Magnetic Field Structures of BL Lac Objects on Decaparsec Scales

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Abstract

Relatively few Very Long Baseline Interferometry (VLBI) polarization observations have been carried out at 18 cm. The importance of such observations lies in their ability to reveal information about the jet magnetic (**B**) field structure and the environment of the jet on scales intermediate between those probed by higher-resolution VLBI and connected-element interferometers such as the Very Large Array. We have obtained polarization observations of 34 BL Lac objects [Kuhr & Schmidt 1989] with the Very Long Baseline Array (VLBA), at 4 separate wavelengths in the 18-20 cm band. The 18-cm jets typically extend to tens of parsecs. In some cases, the decaparsec jet is a continuation of the jet on smaller scales, while in others, we see appreciable bending. We have constructed Faraday rotation-measure maps and used them to study the jet **B** field structures and distribution of thermal plsama around the jets. The Faraday rotation is typically large at these wavelengths, and knowledge of the rotation-measure (RM) distribution is essential to derive the **B** field structures of the jets. The high sensitivity of these observations to Faraday rotation makes them an effective tool for studies of possible interactions between the jets and the media through which they propagate.

Project Description

BL Lac objects are active galactic nuclei with weak or nonexistent optical line emission and highly variable intensity and polarization.

To our knowledge, the images obtained for this project are the first 18 cm VLBA polarization images of BL Lac objects. Since 18 cm is longer than the wavelengths of most previous observations, we can map the jets further from the active nucleus. There are two reasons for this: (1) the radio emission is synchrotron radiation, which is more powerful at longer wavelengths in optically thin regions, such as the jets, and (2) the resolution is proportional to the observing wavelength λ, increasing sensitivity to faint, extended emission in longer-wavelength observations.

The effect called Faraday rotation results in the rotation of the plane of polarization when the radiation travels through plasma with charged particles and **B** fields. The rotation is given by $\Delta\chi \propto \lambda^2 \int N_e B_{||} dl$, i.e., the integral of the line of sight **B** field $B_{||}$ times the electron density N_e along the line of sight.

We have carried out the initial calibration of the data, and have made maps of the total intensity and linear polarization at the four wavelengths near 18 cm for most of the objects in the sample. Faraday rotation is typically large at these long wavelengths, and must be taken into account if we wish to derive the intrinsic B-field structure of the source. Before making a Faraday-rotation map, we subtract the Faraday rotation occurring in the Milky Way – this way, the Faraday-rotation map obtained is due to magnetized plasma near the AGN. By correcting the observed polarization angles for the total observed Faraday-rotation, we can reconstruct the intrinsic **B** field structure of a source.

Active Galactic Nuclei usually have an optically thick core region and an optically thin jet. The linearly polarized radiation in the optically thin/thick case is perpendicular/parallel to the **B** field responsible for the synchrotron radiation.

There is mounting evidence that helical **B** fields are present in the jets of BL Lac objects [Gabuzda 2006], and quite possibly other AGN as well. We thus expected that we might find signs of helical **B** fields in our 18 cm polarization observations. Bearing in mind that we see the objects projected onto the plane of the sky and that the jet is pointing at a small angle to the line of sight, if the **B** field is indeed helical and has a relatively large pitch angle, we will see the **B** field vectors as perpendicular to the jet, possibly becoming longitudinal toward the jet edges (a **spine-sheath** structure). Another clue we can look for is a **gradient in the rotation measure** perpendicular to the jet's direction, due to the changing line-of-sight component of the helical field (see the poster by Mahmud & Gabuzda).

References

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Observations and Discussion

Here we present resuilts for several objects to date. In all cases, the observed polarization vectors have been corrected for the total observed Faraday rotation. In all but one instance (0119+115), we find signs of a helical jet **B** fields.

