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Investigation of a possible conical shock and the magnetic field structure of the VLBI jet of 3C380

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An earlier study of the complex jet of 3C380 by Papageorgiou et al. [9] revealed intensity and polarization structure associated with a bright knot K1 about 0.7 arcsec from the core that was reminiscent of that expected for a conical shock wave. We present here new 1.4, 1.6 and 5-GHz intensity, polarization and Faraday rotation images derived from observations with the Very Long Baseline Array plus one antenna of the Very Large Array. These new images confirm the overall polarization (magnetic-field) structure of the knot K1 indicated in the earlier observations, and provide some additional support for the hypothesis that this is a conical shock. In addition, a clear Faraday Rotation gradient has been detected across the parsec-scale jet, extending roughly from 10 to 30 mas along the jet from the core. This gradient spans roughly 3.5 beamwidths, and the difference in the Rotation Measure values on either side of the jet is 4–5σ, satisfying even the most stringent criteria for reliability of the gradient. We interpret this transverse Faraday-rotation gradient as reflecting systematic variation of the line-of-sight component of a helical magnetic field associated with the jet of 3C380.

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1. Introduction

The radio emission associated with Active Galactic Nuclei (AGNs) is synchrotron emission, which can be linearly polarized up to about 75% in optically thin regions, where the polarization angle χ is orthogonal to the underlying magnetic field **B**, and up to 10–15% in optically thick regions, where χ is parallel to **B** [1]. Linear polarization measurements thus provide direct information about both the degree of order and the direction of the **B** field giving rise to the observed synchrotron radiation.

Multi-frequency Very Long Baseline Interferometry (VLBI) polarization observations also provide information about the parsec-scale distribution of the spectral index (optical depth) of the emitting regions and Faraday rotation occurring between the source and observer. Faraday rotation of the plane of linear polarization occurs during the passage of an electromagnetic wave through a region with free electrons and a **B** field. When the Faraday rotation occurs outside the emitting region in regions of non-relativistic plasma, the rotation is given by

$$\chi_{obs} - \chi_o = \frac{e^3\lambda^2}{8\pi^2\varepsilon_o m^2 c^3}\int n_e \mathbf{B}\cdot d\mathbf{l} \equiv \mathrm{RM}\lambda^2$$

where χ_{obs} and χ_o are the observed and intrinsic polarization angles, e and m are the charge and mass of the particles giving rise to the Faraday rotation, usually taken to be electrons, c is the speed of light, ε_o is the electrical permittivity in free space, n_e is the density of the Faraday-rotating electrons, $\mathbf{B}\cdot d\mathbf{l}$ is an element of the line-of-sight **B** field, λ is the observing wavelength, and RM (coefficient of λ^2) is the Rotation Measure (e.g. [2]). Simultaneous multifrequency observations thus allow the determination of both RM, which carries information about the electron density and **B** field in the region of Faraday rotation, and χ_o, which carries information about the intrinsic **B**-field geometry associated with the source.

Systematic gradients in the Faraday rotation have been reported across the parsec-scale jets of several AGN, interpreted as reflecting the systematic change in the line-of-sight component of a toroidal or helical jet **B** field across the jet (e.g. [3, 4, 5] and references therein). Such fields would come about in a natural way as a result of the “winding up” of an initial “seed” field by the rotation of the central accreting objects (e.g. [6, 7]).

The quasar 3C380 has been extensively studied with VLBI, for example, by Polatidis & Wilkinson [8] and Papageorgiou et al. [9] [henceforth P2006]. On kiloparsec scales, 3C380 has a one-sided jet with two bright knots, detected in both the radio and optical, embedded in a diffuse halo [10, 11]. The jet of 3C380 is also one-sided on parsec scales, with a sharp apparent bend roughly 9 mas from the core, at the position of a bright knot labeled “component A” in [8]. Various superluminal components have been monitored over time scales of order 10–20 yr [8, 12].

