*Extragalactic jets from every angle*
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# Rotation measures in AGN jets seen by VLA at 21 cm to 6 mm

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**Abstract.** We present Faraday rotation measure (RM) properties of seven active galactic nuclei (AGN), observed with the NRAO VLA at three epochs in 2012-2014. Data was taken at 1.4, 2.2, 5.0, 8.2, 15.4, 22.4, 33.5 and 43.1 GHz quasi simultaneously in full polarization mode. For the first time RMs were calculated in a range of wavelengths covering more than one order of magnitude: from 21 cm up to 6 mm. We measured RM for each source and showed a tendency to increase its value toward high frequencies according to the law $|RM| \sim \nu^a$ with $a = 1.6 \pm 0.1$. For 0710+439, we observed an increase over the frequency range of 4 orders of magnitude and measured one of the highest RM ever, $(-89 \pm 1) \cdot 10^3$ rad/m$^2$. Analysis of different epochs shows variations of the value and the sign of RM on short and long time-scales. This may be caused by changing physical conditions in the compact regions of the AGN jets, e.g., strength of magnetic field, particle density and so on.

**Keywords.** galaxies: active, nuclei, jets, magnetic fields

## 1. Introduction

Due to presence of highly magnetized media in the close vicinity of, and in AGN jets themselves, polarized emission is the subject of Faraday effects (Faraday 1993). One of them is Faraday rotation, which causes rotation of the plane of polarization of an electromagnetic wave. As a result, the intrinsic position angle (EVPA), $\chi_0$, of the jet electric vector will be rotated on a factor, depending on the plasma properties and observed wavelength. In the simplest case, when magnetized plasma isn't intermixed with the emission region and depolarization effects are small, the EVPA depends linearly on $\lambda^2$: $\chi_{observed} = \chi_0 + RM \cdot \lambda^2$, where the constant $RM$ is the rotation measure:

$$RM = \frac{e^3}{8\pi^2 \epsilon_0 m^2 c^3} \int n_e \mathbf{B}_{\parallel} \mathbf{dl}.$$

Thus, $RM$ is proportional to the magnetic field component, parallel to the line of sight, $\mathbf{B}_{\parallel}$ and particle volume density $n_e$ along the path $d\mathbf{l}$. The study of Faraday Rotation can be done only in multi-frequency observations.

Study of the polarized emission variations in AGN jets on short time scales is of particularly interest because it provides information about the jet structure and points to the locations of the regions where the emission originates and how it propagates to an observer.

Variability of the electric vector position angle in blazars on weekly, monthly and year-time intervals was shown more than once (e.g. D'Arcangelo *et al.* 2007, Jorstad *et al.* 2007, Agudo *et al.* 2014). So far, only few a works have been done (e.g. Gómez *et al.* 2011) analyzing the region of the jet where this variability goes from and it remains to be the subject of future studies.

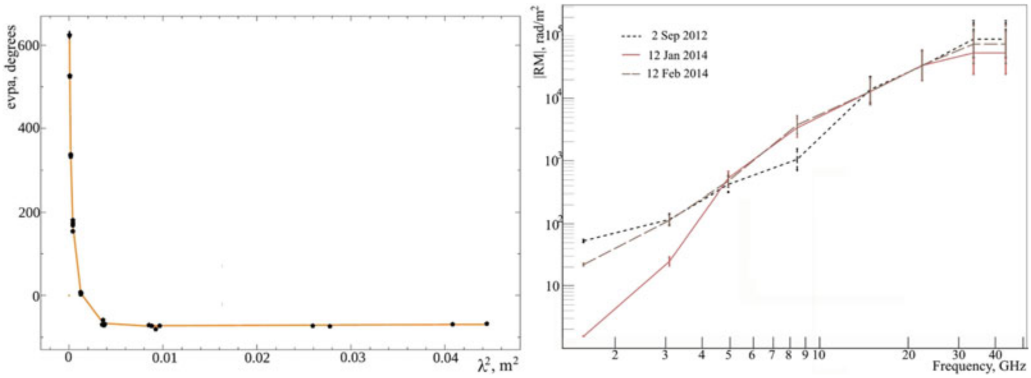


**Figure 1.** (left) Example of reconstructed dependence of electric vector position angle with wavelength squared for 0710+439. (right) Derived Rotation Measure versus frequency for 0710+439 at three epochs in logarithmic scale.