0735+178

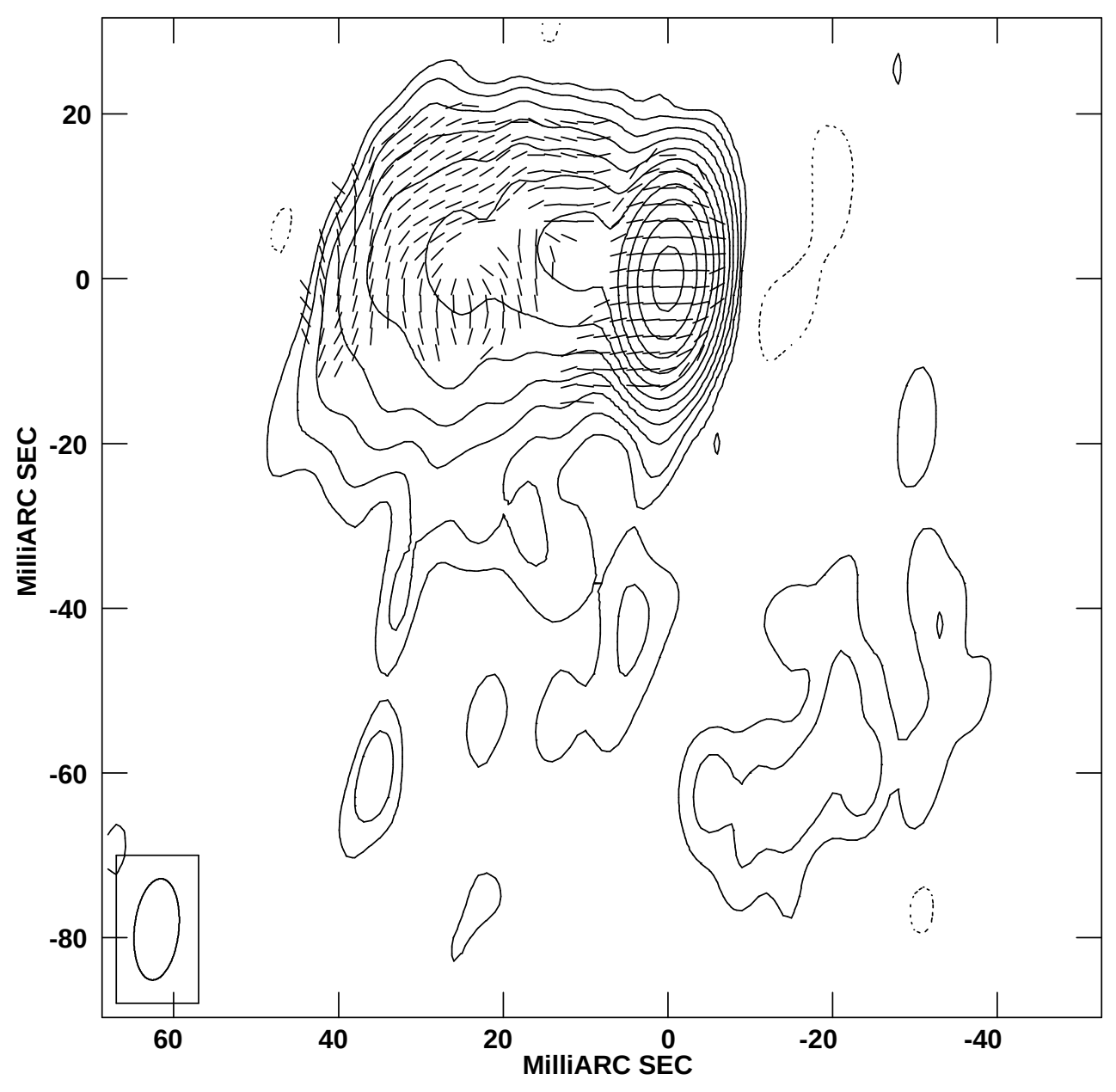

FIGURE 1: The structure of the magnetic field in 0735+178.

In contast to shorter wavelength observations, which show the jet-axis oriented in a roughly NE direction, with a "zig-zag" structure visible at some epochs [Gomez 2001], the 18 cm jet (Fig. 1) extends almost exactly Eastward. There is some evidence that the jet bends toward the South and further to the Southwest, suggesting a spiral-like structure.

The superposed **B** field lines indicate that the field is perpendicular to the jet near the central axis, while the field at the northern edge of the jet is oriented along the jet, apparently curving with the jet as it bends - in other words, we see a spine-sheath structure, characteristic of helical fields.

