Faraday rotation in jets of AGN: the case of 3C 120

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Abstract. The source of Faraday rotation in the jet of the radio galaxy 3C 120 is analyzed through Very Long Baseline Array observations carried out between 1999 and 2007 at 15, 22 and 43 GHz. Uncorrelated changes in the linear polarization of the underlying jet emission and the Faraday rotation screen indicate that the emitting jet and the source of Faraday rotation are not closely connected physically and have different configurations for the magnetic field and/or kinematical properties. Furthermore, the existence of a region of enhanced rotation measure whose properties remain constant over three years requires a localized source of Faraday rotation, favoring a model in which a significant fraction of the rotation measure originates in foreground clouds.

1. Introduction
Helical magnetic fields are thought to play an important role in the formation and collimation of relativistic jets in active galactic nuclei (AGN) (e.g., [1–3]). The structure of the magnetic field in jets of AGN can be studied through polarimetric Very Long Baseline Interferometric (VLBI) observations, however, recent observations have revealed that the orientation of the polarization angle at parsec scales may be affected by Faraday rotation (e.g., [4, 5]). Therefore, the analysis of the Faraday rotation in jets of AGN is of special relevance to determine the actual orientation of the magnetic field structure on the plane of the sky.

Several possibilities have been suggested as the source of the Faraday rotation seen in jets of AGN. The first suggestion that it is produced in a sheath that is in close proximity with the jet was given by [6], based on the observation of a rotation measure (RM) gradient across the jet width in 3C 273. Such gradients are expected if the sheath is threaded by a helical magnetic field due to the change in the line of sight component of the magnetic field across the jet [7]. Further observations have also provide evidence for the existence of such gradients in other sources (e.g., [8–13]). However, [14] have raised concerns about the claimed transverse RM gradients by arguing that most of these observations lack the necessary resolution transverse to the jet. Additionally, there is strong observational evidence for the existence of foreground clouds (e.g., [15, 16]) that may contribute significantly to the observed RM [9, 17]. In particular, [9] present a study of the radio galaxy 3C 120 revealing the existence of a localized region of high RM between approximately 3 and 4 mas from the core. A smooth sheath around the jet in 3C 120 cannot produce a localized region of enhanced RM (although it successfully explains the observed gradients in RM and degree of polarization along and across the jet), so the RM was...
Figure 1. 15 (left), 22 (middle), and 43 GHz (right) VLBA images of 3C 120 in 2001. Total intensity contours are overlaid at 0.5 (0.8; 1.0), 1.1 (1.7; 2.2), 2.5 (3.6; 4.6), 5.6 (7.7; 9.9), 13 (16; 21), 28 (35; 45), 62 (74; 95), 138 (158; 203), 310 (337; 433), and 692 (716; 923) mJy beam$^{-1}$ at 15 GHz (22; 43 GHz). Gray scale images show the linearly polarized intensity. Bars (of unit length) indicate the electric vector position angle, uncorrected for Faraday rotation. Note the different scale size used for each frequency.

assumed to originate in a foreground cloud, presumably interacting with the jet. In this paper we present further observations of the jet in the radio galaxy 3C 120 aimed to obtain a better understanding of the origin of the Faraday rotation seen in this source.
2. Observations

We present Very Long Baseline Array (VLBA) polarimetric observations of the jet in 3C 120 carried out in 2001 and 2007 at the standard frequencies of 15, 22, and 43 GHz. Observations during 2001 cover a total of 12 monthly epochs, while those in 2007 were performed on November 7. Reduction of the data was performed with the AIPS software in the usual manner [18]. Opacity corrections at 22 and 43 GHz were introduced by solving for receiver temperature and zenith opacity at each antenna. The feed D-terms (instrumental polarization) were found to be very consistent over all observed sources and to remain stable across epochs during the 2001 observations.

The absolute phase offset between the right- and left-circularly polarized data, which determines the electric vector position angle (EVPA), was obtained by comparison of the integrated polarization of the VLBA images of several calibrators with VLA observations, as well as archival data from the UMRAO, MOJAVE, and NRAO long term monitoring programs. Estimated errors in the orientation of the EVPAs lie in the range of 5°-10°. After the initial reduction, the data were edited, self-calibrated, and imaged both in total and polarized intensity with a combination of AIPS and DIFMAP. For further details we refer the reader to [9, 19].

