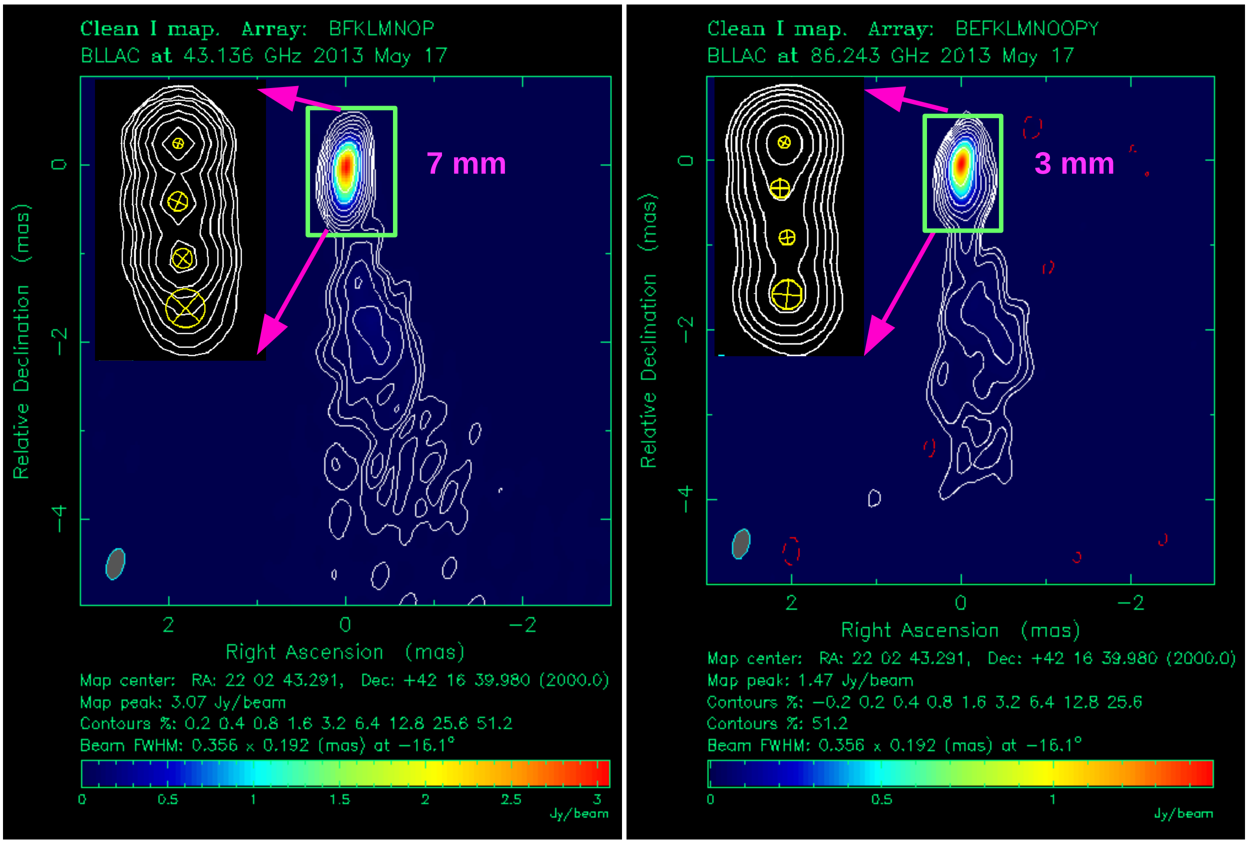

Figure 2. Total intensity maps of BL Lac at 7 mm (left) and 3 mm (right) radio bands. For comparison purposes the 3 mm map is resolved with the 7 mm beam. A zoomed version (resolved with a beam size of 0.1 mas) of the central region is shown in the upper left corner for each case; the yellow circles are the fitted circular Gaussian components.

the source; to do so, we compare the EVPA orientation of the super-resolved map (especially of the optically thin region) with the close-in-time single EVPA measurements. The difference between the two is then applied to the final image. A detailed overview of polarization calibration and imaging can be found in Martí-Vidal *et al.* [15]. In the following section, we present the preliminary results of our study.

3. Results

Figure 2 shows the 7 mm (left) and 3 mm (right) total intensity maps of BL Lac for an experiment conducted in May 2013. The 3 mm map is convolved with the 7 mm beam to compare the extended jet morphology. Apparently, the two maps look very similar; the extended jet region is however much fainter at 3 mm compared to the 7 mm map. In the top left corner, we show a zoomed version of the inner jet region (<0.4 mas), which corresponds to a linear distance of <10,000 Schwarzschild radii. The inner jet region can be well described by four circular Gaussian components (yellow circles) both at 43 (7 mm) and 86 GHz (3 mm) frequencies. This implies a remarkable similarity of jet morphology in the inner region as well. The simultaneous multi-frequency observations will be used to determine the spectral turnover for individual jet knots. Given their spectral indices and VLBI sizes, the magnetic field can be determined. The estimated magnetic field strengths at different separations from the jet apex will then be used to constrain the magnetic field strength at the jet apex. Recent evidence suggests that the central black holes in jetted AGN are surrounded by magnetically arrested disks [16], which implies high magnetic fluxes close to the central engines. Our observations