1803+784

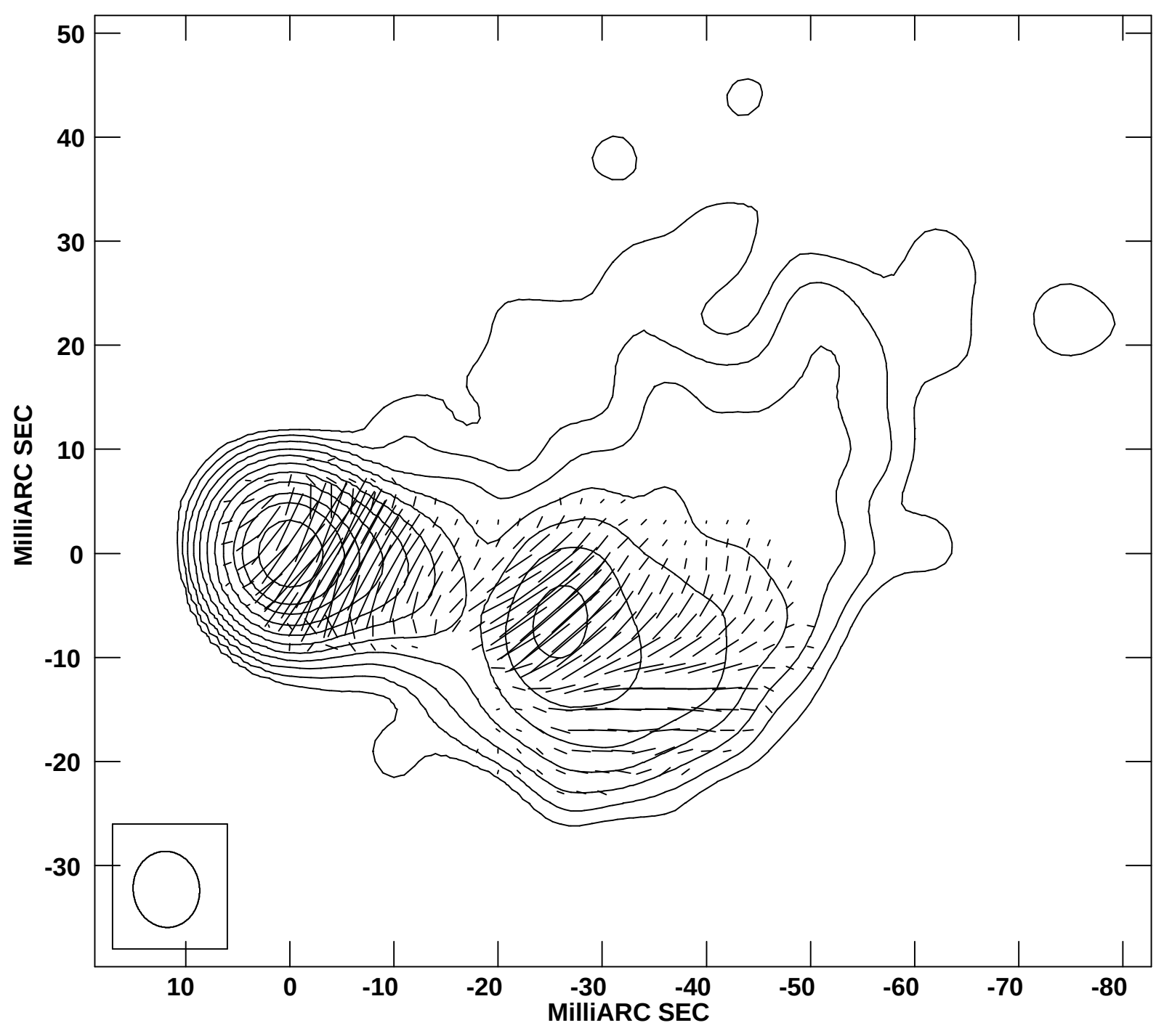

FIGURE 2: The direction of the **B** field in 1803+784.

This AGN is known to show evidence for the presence of helical jet **B** fields based on shorter-wavelength measurements (see the poster by Mahmud & Gabuzda). Our 18 cm image (Fig. 2) enables us to determine if there is also such evidence further out in the jet.

The **B** field is perpendicular to the jet all along the central part of the jet, suggestive of the toroidal component of a helical field. The **B** field is very different at the southern edge of the jet, and bears no obvious relation to the jet direction. The origin of this **B** field structure is not clear, but may be related to the bend to the north observed in this same region.