The total and linearly polarized intensity images corresponding to the 2001 monitoring program and those taken during 2007 are shown in Figs. 1 and 2, respectively. These images show a rich structure in both total and linearly polarized intensity even at the shortest wavelengths, being the emission at 80 mas particularly remarkable, as reported by [20].

2.1. Faraday rotation images

The analysis of the sequence of Faraday rotation images obtained from the 2001 observations (see [9]) reveals the presence of an RM screen in 3C 120 whose properties remain constant over one year, allowing the determination of the mean RM image shown in Fig. 3. The Faraday
screen displays a localized region of enhanced RM between approximately 3 and 4 mas from the core, with a peak of $\sim 6000$ rad m$^{-2}$, as well as gradients across and along the jet. The RM image obtained from observations in 1999 January 10 (see [21]) is also shown in Fig. 3.

The rotation measure image for observations in 2007 combining the 15, 22, 43 GHz data is shown in Fig. 4.

3. Uncorrelated changes in the emitting jet magnetic field and Faraday screen
In order to quantify any possible variation in the Faraday screen across epochs we have subtracted the rotation measure values of 1999 January from those of the mean RM map for 2001 and computed the mean value of the difference in the components (jet areas in the mean 2001 map) labeled in Fig. 3. Component $S_1$ is located at the localized region of high Faraday rotation, which is found to remain in the same jet area as in 2001, with very similar values of the rotation measure. However, the RM-corrected EVPAs show significant rotation, with a mean difference between both epochs of $-64 \pm 9^\circ$. A similar situation is found for component $S_2$. On the other
hand, component $N_2$ shows no significant changes in either the RM-corrected EVPAs or RM, with variations of $-3 \pm 19^\circ$ and $810 \pm 930 \text{ rad m}^{-2}$, respectively. For component $N_1$ we also find very similar RM-corrected EVPAs, with a variation of $8 \pm 28^\circ$. However, the rotation measure in $N_1$ is observed to have changed significantly, with a difference between both epochs of $2730 \pm 910 \text{ rad m}^{-2}$.

Therefore, we find uncorrelated changes in the linear polarization of the underlying jet emission and the Faraday rotation screen. While the RM remains constant in the outer jet (including the localized region of high RM) the RM-corrected EVPAs of two particular components ($S_1$ and $S_2$) rotate by almost $90^\circ$. On the other hand, in the innermost 2 mas the RM changes significantly but without variations in the RM-corrected EVPAs. These uncorrelated changes suggest that the emitting jet and source of RM are not closely connected physically. Furthermore, the existence of a three-year-long stationary region of enhanced RM requires a localized source of Faraday rotation, which favors a model in which a significant fraction of the Faraday rotation measure found in 3C 120 originates in foreground clouds, rather than in a sheath intimately associated with the emitting jet. In this case, Faraday rotation studies will provide valuable information about the ambient medium through which jets propagate, but will not be able to reveal further details about the emitting jet, such as the line-of-sight magnetic field, and hence to test whether they are threaded by helical magnetic fields.

4. No detection of the localized high RM region 2007: an effect of sampling

The RM map of Fig. 4 does not show the localized region of high RM that was found in previous observations. This can be understood by examining Fig. 5, which shows the superposition of the 15 GHz total intensity images at the 2001.00 and 2007.85 epochs, revealing a significant change in the jet geometry with time. The position angle of the innermost 3 mas structure has changed from $-126^\circ \pm 2$ in 2001.00 to $-114^\circ \pm 2$ in 2007.85. That is, the jet direction of ejection rotated to the north by $12^\circ$ between these two epochs. As a consequence of this rotation the
components in the 2007 jet do not travel across the localized region of enhanced RM, failing to reveal it, since it is only through the motion of superluminal components that we are able to map the jet polarization owing to the increase in energy density and magnetic field ordering that they produce.

The rotation of the direction of ejection is in agreement with the helical structure suggested by [22], and the proposed precessing/helical models of [23] and [24]. In particular, [23] estimated a precession period of 12.3 yr, predicting a swing to the north of the direction of ejection in the jet between our 2001 and 2007 epochs, as is indeed observed. Similar changes in the geometry of the innermost structure of the jet have also been found in the BL Lac object PKS 0735+178 related to changes in the overall activity of the source [25–29].

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