The earlier 1.6-GHz (carried out with the Very Long Baseline Array (VLBA), phased Very Large Array (VLA) and the orbiting HALCA antenna) and 5-GHz (VLBA) polarization-sensitive observations of P2006 yielded a two-frequency RM map of the 3C380 VLBI jet made with the 1.6-GHz space-VLBI image and the 5-GHz ground-based image, indicating relative modest variations in the Faraday rotation in the region of the VLBI jet; these measurements were tentative, since the difference between the two polarization angles was subject to an ambiguity of 180°. The high-sensitivity 1.6-GHz VLBA+phased VLA data also revealed polarization associated with a bright

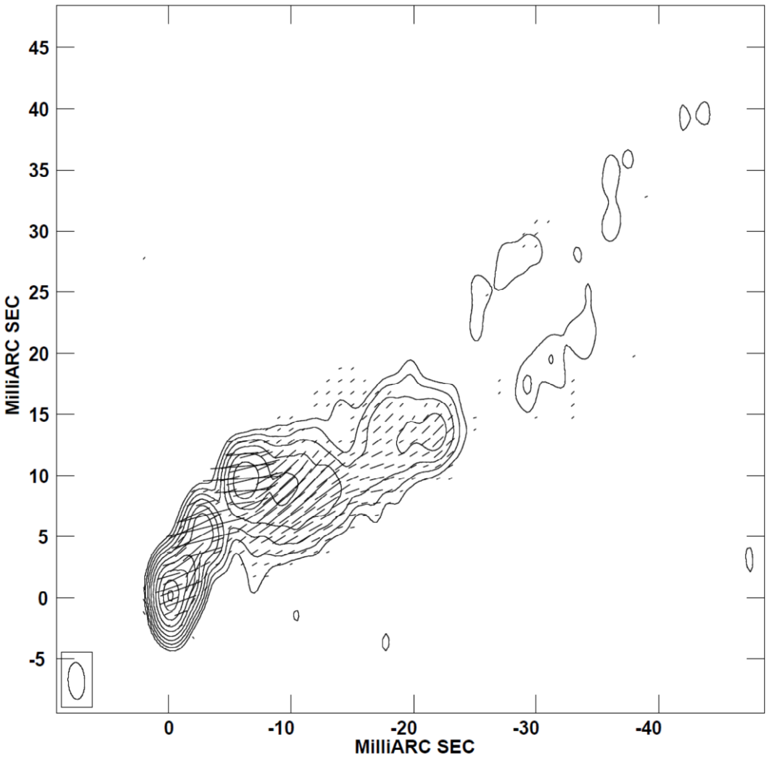

Figure 1: 5-GHz intensity map of 3C380 with **B**-field sticks superposed. The contours shown are −0.25, 0.25, 0.50, 1, 2, 4, 8, 16, 32, 64 and 95% of the peak of 1.46 Jy/beam. The **B**-field sticks were obtained by rotating the calibrated polarization angles corrected for Galactic but not local Faraday rotation by 90°.

knot K1 located about 0.7 arcsec from the VLBI core [11] that was reminiscent of that expected for a conical shock wave.

The new 1.6 + 1.4 + 5-GHz observations presented here were obtained to further probe the structure of the knot K1, and also to provide additional information about the parsec- and decaparsec-scale RM distribution in the vicinity of 3C380.

2. Observations and reduction

Our 1.6 + 1.4 + 5-GHz observations were obtained on March 26, 2006 with the VLBA and one antenna of the VLA, at an aggregate data rate of 128 Mbits/s in dual-polarization mode. The total duration of the VLBI observations was about 5.5 hours. The preliminary phase and amplitude calibration, polarization (D-term) calibration and imaging were all carried out in the NRAO AIPS package. The compact polarized AGN 1823+568 was used for the EVPA calibration at all three frequencies; due to the very stable polarization structure of 1823+568, we believe our EVPA calibration to be good to within about 2°. Due to the extended nature of the emission in 3C380, the imaging of this source was carried out initially using only the inner VLBA antennas and the VLA, before adding in the other antennas, similar to the procedure used by P2006. The RM map of 3C380 was made using both AIPS and CASA.

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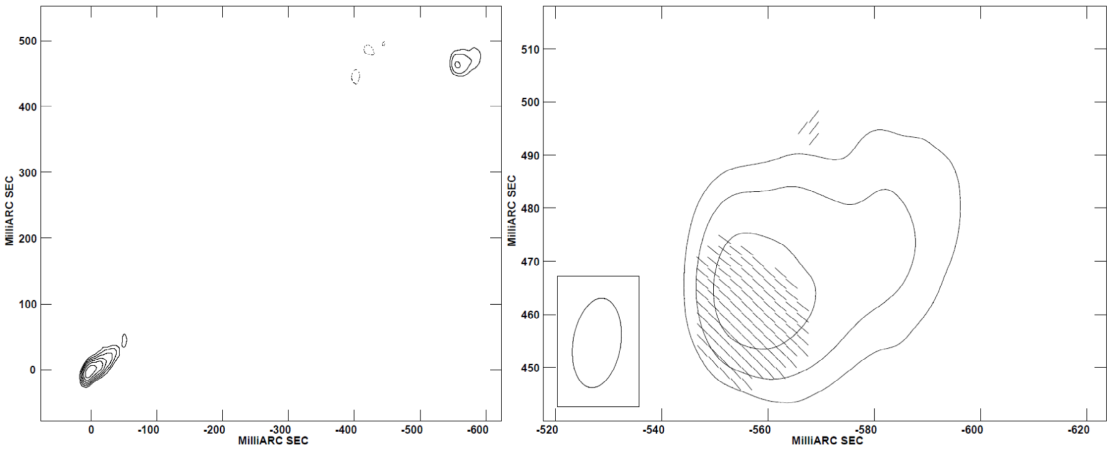