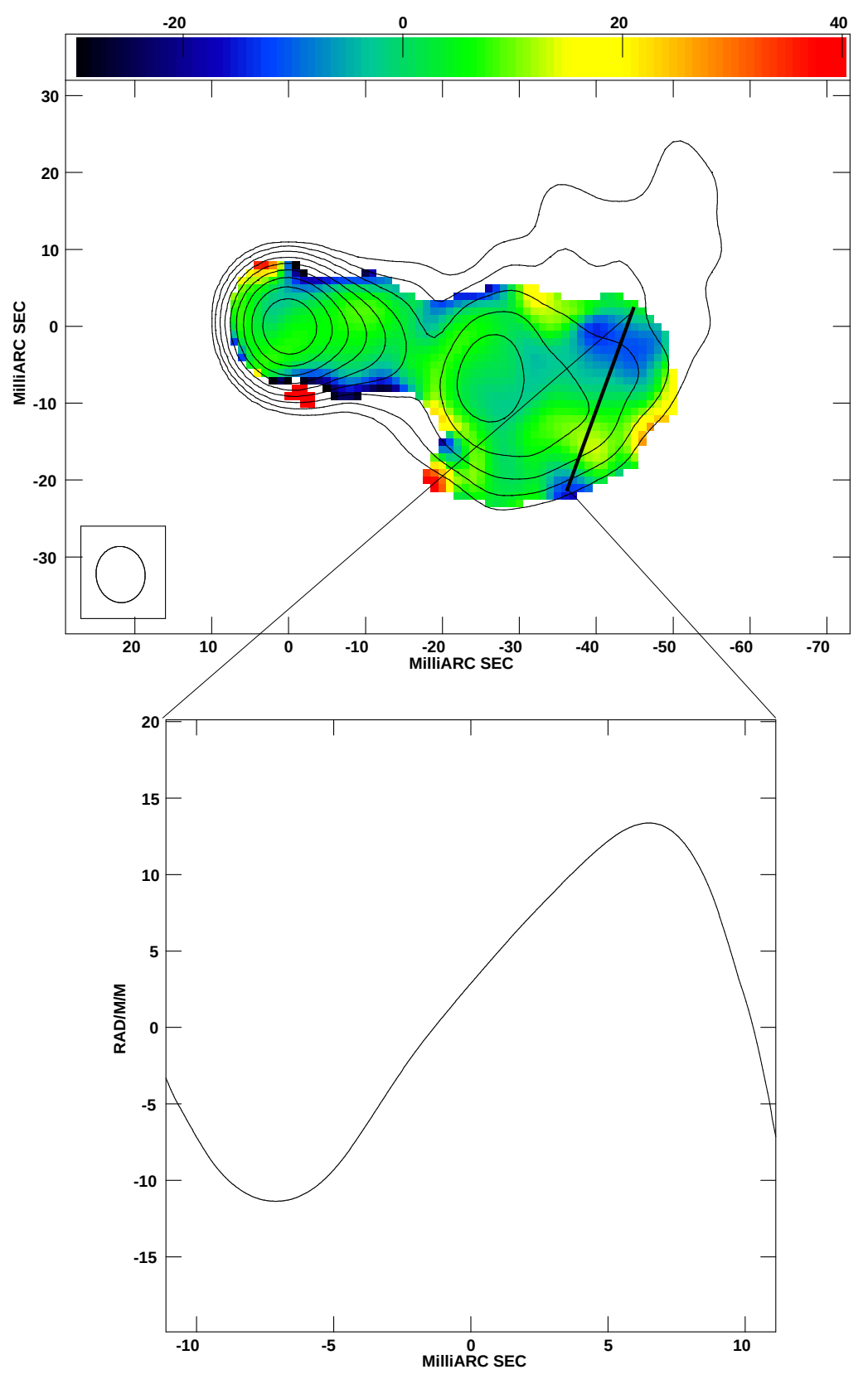

FIGURE 3: The Faraday rotation measure in 1803+784 and a slice in the RM distribution perpendicular to the jet direction.

Figure 3 shows a tentative gradient in the rotation measure across the jet, providing further support for the presence of a helical jet **B** field in this object.