**Table 1.** Frequency setup.

| Band | Central frequency of channels, GHz | Channel bandwidth, MHz |
|---|---|---|
| L | 1.423, 1.485, 1.801, 1.863 | 64 |
| S | 3.055, 3.124, 3.197, 3.253 | 64 |
| C | 4.863, 4.925, 4.991, 5.053 | 64 |
| X | 8.365, 8.431, 8.497, 8.559 | 64 |
| $K_u$ | 14.863, 14.927, 14.991, 15.055 | 64 |
| K | 22.373, 22.457, 22.543 | 85 |
| $K_a$ | 33.473, 33.559, 33.645 | 85 |
| Q | 43.215, 43.343 | 128 |

The goal of this work is to probe the physical conditions in AGN jets and their structure by studying the Rotation Measures in different sources, through frequency and time.

## 2. Observations

We use data from the EVLA polarization calibration program (Taylor & Myers 2010), available from NRAO Archive† under project TPOL0003. Data consists of observations made at eight frequencies quasi simultaneously, with switching between frequencies made within 30 minutes sequentially. The bandwidth in each frequency band is 256 MHz. To avoid bandwidth smearing (Gardner & Whiteoak 1966) we split bands onto 2 to 4 frequency channels, depending on the wavelength. The resulting frequency setup is given in Table 1.

Target sources are presented in Table 2. There are 13 epochs of observations available with the frequency setup given above, starting in 2011. The configuration of the VLA during these observations goes through all possible setups. Here we present results from last 3 epochs only: 2 September 2012, 12 January 2014 and 12 February 2014.

† https://archive.nrao.edu/archive/advquery.jsp

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**Table 2.** Target sources.

| B1950 source name | Alias | Optical class | Spectral type |
|---|---|---|---|
| 0552+398 | DA 193 | Quasar | peaked |
| 0710+439 | B3 0710+438 | Radio galaxy | steep |
| 0736+017 | OI 061 | Quasar | double-peaked |
| 0851+202 | OJ 287 | BL Lac | flat |
| 0923+392 | 4C +39.25 | Quasar | flat one-peaked |
| 1253−055 | 3C 279 | Quasar | double-peaked |
| 1308+326 | OP 313 | Quasar | flat |

## 3. Data reduction

Data calibration and imaging is done using the Obit package‡ (Cotton 2008). Since our observations cover wide frequency range, we probe regions in AGN jets with different Faraday depths and different physical properties. Supposing the external to the jet nature of Faraday media, EVPA should depend from wavelength-squared linearly. To sum up these two assumptions, EVPA is linear with $\lambda^2$ within different intervals, but may arbitrarily change through the whole range of $\lambda^2$. Thus we identify the Rotation Measure as a linear slope in the dependence EVPA-$\lambda^2$ at individual $\lambda^2$ intervals. We let EVPA wrap on 180° between different channels and pick the solutions with the minimal $\chi^2$ and minimal number of wraps. Example of the reconstructed curve is shown on Figure 1.

Length and number of the individual intervals, where RM were obtained, varies from source to source. For instance for 0710+439, given on Figure 1, RM were identified at seven $\lambda^2$ intervals, solutions for which with frequency are shown on Figure 1 with solid curve.

Target sources are roughly point-like even for the most extended VLA configuration. Thus, we carry out the analysis only on the central region of the map, which is composed of the optically thin and thick components of the parsec-scale jet. To conclude what component dominates in the map we analysed fractional polarization and spectral index of the sources.

Spectra have different types: flat or steep behavior, one or double peaked and are given in Table 2. The distribution of the fractional polariation, given on Figure 2, also indicates that we observed a mix of regions with different optical depths.

During the analysis, each epoch were considered independently. The typical value of rotation from Galactic media (Taylor *et al.* 2009) is a few radians per meters squared which is significant only at low frequencies. We didn't correct our measurements for it.

## 4. Results

We have estimated RMs for all target sources through the whole $\lambda^2$-interval at three epochs, the distribution of which is represented on Figure 2. Variations of a few orders of magnitude in the value of RM can be seen there, meaning strong variations of physical conditions in AGN jets among sources.