Figure 2: Left: 1.4-GHz intensity map of 3C380. The bottom contour is 1.7% of the peak of 1.45 Jy/beam, and the contours increase in steps of a factor of two. Right: 1.4-GHz intensity map of the region of the knot K1 with **B**-field sticks superposed. The contours shown are 1, 2 and 4% of the overall peak of 1.45 Jy/beam. The **B**-field were obtained by rotating the calibrated polarization angles fully corrected for Galactic and local Faraday rotation by 90°.

3. Results

Figure 1 shows our 5-GHz intensity image of 3C380, which shows the inner jet, with superposed **B**-field vectors. The **B**-field vectors were obtained by rotating the observed polarization vectors, corrected for Galactic but not local Faraday rotation, by 90°. This image shows that the jet **B** field is predominantly longitudinal on these scales, consistent with previously published image of P2006. The intensity map seems to show hints of limb brightening beyond about 30 mas from the core.

Figure 2 (left) shows our 1.4-GHz intensity image of 3C380, showing the inner VLBI jet together with a more detailed view of the knot K1 at a distance of about 0.7 arcsec from the core. This image is quite consistent with the 1.6-GHz image presented by P2006. The overall morphology and **B**-field of the distant knot K1 at 1.4 GHz presented in Fig. 2 (right) are similar to those reported by P2006. The region in which polarization is detected covers a somewhat larger area than in the 1.6-GHz map of P2006, and this polarization displays additional structure consistent with this feature being a conical shock, as was suggested by P2006. Note that the image of K1 presented by P2006 was only corrected for Galactic Faraday rotation, whereas our new image has also been fully corrected for Faraday rotation local to the AGN as well.

Our new three-frequency RM measurements (Fig. 3) indicate that the (reasonable) assumption made by P2006 that the correct difference between their 1.6 and 5-GHz polarization angles was the smallest possible value was, in fact, incorrect: the $n\pi$ ambiguity is broken by our new 1.4 and 1.6-GHz measurements. The new RM map of the jet of 3C380 within about 70 mas from the core displays relatively modest RM variations, but a transverse RM gradient is clearly visible roughly 10–30 mas from the core, suggesting the presence of a helical or toroidal magnetic field component associated with this jet. This RM gradient spans roughly 3.5 beamwidths, and the difference in the