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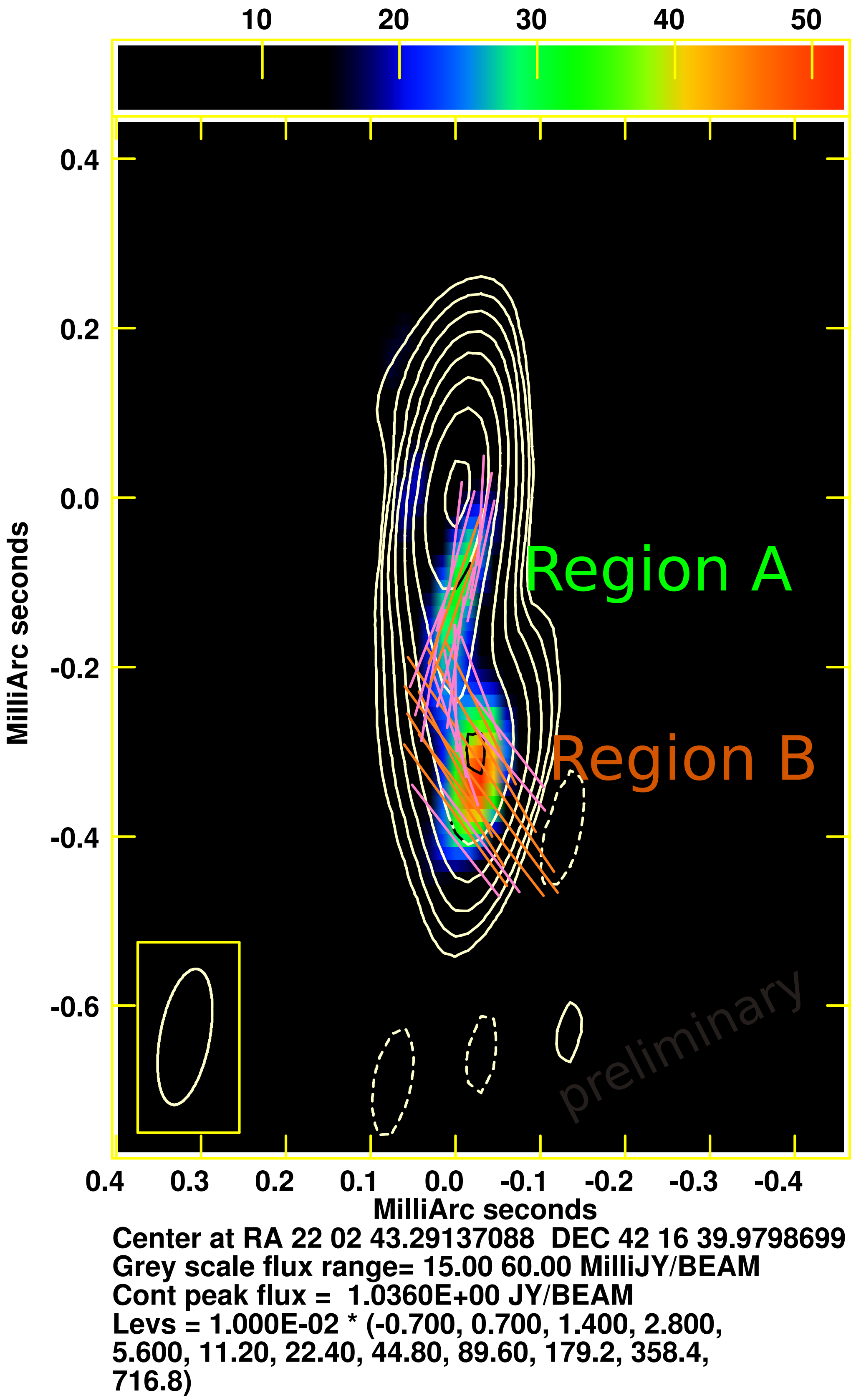

Figure 3. High-resolution intensity and polarization image of BL Lac at 86 GHz (3 mm) obtained in May 2013. Contours represent total intensity, and the polarized intensity is shown via the color scale. The solid ticks mark the EVPA direction.

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will provide observational constraints on the magnetic field strength and configuration close to the super-massive black holes.

In Fig. 3 we show as an example the 86 GHz polarization map of BL Lac convolved with its natural beam. The color scale represents the polarized intensity which is plotted over the total intensity contours (I-map), and the solid lines mark the EVPA direction. Two regions of polarized intensity are of particular interest here; we mark these regions as Region A and Region B. Region A is a bright polarized region elongated from the core up to a distance of $\sim$0.2 mas. The EVPA in this region is roughly inclined by 40-50° to the jet axis. In region B we noticed an almost 90° change in the EVPA direction in comparison to region A. Region B roughly extends from a distance of 0.2 to 0.5 mas and it is even more brighter than region A. The polarized intensity scale roughly follows the total intensity contours in the two regions. The change in the EVPA direction could either be due to the presence of helical magnetic field, which is a natural consequence of rotation of the central accretion disk and outflow, or it could simply be due to the presence of multiple oblique shocks. A comparison of multi-epoch polarization maps will allow us to resolve this question.

4. Summary and outlook

Understanding the physical processes happening close to the central engines and their connection to the jet activity and to the broadband flaring activity in blazars are the key challenges in active galactic nuclei physics. Ultra-high angular resolution mm-VLBI observations are the most feasible ways to answer these questions. We demonstrated the high-frequency and high-resolution polarization imaging capabilities of GMVA. In the very near future, ALMA will participate in the observations at 3 mm and 1.3 mm. This will significantly enhance the imaging and polarization capabilities of global mm-VLBI observations.

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Conflicts of Interest: The authors declare no conflict of interest.

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