1147+235

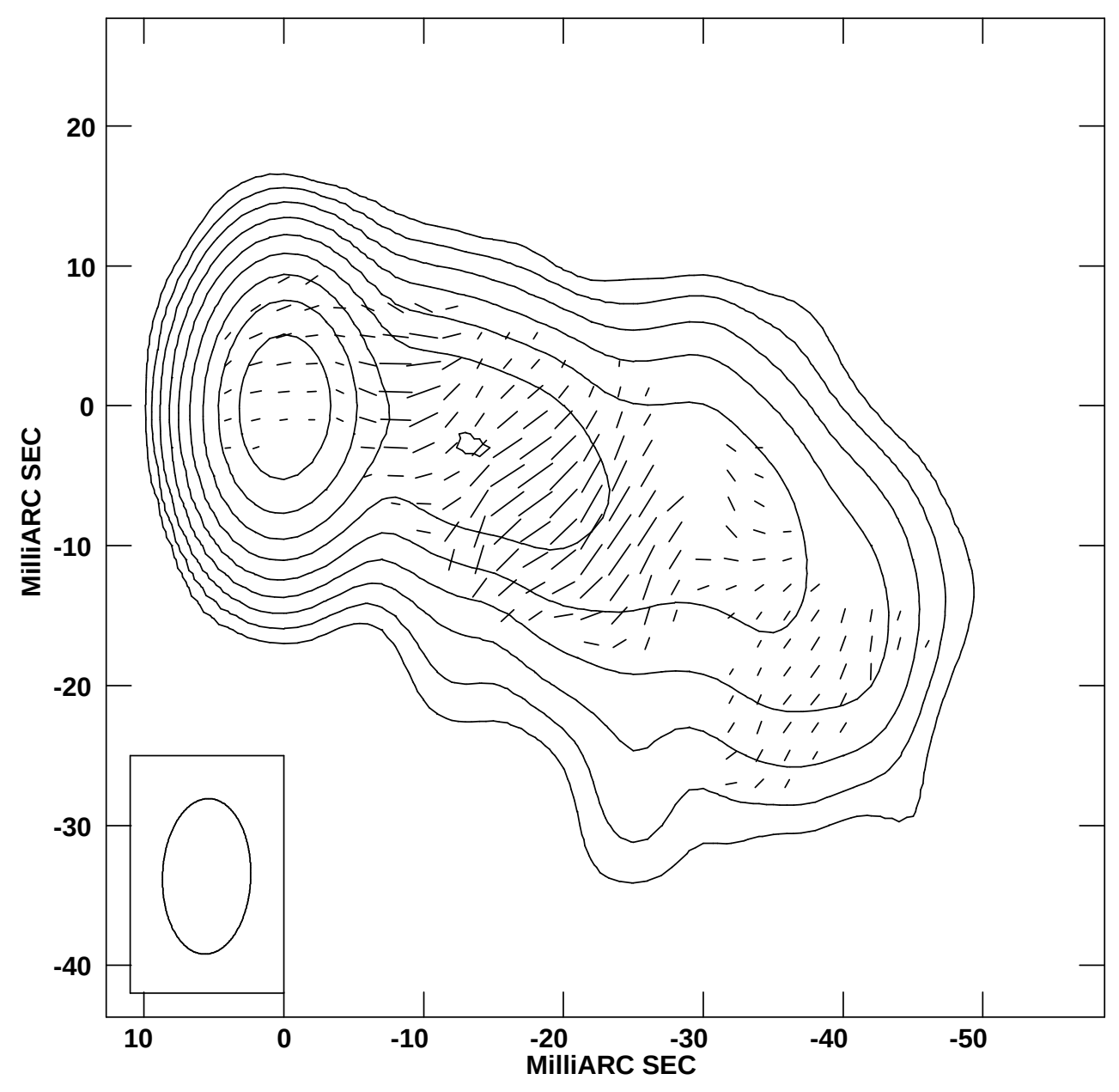

FIGURE 4: **B**-field structure in 1147+235.

The **B** field lines in this object (Fig. 4) are almost perpendicular to the jet's direction, again suggestive that we are observing a toroidal magnetic-field component. There are also signs of a poloidal field at ∼ 35 mas West from the core.