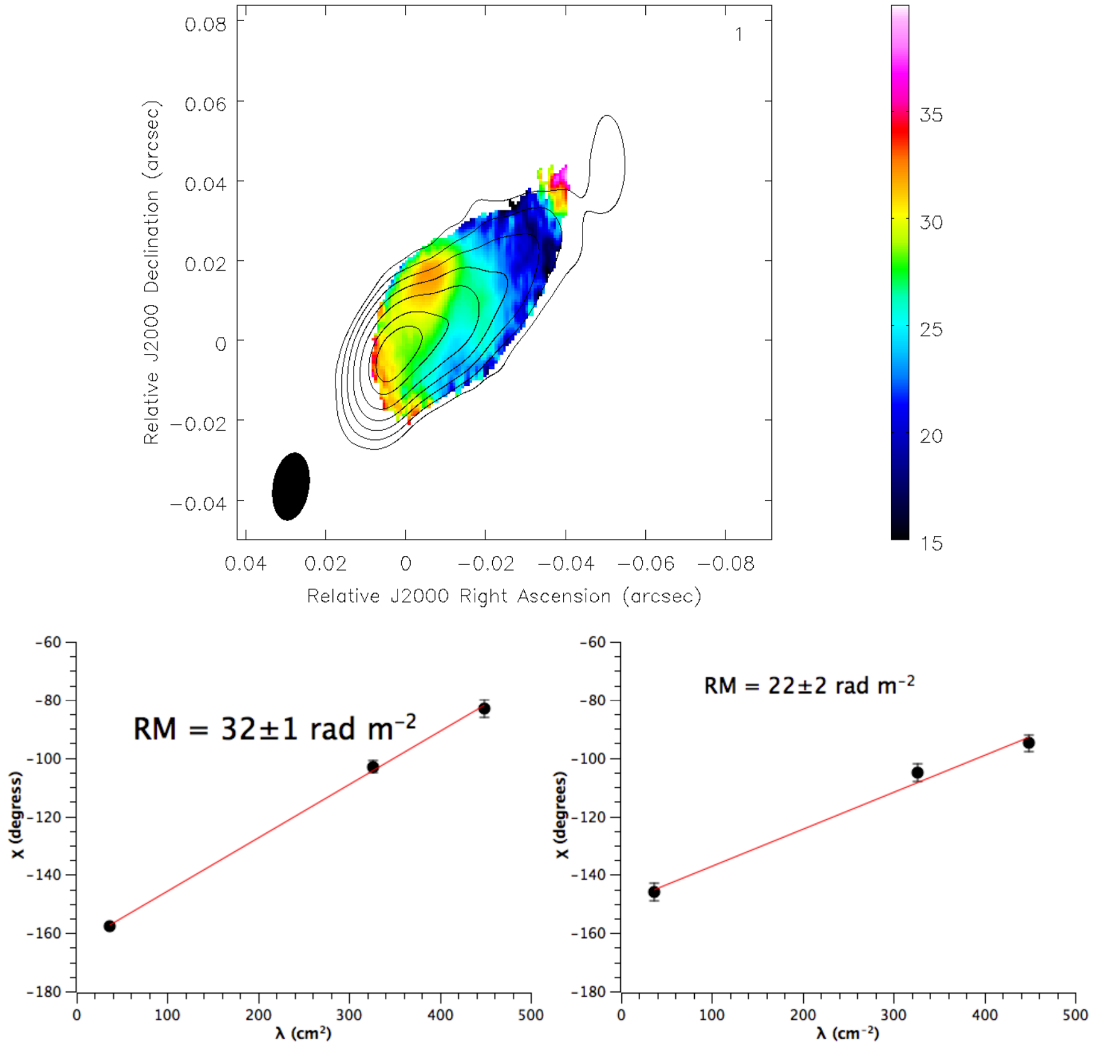

Figure 3: Upper: 1.4-GHz intensity map of the inner jet of 3C380 with the distribution of the RM superposed. Lower: Examples of plots of χ versus λ^2 for corresponding regions on opposite sides of the 3C380 jet in the region of the RM gradient. The χ errors shown are 1σ. The RM difference across the jet corresponds to about 4.5σ.

RM values on opposite sides of the jet is roughly 4–5σ, satisfying even the most stringent criteria for reliability of the gradient [13].

Figure 3 also shows examples of plots of the EVPA χ versus the wavelength λ squared for corresponding regions on opposite sides of the 3C380 jet, in the region of the RM gradient. The adherence to a linear λ^2 dependence is excellent. The RM uncertainties in the lower panels of Fig. 3 were determined using χ uncertainties estimated in individual pixels, without including the effect of uncertainty in the EVPA calibration, since this cannot introduce spurious RM gradients, as is discussed in [5, 14]. The ability of the 1.4 and 1.6-GHz measurements to resolve the $n\pi$ ambiguity in the observed polarization angles is immediately clear. This combined with the long "lever arm" between the two lower frequencies and 5-GHz yields RM measurements in individual pixels with low uncertainties of $\sim 1-2$ rad/m^2 (these will increase somewhat if the EVPA calibration uncertainties are included in the χ errors).

4. Conclusion

The results presented here support the idea that the knot K1 investigated by Papageorgiou et al. [9] is a conical shock in the jet flow in 3C380. Our 1.4 and 1.7-GHz measurements have enabled us to derive the local Faraday rotation in the vicinity of this knot, which is modest. Derivation of the intrinsic direction of the local magnetic field using these Faraday-rotation measurements confirms that both the morphology and magnetic field of K1 are consistent with this feature being a conical shock.

We have also presented new, very sensitive Faraday RM measurements of the inner jet of 3C380 based on simultaneous observations at 1.4, 1.7 and 5 GHz. These measurements have revealed a clear RM gradient across the jet at distances of about 10-30 mas from the core. This gradient spans roughly 3.5 beamwidths, and the RM values at opposite sides of the jet differ by 4–5σ. This represents firm evidence that the jet of 3C380 carries a helical magnetic field.

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