For the majority of the cases, wraps of 180° in EVPA at some frequency bands relative to the other bands reduces $\chi^2$ considerably. Moreover, an analysis of different epochs shows good agreement between estimated values of RM and its trend with frequency. It

‡ http://www.cv.nrao.edu/ bcotton/Obit.html

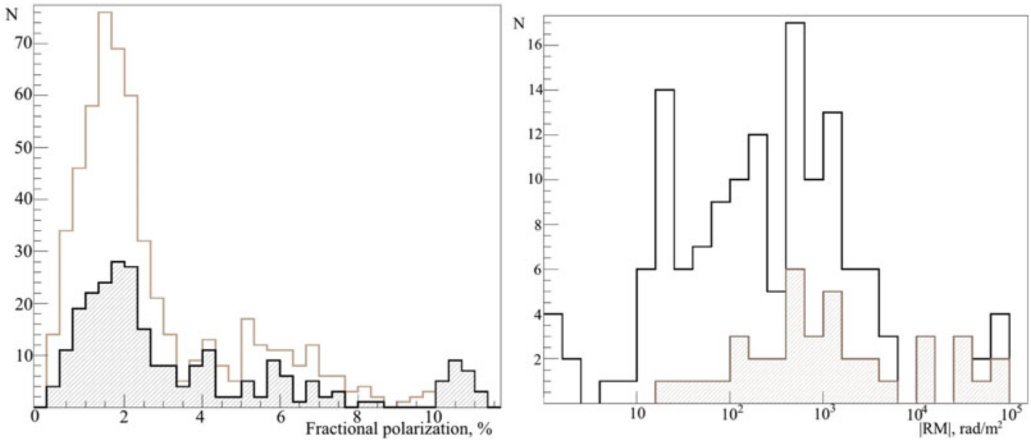


**Figure 2.** (left) Distribution of the fractional polarization for all sources at eight frequency bands and at three epochs of obsevations. Hatched region indicates 14 - 43 GHz frequency range, white - 1.4 - 14 GHz range. (right) Distribution of the obtained Rotation Measures for all target sources at eight frequencies at three epochs. Shaded region indicates measurements in 14 - 43 GHz range, while white region represents 1.4 - 14 GHz frequency range.

is important to note that sometimes we see non-trivial EVPA-$\lambda^2$ behavior which can not be fit by a linear slope. This means that other Faraday effects take place there, such as mixing of the rotating media with the emission region, multi component Faraday media with different optical depths and others.

A tendency of RM to increase in value with frequency $|RM| \sim \nu^a$, example of which is given on Figure 1, is found for all sources. We have used RM values for all available $\lambda^2$ intervals to determine power $a$ for every target performing a linear regression of lg$|RM|$-lg($\nu$) curves. An average over all targets and three epochs is found to be 1.6±0.1.

Because of synchrotron self absorption increasing towards the jet base, we see regions being located closer to the central engine at higher frequencies. A possible explanation of the trend of higher RM at higher frequency is that higher frequencies probe regions closer to central engine with a denser media and stronger magnetic fields. This trend indicates variations of $n_e \mathbf{B}_{\|} d\mathbf{l}$ by up to five orders of magnitude with distance from the central black hole. Theoretical estimations give a value of $a = 2$ (Jorstad *et al.* 2007), asuming an outflowing sheath around a conically or spherically expanding jet with a helically-shaped magnetic field. Our low value of $a$ may result from underestimated contribution of the emission from optically thin regions. We plan to conduct a detailed study of this effect in the future.

*Case of 0710+439.* For this source we obtained the following values of RM (in rad/m$^2$) in the 33 - 43 GHz range: $(-89 \pm 1) \cdot 10^3$, $(-54 \pm 3) \cdot 10^3$ and $(-74 \pm 1) \cdot 10^3$ at three consecutive epochs given above. These values were measured independently and are in good agreement. The behavior of RM over the full frequency range for 0710+439 is shown on Figure 1.

So far, high values of Rotation Measure in AGNs were observed in only a few sources (e.g. Trippe *et al.* 2012, Jorstad *et al.* 2007, Attridge *et al.* 2005) with the highest value of $5.6 \cdot 10^5$ rad/m$^2$ for Sagittarius $A^\star$ (Marrone *et al.* 2006).

Observations of all these sources, except at the center of our Galaxy, are non-simultaneous with the differences between the observational epochs at different frequencies of up to a few months and even years. Our observations have an advantage over these measures, and thereby don't include time variability of the sources which may result in dramatically different interpreted and real polarization pictures. Thus, 0710+439 has one of the highest recorded values of RMs so far made under assumption that Faraday screen doesn't mix with the jet emission region. It may mean that 0710+439 holds dense media with strong magnetic fields in the innermost jet regions.

To continue this study we plan to analyze the other 10 epochs of observations for a more detailed picture of Rotation Measure behavior in time.

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