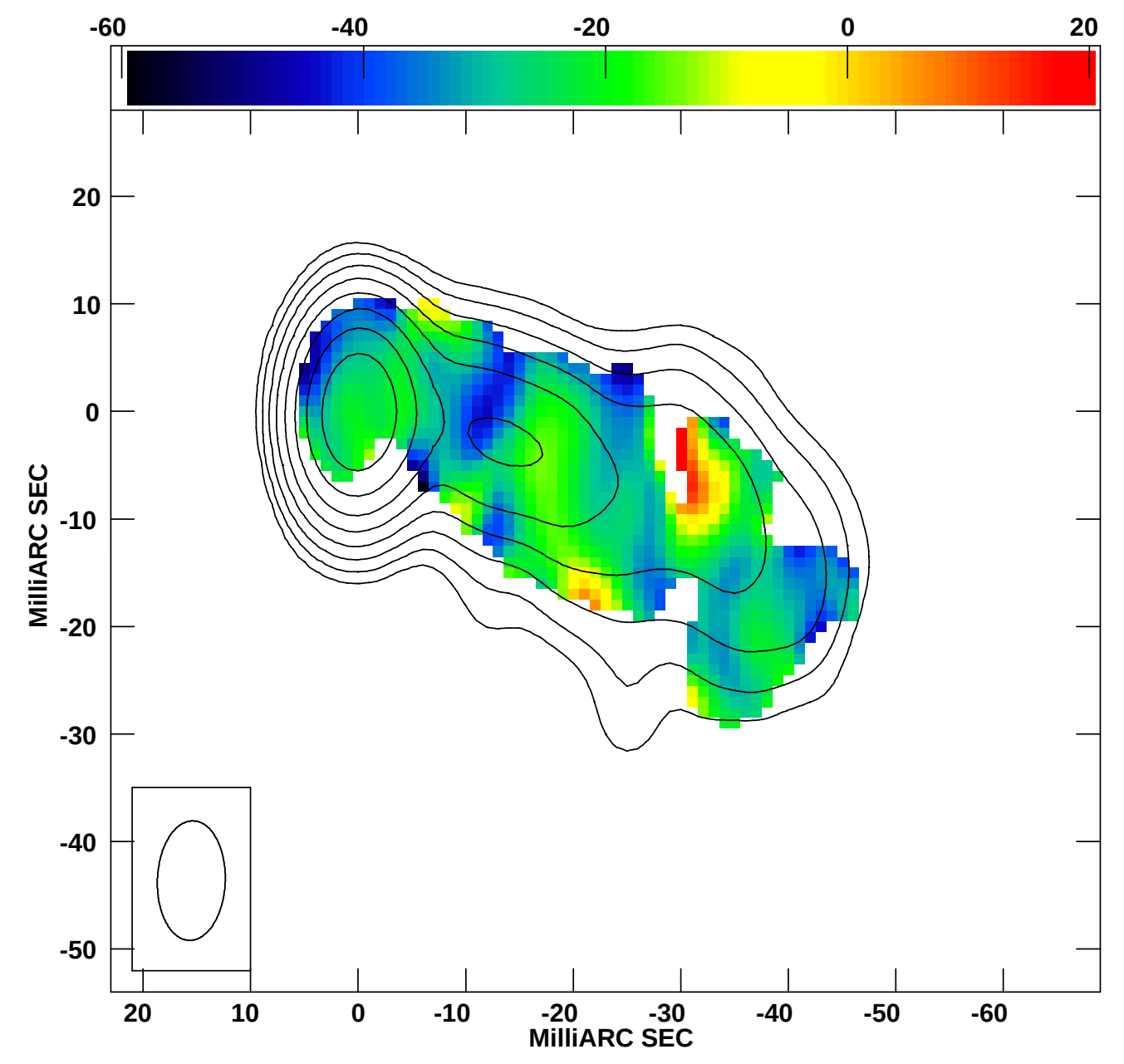

FIGURE 5: Rotation measure map of 1147+235.

0119+115

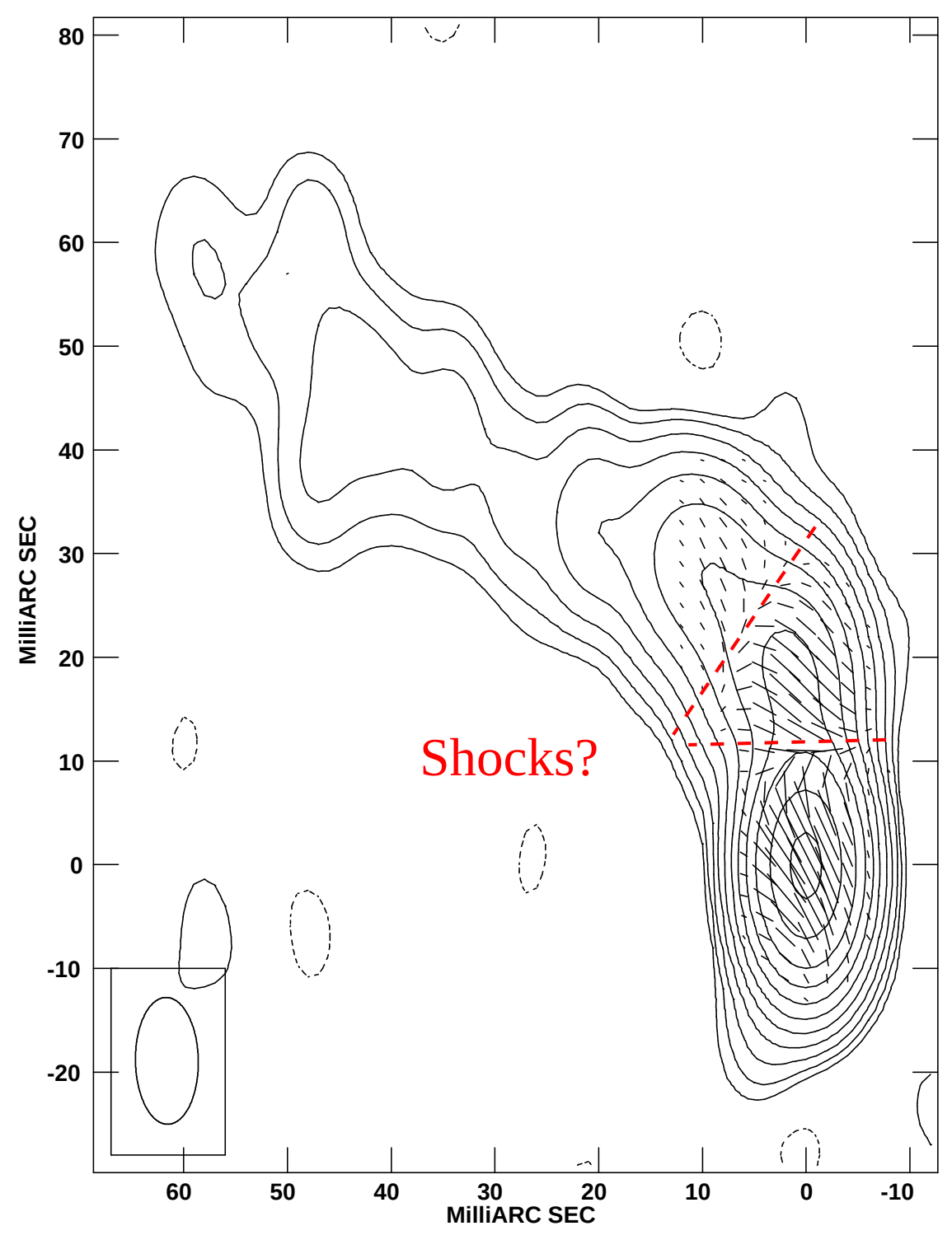

FIGURE 6: **B**-field structure in 0119+115.

This compact AGN is unresolved in previous 5 GHz maps [Gabuzda 1999]. The overall **B** field is aligned with the jet (Fig. 6). Thus, if this jet also has a helical field, the poloidal component is considerably stronger than the toroidal component. It is interesting that the core shows a higher enhancement in its Faraday rotation (Fig. 7) than is typical of our other rotation-measure maps, suggesting a higher electron density in the core region. The **B** field in this object displays sudden changes in two places (marked in Fig. 6), possibly indicative of shocks in the jet that compress the **B** field in a plane perpendicular to the jet direction.

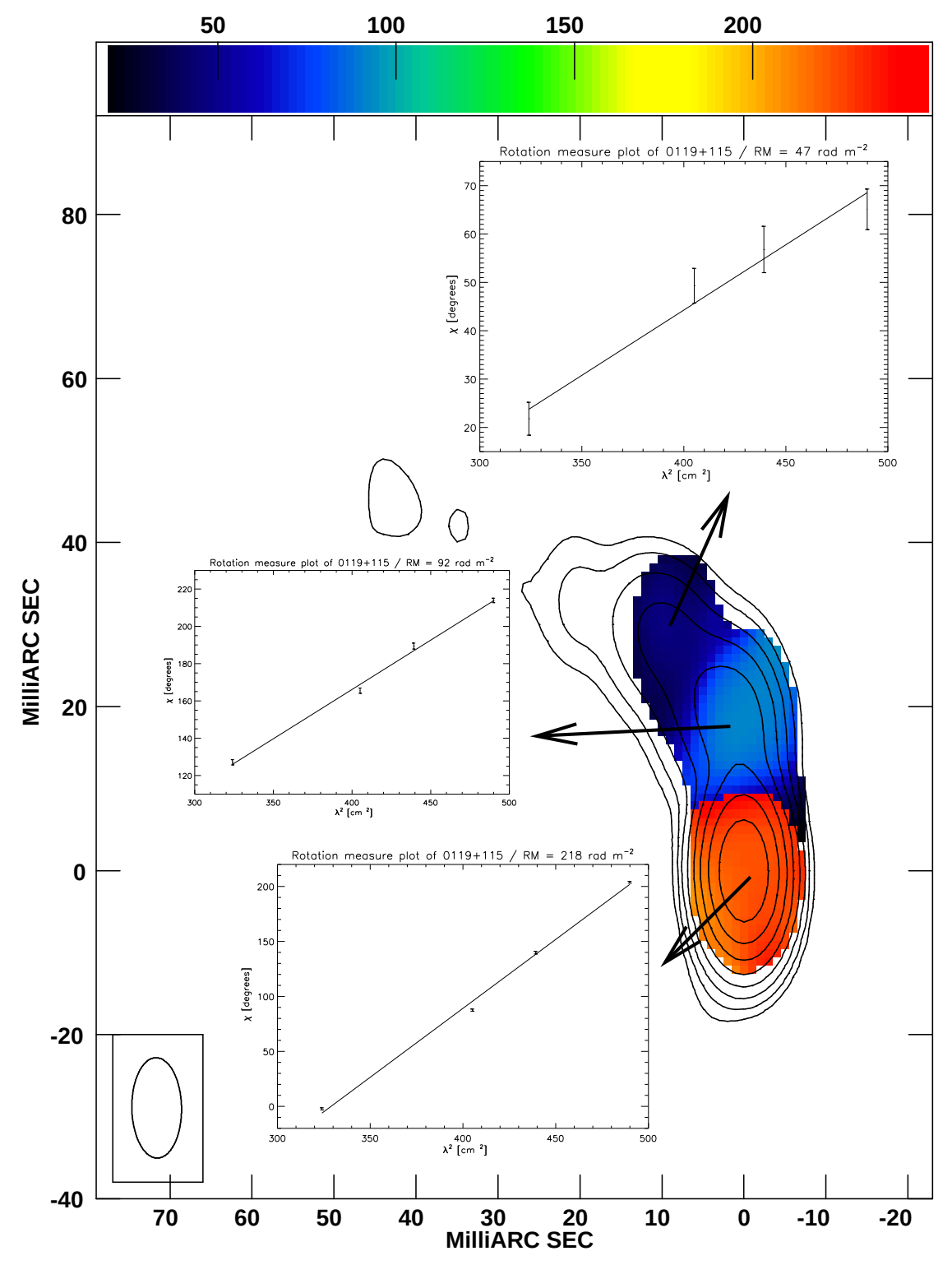

FIGURE 7: Rotation measure map of 0119+115. The plots of polarization angle vs. λ^2 show good fits to a λ^2 law. Since the rotation in the core and inner jet is substantially more than ∼ 45°, the Faraday rotation must be external [Burn 1966].

We can obtain a rough idea of the jet **B** fields in these objects, following the analysis of [Gabuzda & Chernetskii 2003]. The rotation measures are typically a few tens of rad/m^2, say RM $\simeq$ 40 rad $/m^2$. We will assume the gas kinetic and magnetic energy to be in equipartition and to have a temperature of $T = 10^4 K$, and for the sake of this example, use a redshift of 0.50 Using the formulae $RM \simeq 8.1 \times 10^5 N_e B_{||} L$ and $N_e kT \simeq \frac{B^2}{8\pi}$, and supposing the $B_{||} \simeq B$ (N_e is the electron density, $B_{||}$ the line of sight magnetic field, and L the line of path length in the Faraday screen), we get $B \simeq 15 \left(\frac{L}{pc}\right)^{-1/3} \mu G$, implying plausible **B** fields for path lengths of ∼ a parsec, consistent with predictions for the magnetic fields expected for kiloparsec scales ($B \sim 0.15 - 1.5 \mu G$) [Laing & Bridle 1987].